Reengineering Education: Systems Engineering and the LearningGraph as a Means to Develop a Coherent Learning Data Architecture

by

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Submitted to the Program of Media Arts and Sciences, School of Architecture and Planning in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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ABSTRACT

Today's educational systems are complex, political, sociotechnical ecosystems that struggle to meet the needs of most learners and societal demands—and most critically, struggle to change. Yet, learners globally need access to high quality learning environments and coherent learning pathways that support them to thrive in our complex world. Fundamental to every learning technology, environment, and system, is a learning data model and architecture that helps to organize the learner's experience. To date, in traditional educational systems, this has largely been dominated by public policy curriculum standards, which have tremendous limitations and shortcomings on classroom practice and their ability to support complex learning technologies. At the same time, over the past several decades significant advances have been made in the learning sciences, learning analytics, and learning technologies that have greatly expanded our ability to model learning and provide immersive and adaptive learning environments. Yet each of these communities rarely coordinates and aligns these data models. The disjointedness of these structures leaves their architecture in a messy, challenging state, unable to successfully carry us into an advanced future of learning technologies and effective learning ecosystems.

This dissertation explores the use of Systems Engineering as a means to reengineering this critical infrastructure of the system, through the LearningGraph—a research initiative that used this methodology to create a unified data structure for modeling learning constructs in a coherent learning data architecture. The aim of the project is to ultimately inform a new infrastructure to support learning development across learning technologies and environments. In doing so, we create the foundation for closing significant gaps in the current system: between learning sciences research and practice; curriculum and assessment design; the design of learning technologies and all the aforementioned components; and between and across education systems globally. Moreover, it creates the potential for the foundation of a very different future for learning ecosystems.

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DEDICATION

This work is dedicated to my grandparents Helen, Alfred, Barbara, Jack, and Joseph—who personally gave his time, attention, and love in the endless support of my crazy ideas and dreams as a kid, helping me to build prototypes of them, giving me my own little ‘Media Lab’ right in his basement workshop.

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Jennifer Sterling Groff is an educational engineer whose work focuses on redesigning learning environments, experiences, tools, and system structures using emerging technologies. She is also the co-founder of the Center for Curriculum Redesign, an international NGO dedicated to redesigning the general curricula for the 21st century. Previously, Jen was the Vice President of Learning & Program Development for the Learning Games Network—a non-profit organization spin-off from the MIT Education Arcade, where she led the national Playful Learning initiative, and in 2009 was named a Fulbright Scholar to the United Kingdom, where she continued her work on system innovation at Futurelab in Bristol, UK.

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Chapter I

INTRODUCTION

Education is the foundation to a free, literate, and thriving society. Stated more completely, access to free, equitable, and quality learning environments at scale is the foundation not just for a healthy and thriving society, but for healthy, thriving individuals in that society. It is a promise we should be able deliver on for all young people. Yet delivering on that promise has proven challenging, and doing so in our rapidly evolving world will require us to dramatically rethink what that can – and should – look like. How do we rethink the environments, the experiences, and then the systems structures we use to deliver better learning at scale?

What, then, might high quality, equitable, and meaningful learning experiences and environments look like? This question has been asked for quite some time, and we in fact have many good answers. The past several decades have produced a wealth of research and innovation in the learning sciences to help point the way towards delivering on this promise. Now more than ever, we have a broad range of innovative curricula, technologies, pedagogies, and models of learning environments that embody the principles of deep, meaningful, and powerful learning. Yet, the vast majority of these innovations have not scaled into the everyday experience of learners, and we still largely have education systems that in many dimensions are diametrically opposed to our understanding how people learn, grow, and thrive.

This gap – this chasm – between what we know and what we actually do, can no longer be ignored. It is the challenge that most pressingly faces our children and their futures, today. As such, we must then turn our attention to the structures that create their everyday learning experiences, and how we might unravel them, to dramatically reimagine them.
EDUCATION SYSTEMS, ENGINEERED

Education systems are complex, interconnected, distributed systems, and it is the nature of this complexity and interconnectedness that has made them notoriously difficult to change (Hargreaves, Lieberman, Fullan, & Hopkins, 2014). History, and a considerable amount of research, has demonstrated that systems of education are notoriously difficult to manage well, and to reform. Decades of work on centralized, large-scale reform initiatives across a range of educational systems and countries have repeatedly shown the limited impact of these efforts on learning and achievement of young people (Fullan, 2000, 2011a; Harris, 2003). Although the critical need for transformation of learning environments and systems has been well-established, the relationship between systems change and classroom practice has shown to be exceedingly complex (Levine, 2009; Smylie & Perry, 1998). Unfortunately, lack of understanding of this complexity and interconnectedness, and subsequent application of technical approaches to address this complexity has resulted in such poor impact and little transformation (Fullan, 2010).

Education systems exhibit a number of key traits that are contributing factors to this challenge—including a wide range of agents and variables, complex interrelationships, long cycles and delays in policy implementation and data collection, highly dynamic and uncertain environments, and measurement variances/shortcomings (Groff, 2013; Lave Jr & Kyle, 1968; Mital, Moore, & Llewellyn, 2014). These are classic traits of complex, dynamic systems (Sterman, 2001).

Cyberneticists and systems scientists have long understood the need for emphasizing the interactions and connectedness of the different components of a system in order to more effectively understand the structure and functions of systems and their models. As a result, cybernetics and systems engineering have helped enable transformative impact in a range of fields—outside of education.

Even as early as the mid-1960s, researchers have argued for identifying and working with this level of complexity in order to build better learning environments:

"Any attempt to meaningfully aid education decision-making must appreciate the complex environment in which such decisions take place. In other words, the various analysis tasks must occur within a framework which embraces the total system and which integrates the problem elements into a unified whole."

— Lave & Kyle, 1968

Yet few programs, initiatives, or agents in education systems understand the need for this type of complexity approach—let alone have the purview or support for it (Sterman, 2001).
Designing the Future at Bell Labs

Russell Ackoff is known for his tale of how Bell Labs imagined – and created – the telephone system of the future (Ackoff, 2006). It was 1951, and Ackoff was visiting Bell Labs on what happened to be a particularly important day. The vice president there had called a last minute emergency meeting of key personnel—based on his demeanor, something was very wrong. He finally approached the podium, and explained “Gentlemen, the telephone system of the United States was destroyed last night.” After much explanation, the group assembled was aghast. Once the color returned to the VP’s face, he began to laugh and explain the hoax—it was motivation to set the stage for the task they were about to engage in, and to explain that not a single one of any of the most important, current technologies being used in the modern telephone system had been developed in this century. Innovation, in this space, had been barren for quite some time. Using this context as a backdrop, he presented his teams with a challenge: “We are going to begin by designing the system with which we would replace the existing system right now if we were free to replace it with whatever system we wanted, subject to only two not-very-restrictive constraints: First, technological feasibility, meaning we cannot use any but currently available knowledge. No science fiction. We can’t replace the phone with mental telepathy; Second constraint, the system we design must be operationally viable—meaning it must be able to function and survive in the current environment.”

From this context, the design teams went on to build a range of innovations, still in use today—including the keypad dial, touch-tone phones, consumer ownership of phones, call waiting, call forwarding, voice mail, caller ID, conference calls, speakerphones, speed dialing of numbers in memory, and mobile phones. Such a “green field” approach created the possibility for innovations that might never have come about, yet have brought much advancement to end user’s experience and benefit.

ENGINEERING FOR LEARNING AT SCALE

Such approaches have rarely been used in education. What innovations and new future might we be able to develop if we did?

Education is arguably one of society’s most complex endeavors. Unlike mechanical engineering and chemical engineering, education’s primary object of focus (learning) is invisible and largely intangible; the end users (learners and educators) have limited say and authority over decision-making, while multiple layers of local, state, and national policies come together to create the governance structures that ultimately largely define the everyday practices that ultimately define learning outcomes (Bar-Yam, 2004). This is not to say that building a skyscraper or even landing a man on the moon are not incredibly complex endeavors. Yet these are concrete, bounded, and tangible objectives. This is also not to give the impression that education is just a free-for-all that has no rigor applied to it. In fact, today we can stand on an considerable foundation or research, methods, and
applications that define the nature of human learning. Yet given the challenges and complexity of enabling quality learning at scale across our societies, now more than ever we need a science of education systems, and to apply the same intensity of approaches to the design of these systems. Now more than ever, we need educational engineers—to tackle the reengineering of the systems that deliver learning at scale.

**Engineering Future Systems of Learning**

*How do you create systems and structures that manage learning experiences for millions of children?* Certainly, it is no simple task. Through the late 1800s and early 1900s as one-room schoolhouses evolved into the education systems we have today, consider the design decisions that had to be made about how to manage that complexity—long before our current technologies were available. In this light, and given the previously defined goals of the system, the system structures such as grade levels, school timetables and calendars, curriculum documents, etc., make a fair amount of sense. Yet, given a blank slate today, is this what you would design?

We can view these existing educational system structures through the lens of “first-order structures”, such as curriculum/standards, assessment, grade levels, etc., which act as core pillars to the structure of the system and influence the manifestation of the second-order structures—such as pedagogy, application of learning technologies, etc. In other words, the shape and nature of the first order structures dictate the type and the manner in which the second order structures integrate (Adamson, Åstrand & Darling-Hammond, 2016). As a result, these structures have a significant impact on the daily practices and ultimate outcomes of the system (Darling-Hammond, 2004).

Assessment has garnered much of the attention as the foremost first-order structure of the system that must be reformed, as it – and the policies that implicate its use – are the ‘tail that wags the dog’, and ultimately drives much of the changes and mechanics that translate into day-to-day practices of the system (Darling-Hammond, 2004). Although the considerable focus on improving assessments is warranted, *curriculum* (or the “what” of education—what is to be learned, including skills, knowledge, competencies) – or more specifically, *how we organize and model the learning outcomes* – is often overlooked as an area in deep need of redesign.

The curriculum of many schools is generally dictated by the state or national standards under which they operate. Content standards have become the core pillar of most educational systems because they set the course for the way in which so many other elements of the system play out—dictating what is taught when, determining the very nature in which instruction and assessment are implemented, deeply influencing the type of curriculum and instructional materials are built, and implicating what/how data is modeled and collected in many new learning technologies.

In the U.S., when the new Common Core State Standards (CCSS) were released and adopted by 46 states, we essentially saw an entire reorganization of the educational ecosystem around them. Publishers scrambled to
create new instructional materials that were aligned with the CCSS (and/or retrofit previous materials to now explain how they align with it), learning technologies needed to do the same in order to be purchased/adopted, and new national assessments were developed. In Brazil, a new national curriculum was launched in late 2017, where the same dynamics are playing out. It is a pattern seen over and over again in educational systems around the world.

Once policy is set around a set of standards, it becomes the bar by which everything else is structured because it becomes the non-negotiable starting point for teachers, the end-users of the system. Instructional materials, learning technologies, assessments, professional development, all are nearly designed either using the standards as their starting point or are designed in coherence with them. In other words, because of the policy surrounding state and national standards, and therefore dictate what schools teach, all the other core elements used in educational systems are influenced, adapted, and aligned to them. When the CCSS was launched, for example, we saw a cascade effect of adjustments in the system, where two new assessment consortia were established to create the assessments that should support the new standards, and publishers moved quickly to retrofit their previous materials to align to the CCSS while also developing new materials. What can be seen is that in the end, nearly everything comes back to these standards. As such, they serve as essentially as the ‘foundational layer’ to the learning data infrastructure in education.

Yet the infrastructure and methods by which we currently manage this core element of the system – largely standalone, flat PDF documents adopted by each system that only get revisited every 10-15 years – is problematic on a number of levels—including the manner in which we attempt to align instructional tools, capture learning data, and share resources and make meaning across systems or sets of standards. Moreover, key players in education, such as assessment designers and learning scientists, work with critical material related to content, but in a way that doesn’t currently map onto or coordinate with content standards. The ways in which we model learning in the learning sciences and leading edge technologies very poorly aligns with the infrastructure set by standards, fundamentally leaving us at impasse, where the evolution and impact of modern learning technologies as a key part of this ecosystem will be seriously impeded. This inadequate infrastructure is both a data and socio-technical problem that is ripe for re-engineering. Purposefully engineering a learning data architecture to work across these practices and user groups has the potential to significantly reduce these gaps.

**THESIS OVERVIEW**

The focus of this thesis is the development of a reengineered data model and architecture to more effectively support the needs of all users, practices, and tools across educational ecosystems. Being able to successfully address these challenges through an integrated and modernized infrastructure has implications for not only improving educational systems, but for opening up learning methods, tools, and practices beyond educational
systems through having a better infrastructure for capturing and supporting individual learning pathways in all learning environments.

For decades we have used archaic tools such as grade levels to help manage the complexity of supporting large numbers of learners in their development, and with a much more robust infrastructure for managing and modeling learning progress, we are enabled abandon grade levels and other system design parameters which have such detrimental effects on learners.

A fundamental principle of system dynamics states that the structure of the system gives rise to its behavior (Sterman, 2001). Therefore, if we are not seeing the behaviors we desire, we must look to redesign the fundamental structures of the system. That is the focus of this thesis, looking specifically at a central axis of the current education system infrastructure: the way in which we model and manage learning data. To do this, a systems engineering methodology will the guiding framework to purposefully engineer a new modern data model architecture for learning targets. If successful, such a new architecture would serve as a foundation to not only more effectively support the role that standards seek to play, it would bridge many of the challenges seen across the system, bringing much more coherence across stakeholders and practices and the coordination of information and data across all of them.

To be clear, this thesis is not about education reform. The intention is not necessarily to improve current education systems, but rather, to use systems engineering as the fundamental approach to reengineer key management and organizational structures that enable meaningful learning at scale. The framing is notable, because the emphasis is not on how to fix current education systems necessarily, but rather to zoom out more broadly, see the system as the engineered (purposefully or not) infrastructure that it is, and seek to purposefully engineer ways in which we can more effectively create meaningful and effective learning environments at scale. The primary focus and hypothesis here is that engineering a better learning data model architecture is the central lever to enable us to be able to meet that goal. The answer to this challenge may look quite different from what we have now in education systems—which is of course the point, to break free from the long-standing frames that have hindered us for so long, so that we may more purposefully and effectively design environments and systems that support good learning.

Using a systems engineering methodological framework, this will explicitly include both a needs analysis and design-based research methods to explore:

- the challenges and shortcomings of the existing system for managing learning constructs¹;

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¹ The term 'construct' is used in the learning sciences to refer to a concept, skill, or competency that can be learned or observed in a learner.
• the needs and use cases across system stakeholders (including educators, content developers, technologists, assessment designers, etc.) as well as modern technical infrastructure (i.e. semantic web, current cognitive tools, etc.); and

• the development of a potential solution for a reengineered infrastructure.

PROBLEM STATEMENT:
Background & Significance of the Problem

Currently, learning content in K-12 education is generally managed in two ways:

1. State, regional and national standards frameworks are policy documents that dictate the scope and sequence of content and skills to be covered.

2. Content providers (i.e. textbook publishers, educational technologies, online media, etc.) create their own taxonomies and curriculum maps for the content they have created, when they don’t otherwise choose to organize their material around a given set of regional or national standards.

This existing infrastructure has evolved out of direct practical needs, but presented a number of challenges across the educational ecosystem.

Challenges with the current infrastructure: Systems Of Standards

Standards are policy documents, developed by a jurisdiction (e.g. Massachusetts, Ontario, Finland) to set a standardized pace and benchmark of student learning outcomes in each major domain (i.e. mathematics, literacy, science, etc.). Although a robust structure of experts is typically employed to derive a set of standards, ultimately the finalized set is adopted and endorsed by a governing body that also puts legislation in place with the standards that has implications for schools that then must teach with them. Standards are often written intentionally to be both comprehensive yet also vague, so as not to over-prescribe what and how teaching and learning plays out in each classroom and allow room for the teacher’s professional judgment as needed when designing instruction around a given standard (Konrad et al., 2014). In other words, this is largely what distinguishes curriculum from standards: standards are not curriculum, but rather benchmark statements encompassing a mix of content and skills that must be translated into curriculum. Standards began to emerge in the early 1990s as a response to the influential 1980s education reform movement (Beatty, 2010). Since that time, they have largely served as the core infrastructure for managing content in K-12 education, which is evidenced not only by the systemic adoption in schools, but by the extent of their reference and usage in educational technologies and products. In other words, new learning technologies and published content are
typically aligned to one or more sets of standards. However, using standards as the core infrastructure for managing content/curriculum in education is problematic on a number of levels:

- **Lack of detail / support for educators.** Standards are written intentionally to be concise, often integrating numerous topics, and often display little to no further detail on key aspects for teaching that content, such as misconceptions, evidence of mastery, etc. Moreover, a large body of research shows that effective student learning in the classroom is most dependent upon teacher expertise, including pedagogical content knowledge, understanding the role of student misconceptions and how they must be addressed in instruction, the role of specific pedagogies, as well as tasks to elicit understanding and mastery (Darling-Hammond & Ball, 1998; Bransford, Brown & Cocking, 2000).

- **Integration / conflation of learning constructs within a standard.** An individual standard as a unit of learning can vary greatly in scope and complexity, which impacts and complicates the way in which learning technologies and resources support and capture learning data for the teacher or learner to interpret.

- **Lack of coherence / alignment across jurisdictions.** Due to this conflation of constructs, as well as variation in design, sets of standards from various jurisdictions do not correlate to one another—effectively each jurisdiction working on within its own system.

- **Semantic web integration.** Since a common language for these learning constructs has not yet been defined, semantic web tools like knowledge graph cannot yet be easily employed—limiting our ability for information, data, and knowledge-sharing across learning objects, and more broadly in the domain learning and education.

- **Standards are not 'living', and as such, not able to accommodate more current and relevant research findings and societal demands.** Typically, a jurisdiction will redesign and adopt a set of standards every 10-15 years, with long cycles of responsiveness and adaptation to modern insights and demands.

### Challenges related to content and learning constructs outside of standards

Although standards largely serve as our current infrastructure for managing learning goals, there is a much larger ecosystem around which we study, model, and support learning.

Looking more broadly at how learning constructs outside content standards is managed, we see additional challenges with existing infrastructure:
- **The learning sciences' research-to-practice divide.** The massive gap between the research produced around learning and its translation to and implementation in practice—as well as the gap from insights from real-world learning environments feeding back to inform learning sciences' models and frameworks, such as learning progressions. However, getting this knowledge into the hands of practitioners, and ultimately show up in everyday classroom practice, is a persistent gap and an ongoing challenge in education (Hattie, 2009; Hille, 2011). Today, a large swath of learning constructs—from physics and mathematics to literacy, computational thinking and beyond—and the nature of how learners come to understand them, have been studied extensively. This includes identifying misconceptions, elucidation of specific learning tasks and strategies to facilitate more effective learning, common learning trajectories, and more. Yet the 'thin' documentation of standards does not allow for (or has not traditionally) been able to fit in this critical knowledge as well. As a result, it’s up to professional development and access to other teacher resources to support them in this critical knowledge—which is non-uniform and mediocre at best.

- **The movement towards competency-based education.** Across Europe and more recently in the US, there is a pronounced movement of leading districts moving to competency-based education (Singer, 2006; Sturgis, 2015a), where personalized learning and individual paths towards mastery are supported, versus standards-based education, which focuses on 'proficiency'. There is considerable support from a variety of education stakeholders², because competency-based education can more effectively support learning environments in mastery-based learning, and more effectively aligns with learning progressions and a learning sciences'-based understanding of the nature of learning. However, the field has yet to common define a model for a competency, and as a result, these leading-edge schools are left to define these on their own. In many cases, districts will appoint a small subset of teachers to collectively define the competencies they will use based on the existing standards they follow³; as a result, what constitutes a 'competency' varies significantly within those competencies and across districts.

- **The movement towards broader skills and competencies.** There is a long-standing discussion in education about the critical need to move away from solely focusing on content-area skills (i.e. math, science) to more broad or 'higher-level' skills such as collaboration, design, inquiry, persistence, etc. (CASEL, 2007; Duckworth & Gross, 2014; Hilton, 2014). The recent surge in research of what have been dubbed non-cognitive skills have helped this movement, however the central challenge remains that these are not currently “tangible”—meaning, they are not fleshed out at the construct and assessment level, making them a bit like black boxes.

² Including major foundations, as well as organizations such as Digital Promise.

³ Personal communication with Paul Leather, Deputy Commissioner of Education in New Hampshire, leading the competency-based learning work there.
- **Coordination of learning metrics across modern learning technologies.** Emerging learning technologies, such as intelligent tutors, game worlds, and game-based assessments represent some of the most robust and complex learning tools available today. Due to their complexity and the way they are constructed, they are still ‘black boxes’ for many educators—unclear of exactly what learning the tool is directly supporting and/or assessing. If we look ahead to the future, this complexity and ambiguity will only increase as these tools evolve. At the same time, there is little coherence amongst the tools themselves. Many game-based learning tools and game-based assessments are built on similar learning model frameworks, yet are constructed differently, so that data about learning (and therefore the learner) cannot coordinate between them. To be clear, this is a problem that goes beyond the scope of managing content and learning constructs, though this is a core aspect of it.

- **Supporting learning beyond the current educational system.** How do learners use, need, and/or benefit from maps of learning that support them as they drive their own learning in skills in and beyond what is covered in school?

### Statement of the Problem

A modern learning data architecture is able to both overcome these existing shortcomings, and be flexible enough to accommodate the emerging dynamics and directions of learning environments and systems. A coherent learning data architecture supports the range of needs and practices across the various stakeholders, through data models that are integrated and create congruency. In other words, we should see integration, not segmentation; coherence, not disjointedness.

Each of the aforementioned challenge areas works with learning constructs in some way, often with similar (but not standardized) language or data structures. This lack of coherence and infrastructure leaves a very fragmented knowledge base, tools, policies and practices in relation to content and learning goals. These aforementioned challenges are in fact symptoms and surface-level challenges of a deeper root-level problem: there is no unified data architecture for learning constructs, and the infrastructure to support content in education is insufficient, and largely missing.

### Theoretical Framework for the Study

With each of these challenges, we can imagine pursuing solutions to help mitigate them, such as,

- Build a teacher dashboard (an interface to more easily work with the data) around constructs, to help flesh out key details about standards;

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4 Personal communication with dozens of educators through the work of the Playful Learning project.
Create a digital sandbox to model learning competencies, and to serve as an online place where they can continue to be built and studied.

While any of these might be useful tools, each would create a tool that only addresses one facet of the problem, and like most research-based ed-tech projects, will likely garner limited adoption. This only perpetuates the fragmentation of the field and limited effects in an attempt at reform.

The complexity of educational systems, and the pernicious nature of a wide range of barriers to innovation, suggests the need for root cause identification, redesign practices, and systems engineering as necessary approaches for effective change to take place (Fullan, 1993; Groff, 2009, 2013; Lemke & Sabelli, 2008). Across the complex landscape of educational ecosystems, there are a myriad of structures that may benefit from such a systems or redesign approach, including assessments, the management of student learning records, and more. The factors discussed above can be seen as systemic symptoms of visible and tangible structural problems, that ultimately can be traced back to a root cause—a disjoined, limited, and insufficient learning data architecture (see Figure 1-1). The far-reaching impact of learning construct models across the ecosystem—from policy and practice (standards) to learning sciences and the design of a wide range of learning technologies—suggests that this is a root cause factor in the system that is ripe for reengineering.

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Figure 1-1. Root Cause Diagram

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Therefore, the goal of this research is to use systems engineering processes to explore the reengineering of a data architecture for the management and support of learning data and constructs in K-12 education, that results in:

- a unified data architecture, where the central data entities have multiple views to be viewed and managed by multiple stakeholders; and
- a workflow for the ongoing development and management of these entities.

Research Questions

Situated in a systems engineering methodology, the three research questions explored in this thesis are:

**RQ1:** *In order to define a unified data model entity for learning constructs, what are the user needs/requirements of key education stakeholders related to learning constructs and outcomes?*

*Hypothesis 1:* There are distinct but overlapping needs of various education stakeholders, and distinct but overlapping data sets of information as it relates to learning constructs and outcomes.

*Hypothesis 2:* The current, limited infrastructure for learning data creates many problems and inhibits education systems and innovation in a number of dimensions.

*Hypothesis 3:* By defining the needs and overlaps, through modern methodologies such as human-centered design, lean startup, and systems engineering, we can define a core data model that not only overcomes many of these challenges but bridges stakeholders in doing even better work.

**RQ2:** *How can tools built from a reengineered data model advance a construct-centered approach and improve classroom practices?*

*Hypothesis 1:* There is a demonstrable need for better tools that help unpack learning constructs, for a range of education stakeholders, especially educators.

*Hypothesis 2:* Tools that are designed to support these populations using a more coherent learning data model architecture, can have a significant impact on their work.

*Hypothesis 3:* Piloting these tools in the context of a larger systems engineering endeavor in education, helps us to not only further refine the tools built to support
RQ3: How can a systems engineering methodology help guide the reengineering of systemic challenges in education?

Hypothesis 1: The complexity of systems of learning requires us to reach for that better embrace and work with this complexity, in order to see the changes and outcomes desired.

Hypothesis 2: Systems engineering and redesign methods have successfully supported other complex, system challenges.

Hypothesis 3: Exploring how systems engineering processes applied to a core element of education systems can help us better understand those challenges and how we may benefit from approaches that engage their inherent complexity.

Methodological Framework

The guiding methodology for this work, including the research, design, and development, is systems engineering. The Systems Engineering (SE) process is a comprehensive, disciplined, and iterative problem solving process, used to transform needs and requirements into a set of system product and process descriptions required to produce system-level results (DoDSMC, 2001; NASA, 2007). It is a methodology for creating effective solutions to problems, and managing the technical complexity of the resulting developments (Stevens et al, 1998). NASA and the U.S. Dept. of Defense have developed and institutionalized SE, which in turn have been adopted by a wide range of fields and industries. SE is a helpful architecture that brings a robust framework to a complex systems problem, balancing both an “expert” approach versus a “stakeholders” approach in educational systems design. These frameworks will be discussed further in Chapter 2.

DESIGN: The LearningGraph Project

With the aforementioned problem space in mind, the LearningGraph Project (LGP) is a research initiative established in 2012, that aims to help bridge these gaps by (1) using systems engineering processes to re-engineer a modern and unified architecture for the management of learning constructs in education and support the work of a variety of stakeholders in the system; and (2) to create an on-going research and development project that supports this data architecture as the continual work of the learning sciences evolves. The LGP serves as the backdrop for these research questions, and is discussed in more detail in Chapters 3 and 4.
The work of this project has included an extensive review of existing learning data frameworks, developing an data architecture platform for the modeling of learning data from 12 countries/jurisdictions, designing a number of prototype data models, and working with a range of stakeholders to understand current practice in industry and educational technology, as it relates to modeling learning data.

**Key User Groups & Tools/Frameworks**

Although standards are currently the ‘core’ framework for working with content and learning constructs in education, there are a number of other frameworks and data models used by key stakeholders that have considerable overlap with the content covered in standards. These are reviewed more comprehensively in Chapter 4, and include:

- Learning Progressions
- Domain Models
- Construct Models
- Concept Inventories

Similarly, there is a range of stakeholders that work with these data models in various ways. These stakeholders will be at the center of this research project, and include:

- Educators, and informal learning environment facilitators
- Assessment Developers
- Educational Technologists, Designers, and Publishers
- Researchers
- Learners

The primary technical goal of this project is to look at user tools, needs, and practices, identify the common underlying content structure, and define a unified data model (see Figure 1-2), which can support all users and facilitate core content/knowledge sharing amongst these groups (RQ1); then, upon this architecture, user-group-specific tools (i.e. teacher tools, assessment designer tools, etc.) will be developed to support and improve practice (RQ2).
Significance of the Study

The focus of the research addresses an "enduring problem" in education, which is particularly impacting developers of educational technologies—who must confront some of these challenges in their technology design, but generally do not have the time or resources to dive deeply enough into the problem to help support a systemic solution. We see evidence of this by looking at a range of educational technologies that have created something inside their platform that helps solve some of these gaps to immediately meet the needs of their tool, but do not go far enough in addressing all of these challenges. For example, Khan Academy ultimately built a "knowledge map" to help visualize all the content across their site, but this only marginally integrated with existing learning standards; similarly, a number of learning technologies have been forced to build an internal data architecture that relates standards to the way they are modeling data in their tool—an endeavor each company has had to take on independently, that is both time-consuming and costly, which are not able to share data easily outside of their platform. Yet the real loser in this scenario is the end user—the educator and the learner—who are forced to become familiar with a range of dashboards and tools, that ultimately do not integrate to more deeply meet the learner’s needs.

Aspects of this problem, and the need for common and robust 'learning map' have been demonstrated and pursued previously by others, most notably for the $100 million Gates Foundation initiative, inBloom (Hillis, 2012). Although that effort failed largely for political reasons, the powerful need and opportunity still remain.

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6 A framing offered by Jeremy Roschelle (personal communication with the author, August 2017).
Contribution

In light of the significance of this systemic problem, there is a strong opportunity to generate meaningful insights that could have wide-reaching impact across a range of stakeholders and applications in learning tools, experiences, environments, and systems.

The primary contribution of this dissertation is the development of a unified data model and architecture for the management of learning content and constructs, to help close a number of gaps and challenges around this core pillar of education. Additionally, this will also include a complete needs analysis of this aspect of the field, as well as prototypes of tools and proposed further work to extend this architecture into tools for key stakeholders. More specifically, the contributions of the proposed dissertation will be:

1. A meta-synthesis of how content and learning constructs are modeled, refined, and used in the development of educational elements (i.e. curriculum, learning trajectories, assessments, etc.).

2. A needs analysis and review of needs/practices of the various education stakeholders (including teachers, assessment designers, learning sciences researchers, content publishers / educational technology designers, and informal learning environment facilitators) in relation to how they work with learning constructs.

3. A preliminary unified data model and prototype data architecture for the common management and integrated use of learning constructs and content.

4. A designed prototype application (in the form of wireframes) that would sit on top of the proposed data architecture to support classroom practitioners.

LOOKING AHEAD

Proposing, and successfully implementing, a modern data architecture for learning is surely no easy task. In many ways, the disjointed evolution of policy and practice over decades is what has created the shortcomings we see today. In the chapters that follow, we will explore the argument for why a systems approach is so critically needed in the design of effective education systems that hope to have the potential to bring us into a future of powerful learning potentials.
Chapter II

SYSTEMS ENGINEERING AND EDUCATION

"Adjusting a design rooted in an outdated image creates far more problems than it solves."

— Bela Banathy, 1994

Engineering a new data architecture across educational stakeholders and environments is a formidable task. Successfully achieving this goal requires understanding the needs and practices within each user group, ways in which to effectively support those needs and practices, and then understand the interactions and workflows between those user group—all while keeping an eye on the larger global dynamic you are trying to cultivate, and the core structures that will enable it. This represents both a local and global perspective, to analyze and coordinate across these vantage points in the system.

Systems approaches have been utilized in a range of fields in order to do exactly that, helping to engineer some of society’s most complex and elegant solutions. Over the past 50 years, systems work has evolved into a range of disciplines, methods, and tools—including system dynamics, complex systems modeling, systems engineering, concurrent engineering, and more— which have helped us to better understand, manage, and improve many challenges across a range of fields, including economics, urban planning, ecology, policy, civil and mechanical engineering, and more. These systems approaches have been effective because they have helped us to better harness the inherent complexity of the systems, and purposefully engineer better products, systems, policies, etc., in response to that complexity (Sterman, 2001). In this chapter, we explore this history and these systems approaches, discuss how it may be used in this problem space, and why it is critical to do so.
WORKING IN SYSTEMS

Systems make up our world, and they come with inherent complexity and dynamics that can give rise to unprecedented outcomes (just think of the elements at play that allow a rocket to reach the moon), while also being incredibly challenging and daunting to work within (i.e. “fixing” the healthcare system or education). Much of what creates the complexity of so many systems is due to what is termed dynamic complexity—“the counterintuitive behavior of complex systems that arises from the interactions of the agents [and loops] over time” (Sterman, 2001, p. 11). The challenging differences between simple and complex systems are many and often direct opposites of one another. For example, in a complex system the actual cause of a behavior may originate from another part of the system, often from a place that is distantly removed; in complex systems, achieving a short-term goal can often mean undesirable long-term consequences; and in complex systems the obvious decision often turns out to be an ineffective one (Forrester, 1997). Adding to this complexity of decision-making is the hierarchical nature of complex systems—the goals of a subsystem can contradict or endanger the welfare of the larger system.

The traits of dynamic complexity in systems are described in Figure 2-1. By their inherent nature, these systems are complex, interconnected structures that are filled with feedback loops where behaviors and actions in one part of the system impact (or are constrained) by other parts of the system, and they are characterized by nonlinear, counterintuitive behavior, where ‘effect’ is rarely proportional to ‘cause’, but often cause/effect dynamics are far apart in the system. In other words, effects or changes to one part of the system often play out much differently than intended because the change causes dynamic effects in the system as a whole. This complexity makes all systems inherently difficult to understand intuitively and therefore policy resistant—what Sterman describes as the "tendency for interventions to be defeated by the response of the system to the intervention itself" (2001, p. 8).
Characteristics of Dynamic Complexity in Complex Systems

**Constantly changing:** Change in systems occurs at many time scales, and these different scales sometimes interact.

**Multi-Loop:** Multiple, confounding variables and loops that produce ambiguity, and ultimately, flawed cognitive maps of causal relations.

**Tightly coupled:** The actors in a system interact strongly with one another and with the natural world; everything is connected to everything else.

**Governed by feedback:** Our actions feed back on themselves, giving rise to a new situation as a result of our actions.

**Nonlinear:** Effect is rarely proportional to cause, and what happens locally in a system often does not apply in distant regions; it arises as multiple factors interact in decision-making.

**History-dependent:** Taking one road often precludes taking others and determines where you end up; many actions are irreversible.

**Self-organizing:** The dynamics of systems arise spontaneously from their internal structure, generating patterns in space and time creating path dependence.

**Adaptive:** The capabilities and decision rules of the agents in complex systems change over time. Adaptation also occurs as people learn from experience, especially as they learn new ways to achieve their goals in the face of obstacles. Learning is not always beneficial, however.

**Characterized by trade-offs:** Time delays in feedback channels mean the long-run response of a system to an intervention is often different from its short-run response. High leverage policies often generate transitory improvement before the problem grows worse.

**Counterintuitive:** Cause and effect are distant in time and space while we tend to look for causes near the events we seek to explain.

**Policy resistant:** The complexity of the systems in which we are embedded overwhelms our ability to understand them, resulting in many seemingly obvious solutions to problems that fail or actually worsen the problem.

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Figure 2-1. Dynamic complexity characteristics of complex systems (adapted from Sterman, 2001, p. 12)

This complexity requires us to rely on more than our mental models for analyzing complex systems, and creating policies and structures that govern the futures of these systems. Yet it also requires us to move beyond traditional analytical methods as well.

Systems work evolved through the middle of the 20th century in response to these shortcomings. Russell Ackoff (2005) explains that operations research, which was one of the key tools attributed with helping the Allies win World War II, was an analytical methodology of breaking down a system into its parts in order to understand
those parts better, helped us to develop incredible knowledge about parts of systems yet often produced solutions that generated many more problems, and the solution to one problem depended critically on how the solutions to other problems were being treated at the same time. According to Ackoff, what many discovered in the 1940s and 50s, is that analysis cannot produce understanding of systems—and that rather, a system’s operations is not the sum of its parts, but it is a whole whose characteristics derive out of the interactions of its parts.

“...analysis, we discovered, yields information about the structure of something, and how it works, that’s knowledge, know how. Explanations lie outside, that’s synthetic thinking. Synthesis yields understanding, analysis yields knowledge, and it was that distinction that was critical for the emergence of the systems sciences. It uses both, but to understand systems, particularly those that involve people, synthetic thinking is required.”

~ Ackoff, 2005

What emerged was cybernetics and later, the systems sciences, which includes systems thinking and system dynamics (SD)—a methodology and larger field of study developed more than 50 years ago in an effort to cope with the complexity and difficulty in working with complex systems, and has subsequently been applied to numerous fields, including businesses, medicine, economic behavior and even environmental change (Forrester, 1998). In essence, this SD helps us create models of the key dynamics in a given system, by offering tools to:

* map the feedback structure of a system in order to understand why a system is behaving the way it is;
* test and plan for policies before implementing them; and
* to increase the likelihood they produce the outcomes desired.

**SYSTEMS WORK IN EDUCATION**

Although from a philosophical perspective, efforts to redirect the trajectory of systems of learning began back in the early 1900s with the work of John Dewey (1916), it wasn’t until decades later that more tangible efforts had been initiated in order to produce such change. These more recent efforts have operated under many labels, most notably school reform, education reform, and whole system reform (Fullan, 2011a). Over the decades, many of these initiatives have demonstrated limited impact, and most efforts to improve learning experiences and outcomes has been focused at the level of instructional interventions and reform initiatives focused on an aspect of the system, including teacher support and training, school organization, and even district-level/community-centered efforts (Harris, 2003). Most of these efforts have focused on piecemeal or incremental reform, and are rarely organized into a comprehensive system of change (Noguera, 2017; Banathy & Jenks, 1993). With such system complexity, and disjointed reform efforts, these initiatives would be ultimately blocked or inhibited by
another aspect of the system (Fullan, 2011a). In other words, we simply weren’t looking broadly enough at the system itself, and perhaps bringing the right complexity tools to bear on the problem.

Yet according to Reigeluth (1993), since the seminal publication of “A Nation at Risk” in 1983, over 150 reports have called for fundamental change rather than the traditional, piecemeal, “tinkering at the edges” approach to educational improvement (Perelman, 1987, 1988). That was in 1993. Yet here we are, 25 years later, and while there are more pockets of innovation in the system, the system itself has not changed much for the better.

Banathy & Jenks (1993) have argued that this stems from two persistent phenomena in education: 1) the compartmentalized nature of traditional reductionist approaches to inquiry that still prevail; and 2) failure to integrate problems into a system (of problems). Such reductionist approaches have been beneficial, and have helped to produce a wealth of knowledge in the learning sciences about how people learn; and more recently, there has been a push to more integrative research methods, such as design-based implementation research (DBIR) that place an emphasis on responding to context-based needs while demonstrating impact (Fishman et al., 2013). This then begs the question, how do we build on this knowledge base to more coherently design systems solutions?

Although over the years notable stakeholders in education have advocated for transforming the entire system (Sizer, 1996; Clarke & Miles, 2003), Michael Fullan is perhaps the most notable figure in this space, because he led whole-system initiatives in England, Ontario (Canada), and New South Wales (Australia) with notable results (Fullan, 2011b). Fullan has argued that the largest hindrance to reform is the presence of too many ad hoc, uncoordinated innovations and policies (1999), and has advocated for his approach of whole system reform, where the “100 percent of the system – a whole state, province, region or entire country” – and every vital part of the system – school, community, district, government – contributes individually and in concert to forward movement and success (Fullan, 2010; 2011a, p. 3). In practice, these approaches look like systemically coordinated initiatives and policies that target all areas of the system in concert.

Seymour Papert framed this dichotomy as the problem-solving approach versus the systemic approach to ‘renovating school’ (as he quipped)—identifying and trying to solve the many problems that afflict schools versus stepping back to understand how the whole system works (Papert, 2000). Similarly, this has been framed an ‘ecological’ systemic thinkers view to changing education, because this view embraces the powerful relationship between the components in and out of the system, and thus advocate for a comprehensive approach to systemic change that considers the redesign of all aspects of the system (Banathy, 1992; Squire & Reigeluth, 2000).
Despite promising many outcomes in Ontario, even Fullan feels that the results of these efforts have fallen short in the aim of producing the type of deeper learning valued for learners today (Fullan, 2011b, p. 8). From a systems view, Fullan has framed this challenge well:

"...the US, for example, has a habit of breaking things into pieces – and what looks like a system is not, because the pieces are not well connected. This problem is aggravated when some of the pieces are the wrong ones to begin with. Standards over here, assessments over there, and teacher appraisal and incentives in still another box: what can be portrayed as a system (the pieces are there, and can be made to sound comprehensive) is not integrated as a coherent whole, and thus does not function ‘systemically’. Implementation then becomes a hodgepodge.... “In the absence of a system mindset, individual pieces – each of which contains half-truths – are pitted against each other as vested interests bash each other with proverbial baseball bats. No one wins; the system loses every time.”

— Fullan, 2011a, p. 16

Education is most certainly a complex system—a non-linear system within systems, that is policy resistant, surrounded by feedback loops (Ghaffarzadegan, Larson & Hawley, 2017). Fullan’s comments reflect many of the traits of dynamic complex systems as described in Figure 2-1, and many of the consequences of approaching complex problems with limited, mental models (Sterman, 2000). Even with Fullan’s approach to addressing all aspects of the system as much as possible, this work still has not included many of complex systems methods and tools that have been so successfully leveraged in a range of fields. As Jay Forrester, father of System Dynamics noted, “The question is not to use or ignore models. The question is only a choice among alternative models” (Forrester, 1971, p. 4). Meaning, we are all working with models—our own mental models, or increasing complex models built with external, sophisticated tools and technologies. Extensive prior work in other fields has demonstrated the power of the latter.

**Systems Tools in Education**

Understanding the structure and interconnections that create the behavior of a defined system is the goal of SD. SD helps us to overcome policy resistance and the inherent human limitations described above. The tools of system dynamics demonstrate and unpack the complexity of a system that we might otherwise not recognize; and it counteracts the tendency towards analysis by seeing the system as a whole—which makes the field inherently interdisciplinary. System dynamics, systems engineering, and other related methods, have helped produce more effective outcomes to complex problems because they have enabled the development of complex models that serve as the foundation to more effective solutions.

Yet despite the success of many more rigorous systems tools and frameworks in such a broad range of fields, they have been slow to be picked up in education. Since the early 1990s, Bela Banathy – also of the ‘ecological’
mindset to education systems change – had been arguing for the use of systems design approach for emerging a new education system (1992); however, the idea has gotten little traction since then.

More recently there has been some renewed interest in using SD and agent-based modeling to more effectively unpack system problems in education systems, such as the STEM teacher pipeline (BHEF, 2013), systems influences and changes on STEM education (Larson & Murray, 2017), and the success of interventions (Mital, Moore, & Llewellyn, 2014), but to date, they represent examples of what might be possible rather than systemic initiatives using SD in education.

These tools help us to better understand the nature of the dynamics at play in a given complex system, and therefore better enable us to make more informed design decisions about how to influence that system for more optimized results. Moreover, they represent a mindset about systems and complexity that has only been dabbled with in education. The evidence from the success in other domains would suggest that these are important directions that should be further pursued in education because they would likely help us improve education systems and ultimately learning environments.

However, these tools alone may not be able to dramatically take us to a newly imagined reality, where learners are able to engage in their passions and strengths, in robust and meaningful learning experiences, to develop a broad range of competencies—a reality that even future generations of our now society need.

**DESIGNING SYSTEMS**

Although powerful in their own right, these dynamic systems modeling tools will not inherently get us out of a narrow mindset from what is familiar, and move us to what could be possible, what could be optimal, and help us get to reimagined futures. Our mental models of what is, creates assumptions about that might not hold true. Banathy explains that a ‘focus within’ limits our perception to designing better systems; our current educational system design is “still rooted in the 19th century machine age. A design rooted in an outdated image creates more problems than it solves. Our ‘horse-and-buggy’ system of education cannot be rebuilt or restructured into a ‘spacecraft’ model.” (Banathy, 1992, p. 42).

Instead, we must leverage these tools to engage with the complexity of delivering meaningful learning at scale, while also engaging a design mindset to build the system that meets our needs. By removing the constraints we clear our minds to think creatively about what might be possible, and what might best meet our needs.

More than two decades ago, Banathy noted the tension of complexity in human activity systems, and the critical need for the purposeful design of systems:
“However, living systems, social systems, such as educational activity systems, are open systems, having intensive co-evolutionary interactions with their environment. Often, these systems are guided by positive feedback, that call for new goals, new perspectives, new functions; that call for changing the whole system. And the method of change here is systems design; the redesign of the system or the design of new systems. In the educational reform movement, however, we rarely use systems design.”

— Banathy, 1995, p. 54

**Idealized Design**

Russell Ackoff’s experience at Bell Labs as described in Chapter 1 was a convincing example of how this framing can move mountains of change—an approach he went on to frame as *idealized design* (2006). The idealized design process takes organizations and systems through two phases, outlined in Figure 2-2. According to Ackoff, “the impact of the design we produced was greater than the impact of any other effort to change a system that I had ever seen. As a result, I began to adapt and modify the procedure to fit such other applications” (p. xli)—including business and non-profit applications, and even reorganizing communications in the White House.

This approach provides a number of benefits, including:

- Promotes understanding of that which is designed
- Transforms the designers’ concept of what is feasible
- Simplifies the planning process
- Enhances creativity
- Facilitates implementation

**Ackoff’s Process of Idealized Design**

1. **Idealization**

   1. **Formulating the mess:** To determine how the system would eventually destroy itself if it were to continue doing what it is doing currently—that is, if it were to fail to adapt to a changing internal and external environment, even if it could predict the course of this change perfectly. This involves four main steps:
      - Prepare a systems analysis
      - Prepare an obstruction analysis
      - Prepare reference objections
      - Prepare a presentation of the mess

   2. **Ends planning:** The heart of idealized design. It involves determining what planners would like the organization or system to be now if it could be whatever they wanted. It
then identifies the gaps between this idealized design and the organization as it is, thus revealing the gaps to be filled by the rest of the planning process.

II. Realization

3. **Means planning:** This phase requires planners to determine what should be done to approximate the ideal as closely as possible to avoid the self-destruction projected in the formulation of the mess. Planners must invent and select courses of action, practices, projects, programs, and policies to be implemented.

4. **Resource planning:** Identify and marshal the resources needed to accomplish the planned changes, including the following:
   - Determine how much of each type of resource—personnel; money; materials and services; facilities and equipment; and information, knowledge, and understanding and wisdom—are required. Also determine when and where to deploy the resources selected.
   - Determine how much of each type of resource will be available at the desired times and places and determine the difference between what will be available in any event and what will be required.
   - Decide what should be done about shortages or excesses identified in Step 2.

5. **Design of implementation:** Determine who is to do what, when, and where. Create a schedule and allocate resources to the tasks to be carried out.

6. **Design of controls:** Determine:
   1. how to monitor these assignments and schedules;
   2. how to adjust for failures to meet or exceed schedules; and
   3. how to monitor planning decisions to determine whether they are producing expected results (and, if not, determine what is responsible for the errors and correct them).

Figure 2-2. The idealized design process (adapted from Ackoff, 2006, p. 5)

Ackoff draws particular attention to what he calls ‘idealized redesign’—a design to replace an existing system right now, if it were able to be replaced with whatever we wanted; to this he attaches three design constraints (Ackoff, 1988, p. 242):

1. It must be technologically feasible—no science fiction.

2. It must be able to survive in the current environment and, therefore, satisfy whatever legal, social, economic and other externally imposed constraints or regulations apply in that environment; there is no requirement, however, that the system designed be capable of being implemented.

3. The system must be designed so that it is capable of learning and adapting rapidly and effectively.
Designing Alternate Futures of Learning, Learning Environments, and Systems

This emphasis on design, and Ackoff’s framing with design constraints, are of particular interest because they have so rarely been brought to the systems level for how we think of learning environments and learning systems. We don’t often give ourselves the space to ‘greenfield’ at the systems levels in education. It has rarely showed up in discourse, and certainly less so in practice. Perhaps it is because of the gravitas to the current system. Perhaps it is because the systemic, pervasive nature of our current reality of these systems makes it difficult to imagine, and reach for, something drastically different. Perhaps it is because when we envision the ‘micro’, day-to-day experiences that we hope for learners to have, it’s not intuitive or common practice to zoom out and think about the type of radically different system structures that would be required to make that a systemic reality for all learners. Yet it is for these reasons that we must engage with these types of systems tools and realities if we ever want to arrive at a better future for learning—because as Banathy’s (1993) quote at the beginning of this chapter denotes, “adjusting a design rooted in an outdated image creates far more problems than it solves.”

What visions of future realities of learning systems might we conjure? More than a century ago, John Dewey gave us visions of what a learner-centered system in a democratic society might embody (1916). As the semantic web began to come into view, Danny Hillis gave us a vision of a future where every learner has their own digital ‘Aristotle’ personal tutor—that knows where you are as a learner, where you want to go, and how to support you on that individual pathway (Hillis, 2004). Some have even suggested that we need to hold out for this reality because systems of education will never be able to catch up and transform before the AI revolution. Even if you fall into this camp, the AI revolution won’t inherently create this vision of reality, and it doesn’t mean every learner will even necessarily understand how to engage with it well. Getting to better visions of learning will require that we not only design, but that we engineer our way there. If we were to take a ‘first principles’ approach to education, how might we take the fundamentals of learning to reorganize how we conceive of learning environments but also the systems that are able to enable them?

---

7 A ‘first principle’ is a basic assumption that cannot be deduced any further, first defined by Aristotle in The Metaphysics. “First Principles Thinking” is an approach for breaking down complicated problems and generating original solutions through the act of deconstructing a problem down to the fundamental parts that you know are true and redesigning possible scenarios and solutions from there.
In our current reality, there is general agreement – in both research and policy/practice – on the type of learning environments and experiences that promote deep and meaningful learning, and are therefore, what we should be striving for as we seek to overcome the challenges in our current education system. A more comprehensive list of resources that represent this consensus can be found in Appendix B, but these notions could be summarized as, the learner's experience (needs, motivations, background) is at the center, though learning is constructed through playful, context-based, social/collaborative, embodied experiences, that enable the learner to construct their own understanding and experiences by engage with a wide range of tools and modalities. Figure 2-3 shows the “7 First Principles of Learning” as defined by the OECD project on Innovative Learning Environments, derived from a meta-analysis from the learning sciences literature. In this literature, calls for using learner-centered principles as the foundation for a systemic redesign of K-20 education show up more than 15 years ago (McCombs, 2003). Since that time there has been much emphasis on the learner-centered aspect, but much less on the systemic redesign.

![Figure 2-3. “7 First Principles of Learning” as defined by the OECD project on Innovative Learning Environments, derived from a meta-analysis from the learning sciences literature (DuMont, Istance & Benavides, 2010).](image)

**The Tension of Learning, Systems & Complexity**

The fundamental tension playing out in our current reality is to how to create the supports, structures, and systems that enable this to be every child’s experience—without the system being the problem itself to impeding this outcome. It is the tension framed by German philosopher, Jurgen Habermas, who explained that all of
society’s enterprises – from the family to the corporation – possess both a *lifeworld* and a *systems world* (1987). In societal learning, the lifeworld is made up of the traditions, practices, needs, and purposes of learners and teachers; the management decisions, protocols, policies, procedures, and accountability assurances comprise the systems world. The quality, health, and effectiveness of a learning environment erodes when a systems world is the generative force determining the nature of the lifeworld (Sergiovanni, 2000). Habermas refers to this latter situation as the “colonization” of the lifeworld by the systems world and attributes many of society’s ills to this situation (Sergiovanni, 2000).

Our current state of systemic learning environments (education), is akin to the colonization of the learner’s lifeworld, with learning environments dominated by the systems world (Darling-Hammond, 2000). *How we can envision a lifeworld that aligns with first principles of learning, and that aligns with our aspirations for inspired, engaged, and empowered learners across a coherent ecosystem of learning?* Moving beyond our current reality, and beyond this critical tension, will require that we consider these questions and then bring together modern tools and methods with evolving technologies, to engineer systems worlds that support those answers.

**ENGINEERING FUTURES OF LEARNING**

More than 25 years ago, Banathy and colleagues made a compelling case for designing systems of education and moving beyond our current image of education to create one that served everyone better (1998; 1992; 1994; 1995; Banathy & Jenks, 1993; Kahn & Reigeluth, 1993). Their work argued for why reform was largely piecemeal and incremental, and from a systems design approach was vital, and unpacked the layers of the system that would need to be considered in that redesign. What was missing in this work was the actualized design and implementation of such a new system.

Their ideas and arguments still hold true today; et since that time, digital technologies have transformed our daily lives, our ways of communicating, collaborating, learning, and working. At the same time, since their work, systems engineering practices have come to bear robust approaches that helped to engineer complex solutions in a wide variety of domains—building on the idea of redesign to ultimately engineer a new reality.

This significantly shifts the landscape of what an idealized design for education might look like, and perhaps most critically, it adds a layer of technological complexity that was not there at the time of Banathy’s work. These technologies have created the opportunity to dramatically redesign systems to support deeper learning at scale in a way that was perhaps imaginable nearly three decades ago, but not yet possible. In Banathy’s time, redesigning systems structures in education might include rethinking the use of grade levels, curriculum topics, class schedules, etc. These are all parts of the current system, still, worth rethinking. Yet in the last two decades, the impact of new technologies has created a new reality and an emerging infrastructure that completely changes how learners engage with ideas, materials, other learners—across space and time. All of these
innovations in technology and practice must be considered in any systems redesign, but they create the opportunity for rethinking systems structures for learning in bold and dramatic ways—some of which might not be immediately evident to those in the current system.

To be sure, this is indeed an exciting opportunity. Yet the technical aspects to such an opportunity creates complexity that will require more than just design methods, it requires engineering. We can, and should, design systems—but we must engineer solutions.

Balancing Idealized Design with Systems Technological Complexity

Systems science has given us the conceptual power and intellectual technology to shape our future through purposeful design (Banathy, 1995). If we take a ‘greenfield’ approach to systems structures in order to deliver better learning at scale – particularly as we engage with new technologies and their emerging futures as introduced in Chapter 1 and discussed further in Chapter 4 – then we must engage with systems methodologies that provide a way for us to effectively manage and harness that technical opportunity. The required competencies for systems development – particularly sociotechnical systems – increases the depth of perspectives and stakeholders involved, as well as the complexity of the system itself (Wiesner, Peruzzini, Hauge, & Thoben, 2015). Yet this is an especially critical time for the consideration of the type of engineering methodologies that may need to be applied to such a task, because with the complexity of emerging AI technologies future engineering systems will continue to increase in complexity technically and organizationally (Moser & Wood, 2015).

In short, idealized design offers a powerful and much-needed perspective at the systems level of learning environments and systems, but capitalizing on the reality and potential of today’s technologies will require a robust and rigorous methodology to ground and actualize those potential, idealized futures.

Systems Engineering

Systems Engineering (SE) is a methodology for creating effective solutions to problems, and managing the technical complexity of the resulting developments (Stevens et al, 1998). As such, it can support us to work with idealized design and work through some of the technical and systems complexity we face in learning systems. SE is an interdisciplinary approach and means to enable the realization of successful systems (INCOSE, 2006). Originally developed by NASA as a way to structure some of their most complex and ambitious projects, their complete definition of SE is:

“System engineering is a robust approach to the design, creation, and operation of systems. In simple terms, the approach consists of identification and quantification of system goals, creation of alternative system design concepts, performance of design trades, selection and implementation of the best design,
verification that the design is properly built and integrated, and post-implementation assessment of how well the system meets (or met) the goals.”


There are a range of SE frameworks available, all with a generally similar idea to the overall structure and means to SE development. Below are the SE process frameworks used by NASA (Figure 2-4), the U.S. Dept. of Defense (Figure 2-5), and a more recent, popular derivation used in industry is the “V” model (Stevens et al., 1998) (Figure 2-6).

**NASA’s Systems Engineering Engine**

![Diagram of NASA’s Systems Engineering Engine](image)

*Figure 2-4. NASA’s Systems Engineering Engine (NASA, 2007, p.5)*
US Dept. of Defense's Systems Engineering Process

Figure 2-5. U.S. Dept. of Defense's Systems Engineering Process (DoDSMC, 2001, p. 31)

V-Diagram for System Engineering Processes

Figure 2-6. V-Diagram for a more broadly-applied SE process (Stevens et al., 1998).

Related Terms:
- Customer
- Primary Functions
- Systems Elements
- Hardware, Software, Personnel, Facilities, Data, Material
- Services, Techniques

Process Input
- Customer Needs/Objectives
- Requirements
- Missions
- Measures of Effectiveness
- Environments
- Constraints
- Technology Base
- Output Requirements from Prior Development Effort
- Program Decision Requirements
- Requirements Applied Through Specifications and Standards

Process Output
- Development Level Dependent
  - Decision Database
  - System/Configuration Item Architecture
  - Specifications and Baselines

Figure 2-5.

Figure 2-6.
SE is a helpful architecture that brings balance to a complex systems problem. Reigeluth (1993) argued for the pros and cons of using an “expert” approach versus a “stakeholders” approach in educational systems design—the former being where a few creative experts engage in designing a new systems, the latter where systems approaches are used to help stakeholders design their own new systems solution. The cons to picking either one approach are sizable, especially in education where both influences on change have had poor adoption (Fullan, 2012) and most stakeholders in the system may not have a large enough systems view to design optimal complex solutions. SE bridges the abstract early stages and the grimy details of implementation to establishes what is possible, then what is feasible, and then supports the creation of the architecture for the system to be produced (Stevens et al, 1998).

When done well, SE can help generate solutions to complexity that not just solve ‘now’ problems, but solutions that can help serve as the foundation upon which evolutions of solutions and possible futures can evolve. In other words, the new system is structured in a way – and continues to be supported in a way – that enables the system to be one that is reflexive, that learns, and responds to that learning.

NASA’s framework consists of seven life cycle phases (see Figure 2-7)—the first three of these phases will be the scope of this thesis, discussed further below.

- **Pre-Phase A:** Concept Studies
- **Phase A:** Concept and Technology Development
- **Phase B:** Preliminary Design and Technology Completion
- **Phase C:** Final Design and Fabrication
- **Phase D:** Assembly, Integration and Test; Launch
- **Phase E:** Operations and Sustainment
- **Phase F:** Closeout
### Phases of the Systems Engineering Process

<table>
<thead>
<tr>
<th>Phase</th>
<th>Purpose</th>
<th>Typical Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Phase A Concept Studies</td>
<td>To produce a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected. Determine feasibility of desired system, develop mission concepts, draft system-level requirements, identify potential technology needs.</td>
<td>Feasible system concepts in the form of simulations, analysis, study reports, models, and mockups</td>
</tr>
<tr>
<td>Phase A Concept and Technology Development</td>
<td>To determine the feasibility and desirability of a suggested new major system and establish an initial baseline compatibility with NASA's strategic plans. Develop final mission concept, system-level requirements, and needed system structure technology developments.</td>
<td>System concept definition in the form of simulations, analysis, engineering models, and mockups and trade study definition</td>
</tr>
<tr>
<td>Phase B Preliminary Design and Technology Completion</td>
<td>To define the project in enough detail to establish an initial baseline capable of meeting mission needs. Develop system structure end product (and enabling product) requirements and generate a preliminary design for each system structure end product.</td>
<td>End products in the form of mockups, trade study results, specification and interface documents, and prototypes</td>
</tr>
<tr>
<td>Phase C Final Design and Fabrication</td>
<td>To complete the detailed design of the system (and its associated subsystems, including its operations systems), fabricate hardware, and code software. Generate final designs for each system structure end product.</td>
<td>End product detailed designs, end product component fabrication, and software development</td>
</tr>
<tr>
<td>Phase D System Assembly, Integration and Test, Launch</td>
<td>To assemble and integrate the products to create the system, meanwhile developing confidence that it will be able to meet the system requirements. Launch and prepare for operations. Perform system end product implementation, assembly, integration and test, and transition to use.</td>
<td>Operations-ready system end product with supporting related enabling products</td>
</tr>
<tr>
<td>Phase E Operations and Sustainment</td>
<td>To conduct the mission and meet the initially identified need and maintain support for that need. Implement the mission operations plan.</td>
<td>Desired system</td>
</tr>
<tr>
<td>Phase F Closeout</td>
<td>To implement the systems decommissioning/disposal plan developed in Phase E and perform analyses of the returned data and any returned samples.</td>
<td>Product closeout</td>
</tr>
</tbody>
</table>

Figure 2-7. Phases of the SE process (NASA, 2007).

### SE as the conceptual framework of this study

With this backdrop, the goal of this study is to use a systems engineering methodology to explore a systems level redesign of the structural organization of learning environments at scale, focusing in this work on the core pillar of most education systems, the way we manage and model learning data. To date we have looked at this problem in the silos of the core stakeholder group that work with learning data (i.e. the teacher perspective, the assessment perspective, the learning technology perspective, etc.), each user group designing tools and practices to meet their needs, but often little consideration about how that integrates with other user groups and/or the whole system. As we will see in the following chapters, each key user group in the system has their own needs and practices with learning data that are related but distinct from the other groups. Yet building tools or seeking improvements in each silo will never bring us to the integrated data model and firm foundation upon which we can build modern learning systems and ultimately bypass many of these problems in education.
From this set of assumptions, the research and development of this thesis will use SE processes as framed in this chapter, particularly centered on the “System Design Processes” in Figure 2-4:

I. stakeholder expectations definition
II. technical requirements definition
III. logical decomposition
IV. design solution definition

These four elements of the formulation phases will be the subcomponents of the three phases of the SE process within the scope of this thesis (see Figure 2-7 also):

**Pre-Phase Concept A: Concept Studies**

The SE engine is used to develop the initial concepts; develop a preliminary/draft set of key high-level requirements; realize these concepts through modeling, mockups, simulation, or other means; and verify and validate that these concepts and products would be able to meet the key high-level requirements. Note that this is not the formal verification and validation program that will be performed on the final product but is a methodical run-through ensuring that the concepts that are being developed in this Pre-Phase A would be able to meet the likely requirements and expectations of the stakeholders. Concepts would be developed to the lowest level necessary to ensure that the concepts are feasible and to a level that will reduce the risk low enough to satisfy the project.

**Phase A: Concept and Technology Development**

The recursive use of the SE engine is continued, this time taking the concepts and draft key requirements that were developed and validated during Pre-Phase A and fleshing them out to become the set of baseline system requirements and Concept of Operations (ConOps). During this phase, key areas of high risk might be simulated or prototyped to ensure that the concepts and requirements being developed are good ones and to identify verification and validation tools and techniques that will be needed in later phases.

**Phase B: Preliminary Design and Technology Completion**

The SE engine is still applied recursively to further mature requirements for all products in the developing product tree, develop ConOps preliminary designs, and perform feasibility analysis of the verification and validation concepts to ensure the designs will likely be able to meet their requirements. To define the project in enough detail to establish an initial baseline capable of meeting mission needs. Develop system structure end product (and enabling product) requirements; generate a preliminary design for each system structure and product.
In this thesis, these phases roughly translate to the foundational project development (Pre-Phase A, as discussed in chapters 3 and 4), research question 1 (Phase A, see chapter 5), and research question 2 (an aspect of development for Phase B, see chapter 6) (see Figure 2-8).

**Systems Engineering Methodology & The Learning Graph**

<table>
<thead>
<tr>
<th>PHASE</th>
<th>SCOPE</th>
<th>OUTPUTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Phase Concept A:</td>
<td>Determine feasibility of desired system, develop project concepts, draft system-level requirements, identify potential technology needs.</td>
<td>Feasible system concepts in the form of simulations, analysis, studies, models, mockups.</td>
</tr>
<tr>
<td>Concept Studies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase A:</td>
<td>To determine the feasibility and desirability of a suggested new major system; to develop final system-level requirements and needed system structure technology developments.</td>
<td>System concept definition in the form of simulations, analysis, engineering models, mockups.</td>
</tr>
<tr>
<td>Concept and Technology Development</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase B:</td>
<td>To define the project enough in detail to establish an initial baseline capable of meeting mission needs.</td>
<td>End products in the form of mockups, trade study results, specification docs, and prototypes.</td>
</tr>
<tr>
<td>Preliminary Design and Technology Completion</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2-8. The phases of the SEP explored in the LearningGraph Project.

**Why reengineering?**

A final note about SE and the idea of *reengineering*. The title of this thesis intentionally begins with a word not yet discussed in this section. de Weck (2015) observes that although NASA's SE process is helpful, but it denotes a "blank slate" scenario where there are no existing systems, preconceptions, or assumptions to overcome (i.e. such as when NASA used SE to develop the tools to land a man on the moon), which is rarely the case for many complex SE projects. This doesn't mean you would not potentially take a 'greenfield' or idealized design approach to the problem, but it does mean that you must consider aspects of the current system and context in your efforts, and if you don't solve for where people and systems currently are, you may not easily get adoption, funding, or traction.

Although it is certainly the hope that this project covers new ground, we are not designing for something entirely new. Unlike using systems engineering processes to design the fuel systems for the space shuttle, this project operates under the understanding that new tools and systems do not easily get adopted in education (Fishman, Marx, Blumenfeld, Krajcik & Soloway, 2004; Groff & Mouza, 2008); as a result, although a powerful new solution to this pillar of the education must be explored, it must be done so in a way that accounts for,
accommodates, and helps to transition existing stakeholder needs and practices. At the same time, operating with the assumption that good and powerful engineering solution to this problem also creates the foundation upon which a range of innovations and possible futures of learning can build, grow, and scale.

In much the same way Tim Berners Lee defined protocols for the immediate need of sending files and communications from one computer to another while purposefully designing those protocols with a much larger vision in mind, this project will consider itself successful if it can both meet current needs of education systems in a more meaningful way, while effectively setting the foundation for a much different ecosystem of learning technologies and environments to emerge. Doing so allowed Tim’s innovation to be immediately useful and adopted, and enabled those users to become early adopters and drivers on the highway to a new world. This thesis, and the LearningGraph project that is its focus, is an early effort to see if SE methods might help us move in a similar direction in learning and education.
Chapter III

MODELING LEARNING

INTRODUCTION

In any domain, the work begins by asking, how does it work? The domain of learning is no different. How do people learn? Asking this question has produced a wealth of material to help us understand how to model learning and the development of learners. It has also informed how we use this knowledge in the engineering of structures that help us support learners on their pathways—and at times, structures that likely hinder learners as well.

In practice, these structures have emerged in a variety of formats, including curriculum, standards, ontologies, domain models, learning maps, and more. The idea of “maps of learning” – an understanding where a learner is and where they want to go next – is critical for the learner as well as those supporting them on their journey. Such a structure lies at the heart of most learning technologies, and even some of the most open-ended learning environments that don’t use curricula still use some type of conceptual structures to help them understand where a learner is in reference to where they may want or need to go next.

However, in education systems, assessment gets the bulk of attention because many it is the element of the system that causes the most problems. Yet, as will be discussed in this chapter, assessment and learning goals are two sides of the same coin. Beyond just standards and assessment, we also must address a glaring gap between research and practice—with emerging frameworks like learning progressions coming to more clearly depict learner growth, where collaboration between researchers and practitioners is essential to more fully developing these frameworks, and yet any infrastructure to actually support such practices is non-existent. A growing number of schools are trying to move towards a more developmental approach to learning through the Competency-Based Education movement – a real opportunity to start to bridge such a gap – yet there is no common framework for what constitutes a ‘competency’ and no common platform where these models might be created.
Yet perhaps the most critical challenge we see is that we have a complex ecosystem of players, all helping to add to our knowledge base of learning and yet little alignment of knowledge structures or shared data models. Beyond just standards, curricula, and assessment, we see movement towards common ontologies, but not ones that are complex enough to support the needs of emerging artificial intelligence and adaptive learning technologies.

We struggle to reinvent how we capture learning, and yet as current practice indicates, we’re trying to “build a new house on sand”. Perhaps because standards are passed by governing bodies, we don’t question the need to rethink this critical (if not core) pillar of the system; yet evidence of this faulty foundation shows up again and again across all parts of the learning ecosystem. To get to a much different future of learning environments and systems, such a core pillar must be engineered in a way that serves as a strong foundation upon which those new futures can be built. How do we take the expanse of what we know about this pillar, about how people learn and how we can model that, to engineer new structures and new futures of learning?

In this chapter, we begin the SE process by looking across the problem-space as broadly as is needed, across all stakeholders that engage with this aspect of the system—to understand what and how stakeholders work with learning models, the problems that show up in the system, using this information to begin to define the requirements analysis. This chapter will review the systems structures that are most central in this problem space, in order to comprehensively deconstruct the users/stakeholder community that engage with learning data, the frameworks and methods they use, and the gaps in between these communities. This review is divided into four areas:

I. **Standards, Curricula and Competencies** – the infrastructure around which educators and practitioners most engage, which arguably currently serve as the essence of this pillar of the system;

II. **Learning Sciences** – the decades of research that have produces models of cognition and developmental progression frameworks;

III. **Assessment** – the methods and frameworks by which we model and capture learning;

IV. **Learning Technologies** – the needs and practices of learning technologies and AI in Education, and exploring not only current but future realities and how they relate to this problem space.

Finally, using this analysis to explore the case for a proposed common data model as an essential element of an effective design for a systems reengineering approach to this problem.

These four areas represent the main user/stakeholder communities that engage with learning constructs, models, and data, however as will be demonstrated in the text, there are interplays and overlaps of each section of the problem space.
Note to the reader: Due to length and space constraints, all examples of the constructs discussed in this chapter will be found in Appendix C.

I. IN PRACTICE: Standards, Curricula, and Competencies

Educators, schools, and school systems have embraced a number of frameworks and structures to help them manage understanding and support what children learn – including standards, curriculum, rubrics, and competencies – which will be discussed in this section.

A. Standards

As discussed in Chapter 1, standards are policy documents developed by a jurisdiction (e.g. Massachusetts, Ontario, Finland) to set a standardized pace and benchmark of student learning outcomes in major domains such as mathematics, literacy, science, etc. They are written intentionally to be both comprehensive yet vague, so as not to over-prescribe what and how teaching and learning plays out in each classroom, and to allow room for the teacher’s professional as needed when designing instruction around a given standard (Konrad et al., 2014).

Performance Standards. Many standards implemented at the state and national level are content standards, which outline the scope and sequence of the academic content a student is expected to learn at each grade level. Yet an emerging approach is the development of performance standards, which measure a student’s progress toward learning that content (Phillips & Garcia, 2015). They are typically written as achievement goals, setup to identify different levels of performance, which include the knowledge, skills, and abilities that are evidenced at each level (see Figure A3-IA) (Wyse, 2013; Cizek & Bunch, 2007; Perie, 2008). This continuum of achievement is referred to by some as a construct (Wyse, 2013).

Part of the goal for using performance standards is that they help us clarify the level of mastery needed for college-level courses, for a degree, or for a profession (Fields, 2011). Like all standards, they too have been met with sharp criticism, particularly when they are used to compare and enhance large-scale measurement; as such, some advocate for the use of achievement levels via the achievement level description method (Beaton, Linn & Bohrstedt, 2012). However, they have also been used to define the level at which a student must perform at a given grade level, rather than more open-endedly describe a progression of mastery. In other words, the design of the framework does not necessarily imply how teaching and learning may be supported, but rather it is the interpretation and policies surrounding the approach that dictates how teaching and learning unfold.
In addition to standards at the state and national level, it is worth noting that there are a number of frameworks developed by international bodies that often have a significant influence on the nation/state level frameworks. This include:

- Council of the European key competencies of the Education and Training 2010 programme
- OECD’s DeSeCo project (2002)
- OECD Education 2030 Project (2016)

There are similarities in these frameworks, yet each is distinct. A major challenge across all of them is that there are not clear and/or agreed upon definitions for all skill or competencies as defined in each framework.

Standards are used to dictate what is learned, when, and to some extent how, and performance standards have been found to often be so low that they convey a false sense of student proficiency—in other words, they inaccurately capture what mastery would look like for the learner (Phillips & Garcia, 2015).

Even amongst the international NGO community of the OECD, UNESCO, etc., there are not agreed upon frameworks or even definitions of the constructs within the framework. In fact, at the writing of this document, there is another initiative in process again at the OECD called the Education 2030 project, to update their framework of modern competencies. A major body of work of this project is seeking to pull together basic definitions of commonly discussed competencies—such as ethics, mindfulness, meta-learning and eve things like gratitude and hope—that they are constructing two-page briefs in order to begin to put ‘handles’ on these central yet nebulous constructs. An overview of the elements of their two-page models can be found in Figure 3-1. Yet across these global agencies such as the OECD and UNESCO that develop materials to support education systems globally are neither in alignment nor even pulling from agreed upon models of standards—resulting in increased overlap, redundancy, and confusion.

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8 http://www.oecd.org/education/2030}
Construct Analysis Framework for the OECD Education 2030 Project

<table>
<thead>
<tr>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Relevance for 2030</strong></td>
</tr>
<tr>
<td><strong>Impactfulness</strong></td>
</tr>
<tr>
<td><strong>Interrelatedness</strong></td>
</tr>
<tr>
<td><strong>Malleability</strong></td>
</tr>
<tr>
<td><strong>Measurability</strong></td>
</tr>
</tbody>
</table>

| References |

The intentionally terse nature of standards creates a number of problems. Daro explains, “A sequence of topics, or standards, skims the surface and misses the substance and even the form of a subject...the standard gives a goal, but does not characterize the knowledge and competencies needed to achieve the goal” (Daro, 2010, p. 13). According to Kennedy, “Many standards are broadly defined, do not identify specific competencies linked to the types of activities that students should engage in to produce evidence of those competencies, and do not guide how evaluation of student work should proceed to provide useful inferences about competence and learning needs” (2005). Moreover, the Committee on Science Learning K-8 (Duschl, Schweingruber, & Shouse, 2007, p. 231) cites, “many standards and curricula contain too many disconnected topics that are given equal priority. The way many standards and curricula are conceived limits their utility for planning instruction and assessing learning. Too little attention is given to how students' understanding of a topic can be supported from grade to grade”. In short, the inherent structure of the learning goals/curricula/standards has a deep impact on the way in which learning plays out in the classroom and it often does not align with the learning sciences conception of deep learning or mastery development over time (Heritage, 2008).

This terse structure also creates a significant challenge for educators particularly, who need further detail to effectively support learning around a given construct, such as common misconceptions, evidence of mastery, etc. (Heritage, 2008; National Research Council, 2000). Understanding these aspects has a significant impact on supporting learner development (Grotzer & Perkins, 2000; Smith III, diSessa, & Roschelle, 1994). This
challenge was underscored by the majority of educators interviewed for this project (see Chapter 5). A large body of research shows that effective student learning in the classroom is most dependent upon teacher expertise, including pedagogical content knowledge, understanding the role of student misconceptions and how they must be addressed in instruction, the role of specific pedagogies, as well as tasks to elicit understanding and mastery (Darling-Hammond & Ball, 1998; NRC, 2000). This knowledge is nuanced and well understood in the learning sciences research, but is exceedingly difficult to be put into practice at scale (Nuthall, 2004). In order to make standards actionable in a learning environment, they must be deconstructed to be turned into actionable learning objectives, and to identify how to support learners in a clear path towards mastery, which is time-consuming and often complicated (Konrad et al., 2014).

Standards lie at the heart of most educational systems, and therefore everyday classroom practice as well. As a result of that, they are often at the heart of most learning technologies and content. If we zoom out and look across the system, we see a number of structural problems:

1. Integration / conflation of learning constructs within standards. The lack of ‘ontological cleanliness’ in the design of standards creates challenges for both educators as well as instructional designers and publishers. Some standards are fairly discrete in scope, such as, “Fluently divide multi-digit numbers using the standard algorithm.” (see Figure 3-2). However, some integrate multiple, complex elements into one standard (see Figure 3-3). This is done intentionally, as the endorsing jurisdiction wants to see this type of complex learning situation in the classroom; however, this is problematic for anyone other than educators using standards to align learning tools and technologies to a given set of standards—such as a learning game, which may only be targeting one aspect of a given standard. This leaves it up to educators to look at a given learning tool and determine which parts of a standard it is actually meeting. Potentially more problematic, is it creates misalignments between the standards have been tagged as targeted by a learning technology and the actual data collection on learning progress in more complex learning tools employing learning analytics, such as gaming worlds, simulations, cognitive tutors, etc. As these types of tools evolve, this misalignment only becomes more problematic.

CCSS.MATH.CONTENT.6.NS.B.2
Fluently divide multi-digit numbers using the standard algorithm.

Figure 3-2. Example of a discrete standard [from the Common Core State Standards, Mathematics, Grade 6, The Number System]
2. **Lack of coherence / alignment across jurisdictions.** Due to this conflation of constructs, as well as variation in design, sets of standards from various jurisdictions do not correlate to one another—effectively each jurisdiction working on within its own system. Although from a policy perspective each jurisdiction would likely always write and endorse its own set of standards, it makes identifying and sharing learning tools, content, and assessments across jurisdictions extremely difficult.

3. **Semantic Web integration.** Similarly, because there is no common language for these learning constructs, semantic web tools like knowledge graph cannot be easily employed. The Semantic Web is about creating structures to give data meaning that is usable by the computer through standardized metadata formats, enabling computers to analyze and build connections between data on the Web—ultimately making it possible for the browser to more easily identify relationships in related content and understand what you are looking for. The linked data structures at the heart of the Semantic Web allows now to move from just getting ‘search results’ to getting answer to questions, such as, “When was the President of the United States born?” More usefully and powerfully, it allows us to ask questions like, “what proteins are involved in signal transduction and are related to pyramidal neurons?” and instead of getting back thousands of webpages in the search results that you must dig through, you get 32 that are in direct response to your question. It is structured data, linked data that creates the meaning in order for computers to be able to do that.

In learning and education, we cannot yet ask such queries for “tasks that elicit understanding of systems thinking” or “what is the next element in a mathematics learning progression after factoring simple polynomial expressions?” Although recent efforts such as LRMI (Learning Resource Metadata Initiative) have sought to bring metadata to learning objects, this metadata format only points to a set of standards—not offering a universal index of learning constructs across which to link or map to standards. This limits our ability to easily find content and instructional materials within an educational system, and makes it difficult to share resources across educational systems (i.e. finding web materials from England that could be used in the United States).
4. Standards are not ‘living’, and as such responsive to quickly changing demands and contexts. Typically, a jurisdiction will redesign and adopt a set of standards every 10-15 years. This is understandable from a policy perspective, however they are then not dynamic maps able to reflect what knowledge the learning sciences comes to understand around a given construct in a reasonable amount of time. The development of standards was driven by policy needs, but does not reflect a more coherent design of a learning map infrastructure upon which standards could be derived. How might we design a more technically modern, robust infrastructure to serve as the foundation for policy-driven standards?

B. Competency-Based Learning

Although not a new concept in education, competency-based learning (CBL) is seeing a recent surge in interest and application in schools globally. CBL moves education from focusing on what academics believe graduates need to know to what students want and may need to know and be able to do in varying and complex situations (CEPH, 2006).

A competency is defined as “a combination of skills, abilities, and knowledge needed to perform a specific task” (U.S. Dept. of Education NCES, 2001, p. 1). In concept, they are developed by breaking down large skill sets into competencies, which may have sequential levels of mastery (CEPH, 2006). Figure A3-1B is an example of a competency model developed by a US public school district.

A core goal of a competency-based program is to provide a learning environment that is more flexible in order to move students along the K–12 continuum only when they exhibit mastery, not as a unified class cohort or time spent in the classroom, and sparks interest in learning and inspire a wide range of students to reach their potential (Achieve, 2015). The benefits of CBL include (Anderson, 2017):

- increased flexibility in pacing and pathway—both in what learners learn, and when/how/where they learn it;
- customization of learning based on learner needs and interests;
- more effectively supports learners towards mastery because competencies can more clearly define the knowledge, skills, and attitudes that constitute mastery;
- more transparency and alignment with industry and professional pathways;

With these traits, it has been argued that designing a competence-centered curriculum is in line with the results of research in the learning sciences (Singer, 2000).

Moving towards a growth perspective of education is a central driver of the CBL movement, because it creates a model that more directly reflects the nature of human development, and moves us away from “one shot”
testing situations and towards an approach that focuses on the process of learning and on an individual’s progress through that process (Wilson, 2009).

In the past decade, this idea has gained considerable momentum in education and a growing number of states and districts across the country are taking steps to implement competency-based pathways to learning. Since 2016, more than 600 colleges and universities have a CBL program in place or in development (Fain, 2016) and the entire state of New Hampshire has formally converted to mastery-based learning. CBL has become the central topic in the League of Innovative Schools at Digital Promise and at UNESCO, and amongst the 70+ ministers of education who convene at the annual Global Education Forum. Chief of their concerns are exactly how to implement it, and how to define competencies. Though, there has been a steady call for the dramatic rethinking of what competencies are supported by schools by major international organizations such as the OECD and UNESCO since the early 2000s (OECD, 2005; Aguerrondo, 2009).

One positive example of the movement towards performance standards has been the New York Performance Standards Consortium—a 20-year-old network of nearly 40 public high schools that use performance-based assessments to understand the development of learner knowledge and skills over-time. The Consortium’s system of assessment centers around tasks in various disciplines that use rubrics unpacking the key skills in that discipline (Barlowe & Cook, 2016).

In the e-learning community, there is a considerable push to standardize the definition of competencies as well as Learning Objects (LOs)—small reusable learning units that are at the heart of many e-learning platforms.

i. IMS “Reusable Definition of Competency or Educational Objective” (RDCEO) specification (IMS, 2002)


iii. HR-XML Consortium “Competencies (Measurable Characteristics) Recommendation” (HR-XML, 2006)

Perhaps the most glaring difficulty is the fact that there is no agreed upon definition or model for what a competency is, or how it is compiled or developed. Currently, schools must design their own competencies. To do this, advocates of CBL explain that schools should be integrating a mix of discipline essentials, knowledge frameworks, real-world challenges, and learning progressions (Sturgis, 2014). This is an incredible task for even the best instructional designers, let alone the average teacher in an average school. Moreover, as one of the major

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9 As described in personal communication with Aubrey Francisco and Sara Schapiro, who lead the League of Innovative Schools program, and with Gavin Dykes, who oversees the Global Education Forum.
organizations advocating for CBL put it, “designing competencies is a creative process” (Sturgis, 2012). That
may be, but if each school is creatively developing their own, there is no internal consistency and typically little
if any quality assurance. Even more concerning, those implementing CBL advocate that schools begin by using
or building a learning progression (Sturgis, 2014), but are not also indicating using the rigorous and cautious
methods by which learning scientists develop learning progressions (i.e. research-based, cautiously used until
vetted – discussed more fully in the next section).

Schools have also voiced that the biggest logistical challenge to implementing CBL is the lack of high-quality
data and technological tools to monitor student progress that are tailored to each initiative’s specific approach
(Priest et al, 2012).

C. Rubrics

Rubrics, a long-time favorite of educators, are used to communicate expectations of quality around a task, often
used to delineate consistent criteria for grading. They can be a useful way to support the development of
complex skills in learners (Jonsson & Svingby, 2007; Panadero & Jonsson, 2013), supporting both mental
model formation as well as self-regulation processes through self, peer, and expert feedback and reflection on
performances (Rusman & Dirkx, 2017). Rubrics can fill a critical need in the classroom: to more clearly define
what evidence of achievement looks like, to help learners understand what mastery looks like, and to support
more useful formative feedback in the learning process.

There a number of types of rubrics that range in capability and complexity (see Figure A3-IC for an example).
Holistic rubrics contain a single scale with all criteria considered together. Analytic rubrics offer more
dimensionality, and provide textual descriptions of the mastery levels with performance indicators in a given
skill, which describe concrete behavior for sub-skills at each mastery level (Reddy, 2011). Performance
indicators make the mastery level for a given skill explicit for pupils which supports learners to have a more clear
picture of what mastery looks like (Jonsson & Svingby, 2007; Reddy & Andrade, 2010). Developmental rubrics
are considered a subset of analytic rubrics and are based on relevant developmental theory to identify
performance criteria (Balch, Blanck, & Balch, 2016).

Their efficacy, however, largely depends on the quality of the rubrics used (Rusman & Dirkx, 2017). Popham’s
seminal paper on the topic emphasized that effective rubrics must have (i) evaluative criteria, (ii) quality
definitions for those criteria at particular levels, and (iii) a scoring strategy, and cautioned that rubrics can harm
learning when there are a lot of inconsistencies in the performance indicator descriptions across mastery levels
(1997). Yet later empirical work showed few teachers understand these traits of quality rubrics and enact them
According to Dawson (2017), the lack of alignment and understanding on what constitutes a rubric – let alone a high-quality rubric – is not defined and highly problematic; some institutions have adopted policies that mandate the use of a ‘rubric’ without providing a working definition of the term, leaving it open to a very diverse array of interpretations. Similarly, many learning management systems provide ‘rubric’ tools that each represent particular interpretations of varying quality. These are all symptoms of a ‘label naivety’ that is common to education and many other areas of social science as well (Pawson 2006; Dawson, 2017).

As is so often the case with curricula as well, educators construct their own rubrics to meet their current classroom needs. Yet each teacher has a different set of criteria of what qualifies as good versus poor, or mastery or not, in a given construct (Erdosy, 2003; Lumely, 2002; Lumely, 2006). The dimensions used to describe the different mastery levels vary within and across rubrics, and are typically not consistent and often trivial (Rusman & Dirkx, 2017). As a result, many have called for rigorous rater training for educators, and clearly defined rubrics agreed upon as assessment constructs (Jeong, 2015; Lovorn & Rezaei, 2011; Alderson, 1991). Additionally, one of the major challenges is the lack of research and infrastructure to support the formulation of uni-dimensional constructs for the creation and refinement of rubrics (Reddy, 2011; Tierney & Simon, 2004).

**Summary Discussion**

In practice, we see a messy landscape of structures and initiatives aimed at coordinating models of learning, and improving them. The everyday teaching and learning dynamics in classrooms are largely driven by the intricate dance between the design of curriculum, assessment, and policy structures. It is well-documented that for many traditional educational contexts, these dynamics play out in a way that provide learners with a thin experience of content, and a shallow understanding of concepts that overly emphasizes facts and memorization (Corcoran, Mosher & Rogat, 2009). In other words, the design of the framework does not necessarily imply how teaching and learning may be supported, but rather it is the interpretation and policies surrounding the approach that dictates how teaching and learning unfold.

The field is demonstrating the critical need for tools that support mastery- and competency-based learning, yet the infrastructure to bring those that are research-based and grounded in a methodology that ensures quality, to scale, is not yet available. Although it is unlikely that every learning environment might adopt the same competency models, having a shared knowledge base that helps all stakeholders learn from one another and build on the same foundation would be prudent. Given the prominent role of the emerging CBL landscape in education, this presents an opportunity as one of the key spaces to test new data model designs.
II. THE LEARNING SCIENCES: Understanding & Modeling Learning

How do we come to understand the nature of learning and human development? How do we map and model pathways from novice to expert? How do we support learners as they grow, explore, and master a range of skills and competencies? These questions have been at the heart of learning sciences research for decades, and despite all that we have learned about learning, in many ways these questions still continue to be a central focus today.

How does one capture something intangible and invisible? The constructs and framings discussed in this section are an overview of our attempts to capture and communicate the intangible, and like so many models in any field, each offers a validated cross-section of a complex reality. How do all these models interrelate? This section will give an overview of the core constructs and frameworks developed by learning scientists, as it relates to this problem space.

A. Schemas and Models

Much of the early work on understanding cognition was focused on unpacking differences between novices and experts, and the natural nature of human development. Over the decades of a range of framings were termed by cognitive psychologists in an attempt to refer to the cognitive states and conceptual models of individuals that were in part influenced by the field of artificial intelligence (AI) which also had a critical need to model knowledge and knowledge representations (Anderson, 1985; Markman, 2013). These included:

- **mental imagery** – system of imaginal symbols to represent figural and conceptual aspects of objects, concepts, relations, and transformations for representation of the formal environment (Piaget & Inhelder, 1971; Paivio, 1971; Kosslyn, 1981; Greeson & Zigarmi, 1985);

- **schemas (and schematas)** – a cohesive, repeatable action sequence possessing component actions that are tightly interconnected and governed by a core meaning; abstractions from specific instances that can be used to make inferences about instances of the concepts they represent (Piaget, 1952; Bobrow & Norman, 1975; Rumelhart & Ortony, 1977; ERIC database, 2018);

- **mental models** – internal representations of external reality that enable an individual to make inferences, deductions, and predictions, to understand and explain a process, and to decide on the best course of action to take in particular situations or contexts (Johnson-Laird, 1983; Vosniadou & Brewer, 1992; diSessa, 1996);

- **frames** – a data-structure for representing a stereotyped situation (Minsky, 1975);
knowledge representations – a surrogate or substitute for reasoning about the world, that operates under a set of ontological commitments, and serves as a medium for intelligent reasoning, pragmatically efficient computation, and human expression (Brown & Burton, 1978; Fodor, 1981; Davis, Shrobe & Szolovits, 1993; Riegler, Peschl & Stein, 1999; Markman, 2013);

concepts – units of mental representations of real-world constructs, roughly the grain-size of single lexical items (Farah & Kosslyn, 1982; Klausmeier, 1990; Carey, 1992; diSessa, 2002)

These were the initial “building blocks” of the learning sciences, a unit of analysis and as a means to explain state changes in learners. Prominent psychologists – including Piaget, Bruner, and Werner – all claimed that it was these changes in the nature of a mental representation over time which accounts for much of the child’s increasing cognitive abilities (Farah & Kosslyn, 1982). This era of work, which later moved toward a central framing of ‘concepts’ and ‘concept models’, was focused on capturing the states/models themselves and the overall ‘conceptual ecology’ of a learner (see Figure 3-4) (diSessa, 1988). Network representations such as semantic networks have been used to encode conceptual knowledge as well as propositional knowledge (Quillian, 1966), but such networks are not able to capture general representational knowledge, cognitive science researchers called such representational structures schemas (Rumelhart & Ortony, 1976). This then later gave way to understanding the nature of changes of states/models—i.e. the work in conceptual change (Carey & Spelke, 1994).

![Figure 3-4. A conceptual ecology perspective. Source: diSessa, 2002.](image)

B. Developmental Frameworks

Alongside this research, there have been similar efforts to understand how knowledge states and developmental stages integrate over time to create natural pathways of human development. This work has contributed greatly
to the learning sciences, and has had a considerable influence on the design of curriculum and assessments. Prominent frameworks include:

**Piaget's Stages of Development**

Jean Piaget's work on Stages of Cognitive Development (1952) was the first major contribution to this space (see Figure 3-5), offering a model of general development from infancy to adulthood:

I. *Sensorimotor* - birth through ages 18-24 months

II. *Preoperational* - toddlerhood (18-24 months) through early childhood (age 7)

III. *Concrete Operational* - ages 7 to 12

IV. *Formal Operational* - adolescence through adulthood

Piaget's work had a significant impact on education and set the foundation for modern day developmental psychology and what is now the learning sciences.

![Figure 3-5. Piaget's Stages of Cognitive Development](image)

Several notable frameworks built on Piaget's framework, exploring various possibilities of developmental stages or "orders of hierarchical complexity"—a notion that most developmental stage theories employ (Dawson, 2003).
**Kohlberg's Stages of Moral Development**

Building on Piaget’s assertion that logic and morality develop through constructive stages, Kohlberg’s concluded that human psychosocial competence (including ethical development) lies in the ability to see another’s perspective (Kohlberg, 1969), and this psychosocial development has six identifiable stages (see Figure 3-6).

<table>
<thead>
<tr>
<th>Level/Stage</th>
<th>Age Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I: Obedience/Punishment</td>
<td>Infancy</td>
<td>No difference between doing the right thing and avoiding punishment</td>
</tr>
<tr>
<td>I: Self-Interest</td>
<td>Pre-school</td>
<td>Interest shifts to rewards rather than punishment — effort is made to secure greatest benefit for oneself</td>
</tr>
<tr>
<td>II: Conformity and Interpersonal Accord</td>
<td>School-age</td>
<td>The “good boy/girl” level. Effort is made to secure approval and maintain friendly relations with others</td>
</tr>
<tr>
<td>II: Authority and Social Order</td>
<td>School-age</td>
<td>Orientation toward fixed rules. The purpose of morality is maintaining the social order. Interpersonal accord is expanded to include the entire society</td>
</tr>
<tr>
<td>III: Social Contract</td>
<td>Teens</td>
<td>Mutual benefit, reciprocity. Morally right and legally right are not always the same. Utilitarian rules that make life better for everyone</td>
</tr>
<tr>
<td>III: Universal Principles</td>
<td>Adulthood</td>
<td>Morality is based on principles that transcend mutual benefit.</td>
</tr>
</tbody>
</table>

*Figure 3-6. Kohlberg's Stages of Moral Development (source: psychologynoteshq.com).*

**Dreyfus Model of Skill Acquisition**

Another well-known model of development was presented by Dreyfus and Dreyfus, who argued that counter to the Piagetian view that proficiency is inherent as one moves from concrete to abstract, rather skill is developed only through ongoing tangible experience and that any meaningful development of learning tools must build on knowledge of general of stages of development in the targeted domain (1980). Examining the skill-acquisition process of airplane pilots, chess players, automobile drivers, and adult learners of a second language, they observed a common pattern in all cases; this work resulted in their “five stages of skill acquisition” (see Figure 3-7) (Dreyfus, Dreyfus & Athanasiou, 2000; Benner, 1982). Dreyfus went on to advocate for the benefits of understanding the ‘phenomenology of everyday expertise’ as a means to overcoming Minsky’s AI problem of modeling common sense knowledge (Dreyfus, 2005).
Level Novice Observer
1 Rigid adherence to taught rules or plans Little situational perception
No discretionary judgment performed by a colleague

Level Advanced Beginner Assistant
2 Guidelines for action based on attributes or aspects Situational perception still limited
All attributes and aspects are treated separately and given equal importance

Level Competent Directly supervised
3 Coping with crowdedness Sees actions at least partially in terms of longer-term goals
Conscious deliberate planning

Level Proficient Indirectly supervised
4 See situations holistically rather than in terms of aspects
See what is most important in a situation Perceives deviations from the normal pattern Decision-making less labored
Uses maxims for guidance, whose meaning varies according to the situation

Level Expert Independent
5 No longer relies on rules, guidelines, or maxims Intuitive grasp of situations based on deep tacit understanding
Analytic approaches used only in novel situation or when problems occur
Vision of what is possible

Observer
Observes the procedure performed by a colleague

Assistant
Assists a colleague in performing the procedure

Directly supervised
Performs the entire procedure under direct senior supervision

Indirectly supervised
Performs the entire procedure with indirect senior supervision

Independent
Performs the entire activity without the need for supervision

Figure 3-7. Dreyfus’s Five Stages of Skill Acquisition (Dreyfus, Dreyfus & Athanasiou, 2005).

Building on Kohlberg’s work, Selman (1980, 2003) demonstrated developmental progressions of social perspective-taking—the competency underlying psychosocial development (see Figure 3-8).

<table>
<thead>
<tr>
<th>Shared Experience: Relatedness Aspect</th>
<th>Social Perspective Coordination Levels</th>
<th>Interpersonal Negotiation Strategies: Autonomy Aspect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unreflective imitation or enmeshment; lack of differentiation</td>
<td>Level 0: Undifferentiated, egocentric</td>
<td>Physical force: impulsive fight or flight or freeze</td>
</tr>
<tr>
<td>Unreflective sharing of expressive enthusiasm</td>
<td>Level 1: Differentiated, subjective</td>
<td>One-way, unilateral power: orders or obedience</td>
</tr>
<tr>
<td>Reflective sharing of similar perceptions and experiences</td>
<td>Level 2: Reciprocal, self-reflective</td>
<td>Cooperative exchange reciprocity: persuasion or deference</td>
</tr>
<tr>
<td>Empathic sharing of beliefs and values</td>
<td>Level 3: third-person, Mutual</td>
<td>Mutual compromise</td>
</tr>
<tr>
<td>Interdependent sharing of vulnerabilities and self-identities</td>
<td>Level 4: Intimate, in-depth; Societal</td>
<td>Collaborative integration of relationship dynamics (commitment)</td>
</tr>
</tbody>
</table>

Figure 3-8. Selman’s Levels of Social Perspective-Taking (Selman, 1980).
**Fischer’s Dynamic Skill Theory**

A handful of researchers (Esther Thelen, Paul van Geert, Kurt Fischer) brought dynamic complexity to modeling and understanding human development in order to capture the richness and complexity of development (Fischer, 1980; Thelen & Smith, 1994; Rose & Fischer, 2009). Expanding considerably on Piaget’s stages, so as to more accurately capture the “unevenness” of human development, Fischer’s *Dynamic Skill Theory* attempts to provide tools for the prediction of developmental sequences in any domain at any given point in development by integrating behavioral and cognitive-developmental concepts, and that collectively, cognitive development is explained by a series of integrated skill structures levels together with gradually increasing complexity (Fischer, 1980). In addition to Piaget, Fischer’s theory built on the range of work by previously psychologists including Bruner (1971, 1973), Werner (1948, 1957), and Skinner (1938, 1969), information-processing psychology (Case, 1974; Pascual-Leone, 1970; Schaeffer, 1975), and the study of skill learning (Baron, 1973; Gagne, 1968, 1970; Reed, 1968).

Fischer (1980) and colleagues (Thelen & Smith, 1994; Fischer & Bidell, 2006; Rose & Fischer, 2009; Stein, Dawson & Fischer, 2010) demonstrated that skills develop step-by-step through a series of 10-hierarchical levels divided into three tiers (see Figure 3-9), later expanded into 12-hierarchical levels (see Figure 3-11). The tiers specify skills of that align: sensory-motor skills, representational skills, and abstract skills. The levels specify skills of gradually increasing complexity, through a repetitive cycle, with a skill at one level built directly on skills from the preceding level (see Figure 3-10). Each level is characterized by a reasonably well-defined type of structure that indicates the kinds of behaviors that a person (child or adult) can control at that level (Fischer, 1980).

### Skill Scale

<table>
<thead>
<tr>
<th>Tiers</th>
<th>Levels</th>
<th>Age of Emergence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ab4</td>
<td>Principles</td>
<td>23-25 years</td>
</tr>
<tr>
<td>Ab3</td>
<td>Systems</td>
<td>18-20</td>
</tr>
<tr>
<td>Ab2</td>
<td>Mappings</td>
<td>14-16</td>
</tr>
<tr>
<td>Rp4/Ab1</td>
<td>Single Abstractions</td>
<td>10-12</td>
</tr>
<tr>
<td>Rp3</td>
<td>Systems</td>
<td>6-7</td>
</tr>
<tr>
<td>Rp2</td>
<td>Mappings</td>
<td>3½ -4½</td>
</tr>
<tr>
<td>Sm4/Rp1</td>
<td>Single Representations</td>
<td>2</td>
</tr>
<tr>
<td>Sm3</td>
<td>Systems</td>
<td>11-13 months</td>
</tr>
<tr>
<td>Sm2</td>
<td>Mappings</td>
<td>7-8</td>
</tr>
<tr>
<td>Sm1</td>
<td>Single Actions</td>
<td>3-4</td>
</tr>
</tbody>
</table>

**Figure 3-9.** Levels of Development in Dynamic Skill Theory (Fischer & Bidell, 2005).
### Figure 3-10. Metaphor for Fischer's four levels of skill development (Fischer, 1980).

<table>
<thead>
<tr>
<th>Level</th>
<th>Level name</th>
<th>Age of onset</th>
<th>Education</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Single reflexive actions</td>
<td>Birth</td>
<td>n/a</td>
</tr>
<tr>
<td>1</td>
<td>Reflexive mappings</td>
<td>6 wks</td>
<td>n/a</td>
</tr>
<tr>
<td>2</td>
<td>Reflexive systems</td>
<td>3 mos</td>
<td>n/a</td>
</tr>
<tr>
<td>3</td>
<td>Single sensorimotor actions</td>
<td>6 mos</td>
<td>n/a</td>
</tr>
<tr>
<td>4</td>
<td>Sensorimotor mappings</td>
<td>10 mos</td>
<td>n/a</td>
</tr>
<tr>
<td>5</td>
<td>Sensorimotor systems</td>
<td>15 mos</td>
<td>n/a</td>
</tr>
<tr>
<td>6</td>
<td>Single representations</td>
<td>21 mos</td>
<td>n/a</td>
</tr>
<tr>
<td>7</td>
<td>Representational mappings</td>
<td>4-5 yrs</td>
<td>0-K</td>
</tr>
<tr>
<td>8</td>
<td>Representational systems</td>
<td>7-8 yrs</td>
<td>1-2</td>
</tr>
<tr>
<td>9</td>
<td>Single abstractions</td>
<td>10-11 yrs</td>
<td>4-5</td>
</tr>
<tr>
<td>10</td>
<td>Abstract mappings</td>
<td>14-15 yrs</td>
<td>8-9</td>
</tr>
<tr>
<td>11</td>
<td>Abstract systems</td>
<td>22+ years</td>
<td>15-16</td>
</tr>
<tr>
<td>12</td>
<td>Single principles</td>
<td>26+ years</td>
<td>Ph.D.+</td>
</tr>
</tbody>
</table>

### Figure 3-11. General framings of the Levels of Fischer’s Dynamic Skill Theory (Source: http://lecticalive.org).
Central to Fischer’s model is **hierarchical complexity theory**, which predicts that some increasing levels of developmental complexity will take the form of increasing hierarchical order of abstraction because new concepts are formed at each complexity order as the operations of the previous complexity order are "summarized" into single constructs (Fischer, 1980). Such summarizing or "chunking" makes more complex thought possible by reducing the number of elements that must be simultaneously coordinated, freeing up processing space and making it possible to produce an argument or conceptualization at a higher complexity order (Burtis, 1982; Halford, 1999) (see Figure 3-12).

![Figure 3-12. Model of hierarchical integration. Source: http://lecticalive.org](http://lecticalive.org)

Fischer’s framework departs from the rigid step-ladder sequence and instead models “skill webs”—more complex graphs of different learner pathways (see Figure 3-13). Fischer and Rose emphasize that the order of the strands in a web are not predetermined, nor is there one universal sequence, and that students commonly show similar strands, branches, and connections, as well as similar start and end points—dynamics that are essentially lost in a one-dimensional image of a ladder, which forces all students into one rigid model (Fischer & Rose, 2001).
Fischer and Rose explain that all pathways of reading development begin with word definition skills, but these alternate pathways to reading show different skills developing independently; Learning to read is more difficult for most learners following alternate pathways, but eventually many become skilled readers (2001). Examples of these different pathways to literacy can be found in Appendix C, Figures A3-IIB-1 and Figures A3-IIB-2.

Fischer’s Skill Theory is the most complex of the field, and robust, in terms of its capacity to offer a coherent framework that can support a wide range of constructs and competencies. It has served as the foundation for one of the most robust development models in practice today, the Lectical® Levels\(^\text{10}\) of skill development, a developmental scale that goes from birth to the highest levels of development we know how to measure (Dawson-Tunik et al., 2005). It is a scale of increasing complexity, which can be used to identify the developmental level of any phenomenon that represents hierarchical complexity—with a Lectical Score on the Lectical Scale represents the complexity level of a particular performance. An overview of the Lectical Scale is provided in Figure 3-14. Recently, the Lectical scale has been used to detect 10 statistically-distinct developmental phases in adulthood, which brings a number of advantages, including making it possible to

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\(^{10}\) [https://lecticalive.org/about/skill-levels](https://lecticalive.org/about/skill-levels)
customize learning experiences to meet the specific needs of individuals. Most interestingly, the domain-general models allow for multiple assessments of diverse competencies in a variety of areas—including ‘Leadership’, ‘Creativity’, and ‘Decision-Making’ (Stein, Dawson & Fischer, 2010; Dawson, 2004; Dawson & Gabrielson, 2003; Dawson & Stein, 2004). Figure A3-IIB-3 in Appendix C shows an example of Lectical Levels for decision-making skills.

<table>
<thead>
<tr>
<th>Level</th>
<th>Concepts</th>
<th>Logical structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Concepts are 1st order representational sets; these coordinate symbolic systems.</td>
<td>The logical structure is definitional; It identifies one attribute of a single representation—as in &quot;The tent is blue,&quot; in which &quot;blue&quot; is an attribute of the tent.</td>
</tr>
<tr>
<td>Single representations 26-40 mos</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Concepts are 2nd order representational sets; these coordinate or modify representational sets (the concepts constructed at the single representations level).</td>
<td>The logical structure is linear; It coordinates one aspect of two or more representations—as in, &quot;If you do not do what your father tells you to do, he will get really mad at you,&quot; in which doing what your father says and not doing what your father says are coordinated by his anticipated reaction.</td>
</tr>
<tr>
<td>Representational mappings 4-5 years</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Concepts are 3rd order representational sets; these coordinate elements of representational systems. For example, the concept of trust, articulated for the first time at this Lectical™ level, can be used to describe the system of interactions between Joe and his father. &quot;Joe trusted [his Dad] that he could go to the camp if he saved enough money, and then his father just breaks it, and the promise is very important.&quot;</td>
<td>The logical structure is multivariate; It coordinates multiple aspects of two or more representations—as in, &quot;If Joe’s Dad says Joe can go to camp, then he says he can’t go to camp, that’s not fair because Joe worked hard and then his Dad changed his mind,&quot; in which two conflicting representations of Dad’s authority are evaluated in terms of his changed mind and Joe’s hard work.</td>
</tr>
<tr>
<td>Representational systems 6-7 years</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Concepts are 1st order abstractions These coordinate representational systems. For example, the concept of trustworthiness, articulated for the first time at this Lectical™ level, defines those qualities that make a person trustworthy rather than describing a particular situation in which trust is felt or not felt.</td>
<td>The logical structure is definitional; It identifies one aspect of a single abstraction—as in, &quot;Making a promise is giving your word,&quot; in which giving one’s word is an aspect of a promise.</td>
</tr>
<tr>
<td>Single abstractions 8-11 years</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Concepts are 2nd order abstractions; these coordinate or modify abstractions. For example, the abstract mappings level concept basis can be employed to</td>
<td>The logical structure is linear; The most complex logical structure of this Lectical™ level coordinates one aspect of two or more abstractions—as in, &quot;Joe has a right to</td>
</tr>
</tbody>
</table>
coordinate the elements essential to a good relationship. "To me, [trust and respect are] the basis of a relationship, and without them you really don’t have one." Concepts like coming to an agreement, making a commitment, building trust, and compromise are also rare before this LecticalTM level.

### 11 Abstract systems

Concepts are 3rd order abstractions; these coordinate elements of abstract systems. For example, the concept of personal integrity—which is rare before the abstract systems level—refers to the coordination of and adherence to notions of fairness, trustworthiness, honesty, preservation of the golden rule, etc., in one's actions. "[You should keep your word] for your own integrity. For your own self-worth, really. Just to always be the kind of person that you would want to be dealing with." Concepts like verbal contract, moral commitment, functional, development, social structure, and foundation are also uncommon before the abstract systems level.

The logical structure is multivariate; The most complex logical structure of this level coordinates multiple aspects of two or more abstractions. "Following through with his commitment and actually experiencing camp combine to promote Joe’s growth and development, not just physically but psychologically, emotionally, and spiritually." Here, multiple facets of Joe’s personal development are promoted when he both keeps his commitment and accomplishes his goal.

### 12 Single axioms/principles

Concepts are 1st order axioms/principles; these coordinate abstract systems. A single principles notion of the social contract, for example, would result from the coordination of human interests (where individual human beings are treated as systems in interaction with other individual and collective systems).

The logical structure is definitional; It identifies one aspect of a principle or axiom coordinating systems—as in, "Contracts are articulations of a unique human quality, mutual trust, which coordinates human relations." Here, contracts are seen as the instantiation of a broader principle coordinating human interactions.

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**Figure 3-14.** Overview of the Lectical® Levels in the Lectical® Scale, adapted from https://lecticalive.org/about/skill-levels

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**C. Construct Models & Cognitive Models**

Over the decades, analysis of learner understanding of wide range of domains has been executed at vary levels of granularity—from the impact on shifting learner misconceptions on adding fractions by using specific math problems (e.g. Lampert, 2003) to “big ideas” that are concepts in a given domain. The author uses the term “construct models” to refer to all of the various research that has been conducted in this way, but does not otherwise fall into one of the previously depicted frameworks discussed in this section. At times, aspects of
research on learning in a given domain (i.e. number sense, literacy, celestial motion, systems thinking, etc.) has been organized into a more formal model of that domain.

Wilson first defined a construct as, the ideas or concepts that we wish to learn about and measure (Wilson, 2005). **Construct modeling** is the development of a model of cognition that is defined by one or more proficiencies along a continuum of progress towards higher levels of sophistication and competence as new knowledge is linked to existing knowledge and deeper understandings are developed (Brown & Wilson, 2011). **Construct maps** are representations of models of cognition by which certain learning data can be interpreted (see Figures A3-IIC-1 to A3-IIC-4 in Appendix C for examples), and have served as a foundational aspect towards the more recent development of learning progressions (NRC 2007; Smith et al. 2006; Songer et al. 2009; Wilson 2009). These maps are intended to be a somewhat less complex concept than a learning progression (see section II. D. of this chapter), with an emphasis on how to conceptualize assessments that can be constructed to relate to theories of cognition (Wilson, 2009). Wilson further proposed using sets of construct maps, which can be stacked or aligned to create learning progressions (discussed further in the next section), as a way to address complexities of learning competency development (2009).

**Construct-Centered Design (CCD)** which integrates aspects of learning-goals-driven design (Krajcik, McNeill & Reiser, 2007), the assessment triangle (Pellegrino et al., 2001), and evidence-centered design (Mislevy et al., 2003) – has been proposed as a powerful framework for generating learning progressions because it provides a systematic approach to developing instructional materials (for students and teachers), and assessment (formative & summative) (Shin, Stevens, Pellegrino, Krajcik & Geier, 2008).

**D. Learning Progressions**

One of the most current iterations of these efforts to model learning in the learning sciences has come in the form of what has been termed “learning progressions”. Also referred to as **learning trajectories, learning pathways, progressions of developmental competence, and profile strands**, they are descriptions of the successively more sophisticated ways of thinking about an idea that follow one another as students learn, that describe a series of conjectures about states of student knowledge coordinated with the means of supporting transitions in these knowledge states (Simon, 1995).

LPs are research-based frameworks used to model our understanding of how learners develop competency in a domain over time. LPs are empirically-grounded and testable hypotheses about how students’ understanding of, and ability to use, core concepts and practices grow and become more sophisticated over time, as they move from naïve to more sophisticated ideas (The U.S. National Research Council, 2007; Confrey, Maloney & Nguyen, 2014; Heritage, 2008). Some view LPsas a natural evolution of the previous work on “construct models” (Plummer & Maynard, 2014) and “progress maps” (Wilson & Draney, 1999), which plot general progress indicators in a given domain.
The distinction between LPs and traditional curricula is that they are grounded in empirically-testable hypotheses about the ways children's thinking actually develops in interaction with experience and instruction, focusing not only on what the teachers and curriculum are trying to teach but looking closely at what the students are actually attending to and learning, and at the ways their thinking is becoming organized (Mosher, 2011).

The actual structure and format of LPs can vary, depending on the domain and the author. Figures A3-IID-1 to A3-IID-7 in Appendix C provide examples of a number of depictions of LPs in a variety of domains, which demonstrate how their design and structure can vary. However, these depictions typically have a number of traits in common, which also have been underscored as essential traits of LPs by a number of experts in this area (Corcoran, Mosher & Rogat, 2009): (i) a description of the concept that is the focus of the LP, with clear learning targets as defined by societal competencies and/or in the research of a given domain; (ii) progress variables that identify critical dimensions of understanding and skill development over time; (iii) levels or stages of progress that define significant intermediate steps learners are likely to pass through as they move towards mastery; (iv) learning performances, operationally defining what competency looks like at each stage; and (v) assessment tasks that elicit and measure understanding, and track progress over time.

LPs roots are in research, and traditionally have been used as a research framework for modeling learner development in a given domain over time, with the intent of doing so to impact and improve instruction. There are several aspects to LPs that are emphasized:

1. **LPs are hypotheses** that describe the multiple possible pathways students are likely to follow to the mastery of core concepts, and then tested empirically to ensure their construct validity (Corcoran, Mosher & Rogat, 2009).
2. **There are multiple paths to competence.** It is also emphasized in the literature that LPs are not prescriptive depictions of how learners will ultimately come to mastery in a domain, but rather maps of possible routes and indicators to be aware of when supporting learners towards mastery (Rich et al., 2018). Figure 3-16 depicts the various types of multiple trajectories of a learner.

![Diagram](image)

*Figure 3-15.* The learning trajectory creation process (Rich et al., 2018).

![Diagram](image)

*Figure 3-16.* Shapes and content of LPs as in influenced by theoretical framings (Rich et al., 2018).
3. **Instruction is a factor that affects the actualization of a LP in real life.** Simply, the character of the instruction provided can affect the developmental pathway that most children follow. In this way, LPs are not developmentally inevitable, but rather dependent on the instruction that students receive. Since a LP must be empirically validated, it will be done so in the context of specific learning experiences and pedagogies experienced by students. This has implications for how a LP is perceived and applied later, since if a LP is based on evidence drawn from students who are all receiving a particular type of instruction, then it maybe less generalizable than one based on evidence drawn from studies of children receiving different forms of instruction (Corcoran, Mosher & Rogat, 2009).

Initial development of LPs began in the domain of science, in part due to the nature of studying how children learn science concepts over time—including their misconceptions and early cognitive models, and tasks that help elicit these to inform the educator on how to best support them in the classroom. However, LPs have begun emerging in a variety of domains, including systems thinking, and many non-cognitive skills, but perhaps most dominantly in mathematics thanks to the work of Jere Confrey and colleagues (Confrey, Maloney & Corley, 2014; Maloney, Confrey & Nguyen, 2014).

![Diagram of potential order and organization of science content in the entire learning progression](image)

**Figure 3-17.** Illustration of a LP and how it can be supported through a process of development, refinement and empirical testing (Stevens, Shin & Krajcik, 2009).
Although considerable research in LPs has been conducted over the past decade, this is still considered a nascent area of the learning sciences, with decades of work ahead. Additionally, despite clear progress in the development of LPs in a number of domains, in many ways they are still contested in the field of learning sciences—as to whether they are valid constructs, if and how they can be accurately used in classroom instruction, and so on. This is in part due to the fact that researchers disagree about the degree to which curriculum and instruction should be linked to learning progressions, because it is unclear the extent to which an instructional intervention affects the development and validity of an LP; paradoxically, they also argue that LPs are simply theoretical constructs that are not intended to be tied to specific instructional interventions (Duncan & Hmelo-Silver, 2009).

Despite this contention, LPs have already begun impacting classroom practice. For example, a number of LPs have informed the design of standards such as the Common Core State Standards for Mathematics. Yet broadly speaking, there is still a considerable translation gap between deeply nuanced research-based knowledge of LPs and the design (and subsequent implementation) of standards (Daro, 2010). This, in part, points to the persistent challenge of a significant amount of research and knowledge still sitting in journals (the literature), rather than being translated into tools for practice—or even digital tools for better knowledge management just within the research community. Teachers need to be able to understand and apply this research, and the design of the common tools that support their practice (like standards) have implications for their ability to do so (Cromley & Mislevy, 2005). Building effective tools for teachers to leverage LPs in their daily instruction, as well as providing educators with the necessary professional development and support to understand how to do that, are both still significant gaps in the field.

The movement towards competency-based education is helping to give an additional push of movement to the work in the development of LPs. Across Europe and more recently in the US, there is a pronounced movement of leading districts moving to competency-based education (Singer, 2006; Sturgis, 2015), where personalized learning and individual paths towards mastery are supported, versus standards-based education, which focuses on ‘proficiency’. There is considerable support from a variety of education stakeholders (including foundations and NGOs) because competency-based education can more effectively support learning environments in mastery-based and personalized learning, and more effectively aligns with a learning sciences’-based understanding of the nature of learning (OECD, 2010). However, the field has yet to define a common model for a competency, and as a result, these leading-edge schools are left to define these on their own. In many cases, districts will appoint a small subset of teachers to collectively define the competencies they will use based on the

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11 Personal interview with Richard Halverson, Ph.D., June 16, 2012.
existing standards they follow\(^\text{12}\); as a result, what constitutes a ‘competency’ varies significantly within those competencies and across schools/districts.

The research community has also begun to show how LPs can help us build models of student thinking and development in a variety of domains, and have found LPs to be practically useful now in the setting of curriculum and standards (Wilson, Mojica, Confrey 2013; Clements, Wilson, & Sarama, 2004). Additionally, LPs have shown their potential for bridging the gap between summative and formative assessments (Briggs & Peck, 2015). Well-developed LPs provide the integrated, rich descriptions that can serve as the foundation for both defining summative assessment construct and how teachers can construct everyday formative assessment tasks.

LPs are a promising, but labor-intensive practice. Building an LP is an iterative process of development, empirical validation, and revision (Duschl, Maeng, & Sezen, 2011). As this field of work is still quite young, there is much to be done yet in defining and understanding the nature of LPs and how they can best support classroom instruction. Additionally, early work in developing LP-based assessments have led some experts to conclude that this work is extremely challenging, because of the resources and the interdisciplinary expertise that are required to develop them (Penuel, 2015; Shea & Duncan, 2013). Still further, LP researchers assert that because alternative forms of activity could prove more fruitful for developing student understanding, articulating a learning progression requires specifying “how particular forms of activity support conjectured mechanisms of learning” (Lehrer & Schauble, 2015, p. 433). That means having to go much deeper into detail and nuance to truly build effective and reliable LPs that can support classroom instruction.

It has been suggested that the development of learning progresses represents an excellent area for critical collaboration between researchers and practitioners. As discussed earlier, by their very definition LPs emerge through understanding real world learning—but are synthesizing into an overarching schema through research. The development of learning progresses “requires extensive dialogue among science educators, learning scientists, and measurement specialists and should bring these communities together to develop more aligned curricula and assessment” (Corcoran, Mosher & Rogat, 2009, p. 22).

Unfortunately, as is too often the case with research, the work on LPs still largely sits in journals and literature, rather than being translated into tools for practice or even digital tools for better knowledge management just within the research community. Teachers need to be able to understand and apply this research, and the design of the common tools that support their practice (like standards) have implications for their ability to do so (Cromley & Mislevy, 2005). This is a powerful and central example of how such a common data architecture,

\(^{12}\) Personal communication with Deputy Secretary of Education for the state of New Hampshire, Paul Leather, who oversees their state transition to competency-based learning.
with useful interfaces on top of it, could bring exponential growth of knowledge in the field and as a result a
dramatic impact on practice and our ability to then build on such advancements together.

Leveraging LPs in the design of standards and curricula is delicate – yet critical – work. Like many innovations
in education, when not carefully applied you not only miss the opportunity for positive impact from the
intervention but it can have damaging effects as well. We need more discussion and analysis on what LPs are to
be defined and how they are to be used in classrooms. This bridge from research to practice is not always clear.
Mosher (2011, p. 7) frames this tension best:

“It is important to recognize that there is a fundamental tension, or difference in perspective, between
characterizing points on this path the way current standards do—as the particular knowledge and skill
that students ought to have acquired by the end of each grade, or at some point in high school, depending
on their courses—and the progressions approach that describes the full array of significant steps that
students are likely to go through along the way, if they eventually succeed in meeting the goals of
instruction. The progressions orientation encourages determining where students actually are on that
path rather than simply noting whether they have reached the level the standards expect them to at the
end of each grade, grade band, or course.”

The key difference is in focus. By focusing on what children ought to be able to do by now, as opposed to what
they are in fact now doing makes a difference for both practice and policy. For example, in reference to Figures
A3-IID-3 and A3-IID-4 in Appendix C, the authors of this LP caution,

“Note that in this learning progression, at least as it has been initially hypothesized, there is not a one-to-one
relationship between the number of distinct levels of the progression and the number of grades through
which a student will advance over time. It may be the case that as we gather empirical evidence about
student learning along this progression that we discover additional levels or collapse existing ones. Rather
than assigning a single grade with a single level, we might instead associate grade bands with each level,
recognizing that grade designations are largely arbitrary and that a student’s sophistication in
proportional reasoning is likely to depend upon the quality of focused instruction he or she has received on
this concept rather than the age the student happens to be. Notice also that the levels of the learning
progression are not always defined by standards pulled from a single grade of the [Common Core State
Standards].”

This points to the nature of inherent alignment and misalignment between standards and learning progressions,
and the work that is required to mitigate these gaps in order to make LPs actionable tools in the classroom. A
statement by learning progression researchers that expresses a key sentiment about the nature and usage of LPs
is, “we think a sensible way to think about learning progressions is to see them as being hypotheses about, or
models for, the likely ways in which students’ understanding of core scientific explanations and practices and
their skills in using them grow over time with appropriate instruction and opportunities to learn” (Corcoran, Mosher & Rogat, 2009, p.41). In this way, in the consideration of the use of LPs in classroom practice, they are hypothetical guides that can inform teaching and learning, but can and must be tested in that process.

Summary Discussion

Seeking to understand the nature of learning and general human development has produced a range of models and frameworks—and ultimately, a robust but disjointed field we call the learning sciences. In some regards, we have seen an evolution an integration of these models, such as the use of construct maps and construct-centered design to inform the more recent development of learning progressions. At the same time, there is inconsistency and lack of alignment between competing models of developmental or skill progression. We have a wealth of knowledge about micro-aspects of learner development across a range of domains, such as common misconceptions or incongruent cognitive models and various developmental ranges, yet some of this never gets translated into the design of standards and this in part is the result of it often not being reflected in classroom practice. There is a promising future for the work of learning progressions, but we are only at just the beginning of this work, and currently are really neglecting the infrastructure needed to more fully develop it and bring it to scale. Moreover, it is most critically the nature of implementation of LPs and the tools that reflect them that ultimately determine their positive or negative impact on learners. What tools and infrastructure are needed to more effectively pool and integrate the knowledge about learning to create more robust models of learning? What tools and infrastructure are needed to more quickly and effectively build out learning progressions in a way that integrates the insights and feedback of real-world learning environments and learners (i.e. a closed circuit between researchers and practitioners)?

III. ASSESSMENT

Assessment plays a central role in the learning data modeling conversation, because it was often the impetus for considerable development of tools and frameworks in the learning data modeling space. To measure something, you must first model what it is you want to measure—when that thing is not outwardly concrete and tangible. There is much confusion and misrepresentation about the broader assessment field, because of the negative implications of particularly more recent applications of assessments in traditional school systems. Yet the core tools that lie at the heart of many assessments have not only offered some of the best models for learning data, they have set the foundation for many more recent, exciting innovations—including making a mod of the popular video game SimCity to capture complex learning data13. This section will discuss the core assessment models relevant to this conversation.

13 SimCityEDU, developed by Glass Lab. See https://www.glasslabgames.org/games/SC
A. Foundational Frameworks

**Assessment Triangle**

The "assessment triangle" is perhaps the most referenced assessment framework, which arguably sits at the heart of many of the others.

In the early 2000s, the Committee on the Foundations of Assessment developed this framework to serve as the foundations reasoning about assessment, based on the idea of assessment as a process of reasoning from evidence, and it involves three integrated elements (National Research Council, 2001; Mislevy, 1996):

1. A model of how students represent knowledge and develop competence in the subject domain (Cognition);
2. Tasks or situations that allow one to observe students’ performance (Observation);
3. Interpretation methods for drawing inferences from the performance evidence collected (Interpretation)

These three elements are depicted in the framework schematic (see Figure 3-18) as cognition, observation, and interpretation. The framework’s developers, Pellegrino and Chudowsky, further assert that these three elements must be explicitly connected and designed as a coordinated whole (2003).

![The Assessment Triangle (Pellegrino & Chudowsky, 2003).](image)

It is worth noting here that ‘cognition’ aspect of the assessment triangle is indeed a domain model, similar to the construct models discussed previously.
The Committee on the Foundations of Assessment advocates that a cognitive model should have as many as possible of the following key features (NRC, 2001, p. 127):

1. Be based on empirical studies of learners in the domain.
2. Identify performances that differentiate beginning and expert performance in the domain.
3. Provide a developmental perspective, laying out typical progressions from novice levels toward competence and then expertise, and noting landmark performances along the way.
4. Allow for a variety of typical ways in which children come to understand the subject matter.
5. Capture some, but not all, aspects of what is known about how students think and learn in the domain. Starting with a theory of how people learn the subject matter, the designers of an assessment will need to select a slice or subset of the larger theory as the targets of inference.
6. Lends itself to being aggregated at different grain sizes so that it can be used for different assessment purposes (e.g., to provide fine-grained diagnostic information as well as coarse-grained summary information).

**Evidence-Centered Design (ECD)**

An evolution of the Assessment Triangle is the widely utilized seminal framework, Evidence-Centered Design (ECD) (Mislevy, Almond & Lukas, 2003; Mislevy, Haertel, Riconscente, Rutstein, & Ziker, 2017). Like the triangle, ECD coordinates the alignment of the competency model with given tasks and how to make meaning of the evidence they elicit through three similar core components (see Figure 3-19), informed through the broader development of a domain analysis and domain model (see Figure 3-20).

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**Figure 3-19.** The three core components of ECD (adapted from Shute et al, 2010).
ECD has become one of the most widely-adopted assessment frameworks that has been the foundation for innovative stealth assessments and game-based learning and assessment environments (discussed further below). Examples of design templates using ECD can be found in Figure A3-IIIA-1 in Appendix C.

Some ECD models have been made freely available, and the PADI project at SRI has made a huge contribution to this space. In particular of note, are the ‘design patterns’ generated to serve as openly available resources for designing assessments (see Figure A3-IIIA-2 in Appendix C). These design patterns do an excellent job of outlining the interrelated elements of ECD that offer a potential, partial competency model.

Yet generally, like many assessment tools, they are not made publicly available—in part because they are an aspect of an assessment, in part because they can be proprietary information, and in part because they aren’t central mechanisms to easily share such models, especially with those outside of the assessment community.

**Assessment Engineering (AE)**

Assessment Engineering (AE) builds on the core ideas of ECD but also provides a highly detailed operational process for manufacturing assessments. A key aspect of AE is that the construct measured by the task and
subsequent claims about student performance should be connected at the outset and explicitly linked to an *ordered proficiency scale*—which indicates what it means to be at increasingly higher levels along the construct of interest, including the performance-level descriptors that provide evidence for this position on the scale (Luecht, 2013; Shute, Leighton, Jang & Chu, 2016).

![Figure 3-21. Luecht's (2013) development of task models based on the cognitive psychological literature.](image)

In contrast to traditional assessment design, Leucht’s AE model emphasizes attention on cognitive complexity in order to generate maps that are grounded in empirical evidence; the evidence model becomes a repository of relevant empirically based task variables to guide the design of task model templates at different levels of difficulty along the ordered proficiency scale (Shute, Leighton, Jang & Chu, 2016).

### B. Concept Inventories

Concept Inventories (CIs) are multiple-choice research-level instruments designed to test students’ conceptual understanding, and evaluate whether a person has an accurate and working knowledge of a concept or concepts (Lindell, Peak, & Foster, 2007). CIs are based on a number of key concepts in a subject domain, where each question or item has one correct answer and a number of incorrect answers that are designed intentionally to reflect known, common student misconceptions (Jorion et al., 2015; Sadler et al., 2009).

CIs became increasingly popular since the first of its kind – the Force Concept Inventory (FCI) – was introduced in 1992 as a means to get sense of a learner’s understandings, misconceptions, and cognitive models...
in relation to certain aspects of physics (Hestenes, Wells & Swackhamer, 1992; Savinainen & Scott, 2002). Since that time, a wide range of CIs have been developed in nearly every scientific discipline, including Genetics, Astronomy, Engineering, Biology, Chemistry, and Geoscience, many of which were developed through The Foundation Coalition—one of eight engineering coalitions funded by the National Science Foundation, established as an agent of systemic renewal for the engineering educational community (http://fc.civil.tamu.edu).

Because CIs’ have been shown to more clearly define learner misconceptions and conceptual development, and the impact of certain pedagogies on supporting learners in relation to these misconceptions, research on CI’s and the FCI itself are partially credited with much of the large-scale reform that has taken place in physics education over the past two decades (Scott, Peter, & Harlow, 2012; Reed-Rhoads & Imbrie, 2008). CIs are interesting tools, because to construct one well, one has to have a well-constructed model of a domain—including the common misconceptions that are demonstrated by learners as they progress in their understanding.

CIs broadly have demonstrated their value as a ‘work-in-progress’, particularly in areas like Physics, where CIs have been particularly valuable at identifying more effective pedagogies versus lesser ones. Sands and colleagues have argued that in a learning as progression view (or a view of learning gains as a ’distance travelled’), CIs appear to be well placed to act as effective instruments—and that most importantly, the effectiveness of the FCI as a measurement of learning gain “derives from its intention to measure student thinking rather than declarative knowledge about laws and principles and procedural knowledge about mathematics” (2018, p. 65).

Unfortunately, similar to other modalities in the learning sciences, there is not an agreed upon framing of these instruments, there also seems to be discrepancies in the methodologies utilized to create these inventories (Lindell, Peak, & Foster, 2007). CIs are not without criticism, as many have cited the flaws observable in them, and not all CIs have the same level of validity and reliability. The need to go beyond the multiple-choice question format is a clear need, and the shortcomings of this format well-documented (Sands et al., 2018; Roediger III & Marsh, 2005). Yet a well-constructed CI offers a powerful model for mapping learner conceptual patterns in a domain—how might these be leveraged for designing more robust learning environments and tools?

C. Performance-Based Assessment

Performance-based assessments (PBAs) deserve specific attention here, because they represent a significant effort to rethink traditional assessment systems. Performance assessments frame tasks that require students to use high level thinking to perform, create, or produce something with transferable real-world application (Wei, Schultz, & Pecheone, 2012). Moreover, such assessments align with the principles of assessment for learning: assessment that supports learning and the learner first and foremost (based on Black and Wiliam’s extensive
review, 1998) including clearly articulating learning targets, providing actionable and specific feedback, and providing opportunities for self-assessment.\(^4\)

A recent report by the Stanford Center for Assessment, Learning, and Equity has underscored the recent, renewed interest in performance-based assessments which brings a number of advantages: more diverse and richer forms of learning data, being closer to formative assessments that bring real-time feedback benefits to learners, and being able to capture and support more complex, higher-order, and transferable real-world competencies (Wei, Pecheone, & Wilczak, 2014; Chung & Baker, 2003).

PBAs were first pursued back in the 1990s, but abandoned by most systems due to policy and infrastructure challenges. With the recent surge in competency-based learning, PBA systems have as well. Yet, the Stanford group highlights the persistent need for a coherent system around learning constructs, data, and related materials, including the emphasis on a lack of standardization and comparability across PBA data:

"[There is a] need for a coherent system of curriculum, instructional resources, and professional development. Standards-based reform envisions a coherent system of standards, assessments, curriculum, and instruction. Unfortunately, in many cases, state policies and budgets did not prioritize such comprehensive approaches to instructional change. Instead, the focus was on creating systems of accountability, with little attention to the opportunities to learn needed by teachers and students. A single-minded focus on assessment as a lever for reform did not lead to widespread instructional improvement or sustained teacher and parent support."

- Wei, Pecheone, & Wilczak, 2014, p. 12

In short, learners benefit significantly by being supported with an infrastructure that gives them meaningful, contextual, immediate/real-time, and actionable feedback. Yet education systems have struggled to put together the infrastructure to make this a reality. This is in part due to political reasons, but pertinent to this discussion, also due to technical and implementation challenges. The Stanford review of this space concluded on a number of aspects to these, including:

- Lack of standardization and comparability of performance assessments
- Validity and content issues
- Inter-rater reliability and insufficient item reliability
- Need for a coherent system of curriculum, instructional resources, and professional development.

\(^4\) For examples of PBAs, visit: [www.performanceassessmentresourcebank.org](http://www.performanceassessmentresourcebank.org)
Overcoming these obstacles, in part, points to the need for a foundational architecture to install such an infrastructure for learning-supported assessment and feedback mechanisms.

D. Stealth Assessment

Embedded, or stealth assessments, have been described as, “when embedded assessments are so seamlessly woven into the fabric of the learning environment that they are virtually invisible” (Shute et al., 2009, p. 287). Dissatisfaction with the current state of assessment combined with the increasing range of affordances offered by rich, dynamic game-worlds and game-based learning environments at the intersection of learning analytics and educational data mining has created a deep interest in designing these environments in such a way that seamlessly supports the data collection, analysis, and formative feedback loop to support learning.

In a typical digital game, as players interact with the environment, the values of different game-specific variables change and respond to the players actions accordingly—through micro-movements a small game variables to larger problem-solving that enables “leveling-up” (Shute & Ventura, 2013). As such, it has been argued that all games are assessments (Gee, 2014; Shute & Ventura, 2013). Such technologies enable us to collect multi-faceted information from a learner, and react in immediate and helpful ways, as needed (Shute et al., 2010).

Stealth assessment is one of the domains that has leveraged evidence-centered design (ECD) modeling, combined with employing Bayesian networks (Pearl, 2014) to identify both diagnostic and predictive inferences to handle uncertainty in learner models of competencies (Shute et al., 2010). Figures A3-IIID-1 and A3-IIID-2 in Appendix C depict the competency model developed to serve as the core of the design for the stealth assessment, *Newton’s Playground*, and the Bayesian network model uses to interpret the evidence generated in the game.

Researchers have argued that these types of environments are possibly the best way to support the most valuable competencies needed to succeed in the twenty-first century, because during gameplay students naturally produce rich sequences of actions while performing complex tasks, drawing on the skills or competencies that we want to assess (e.g., scientific inquiry skills, problem-solving, etc.)—and assessment in this way is not intended for evaluative purposes but to support learners as effectively as possible in their development of these complex competencies (Shute & Ventura, 2013; Shute et al., 2010). Such technologies are not simple to construct, however; building the domain model for a stealth assessment game alone has taken researchers upwards of six months15. Building game-based assessments can be labor intensive in part because it takes an integration of a range of skill sets (i.e. game designer, assessment developer, instructional designer, etc.), but also because it takes such effort to pull together the research around a given construct in order to create a

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15 Personal communication with Valerie Shute, Ph.D., 2016.
competency model to sit at the heart of the tool—constructs and competencies that modeled in part in various ways across the other domains discussed here already.

**Summary Discussion**

Assessment broadly offers us much in expanding our ways of modeling learning. Unfortunately, as a domain of work, they are an often-segregated community disassociated by a barrier of poor image, and a high bar of entry of foundational understanding needed to engage with many of the tools. Yet there is a large missed opportunity here, as there is considerably valuable work in this space that can help inform an improved evolution on a coherent and collective learning data architecture.

Tools and insights generated through innovative assessments and assessment frameworks have helped us to make great strides in understanding the nature of learning in traditional domains such as science, but even more promising is their impact in non-traditional competencies such as creativity, collaborative problem-solving, and more. Leading technology-based assessment designers have argued for a future vision of learning environments, in our complex, interconnected digital world, we are learning constantly and producing numerous digital footprints or data along the way that allows us to continually collecting complex learning data as students interact with digital environments both inside and, of importance, outside of school—and that in such a vision assessment should;

(a) support, not undermine, the learning process for learners

(b) provide ongoing formative information (i.e., be part of a system of giving useful feedback during the learning process that informs what can best support the learner next); and

(c) be responsive to what is known about how people learn, generally and developmentally (Shute, Leighton, Jang & Chu, 2016).

In service of such a vision, they also argue that *principled assessment design* (using methodologies like ECD and AE) is critical for building state-of-the-art innovative assessments—to design tasks that are expected to evoke knowledge and skills of interest in students and can also orient learners – and possibly other stakeholders – as to the current status of the learner and to where attention should be focused for the next phase of learning (Shute, Leighton, Jang & Chu, 2016). Yet without a more robust architecture beyond traditional standards, it will be difficult to build bridges between research and development of resources for non-traditional domains, and further supporting learners in these areas. The current state of the field in terms of the existing structure of learning standards is difficult to integrate with innovations like ECD (and subsequently the resources such as game-based environments and assessments) that are built on it. The creators of ECD have extensively noted the problem with the lack of coherence between the design of standards and construct/assessment models, and...
further advocated that, “ECD can aid in the redesign of standards and benchmarks and their subsequent greater alignment to learning progressions and learning progression-focused instructional programs by supporting greater differentiation among the characteristics of student reasoning at different grade levels” (Zalles, Haertel, & Mislevy, 2010, p. 19).

IV. LEARNING TECHNOLOGIES

Although there is the an incredible spectrum of types of learning technologies available, there are several worth discussing here, because they represent some of the most complex, current learning technologies that use learning model data at the heart of what they do.

A. Cognitive Tutors

Cognitive Tutors also known as Intelligent Tutoring Systems (ITS), are computer programs that model learners’ psychological states to provide individualized instruction, and have been developed for a range of subject areas (e.g., algebra, medicine, law, reading) to help learners develop understanding in these areas (Ma, Adesope, Nesbit, & Liu, 2014). A Cognitive Tutor or ITS, scaffolds student learning through ongoing real-time cognitive diagnosis (or student modeling), and adaptive response of questions and interactions based on that real-time diagnosis—in multidimensionality of the student and domain model (as opposed to traditional single parameter adaptive systems (Anderson, Corbett, Koedinger, & Pelletier, 1995; Shute & Psotka, 1996)). ITSs have been to be considerably effective tools for supporting learning growth in a range of domains (Ma, Adesope, Nesbit, & Liu, 2014).

At the heart of Cognitive Tutors lie Bayesian networks—a tool for probabilistic reasoning and representation of uncertain knowledge, which are used to represent a multidimensional domain model consisting of multiple variables (Pearl, 1988). Connections between variables are specified to form a network, with inferences about the value of a variable in the network derived through Bayesian calculations on other variables connected to it (Millán, Loboda & Pérez-de-la-Cruz, 2010). Put more simply, a list of binary target variables representing concepts and misconceptions would constitute the domain model, and a list of evidence variables representing test items might feed forward with connections to the target variables; the system then uses student performance on the test items as input, and the Bayesian network then calculates the probability that the student has each concept and misconception (Ma, Adesope, Nesbit & Liu, 2014). Dynamic Bayesian Networks (DBN) have been used to create much more complex, dynamic models of student problem-solving in tutors that provide hints and coaching (Conati, Gertner & VanLehn, 2002).

ITS developers are known to disagree over the representation of knowledge, skills, and strategies in the learner model, because the computational models are very different in the various types of cognitive tutors (Sottilare,
Graesser, Hu & Holden, 2013). Previous efforts, such as the SCORM initiative, attempted to push for a standardized representation of knowledge, skills, and strategies—but it has been suggested that it is still too early in ITS development to push for such standardization because, “researchers are deeply wedded to their pet computational architectures and algorithms as they pursue cycle after cycle of model testing” (Graesser, 2013, p. 5). Yet it is this complexity and range in variations in representations that have been identified as one of the key barriers to scaling up ITS, and as such, experts have advocated that,

“There needs to be systematic R&D on authoring tool development that is tested on personnel outside of the camp of the original ITS developers. We need an applied empirical science of authoring tool development that has analogues to research on writing or to design. To what extent are the learner model representations developed with sufficient fidelity, scope, grain-size, and level of abstraction? How much training is needed for new personnel to develop learner models for new applications? What is the time course and costs of developing new learner models?”

~ Graesser, 2013, p. 3

B. Game-Based Learning Environments and Assessments

The complex, dynamic environments of modern digital games have also gotten the attention of learning designers, in part because of their ability to engage and support learners, but also because of their overlap in structural features that support the gathering of learning data and real-time adaptive responsiveness to learner needs (Behrens, Frezzo, Mislevy, Kroopnick, & Wise, 2008; Rowe & Lester, 2010; Shute, 2011).

There have been a number of recent examples of digital game-based assessments, including popular commercial games being retrofitted as learning assessments. Examples include the previously referenced Newton’s Playground (Shute, Ventura, & Kim, 2013), which assesses physics, systems thinking, and creativity; and SimCityEDU16 (Mislevy et al., 2014), which assesses critical thinking, problem-solving, and a range of content. Shute and colleagues at the Florida State University have made considerable contributions to the field of GBA through their work on designing and researching game-based stealth assessments, discussed earlier (Shute, 2011; Shute & Ventura, 2013). These assessments use the ECD framework while designing strategic data collection into the game mechanics, thereby overcoming one of the greatest challenges of GBAs—keeping the playful engagement of the game environment that can validly and reliably measure learning in the game without disrupting engagement and then leveraging that information to bolster learning (Shute, Ventura, Bauer, & Zapata-Rivera, 2016).

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16 https://www.glasslabgames.org/games/SC
These tools also use ECD and DBNs at the heart of their design (Shute, Ventura, Bauer, & Zapata-Rivera, 2016; Levy, 2014). The assessment tasks embedded in the game are clearly linked to claims about personal competencies and the estimates of competency levels can be used diagnostically and formatively to provide adaptively selected game levels, targeted feedback and other forms of learning support to students as they continue to engage in gameplay (Shute & Ventura, 2013).

C. AI in Learning

Artificial Intelligence has a long history with education, and arguably its roots can in-part be found with observing learning and learners. With the rebirth of AI we have seen a new dawn on the horizon for AI in Education (AIEd), moving towards ‘smart learning environments’ where AIEd technologies are distributed and ubiquitous, creating a seamlessly personalized and responsive experience (Pinkwart, 2016; Woolf, 2010; DiCerbo, Behrens & Barber, 2014). Such a future represents a virtuous cycle, whereas this integration increases so does our data, models, and understanding of learning and learners, in order to create even more powerful learning technologies.

Yet, we are still far from such a future—there are a number of current, significant barriers to arriving at such a future. Nye has argued that,

“Future barriers will not be about getting learning technology into schools; they will be about competing, integrating, and collaborating with technologies already in schools ... Hidden beneath this issue is a complex ontology alignment problem. In short, each learning technology frames its experiences differently. When these experiences and events are sent off to some other system, the designers of each system need to agree about what different semantics mean. So then, ontology development must play a key role for the future of ITS interoperability.”

~ Nye, 2016, p. 757-764

Previous efforts to creating integrated distributed systems of AIEd began more than two decades ago but made little progress (Roschelle & Kaput, 1996), and the failure to embrace these designs was largely due to lack of absolute need—the use of ed tech was low, there were not many platforms to integrate, and architectures for distributed web-based services were in their infancy (Nye, 2016). Yet Nye goes on to argue that for AIEd today, moving towards integrated, distributed systems is an ‘existential necessity’ because without this, serious academic research into educational technologies may be boxed out to commercial applications, and critical research on learning through scaled data will be missed. In light of this, Nye argues it is essential that AIEd move toward open standards for sharing data, and that “while this process may be painful initially, standards for
integrating data across multiple systems would enable the development of powerful adaptation, analytics, and reporting functionality” of AIEd technologies (2016, p. 758).

D. Industry Movements

This section would not be complete if there was no mention of recent efforts by research and industry to help organize, and potentially standardize, the way learning data is utilized and shared in adaptive learning technologies. Notable initiatives include the Learning Resource Metadata Initiative (LRMI), a common metadata vocabulary for educational resources now adopted by the Dublin Core, and most recently by the IMS Global Competencies and Academic Standards Exchange® specification (CASE)® launched in the spring of 2018, used to exchange information about learning and education competencies. CASE aims to make standards machine-readable and organize them around a system of unique identifiers so that learning goals and competencies can be interchangeable across frameworks.

In more complex learning technologies, there was the development of the Generalized Intelligent Framework for Tutoring (GIFT) (Sottilare et al., 2017), designed to be an empirically-based framework of tools, methods, and standards to more easily facilitate the construction of ITSs. More recently, the IEEE¹⁸ launched the Learning Technology Standards Committee (LTSC), and in June 2018 approved the AIS Standards Working Group, which seeks to assure compatibility across educational technology product categories.

Initiatives like CASE have helped to open up data sharing and interoperability between learning platforms, particularly related to learning data. However, the construction of this infrastructure is very US-centric, and generated on the foundation of curriculum standards, and demonstrates a number of deeply problematic issues such as the misappropriation and use of the “learning progression” frame, and the integration of assessment data that only reinforces old models of testing. As we look to engineer coherent systems of learning that reflect the pedagogies of learning we desire, this should be pause for concern. The movements of the IEEE work in this space presents a renewed opportunity to more robustly define how we will model learning domains, if the committee considers and integrates the perspectives of all stakeholders as discussed in this text, and not just those represented by industry and practice.

Summary Discussion

Leading edge learning technologies are offering powerful tools for learning, that unfortunately still, a limited number of students in today’s schools have access to. This can be attributed to a number of reasons (Groff & Mouza, 2008), but yet again we are led back to the challenge of aligning learning models and data. Graesser (2013) has suggested that the grain size of measurement in ITSs is currently three orders of magnitude beyond

¹⁸ Institute of Electrical and Electronics Engineers
the data collected in school systems throughout the country. Researchers and designers of game-based learning environments are pursuing the development of competency models and games that currently are not yet – but based on global analyses should be – central to a child’s learning experience (Shute et al, 2010). This is important work to continue, but if these tools aren’t being used in schools and broadly aren’t available to the general public, we are losing the conversation on how best to support learners in this broad range of competencies.

These barriers do not just exist across stakeholders in this way, but within these groups as well. Most ITSs make little or no attempt to exchange even basic results data with other systems—a trait of isolationism that is typical of new learning technologies (Graesser, 2013). What infrastructure and incentives are needed to make this the exception rather than the rule? It is quite possible that significant advancement in fields like AIEd simply will not be possible without a cohesive infrastructure.

As we look to the future, we can see how a foundation of competency models can serve as a foundation across this broad range of learning technologies. Imagine how a learner using one of the many powerful constructionist tools such as Scratch¹⁹ and App Inventor²⁰ could give feedback to the learner on their development of skills in problem-solving and creativity while they worked on their project in the platform. The possibility of a coherent learning data architecture presents the opportunity for this, but also for the feedback for learner on these competencies across learning technology to help them understand where they are in that developmental progression and what they may benefit from next.

Many have advocated for a future of “self-directed schools” or a self-initiated process of learning, where learners manage and plan their own learning (Chen, Cheng, & Chew, 2016). Until we have such a seamless and ubiquitous digitally-supported learning environments, how might learners do that when they don’t enough resources to understand what they might learn, where they are on that map, and where they might go?

**LOOKING ACROSS DOMAINS**

Across these domains, we see a number of similar barriers in structure and design. There are unclear relationships to some models, such as the various models of skill development, and yet we also already see a significant overlap and convergence in frameworks (i.e. LPs being built using CCD, ECD; standards being built on LPs); the authors of construct maps (Brown & Wilson, 2011) acknowledge that the models of cognition

¹⁹ [http://scratch.mit.edu](http://scratch.mit.edu)

²⁰ [http://appinventor.mit.edu](http://appinventor.mit.edu)
built in these maps are compatible with those built using ECD, and that either approach are effective at building effective models of student knowledge states and competence.21

There is a subset of leading experts working at the intersection at a number of these domains — including ECD, game-based assessment, intelligent tutors, and Bayesian network cognitive modeling — who have proposed dividing up large networks up into a library of graph fragments that are then assembled to create the Bayesian networks to answer a specific query, and that such a notion of a universe of possible Bayesian networks as a library of fragments has shown to be a viable mechanism for managing large domains with many potentially observable variables (Almond, 2007; Mahoney & Laskey, 1996; Koller & Pfeffer, 1997; Laskey & Mahoney, 1997; Neil, Fenton & Nielsen, 2000). Almond (2007) in particular, has argued that this capitalizes on the “natural design patterns in network construction to produce prototype networks that are applicable to a wide collection of data gathering tasks” and that “networks based on these design patterns typically share the same structure and differ only in parameters relating to the strength of the relationships among the variables” (p. 168). Similarly, Almond and Mislevy (1999) — two of three developers of ECD — argue that a core learner proficiency model captures the relationship among the status variables for the subject as a complete Bayesian network, and that specifying a Bayesian network can be achieved by outlining two matrices: (i) the augmented Q-matrix which provides the basis for the evidence models, and (ii) the (inverse) covariance matrix which provides the basis for the proficiency model—which together can unpack the nature and strength in relationships of a competency inside a compact but complex model (Almond, 2007). Although there was an attempt to build such a library, called ‘Portal’ (Mislevy, Almond, Yan, & Steinberg, 1999), it was ultimately abandoned due to development and project management logistics.22

This notion of the value and impact of a central repository of domain competency models shows up across these communities. The seminal publication by the National Research Council (2001) report, Knowing What Students Know, describes three necessary components of a valid assessment system: “a model of student cognition and learning in the domain, a set of beliefs about the kinds of observations that will provide evidence of students' competencies, and an interpretation process for making sense of the evidence” (p. 44). In their paper, “A Model of Cognition: The Missing Cornerstone of Assessment,” Brown & Wilson (2011) underscore that more than “10 years later, most measures still lack the first leg of the stool: an explicit model of cognition” (p. 221). The model of cognition “refers to a theory or set of beliefs about how students represent knowledge and develop competence in a subject domain” (National Research Council 2001, p. 44). This is a research-oriented framing of what might otherwise be called a competency model or learning progression in educator communities. Mislevy (1996) argues that most educational measurement lacks such a model of cognition, and as a result, instead uses many features of classical test theory, generalizability theory, item

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21 With the caveat that the primary emphasis should be on the search for coherence between the four cornerstones of assessment (Brown & Wilson, 2011).

22 Personal communication with Russell Almond, 18 July 2018.
response theory, and factor analysis or structural equation modeling—all of which are bound up in a paradigm of behavioral psychology in which the target of interest is (Mislevy 1996; Brown & Wilson, 2011). As a consequence, the valid interpretations of test scores are limited, and most critically, we are stuck in a world of testing that embodies many of the features for which it is severely criticized (i.e. removed from context, linear, isolated measures attempting (or incapable of) measuring complex competencies, and so on).

This has serious implications for education systems, because this gets at the fundamental reason behind the dynamic in the system that frustrates so many: assessments driving learning environments in a way that goes against meaningful and effective deeper learning (Darling-Hammond, 2004). These models of cognition are critically important to classroom practice as well; having a model of how learners represent knowledge and develop competence strongly supports the development of more effective sequences of learning experiences in and out of the classroom (Brown & Wilson, 2011).

The review in this chapter, looking broadly across this space, would still underscore this sentiment and that this can be said for more than just in reference to assessment, and that all domains discussed here suffer because we do not have easily-accessible and shared models of cognition. Construct Maps and ECD models have been proposed as the type of models of cognition that can be used to fill this gap in a foundation for assessments (Brown & Wilson, 2001). But these are assessment frameworks and tools. If they are not adjusted in within a larger architecture that can support the needs and practices of not just assessment developers but all key stakeholders, particularly classroom practice, we run the risk that has plagued so many initiatives, namely limited adoption and impact.

Engineering such shared architecture of models of cognition may create the foundation by which we flip the assessment conundrum on its head—instead of designing assessments and tasks that end up driving learning, we instead have the foundation upon which we can better understand and support authentic, meaningful learning.

Looking back even to 2001, the National Research Council’s Committee on Assessment, in setting the vision for a healthier future for learning and assessment, underscored the importance of designers and educators of having access to high quality domain models—as well as both communities being key contributors to the ongoing curation of such a knowledge base:

“In this report we argue that assessment will be most effective if the designer (in many cases the teacher) starts with such an explicit and clearly conceptualized cognitive model of learning. This model should reflect the most scientifically credible understanding of typical ways in which learners represent knowledge and develop expertise in a domain. These findings should derive from cognitive and educational research about how people learn, as well as the experience of expert teachers (Webb, 1992).”

~ National Research Council, 2001, p. 45
This is an aspect we see highlighted again and again in the learning sciences literature, yet not only do teachers rarely have access to such models, there is little to no feedback mechanism in order for them to contribute to that conversation.

In recent years, through programs such as the Global Learning XPrize, the Global Education First Initiative, and others, we have seen a global push to support universal learning, in the form basic reading, writing and math skills, expresses this nicely. Researchers argue that this is illustrates the need for effective (and, thus, adaptive) learning software that works globally. Yet the current practice of such technologies has not yet demonstrated they are able to seamlessly and ubiquitously support learners outside of one independent platform.

**Beyond Ontological Engineering**

The existing infrastructure of standards is inadequate and problematic on a number of levels, and at its core, it’s both a wicked problem of ontological design and of complex systems. Indeed, many of the challenges laid out in this chapter are ones familiar to ontological engineering across many domains, including human and technical idiosyncrasy (stakeholders using different, and sometimes incommensurable, specialist terminologies), computer limitations (the very nature by which our technologies work with ontological data at mass scale creates limitations on how we can best use it), and the problem of imprecise thinking (i.e. existing repositories of scientific data often contain not only ambiguities and inconsistencies in the use of technical terms, but also basic errors of logic) (Arp, Smith, & Spear, 2015).

In a 2009 article titled, “Using Ontological Engineering to Overcome AIEEd Problems” (then revisited/updated in 2016), authors Hayashi, Bourdeau, and Mizoguchi argued for the critical need for Ontological Engineering (OE) to disseminate ontology-based knowledge that is “fundamental and long-lasting” and “task-independent underlying the target domain” (Mizoguchi & Bourdeau, 2016, p. 92). They go on to explain that these must be similar to those ontologies used for the semantic web, but whereas the semantic web has used lightweight ontologies that are vocabulary oriented and used as metadata for searches on the Semantic web, AIEEd needs heavy-weight ontologies that are concept-oriented—where “the conceptual artifacts that intend to explicate the underlying structure of the target world and used for modeling the things and matters in it, and hence they are sometimes required to have philosophical validity” (Mizoguchi & Bourdeau, 2016, p. 92). Figure 3-22 shows the ontology-supported authoring system they imagined.
These are important considerations to be made, and arguably are one reason why educational ontologies haven't made further progress—philosophical underpinnings must be asserted. When we step out from learning and education and look more broadly at the future of the Web, and even AI, it is clear that any innovations in learning technologies must be in alignment with—or at least moving towards—alignment in structure at the ontological or data modeling level.

Although Mizoguchi and Bourdeau’s considerations are vital, they are not enough for supporting and aligning all stakeholders. The “learning objects” metadata database in their model (Figure 3-22) alone requires more complex engineering that they have eluded to, because that must not just satisfy the needs of AI but those of the broad range of stakeholders and communities discussed in this chapter. The “build it and they will come” approach has a poor track record in education—see the well-documented inBloom initiative as an example (Kharif, 2014).

We have made notable progress in defining aspects of a possible ontology for learning models, yet there are still numerous conflicts, inconsistencies, and gaps in how we model learning. The movement by educational systems towards performance standards, which include indicators of level of performance and examples of student performance at these levels, demonstrates movement in a similar direction as the work in learning progressions, competency models, and ECD frameworks. Yet there largely are not coordinated efforts by these communities—further continuing the lack of integration of research/practice, and ultimately once again limited impact and progress across stakeholders and practices in the field.
Across all of these, ultimately what we see is a subset of stakeholders working with a subset of artifacts or frameworks to make improvements in practice and ultimately evolve the nature of education. In some regards, this makes sense, as any group or organization is inherently limited by time, resources, and access or opportunities for impact. Few would advocate for “boiling the ocean”. And yet, when we look across the history of educational system reform, it is often these limitations and constrained efforts that have limited impact because they can find limited integration with other aspects of the system, and ultimately lead to nowhere.

![Figure 3-23. The Elephant: 'Context Matters'.](image)

In short, what we have is many stakeholders touching a piece of the elephant, trying at times to build connections to another piece of the elephant, with no coherent communal approach to the elephant—and everyone in the field suffers for it. When so many stakeholder groups use something different, to meet their own understands and needs of the space, the resulting knowledge-sharing, knowledge-building and integration across learning environment is greatly hindered—and in the end, it is the end-users – learners and educators – who suffer most because they end up having to be the bridge across them and learn to use the different tools, interfaces and structures.

In light of this history, and our learnings from it, and in light of the complexity and pervasiveness of this problem space, a case can be made for — in this instance — the need to boil the ocean. Put more accurately, we
need an architecture that supports alignment and coherency amongst these data models and practices. We cannot wait for these inconsistencies and gaps to be filled before converging on an ontological design, because those very gaps likely won’t ever be filled until we do begin to converge. Rather, we should seek to employ a more rigorous engineering mindset, along with an effective collaborative and open workbench, to work towards bridging that gap. That is the focus of the LearningGraph project, and the focus of the next chapter.
Chapter IV

REENGINEERING EDUCATION: The LearningGraph Project

"We cannot predict the future, but we can invent it."

— Nigel Calder

This backdrop of the problem space served as the motivation and the methodological foundation for a research project at the MIT Media Lab – The LearningGraph – framed to explore how these gaps might be bridged, intentionally using a systems-oriented approach. Work on the LearningGraph project began in 2012, and the structure and progress of the project will be the focus of this chapter.

GOALS & TENETS

Employing a systems engineering methodology as discussed in Chapter 2, the project’s focus is to explore the potential development of a coherent and unified learning model architecture that can bridge many of the structural problems in this problem space, with the potential of ‘raising all ships’ by bringing stakeholders and user groups closer together, with their work and knowledge-sharing more integrated. To that end, the project was established along with several key tenets:

- The project should include as many stakeholders / user groups as possible.

- Designing not just for theory but adoption and impact, the project seeks to define an underlying data model and architecture that at a foundational level can meet the needs of all user groups, and additionally consider the types of tools and UIs the various user groups would need to effectively engage with such a resource. To do this, and effectively meet the overarching objective of the project, this means the inclusion of industry-standard methodologies that help effectively coordinate across
research-industry-practice—including Design-Based Research (DBR) and Lean Startup methodologies for demands the needs and demands of a user base, as well as their insights on how innovations might most effectively be designed.

From a technical perspective, the primary goal in this aspect of the research is to look at user tools and needs, identify the common underlying content structure, and define a potential unified data model which can support all users and facilitate core content/knowledge sharing amongst these groups (RQ1); then, upon this architecture, user-group-specific tools (i.e. teacher tools, assessment designer tools, etc.) will be explored to support and improve practice—in this case, for educators (RQ2).

The LearningGraph Project Initial Concept: Pre-Phase A

Initial development of the project was centered the tenets of Pre-Phase A—Concept Studies of the SE methodology. As discussed in Chapter 2, Pre-Phase A is centered on developing the initial concepts; developing a preliminary/draft set of key high-level requirements; realizing these concepts through modeling, mockups, simulation, or other means; and verifying/validating that these concepts and products would be able to meet the key high-level requirements—where concepts would be developed to the lowest level necessary to ensure that the concepts are feasible and to a level that will reduce the risk low enough to satisfy the project. The work completed on the LearningGraph project in Pre-Phase A included a range of actions listed here, and discussed further in this section:

- defining the problem space (as discussed in Chapters 1 and 2)
- completing a meta-analysis on existing frameworks and structures used by key stakeholders (as discussed in Chapter 3)
- conducting initial user interviews
- drafting preliminary technical requirements
- developing preliminary concepts

The author would like to acknowledge the many contributors to the project thus far, including:

Advisors: Prof. Eric Klopfer; Committee Members: Prof. Mitchel Resnick, Danny Hillis, and Jeremy Roschelle;
MIT VMS Mentors: Kathy Brand, Jerry Zadow, Steve Willis, and Roman Lubynsky
MIT UROPs: Diane Zhao, Mohannad Abunassar, Peter Griggs, Caitlin Hardwick, Lisa Truong, Corey Ferrier, Ariana de Zavala, ChunChun Wu, Ryan Berg, Patrick Egbuchulam, Alex Sludds, Anna Hair, Lia Bogoiev, Ryan Stuntz, Veronica Lee, Erik Nguyen, Amanda Ke, and Subby Olubeko
Colleagues: David S. Buck and Peter Stidwill
• drafting a preliminary data model, based on the technical requirements
• creating a prototype research platform

Initial User Interviews

Given the notorious difficulty of adoption and scale of innovations in learning environments (Groff & Mouza, 2008), to explore the ways in which we might build a unified, coherent data architecture without engaging key stakeholder communities and designing for their engagement and adoption would be a fool’s errand.

The review of system practices and challenges as discussed in Chapter 3 provided the detail needed to define system needs from a technical perspective. User interviews with educators were conducted in 2016 to determine challenges and needs from the user perspective of a key stakeholder audience in relation to this problem space—particularly the way in which standards and curricula are modeled, which limits their utility for planning instruction and assessing learning. Too little attention is given to how students' understanding of a topic can be supported from grade to grade. The structure of the learning goals/curricula/standards has a deep impact on the way in which learning plays out in the classroom (Heritage, 2008); however, it also creates a significant challenge for educators particularly, who need further detail to effectively support learning around a given construct (Bransford, Brown & Cocking, 2000).

The impact of this challenge on educators’ practice was underscored by the majority of teachers we interviewed. In the 30 teacher interviews we conducted in the spring and summer of 2016, 22 of the participants emphasized that this lack of deeper explanation and unpacking of how to support the standards in their classroom is a problem for them and as a result limits their classroom practice. Moreover, that they would like a resource that helped them to better unpack a standard to be able to teach to it more effectively. Figures 4-1 and 4-2 show an example of what existing standards present to educators, and what an expanded data model to meet these needs might look like.

Of the eight teachers who said this was not an issue for them, many of them also said that understanding learner misconceptions and evidence of mastery wasn’t necessary, when the learning sciences research demonstrates otherwise (Grotzer & Perkins, 2000; Smith, diSessa & Roschelle, 1994). The semi-structured protocol used for these interviews can be found in Appendix D. It is worth noting here that this protocol was created using the Lean Startup methodology to better define user needs, rather than interest or fit in a preconceived product or tool (Ries, 2011; Blank, 2013).
Figure 4-1. Sample standard from the Common Core website.

5.NF.A.1
Add and subtract fractions with unlike denominators (including mixed numbers) by replacing given fractions with equivalent fractions in such a way as to produce an equivalent sum or difference of fractions with like denominators. For example, 2/3 + 5/4 = 8/12 + 15/12 = 23/12. (In general, a/b + c/d = (ad + bc)/bd)

Figure 4-2. Expanded data model supporting standards and classroom practice.
Preliminary Technical Requirements

The preliminary system-level technical requirements for the project offer the initial identification of the system’s functions, characteristics, and constraints in order to meet the users’ needs. In this phase of the project, the draft system requirements were used to guide the development of the experimentation system to confirm, clarify, and further discover user requirements (MITRE, 2007).

Building on the previously defined problem space, these preliminary technical requirements are outlined in Figure 4-3.

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**Preliminary Technical Requirements for the LearningGraph**

The system shall:

- be Open Source standards compliant, operating on a Creative Commons Attribution International license;
- employ a data architecture that is capable of supporting integrated tools that support the practice/needs of the range of stakeholders and user groups previously defined;
- use a unified data model that is able to seamlessly implement and share various aspects of the data model across user/stakeholders tools and practices;
- provide a data model architecture that integrates with existing industry standards, including LRMI, IMS Global,
- employ an object-oriented, modular open system architecture;
- provide clear support for APIs;
- support a structured publishing methodology, that enables both the consumption and creation of possible content, with a defined methodology by which submissions are reviewed and released (published) to the community;
- employ Uls that are centered on transparency, usability, and flexibility across the range of users/stakeholders.
- directs data modeling towards semantic web methods

---

**Figure 4-3.** Preliminary Technical Requirements for the LearningGraph
Preliminary Data Model & Architecture

In order to meet these requirements, the preliminary data model and data architecture implicates a number of key design configurations. The data architecture must integrate existing user/stakeholder objects. This is particularly true for educators, who are often bound to policy or legal requirements in regards to standards. Figure 4-4 shows the range of stakeholders and their tools/frameworks/data models that must be considered for integration in the LearningGraph data architecture.

![Figure 4-4. Users/stakeholders and associated tools/frameworks/data models.](image)

Building on the meta-analysis discussed in Chapter 3, we have developed a prototype data model (Figures 4-5 and 4-6) and initial projected database architecture (Figure 4-7). The prototype data model is a converged schema of the core schemas discussed in Chapter 3, organized around “constructs” as previously defined. This data model is designed to meet several core objectives. First, it is constructed to include the necessary data elements needed for all stakeholders groups, so that no matter which user/stakeholder group is pulling (or contributing) information to a construct model, each is able to find what they need in the way that they need to access it, while still pulling from a centralized model supporting all core users/stakeholders. Second, it proposes an integrated conceptual schema for integrating the overlapping core frameworks utilized across the key user groups – domain analyses, domain models, and CAF models from ECD, and learning progressions – into a coherent construct model, and actionable competency model, to ultimately improve support for learners in
practice, but moreover, to offer a coherent model of constructs, cognition, and development to be refined over time and enable us to collectively make significant gains in our models of learning and cognition. ECD is now used broadly across a number of areas and as the foundation for the design of many complex digital learning environments because of its robust nature to model a construct, which is also why these ECD structures were selected in the development of our prototype data model. However, an ECD model does not always articulate a developmental progression around a given construct, but rather how to frame and capture the understanding or ability of a learner at a snapshot in time. For this reason, learning progression structures were also integrated into our prototype data model. Leading work on the implementation and refinement of learning progression models reflects a practice of defining the types of evidence one might see in a learner as they progress in their ability, the types of tasks that both support the learner in growth and that elicit such evidence, and the types of errors or misconceptions they may demonstrate along the way. This work is reflective of the CAF model used in ECD. Together, these both integrate common, core structures used in a number of user groups, and offers a structure for a competency model(s).

In the LearningGraph prototype data model, around a given construct there is a domain analysis, a domain model, which set the foundation for the competency or developmental model. The constructs are then organized in relation to a universal index of constructs and sub-constructs, which are correlated to a meta-index of state and national standards.
Within the levels of the competency or developmental model, key data aspects that support a range of user groups/stakeholders are indicated—including tasks, evidence and indicators, misconceptions and alternate cognitive models, and so on (see Figure 4-6). Appendix E offers sample constructs of Systems Thinking and Computational Thinking modeled using this prototype data model.
CONSTRUCT MAP: “Scientific Modeling”

LEVEL I
At this level, students construct and use models that show broad illustrations of a single phenomenon, depicting only observable features, rather than attempting to represent the phenomena or processes.

LEVEL II
This level includes the manner that students construct and use models to explain how a phenomenon occurs and how the model leads to evidence related to the phenomenon. There is still a level of intuition and creativity, but the level of abstraction is lower, and the model increasingly represents the modelers' conceptions of the phenomenon.

LEVEL III
At this level, students construct and use models that show and communicate the phenomenon. Not all students are able to solve initial needs defined by the Pre-Phase A analysis. Effective instructional strategies & learning tools/technologies tasks & formative assessments examples of student work

DATABASE ARCHITECTURE

competencies, learning progressions, task assessments

constructs

universal index

standards

Figure 4-6. Construct-centered view of the LearningGraph data schema developed through Pre-Phase A.

Figure 4-7. Projected database architecture to support the initial needs defined by the Pre-Phase A analysis.
Prototype Research Platform

The initial research prototype was built in Plone\textsuperscript{24}, for its ability to support many of the preliminary technical requirements. During its development, several key tasks were completed:

- the state or national standards of 15 jurisdictions in mathematics, literacy, and science were modeled, including:
  - the US Common Core State Standards (CCSS) and Next Generation Science Standards (NGSS)
  - Massachusetts
  - Brazil
  - Alberta (Canada)
  - Ontario (Canada)
  - New South Wales (Australia)
  - Victoria (Australia)
  - England
  - Scotland
  - Finland
  - Singapore
  - Sweden
  - Switzerland
  - Brazil
  - Hong Kong

- initial competency maps for broader competencies were drafted, including:
  - computational thinking
  - systems thinking
  - ethical development
  - statistical reasoning
  - scientific reasoning
  - problem-solving

\textsuperscript{24} Plone is a free and open source object-oriented content management system (CMS) that is noted for its capacity to support large, complex object-oriented databases, and for supporting community publication and version management.
✓ engaging machine learning tools to aid in the development of the Universal Index

DEFINING SUCCESS

To most effectively utilize the SE process, we must define a set of indicators that should be sought as central to defining success and further advancement of the project:

✓ The prototype data model for constructs meets the needs of all user groups/stakeholders.
✓ User groups/stakeholders report the reduction in previously identified gaps and challenges.
✓ Previously identified system-level gaps and challenges are also indicating aspects of reduction or mitigation.
✓ Specific tools built for each identified user group is able to integrate with the data model and architecture.
✓ We see opportunities for and early indications of more easily facilitated knowledge sharing across user groups/stakeholders.

In essence, the data model and architecture are successful if we see a lessening of the gaps and challenges identified in Chapter 3, and increase or movement towards integration, coherence, and expression or extension of practices across the system. Further building out and testing the working hypotheses of this project and its outputs are the focus of the next two chapters.

RELATED WORK

Finally, it is worth noting prior and related work that is in a similar effort to the LearningGraph project, the gaps they comes up against, and how the LearningGraph project is differentiated.

There are a number of prior research and commercial projects related to this need problem area that have helped to demonstrated the need for a more robust infrastructure of content beyond standards, and have in part, set the foundation for this work (see Figure 4-8). They also help demonstrate the shortcomings of trying to bridge some of the problem area challenges when only taking a limited number of user groups in mind.

Many of these projects are targeted at educators, seeking to help create a better foundation for classroom practice. The NSDL Literacy Maps is a tool for teachers and students to find NSDL resources that relate to specific science and math concepts, to help illustrate connections between concepts as well as how concepts build upon one another across grade levels, and to serve as a browsing interface to NSDL resources. Similarly,
the *Dynamic Learning Maps* is an assessments system for younger age children, built around common competency models they have developed. For later stage learners, projects like the *Competency Model Clearninghouse* was intended to inform the public workforce investment system about the value, development, and uses of competency models, and to serve as a workbench and repository for building and referencing competency models and career ladders. And projects like *TurnOnCCMath* have done a nice job at visualizing learning progression research in order to make it more actionable and usable for educators.

Other projects such as *CASE* and *OpenSALT*, are targeted helping to support the technical challenges with learning data across learning technologies and platforms. The effort by the inBloom project to build a common learning map at the heart of their data architecture intended to bring an all-encompassing data architecture to education is perhaps the most well-known in this spaces. Finally, projects like *PADI* helped to create a common space where assessment domain models could be crated and shared.

The limitations of each of these are described more fully in Figure 4-8, yet the common theme that can be seen across all of them is that they have largely focused on an aspect of this problem space, and/or have focused too narrowly on a set of standards, a domain, and/or a function or user group—and consequently have had limited impact or crossover between user groups. Figure 4-9 gives a general sense of the ways in which each of these tools is able to meet the needs of the various user group / stakeholders in education.

<table>
<thead>
<tr>
<th>NEED / FOCUS</th>
<th>OUTCOME</th>
<th>GAPS / SHORTCOMINGS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NSDL Literacy Maps</strong></td>
<td>Research-based tool to help teachers and students</td>
<td>An interactive tool for teachers and learners to explore specific science and math concepts. Excellent mapping of core science domains and supporting research.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- science only</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- difficult to navigate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- does not link to standards</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- not widely adopted</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- incomplete data model to meet all stakeholders needs</td>
</tr>
<tr>
<td><strong>Competency Model Clearinghouse (CMC)</strong></td>
<td>To provide competency models for common industries and professions, such as retail, finance, healthcare</td>
<td>Interactive competency model pyramids across a range of professions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- It is not clear what research or resources they are using to support the design of their models</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Not well adopted in education</td>
</tr>
<tr>
<td><strong>CASE (Competencies &amp; Academic Standards Exchange®) – IMS Global</strong></td>
<td>To organize learning data within the IMS Global common learning data architecture, so that it is possible to digitally exchange definitions of competencies across platforms.</td>
<td>Used to exchange information about learning competencies and standards, as well as rubrics, criteria for performance tasks, which may or may not be aligned to competencies.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Competencies maps are not readily available or visualized as tools.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Does not integrate current models of development and assessment constructs.</td>
</tr>
</tbody>
</table>
**OpenSALT**

A competency management tool based on the [CASE® standard](#) from IMS Global Learning Consortium, seeking to have a complete set of open, certified frameworks available in the best human and machine readable formats.

Their open-source website allows you to search standards and competencies, and find those related even outside the US.

- Nearly all of the content is not competencies but standards
- The UI is limited
- Claims to make connections to other standards, but does not in any meaningful way from a technical perspective

**Applied Minds — The Learning Map Project** (later, in partnership with the Gates Foundation / inBloom)

To create a “learning map” to guide an individual AI learning tutor called Aristotle; later, this work was used to support the Gates Foundation’s inBloom project.

Through work on the Freebase project and through funding of the Gates Foundation, a technical specification, data model, and a number of tools/APIs were developed.

- published on GitHub, but not actively used (inBloom was shut down in 2014)
- data model did not include robust specifications for the definition of assessments and competency models

**Dynamic Learning Maps® (DLM®), Alternate Assessment System Consortium**

A collection of 15 US states using this computer-based assessment system for students with cognitive disabilities.

Research-based maps, derived from the CCSS, but distill the essential elements for assessment. Good example of how common learning maps can be helpful in teaching and assessment.

- CCSS only
- PDF & .xls documents — not dynamic
- Proprietary to consortium members
- Incomplete data model to meet all stakeholders needs

**TurnOnCCMath**

Visual display of learning trajectories, aligned with the CCSS.

Rich, dynamic free resource giving deeper explanations to learning trajectories and core concepts in math.

- CCSS math only
- Does not include evidence/assessment data

**SRI — PADI**

Platform to organize expert-created assessment design templates (using ECD framework)

Online platform of a range of assessment models, partially 'open'.

- Geared towards assessment experts
- No longer active?
- Incomplete data model to meet all stakeholders needs (not aligned to standards; no domain models)

**Figure 4-8.** Prominent related projects, and their scope, outcomes, and shortcomings.
Figure 4-9. A review of the related work in Figure 4-8, and their general capacity to meet the user needs of each of the identified communities.
Conversely, the goal of the LearningGraph project is to explore the capacity to engineer a coherent and unified data model, that is able to serve as the foundation of a range of tools and platforms to more effectively meet the needs within each user group/stakeholder community, as well as across them (see Figure 4-10).

![Figure 4-10](image.png)  
**Figure 4-10.** A visualization of the impact goal across user groups for the LearningGraph project.

**SUMMARY**

The LearningGraph project is a research initiative intended to employ systems engineering processes (SEP) in order to reengineer a fundamental pillar by which learning environments and technologies are supported—the data model and architecture of learning objectives and developmental models. From 2012-2016, the initiative completed the Pre-Phase A elements of SEP, resulting in an initial data model and proposed architecture that suggests a coherent modeling schema for learning constructs.

In the next two chapters, we will discuss the continued development of the project through aspects of Phase A and Phase of the SEP, which are aligned with research question 1 (RQ1) and research question 2 (RQ2) of this thesis.
Chapter V

NEEDS ANALYSIS

INTRODUCTION

Many practices come out of habit or tradition, inhibiting the potential for an innovative design or solution. What are the actual needs of users that a potential new tool must meet, and hopefully improve to make tasks easier, clearer, and faster for the user?

The meta-analysis of the problem space in Chapter 3 set a good foundation for understanding the needs broadly across the system. Further analysis is needed to define the needs of the users, in order to more clearly articulate the baseline system requirements, and to use these to determine the feasibility and desirability of a suggested new system (SEP Phase A). This chapter focuses on research question 1,

\[ \text{RQ1: In order to define a unified data model entity for learning content, what are the user needs/requirements of key education stakeholders related to learning constructs and outcomes?} \]

Based on the system meta-analysis, this section of work is based on several assumptions:

- There are distinct but overlapping needs of various education stakeholders, and distinct but overlapping data sets of information as it relates to learning constructs and models.
- User \( \text{needs} \) are linked to, but distinct from, user \( \text{practices and tools} \)—in that some practices and tools are artifacts of the past and have the potential for being improved and replaced, whereas \( \text{needs} \) set the baseline design parameters for a new system.
- By eliciting user needs, we can more clearly define a core data model to serve as the foundation for improving existing practices, and to more effectively define new system tools and practices.
RESEARCH OVERVIEW

To answer this research question, in alignment with SEP Phase A practices, a Needs Analysis was conducted in 2016-2018 with a range of key stakeholders that would need to work with a proposed new data model, in their own way. These stakeholder participant groups included:

- Educators
- Learning Scientists / Researchers
- Assessment Developers
- Instructional Designers / Educational Technologists / Publishers

Methods

The needs analysis consisted of individual interviews using a semi-structured interview protocol; the full semi-structured interview protocols for each user group can be found in Appendix F. The interviews questions were organized around six themes:

I. User's current practices. How do users currently engage with standards as well as other frameworks, tools, structures, communities, etc.? How do you do your work? The goal is understand the practices and structures they use as it relates to learning models and data.

II. The tools and artifacts they use. In these practices, what are the specific tools, frameworks, structures, etc., used? How do they use them to work with learning models and data?

III. The needs users have as it relates to their work and their role in working with learning data and models of learning. What are needs as required by the role and work? The goal here is to understand the general practices and tasks they must do, as distinct from how they have traditionally done that work, in order to create space for new designs for tools and methods.

IV. Problems and shortcomings users encounter when working with existing structures. How do their current tools and practice fall short? In what way?

V. Wishes or thoughts about ways in which it might be improved. How might they imagine these shortcomings could be improved? What do they wish existed, or what changes would they like to make?

The purpose of the interview questions organized in this way is to understand the specific needs and practices across user groups, and to gain insights on their challenges and gaps they have identified, so that we can use that information to ultimately build new infrastructure that (A) not only meets but improves their specific needs
and practices; and (B) to identify overlap in the practices and tools of each user group community, so that such a new infrastructure can provide more coherence and alignment across the ecosystem.

**FINDINGS**

**EDUCATORS**

Twenty-two K-12 educators were interviewed; most of these participants work in public schools in the U.S. The key points from their feedback about needs and practices is listed below, with select quotes included as points of reference:

i. **Need for more detail and information.** Nearly all participants said that the Common Core standards (and its locally-adapted derivatives) do not give enough information for them to understand exactly what is intended by the standard, and how to design instruction and guide learners’ development of the learning in the classroom.

   “The county has put one sample question – one, as in singular! – of a math question to use for learners at 3rd grade and 5th grade. They’re not giving us enough resources.”

   “More in-depth explanation of the learning targets and what they’re really getting at would be good because they’re kinda broad.”

   “Rubrics are the starting point for most teachers.”

Moreover, teachers expressed that they typically don’t understand what colleagues – particularly at different grade levels – are teaching, and that this particularly impacts students when they move schools. As a result, there is a lot of repetition of content and experiences for the learner.

Districts provide varying levels of support around standards; some provide crosswalk documents to help teachers understand the relationship between new standards like the Common Core and the existing district- or state-level standards. Others, such as New York City public schools, have a robust curriculum already that acts as a scope-and-sequence (described as “something between standards and curriculum”, that fleshes out a topic and even aligns with ELA and MATH—but does not include key data on common misconceptions, assessments, tasks, etc.

ii. **Need for more tools and resources.** Educators make an effort in a number of ways to help bridge their needs in relation to standards. Some teachers seek out external tools like Mastery Connect – an ed tech platform that helps to model learner progress by allowing teachers to capture formative assessment data in relation to the Common Core State Standards – to help them understand how to support
instruction with standards. Others create handmade documents in a spreadsheet that outline the key standards they are working with, to help them unpack and visualize the standards they must work with in a collaborative planning with other teachers.

Educators also emphasized how much they lean on colleagues and the educator community to help fill the gaps left by the existing structures.

"I Google search the topic I am teaching and look to see how other teachers have taught the content. I look at Pinterest and teacherspayteachers.com"

"Sharing materials is huge—it’s what teachers do. Having teacher materials right there [in the standards] would be awesome. A place where you can share info right there, like, 'If you have 9th graders, would recommend this' or 'I did this but this is what didn’t work'.”

"We create and share lessons a lot, and I do with a few friends in other districts. Often they are Google Docs or hardcopy I just make a copy of."

Many participants interviewed complained about the amount of time they spend searching for good materials to support instruction. In addition to tools that help them more clearly understand the standards and how to teach to them, many also advocated for more material that has been vetted to effectively support the standards they are expected to teach, and tools that help them visualize learning goals and standards more easily—such as allowing them to easily move between grade levels and see the connections between the skills and content targeted at each.

"When I’m doing planning, after identifying the next standard to teach, I often spend hours then looking for material. I often use YouTube now but it would be great if the good materials were all organized in one place instead of having to search all over for it.”

"We use Next Generation Science Standards now, and it’s overall good. But I want to be able to have an app that lets you pick a standard, then be able to see 'what it looks like in the end', ideas of tasks and things to do with it, 'What basic looks like' and 'what proficient looks like'."

"An interactive dashboard would be great, where I can upload my lessons and see what my teacher next door is doing.”

iii. **Assessment was a commonly underscored challenge.** Many cited that the summative assessments administered by their districts do not align with the Common Core—explaining that the assessments target a much higher level of rigor than that outlined in the standards. Moreover, that the standards can dictate that certain concepts are important to teach, but that they won’t get actualized in the classroom if those concepts are not on the assessment.
"Our tests were recently tossed out because they were not rigorous enough. But now there's a big gap between what the tests actually target — more rigorous — and what the standards are generally advocating for. They created this new Milestones guide to try to help teachers teach to the higher levels, but it's really up to the teacher to connect these things."

"We really need assessment materials. We look at other states materials because ours is so bad."

This lack of clarity often creates the scenario where teachers capacity, and the nature by which they implement the standards, has a lot of variance. Moreover, as educators look to build capacity in a learner, they need to be able to quickly and easily understand where the learner is now — something that is currently very difficult to do, according to most respondents.

**Educators at Competency-Based Schools**

In addition to these aforementioned educator interviews, seven educators in both public and private schools that are in the process of converting to a competency-based education (CBE) model were interviewed. Whereas traditional standards dictate what is taught when, the goal of CBE is to support learners on their own natural developmental progression across a range of competencies and skills. As such, competencies are typically structured without explicitly outlining related grade levels or dictating what is taught at a given time in the curriculum. A number of key themes emerged from these participants:

1. **There is still a steep learning curve for best practices in modeling competencies.** Moving from 'standards' to 'competencies' is still an emerging picture. Since CBE is still an emerging approach broadly-speaking, most schools moving in this direction must create their own competency models and purposefully define how they want CBE to look like in their school. For some, their competencies include age-specific benchmarks while others make no indication of ages or grade levels, but simply identify stages of development such as a scoring system of “Level 1-4” with ‘1’ being ‘novice’ and ‘4’ being ‘expert’. This has a significant impact on practice, where the classroom instruction is not dictated by a scope-and-sequence, but rather learning experiences are created for the learners that support their growth where they are, and data generated from these experiences in used to plot their growth on the leveled scale. This implicates significantly different day-to-day classroom practice for the learners, but particularly for the educators who are now (intended to be) less focused on covering content and more focused on supporting learner growth broadly.

   All participants described the process of their school first needing to unpack what they mean by a "competency" and how they will model/build competencies. Some design their competency targets by starting with standards documents, others design their competency targets outright from external experts and resources. In some of the schools where the CBE educators interviewed work, they use standards as their starting point for generating the competency frameworks they will use — such is the
case across the state of New Hampshire. Even as educators at leading-edge schools, with their hands perhaps more “in the clay” of working with learning data as they design competencies, they expressed considerable challenges in being able to understand the standards. One participant described that they have spent years pouring over the Next Generation Science Standards (NGSS) in order to understand exactly what is meant or intended by them (both in learning targets as well as what is intended about how learning is expected to be supported).

“[Standards] are helpful, but they are spreadsheets. They are clunky and not dynamic.”

“Connections to industry is useful, academic standards are not.”

In science, one school used the AAAS assessment bank (a rigorous and free assessment bank), to backward map from these assessments to the instructional goals they desired. Similarly, another school has constructed a “big picture map” of what they want to cover in science, and plan backwards from that. Participants from one school, who built their competencies models from the ground-up, emphasized that “one big mistake they made was marking the levels of competency to grade levels, rather than more agnostic levels such as ‘1, 2, 3, 4...’”

Some participants in public schools moving to CBE had additional pressures or constraints from their education department, such as being asked to align their targets with Webb’s Depth of Knowledge, horizontally and vertically across grade levels, and feel that they need a tool to help them to do all of that alignment work.

ii. Lack of tools to meet their needs in supporting CBE. Many described the challenge that as instruction is CBE schools is now often more project-based, problem-based, and interdisciplinary, this has made planning learning and reporting learning outcomes using traditional tools challenging. Google Docs are a common tool being used to do their planning, where the simplicity of this tool is both an advantage and a disadvantage.

“There aren’t many products out there that are designed to do what we’re trying to do.”

“We use a digital portfolio tool, but it still is built around traditional structures of periods and grade levels. We need one that isn’t built around those traditional structures.”

A number of additional tools were requested, including those that quickly help them assess and easily understand where a learner is on a competency, and that collects the data, were described having the potential to be “powerful and very helpful.” Similarly, many echoed the need for an assessment tool

25 Personal communication with Paul Leather, Deputy Secretary of Education New Hampshire; July 2016.

26 Norman Webb’s cognitive rigor taxonomy, similar to Bloom’s Taxonomy. See Webb, 1997; 1999.
that does short-essay analysis—additionally noting that, “a tool that would allow that data stay with the student over time and not ‘reset’ at the beginning of a new school year would be very helpful.”

The broad themes that emerged from both groups of educators were around the shortcomings of how existing structures are presented, as well as the lack of tools that can help support the needs of the field and to build capacity in the field. Summarizing the sentiment of this group of participants is perhaps best framed by a quote from the founder of an innovative CBE school:

“The lack of [collective knowledge-building in the field] is the biggest problem I think that the field faces. There are so many people all around the country doing this work, and we meet at a conference every two months, and we hang out and talk, and every single one of us is building our own LMS, we’re building our own [competency] frameworks, we’re building our own instructional models, and they’re so similar. It’s crazy that we’re all spending so much time on it.”

INSTRUCTIONAL DESIGNERS, EDUCATIONAL TECHNOLOGISTS, and PUBLISHERS

The next stakeholder group represents a range of professionals involved with the design and development of learning technologies and instructional materials. The individuals interviewed in this area are all working in the more complex range of learning technologies, such as cognitive tutors, simulations, and game-based learning environments.

Although each had their own flavor of methods to do the work, there were a number of common sentiments and dominant themes across their interviews:

i. **Standards are often a starting point, or a reference point later, but play a small role in the work of designing learning tools—and much work goes into hand-building domain models at the heart of the learning technology.** When starting a new project, often they look to standards, or example syllabi they can find, or table of contents from textbooks, but these fall well short what they need to do their job well. One participant described starting first with the relevant standards and then making those the learning objectives of the game, noting that the quality and ability of a standard to be turning into an active learning goal does vary quite a bit; and if there is no set of standards for the topic of the game, they will create them on their own.

Yet most participants interviewed described a process of conducting considerable further inquiry into research, resources, and often extensive interviews with experts in a given domain area in order for them
to be able to pull together the type of construct or domain model they need. This can be quite beneficial for the design team on the one hand, as they themselves are the ones getting their “hands in the clay” to understand the domain space and put together the domain model they see emerging through all of this inquiry. There are a number of downsides however, including the time and resources diverted to do this work, the challenge of gaining adequate access to experts can be quite difficult, and the fact that then each project and group has their own model that may or may not be shared in some way, for others to build upon and build coherence across. As a result, the critical work of building the domain model to serve as the foundation for the learning tool is very laborious and time-consuming.

ii. The need, and request for, organized domain models. In light of this previous dynamic, one of the underscored needs of the group was the translation of the content (domain) models from the experts into a usable and yet ‘accurate’ model the game designers can use. In order to serve the learning goals of the game, designers need to understand the nature of the domain, core conceptual aspects they should be targeting, misconceptions, and developmental changes to look for in learners—to inform both the design of the content and experience, and the underlying data model. As one participant put it,

“There is a lack of shared models, so a lot of work has to happen on the front end of designing the domain model and competency model before the design begins.”

And similarly by others,

“It would be hugely helpful to them if there was a more coherent place that aggregated this information, rather than them having to do this every time.”

“It feels like everyone is doing a slightly different thing. If there was a better way of the collected models to be organized—just having a tagged database of all the models that are out there, and any research that's been done, would be super helpful. If we already knew that there were similar models to what we are trying to build...a better way showing of the collected models that have been done...even if it's just a piece of the model, and any research that's been done.”

One participant who leads the development of a very popular early childhood learning app explained,

“We purposefully started with Number Sense because it's such a baseline conceptual need for kids. But we were astounded that there were no real curricula or progression maps in this space. We had to develop it in house.”
iii. **The need, and request for, more organized related information.** In addition to core domain models, there was an emphasis on needing additional information in order to effectively build relevant tools—for example, situating the domain or competency in the real world:

“There is a need beyond content—we need models around how people use that knowledge, where and when.”

Understanding the landscape of tools (i.e. measures, inventories, digital tools accessing the construct, etc.) that have been built in support of various domains and competencies was also highlighted as a gap:

“There’s no central repository that catalogues key instructional tools that have been built for critical parts of the curriculum, and that’s what is still missing.”

“We needed a construct for ‘self-efficacy’ and we looked for two weeks and had a really hard time finding anything.”

“Like the OER approach, where things are tagged and searchable and more accessible... Physport[^27] is an example, it’s a site that has a bunch of different instruments, a little info about what the instrument is, who the audience is, and links to the instrument. If I had a resource like that for every content domain – what are the instruments and constructs out there for each of these domain areas – that would certainly help.”

iv. **Feedback mechanisms.** Since designers rely heavily on experts and researchers in a domain, designers also noted how helpful it would be to get feedback from those experts on what they ultimately build in the end, and if the experts feel it accurately captures the significant elements of the domain.

“In [learning game] we needed to do updates because the initial subject matter experts were a little less expert in certain areas. So that needed to be fixed. It would be great to have peer review for games. I think that would be really integral, both to integrate and fix things to make it better, but to also know who else looked at this because there are a lot of terrible games out there.”

Similarly, designers discussed the idea of getting feedback from educators on if/how they feel the competency model used to build the learning tool is reflecting what they are seeing in the classroom—a similar discussed in the learning progressions literature.

[^27]: [https://www.physport.org](https://www.physport.org)
v. The need and request for a common learning map. A common reference, particularly among learning game designers, was the wish for a general map of learning constructs, so that it would be easier to visualize aspects of the curriculum that learning technologies have been developed for, and the parts of the curriculum that still needed attention.

"Through later phases of [our work at a leading R&D group working on game-based assessment], we started to think that what we needed was a common data map of learning. As a game designer, I felt like what I needed was a topology of learning and how kids learn, and then do an overlay of what is best to learn at what ages. And that's what we started to chip away at."

ASSESSMENT DEVELOPERS

Five assessment specialists, who work in both research and industry, were interviewed for this study. Participants included assessment-focused researchers/developers in university settings, leading experts in the field of assessment, situated at a national assessment development agency, and a former researcher focused on innovative uses of technology as applied to assessment goals, who now works at the largest early childhood digital app company, leading the development of their data collection and modeling of learning inside the app. The core insights from their interviews are discussed below.

Amongst participants, the main tasks they engage in include:

(i) building domain models through an extensive review of the literature to serve as the theoretical basis of what has come before;

(ii) building tools and materials that apply those domain models; and

(iii) subsequently refining those domain models based on what they are seeing in the application of the tools in real contexts.

Building domain models was described similarly by all, as an extensive and iterative process that is both top down and bottom up in order to build a more accurate model, which can take years. One participant described on ongoing process at his organization to build and refine their model of “argumentative writing” has taken nearly 10 years to generate. The iterative nature of this model-building was emphasized, because there are often gaps in the literature that must be bridged, which is in part done so by building tasks, testing them and refining them—as such, domain models are really evolving theories that continually get applied and refined. Moreover, some participants stressed that because of the rich technologies we have access to today, they are increasingly taking a “bottom up” approach to generating models of learning based on the participant data emerging from
real contexts. One participant also said she purposefully uses the term ‘competency model’ because ‘domain model’ is so broad and means so many things, and sometimes you’re just looking at an aspect of a domain.

Some participants who work at non-profit organizations, felt strongly about sharing the work of domain models, and that is was important to do and part of their organization’s mission. Others expressed that this is largely not currently done, for a number of reasons: there is little reason or incentive to do so; building assessments and models is expensive and labor intensive, and for some organizations ultimately then not just proprietary but the most valuable asset of the organization; finally, some expressed interest in possibly building on others’ models, but to do so requires very clear unpacking of the research and logic behind its construction. One participant noted that researchers are moving towards sharing data models, but those data models are not as connected to practice. Another expressed that she sees a move towards open models, but that they must be “manipulateable” and able to be applied in context.

In addition to better sharing of models, participants expressed another central challenge: how to pull data across learning environments to know a learner’s competency growth.

“The lack of coherence across the system, means that anytime anyone wants to do something they have to reinvent a lot of stuff that they otherwise wouldn’t need to.”

Innovation in this space was seen as both a positive and a negative. One participant expressed that approaches such as Educational Data Mining (EDM) is only reinforcing a faulty architecture, and that it represents “using a new toy to rebuild the old thing”. Yet other participants expressed that innovative approaches such as game-based assessment are helping us define better learner models from the ground up, and that approaches such as these are helping to inform the integration for learning sciences frameworks. For example, in the work at GlassLab28 – an innovative research and development group exploring the intersection of learning, assessment and digital technologies, known for their work in adapting commercial video games to be data-rich learning environments – learning progressions were used to support the game design, helping to define a higher level of abstraction of a given state, level, or location in some kind of progression or web.

Finally, a number of system-level requests were expressed:

i. **A repository of models.** A common workspace or knowledge base around a range of models was emphasized by a number of participants. This request came with a number of considerations:
   
a. Sharing models is helpful, but clearly articulating the background literature and development underlying the model is critical if it is to be considered reusable in any way;

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28 [https://www.glasslabgames.org](https://www.glasslabgames.org)
b. Graphical representation (i.e. graphics, networks, visual models) of all the elements in a competency model and how they are connected.

ii. **Collaboration channels.** In addition to making models more visible and accessible, participants requested ways to make these accessible to experts and get their feedback on their completeness and suggested edits.

iii. **Tools for applying innovation in the field.** A number of participants have discussed the need for, and are exploring ways in which, we might create more generalizable, broadly applicable structures and tools that can be assembled and customized on the spot in light of local knowledge. In other words, ways in which to make this specialized knowledge organized in a way that it can be leveraged and situated in local contexts. Several participants suggested something in a similar form, based on previous successful research projects, where users can adapt templates of useful tasks in a given competency development level.

One example given was an ECD “meta design pattern” that essentially modeled key tasks across a competency progression. The participant reported that the first several attempts took quite a lot of time for the educators to figure out, and after that they were able to quickly apply them in practice. He further articulated this as the “microwave example” where most people don’t want or need to know how the microwave works, but they just need to know how to cook what they need to cook, and they benefit greatly by being able to utilize the microwave. A similar analogy was made to the “Apple Developer Kit” that first was incredibly difficult for even some of the best developers to use, but eventually became refined and made it very easy for a range of developers to use.

**LEARNING SCIENTISTS / RESEARCHERS**

The last group of professionals interviewed—researchers in the learning sciences—had the broadest range of work, and variance in their needs and practice. Their areas of foci included work on further defining learning progressions, mental models and cognitive development over time, construct-centered modeling, and human developmental progressions. Some participants in this group viewed themselves solely as one who conducts primary research on learning, others described their work as what would be described as applied research, seeking to build and apply tools that bring the learning sciences to practice while then also being able to feedback into the theory.

With this group of participants, there was a much heavier focus in discussion on the challenges and needs of improving the current system. All participants discussed their work in relation to the larger ecosystem built around standards, and several had extensive critique of the current system as well as considerations for how research indicates it might be improved:
“There’s a lot of critical information missing from standards in order for teachers to effectively teach to them.”

“There is so much stuff in standards ad hoc. They aren’t operationalized.”

“Teachers are forced to work at a general level, and aren’t really supported to look at the more phenomenological level of development.”

One participant whose work has largely been in regards to Construct-Centered Design (CCD), explained that “curriculum should be expressing learning goals in context of what you want them to be able to do,” which is lacking in most standards documentation. It is worth highlighting here, that this aligns with the contextual/situated view of competencies as was discussed by the Assessment group participants.

Perhaps the most interesting common theme across the interviews in this group was their emphasis on the state of learning progressions, and the common discontent with how they have been applied (or misappropriated) in practice:

“When the Common Core came out, people said the Common Core was a learning progression. One researcher who helped author the math [CCSS framework] finally said, ‘You’re right, it’s not a learning progression. We talked about learning progressions [when we designed it] but it’s really defining what do we want 12th graders to know. They promote this idea that it’s a progression, but it’s a curricular progression.’”

“Most are teaching progressions, not learning progressions.”

“Standards are not pedagogically complete. You want something more like a learning progression.”

One participant whose work has consisted of several decades of understanding learner cognition and development over time, was highly critical of how this larger field of work is playing out:

“The ‘Learning Progression people’ by-and-large don’t do technology...that frustrates me because I think we can make big changes in [our understanding of] how things are learned, but that’s nowhere in the picture—and the role of computation [to help us build this understanding] is totally invisible to these people. This is not just an impression, this is a life’s work of mine, and I think we can really change things.”

What the participant is highlighting here, is that despite the traction and potential in the work on learning progressions, much of the research conducted to date in this space has been done ‘manually’ through essentially
hand collecting data—which is highly useful, but little if any attention has been paid to how digital technologies can further enhance the collection of data, building of models, and formulating these materials effectively for practitioners. In short, the development of learning progressions presents one of the most exciting developments in learning theory, and yet we have taken the necessary next steps to further expand and scale this work through the use of modern tools.

In regards to these concerns and their broader work, a range of need areas were expressed by participants, including:

i. **More research on the development of learning progressions.** The properly research-based work in learning progressions is promising, but still young, and there needs to be more attention and resources directed at further developing them and supporting other communities in engaging with them.

ii. **Tools for engaging practitioners with research-based materials.** As such, participants requested and suggested tools that into make generating learning progressions – and visualizing and working with them in practice – more accessible. One participant has begun this work, but from a conceptual standpoint, creating handout materials for educators, yet more is needed to bring this effectively to scale. One participant suggested,

   "It seems to me that someone should put together some sort of a funded project that serves as a seed or prototype of a larger sustainable relationship between teachers and researchers, around doing the learning progression research together—so that the validity of the learning progression is really ascertained through the real understanding of what’s going on in learning environments, and so that this research can really inform learning. Because if it’s just done as an academic exercise in research journals, that’s not really going to convince anyone to spend money on it."

In line with this, a database of exemplar tasks, and an interactive structure to grow that database from the community over time. Making things like ECD frameworks more generally accessible and applicable was also emphasized here. Additionally, this must include a structure to feedback insights from teachers into the theoretical learning progression—and the PD and incentives to do that. This was expressed in a slightly different framing by one participant, who asked for a "common database that has 3D learning objects organized in a way where it has practical knowledge for teachers, but is a useable framework at the state or national level. We can’t have each state trying to make their own [models], we have to build on this together."

Together, these needs were summarized nicely by one participant:
"Ultimately we need to be driving towards developmental models that help teachers see how to interpret evidence of where a learner is now, and what they need next."

Finally, it is worth summarizing here some work in process by participants as efforts to mitigate some of these gaps—as indicators of their insights as well as considerations for directions in design approaches of what we might ultimately build for more scaled solutions. As was previously noted, one participant is building tools in the form of templates and handouts, which help scaffold for educators how to identify and leverage learning progressions in their classrooms. These tools help teachers identify where a learner is in their understanding of a concept, in part by being able to interpret learner artifacts, and how to build learning experiences that are relevant for the learner based on that interpretation. The two core artifacts she creates are learning development progressions and task shells. The progressions outline common developmental milestones in the cultivation of a concept or competency, also mapping out common misconceptions that may accompany these stages, the types of tasks that can be useful in eliciting insights into where a learner may be in that progression, and giving examples and samples of student work with indicators of how to ‘read’ the artifacts for insights as to where they are on the progression. The task shells create the opportunity for a learner to be working on a range of content, projects, or tasks, and from that discern their developmental needs. She has found that such work actually pulls the teacher deeper into the learning, by engaging them in hands-on work of understanding learner development. She creates learner profiles that model a progression connected to the standards, and in her pilot schools could pull a file on any learner and identify where they were on a progression and the tasks/evidence that documents this. These progress maps have allowed teachers across grades to be able to pick up a profile of a learner and understand where they are and what they need next.

She also now works with a number of districts that are moving to competency-based learning, where “instead of having 35 ELA standards, we have 6, 7 or 8 competencies in literacy.” Interestingly, she has found that as long as these developmental progressions reference standards in some way, it takes them out of the equation:

“If you have the right learning progression, it doesn’t matter if the standards change because the learning doesn’t.”

**DISCUSSION**

Across these stakeholder groups, there a number of very clear themes that can be seen, summarized as:

*Standards do not meet the needs of stakeholders, and in some dimensions are antithetical to the research-based practices and outcomes we may desire. User groups do a range of things to fill the gaps left by standards, that translates into considerable work that is often redundant*
and isolated. For educators, standards provide little of the necessary knowledge to effectively implement them—knowledge that must be sourced at great lengths from various resources. It also creates additional gaps, such as a larger developmental understanding of growth and mastery, and how their classroom instruction situates in that larger understanding. This requires they go to extra lengths to unpack standards and find the resources they need to understand them and implement them effectively. For competency-based educators, the gap is wider because there are not yet common definitions of what constitutes a competency, nor common frameworks of competencies to utilize. For designers and assessment developers, it means going to considerable extra lengths to build the necessary domain models and construct maps needed to serve as the foundation for what they will build. For the learning scientists, the standards at times often misappropriate learning sciences research by the way they are designed, also preventing educators from understanding learner development more deeply.

The need for organized and shared models, and the tools for working with and applying those models. Though expressed in slightly different terms, each group (except standards-based educators) discussed the need for having access to shared models that in some way relate what to ultimately is some form of a domain model or construct map. Referred to as a competency model, domain model, construct map, or learning progression, these terms were being used to reference some form of developmental progression modeled in a way that can effectively meet their needs. Looking more deeply at what is meant by these terms and what is needed in each group, would be a central next step for the larger engineering project. As one assessment and technology developer put it,

“I don’t believe there likely will ever be a common ontology in education, but that there could be tremendous impact by creating a common resource that isn’t proprietary.”

The need for collaboration and feedback loops. Finally, across groups there were requests for feedback loops between communities, in one capacity or another—including domain experts on the work of instructional designers, teachers on the design of learning progressions, learning scientists on the feedback of models developed by assessment developers. This request can be viewed in two ways: 1) is the need for expert feedback on what is developed by a practitioner; and 2) various stakeholder groups seeking input and validation on the development of our common developmental models from all dimensions—top down, bottom up, and 360 input, as a means to most accurately model learning.

These insights point to the clear pain points in the system, that are highly problematic for a number of reasons: they create considerable extra work, redundant and isolated practice, that has little if any feedback loops within each user group—let alone across user groups. These are indicators of a system that is setup for poor performance, malpractice, and stagnancy. In fact, many of these deficits in feedback loops, shared knowledge bases, and tools for collaboration and implementation are the very elements expressed as central to innovation in systems (Utterback, 1994).
CONCLUSION

From RQ1 we have identified a range of needs from the participants groups interviewed—needs that are overlapping in a number of ways. The pain-points described by these groups indicate the potential for a common knowledge base that organizes core models of domains, constructs, and developmental progression could be beneficial to all groups. Is such a common data model architecture possible? Considerable work on the development and iterations of data models would be needed to further test this—which is the focus of RQ2 in Chapter 7.

In the next chapter, we further extend the needs analysis of RQ1 to discuss a number pain-points that play out at the systems level of this existing infrastructure of learning data models.
Chapter VI

SYSTEMS NEEDS: Case Studies

In order to further situate and extend the application of this research, the LearningGraph project has collaborated with two systems-level projects that have further helped to define the needs analysis. The first collaboration is in relation to the launch of the new national curriculum in Brazil, through support of the Lemann Foundation, who asked that we explore the system structures that may be needed to ensure teacher implementation success, such as our prototype EDmaps. The second collaboration is with OECD Education2030, a global initiative of more than 30 countries collaboratively exploring the critical competencies needed to prepare for our future societies, where I serve as a SME advisor.

Both of these have been illustrative, systems-level contexts, which have helped to further define the problem space as well as to further elucidate the various needs across the system in relation to the problem space. In this chapter, these case studies are presented along with discussion as to how these further define the needs analysis.

CASE STUDY 1: “The New Brazilian National Curriculum”

From 2013 to 2017, the Brazilian Ministry of Education engaged in an extensive redesign of their national curriculum, resulting in the National Common Curricular Base (referred to as the BNCC). A primary focus of the redesign was to bring a more competency-based model of teaching and learning into the framework. The government has invested more than R$100 million in the implementation of the new standards, with additional significant investment in supports by organizations such as the Lemann Foundation.

The Lemann Foundation is a very active organization that heavily invests in resources and supports broadly across education in Brazil. For the BNCC specifically, they have devoted 10 of their staff members to lead a range of initiatives in supporting curriculum/content development, professional development, and the design of learning technologies that are able to support the implementation of the BNCC.
A primary concern of the Lemann Foundation is the extent to which educators are able to effectively ‘read’ the BNCC and support learners in the classroom to meet the intended objectives of the new standards. In 2017, the Lemann Foundation awarded an exploratory research grant to the LearningGraph project at MIT, along with collaborators from the University of São Paulo (USP), to:

1. identify gaps and needs for key stakeholders, especially educators and students, to be able to effectively understand and implement the new BNCC; and
2. explore to what extent tools like EDmaps (an educator resource prototype that is built on the LearningGraph that helps educators understand the critical features of the development of a competency area—further discussed in Chapter 7) may help mitigate those critical still existing gaps and needs.

These goals were translated into three research questions:

- What are the needs and opportunities across the pipeline of activities in relation to educators being able to successfully implement the BNCC—especially the competency-based aspect of the BNCC?
- How can the EDmaps tools and competency prototypes better support educators in the implementation of the BNCC?
- What types of data visualizations and tools can support educator understanding and implementation of the BNCC?

**Outcomes as of Summer 2018**

In the spring of 2018, the participating researchers at MIT and USP conducted three focus groups and co-design workshops in São Paulo with a range of stakeholders connected in some capacity to the BNCC. Participants included educators (urban and rural), pedagogical school advisors, and educational consultants at the Brazilian Ministry of Education (MEC).

The focus group discussions centered on the nature of their role, their reflections on the structure and implementation of the BNCC, gaps and problems areas they have identified, and insights on potential opportunities for building interventions to enhance the implementation goals of the BNCC. Reflecting on the new standards’ documents specifically, participants had a range of illuminating comments (for reference, the BNCC is structured with a set of overarching competencies, supported by traditional content standards in math, science, etc.—see Figure 6-1 for further overview):
"When you look at the BNCC, you first ask 'what do these competencies really mean?' But in fact, the document is really emphasizing a lot of content."

"There is too much in this document. It says it is not a curriculum but when you really look at it, it is."

"We're curious about what you can make us to help make this bunch of pages useful."

"[in the BNCC] they introduce the idea of competency, but don't explain what it is or how to use it. This is the challenge. We have to change in a short time to competencies and abilities but don't know how. ... you have to educate the teachers on how to teach the competencies."

"We have too many 'abilities' (referring to the content standards) to work effectively in the classroom."

"A woman from the Ministry of Education said the focus is on the abilities and not on the competencies. So all the concept in our minds has changed in this meeting because of that."

"Teachers will still focus on what they are teaching, not knowing what students can do and where they are in competency development."

"The teachers won't think about competency and the BNCC when they can just use the textbooks. If teachers didn't have textbooks to follow, they would be obligated to think about 'what does ability/competence represent?'"

"The college entrance exam still has a big impact on what is taught in the classroom."

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**Figure 6-1.** Schematic overview of the BNCC.
A number of observations and outcomes came to light from the various perspectives at the table:

- There is a big gap between teacher perspective and needs/actions, and those of policy-makers. In other words, policy-makers construct these standards documents because it has now become common practice to do so (and in fact Brazil consulted with a number of countries on how they structure their standards), but there is little thought given to how teachers use these documents, and if designing them in this way actually produces the desired outcomes of implementation. As such, there is a big gap between these documents and how teachers need to actually do their job.

- In Brazil, it was suggested that the idea may be that textbooks help bridge this gap, but research suggests otherwise, especially with textbooks being a long-outdated modality of supporting learning.

- Even though the BNCC puts a heavy emphasis on being competency-based, most teachers do not know what that looks like in practice, how to change their teaching, and how to use the BNCC as it is now to support competency-based education (CBE).

- The “overarching” competencies of the BNCC (communication, digital literacy, argumentation, empathy and collaboration, etc.) will likely not get much attention because these are unfamiliar to teachers, and they will focus their practice where it largely has been thus far—on the core content areas of math, science, etc.

- Even the very beautiful document29 on these overarching competencies published by Movimento Pela Base Nacional Comum and the Center for Curriculum Redesign does a good job of ‘unpacking’ these competencies, many in the focus groups felt that the document is still not an actionable tool for teachers, that will help teachers effectively support these in their practice.

- Assessments – both summative and formative assessment tools – have not yet been defined for the BNCC. As a result, very few teachers today can say where a learner is in their ability in a given area—a critical aspect of effectively implementing CBE. Yet this gap also creates a real opportunity for innovation and the creation of tools that support practice to move in the direction desired.

- The BNCC, like many countries’ national standards, suffers from the “ontology problem”—where more rigorous ontologies of competencies need to be built, but the time and resources are not put into properly building those out so instead we create this frameworks that constrain practice and fall short in many ways.

- Similarly, education broadly has suffered from not adopting user-centered design practices—which is instead how most products across a range of industries are created to effectively meet the users needs.

The BNCC frameworks like most national frameworks, were designed from a conceptual model of how to construct standards/curricula, rather than identifying the kinds of classrooms we want in Brazil and then designing backwards to create the tools and frameworks that enable an educator to do that.

- Researchers from the USP report that in the schools they work with, many educators just open the textbook to the page they are on and teaching from that. Moreover, student comments in class at times reflect that they are not sure of what to do when they don’t have a book to look up the answer in—a critical problem in terms of preparing them for the real world. Teachers often stay with the textbook in part because it is familiar but also because it is secure—they feel insecure when a students asks them a question they do not know the answer to. Helping teachers to become more comfortable with this type of classroom dynamic is critical.

- As textbooks are still required, this is an example of a very significant barrier to change, and is likely to keep practice in the traditional space. How might the ‘textbook’ be reimagined to be a modern day ‘technology’ to support educators and learners? Innovating in this area especially seems critical to ultimately seeing a significant change in teacher practice.

- Teachers need more examples of what CBE looks like in practice—globally but more ‘locally’ in terms of smaller-grained elements of the standards and how to support them in the classroom.

- There are a number of barriers that we must consider in designing tools to ultimately be adopted and change teacher practice—including the diverse range of contexts across Brazil, factors such as textbooks and the lack of formative tools. We should first design for one location that can receive these innovations well, to show them what is possible, before ultimately trying to scale across all of Brazil.

- Many public school professionals take part in training activities offered by local Education departments, often motivated by career progress associated with the training certificates. Those activities may also work as an entry point for deploying innovations we design in EDmaps.

**Discussion**

The new BNCC presents a real opportunity for supporting deep change in classroom practice. Yet there are a number of significant barriers that, unless also altered or designed around, there is a very strong likelihood that classroom practice will not see much change and competency-based teaching and learning will not be implemented. This includes especially the prominent role textbooks in the ecosystem, the lack of understanding and training on what CBE is and how to implement CBE in the classroom, and most critically, designing actual teacher-centered tools and resources that not only make this more clear but provide much needed supports in helping educators understand how to effectively implement the BNCC. Assessment tools are central to any learning environment, but particularly CBE environments because the foundational premise of CBE is to allow learners to move at their own pace, but *educators can only do that when they know where a learner is in their*
ability. The lack of assessments—particularly formative assessment tools (also known as “assessments for learning”) creates a significant concern. Despite these critical challenges and gaps, there is also an opportunity to further define these gaps and teacher needs/practices, and purposefully design tools from the user perspective (in this case educators and teacher trainers) that directly and effectively meet their needs and demonstrate effective shifts in practice. Engaging in the work needed to more clearly understand the teacher practice perspective (via user-centered design) and moving beyond just publications and frameworks, into tools and dynamic resources is a key opportunity to bridging these gaps.

In relation to this situation, the research literature shows a number of insights to be considered:

- The nature of assessment, and available assessment tools, plays a critical role in HOW standards (and ultimately teaching and learning) are implemented in classrooms (Darling-Hammond, 2004).

- Similarly, the very design and structure of standards/curricula has a significant impact on how instruction is designed. For example, when the new national curriculum was launched in Scotland in 2010, educators underscored that they were able to implement project-based learning (PBL) much more easily now because the new curriculum was structured in a way that allowed educators to focus on the higher-level competencies emphasized (Groff, Howells & Cranmer, 2012).

- There are a range of barriers to innovation in education that ultimately influence the teacher and student level experience, and these must be considered, designed around, and mitigated when seeking to really transform day-to-day teaching and learning (Groff & Mouza, 2008).

The Lemann Foundation has a number of initiatives in process to support the implementation of the BNCC. Yet it is not clear how infrastructure is created across them in order to effectively and seamlessly support the experience of the educator to meaningfully implement the BNCC and CBE. Similarly, the Lemann Foundation has funded a 5-year study at Teacher’s College to analyze the entire pipeline from inception of the BNCC to the everyday experience of learners, in order to identify the big gaps and barriers—yet this will not include the design or development of potential tools to fill these gaps. Situating a design and engineering group to work alongside them could be a powerful way to leverage that research to build the necessary tools and supports to change everyday classroom practice.

The findings of this work reflect many of the themes identified in RQ1. The new BNCC is designed in similar structure as most traditional national standards globally, mapped to traditional grade levels and lacking critical information about how to pedagogically support learners in the development of these learning goals. Perhaps even more challenging is that the BNCC is attempting to occupy this ‘gray zone’ between standards and competencies—expressing that the clear intention is to be more competency-based, and yet the frameworks they published in traditional standards formats, and are not in a designed to support a competency-based progression structure. Being freshly published national policy documents, we likely cannot consider how to redesign the BNCC, but rather ask, what tools and supports can be engineered around them in order to support the
pedagogical shifts that have been advocated for by the government. As such, the next level of work for this grant: to begin to co-design and prototype tools like EDmaps that will support educators in understanding the nature of competencies, what CBE looks like, and how to more generally move teacher practice to focusing on competency development in learners. Key features to be considered in the EDmaps tools include providing competency models of the core overarching targets of the BNCC (such as ‘communication’, ‘argumentation’ and ‘empathy’), providing examples of student work at various stages of development and how teachers can interpret that work, and interactive features where teachers can share resources, comment, and collaborate on projects, tasks, and student artifacts. The testing of the EDmaps prototypes is also the focus of RQ2, and the next chapter.

CASE STUDY 2: “OECD Education 2030”

Launched in 2015, the Future of Education and Skills 2030 project – also known as Education 2030 – is a central body of work in development at the Centre for Educational Research and Innovation (CERI) division of the OECD (Organisation for Economic Co-operation and Development). The project brings together representatives from the more than 30 constituent countries of the OECD, with the aim to collectively help countries find answers to what knowledge, skills, attitudes and values are needed for today’s students to thrive and shape their world, as well as how instructional systems can effectively develop them. Practically, this boils down to several strands of work, including defining the ‘Learning 2030’ framework that seeks to “define a clearer vision and set of goals for education systems”30—i.e. create a common framework of skills and competencies as the core to competencies to preparing learners for 2030.

The project largely consists of Working Group meetings that occur several times a year, with representatives from the participating constituent countries as well as subject matter experts in the areas of the learning sciences, curriculum and content, and educational design. Much of the work has centered on exploring the various skills and competencies that are central to a holistic education for the projected future world of 2030. This has included prominently discussed constructs such as ‘problem-solving’ and ‘critical thinking’, to those much less common, such as ‘hope’ and ‘spiritual identity’.

A primary challenge in the project has been the need to give some sort of “handles” or unpacking of these constructs. A central challenge of the project has been to do quick literature reviews of the constructs. Since the launch of the project in 2015, I have served as an advisor to the project, and have participated in the working group specifically focused on this challenge, called “Construct Analysis”. In an effort to get more clarity, the group performed a brief analysis on each construct using a template they had created (see Figure 6-2). The aim of the template was to succinctly give an overview to the construct in short form (2-pages), including a

definition of the construct, its relevance for future society and relation to other key constructs, research on if/how it can be developed in learners, examples of how it is measured in various contexts, and so on.

<table>
<thead>
<tr>
<th>Construct Name</th>
<th>Definition</th>
<th>Relevance for 2030</th>
<th>Impactfulness</th>
<th>Interrelatedness</th>
<th>Malleability</th>
<th>Measurability</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition</td>
<td>Commonly used and understood description, defining the construct.</td>
<td>Conceptually coherent with the OECD learning framework.</td>
<td>Extent to which it has been shown to why this construct has an impact on future life outcomes in 2030</td>
<td>Interdependence and connectedness to other 36 constructs of the Education2030 project</td>
<td>Research-based evidence of if/how the construct can be developed and at what ages.</td>
<td>Evidence of its ability to be measured.</td>
<td>Supporting literature.</td>
</tr>
</tbody>
</table>

Figure 6.2  Construct Analysis framework for the OECD Educaiton2030 project.

Discussion

The approach of the Construct Analysis working group is much needed in order to do this type of global research/policy work, and by its presence demonstrates the gaps and needs in the field. There is clearly a gap in a collective knowledge base around the nature of these competencies and domains, and a real need to aggregate key information around them.

In the context of the Education 2030 project, the need to keep the scope to two pages is understandable, in order to keep the scope manageable, however it is insufficient in a number of dimensions. These short analyses of key constructs may in part meet the objectives of the OECD project, and help serve as a quick reference on where to gather further information in the literature, however by themselves they are not robust enough to be
usable as a construct or competency model for instructional designers or curriculum developers, for example. In this way, this project demonstrates what has been a recurring theme from RQ1: the expressed need for shared, open domain or competency models.

**CONCLUSION**

The case studies presented in this chapter help to further demonstrate the various ways in which different contexts, systems, and stakeholders must engage with constructs, learning data models, and frameworks—and the systems-level gaps and challenges that create difficulty to effectively doing so. Even more usefully, it helps to more clearly demonstrate the in-situ needs of a range of stakeholders at the systems level, and the types of documentation they are using to meet their needs. In the next chapter, we look at the further application of prototypes to potentially bridge these gaps.
Chapter VII

SUPPORTING EDUCATORS: Design-Based Research on EDmaps

“If you can both listen to children and accept their answers not as things to just be judged right or wrong but as pieces of information which may mean what the child is thinking, you will have taken a giant step toward becoming a master teacher rather than merely a disseminator of information.”

J.A. Easley, Jr. & R.E. Zwoyer, 1975

INTRODUCTION

Through these first phases of work, a clearer picture around the challenges of our current system and insufficient infrastructure were defined. Yet there is a long journey between more clearly defining the problem space and effectively defining solutions.

Moving forward in this process includes a long iterative effort of testing and refining data models with various stakeholder groups. In this study, RQ2 focuses on the testing of potential application of a core data structure when modeled through prototyped tool for the educator user group:

RQ2: How can tools built from a reengineered data model advance a construct-centered approach and improve classroom practices?

EDmaps is an educator tool prototype built on the LearningGraph data model, designed to help bridge these gaps and to potentially more effectively model competencies as related to the standards as well. The EDmaps prototype was used as the artifact to explore RQ2 and to offer refinements to the LearningGraph data model based on feedback. This chapter will discuss the findings from this pilot.
STUDY 1: STANDARDS-BASED EDUCATORS

RESEARCH OVERVIEW

The focus of this study was to use the co-design methodology, Design-Based Research (DBR), with educators, for several objectives:

- Identify refine insights about teacher needs and gaps in practice through engaging with an artifact like the EDmaps;

- Receive situated feedback based on the implementation of the EDmaps prototype in order to further improve its design;

- Identify potential for usability and impact of the EDmaps prototype on educator capacity and impact on learner development;

- To use all dimensions of this feedback in a way that further refines the EDmaps proposed data model.

METHODS

Four participants piloted the EDmaps prototype in their classrooms. Two completed one round of feedback and refinement of the prototype and three completed two rounds of feedback and refinement of the prototype. All four participants are in public and charter middle schools and high schools in the northeastern United States, teaching computer science / technology.

Participants were offered the choice of using one or more EDmaps prototypes, in “Computational Thinking”, “Systems Thinking” and “Problem-Solving”. These competencies were selected for the prototypes because they represent core competencies that show up often across standards set (e.g. problem-solving is found across traditional math and science standards) and as such increased the likelihood of finding teacher participants who would be willing to participate in the study because they would fit well in their classroom needs. An overview of these prototypes can be found in Figure 7.1 with further detail found in Appendix G.
Competition 
Computational Thinking

Definition
What is Computational Thinking? The conceptual foundation required to solve problems effectively and efficiently (i.e., algorithmically, with or without the assistance of computers) with solutions that are reusable in different contexts.

Overview
Computational Thinking (CT) is a problem-solving process that includes (but is not limited to) the following characteristics:

- Formulating problems in a way that enables us to use a computer and other tools to help solve them
- Logically organizing and analyzing data
- Representing data through abstractions, such as models and simulations
- Automating solutions through algorithmic thinking (a series of ordered steps)
- Identifying, analyzing, and implementing possible solutions with the goal of achieving the most efficient and effective combination of steps and resources
- Generalizing and transferring this problem-solving process to a wide variety of problems

Keywords
- programming
- coding
- algorithms

Related Standards
L1.3.CT.1  L1.3.CT.2  L1.3.CT.3  L1.3.CT.4  L1.3.CT.5  L1.6.CT.1  L1.6.CT.2  L1.6.CT.3  L1.6.CT.4  L1.6.CT.5  L1.6.CPP.4  L1.6.CPP.5  L1.6.CPP.6  L1.3.CP.1  L1.3.CP.2  L1.3.CP.3  L1.3.CP.4  L1.3.CP.5  L1.3.CP.6

Figure 7.1  Overview of EDmaps prototypes.
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Participants were asked to first review the prototypes and give their feedback in a short form. Next, participants were asked to use the prototype(s) as a reference or planning tool over the course of three weeks, as they found it most helpful to do so. At the end of the three weeks, participants were asked to submit their
feedback, in the form of critique and suggested edits. After the possible changes were made to the prototypes based on this feedback, participants were again asked to review the new prototypes and use them as a reference tool in their classrooms over the course of three weeks.

**FINDINGS**

Three participants elected to work solely with the prototype on Computational Thinking [CT], with two participants electing to use the prototype for Problem Solving [PS] as well.

*Positive initial impressions.* Upon initial review of the prototype, participant impressions were generally quite positive:

"I like this as a guide to frame computational thinking and problem solving."

"It took me a while to look through the whole packet to get the idea of what this prototype is for (I thought it would be a visual tool for students to use). It showed all the content very clearly from the overview to the competency model and tools in a concise fashion which I really like."

[CT]: "This is a very helpful tool. The competency models are a great way to frame the progression of a class. I teach both a one semester Intro to Programming class and an AP CS Principles class, and the competency model helps me."

[PS]: "This tool is intriguing but I don't have any way to use it directly."

"I did like the design and organization of the material presented. The video preview was helpful in understanding the use of the template. I do have comments and clarifications for the content in the template that I will attempt to organize in this form."

"Very impressive...the design of the prototype was fine, visually attractive and simple to use. Great frame of reference to use as a context. The CT prototype was useful in filling in details about my scope and sequence for a Java programming curriculum. The introduction of concepts within a programming course is a deepening spiral, where the application of each concept is integral to the understanding of the next. For instance, conditionals are key elements of iteration structures. This prototype allows a framework for identifying meta-concepts within each of the concepts; e.g., where the three algorithm subcategories fit within each unit."

*Helpfulness in the classroom.* When asked to describe what was helpful about the prototype, the comments largely centered around the competency or developmental model in the prototype:
"I teach game design and coding so again it would serve as a great guide. I would likely pull things out of the prototype to share directly with students to put learning in context."

"I like how the competency is split up into several sub-skills/concepts and the different development levels. It is very helpful for me as the practitioner to start checking which level my students are in each category as well as checking which concepts/skills have not been covered in my current curriculum to support developing the competency."

[CT]: "I had the 'Programming and Development' competency model open while I was teaching my intro to programming, and I made a point of thinking about where student questions fell on the scale – this helped me formulate my answer, and also how to ask students the next question."

[PS]: "Not directly applicable. I'm not really teaching 'Problem Solving', though perhaps I should be."

"The description of the sub-skills was most helpful. I liked the breakdown and sequencing of the prototype. I also like the graphic and display of showing how these concepts can be taught across eight levels progressing in thinking and complexity. And I liked the slide on the different constructs which distinguished one from the other."

**Shortcomings.** Participants were next asked to describe in what ways the prototype was confusing or not helpful. Responses could be organized into two categories: those about the content and conceptual design, and those in regards to the technical shortcomings and limitations of the prototype. Since the latter grouping would not be a factor in the final development of the tool, those comments were not included here.

Some comments on content were critical of the standards’ frameworks referenced, and concerned on how the competency model was derived. Interestingly, beyond content concerns, many of the comments here were reflective of the fact that this was a very different resource than most participants had seen before, and therefore they felt much more support was needed in order to understand how to effectively use it.

"I wasn’t entirely sure the intent of the prototype but as I mentioned as a guide that I could use and have handy I see great value. So, the confusion may just be in framing the intended use."

"The prototype per se is very rigorous. However, I feel it would be more clear with an overview to guide the teachers through the purpose of this model and the recommended way of reading and using this model. It is not clear to me which set of standards the related standards belong to. Since we are using CSTA and ISTE standards when designing curriculum, it’s also good for me to know how these concepts and skills aligned to these standards."
“The Tools section really needs some work. In the Programming and Development competency model, at level 5 (of 8) you put, ‘Has practical experience of a high-level textual language’. But none of the tools you reference would get a student this far.”

“The Overview of CT had a graphic that highlighted 4 areas: decomposition, pattern recognition, abstraction and algorithm design. The typed characteristics seemed to miss decomposition, iteration, and seemed to tie abstraction to Data. I would have data separated from abstraction and describe abstraction differently.”

“On competency models, the difference and trajectory of the competency levels were not clear. My assumption is that the 8th level is the highest level of competency. However, I disagree with some of these distinctions. The ability to distinguish condition-controlled (e.g., while loops) and counter-controlled (e.g., for loops) loops should not be the highest-level of competency (8), while the use of a condition for a loop is 4 levels prior (4). Also, more detail should be provided on the Problem Solving prototype. The IDEAL model does not explicitly include an iterative approach to problem solving. Perhaps adopting an iterative model similar to the definition used within the Exploring Computer Science would be more clear.”

**Suggested changes.** Many of the direct suggestions on adjustments to the prototypes were related to extending the application and practicality in the classroom—i.e., extending their functionality to support direct instructional needs, such as planning lessons and making the suggested tools active within the platform.

“I would add additional resources and possibly links to interactive activities. I love that some products for coding and game design were included but I wouldn’t consider the resources selected to be a definitive guide and I think teachers like to be pointed to a variety of resources to explore. This would also take the experience from conceptual to practical.”

“I would appreciate if more resources like tools and assessment be added to the prototype.”

[CT]: “I’d add some tools that could help a teacher get started with a high level language or two. Swift Playgrounds, IDLE (Python light IDE), Something with Javascript? Objects/Classes probably belong near the top of your ‘Programming and Development’ competency model. Also, some kind of reference of data structures other than ‘one dimensional’ or ‘two dimensional’. Key-value (Dictionary) structures, objects—not sure this kind of thinking about data is dealt with in the competency model.”

[PS]: “This model is much less fleshed out, and the behaviors referenced are much more difficult to measure. I like the idea of using games—there is a great game called ‘Fish Banks’ I think, that our Biology teachers use to teach about the ‘Tragedy of the Commons’.”
“I would like to determine clarity on the aim. I thought I knew the aim but it seemed to get fuzzy with the early intro of Math/Science with CT. Are we referencing the National CSTA standards/framework, or are we designing a subset of these. If so, this can be confusing to the user.”

Impact on practice. When asked about any impact the prototype may have had on their classroom practice, answers varied quite a bit. Some participants' comments reflected traditional practices, such as valuing the organization of pedagogical tools that support that competency. Other comments were more about the conceptual shifts they saw in themselves, around the larger goals of building competencies in learners.

“Set a great context and would serve as a great reference when teaching these skills that could otherwise seem a bit abstract and considered often ‘in name’ only.”

“Right after I read through the prototype, I had a group of students test the tool Lightbot and I also plan to have it as alternative individual practicing tool for algorithmic thinking. And that’s how I find the resource of the tools and assessment can be very supportive for the teachers to enrich the lesson. It is also helpful for me to align the core concepts in each lesson to the whole development model of the competency and remind me to be more mindful while designing and delivering the lesson.”

[CT]: “I found it helpful in discussions with students as stated above—also I’ll be using the competency models to modify my curricula going forward.”

[PS]: “Again, not directly applicable. I’d like to address this more in the future though.”

“It provided additional resources for assessment and tools. In my teaching, the prototype provided a framework to give feedback to students beyond the programming concepts. I was able to point out where in their programs they used things like parallelism, pattern recognition, etc. and to what level of competency. It also gave me some talking points to raise with my administration as I push for more CT in the curriculum.”

“In my teaching, the prototype provided a framework to give feedback to students beyond the programming concepts. I was able to point out where in their programs they used things like parallelism, pattern recognition, etc. and to what level of competency. This was the biggest difference in how I’ve used standards in planning instruction. My students’ projects include more than just single concepts and this prototype provided a structure for looking at project solutions (e.g., software flowcharts, etc.) at a more abstract level.”

Impact on conceptual understanding. Participants were asked to reflect on if/how working with this prototype influenced their understanding of these competencies. Responses reflected shifts in thinking about
the specific competencies they are teaching in their classrooms, as well as more broadly about how they think about competency development and learner progression of their students.

"It gave me a much more zoomed out view of the competency which is really helpful because often in the classroom we get really zoomed in on the lesson and what kids are doing in the moment, and we lose the bigger picture of where they are and where they are going."

"This prototype is a very helpful reminder for me of these competencies. While I teach each specific knowledge point, I sometimes forget the big picture we are reaching through these specific steps. It’s great to have this simple tool with me to check from time to time. I also like the development level which makes explicit the developing path of these competencies since it is essential to teachers and students."

"This is a very good attempt at a classification scheme for this stuff. I’ll definitely be referencing it for next year’s courses."

"I believe for me who has worked on standards and have participated in discussions around CT it lead to some weariness of how you summarized CT especially in the early page in the overview."

"It’s made me realize I could teach problem solving outside of CT—teach students to break things down into smaller tasks before putting it all together. Seems like a simple concept, but it’s given me an “A Ha” moment, so thanks."

"These prototypes did not affect my understanding of these competencies, given my years of familiarity with computer science. However, it made me reflect on how I view computational thinking and computer science. These sub-skills laid out in the CT prototype fit within my model of CT, though I would include a few more like conditionals and object-oriented concepts. However, I view computer science differently: the design and construction of computational models – which use CT – to solve a problem."

**STUDY 2: CBL EDUCATORS**

**RESEARCH OVERVIEW**

Given the distinct nature of competencies and competency-based schools, feedback on the prototypes was gathered from educators working in the contexts in addition to the iterations with public school educators. The goal of this study was to identify if the feedback on the EDmaps prototype would differ from that elicited in Study 1, and if so, the nature in which the prototype might used or adjusted to meet the needs of competency-based schools.
METHODS

Three focus groups of approximately one hour each were conducted with six educators from competency-based schools, teaching at both the middle school and high school levels. The focus group sessions introduced the prototypes, followed by a discussion about how the prototype interfaces with the existing frameworks utilized at their schools and suggested or edits or changes they would make.

FINDINGS

Reviews of the prototypes by educators in competency-based schools were orthogonal with the reviews by educators in traditional/standards-based public schools. Both had a fair amount of critique in regards to the standards referenced in the prototype in relation to the standards they use. However, the way in which they received the models in the prototype were quite different. For most of the public school educators, the competency model structure was quite unfamiliar to them, and through the course of the DBR pilot there was an observable progression in their own learning curve about competency models and how they might be useful in the classroom. For the CBE educators in the focus groups, it was much more familiar, and they were keen to dig into the model itself and reflect on how it fit their needs for better competency models. Additionally, amongst the CBE groups, the lack of organized options for competency models was an underscored frustration:

“We're building our own competency models in a vacuum because all we had to look at was Summit Public Schools' work and a theoretical scale. We didn't have anybody else to look at. What you're doing is exactly what we were trying to do, and it looks like a better logical framework.”

“We are using the Summit Learning Cognitive Skills [frameworks] and they do have some language on problem solving but it feels limited to me...I'm starting to wonder what might happen if we surfaced problem-solving standards in kid-friendly language in our course (and across out school) and bow naming these things might help students see the value. I'm wondering if your Problem Solving [model] might be just the ticket...”

The models they were able to obtain previously fall short because they do not include indicators of evidence and progress that teachers can use:

“But then here's the gap I always find, there's great stuff out there like this, but teachers have to grade work. We've tried very had to fill that gap, to make it easy for teachers, and students can understand what progress means...the more your model can help organize that information for the teacher on the progression the more helpful it will be.”
In moving to competency-based, several of the educators expressed why this matters as they see their peers grow in the ability to support learning along a developmental progression:

“In exploring how the use of a developmental progression (competency model) can help educators make sense of student work and what they need next, we have teachers who say, ‘I never realized how much time I was wasting doing activities that weren’t actually helping students get better at a skill.’”

The key points made in these focus groups can be summarized as:

- **More model options are needed for schools looking to move to CBE.** What is available now is very limited, and as a result schools are having to build their own or resort to what is available (most seem to be using the frameworks released by Summit Public Schools).

- **Breaking down the competency into sub-skills is helpful;** though this does raise the question about grain size, and participants comments elude to the notion that different schools will choose different options for how they might model or unpack a competency.

- **Grade-level-agnostic levels of a developmental progression is better;** if you apply grade levels to the developmental progression, it gets used like benchmarks standards.

- **The competency model (developmental progression) needs unpacking so that even parents and students know how to make meaning of it.** They are used to being told they are on the same level as everyone else (grade level) so they need support in understanding how to work with competencies and not feel like they are desperately behind peers or ‘where they should be’.

- **Teachers need to be able to actualize the competency model.** In other words, they need to be able to use it to inform how they organize their classroom. The rub is when they have to review student work; a competency model that doesn’t help the teacher be able to interpret student work in order to get an estimate of where they are in the competency model and what they need next, is of little use to them.

**DISCUSSION**

The feedback from participants in both of these groups helped to shed light on the shortcomings and strengths of the LearningGraph data model. Yet moreover, it presented deeper insights on the variances in the current mindsets and practices of educators. The general feedback on the prototype was that it would overall bring
value to classroom practice, and that for it to be more useful and usable, would require that it is more clearly aligned to the various standard frameworks the educators use, that more instructional tools were embedded, and that it was made more actionable by integrating detailed discussion of tasks and evidence in practice that can be used by educators to more effectively facilitate learner development in day-to-day classroom practice. The insights from this pilot suggest a number of indications for future directions of the LearningGraph data model, and subsequent tools like EDmaps that may be built on top of it:

- The correlations to commonly used standards frameworks related to the competency must be clearly modeled and well-documented, so that educators feel that this resources aligns with their current tools and understanding of a domain.

- The breakdown of a competency into sub-skills must be at an appropriate level of granularity that is accessible and usable at the classroom level, and reflects the practical nature of how these are supported in the classroom—and the mental models educators have built over time. This elements points to the fact that the construct model for a given competency must not be so high-level that it feels useless to an educator (something they might read once, find interesting, but never come back to again), but also the level of the granularity must correlate in some capacity to the way in which educators conceive of that competency and how they would break down the modeling of student growth in the competency, so that indeed the construct model because a useful tool and guide to help them do their work. This is likely the ‘ontological’ curation that will need to happen over time to determine exactly what those might look like in a given construct, and there may never be just one competency model for a construct in the LearningGraph. A comment made by several participants was how much more developed the Computational Thinking model was versus the model in the Problem-Solving prototype:

  "The Problem-Solving model is so broad, I wouldn’t even know where to start."

  "Build out each sub-skill with instructional resources that they can use to help guide learners through a competency development. You were on the track towards that with the CT one."

- The clear integration of rubrics and/or rubric-like data, reflected in the developmental model. Formative assessment in the classroom is essential, but particularly when using a competency-model, so that both the learner and educator know where the learner is and what they need next. A dominant tool in educator practice — that was also referenced frequently in the interviews and focus groups — is the use of rubrics. As one participant put it,

  "Rubrics are the starting point for all teachers."
Being so core to their practice, the essence of rubrics and their functionality of what rubrics do – break down sub-skills into developmental levels, with indicators of evidence – must be reflected in a teacher-facing tool, and integrating rubric-type structures can support educators as they become more capable with competency-based learning in the classroom. This currently is the essence of the prototyped data model for the LearningGraph, which in many ways reflects modeling constructs through the intersection of learning progressions and ECD, but in its current form does not immediately resemble a rubric. By helping to create that practical bridge for educators, it also creates a natural on-ramp for most educators’ existing practice, to begin to work with an expanded competency model.

An additional comment made by one participant is particularly reflective of how the ontological problem referenced in the last bullet point, intersects with rubrics in practice:

“*We assess problem-solving. We use a rubric. It generally meets my needs, but it is too focused on the creativity aspect of problem-solving (in many construct models, creativity is a core sub-skill of a competency in creativity).*

• A common data model may be useful at even a most basic level, but tools like EDmaps will require additional professional development and support for most educators to effectively use it. The way in which the LearningGraph models the data into a tool, reflects more of a competency view of learning, and is modeled very differently than standards.

This was one of the most interesting observations of the study: seeing the evolution in thinking about a domain or competency. Several participants initially expressed confusion about the model, and comments that reflected their day-to-day practice needs of planning lessons and assessing student work. Yet over the course of the study, they expressed deeper awareness on a larger scope of learner growth and a more conceptual arc of development in a domain—and why that might be valuable for their teaching and their learners.

“*I wasn’t sure how to use it to plan a specific lesson, but if I bring it up a level, it makes sense of the kind of competencies we’re looking for, and what does that really look like in practice.*”

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Throughout this study, what was most encouraging was to see the evolution in mindset of the educators from standards-based schools. In many ways, the shape and structure of standards has organized learning into unnatural, discrete ‘chunks, and subsequently have taken away a teacher’s role in having deeper engagement in the learner’s overall cognitive and competency development. Yet throughout the course of working with the
EDmaps prototype, several participants expressed ideas that indicated even deeper movement towards a more integrated approach to learner development, and collaborative participation in this space:

“This got me thinking, how can we integrate these three competencies [computational thinking, problem-solving & systems thinking] into our curriculum—I think they are related, and how can we support kids to build them in an integrated way at a given grade level?”

“We already have lesson plans, we’re now going to make sure the kids can demonstrate the competencies we want them to be able to demonstrate in middle school after their study of python and data. After that, maybe we can contribute back to the model, what does the evidence look like for a 7th grader given the sets of tasks that is specifically trying to build a competency in data modeling, problem-solving, systems thinking, what would that look like.”

“I appreciate the bigger picture part, especially on CT because we throw the term around but you’ve narrowed the focus on what that actually means. And I think there’s a huge need for that.”

“Your work showed a real blind spot for me, because I have lots of great lessons and hope the key ideas come out in the reflections, but this had me thinking about the conceptual stuff.”

These comments reflect many of the goals described in the learning sciences literature, and by participants in the RQ1 study, for more integrated learning experiences to cultivate core competencies and teacher participation in the feedback and design of learning progression models.

**Future Development of EDmaps**

This prototype testing suggests several design and feature considerations for further development with the EDmaps tool:

- **Bridging structures with current practice**, which includes:
  - **Tight alignment with standards.** Many educators are tightly bound to the standards they must cover. As such, they must feel that the model of standards they use is accurately mapped to the competency model(s) offered in the platform.
  - **Rubric-like features that support formative assessment.** Teachers need ways to appropriately formatively assess students, and they rely on familiar tools such as rubrics. The competency model with examples of tasks and artifacts may at first look more like a rubric so that it is a more accessible way to engage with the competency model.
• Bi-directionality, for content consumption as well as personal customization and feedback. Providing richer models and resources for educators is a helpful step forward, but the tool also needs to support their more active engagement with the materials. Dashboard-like features can support educators to add their own content, such as helpful tasks and examples of student evidence, around which they can discuss and collaborate with colleagues. This must also include ways that they more 'globally' are able to contribute back their observation of the learning progression or competency model as they experience it with their learners, helping to contribute to the collective refinement of the construct models.
Chapter VIII

ENGINEERING FOR LEARNING AT SCALE

“\textit{I never teach my pupils, I only attempt to provide the conditions in which they can learn.}”

\hspace{1cm} \textit{\footnotesize{\textsc{Albert Einstein}}}

The final research question in this study looks at the methodology itself, used to guide this work, exploring if and how Systems Engineering be useful in education and the design of learning at scale.

Systems Engineering has been used successfully in such a broad range of fields, to ultimately create solutions that were able to solve tremendous challenges or imagined potentials. Yet systems work to date as been slow to be embraced by the field of education—a realization that so often surfaces in this field, education is a field unlike any other. Perhaps it is due to its distributed complexity, or perhaps it is this very complexity that kept shrouded the insights and critical need for engineering such systems-level solutions.

In this chapter we take stock of how the SE methodology has facilitated this inquiry, discussing the strengths and limitations, reflecting on the third research question in this thesis:

\textbf{RQ3: } \textit{How can a systems engineering methodology help guide the reengineering of systemic challenges in education?}
REVIEW OF THE METHODS

SE is an extensive, multilayered design framework to support effective development and implementation of complex innovations. To review the SE methods as applied to this study thus far, we have focused primarily on the System Design Processes of NASA’s Systems Engineering Engine framework. Yet also with the focus on the development of a first application for a user community - EDmaps for educators - we have also included some of the Product Realization Processes as well.

![Diagram of NASA's Systems Engineering Engine](image)

**Figure 8-1.** NASA’s Systems Engineering Engine as applied to the LearningGraph research project.

OBSERVATIONS & REFLECTIONS

Through conducting this work on the LearningGraph project, a number of themes and observations emerged:

*Taking a true systems view at the start of project – defining the problem space in a larger, systems-level view – helped to elucidate systems-level challenges and dynamics that are not otherwise (commonly) identified.* This is in part due to the fact that the scope of many studies and
projects is intentionally contained to one community—for good reason, to keep it manageable and as an effort to increase the likelihood of successful implementation and adoption. However by doing so we are often not identifying and unpacking the impact of the problems across these spaces and communities. The insights elucidated from a SE view would likely be even further enhanced had we conducted a more complete system dynamics modeling analysis on the problem space, such as dynamic systems modeling approaches outlined in Chapter 2. In short, holistic analysis produces different elements of the problem, different opportunities, and different designs.

The discussion of this problem space in the first few chapters of this thesis raised systems-level problems related to this problem space that are often discussed in the literature, while others that are not. Perhaps even more critically, of all these elements, they are rarely if ever discussed together in one space. In this study, an example of such instances were the number of users and user groups that felt frustrated by the extensive work needed to build domain/competency models in learning technologies, assessments, and innovative learning environments, but little discussion to the call for a common resources supporting them, or the fact that the models and the data they produced can not be shared across them (i.e. learning data from a cognitive tutor cannot easily be integrated to a game-based environment, or a school’s competency framework, etc.). This is most likely due to the distributed and complex nature of systems of education, and the wide range of stakeholders that influence the system in some capacity—and for scope containment and traction, we typically focus just on one – maybe two – stakeholder groups at one time in engineering new solutions.

Yet the evidence of more than 60 years of education reform might suggest that this simply is not good enough if we want to see the kind of dramatic transformation of learning environments called up by many today. We can see from the exploration of the problem space of this thesis, there are considerable hidden dynamics between groups in the system, and redundancy in their work—perhaps because we haven’t engineering solutions for the system more coherently.

A final example that exemplifies these ‘hidden’ problem spaces was shared by a participant from the instructional designer participant group, who recounted the story of their recent experience in building a learning game for Introductory Astronomy to be used across their entire state higher education system. In their efforts to design the core learning goals of the game, they collected many different syllabi for “Astronomy 101” across the state university classes to inform the design of the domain model to be used for the game. What they found was tremendous variance in the experience students receive in terms of learning goals and topics covered in the courses. Going further, they also then interviewed the professors teaching these classes, about the key takeaways they want learners to get from the class, and not only do these vary significantly, but when they also then looked at the assessments used by these professors they found that most do not assess the very things they articulated as being meaningful. Meaning, the things the professors
said they valued as key takeaways were not evident in the assessments and projects used in their classes. In short, not only was the competency model across these courses not aligned, it was essentially non-existent. The participant telling this story explained that for them, this is one of the biggest problems they encountered—that professors and educators aren't actually measuring what they say they value. If that is true, then what is the point of using assessments? Such a story goes beyond identifying gaps and needs in the current system of stakeholders, and points to real indicators of how the structures we perhaps haphazardly create make for very poor learning experiences for kids and adults in society.

The needs analysis is a simple yet powerful way that helped bring to insights that might otherwise not come to the surface. When was the last time we sat down and really asked learning scientists what they needed to do their job more effectively? Or instructional designers? Some of the points raised in those discussions are fairly familiar, but surprisingly a fair number were not. Especially those things that seem to be “problems in-between”—meaning they are at a systems level or occur between communities of practice and therefore don’t get much discussion within a given stakeholder group. For example, the “Astronomy 101” example that discussed the variance and shortcomings in instruction and assessment practice across an entire state education system; or the design considerations suggested by learning scientists on how to most effectively model learning progressions if you were able to design a new system of standards from the ground up. There is a lot of tacit knowledge and powerful anecdotes from these professional communities that otherwise might not make its way into a journal article or conference proceedings, but they’re happy to tell you—if you just ask. This raises the notion that someone—a research group, foundation, if not a Ministry of Education—play a role in helping to capture these systems-level challenges and insights. The needs analysis is a central tool of the SE methodology that can be a useful research approach in its own right, in understanding more deeply the actors, structures, and practices in a system.

However, for many people articulating their needs is difficult; observing and participating in their work helps. Although the needs analysis produced a wide range of incredibly helpful insights and considerations for a future engineering design, it perhaps is not actually a very effective way of capturing completely the defined needs of each stakeholder community. Reflecting on needs is often not easy, and for many, identifying these needs is not something they can easily articulate. This may in part be due to the fact that some needs aren’t so immediately obvious when you are just being asked to reflect on your practice, and that some needs are actually challenges you don’t feel like you have any control over, or the potential for an imagined different future.

Some learning scientists especially, often could not say what they needed; my sense is this was possibly due to the fact that they are conducting primary research on learning, and therefore their work doesn’t present the same needs as those doing applied research or working in industry or practice. Yet many can, and often happily will, go into long discussions about this problem-space, articulating the challenges within it, and
how they are possibly approaching those challenges with interventions—also very helpful when considering systems needs and design considerations.

I believe in addition to interviews, an effective needs analysis also must include a period of time where the systems engineers are working side-by-side with the stakeholders, in their work, to more deeply identify the needs, gaps, and challenges—with the large systems engineering project in mind. This might mean spending a few months shadowing in a learning technology lab, or on a learning sciences research project.

**Similarly, experts have insights that aren't necessarily reflected in their work or design choices.** The tools or interventions a design or researcher is working, are also inherent of design choices they had to make to be able to work effectively within a given community or context. In other words, like any good designer, they make design choices and concessions as needed to most effectively do their work and to build innovations for impact in the area they are focused on. But given the blank slate to engineer a new system that is beyond the scope of their body of work, the design choice may likely look different. For example, one learning scientist is building tools to help bring learning progressions to classroom practice. What she is designing now takes a certain form in order to be adopted today with the population she is working with. Yet, if we asked her to help create a standardized model of learning progressions to replace curriculum standards going forward, it would look a fair bit different. In other words, tools and artifacts built by experts bring value but must be considered on context, and to engineer effective systems solutions we need to build on the existing work of experts but also look through it as well, to the deeper goals and values about what might be best to design for a new structure going forward.

**The tools built on top of a new foundational data model to support each of the stakeholder groups may need to be piloted and explored at the same time as the data model is itself is defined.** RQ2 of this study was using a prototype of a tool that might ultimately be built on top of a new learning data architecture for one of the core stakeholder communities; in this case, for educators. This brought a number of benefits, including further eliciting practitioner needs and challenges, as well as their mindsets and approaches to how to work with learning data, insights on if/how such a tool might be used, and finally how the tool would need to be adjusted in order to be adopted effectively. In many ways, it's like an ‘appendage’ on the ‘core’, that helps us extend the core data model to see how it might most effectively make it’s way into practice, while leveraging the appendage as a means to feed back into the core for refinement. Such an approach might not only be helpful to use with all stakeholder communities, it may be essential to assure adoption of a systemic intervention.

A critical consideration is the fact that there may be real value in doing a SE process to make a better learning data architecture, but if no one uses it, it becomes virtually pointless. In the current ecosystem, what is set by policy/governance sets the pace in some capacity for what all stakeholders in the system engage with in some form (i.e. state and national standards have a tremendous – though not complete –
influence on the entire ecosystem). So, if we were charged with creating a better learning data infrastructure and tools to replace standards, then worrying about the end user experience may not be so critical early on in the SE process. Yet as was discussed in Chapter 6, Brazil is a country that just went through an entire redesign of their national curriculum and structured it based on what other countries have done for decades. So unless there is a very progressive country that comes around to the idea of needing to rethink this entire infrastructure, this might not happen any time soon. Instead, we most likely need to consider building an infrastructure that goes above and around standards, meeting the needs of the stakeholders, without explicitly trying to replace the old system (yet, anyway). This is a somewhat common approach, where for example, CBE schools use standards to define their new ‘competencies’, and learning scientists modeling learning progressions will tag them to certain standards but encourage educators to work off the learning progression itself instead.

With such an approach, a strong argument can be made for needing to explore early on in the SE process the types of tools a stakeholder community might actually adopt. There is good reason that many groups in industry today embrace a Lean Startup methodology, where the business model is essentially not set until the market need/demand has been captured and modeled into an intervention that looks like the evidence clearly states it has the potential for adoption. So rather than “inventing something”, creating a business plan, then trying like crazy to market and sell it, you invert that approach—to first very deeply and clearly define the market need and gap, and iteratively prototype possible interventions to fill that gap. This Lean Startup methodology fits very well with the SE approach, though does perhaps complicate things a bit by expanding the scope of the work. But, when taking on an endeavor like building a new learning data architecture, there must be active steps taken to ground and situate the work in ways that will bring it to scaled adoption.

*Within each stakeholder group, there was common practice but many nuances and personalized methods; adoption demands will need to be a big consideration.* Within and even across most user groups there was much overlap in practice, largely centering on mapping a domain and building a learning model on it, in some format (a competency model, a rubric, etc.). Yet within each of these groups, there was notable nuance in the way the work was approached, the ways of working with these models, etc. For example, two teachers may both use rubrics, but the way in which they framed those rubrics and the elements of them that they focused on in their practice differed quite a bit. From a zoomed out view, it looks like generally the same kind of practice. From a zoomed in view, this will likely translate into fairly diverse tool functions and features that are built to support that user group on top of the learning data architecture. This emphasizes the tandem development of the unified learning data architecture at the same time as the careful development of tool extensions and interfaces built on top of that architecture for each group. As such, and as with any good technology development, design and refinement of these tools will likely take considerable work. However, building good tools does not necessarily ensure adoption—so
thinking about adoption opportunities and change management of these communities becomes a central element to this work: i.e., where are the adoption/leverage points in each community that can be utilized as the onramp to engaging with these tools and practices?

**DISCUSSION**

Within these findings, there are a few limitations to keep in mind. Although this thesis project received helpful support from advisors, undergraduate researchers, and colleagues, this is a large-scope project that was essentially led by one graduate student; moreover, a graduate student learning how to apply SE at the same time as well. Although I feel I was able to capture quite a considerable review of insights that we as a field should consider seriously, traditional application of SE would involve a team of professionals – which at the very least would be the starting point for such an endeavor was being pursued to completion – who would elucidate an even richer array of insights and design considerations.

An additional dimension that should be considered further is the depth and breadth of stakeholders in each group interviewed. In this study, it was a fortunate opportunity that many of the participants in the learning sciences and assessment communities that were interviewed are some of the most well-established experts in their respective fields, and some of the greatest innovators trying to build bridges amongst these spaces. This was similarly the case for those interviewed in the instructional designers group; many of these individuals work across genres or at the leading edge of learning technology design. As such, they perhaps brought more depth and diversity of insights from their work, but are not necessarily representative of the average stakeholder in each community. I saw this as both a significant strength, as well as a shortcoming. Working with such stakeholders presented a depth of understanding and complexity of the problem space into the conversation, as well as rich suggestions and insights on the opportunity for innovation. However, if we are designing structures to serve the widest possible range of stakeholders, then we also must interview and interact with a representative range of stakeholders.

On a personal reflection, having professionally played the role of many of the stakeholders in this problem space – I was a classroom teacher, then researcher, then designer of learning technologies (that later evolved into complex assessment-based game environments), and co-founded a non-profit that works with the OECD and over 12 countries helping to guide education policy as it relates to curriculum standards – I got to see this problem-space firsthand, from the inside-out. This helped tremendously. And, while also leading a number of research projects that investigated why innovation doesn’t scale in education, I have no doubt this is ultimately what brought me to this view of systems-level engineering to address critical challenges in education. Although I do not believe having played such a wide range of roles is essential for anyone interested in doing this work, it most certainly enabled a level of knowledge of multiple areas of the problem space, and empathy for the user/stakeholder/community and their needs that we may be engineering for. However, I do believe it is
essential that the people taking on such work have the capacity to occupy more than one identity in the ecosystem, to understand how to identify overlaps in the user needs/practices, and to be able to see the ‘gaps’ between them that present themselves as design opportunities. In fact, one of the learning scientists interviewed for RQ2 explained that in his work that explores how to design progression-based holistic experiences in science, many of his team members have also played various roles in education previously, but that one them — although he is a brilliant educator with deep domain expertise — simply could not see how to design tools beyond the frames of what is (i.e. traditional lesson plans). Flexibility, creativity, and ‘first principles’ thinking of those doing SE work is essential.

If this project were to transition from being a thesis into a larger endeavor, it would be necessary to conduct a deeper needs analysis on a larger number of stakeholders in each group, to more deeply capture the spread of needs and practice in those communities. I would also include guiding stakeholders through an Idealized Design process, and have Systems Engineers running the overall coordination around that.

Overall, the SE process provided a very helpful structure to what would otherwise feel like an incredible mass of complexity to navigate, and ultimately produced insights and potential innovations that might otherwise not have come forth. Given the depth and level of impact of this problem space, and the insights produced from exploring a SE structure, I believe that utilizing SE in the design of education systems for the engineering of larger learning ecosystems is not something we can ignore. Moreover, stories like the “Astronomy 101” example present real problematic dynamics in the current system—no matter what ultimate direction we might pursue with an SE project in education, such dynamics should not be ignored.

The case could be made that for the problem-space that is the focus of this thesis, there is no more fundamental lever or foundation of the ecosystem we call education. In many ways it is governmental policy that ‘sets the pace’ by establishing the policy-directed state and national standards that drive the system. Yet, in the US especially (though arguably to a certain extent in most other countries), they do little to create the rest of the infrastructure necessary to ensure that system is setup to produce the outcomes desired.

Understanding that the key stakeholders must conform to these policies, the larger ecosystem bends in their direction, accommodating needs but sacrificing design—and ultimately incapable of engineering the essential infrastructure needed for the outcomes we seek. The layered complexities of the system present a challenging landscape to create effective, systemic solutions. Systems Engineering presents a structure that may help us navigate more effectively through this complexity, and in other problem-spaces of this field as well—such as creating a “personal learning record” infrastructure (akin to patient medical records).

Ultimately, SE is not just a process to produce a product, but a process to more deeply understand, model, and account for such complexities—so that we more coherently and effectively build sociotechnical systems that
meet the outcomes we desire. As described by Moser and Wood, “Systems engineering is not to be focused only on the product to be developed, instead the whole product creation landscape and processes” (2015, p. 235).

The biggest question that then looms, what player in the ecosystem is focused on that landscape? Who would, or is in the position to, adopt such an approach? Education needs SE precisely because of its distributed complexity as a socio-technical-political system; and yet, it is this very layered complexity that potentially keeps us from being able to utilize it. If we see value in SE, then we must first understand how to bridge this gap.
Chapter IX

CONCLUSION & FUTURE DIRECTIONS

"Theories are more common than achievements in the history of education."

~ Richard Livingstone

Research often raises more questions than answers. What are the possible pathways forward to bridge these gaps? What are the barriers to adoption and success? And what are the implications if we collectively don’t pursue this work? This chapter will discuss the larger questions raised and broader considerations for future work.

SUMMARIZING THE PROBLEM SPACE

This thesis explored the problem space of learning construct models, data, and frameworks used across the ecosystem of education. This analysis followed the initial phases of a systems engineering (SE) methodology that included:

(i) Pre-Phase A – Concept Studies
    a. review of systems-level indicators of challenges;
    b. review of practices/tools used across the field;
    c. definition of initial project requirements for the LearningGraph;

(ii) Phase A – Concept and Technology Development
    a. holistic needs analysis across key stakeholder groups within the problem space;
    b. development of project concepts and preliminary prototypes for the LearningGraph;
(iii) **Phase B – Preliminary Design and Technology Testing**

a. development, testing, and refining of prototypes;

b. review of findings and definition of next steps.

Across these phases, the key findings and outcomes can be summarized as follows:

**Current state of the problem space:**

- There are a number of key stakeholders in education ecosystems that work with learning construct data; there is some influence by some of the format of this data on others, yet largely there is little crossover between them in terms of knowledge-sharing or practice.

- Curriculum standards demonstrate a dominance of influence on the system, yet present a number of shortcomings in their ability to meet user needs across the system and to support the types of learning dynamics identified in the learning sciences research, as well as emerging complex learning technologies.

- Some structures such as learning progressions (LPs) and evidence-centered design (ECD) have generated considerable interest because of their potential to meet a broad range of needs in modeling learning, and have been used across more than one user group—further demonstrating their potential utility in organizing a unified learning construct data model.

**Needs analysis:**

- The needs analysis demonstrated that the current design and structure of standards presents clear challenges for the primary user group they were intended for (educators) as well as infrastructure challenges across the education ecosystem; specifically, the present format of standards is too far removed from the actual work of educators.

- The tools and frameworks for modeling learning constructs used by other stakeholder groups presented a range of utility and advantages, however limitations in infrastructure and feedback across them was the most-cited shortcoming. This is part due to the fact that each stakeholder group used its own tools/frameworks, which were similar and overlapping but distinct from the others. This presents both a barrier to overcome, but the potential opportunity for synthesis and cohesion.

- 'Workbench'-like features of a common platform, where users can find others’ models, give feedback on them, remix and reuse them, was a request cited across all stakeholder groups interviewed.
Whereas the current infrastructure largely built on standards is top-down, this indicates the need for a two-way, cross-stakeholder approach to build, share, and refine information and ultimately meet user needs.

**LearningGraph prototyping and testing:**

- A reengineered learning data architecture to coherently support educational ecosystems will need to meet a number of systems levels objectives, including: organizing a unified data model that is able to serve as a foundation to the needs of each stakeholder group, a flexible architecture that for specific and appropriate data objects to be pulled for each user group; and 'workbench' features that allow users to feedback, refine, and collaborate on data models.

- The *LearningGraph* puts forth a more unified construct data model and architecture that is able to conceptually meet these requirements, and has demonstrated initial end-user support of one stakeholder group (educators) through the *EDmaps* pilot—however further testing will be needed across all stakeholder groups.

- The *EDmaps* prototype has suggested positive impact on educators' understanding and practice. Although modifications that more directly align the UI to reflect practices in standards-based schools must be considered such as the integration for rubric-like features, initial testing demonstrated support in improved teacher practice with formative assessment and general growth in the ability to support competency-based learning through conceptual maps.

**Next steps and future work:**

- These findings suggest the consideration of further development of the *LearningGraph* initiative, expanding and iterating the work completed thus far across all stakeholder groups, as well as continuation of the SE process to further completion.

- The movement towards competency-based learning and the continued development of complex learning technologies creates an opportunity to pursue this systemic work with an increased likelihood of adoption and impact.

- If, in time, a common or unified construct model architecture is adopted, it presents a potential for a true 'graph' of learning objects and competencies to emerge.
Stepping back from the focused research questions and looking broadly across the analysis conducted in this problem space, several core findings emerged:

- **Poor knowledge management.** The frustrations and needs across the stakeholder communities points to ultimately what can be defined as a “knowledge management” problem. In regards to learning models, each stakeholder group complained of not having enough structured information, having to manually and laboriously build their own models, not being able to easily find and share models, and not easily being able to collect feedback on the models they’ve build. As one participant put it, in short, “We have poor knowledge management across the field.” That includes both the ‘verticals’ of the stakeholder communities, and the ‘horizontals’ across and between those communities.

- **Overlapping needs and practices.** There is distinct overlap in the frameworks and types of learning model data that each user group needs. When looking reviewing these needs in regards to learning models, although different terms and frames are used, there is considerable overlap conceptually in what they are referring to—mostly some type of domain analysis/model, and a competency model or progression. This points to redundancy issues, but also presents an opportunity for deeper integration and alignment of these stakeholder groups, and the models/tools they use. Moreover, the watershed moment we are experiences in the movement to competency-based learning creates fertile ground for advancing these practices holistically.

- **A strong foundation to build on.** There has been a range of prior projects trying to tackle a sub-set of these challenges. A number of people interviewed described previous research projects, or proposed the value they saw in pursuing possible projects, that tackled core aspects of this problem space. This has included a “portal of ECD models” that, due to developer challenges, never became public, as well as prototypes of educator tools to use learning progressions in the classroom, and large-scale learning analytics tools to generate progression models from the ground up. This work should be considered in future development of systems-level tools in this space.

For a new architecture, ECD broadly presents a strong foundation to build on because the assessment community is often a more sophisticated developer of such models, often with the funding to do so, and these models have subsequently be able to support some of the field’s most innovative technologies to date. Yet also, the nature of the ECD framework covers the key aspects needed by all users—namely domain models with integrated competency models with specifications on tasks and evidence.

In short, all stakeholders in the field have a usability problem in one form or another as it relates to learning construct models. The data structures and infrastructure they use to do what they need to around learning data falls short, in every group. This points to a deep need for an alternative structure that works better than
standards. Very little research has been conducted on the implementation effects of the way standards have been designed—meaning, if you look at the structure of national curriculum from a design and engineering perspective, do the users effectively engage with the tool to produce the outcomes you desire? Or, what impact does the shape and structure of the tool have on the end-state practice? The impact of how these documents ultimately define the day-to-day and the overall long-term influence on a learner's education cannot be understated.

Movement within each stakeholder community in the form of a range of frameworks and tools has helped point the way towards what a direction forward might be. This challenges us to then consider, how can we find convergence amongst them? In many ways we are already seeing the lines between these communities blur. Assessment developers are now working closely with game designers and learning scientists, and we see the movement of some learning game designers becoming assessment developers, and so on. As experts move across these boundaries, they continue to develop what they need to do their work, but this moves farther away from the traditional, common structures and frameworks. Although such practice may move us farther away from core knowledge structures and knowledge bases, such convergence of identities and roles is also pointing us to the possibility of converged data models. The LearningGraph architecture presents an opportunity to create this infrastructure through an integrated but flexible data model that more coherently represents learning data models—to bring together these communities and practices, building the foundation for better learning environments and experiences, and ultimately our collective modeling and understanding of learning and development.

The ultimate potential for impact on an initiative like the LearningGraph is to ultimately help us generate a true graph, in the vein of graph theory and network analysis, that enables us to understand the shape of skills and competencies and answer key questions like,

what are the sub-skills and related competencies to a core competency such as critical thinking?

and, what are possible pathways towards cultivating that competency?

and, what are common pathways across learning environments and technologies that we see learners developing these competencies?

and, where can I find good tools that support me in my work of supporting my students to develop this competency?

Such insights are powerful, and possible, when we have the right data modeling and analysis in place. Yet getting to such a future requires that we take key steps first to build the foundation for that work, and as such, the potential impact of the LearningGraph lies on several levels, or stages towards that future. A basic architecture with the ‘universal index’ layer as described in Chapter 4, would go a long way in helping to bring integration
across the many global frameworks of standards, and help us in beginning the development of a graph in traditional domains such as literacy and mathematics. Organizing construct models and/or competency models on a platform with collaboration features would help provide the collective ‘workbench’ across stakeholder groups to be able curate, build, and refine our models. Each of these would be steps forward in their own right, while also creating the foundation for ultimately generating a true learning graph.

**Potential Directions Forward**

This thesis intentionally defined a quite broad problem space. If we were to look at specific slices of the problem space, the insights that emerged indicate a number of possible projects or technologies that could viably be pursued—some of which were directly expressed by the participants themselves:

**Educators:**

- An interactive dashboard that visualizes standards in the large conceptual picture of learning goals and competencies, to help educators see connections, find resources, etc.;
- A platform of formative assessments that help teachers get a quick sense of a learner’s ability;
- An open, common platform of competency models that is participatory;

**Learning Scientists:**

- A knowledge base of learning progressions, interactive and collaborative with educators, to make them classroom usable and so that educators can give their feedback on them to further refine them;

**Instructional Designers, Technologists, and Assessment Developers:**

- A knowledge base of domain/competency models, documented in a way that allows them to easily access, reuse, and refine them over time;
- A platform where learning technologies can be added, catalogued, critiqued by learning scientists, and refined;

From the research, a strong case could be made for why each of these projects presents the potential for impact in each user group. Yet broadly defined, these requests are indicating a need for some form of open, common platform where various forms of learning models can be accessed and shared. Efforts such as these framed in a
more targeted way may help bridge some of these gaps, yet it will not help solve the redundancy and knowledge management problem across the field, and between these communities.

The potential implications for needing a systems approach may go beyond just these themes from this research. Movements in industry particularly, suggest broader considerations around this problem space. One aspect of this is perhaps best indicated through a story from one of the participants in RQ1, who will be referred to as “Kris”.

Kris is a former researcher in learning analytics, whose work was at the leading edge of game-based assessment and learning data modeling. Today, Kris is the Chief Learning Scientist at a learning technology company that has the most successful early childhood learning apps on the market. She works with a large team of nearly 20 people, who build the curricula and learning models in their apps; they do extensive work to build these maps internally in the company. Kris recounted that when they began developing their now highly successful app to build Number Sense in young learners (a domain the research has shown to be highly significant in determining a learner’s later mathematics ability), they were astounded to find there were no progression maps in this space—they had to build it for themselves. Liz explained that the company cares very deeply about getting this right, and this learning model/curriculum team works closely with the analytics group and the game designers to build effective and formative game-based experiences that are effectively feeding back into their learning model. As a company, this is a huge part of their work, and what they cite as their most valuable IP—and as such, they are highly protective of it. As Kris explained, “We often talk about how to get this work ‘out there’ and help more people understand how to build competency in key areas like this, but there is no business strategy that makes sense for us to do that.”

Kris’s story is insightful for a number of reasons. Her background is one of changing identities (she started her career as a teacher, then became a research, game-based assessment developer, whose research then went into learning analytics), and her work today is exemplary of the type of tightly woven design needed to move the design of learning technologies and experiences into more effective directions. Yet it also reflects a trend we see across the field: industry and ed-tech companies have no choice to fill this gap in a learning model architecture in order to make their technologies work, and what they generate ends up becoming their most prized IP. This is true in places where you’d expect it, such as AI-enabled and adaptive learning companies such as ALEKS and Knewton, but also in broader range ed tech companies such as AltSchool, whose goal is to build “an operating system for 21st century school”. In a personal conversation I had with AltSchool’s CEO in 2017, in all

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31 https://www.aleks.com
32 https://www.knewton.com
33 https://www.altschool.com
the technical developments that undertook to meet this objective (along with a $200 million budget), they came to see what a problem the learning data architecture was and as they worked to rebuild that, ultimately is also what they believe is their greatest IP. It’s a story I have personally heard over and over again.

There is advantage to industry making headway in this problem-space, but it will not help the knowledge management problem across the system, and only exacerbate the equity problem in education. These proprietary technologies benefit only those able to afford access to them, and they do not help build our greater collective knowledge on learning models. Yet most critically, it raises the ‘openness’ problem, which is also facing AI (artificial intelligence)—the concern that the worlds biggest companies will own the proprietary models of technologies that deeply influence our lives, without our ability to easily access or influence those models. In much the same way that initiatives like OpenAI34 seeks to help make advances in artificial general intelligence (AGI) while making that knowledge and resulting tools as open as possible, so too must be consider the collective advancement through research and development of learning construct models while making the open, shared, and accessible.

AN ARGUMENT FOR EDUCATIONAL ENGINEERING

Engineering in any domain – mechanical, electrical, chemical, etc. – is about the development and modification of structures, complex systems, and processes that utilizes specialized knowledge and skills (OED, 2018). We see the impact of the disciplined approach of engineering in these areas in many of the complex innovations that are central to our modern societies—including 50 story skyscrapers, bullet trains, and space shuttles. More explicitly, it has enabled us to tackle some of societies biggest needs and challenges. Need to get to Beijing by tomorrow? Better stated, need to get 2.6 million passengers somewhere else in the world via a flight each day35? The complex systems engineering of the modern day airline industry enables that. It is an example of where industry and government were able to come together to enable a new world of possibility that was not possible before. In much the same way, Civil Engineering has helped to create the public roadway infrastructure that each of us benefits from daily. Yet in education, this has not been the case. Policy approaches dominate the U.S. Department of Education, leaving the rest of the work to the states and industry. A good example of this national policies like No Child Left Behind creating the educational climate, states adopting some version of the Common Core State Standards, with non-profits creating the new tests and Yet the problem space of this thesis and the long history of education reform – suggests policy and industry efforts are not enough. Educational systems, and future learning ecosystems, are some of societies’ most complex endeavors. If we want them to look

34 OpenAI (http://openai.com) is a non-profit research company whose mission is to build safe AGI, and ensure AGI’s benefits are as widely and evenly distributed as possible.

35 The number of average passengers in the U.S. per day according to the Federal Aviation Administration; https://www.faa.gov/air_traffic/
differently, history suggests we need to try something very different; other domains suggest we must embrace systems engineering as a core aspect of how to get there. What if we considered education systems as part of civil engineering, engineering the infrastructure for learning environments and systems in the same way we do roads and railways?

The deep challenges education has faced in trying to adapt to modern societal complexities and needs, while coming up against technological advancements, requires that we understand these complexities while also employing equivalent approaches. In many ways, education is one of society’s most prominent examples of where social dynamics, economics, and technological evolution of human-made systems intersect. de Weck and colleagues argue that engineered systems are human-generated, complex structures that interact with innovations (technology) and policy to ultimately help us create better societies and opportunities for humanity, where these blurred boundaries are not feared but embraced, to ultimately determine what works best, what needs to be done, and how to make it all happen (2011, p. 1). As technologies evolve, societies grow, and so do the interactions and policies around them, they generate a dynamic complexity that is unavoidable—and why it is so important to approach these systems holistically. They suggest that successfully working with these systems includes a “(re)visioning perspective” that is not fixed but fluctuating from the “30,000-foot” to “ground level” and therefore constantly changing the viewing angle, defining a more broad scale and scope than is often traditionally identified, defining the system’s function and its decomposed parts as well as their dynamics over space and time, and finally, designing an architecture that is uncoupled in some ways to allow for flexibility.

**FUTURE WORK**

The LearningGraph, as an open-source systems engineering project in this problem-space, presents one possible pathway forward. Critical to any pathway chosen will be ensuring that user needs, interfaces, and pathways to adoption are central to the work. We face the simultaneous challenge of engineering a better core infrastructure, while understanding how to meet the needs of key users while also understanding pathways of adoption, in order to make any endeavor of this magnitude viable—and in short, is what makes this a reengineering problem.

With the convergence, and the emergence, of a variety of complex learning technologies, it is an important time to consider such an endeavor. Yet perhaps even more critically, it is tidal shift we see happening in traditional K-12 educational systems that is the most pertinent opportunity that we should not waste, to pursue such a large-scale endeavor where adoption is critical. As more and more schools and school systems are asking ‘What are competencies?’, ‘How do you model them?’, and ‘How do we shift our practice in that direction?’, we are presented with movement in what is the most locked-down aspect of the educational ecosystem—policy and teacher practice. Some have argued that learning progressions have the potential to transform educational practice by grounding learning experiences in a better understanding of the natural development of learning (Zalles,
Engineering the architecture that brings that work to life, in alignment with the competency-based learning shift, presents us the chance to realize the potential of these learning models—if we create the tools and infrastructure that enable us to use them effectively.

Such an ambitious endeavor will not be short on challenges. Important considerations will be (i) identifying how the prototype data model integrates with and supports existing leading-edge AIED learning technologies with large user bases, such as ALEKS (Falmagne et al., 2013) and ASSISTments (Heffernan et al., 2006); (ii) understanding the subsets of research initiatives, previous and currently active, and build on their work, including prior research projects looking at the potential impact of designing structures at the intersection of ECD design patterns, learning progressions, and learning data collection (Zalles, Haertel & Mislevy, 2010), as well as the leading edge work on learning progression support (Hess, 2018), and competency modeling analytics (Dawson & Stein, 2008; Stein, Dawson, & Fischer, 2010). The insights from this work should be considered and built into an engineered model, as appropriate.

In the interviews conducted for this thesis, a SE approach was well-received by many of the researchers and experts. As one expert put it,

"I think there's a useful relationship between the people who are engineers and those who are more qualitative. There needs to be an exploration of the relationship between the schematic approach to understanding complex issues in individual and group learning, and the ability to engineer a whole system that is actually useful for those dynamics. The way in which an engineered system can support that—that's a really useful question."

**BEYOND EDUCATION**

Whether you believe in a future that includes something like traditional school systems or not, a foundational architecture around learning data models will be critical to any potential learning environment ecosystem—though the shape and nature of that architecture may shift depending on your vision of the future.

What opportunities are we more broadly missing out by not harnessing our understanding of cognitive development over time? As artificial intelligence sets its sights on playing endless hours of video games—built on Bayesian network models—what would happen if we also generated those models from human experience?

Deb Roy’s research – where he embedded cameras all over his house over the course of years to capture and analyze speech and language development patterns in his young children – would suggest that we’re missing a lot:
"He had discovered that human learning was communal and interactive. For a robot, the acquisition of language was abstract and formulaic. For us, it was embodied, emotive, subjective, quivering with life. The future of intelligence wouldn't be found in our machines, but in the development of our own minds."36

He is right. And yet collectively we are missing the infrastructure to understand our own selves—both individually and collectively.

CONCLUSION

Standards are a very big lever for education. Learning models are central, if not the core, of learning ecosystems, and they are inherent with dynamic complexity. We have not been able to collectively grasp and leverage these models at scale, and may not be able to without a collective workbench to do so. Building personalized learning technologies will require us to use more dynamic, more complex, and more accurate models of learners—much more than what we are capable of representing in educational standards or assessment frameworks.

As the Dean of the MIT School of Engineering, Dr. Subra Suresh, explained, most of the great challenges engineers face in the twenty-first century involve fixing the successes of the greatest achievements of the twentieth century (2009). A reengineered learning data architecture serving underlying educational ecosystems creates a new, modern, and more robust foundation on which to build the learning experiences and environments that provide a modern education and more cohesive learning pathway.

At some point, that we may have already passed, we education cannot escape an infrastructure that has evolved to ultimately be incapable of supporting the modern system demands. In describing this phenomenon, and the growth of industries such as aviation, de Weck et al. (2011, p. 8-9) explain that,

"While component technologies continued to evolve rapidly—faster computers, better cars, safer aircraft, and so on—the underlying infrastructure networks that had formed, and especially the regulatory frameworks stagnated, failed to anticipate changes, or simply did not keep up with growth. This mismatch between technological progress and the backwardness of infrastructures and regulations persist to some degree today. Eventually, unintended consequences could no longer be ignored."

Truer words of education could not be written. Yet unlike the aviation industry, there has not been such an urgency to close these gaps.

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What might be an optimal design for a new, engineered system of learning, might be very far from the structures and tools we currently use. Policy has not been able to get us there, and industry alone can not work in such an integrated fashion to solve these infrastructure problems. Industries such as aviation suggest that it is an integrated approach of research, industry, and government-backed policy as well as engineered infrastructure that enables the health and success of the industry. In drawing a parallel between aviation and education, the element that is missing is the engineered infrastructure. In much the same way the car industry has brought modern-day innovations the likes of which Ford may never have imagined, it is the civil infrastructure of highways that let us use and enjoy those innovations to drive coast to coast and safely across mile-wide bridge into New York City. Highways and airports are the infrastructure that emerged as an engineered system to allow those industries – and our modern day lifestyles – to thrive. What collective infrastructure must be the engineered system(s) that allow learning environments to thrive?

The success of engineering systems in many other domains suggest it is something to consider in education as well. Engineering systems approaches create the opportunity for moving education beyond ‘reform’ and into building modern ecosystems of learning that effectively serve learners in a way that reflects good learning—through quality learning experiences and environments enabled at scale. As de Weck and colleagues highlight in this work, “the impact on human well-being must take center stage when developing new artifacts, improving technologies, and designing large-scale systems” (2011, p. 12). Ultimately, it is the impact on human well-being – and therefore also the collective society – that should concern us most.
REFERENCES

CHAPTER I


**CHAPTER II**


CHAPTER III


**Curriculum, Standards, and Competencies**


IMS. (2002). Reusable Definition of Competency or Educational Objective - Information Model. IMS Global Learning Consortium.


Lumley, T. (2002). Assessment criteria in a large-scale writing test: what do they really mean to the teachers?


OECD. (2005). Definition and selection of key competencies (DeSeCo): Executive Summary.


across scale levels. *Practical Assessment, Research & Evaluation, 9*(2), 1-10.


**Learning Sciences**


trajectory. Mathematical Thinking and Learning, 6(2), 163-184.


in the era of the computer. Simon and Schuster.


Werner, H. (1957). The concept of development from a comparative and organismic point of view.


Assessment


Wei, R.C., Schultz, S.E., & Pecheone, R. (2012). *Performance assessments for learning: The next generation of state assessments*. Stanford Center for Assessment, Learning, & Equity (SCALE)


**Learning Technologies**


**CHAPTER 4**


Ries, E. (2011). *The lean startup: How today’s entrepreneurs use continuous innovation to create radically successful*


**CHAPTER 5**


Utterback, J. (1994). Mastering the dynamics of innovation: How companies can seize opportunities in the face of technological change.

**CHAPTER 6**


**CHAPTER 7**

CHAPTER 8


CHAPTER 9


### APPENDIX A. KEY TERMS DEFINED

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Concept Inventory</strong></td>
<td>A multiple-choice research-level instrument designed to test students' conceptual understanding.</td>
</tr>
<tr>
<td><strong>Construct</strong></td>
<td>The knowledge, skills, and/or competencies observed in behavioral outcomes.</td>
</tr>
<tr>
<td><strong>Construct Model</strong></td>
<td>A model of cognition and learning in a domain, defined by one or more proficiencies represented by unbounded continuous latent variables, that includes a set of beliefs about the kinds of observations that will provide evidence of students' competencies and an interpretation process for making sense of the evidence.</td>
</tr>
<tr>
<td><strong>Domain-Specific Cognitive Model</strong></td>
<td>An approximation of cognitive processes for the purposes of comprehension and prediction that is specific to a given domain.</td>
</tr>
<tr>
<td><strong>Learning Progression</strong></td>
<td>Empirically-grounded and testable hypotheses about how students' understanding of, and ability to use, core scientific concepts and explanations and related scientific practices grow and become more sophisticated over time, with appropriate instruction. They typically describe the pathways students are likely to follow to the mastery of core concepts, and are based on research about how students' learning actually progresses—as opposed to selecting sequences of topics and learning experiences based only on logical analysis of current disciplinary knowledge and on personal experiences in teaching.</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Misconception</td>
<td>Conceptual models of the learner that have incongruencies as compared to those of an expert.</td>
</tr>
<tr>
<td>Reengineering</td>
<td>To engineer again or anew, to improve operations, factoring into the design the change management needs of users.</td>
</tr>
<tr>
<td>Systems Engineering</td>
<td>An interdisciplinary approach and means to enable the realization of successful systems.</td>
</tr>
</tbody>
</table>

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7 https://www.merriam-webster.com

8 https://www.incose.org
APPENDIX B. Seminal Learning Sciences Publications Informing Educational Engineering Principles

National Research Council; National Academies Press

DuMont, H., Istance, D., & Benavides, F. OECD publications: Paris, France
APPENDIX C. Examples Referenced in Chapter 3

1-A. Achievement Levels - Example

Example of Achievement Levels in Reading

![Diagram of achievement levels in reading]

Figure A3-IA. Five achievement levels in reading; Adapted from Masters, Adams, & Lokan, 1994.
## I-B. Competency Model - Example

<table>
<thead>
<tr>
<th>CONTENT AREA: Science</th>
<th>STANDARD/STRAND: Life Science</th>
<th>MEASUREMENT TOPIC: Environmental Science</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>STEP: 3</strong></td>
<td><strong>4.0</strong> ASSESSMENT ITEMS:</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>ANALYSIS</strong></td>
<td></td>
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<tr>
<td><strong>4.0</strong></td>
<td>Specifying</td>
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<td></td>
<td>In addition to the 3.0</td>
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<td></td>
<td>knowledge, infers or applies</td>
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<td></td>
<td>beyond what was taught.</td>
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<td></td>
<td>Taxonomy Level</td>
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<td></td>
<td><strong>3.0</strong> ASSESSMENT ITEMS:</td>
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<td></td>
<td><strong>COMPREHENSION</strong></td>
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<td>Integrating</td>
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<td></td>
<td>No major errors or gaps in the</td>
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<td></td>
<td>following TARGETED, COMPLEX</td>
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<td>ideas and processes.</td>
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<td></td>
<td>Understand ways in which</td>
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<td>organisms interact within</td>
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<td></td>
<td>an ecosystem (competition</td>
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<td></td>
<td>for resources, predator/</td>
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<td></td>
<td>prey, mutualism, parasitism,</td>
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<tr>
<td></td>
<td>commensalism etc.).</td>
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<tr>
<td></td>
<td>Taxonomy Level</td>
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<tr>
<td></td>
<td><strong>2.0</strong> ASSESSMENT ITEMS:</td>
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<td></td>
<td><strong>RETRIEVAL</strong></td>
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<td></td>
<td>Recalling</td>
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<td>No major errors or gaps in the</td>
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<td></td>
<td>following FOUNDATIONAL, SIMPLE</td>
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<td>details and processes.</td>
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<td></td>
<td>Knows Terms: predator, prey,</td>
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<tr>
<td></td>
<td>mutualism, parasitism,</td>
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<td></td>
<td>commensalism, symbiosis.</td>
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<td></td>
<td>Taxonomy Level</td>
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<td></td>
<td>As a result of understanding or</td>
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<tr>
<td></td>
<td>being skilled at the knowledge</td>
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<tr>
<td></td>
<td>identified in 3.0, the learner</td>
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<tr>
<td></td>
<td>is able to:</td>
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<td></td>
<td>• Create your own environment,</td>
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<td></td>
<td>animals and plants.</td>
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<td></td>
<td>• Describe how they interact.</td>
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<td></td>
<td>• Identify the type of</td>
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<tr>
<td></td>
<td>interaction.</td>
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<td></td>
<td>As a result of understanding or</td>
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<td>being skilled at the knowledge</td>
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<td>identified in 2.0, the learner</td>
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<td></td>
<td>is able to:</td>
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<td></td>
<td>• Define and give an example</td>
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<td>of the terms: predator, prey,</td>
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<td>mutualism, parasitism,</td>
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<td></td>
<td>commensalism, symbiosis.</td>
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</tbody>
</table>

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**Figure A3-IB.** Sample Competency Model – Life Sciences. from Kennebec Intra-District Schools (RSU2) (2013). Sample Science Measurement Topics; Adapted from Sturgis, 2014.
I-C. Rubrics - Examples

Sample Rubric for a Literature Task

"Write a well-developed literary analysis using a text of appropriate complexity and showing connections between the text and other substantial issues, such as a larger issue or theme, another work of literature, the historical or biographical context, a filmed version of the text, or noted works of relevant criticism."

<table>
<thead>
<tr>
<th>Performance Indicators</th>
<th>Outstanding</th>
<th>Good</th>
<th>Competent</th>
<th>Needs Revision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thesis and organization</td>
<td>• Efficiently organizes paper around a clear, compelling argument</td>
<td>• Has a clear argument</td>
<td>• Has a central idea</td>
<td>• Lacks a central idea</td>
</tr>
<tr>
<td></td>
<td>• Develops argument thoughtfully and persuasively</td>
<td>• Effectively organized and developed coherently around central argument</td>
<td>• Mostly organized around a central idea, but may lose focus at times</td>
<td>• Unfocused organization</td>
</tr>
<tr>
<td></td>
<td>• Uses relevant, convincing evidence and quotations that thoroughly support argument</td>
<td>• Uses relevant evidence and quotations that support central argument</td>
<td>• Uses relevant evidence and quotations to support central idea</td>
<td>• Little, irrelevant, or no evidence used</td>
</tr>
</tbody>
</table>

| Analysis | • Provides deep insight and creates meaningful interpretation of texts | • Creates meaningful interpretation of texts | • Provides basic interpretation of texts | • Summarizes or uses faulty analysis |
|          | • Elaborates on central argument and meaning of supporting evidence, answers question, “So what?” | • Explores central argument and meaning of supporting evidence, answers question, “So what?” | • Develops central idea and explains choice of evidence and quotations | • Little or no interpretation of texts |
|          | • Considers author’s language, craft, and/or choice of genre | • Analysis drives discussion of literary elements when relevant | • Film version of text, or | • Little or no use of evidence or quotations |
|          | • Analysis drives discussion of literary elements when relevant | | | |

| Style and voice | • Evidence of ambition, passion for subject, or deep curiosity | • Evidence of a mind at work | • Communicates ideas clearly | • Relies on conversational language |
|                | • Writer willing to take risks | • Evidence of interest in topic | • Shows some awareness of appropriate language and word choice | • Little or no evidence of formal or appropriate use of language and word choice |
|                | • Displays intellectual engagement | • Clear and appropriate use of language and word choice | | |
|                | • Creative, clear, and appropriate use of language and word choice | | | |

| Connections | Makes insightful connection between text and something outside the text | Makes appropriate connection between text and something outside the text | Establishes a connection between text and something outside the text | Inappropriate or no connection made between the text and something outside the text |
|             | • Another work of literature, or | • Another work of literature, or | • Another work of literature, or | |
|             | • Historical context, or | • Historical context, or | • Historical context, or | |
|             | • Biographical context, or | • Biographical context, or | • Biographical context, or | |
|             | • Larger issue or theme of importance (must be supported with relevant evidence), or | • Larger issue or theme of importance (must be supported with relevant evidence), or | • Larger issue or theme of importance (must be supported with relevant evidence), or | |
|             | • Film version of text, or | • Film version of text, or | • Film version of text, or | |
|             | • Substantial criticism | • Substantial criticism | • Substantial criticism | |

| Conventions (for writing assignment only) | Mechanical and grammatical errors are rare or non-existent, follows accepted conventions of quotations and citations, uses transitions effectively | Few mechanical or grammatical errors, follows accepted conventions of quotations and citations, makes some use of transitions | Some mechanical or grammatical errors, but communication is not impaired, demonstrates knowledge of accepted conventions of quotations | Communication is impaired by errors, little or no use of conventions or quotations and citations; shows little awareness of appropriate use of transitions |
|                                          | | | | |

| Presentation (for oral component only) | Communicates ideas clearly in appropriate, sophisticated, and original way to audience, able to respond to questions and expand on ideas, presents complex, accurate, substantive ideas and information clearly | Communicates clearly in appropriate and original way to audience, able to respond to questions and expand on ideas somewhat on own, presents some substantive ideas and information clearly | Communicates clearly in appropriate way to audience, able to respond accurately to questions, presents some substantive ideas and information accurately | Neither clear nor appropriate presentation to audience, cannot respond well to questions, does not present accurate or substantive ideas or information |

| Needs Revision | • Lacks a central idea | • Unfocused organization | • Little, irrelevant, or no evidence used | |
|               | | | | |

II-A. Knowledge Modeling - Example

Figure A3-IIA. A procedural network for subtraction; Adapted from Brown & Burton, 1979.
II-B. Applications of Developmental Frameworks – Examples

**Fischer’s Dynamic Skill Theory: Example of Literacy Development**

Literacy development begins with visual-graphic skills, such as letter identification, with sound-analysis skills, such as rhyme recognition. The constructive web that illustrates this standard theory, shown as Pathway A (Figure A3-IIB-1), starts with word definition because students must know the word before they can use it appropriately. Initially, the sight and sound domains are independent and not integrated, forming separate branches for the early tasks: letter identification and rhyme recognition. Later, the two branches come together as students integrate sight and sound skills to read words and become proficient readers.

**Pathway A: A Common Web for Reading Words**

In this illustration of the constructive web for the standard theory of reading alphabetic languages, the sight (letter identification) and sound (rhyme recognition) domains are at first independent but then come together as students integrate sight and sound skills to read words.

**Figure A3-IIB-1.** Common Web for the Development of Reading Words; Adapted from Fischer & Rose, 2001.
Two Alternative Webs for Reading Words

Pathway B: Independence of reading and rhyming

- Word Definition
- Letter Identification
- Reading Recognition
- Rhyme Recognition
- Reading Production
- Rhyme Production

Pathway C: Independence of reading, letter identification, and rhyming

- Word Definition
- Reading Recognition
- Rhyme Recognition
- Reading Production
- Rhyme Production

Figure A3-IIB-2. Alternate Webs for the Development of Reading Words; Adapted from Fischer & Rose, 2001.
**Lectical® Levels**

The Lectical Levels of Skill Development have been applied to a wide range of contexts, and used to identify the complexity level of coursework demands and role demands in organizations. Lectical Developmental ranges have been built for a broad array of competencies, including 'Leadership', 'Creativity', and 'Critical Thinking'.

<table>
<thead>
<tr>
<th>Lectical Range</th>
<th>Coursework demands</th>
<th>Role demands</th>
</tr>
</thead>
<tbody>
<tr>
<td>1220-1280</td>
<td>• identify and leverage patterns across multiple systems to simplify decision-making under complexity&lt;br&gt;• employ a wide range of strategies and tools that optimize solutions while mitigating human limitations</td>
<td>multinational CEO, President</td>
</tr>
<tr>
<td>1190-1250</td>
<td>• identify patterns across multiple systems&lt;br&gt;• embed iterative, distributed decision-making processes&lt;br&gt;• reduce impediments to good decision-making under complexity</td>
<td>corporate CEO</td>
</tr>
<tr>
<td>1160-1220</td>
<td>• take into account the numerous nested interconnections among variables that characterize highly complex situations&lt;br&gt;• expertly employ iterative, distributed decision-making processes&lt;br&gt;• deftly determine the level of collaboration or perspective seeking that’s optimal for a given context</td>
<td>Post-doc executive</td>
</tr>
<tr>
<td>1130-1190</td>
<td>• identify multiple relations between nested variables&lt;br&gt;• take into account change over time&lt;br&gt;• consider the level of collaboration and perspective seeking that is optimal for a given context&lt;br&gt;• maintain awareness of common impediments to good decision-making in organizations</td>
<td>Ph.D., M.D. senior</td>
</tr>
<tr>
<td>1100-1160</td>
<td>• work with both individual and group perspectives&lt;br&gt;• identify and attempt to balance competing factors, such as human needs versus organizational needs&lt;br&gt;• identify implicit and contextual causes&lt;br&gt;• identify common impediments to good decision-making in organizations&lt;br&gt;• shift frame of reference to explore alternate ways of seeing a problem</td>
<td>M.A. upper level</td>
</tr>
<tr>
<td>Grade Range</td>
<td>Skills</td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>-----------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>1070-1130</td>
<td>- identify and seek the perspectives of <em>relevant</em> stakeholders</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- take a skeptical approach (because there is always bias or faulty information)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- identify multiple relations between variables</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- identify own frame of reference</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- attempt to remain objective and impartial</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- maintain self-awareness</td>
<td></td>
</tr>
<tr>
<td>1040-1100</td>
<td>- identify and avoid basic forms of bias</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- identify several psychological or interpersonal causes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- weigh multiple perspectives or factors</td>
<td></td>
</tr>
<tr>
<td>1010-1070</td>
<td>- consider the motives or biases behind perspectives, evidence, or actions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- identify a few psychological or interpersonal causes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- consider pros and cons</td>
<td></td>
</tr>
<tr>
<td>980-1040</td>
<td>- try to keep an open mind</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- think about what’s reasonable or logical</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- distinguish between facts and opinions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- consider consequences</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- compare evidence</td>
<td></td>
</tr>
<tr>
<td>950-1010</td>
<td>- listen to or understand two sides of a disagreement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- consider facts, evidence, or opinions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- compare opinions</td>
<td></td>
</tr>
<tr>
<td>900-970</td>
<td>- find out what different people want or like</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- try to understand other people’s ideas</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- think about what you believe or what makes sense</td>
<td></td>
</tr>
<tr>
<td>860-920</td>
<td>- try to figure out the best thing to do or who has the best idea</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- think about what you know</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- try to figure out why something happened</td>
<td></td>
</tr>
<tr>
<td>800-880</td>
<td>- try to figure out what to do or what is right or good</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- try to figure out what happened</td>
<td></td>
</tr>
</tbody>
</table>

*Example of Lectical Levels for decision-making skills; Adapted from https://lectalive.org/about/skill-levels*
### II-C. Construct Models - Examples

**Construct map for student understanding of Earth in the solar system**

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
</table>
| 5     | Student is able to put the motions of the Earth and Moon into a complete description of motion in the Solar System which explains:  
* the day/night cycle  
* the phases of the Moon (including the illumination of the Moon by the Sun)  
* the seasons |
| 4     | Student is able to coordinate apparent and actual motion of objects in the sky. Student knows that:  
* the Earth is both orbiting the Sun and rotating on its axis  
* the Earth orbits the Sun once per year  
* the Earth rotates on its axis once per day, causing the day/night cycle and the appearance that the Sun moves across the sky  
* the Moon orbits the Earth once every 28 days, producing the phases of the Moon |
|        | COMMON ERROR: Seasons are caused by the changing distance between the Earth and Sun.  
COMMON ERROR: The phases of the Moon are caused by a shadow of the planets, the Sun, or the Earth falling on the Moon. |
| 3     | Student knows that:  
* the Earth orbits the Sun  
* the Moon orbits the Earth  
* the Earth rotates on its axis  
However, student has not put this knowledge together with an understanding of apparent motion to form explanations and may not recognize that the Earth is both rotating and orbiting simultaneously. |
|        | COMMON ERROR: It gets dark at night because the Earth goes around the Sun once a day. |
| 2     | Student recognizes that:  
* the Sun appears to move across the sky every day  
* the observable shape of the Moon changes every 28 days  
Student may believe that the Sun moves around the Earth. |
|        | COMMON ERROR: All motion in the sky is due to the Earth spinning on its axis.  
COMMON ERROR: The Sun travels around the Earth.  
COMMON ERROR: It gets dark at night because the Sun goes around the Earth once a day.  
COMMON ERROR: The Earth is the center of the universe. |
| 1     | Student does not recognize the systematic nature of the appearance of objects in the sky. Students may not recognize that the Earth is spherical. |
|        | COMMON ERROR: It gets dark at night because something (e.g., clouds) covers the Sun.  
COMMON ERROR: The phases of the Moon are caused by clouds covering the Moon.  
COMMON ERROR: The Sun goes below the Earth at night. |
| 0     | No evidence, or off-track. |

*Figure A3-IIC-1.*  Example construct map; Adapted from Wilson, 2009.  
*Theoretical Construct Map for Mathematics*
Figure A3-IIC-2. Example of theoretical mathematics construct map; Adapted from Wyse, 2013.
Integrated Construct Maps for Celestial Motion

**BIG IDEA - CELESTIAL MOTION:** Integrated view of the motion of celestial objects in the solar system to explain phenomena from both an earth-based and a heliocentric frame of reference.

<table>
<thead>
<tr>
<th>Explanatory motions</th>
<th>Phenomena: Reason for the seasons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tilt of the earth</td>
<td>Phenomena: Patterns of stars' motion, seasonally and across latitudes</td>
</tr>
<tr>
<td>Spherical earth*</td>
<td>Phenomena: Apparent motion of the planets and retrograde motion</td>
</tr>
<tr>
<td>Orbit of the planets</td>
<td>Phenomena: Eclipses</td>
</tr>
<tr>
<td>Orbit of the earth</td>
<td>Phenomena: Phases of the Moon</td>
</tr>
<tr>
<td>Orbit of the moon</td>
<td>Phenomena: Daily motion of Celestial objects</td>
</tr>
<tr>
<td>Rotation of the earth*</td>
<td></td>
</tr>
</tbody>
</table>

* Students need to understand that the earth is a sphere before learning to explain with the earth's rotation. Later, students will interpret the consequences for our observations of the sky using the shape of the earth and their location on that sphere.

**Figure A3-IIIC-3.** An outline of how earth-based phenomena and the actual heliocentric motions within the solar system can be linked within a learning progression for celestial motion. Each vertical column is a construct map. The gray-shaded bands indicate where explanatory motions (left column) link to each construct map. For example, the gray band for the earth's rotation overlaps all the construct maps because it is part of the explanation for all the phenomena. (Plummer, 2012)
### Integrated Construct Maps for Celestial Motion

<table>
<thead>
<tr>
<th>CLAIM</th>
<th>EVIDENCE</th>
<th>TASK</th>
</tr>
</thead>
</table>
| Students should be able to draw and explain a functional model of the atom. (What is functional depends on their level and the level-appropriate phenomena they need to explain.) | **Level 1:** The student model of an atom should include:  
- atoms (no components) | ✓ Draw a picture of what you think an atom would look like (your model of an atom) and explain it.  
(If appropriate) Tell me about the protons, neutrons, and electrons in your model. How do they compare to each other?  
Clarify their ideas of electron motion. For example, ask, “Do the electrons orbit around like planets?” (or whatever is appropriate from their drawing). |
|                                                                        | **Level 2:** The student model of an atom should include:  
- Atoms are made of electrons, neutrons and protons.  
- Electrons are negatively charged, protons are positively charged, and neutrons are neutral.  
- Neutrons and protons are of similar mass; mass of electrons is much smaller. |                                                                      |
|                                                                        | **Level 3a:** The student model of an atom should include:  
- Level 2 evidence +  
- Electrons are in constant motion, limited to shell (30)/orbit (2D). Only a certain number of electrons allowed per shell. |                                                                      |
|                                                                        | **Level 3b:** The student model of an atom should include:  
- Level 2 evidence +  
- Electrons are in constant motion, but unlike macroscopic objects, they do not have a trajectory.  
- The Heisenberg Uncertainty Principle indicates that it is impossible to predict where an electron will be based upon where it has been.  
- The electron probability density describes the electron distribution.  
- In the ‘electron cloud’ model where the ‘cloud’ describes the probability density of an electron provides a simplified way of visualizing the quantum mechanical behavior of an electron.  
- Only a certain number of electrons allowed per shell. |                                                                      |
|                                                                        | **Level 4:** The student model of an atom should include:  
- Level 3b evidence +  
- The shells in the atomic models represent levels.  
- Only certain amounts (quanta) of energy will move electrons to another level.  
- Electrons are distributed in orbitals that surround the nucleus. Only a certain number of electrons (two) are allowed within each orbital (Pauli Principle).  
- A certain number of orbitals is contained in each level (shell). |                                                                      |

Figure A3-IIC-4. Sample Construct Model for Atomic Structure; Adapted from Stevens, Delgado & Krajcik, 2010.
II-D. Learning Progressions - Examples

LP for understanding 'Matter'

A schematic overview of a learning progression on the atomic molecular theory of matter covered a large grade span (i.e., K-8), from Smith et al. (2006) who posited that three big ideas from chemistry were central to understanding the nature and behavior of matter, and that students should develop increasingly more sophisticated understanding of these three ideas across the grades. These three core constructs were then broken down into eight sub-ideas that operationally defined their meaning. This high level overview of the core concepts of a learning progression helps to provide the ‘shape’ of learning progression.

- **All objects are constituted of matter, which exists in different material kinds, and that objects have properties that can be measured and depend on the kind of matter present.**
  - Existence of matter and diversity of material kinds
  - Objects have properties that can be measured and explained. Three important properties are mass, weight, and volume.
  - Material kinds have characteristic properties that can be measured and explained.

- **Matter can be transformed, but never created or destroyed.**
  - Mass and weight are conserved across a broad range of transformations.
  - Material kinds stay the same across some transformations and change across others.

- **We can learn about the world through measurement, modeling, and argumentation.**
  - Good measurements provide more reliable and useful information about object properties than common sense impressions.
  - Modeling is concerned with capturing key relations among ideas rather than surface appearance.
  - Arguments use reasoning to connected ideas and data.

Figure A3-IID-1. Schematic overview of a learning progression for the science construct of matter; Adapted from Smith, Wiser, Anderson, & Krajcik, 2006.
Figure A3-IID-2. Representation of a portion of the hypothetical learning progression for the nature of matter; Adapted from Stevens, Delgado, & Krajcik, 2010.
<table>
<thead>
<tr>
<th>LEVEL 7</th>
<th>Attributes of What Students Know and Can Do</th>
<th>CCSS-Math</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grades 6 – 8</td>
<td>1: Students can make predictions for linear relationships as ( y = mx + b )</td>
<td>8.EE.B.5</td>
</tr>
<tr>
<td></td>
<td>2: Students can calculate the unit rate given any two values</td>
<td>8.F.A.3</td>
</tr>
<tr>
<td></td>
<td>3: Students interpret slope as a rate of change.</td>
<td>8.F.B.4</td>
</tr>
</tbody>
</table>

| LEVEL 6 | | 7.RP.A.2 |
|---------| | MP.2 |

| LEVEL 5 | | |
|---------| | |
| Grades 3 – 5 | 1: Students can name fair shares multiple ways and explain their evidence. | 5.NF.3 |
| | 2: Students can explain why different methods to create fair shares are equivalent. | 3.NF.3c |
| | 3: Use and justify principle: \( p \) by \( n = \frac{p}{n} \). | MP.2 |

| LEVEL 4 | | |
|---------| | |
| Grades 3 – 5 | 1: Students recognize qualitative compensation as an inverse relationship. | 3.NF.3b |
| | 2: Distinctions made between additive and multiplicative relationships. | MP.2 |
| | 3: Students can use transitivity in explanation. | |

| LEVEL 3 | | |
|---------| | |
| Grades 1 – 5 | 1: Students master concept of "n times as much". If collection or whole is shared by \( n \) people, whole is n times single share. | 5.NF.5 |
| | 2: Can justify equivalence by reconstructing whole from a given part. | 3.OA.1 |
| | | MP.2 |

| LEVEL 2 | |  |
|---------| |  |
| Grades 1 – 3 | 1: In naming shares as counts of "one piece," students consider number and size of pieces. | 3.OA.2 |
| | 2: Students use geometric or measurement ideas to justify equivalence of shares. | 3.G.2 |
| | | 3.NF.1 |
| | | 2.G.2, 2.G.3 |
| | | MP.2 |

| LEVEL 1 | | |
|---------| | |
| Grades K – 2 | 1: Students can name shares from a collection of objects numerically using extensive or intensive units. | 2.G.2 |
| | 2: Students can justify the equivalence of shares by counting. | 1.G.3 |
| | | MP.2 |

Figure A3-IID-3. Learning progression for proportional reasoning: Student attributes; Adapted from Briggs & Peck, 2015.
### Key Activities (Items)

**LEVEL 7**  
*Grades 6–8*  
Activities in which two quantities change together, such that a change in one quantity is associated with a proportional change in the second. Activities in this level are distinguished from those in Level 6 by the presence of an additive constant or "starting amount".

**LEVEL 6**  
*Grades 4–7*  
Activities in this category might include fair-sharing via equipartitioning, but would also include other types of proportional reasoning problems, including comparing two ratios or finding a missing value given equivalent ratios.

**LEVEL 5**  
*Grades 3–5*  
Activities that involve finding the size of one share when multiple wholes are shared by a number of people, such that the wholes cannot be shared equally without partitioning (i.e., the number of wholes is not a multiple of the number of sharers).

**LEVEL 4**  
*Grades 3–5*  
Activities that involve sharing a collection or whole, and then determining the effect of changing the number of sharers. For example, exploring the effect of adding a new person to the group, or of two people combining their shares.

**LEVEL 3**  
*Grades 1–5*  
Activities in which a single share is given, and students are asked to reconstruct the whole. For example, finding the size of a whole rectangular cake that was shared by 10 people if you are given the size of one person’s share.

**LEVEL 2**  
*Grades 1–3*  
Activities that involve finding the size of one share when a single whole is shared by a number of people. This requires partitioning the whole such that it can be shared. For example, finding one person’s share when one is pizza is shared by 4 people.

**LEVEL 1**  
*Grades K–2*  
Activities that involve finding the size of one share when a collection of objects is shared by a number of people, such that the collection can be shared equally. For example, finding one person’s share when 12 cookies are shared by 4 people.

---

*Figure A3-IID-4.*  
Learning progression for proportional reasoning: Key activities; Adapted from Briggs & Peck, 2015.
### A Proposed Learning Progression For Scientific Argumentation

<table>
<thead>
<tr>
<th>Level</th>
<th>Constructing</th>
<th>Critiquing</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td>No evidence of facility with argumentation.</td>
</tr>
<tr>
<td>0a</td>
<td>Constructing a claim</td>
<td></td>
<td>Student states a relevant claim.</td>
</tr>
<tr>
<td>0b</td>
<td></td>
<td>Identifying a claim</td>
<td>Student identifies another person's claim.</td>
</tr>
<tr>
<td>0c</td>
<td>Providing evidence</td>
<td></td>
<td>Student supports a claim with a piece of evidence.</td>
</tr>
<tr>
<td>0d</td>
<td></td>
<td>Identifying evidence</td>
<td>Student identifies another person's piece of evidence.</td>
</tr>
<tr>
<td>1a</td>
<td>Constructing a warrant</td>
<td></td>
<td>Student constructs an explicit warrant that links their claim to evidence.</td>
</tr>
<tr>
<td>1b</td>
<td></td>
<td>Identifying a warrant</td>
<td>Student identifies the warrant provided by another person.</td>
</tr>
<tr>
<td>1c</td>
<td>Constructing a complete argument</td>
<td></td>
<td>Student makes a claim, selects evidence that supports that claim, and constructs a synthesis between the claim and the warrant.</td>
</tr>
<tr>
<td>1d</td>
<td>Providing an alternate counter argument</td>
<td></td>
<td>Student offers a counterargument as a way of rebutting another person's claim.</td>
</tr>
<tr>
<td>2a</td>
<td>Providing a counter-critique</td>
<td></td>
<td>Student critiques another's argument. Fully explicates the claim that the argument is flawed and justification for why the argument is flawed.</td>
</tr>
<tr>
<td>2b</td>
<td>Constructing a one-sided comparative argument</td>
<td></td>
<td>Student makes an evaluative judgment about the merits of two competing arguments and makes an explicit argument for the value of one argument. No warrant for why the other argument is weaker.</td>
</tr>
<tr>
<td>2c</td>
<td>Providing a two-sided comparative argument</td>
<td></td>
<td>Student makes an evaluative judgment about two competing arguments and makes an explicit argument for why one argument is stronger and why the other is weaker.</td>
</tr>
<tr>
<td>2d</td>
<td>Constructing a counter claim with justification</td>
<td></td>
<td>This progress level marks the top anchor of our map. Student compares and contrasts two competing arguments, and constructs a new argument in which they justify why it is superior to previous arguments.</td>
</tr>
</tbody>
</table>

Figure A3-IID-5. A proposed learning progression for scientific argumentation; Adapted from Osborne et al., 2016.
### A Proposed Learning Trajectory of Linear Measurement

<table>
<thead>
<tr>
<th>Trajectory Level</th>
<th>Conceptual Structures</th>
<th>Example of Instructional Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age 6: End-to-End Length Measurer (EE): Lays units end-to-end. May not recognize the need for equal-length units. Needs a complete set of units to span a long object.</td>
<td>Expects that lengths can be composed as repetitions of shorter lengths. This initially only applies to small numbers of units. The scheme is enhanced by the growing conception of length measuring as sweeping through large units coordinated with composing a length with parts (unit sticks).</td>
<td>How long is the black strip, compared to one of the blue strips? Can you find out without moving any more blue strips?</td>
</tr>
<tr>
<td>Age 7: Length Unit Relater and Repeater (URR): Measures by repeated use of a unit (initially may be imprecise as with broken ruler tasks). Relates size and number of units explicitly, but may use units of varying lengths. Can add lengths to obtain the length of a whole. Iterates a single unit to measure. Uses rulers with minimal guidance.</td>
<td>Action schemes include the ability to iterate a mental unit along an object. Cardinal values are connected to space units for small quantities but weaker beyond these. With the support of a perceptual context, scheme can predict that fewer larger units will be required.</td>
<td>If the black strip is reported to be 4 units long by a struggling student, have them find the length of the blue and grey strips. If the student reports 3 and 2 for these measures, ask them to draw a 1 unit long segment. Or, ask them how many 2 unit grey strips would make up a 3 unit blue strip. This should prompt them to re-measure and build up the grey as 1 unit, the blue as 2 units, and the black as 3 units.</td>
</tr>
<tr>
<td>Age 8: Consistent Length Measurer (CLM): Finds length on a bent path as the sum of its parts. Measures consistently, knowing need for identical units, partitions of unit, zero point on rulers, and accumulation of distance. May coordinate units and subunits.</td>
<td>Scheme includes the ability simultaneously to imagine an object’s length as a total extent and a composition of units. Only allows equal-length units. Can measure from starting points other than zero on a ruler. Units themselves can be partitioned to increase precision.</td>
<td>Draw 4 different paths that are shorter than 5 and one half inch and longer than 5 and one-quarter inch. Put the paths in order, and describe the length of each one in inches.</td>
</tr>
</tbody>
</table>

**Figure A3-IID-6.** Modified illustration of a portion of a learning trajectory describing the growth of children’s understanding of linear measurement; Adapted from Mosher, 2011.
A Proposed Learning Progression for the Construct ‘Collaboration’

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Limited Evidence</th>
<th>Emerging</th>
<th>Developing</th>
<th>Accelerating</th>
<th>Proficient</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Working Interdependently as a team</strong></td>
<td>Learners either work individually on learning tasks or collaborate informally in pairs or groups but do not really work together as a team. Learners may discuss some issues or content together, but skip over important substantive decisions (such as how the process will be managed), which has significant adverse impacts on how well the collaboration works.</td>
<td>Learners work together in pairs or groups and are responsible for completing a task in order for the group to achieve its work. At this level, tasks may not be well matched to each individual's strengths and expertise, and group members' contributions may not be equitable. Learners are starting to make some decisions together, but may still be leaving the most important substantive decisions to one or two members.</td>
<td>Learners decide together how to match tasks to the individual strengths and expertise of team members, and then work effectively together in pairs or groups. Learners involve all members in making joint decisions about an important issue, problem, or process, and developing a team solution.</td>
<td>Learners can articulate how they work together in a way that is interdependent and uses each person's strengths in the best possible way to make sound substantive decisions and develop ideas and solutions. Interdependent teamwork is clearly evident in that learners' contributions are woven together to communicate an overarching idea and/or create a product.</td>
<td>Learners demonstrate a highly effective and synergistic approach to working interdependently in a way that not only leverages each member's strengths but provides opportunities for each to build on those strengths and learn new skills. This includes ensuring that substantive decisions are discussed at a deep level that ensures each team member's strengths and perspectives are infused to come to the best possible decision that benefits all.</td>
</tr>
<tr>
<td><strong>Interpersonal and team-related skills</strong></td>
<td>Although learners may help each other on tasks that contribute to a joint work product or outcome, interpersonal and team-related skills are not yet evident. Learners do not yet demonstrate a genuine sense of empathy or a shared purpose for working together.</td>
<td>Learners report and demonstrate a sense of collective ownership of the work and show some interpersonal and team-related skills. The focus is on achieving a common joint outcome, product, design, response or decision, but at this level the key decisions may be taken or dominated by one or two members.</td>
<td>Learners demonstrate not only good interpersonal skills and collective ownership of the work, but an active sense of shared responsibility is also evident. From beginning to end, the team listens effectively, negotiates and agrees on the goals, content, process, design, and conclusions of their work.</td>
<td>Learners can clearly articulate how joint responsibility for the work and its product or outcome pervades the entire task. Strong skills in listening, facilitation, and effective teamwork ensure that all voices are heard and reflected in the ways of working or work product.</td>
<td>Learners take an active responsibility, both individually and collectively, for ensuring that the collaborative process works as effectively as possible, that each person's ideas and expertise are used to maximum advantage, and that each work product or outcome is of the highest possible quality or value.</td>
</tr>
</tbody>
</table>

**Figure A3-ID-7.** Prototype of a learning progression for collaboration. Source: New Pedagogies for Deep Learning, 2016.
### III-A. Foundational Assessment Frameworks – Examples

**Evidence-Centered Design – Design Template**

<table>
<thead>
<tr>
<th>ATTRIBUTE</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Title</td>
<td>A short name for referring to the design pattern</td>
</tr>
<tr>
<td>Summary</td>
<td>Overview of the kinds of assessment situations students encounter in this design pattern and what one wants to know about their knowledge, skill, and abilities</td>
</tr>
<tr>
<td>Rationale</td>
<td>Explanation of why this is an important aspect of scientific inquiry; the underlying warrant that justifies the connection between the targeted inferences and the kinds of tasks and evidence that support them</td>
</tr>
<tr>
<td>Focal Knowledge, Skills, &amp; Abilities</td>
<td>The focal knowledge, skills, and/or abilities targeted by this design pattern</td>
</tr>
<tr>
<td>Additional Knowledge, Skills, &amp; Abilities</td>
<td>Other knowledge, skills, and/or abilities that may be required by tasks motivated by this design pattern</td>
</tr>
<tr>
<td>Potential Observation(s)</td>
<td>Some possible things that one could see students doing that would provide evidence about their focal knowledge, skills, and/or abilities</td>
</tr>
<tr>
<td>Potential Work Product(s)</td>
<td>Student responses or performances (e.g., written product or spoken answer) that can hold clues or provide evidence about the focal knowledge, skills, and/or abilities</td>
</tr>
<tr>
<td>Potential Rubric(s)</td>
<td>Rules and techniques used or adapted for evaluating or scoring work products</td>
</tr>
<tr>
<td>Characteristic Feature(s)</td>
<td>Features of an assessment task or situation that can evoke the desired evidence about the focal knowledge, skills, and/or abilities</td>
</tr>
<tr>
<td>Variable Feature(s)</td>
<td>Features of an assessment task or situation that can be varied in order to shift the difficulty or focus of tasks</td>
</tr>
<tr>
<td>Exemplar Tasks</td>
<td>Sample assessment tasks that are instances of this design pattern</td>
</tr>
<tr>
<td>References</td>
<td>Research and literature that provide backing for this design pattern</td>
</tr>
</tbody>
</table>

Figure A3-III/1. ECD Design Template
### Example Design Pattern for “Designing and Conducting a Scientific Investigation”

<table>
<thead>
<tr>
<th>ATTRIBUTE</th>
<th>VALUE(S)</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Title</td>
<td>7. Designing and conducting a scientific investigation.</td>
<td></td>
</tr>
<tr>
<td>Summary</td>
<td>In this design pattern, students are presented with a scientific problem to solve or investigate. Do they effectively plan a solution strategy, carry out that strategy, monitor their own performance, and provide coherent explanations?</td>
<td>This broad design pattern spans all phases of a scientific investigation. Phases are examined more closely as their own design patterns, “parts of” this one. Anyone planning an investigation should consult both this overall design pattern and the more focused parts of it.</td>
</tr>
<tr>
<td>Rationale</td>
<td>Cognitive studies of expertise show that these are components of reasoning that differentiate more competent from less competent problem solvers in a domain.</td>
<td></td>
</tr>
<tr>
<td>Focal KSAs</td>
<td>Ability to carry out scientific investigations.</td>
<td>This is an overarching design pattern on scientific investigations, which pertains when considering a student organizing and managing the iterative steps in an investigation. See sub-patterns for further discussion of KSAs involved in various aspects of an investigation.</td>
</tr>
<tr>
<td>Additional KSAs</td>
<td>Metacognitive skills</td>
<td></td>
</tr>
<tr>
<td>Potential observations</td>
<td>Self-assessment of where one is in the investigation.</td>
<td>Sample rubrics: John Frederiksen’s, on self-assessment ratings for use during the course of investigation.</td>
</tr>
<tr>
<td></td>
<td>Self-assessment of whether investigation is proceeding appropriately or needs to be refocused.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quiz on process used in investigation.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pose steps of scientific investigation.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>See sub-patterns for observations that can be associated with different aspects of investigation.</td>
<td></td>
</tr>
<tr>
<td>Potential work products</td>
<td>See sub-patterns.</td>
<td></td>
</tr>
<tr>
<td>Potential rubrics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Characteristic features</td>
<td>Motivating question or problem to be solved.</td>
<td>To enable students to come up with own solution strategy.</td>
</tr>
<tr>
<td></td>
<td>Open-ended; little/no cueing.</td>
<td></td>
</tr>
<tr>
<td>Variable features</td>
<td>Holistic vs. discrete task.</td>
<td>The task might require students to develop and carry out solutions from start to finish, or the task might address only a part (or a few parts) of the solution process (e.g., have students come up with a plan for solving problem, but not actually carry steps out).</td>
</tr>
<tr>
<td></td>
<td>Complexity of inquiry activity.</td>
<td>There is a broad range of inquiry tasks that students might be asked to perform. Prior knowledge: tapping into what students already know.</td>
</tr>
<tr>
<td></td>
<td>Extent of substantive knowledge required.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Holistic vs. discrete task.</td>
<td>Provided information: asking students to use what you have taught them</td>
</tr>
<tr>
<td></td>
<td>Focus on domain-specific vs. general knowledge.</td>
<td>Specific: knowledge specific to domain (e.g., conservation of energy). General: principles that cut across scientific domains (e.g., control of variables). Process: emphasis on how students approach the</td>
</tr>
</tbody>
</table>

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Focus on process vs. content.  Content: how students bring to bear their content knowledge in coming up with a plan. E.g., simulations vs. hands-on investigation.

Authenticity. Viewing real-world situation from scientific perspective. Specific: knowledge specific to domain (e.g., conservation of energy). General: principles that cut across scientific domains (e.g., control of variables). Process: emphasis on how students approach the problem.

Focus on domain-specific vs. general knowledge.

| I am a kind of | Model-based reasoning. | [Doesn't exist yet]. |
| These are kinds of me | | |
| I am part of | Planning solution strategies. | |
| These are parts of me | Implementing solution strategies. | |
| | Monitoring strategies. | |
| | Generating explanations based on underlying principles. | |
| Educational standards | NSES: relates to all of the Science as Inquiry standards | |
| Unifying concepts | Systems, order, and organization. | |
| | Evidence, models, and explanations. | |
| | Change, constancy, and measurement. | |
| Science as inquiry standards | Abilities necessary to do scientific inquiry. | |
| | Identify questions that can be answered through scientific investigations. | |
| | Design and conduct a scientific investigation. | |
| | Use appropriate tools and techniques to gather, analyze, and interpret data. | |
| | Develop descriptions, explanations, predictions, explanations. | |
| | Use mathematics in all aspects of scientific inquiry | |
| Templates | Mystery Powders (Baxter, Glaser & Elder, 1996). | In this performance assessment students are asked to investigate which of three white powders (salt, baking soda, and cornstarch)—individually or in combination—are contained in each of six bags. |
| Exemplar tasks | | |

Figure 3A-III-A-2. ECD Design Pattern for Conducting Scientific Investigations; Adapted from Mislevy et al, 2003.
Ill-B. Concept Inventories - Example

Excerpt from the Force Concept Inventory

1. Two metal balls are the same size, but one weighs twice as much as the other. The balls are dropped from the top of a two story building at the same instant of time. The time it takes the balls to reach the ground below will be:

   (A) about half as long for the heavier ball.
   (B) about half as long for the lighter ball.
   (C) about the same time for both balls.
   (D) considerably less for the heavier ball, but not necessarily half as long.
   (E) considerably less for the lighter ball, but not necessarily half as long.

2. Imagine a head-on collision between a large truck and a small compact car. During the collision,

   (A) the truck exerts a greater amount of force on the car than the car exerts on the truck.
   (B) the car exerts a greater amount of force on the truck than the truck exerts on the car.
   (C) neither exerts a force on the other, the car gets smashed simply because it gets in the way of the truck.
   (D) the truck exerts a force on the car but the car doesn't exert a force on the truck.
   (E) the truck exerts the same amount of force on the car as the car exerts on the truck.

3. Two steel balls, one of which weighs twice as much as the other, roll off of a horizontal table with the same speeds. In this situation:

   (A) both balls impact the floor at approximately the same horizontal distance from the base of the table.
   (B) the heavier ball impacts the floor at about half the horizontal distance from the base of the table than does the lighter.
   (C) the lighter ball impacts the floor at about half the horizontal distance from the base of the table than does the heavier.
   (D) the heavier ball hits considerably closer to the base of the table than the lighter, but not necessarily half the horizontal distance.
   (E) the lighter ball hits considerably closer to the base of the table than the heavier, but not necessarily half the horizontal distance.

4. A heavy ball is attached to a string and swung in a circular path in a horizontal plane as illustrated in the diagram to the right. At the point indicated in the diagram, the string suddenly breaks at the ball. If these events were observed from directly above, indicate the path of the ball after the string breaks.

   (A) (B) (C) (D) (E)

Figure A3-IIIIB. Excerpt from the Force Concept Inventory (Hestenes, Wells & Swackhamer, 1992).
III-D. Stealth Assessments - Example

**Competency Model: Creativity**

Below is the competency model and accompanying Bayes Net for the construct of Creativity, in the digital game *Newton’s Playground*.

![Diagram of Competency Model and Bayes Net for Creativity](image)

---

**Figure 3A-IIID-1.** Competency Model of Creativity with indicators, for the game *Newton’s Playground*.  
Source: Shute & Ventura, 2013.
Bayesian Network Model: Creativity

Figure 3A-IIID-2. Competency model and evidence model for creativity—prior probabilities, for the game Newton’s Playground (Shute & Ventura, 2013).
IV-A. Cognitive Tutors - Example

*Simplified schema of model-based cognitive tutor*

![Diagram of model-based cognitive tutor](image)

Figure A3-IVA. Simplified schema of model-based cognitive tutor (Luckin, Holmes, Griffiths & Forcier, 2016).
APPENDIX D. Semi-Structured Teacher Interview Protocol for Initial Data Collection

Warm up: concise intro on the purpose of the conversation

Warm up: basic questions about the person (name, role, basic info)

What do you teach?

How long have you been teaching?

Planning Instruction

How do you plan instruction? Walk me through what a typical sequence looks like.

Do you create lesson plans? What tools do you use?

Do you create them and/or share them with colleagues? How?

What works about that process?

What doesn’t work?

Do you collaborate with other teachers? How? Which teachers? (same subject, same grade, same school... etc.)

Common Core

Does your district use the Common Core?

What tools for working with the CCSS (i.e. planning tools, instructional tools, etc.) do you currently use?

What resources for it have you liked?

What don’t you like about them, or wish they did?

Resources

Where do you go to learn about the best ways to teach or assess a topic?
What kinds of materials are the most valuable to you? The most commonly used?

How do you find useful instructional resources for your curriculum?

How do you plan curriculum for topics not in the CCSS?

What tool do you wish you had?

________________________________________

How much time do you spend:

Looking for materials

Writing lesson plans

Planning the year overall

Organizing the resources you have?

________________________________________

Testing for Price

How much do you currently spend to address this problem?

What budget do you have allocated to this? ...and who controls it?

How much would you pay to make this problem go away?

Who makes purchases? How are they made?

________________________________________

Magic wand 1: “If you could wave a magic wand and have this product do whatever you want, what would it do?”

Magic wand 2: “If you could wave a magic wand and solve any problem, what would you want to solve?”

________________________________________

What should I have asked you that I didn’t?
APPENDIX E. Examples of Sample Constructs Using the LearningGraph Prototype Data Model

<table>
<thead>
<tr>
<th>Construct</th>
<th>Systems Thinking</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
<td>The ability to describe and analyze structures and phenomena in natural, artificial, and social environments to be able to consider all of the elements and relationships that exist in a system and know how to structure those relationships in more efficient and effective ways.</td>
</tr>
<tr>
<td><strong>Overview</strong></td>
<td>A system can be physical, biological, technological, social, symbolic, or it can be composed of more than one of these [4]. Furthermore, many systems are quite complex (e.g., the ecosystem of the world and the human body). Ecosystems are complex open systems, and understanding interdependent relationships in ecosystems (a component of a core idea in life sciences) requires systemic reasoning. Systemic reasoning is also part of the reasoning to understand the crosscutting concept of systems and system models. To understand the behavior of such complex systems, we must understand not only the behavior of the parts, but also how they act together to form the behavior of the whole. Thus, complex systems are difficult to understand without describing each part and each part must be described in relation to other parts. Each system consists of closed-loop relations, and system thinkers use diagramming languages and methods to visually represent the relations and feedback structures within the systems. The National Science Education Standards [4] identifies systems as an important and unifying concept that can provide students with a &quot;big picture&quot; of scientific ideas which can then serve as a context for learning scientific concepts and principles. Thus, a strong background in systems thinking is critical to understanding how the world works.</td>
</tr>
<tr>
<td><strong>Developers</strong></td>
<td>Jennifer Graff</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quicklinks</th>
<th>Domain Analysis</th>
<th>Bayes Nets Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Context &amp; Motivation</td>
<td>Domain Model</td>
<td>Helpful Pedagogies</td>
</tr>
<tr>
<td>Tools</td>
<td>Competency Models</td>
<td>References</td>
</tr>
</tbody>
</table>

Map Details
- Created: 16 Mar 2018
- Updated: 25 Mar 2018
## Computational Thinking

### Related Constructs

- Algorithmic Thinking

### Related Standards

- L1.3 CT1
- L1.3 CT2
- L1.3 CT3
- L1.3 CT4
- L1.3 CT5
- L1.3 CPP1
- L1.3 CPP2
- L1.3 CPP3
- L1.3 CPP4
- L1.3 CPP5
- L1.3 CPP6
- L1.3 CPP7
- L1.3 CL1
- L1.3 CL2
- L1.3 CI1
- L1.3 CI2
- L1.6 CT1
- L1.6 CT2
- L1.6 CT3
- L1.6 CT4
- L1.6 CT5
- L1.6 CT6
- L1.6 CPP1
- L1.6 CPP2
- L1.6 CPP3
- L1.6 CPP4
- L1.6 CPP5
- L1.6 CPP6

### Definition

The conceptual foundation required to solve problems effectively and efficiently (i.e., algorithmically, with or without the assistance of computers) with solutions that are reusable in different contexts.

### Overview

Computational Thinking (CT) is a problem-solving process that includes (but is not limited to) the following characteristics:

- Formulating problems in a way that enables us to use a computer and other tools to help solve them.
- Logically organizing and analyzing data.
- Representing data through abstractions, such as models and simulations.
- Automating solutions through algorithmic thinking (a series of ordered steps).
- Identifying, analyzing, and implementing possible solutions with the goal of achieving the most efficient and effective combination of steps and resources.
- Generalizing and transferring this problem-solving process to a wide variety of problems.

### Developers

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- Elham Beheshti
- Michael Horn
- Kai Orten
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- Aidan Mooney

### Map Details

- Created: 16 Mar 2018
- Updated: 24 Mar 2018


**CONTEXT & MOTIVATION**

Over the past decade, CT has become a very hot topic in educational research and practice. Thousands of entries appear on a general Google search regarding its definition, instructional interventions, and assessment. Many of these entries suggest that CT relates to coding or programming, but considering CT as knowing how to program may be too limiting. According to the National Research Council [77], everyone should acquire CT, not only programmers. CT skills include managing information effectively and efficiently with technologies in our data-driven era [20, 59, 63, 100, 120]. A workforce with individuals possessing CT skills increases the competitiveness of the United States in the world economic market [77].

A primary motivation for introducing computational thinking practices into science and mathematics classrooms is the rapidly changing nature of these disciplines as they are practiced in the professional world [9, 36, 47]. In the last 20 years, nearly every field related to science and mathematics has seen the growth of a computational counterpart. Examples include Bioinformatics, Computational Statistics, Chemometrics, and Neuroinformatics. This rise in importance of computation with respect to mathematics, science and the broader Science, Technology, Engineering, and Mathematics (STEM) fields has been recognized both by those within the STEM education communities and computer science education organizations [126]. Bringing computational tools and practices into mathematics and science classrooms gives learners a more realistic view of what these fields are, better prepares students for pursuing careers in these disciplines [5, 37], and helps equip students to be more savvy STEM citizens in the future.

From a pedagogical perspective, the thoughtful use of computational tools and skillsets can deepen learning of mathematics and science content [43, 33, 76, 90, 97, 102, 104, 17, 119]. The reverse is also true—namely that science and mathematics provide a meaningful context (and set of problems) within which computational thinking can be applied [45, 36, 62]. This differs markedly from teaching computational thinking as part of a standalone course in which the assignments that students are given tend to be divorced from real-world problems and applications. This sense of authenticity and real-world applicability is important in the effort to motivate diverse and meaningful participation in computational and scientific activities [18, 22, 24, 57, 68, 97]. This reciprocal relationship—using computation to enrich mathematics and science learning and using mathematics and science contexts to enrich computational thinking—is at the heart of our motivation to bring computational thinking into science and mathematics classrooms together.

An additional key motivator is to reach the widest possible audience and address longstanding issues of the underrepresentation of women and minorities in computational fields [86]. Currently, only a fraction of high school students have the opportunity to take a computer science course due to a lack of qualified teachers, inadequate facilities, or constraints in class scheduling. Embedding computational thinking activities in mathematics and science coursework directly addresses the issue of student self-selection into (or out of) computer science classes, which has been a challenge long plaguing the effort to reach underserved youth [67, 68]. It also avoids practical issues of fitting new classes into overcrowded school schedules and finding teachers to teach them.

For learners, possessing good CT skills may be a motivator for students to pursue computer science [1] and other STEM-related majors [108]. CT has also been linked to creativity and innovation [73, 92], and it has important applications in other STEM areas [11, 102]. An exact definition of CT, however, remains elusive [10].

**DOMAIN ANALYSIS**

**Defining CT**

Computational thinking (CT) stems back to the constructional work of Seymour Papert [81, 82] and was first coined as a term in a seminal article by Wang [120]. She explained that CT entails "solving problems, designing systems, and understanding human behavior, by drawing on the concepts fundamental to computer science" [120, p. 33]. As such, it represents an ability to analyze...
and then solve various problems. Her arguments provided a fresh perspective on the relationship(s) between humans and computers, and gave rise to a wave of research on CT.

The most oft-cited definition of CT comes from Dury, Snyder, and Wing [25], noting that CT is a thinking process where "...solutions are represented in a form that can be effectively carried out by an information-processing agent" (as cited in Wing, 2010, p 1). This relates not only to well-structured problems, but also ill-structured problems (i.e., complicated real-life problems whose solutions are neither definite nor measurable). Other researchers have come up with their own definitions relative to their particular research areas. For instance, Barr et al. [10] concluded that in K-12, CT involves problem-solving skills and particular dispositions, such as confidence and persistence, when confronting particular problems. Berland and Wilensky [16] defined CT as "the ability to think with the computer-as-tool" (p. 630) and suggested using "computational perspectives" as an alternative to "computational thinking" to emphasize that CT can be constrained by contexts. Additionally, CT has been defined as "students using computers to model their ideas and develop programs" [52, p 264], explicitly linking CT to programming skills.

The earliest work to put this idea into practice was the development of the Logo programming language [35,81]. While Logo was designed most immediately to teach mathematical concepts, its creators quickly recognized the far-reaching benefits of the skills learned through programming, arguing that "computer presence could contribute to mental processes not only instrumentally but in more essential, conceptual ways, influencing how people think even when they are far removed from physical contact with a computer" [81, p 4].

As described above, CT definitions vary in their operationalization of CT in certain studies, and are not particularly generalizable [e.g., 16, 51, 52]. The definition of CT is evolving as researchers begin to aggregate knowledge about CT.

CT in K-12

Extensive research over the last three decades has focused on issues related to teaching and learning skills, concepts, and practices relevant to computational thinking [41]. There have been a few notable efforts towards creating frameworks and guidelines for bringing computational thinking into K-12 education but currently there are no agreed upon models or frameworks for CT [4]. In this section, we examine four CT models proposed by researchers.

Frameworks

I. The first model, by Atmatrakou and Demetriades [4] presented a simple, descriptive CT model, based on their operationalization of CT in previous studies, which also provides examples of behaviors that students should demonstrate as evidence for each facet [see 4]. The model consists of five facets:

   Abstraction - Distilling the core patterns from complicated systems

   Generalization - Applying problem-solving strategies to different contexts

   Algorithms - Ordered steps/instructions to implement solutions

   Modularity - The automation of problem-solving solutions

   Decomposition - The breakdown of complex systems/thing into manageable pieces

II. The second model consists of CT concepts and abilities that should be incorporated into K-12 courses like math, science, social studies, and language arts [11, p 52]. It defines core CT facets (i.e., data collection, data analysis, data representation, decomposition, abstraction, algorithms, automation, parallelism, and simulation) across various disciplines. These CT facets should have different representations in different subjects (e.g., representing data with charts or tables in math, and representing linguistic patterns in language arts). However, the specific demonstrations of CT facets within particular disciplines are not clearly stated in the paper. Moreover, the provided examples of teaching practices are too vague for teachers to actually employ them, for example, abstraction in science class is described only as modeling a physical entity.
The weakness of this model stems from (a) no clear definitions per CI facet making operationalization very difficult; and (b) failure to distinguish concepts from abilities (e.g., abstraction is both a concept and an ability). Thus, this model has room for improvement before serving as a guideline for teachers in K-12 education.

III. Brennan and Resnick [19] presented a CI framework within the context of using Scratch to facilitate CI. They categorized CI into three areas:

<table>
<thead>
<tr>
<th>Concepts: students employ as they program</th>
<th>Practices: that occurs in the process of programming</th>
<th>Perspectives: Students' understandings of themselves, their relationships to others, and the digital world around them</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sequences</strong></td>
<td><strong>Being incremental and iterative</strong></td>
<td><strong>Expressing</strong></td>
</tr>
<tr>
<td>A particular activity or task is expressed as a series of individual steps or instructions that can be executed by the computer</td>
<td></td>
<td>A computational thinker sees computation as more than something to consume computation is something they can use for design and self-expression</td>
</tr>
<tr>
<td><strong>Loops</strong></td>
<td><strong>Testing and debugging</strong></td>
<td><strong>Connecting</strong></td>
</tr>
<tr>
<td>A mechanism for running the same sequence multiple times</td>
<td></td>
<td>Placing value on creating with others, and the value of creating for others</td>
</tr>
<tr>
<td><strong>Parallelism</strong></td>
<td><strong>Reusing and remixing</strong></td>
<td><strong>Questioning</strong></td>
</tr>
<tr>
<td>Sequences of instruction happening at the same time</td>
<td></td>
<td>Young people should feel empowered to ask questions about and with technology - &quot;Can (see computation) ask questions to make sense of (computational things in) the world?&quot;</td>
</tr>
<tr>
<td><strong>Events</strong></td>
<td><strong>Abstracting and modularizing</strong></td>
<td></td>
</tr>
<tr>
<td>One thing causing another thing to happen are an essential component of interactive media</td>
<td></td>
<td></td>
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<tr>
<td><strong>Conditionals</strong></td>
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<td></td>
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<tr>
<td>The ability to make decisions based on certain conditions which supports the expression of multiple outcomes</td>
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<tr>
<td><strong>Operators</strong></td>
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<tr>
<td>Provide support for mathematical, logical and string expressions, enabling the programmer to perform numeric and string manipulations</td>
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<tr>
<td><strong>Data</strong></td>
<td></td>
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<tr>
<td>Storing, retrieving, and updating values</td>
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</tbody>
</table>

A review paper on integrating CI in K-12 settings by Lee and Koh [64] was based on the Brennan and Resnick framework. Later, Zhong, Wang, Chen, and Li [25] revised that model (see p. 356 for details) by adding instruction into the CI concepts and iteration into the CI practices. They also rephrased CI perspectives to emphasize creativity and collaboration. However, they did not elaborate on those modifications, which makes it hard to interpret the revised model.

IV. A fourth recent model aims to merge CI and regular classroom instruction [123]. The researchers analyzed 34 lesson plans for high school math and science courses by coding teaching practices that related to CI facets. Then they categorized the specific facets into broader CI practices, and refined the categorization after consulting with lesson plan designers, in-service high school teachers, and experts in CI and curriculum design. Finally, they came up with a taxonomy containing four CI categories with 22 CI practices (see Figure 1). Their taxonomy is based on specific classroom activities and presented concrete examples of CI classroom activities, showing how lesson plans can be designed by following the taxonomy. This model is tailored to STEM courses in high school, and shows promise with regard to integrating CI in secondary education. However, more research is needed to validate this model.
Lacking a consistent model might cause problems in designing interventions to support CT learning and in assessing CT knowledge and skills in various educational settings.

### SUB-CONCEPTS

| Sequences | Instructions for computer to execute behaviors |
| Loops | Repeat the same instruction for a specified number of times |
| Parallelism | Concurrency of multiple instructions |
| Events | Triggers for certain actions to happen to create interactive environments |
| Conditionals | Constraints on execution of instructions, allowing for different outcomes |
| Operators | Mathematical and string operations |
| Data | Data storage, retrieval, and update |

### SUB-SKILLS

Wing [120] argued that CT does not mean to think like a computer, but rather to engage in five cognitive processes with the goal of solving problems efficiently and creatively. These include:

1. **problem decomposition** – Break the problem down into manageable units.
2. **problem reformulation** – Reframe a problem into a solvable and familiar one.
1. Computing Learning Progression [23]

**LEARNING OBJECTIVE**

- Analyze and apply computational thinking to solve problems.

**DOMAIN MODEL**

<table>
<thead>
<tr>
<th>LEVEL</th>
<th>Algorithms</th>
<th>Programming &amp; Development</th>
<th>Data &amp; Data Representation</th>
</tr>
</thead>
</table>
| 8     | Designs a solution to a problem that depends on solutions to smaller instances of the same problem (recursion). 
       | 
       | Understands that some problems cannot be solved computationally. 
       | 
       | Evaluates the effectiveness of algorithms and models for similar problems. 
       | 
       | Recognizes where information can be filtered out in generating program solutions. 
       | 
       | Uses logical reasoning to explain how an algorithm works. 
       | 
       | Represents algorithms using structural language. 
       | | Designs and writes nested modular programs that enhance reusability, 
       | using sub-routines wherever possible. 
       | 
       | Understands: the difference between 
       | While loop and For loop, which uses a 
       | loop counter. 
       | 
       | Understands and uses two dimensional 
       | 
       | 
       | | Performs operations using bit patterns 
       | e.g., conversion between binary and 
       | hexadecimal, binary subtraction etc. 
       | 
       | Understands and can explain the need for data compression and performs 
       | simple compression methods. 
       | 
       | Knows what a relational database is 
       | and understands the benefits of storing 
       | data in multiple tables. 
       | 
       | Knows the relationship between data 
       | representation and data quality. 
       | 
       | Understands the relationship between 
       | binary and electrical circuits, including 
       | digital logic. 
       | 
       | Understands how and why values are 
       | stored in different languages when 
       | manipulated within programs. 

| 7     | Recognizes that the design of an 
       | algorithm is distinct from its expression 
       | in a programming language (which will 
       | depend on the programming constructs 
       | available). 
       | 
       | Evaluates the effectiveness of 
       | algorithms and models for similar 
       | problems. 
       | 
       | Recognizes where information can be 
       | filtered out in generating program 
       | solutions. 
       | 
       | Uses logical reasoning to explain how 
       | an algorithm works. 
       | 
       | Represents algorithms using structural 
       | language. 
       | | Appreciates the effect of the scope of a 
       | variable e.g., a local variable can't be 
       | accessed from outside its function. 
       | 
       | Understands and applies parameter 
       | passing. 
       | 
       | Understands the difference between 
       | and uses, both pre-tested e.g., while 
       | and post-tested e.g., until loops. 
       | 
       | Applies a modular approach to error 
       | detection and correction. 
       | | Performs operations using bit patterns 
       | e.g., conversion between binary and 
       | hexadecimal, binary subtraction etc. 
       | 
       | Understands and can explain the need 
       | for data compression and performs 
       | simple compression methods. 
       | 
       | Knows what a relational database is 
       | and understands the benefits of storing 
       | data in multiple tables. 
       | 
       | Knows the relationship between data 
       | representation and data quality. 
       | 
       | Understands the relationship between 
       | binary and electrical circuits, including 
       | digital logic. 
       | 
       | Understands how and why values are 
       | stored in different languages when 
       | manipulated within programs. 

| 6     | Understands a recursive solution to a 
       | problem repeatedly applies the same 
       | solution to smaller instances of the 
       | problem. 
       | 
       | Recognizes that some problems share 
       | the same characteristics and use the 
       | same algorithm to solve both. 
       | 
       | Understands the notion of performance 
       | for algorithms and appreciates that 
       | some algorithms have different 
       | performance characteristics for the 
       | same task. 
       | | Uses nested selection statements. 
       | 
       | Appreciates the need for, and writes, 
       | custom functions including use of 
       | parameters. 
       | 
       | Knows the difference between and 
       | uses appropriately, procedures and 
       | functions. 
       | 
       | Understands and uses negation with 
       | operators. 
       | 
       | Uses and manipulates one-dimension 
       | data structures. 
       | | Performs operations using bit patterns 
       | e.g., conversion between binary and 
       | hexadecimal, binary subtraction etc. 
       | 
       | Understands and can explain the need 
       | for data compression and performs 
       | simple compression methods. 
       | 
       | Knows what a relational database is 
       | and understands the benefits of storing 
       | data in multiple tables. 
       | 
       | Knows the relationship between data 
       | representation and data quality. 
       | 
       | Understands the relationship between 
       | binary and electrical circuits, including 
       | digital logic. 
       | 
       | Understands how and why values are 
       | stored in different languages when 
       | manipulated within programs. 

| 5     | Understands and applies parameter 
       | passing. 
       | 
       | Understands the difference between 
       | and uses, both pre-tested e.g., while 
       | and post-tested e.g., until loops. 
       | 
       | Applies a modular approach to error 
       | detection and correction. 
       | | Performs operations using bit patterns 
       | e.g., conversion between binary and 
       | hexadecimal, binary subtraction etc. 
       | 
       | Understands and can explain the need 
       | for data compression and performs 
       | simple compression methods. 
       | 
       | Knows what a relational database is 
       | and understands the benefits of storing 
       | data in multiple tables. 
       | 
       | Knows the relationship between data 
       | representation and data quality. 
       | 
       | Understands the relationship between 
       | binary and electrical circuits, including 
       | digital logic. 
       | 
       | Understands how and why values are 
       | stored in different languages when 
       | manipulated within programs. 

| 4     | Understands the difference between 
       | and uses, both pre-tested e.g., while 
       | and post-tested e.g., until loops. 
       | 
       | Applies a modular approach to error 
       | detection and correction. 
       | | Performs operations using bit patterns 
       | e.g., conversion between binary and 
       | hexadecimal, binary subtraction etc. 
       | 
       | Understands and can explain the need 
       | for data compression and performs 
       | simple compression methods. 
       | 
       | Knows what a relational database is 
       | and understands the benefits of storing 
       | data in multiple tables. 
       | 
       | Knows the relationship between data 
       | representation and data quality. 
       | 
       | Understands the relationship between 
       | binary and electrical circuits, including 
       | digital logic. 
       | 
       | Understands how and why values are 
       | stored in different languages when 
       | manipulated within programs. 

| 3     | Appreciates the need for, and writes, 
       | custom functions including use of 
       | parameters. 
       | 
       | Knows the difference between and 
       | uses appropriately, procedures and 
       | functions. 
       | 
       | Understands and uses negation with 
       | operators. 
       | 
       | Uses and manipulates one-dimension 
       | data structures. 
       | | Performs operations using bit patterns 
       | e.g., conversion between binary and 
       | hexadecimal, binary subtraction etc. 
       | 
       | Understands and can explain the need 
       | for data compression and performs 
       | simple compression methods. 
       | 
       | Knows what a relational database is 
       | and understands the benefits of storing 
       | data in multiple tables. 
       | 
       | Knows the relationship between data 
       | representation and data quality. 
       | 
       | Understands the relationship between 
       | binary and electrical circuits, including 
       | digital logic. 
       | 
       | Understands how and why values are 
       | stored in different languages when 
       | manipulated within programs. 

| 2     | Uses nested selection statements. 
       | 
       | Appreciates the need for, and writes, 
       | custom functions including use of 
       | parameters. 
       | 
       | Knows the difference between and 
       | uses appropriately, procedures and 
       | functions. 
       | 
       | Understands and uses negation with 
       | operators. 
       | 
       | Uses and manipulates one-dimension 
       | data structures. 
       | | Performs operations using bit patterns 
       | e.g., conversion between binary and 
       | hexadecimal, binary subtraction etc. 
       | 
       | Understands and can explain the need 
       | for data compression and performs 
       | simple compression methods. 
       | 
       | Knows what a relational database is 
       | and understands the benefits of storing 
       | data in multiple tables. 
       | 
       | Knows the relationship between data 
       | representation and data quality. 
       | 
       | Understands the relationship between 
       | binary and electrical circuits, including 
       | digital logic. 
       | 
       | Understands how and why values are 
       | stored in different languages when 
       | manipulated within programs. 

| 1     | Uses nested selection statements. 
       | 
       | Appreciates the need for, and writes, 
       | custom functions including use of 
       | parameters. 
       | 
       | Knows the difference between and 
       | uses appropriately, procedures and 
       | functions. 
       | 
       | Understands and uses negation with 
       | operators. 
       | 
       | Uses and manipulates one-dimension 
       | data structures. 
       | | Performs operations using bit patterns 
       | e.g., conversion between binary and 
       | hexadecimal, binary subtraction etc. 
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       | for data compression and performs 
       | simple compression methods. 
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       | Knows what a relational database is 
       | and understands the benefits of storing 
       | data in multiple tables. 
       | 
       | Knows the relationship between data 
       | representation and data quality. 
       | 
       | Understands the relationship between 
       | binary and electrical circuits, including 
       | digital logic. 
       | 
       | Understands how and why values are 
       | stored in different languages when 
       | manipulated within programs. 

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<table>
<thead>
<tr>
<th>1</th>
<th>Understands what an algorithm is and is able to express simple linear (non-branching) algorithms symbolically (AL)</th>
<th>Programs, and can demonstrate this by creating a simple program in an environment that does not rely on text e.g. programmable robots etc (AL)</th>
<th>Recognizes that digital content can be represented in many forms. (AB) (GE)</th>
<th>Distinguishes between some of these forms and can explain the different ways that they communicate information. (AB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Understands that algorithms are implemented on digital devices as programs. (AL)</td>
<td>Uses arithmetic operators, if statements, and loops within programs. (AL)</td>
<td>Recognizes different types of data: text, number (AB) (GE)</td>
<td>Appreciates that programs can work with different types of data (GE)</td>
</tr>
<tr>
<td>3</td>
<td>Designs solutions (algorithms) that use repetition and two-way selection i.e. if, then and else (AL)</td>
<td>Creates programs that implement algorithms to achieve given goals (AL)</td>
<td>Understands the difference between data and information (AB)</td>
<td>Knows why sorting data in a file can improve searching for information. (EV)</td>
</tr>
<tr>
<td>4</td>
<td>Shows an awareness of tasks best completed by humans or computers (EV)</td>
<td>Designs solutions by decomposing a problem and creating sub-solutions for each of these parts (DE) (AL) (AB)</td>
<td>Performs more complex searches for information e.g. using Boolean and relational operators. (AL) (GE) (EV)</td>
<td>Analyzes and evaluates data and information, and recognizes that poor quality data leads to unreliable results and inaccurate conclusions. (AL) (EV)</td>
</tr>
<tr>
<td>5</td>
<td>Understands that iteration is the repetition of a process such as a loop (AL)</td>
<td>Recognizes that different algorithms exist for the same problem (AL) (GE)</td>
<td>Understands that programming bridges the gap between algorithmic solutions and computers. (AB)</td>
<td>Knows that digital computers use binary to represent all data. (AB)</td>
</tr>
<tr>
<td></td>
<td>Recognizes that different algorithms exist for the same problem (AL) (GE)</td>
<td>Represents solutions using a structured notation. (AL) (AB)</td>
<td>Has practical experience of a high-level textual language, including using standard libraries when programming. (AB) (AL)</td>
<td>Understands how bit patterns represent numbers and images (AB)</td>
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<td></td>
<td>Can identify similarities and differences in situations and can use these to solve problems (pattern recognition) (GE)</td>
<td>Uses a range of operators and expressions e.g. Boolean and applies them in the context of program control (AL)</td>
<td>Understands the relationship between binary and file size (uncompressed) (AB)</td>
<td>Knows that computers transfer data in binary (AB)</td>
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<td></td>
<td>Understands what output is (AL)</td>
<td>Detects and corrects simple syntax errors i.e. debugging, in programs. (AL)</td>
<td>Defines data types: real numbers and Boolean (AB)</td>
<td>Analyses and evaluates data and information, and recognizes that poor quality data leads to unreliable results and inaccurate conclusions. (AL) (EV)</td>
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<tr>
<td></td>
<td>Uses logical reasoning to predict outputs, showing an awareness of inputs. (AL)</td>
<td>Uses logical reasoning to predict the behavior of programs. (AL)</td>
<td>Demonstrates care and precision to avoid errors (AL)</td>
<td>Performs more complex searches for information e.g. using Boolean and relational operators. (AL) (GE) (EV)</td>
</tr>
<tr>
<td></td>
<td>Uses diagrams to express solutions. (AB)</td>
<td>Detects and corrects simple semantic errors i.e. debugging, in programs. (AL)</td>
<td>Recognizes that data can be structured in tables to make it useful. (AB) (GE)</td>
<td>Analyzes and evaluates data and information, and recognizes that poor quality data leads to unreliable results and inaccurate conclusions. (AL) (EV)</td>
</tr>
<tr>
<td>LEVEL</td>
<td>Hardware &amp; Processing</td>
<td>Communication &amp; Networks</td>
<td>Information &amp; Technology</td>
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<tr>
<td>8</td>
<td>Has practical experience of a small (hypothetical) low level programming language (AB) (AL) (DE) (GE)</td>
<td>Understands the hardware associated with networking computer systems, including WANs and LANs, understands their purpose and how they work, including MAC addresses (AB) (AL) (DE) (GE)</td>
<td>Understands the ethical issues surrounding the application of information technology, and the existence of legal frameworks governing the use e.g. Data Protection Act, Computer Misuse Act, Copyright etc. (EV)</td>
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<tr>
<td></td>
<td>Understands and can explain Moore’s Law (GE)</td>
<td>Knows the purpose of the hardware and protocols associated with networking computer systems (AB) (AL)</td>
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<td>Understands and can explain multithreading by computers (AB) (AL) (DE)</td>
<td>Understands the client-server model including how computer connections are handled and that web servers process and store data entered by users (AL) (AB) (DE)</td>
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<td>Knows that processors have instruction sets and that these relate to low-level instructions compiled out by a compiler (AB) (AL) (GE)</td>
<td>Recognizes that passwords of data on the internet require careful protection of user identity and privacy (AB)</td>
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<td>7</td>
<td></td>
<td>Knows the names of hardware e.g. hubs, switches, and the names of protocols e.g. SMTP, HTTP, FTP, TCP/IP associated with networking computer systems (AB)</td>
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<td>Understands the Von Neumann architecture in relation to the fetch-execute cycle, including how data is stored in memory (AB) (GE)</td>
<td>Uses technologies and online services securely, and knows how to identify and report inappropriate content (AL)</td>
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<td></td>
<td>Understands the basic function and operation of location addressable memory (AB)</td>
<td>Justifies the choices of and independently researches and uses mobile apps, devices, internet services and applications software to achieve given goals (EV)</td>
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<td>Evaluates the trustworthiness of digital content and considers the legality of digital content, while also maintaining a balance between intellectual freedoms and technology for a known audience (EV)</td>
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<tr>
<td>6</td>
<td>Understands the Von Neumann architecture in relation to the fetch-execute cycle, including how data is stored in memory (AB) (GE)</td>
<td>Knows the names of hardware e.g. hubs, switches, and the names of protocols e.g. SMTP, HTTP, FTP, TCP/IP associated with networking computer systems (AB)</td>
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<tr>
<td></td>
<td>Understands the basic function and operation of location addressable memory (AB)</td>
<td>Uses technologies and online services securely, and knows how to identify and report inappropriate content (AL)</td>
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<tr>
<td>5</td>
<td>Recognizes and understands the function of the main internal parts of basic computer architecture (AB)</td>
<td>Understands how search engines rank search results (AL)</td>
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<td>Understands the concepts behind the fetch-execute cycle (AB) (AL)</td>
<td>Understands how to construct static web pages using HTML and CSS (AL) (AB)</td>
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<td>Knows that there is a range of operating systems and application software for the same hardware (AB)</td>
<td>Understands data transmission between digital computer networks, including the internet e.g. IP addresses and socket switching (AL) (AB)</td>
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<td>Evaluates the appropriateness of digital content and e.g. internet services, and application software to achieve given goals (EV)</td>
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<td>Recognizes ethical issues surrounding the application of information technology beyond the internet (EV)</td>
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<td>Designs criteria to critically evaluate the quality of solutions, uses the criteria to identify improvements, and can make appropriate recommendations to the solution (EV)</td>
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<tr>
<td>4</td>
<td>Understands why and when computers are used (EV)</td>
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<td></td>
<td>Understands the main functions of the operating system (DE) (AB)</td>
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<td>Knows the difference between physical, wireless and mobile networks (AB)</td>
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<td>Understands how to effectively use search engines, and knows how search results are selected, including that search engines use &quot;web crawler programs&quot; (AB) (GE) (EV)</td>
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<td>Selects, combines and uses internet services (EV)</td>
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<td>Demonstrates responsible use of technologies and online services, and knows a range of ways to report concerns</td>
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<td>Makes judgements about digital content when evaluating and repurposing it for a given audience (EV)</td>
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<td>Recognizes the audience when designing and creating digital content (EV)</td>
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<td>Understands the potential of information technology for collaboration when computers are networked (GE)</td>
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<td>Uses criteria to evaluate the quality of solutions, can identify improvements, making some refinements to the quality and future solutions (EV)</td>
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<td>Collects, organizes and presents data and information in digital content (AB)</td>
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<td></td>
<td>Creates digital content to achieve a given goal through combining software packages and internet services to communicate with a wider audience, e.g. blogging (AL)</td>
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<td>Makes appropriate improvements to solutions based on feedback received, and can comment on the success of the solution (EV)</td>
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<tr>
<td>3</td>
<td>Knows that computers collect data from various input devices, including sensors and application software (AB)</td>
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<td></td>
<td>Understands the difference between hardware and application software, and their roles within a computer system (AB)</td>
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<td>Understands the difference between the internet and internet service e.g. worldwide web (AB)</td>
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<td>Shows an awareness of, and can use a range of internet services e.g. VoIP</td>
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<td></td>
<td>Recognizes what is acceptable and unacceptable behavior when using technologies and online services</td>
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<tr>
<td></td>
<td>Use technology with increasing independence to purposefully organize digital content (AB)</td>
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<td>Shows an awareness for the quality of digital content collected (EV)</td>
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<tr>
<td></td>
<td>Uses a variety of software to manipulate and present digital content data and information (AL)</td>
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<td></td>
<td>Shares their experiences of technology in school and beyond the classroom (GE) (EV)</td>
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<tr>
<td></td>
<td>Talks about their work and makes improvements to solutions based on feedback received (EV)</td>
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<tr>
<td>2</td>
<td>Recognises that a range of digital devices can be considered a computer (AB) (GE)</td>
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<tr>
<td></td>
<td>Recognizes and can use a range of input and output devices</td>
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<tr>
<td></td>
<td>Understands how programs specify the function of a general purpose computer (AB)</td>
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<tr>
<td></td>
<td>Navigates the web and can carry out simple web searches to collect digital content (AL) (EV)</td>
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<tr>
<td></td>
<td>Demonstrates use of computers safely and responsibly, knowing a range of ways to report unacceptable content and contact when online</td>
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<tr>
<td></td>
<td>Use technology with increasing independence to purposefully organize digital content (AB)</td>
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<tr>
<td></td>
<td>Shows an awareness for the quality of digital content collected (EV)</td>
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<tr>
<td></td>
<td>Uses a variety of software to manipulate and present digital content data and information (AL)</td>
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<tr>
<td></td>
<td>Shares their experiences of technology in school and beyond the classroom (GE) (EV)</td>
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<tr>
<td></td>
<td>Talks about their work and makes improvements to solutions based on feedback received (EV)</td>
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<tr>
<td>1</td>
<td>Understands that computers have no intelligence and that computers can do nothing unless a program is executed (AL)</td>
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<tr>
<td></td>
<td>Recognizes that all software executed on digital devices is programmed (AL) (AB) (GE)</td>
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<tr>
<td></td>
<td>Obtains content from the world wide web using a web browser (AL)</td>
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<tr>
<td></td>
<td>Understands the importance of communicating safely and respectfully online, and the need for keeping personal information private (EV)</td>
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<tr>
<td></td>
<td>Knows what to do when concerned about content or being contacted (AL)</td>
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<tr>
<td></td>
<td>Uses software under the control of the teacher to create, store and edit digital content using appropriate file and folder names (AB) (GE) (GE)</td>
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<tr>
<td></td>
<td>Understands that people interact with computers</td>
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<td></td>
<td>Shares their use of technology in school</td>
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<tr>
<td></td>
<td>Knows common uses of information technology beyond the classrooms (GE)</td>
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<tr>
<td></td>
<td>Talks about their work and makes changes to improve it (EV)</td>
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A number of genres of tools have been helpful in supporting the development of CT skills, including programming, robotics, and game design. Each one of these areas emphasizes various CT components. For instance, writing computer programs requires the analysis of the problem (e.g., determining the goal to achieve), and then breaking the problem down to its constituent processes (e.g., identifying sub-goals and associated steps to achieve the goal). Writing efficient programs requires abstraction and generalization. For instance, if one step needs to be repeated four times, an efficient solution involves looping the step rather than writing the same code four times. Additionally, part of the programming code may be reused within similar problems, with minor adjustments, rather than rewriting a new program from scratch. To test the correctness and efficiency of a program, debugging is necessary. That is why programming is frequently used to promote CT skills.

Similarly, robotics provides learners with tactile experiences to solve problems via CT skills. Learners need to identify the general problem/goal for the robot, then decompose the problem (e.g., figuring out the number of steps or sub-goals to accomplish the goal). Towards this end, learners develop algorithms for the robot so that it can follow the instructions and act accordingly. When the robot does not act as expected, debugging comes into play. Debugging requires the iterative processes of systematic testing and modifying.

Finally, as with programming and robotics, game design and gameplay entail various goals for players to solve. These can be smaller goals represented within levels of the game, and larger goals represented by boss levels and/or part of the narrative. To succeed, players need to derive solution plans, and if a plan fails, then a modified plan is developed. By systematically testing various plans, players find the most effective strategy to overcome challenges in the game. Moreover, skillful players are able to adopt strategies used before to solve new problems. Thus, problem decomposition, systemic testing and debugging, generalization, and iteration are skills required in gaming and are important components of CT.

Programming Tools

Due to its close relationship with computing and programming, CT skills appear to be improved via computational tools, such as Scratch (MIT, 2003). The strength of Scratch is to help young people learn to think creatively, reason systematically, and work collaboratively, and thus is suitable to facilitate CT. It is easy to use with its drag and drop programming method, and provides a meaningful learning environment where learners engage in specific contexts.

Regarding the equivalence of programming skills to CT skills, Cenin [21] compared the effects of employing Scratch (experimental group) with C language (control group) to teach programming concepts to pre-service IT teachers. This
experiment lasted for six weeks, and the participants (n = 56) completed pre- and post-tests relative to their achievement on programming knowledge and skills, but there were no between group attitudinal differences.

To promote algorithmic thinking via Scratch, Grover, Pea, and Cooper [42] designed a seven week Scratch based CT course for 7th and 8th graders (n = 54). Similar to Detin's [21] study, CT gain was measured as pretest to posttest improvement on programming skills. The aim of this quasi-experiment was to see which approach (face-to-face instruction vs. face-to-face plus online) supported deeper learning relative to computational concepts, such as algorithms, loops, conditionals, and decomposition. The two conditions were matched in terms of receiving comparable instruction for the same duration of time (i.e., four days per week, 55 min per day, across seven weeks). Findings revealed that both approaches lead to significantly higher CT gains, and students in the face-to-face plus online group performed significantly better than those in the face-to-face group. Moreover, both groups successfully transferred their programming knowledge and skills to text-based programming tasks.

Alice (Carnegie Mellon University, 1999) functions similarly to Scratch, equipped with ready-made code blocks. Compared with Scratch, it focuses on creating 3D programming projects and also can be utilized to train CT. For example, Denner, Werner, Campe, and Ortiz [29] randomly assigned 320 middle school students to either a dyadic workgroup or individual programming. Students' CT skills were measured by their ability to accomplish Alice tasks during one semester's course. Results demonstrated that students working collaboratively achieved significantly higher CT scores than students working alone. And collaboration was especially beneficial to students with minimal programming experience. These findings are consistent with those reported in an earlier experiment conducted by Werner, Denner, Campe, and Kawamoto [16], testing 311 middle school students.

Busu, Biswas, and Kinnebrew [13] similarly viewed CT constructs as programming-related concepts, such as sequencing, loops, and variables, and they considered iteration problem decomposition, abstraction, and debugging as CT practices. They designed the CTSM platform to integrate ecology and CT learning for 6th graders. Busu et al. employed a pretest/posttest design to test the effectiveness of scaffolding provided by a virtual agent embedded in CTSM. Both the experimental (n = 52) and control (n = 46) groups learned CT and ecology via CTSM, but only the experimental group received scaffolding. That is, when students failed a given task 3–5 times, scaffolding was triggered. In that case, the virtual agent provided conversation prompts, and students answered by choosing one of the options, which in turn triggered a response from the agent.
APPENDIX F. LearningGraph Needs Analysis
Semi-Structured Interview Protocol

Study Explanation: This interview is part of a research project at MIT that is seeking to use systems engineering methods to explore how we can build a better infrastructure to support and manage learning outcomes. Currently, most education systems use one or more sets of standards, such as the Common Core, but this presents a number of challenges across the system—from how learning technologies can capture and track learning data over time and across platforms, to how assessment data is captured and shared, and more. We are exploring how a new data model architecture can be developed, that integrates with existing standards, but is able to mitigate a number of these challenges.

Systems engineering involves conducting a needs analysis with a variety of stakeholders that use the ‘system’—in this case, anyone who works with curriculum, assessment, standards, etc. You have been identified as a participant because of your work in one or more professional roles as it relates to this system. The interview questions will explore your work in this space—i.e. how you currently work with standards, the challenges you encounter with the existing system, and ways in which you feel your work and the system could be improved. Your answers will be kept anonymous, unless you’d prefer to be quoted directly in the study, and will solely be used to inform the preliminary design of this new data model. Your responses can be changed or removed from the study at any point, up until publication.

General Information

Name:

Title:

Roles You Identify With:
- Educator
- Researcher
- Curriculum Designer
- Assessment Developer
- Technology Designer
- Technology Developer

Areas of Expertise:
ROLE GROUP 1: Educators

K-12 public and private school educators, in a variety of subjects.

General Info

What do you teach?
How many years have you been teaching?
Tell me about your classroom.

Standards

Does your school / district use standards?
If so, which ones?
Can you show me the documentation of these (i.e. the documents, website, etc.) that you use for lesson planning?
Do you feel it provides you with the information you need to effectively teach to a given standard?
What do you find helpful about this documentation?
In what ways does it fall short? How would you change or improve these?

Instruction

Walk me through your process when you’re about to tackle a new standard or start a new unit.
Do you look on the Internet or search for additional information about a given standard? What does that look like?
Do you incorporate ideas around student misconceptions into your instruction? How?
On a given standard or topic that you cover, do students thinking strategies ever present a challenge (in other words, are you ever unsure of how to address alternate and incorrect thinking patterns in a way that supports the student in moving in the right direction?)
Do you ever seek out support or further information on this?
If so, it is easy? Helpful? What do you wish existed to help make this easier?
How do you find good/effective lesson plans? Tools and technologies? What do you wish existed to help make this easier?
Does your school have resources in place to track student learning over time?
If so, what are those and what do they do/look like?
How does this technology fall short? How would you improve it?

**Assessment**

How do you construct assessments?
Do you pull examples from the Internet? If so, can you tell me about one or give me an example of what that might look like?
How do you use assessments in your classroom?
What do you wish existed to help make this easier?

**Competencies & Competency-Based Education (CBE)**

Does your school/district currently use, or intend to move to, competency-based education?
How are you currently defining competencies?
How are you using competencies?
How does this relate to the standards you are required to teach?
What resources do you wish existed to make this work easier?

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**ROLE GROUP 2: Informal Learning Environment Facilitators**

 Anyone in an instructional or support role at an informal learning environment (i.e. afterschool program, club, etc.)

**General**

What is your role?
Would you describe it as involving direct/formal instruction, or more of a coach/facilitator?
Tell me about your learning environment.

**Learning**

How is learning, and learners, supported there?
Do you measure or monitor learning over time?
If so, why? How?
What tools and resources would help make this work easier?
Are you doing any work with competencies, mastery, certificates, etc.?
Do you use tools like badges?
Tell me about how that works in your learning environment.
Do you work or partner with other informal learning environments?
Do you integrate your work with the local schools at all?
If so, what type of data and information do you share?

ROLE GROUP 3: Learning Scientists / Researchers

Researchers who study learning and cognition.

NOTE: Each participating researcher is a specialized expert in a given area, and as such interviews with these participants will include a set of personalized set in regards to their work as it relates to this topic. These personalized sets of questions have not yet been constructed, as all participants in this user group have not yet been identified and/or agreed to participate. However, below is an example of what one set of questions would look like, designed for Mark Wilson (Stanford University professor and developer of “construct maps” and the BEAR Assessment System research project).

**General**

What is your role?
What are your main areas of research?

**Learning Sciences**

What do you feel is the cutting-edge work in the learning sciences?
How does learning sciences research influence the design of standards?
Is this satisfactory?
How would you improve it?
There is considerable research on how to effectively support learners in a variety of concepts (e.g., p-prims, misconceptions, concept inventories, etc.), what do you feel is needed to help more educators apply this knowledge to their classroom practice?

What suggestions do you have for bridging the overall research-practice gap in education?

**Learning Progressions**

What is your sentiment on the work in learning progressions?

The methodology as defined for learning progressions necessitates a tight feedback loop between classroom practice for its ongoing refinement and validation. What, do you feel, is necessary to make this a reality to take place at scale?

**Standards**

How do you currently work with standards like the Common Core?

In what ways do you feel they are lacking in their design?

How might you improve them?

**Learning Outcomes**

What type of learning data do you collect in the tools/innovations you build?

How does this data intersect with standards?

What challenges does this present?

inBloom was an example of an attempt to created a unified data infrastructure for education, around many aspects of the system, but specifically as it relates to our conversation, learning outcomes. Do you think education will ever be able to get to this common infrastructure?

How might that help the work you're doing?

**Ex. Participant-Specific Questions**

What is the state of the BEAR Assessment System?

What do you feel has limited its adoption?

What is the difference between 'construct maps' and 'learning progressions'?

Where should the field (research) be placing its emphasis now?
ROLE GROUP 4: Assessment Developers

Those who study and/or design assessments and assessment innovations.

General

What is your role?
Tell me about the type of work you do.

Assessment Design

What is your process for designing an assessment?
Where do you get the background information needed to model a domain?
Is that information easily findable/accessible?
What would make that easier? (i.e. tools, resources, infrastructure, etc.)
When you’ve developed that for a given assessment, do you store that data? Go back and revisit it?
Is that information you’d be willing to share with others?
Why is that information not already shared more readily?
If we built a common data store for assessment designers to use, would you use it? Would you contribute to it? Why or why not?

Standards

How do standards like the Common Core factor into your work?
Would teachers benefit from seeing the background information you put together about a domain as the foundation for an assessment?
Teachers complain of a misalignment between standards and the questions/tasks that show up on standardized tests—that the latter are often a more difficult level. What attributes to this?
What are your feelings about a shared infrastructure, that integrates the types of domain models you use with other constructs such as learning progressions, and standards—so that researchers,
assessment developers, and educators are all using the same foundation, one that goes beyond just one-sentence standards?

What do you like about that? What don’t you like?

ROLE GROUP 5: Instructional Designers & Instructional Technology Designers

Those who design instruction, such as curriculum developers or e-course builders, and those who design instructional technologies, such as cognitive tutors, educational games, etc.

General

What is your role?

Tell me about the type of work you do.

Design

When designing a new [insert technology here], where do you start?

How do you find more information about the topic or concept you are supporting?

Does this meet your needs?

Where does it fall short?

What tools/resources might make this easier?

How do you model learning goals in your work?

How do you measure them?

If/how do you capture that and feed it back to the learner and/or instructor?

Do you capture learning data across your courses/technologies?

If yes, how?

If not, why not?

Standards

How do standards like the Common Core factor into your work?

What is helpful about them?
What challenges do they present?

If you could change standards – the way they are designed or written – how would you change them?
APPENDIX G. Sample Screens of EDmaps Prototypes

**Computational Thinking**

**Definition**
*What is Computational Thinking?* The conceptual foundation required to solve problems effectively and efficiently (i.e., algorithmically, with or without the assistance of computers) with solutions that are reusable in different contexts.

**Overview**
Computational Thinking (CT) is a problem-solving process that includes (but is not limited to) the following characteristics:

- Formulating problems in a way that enables us to use a computer and other tools to help solve them
- Logically organizing and analyzing data
- Representing data through abstractions, such as models and simulations
- Automating solutions through algorithmic thinking (a series of ordered steps)
- Identifying, analyzing, and implementing possible solutions with the goal of achieving the most efficient and effective combination of steps and resources
- Generalizing and transferring this problem-solving process to a wide variety of problems

**Keywords**
- programming
- coding
- algorithms

**Related Standards**
- L13 CT1
- L13 CT2
- L13 CT3
- L13 CT4
- L13 CT5
- L13 CPP1
- L13 CPP2
- L13 CPP3
- L13 CPP4
- L13 CPP5
- L13 CPP6
- L13 CL1
- L13 CL2
- L13 CL3
Why does teaching Computational Thinking matter?

Over the past decade, Computational Thinking (CT) has become a very hot topic in educational research and practice. References of CT often relate to coding or programming, but it is a competency that is much broader than that. According to the National Research Council [7], everyone should acquire CT, not only programmers. CT skills include managing information effectively and efficiently with technologies in our data-driven era [20,32,43,108,120]. A workforce with individuals possessing CT skills increases the competitiveness of the United States in the world economic market [77).

A primary motivation for introducing CT practices into science and mathematics classrooms is the rapidly changing nature of these disciplines as they are practiced in the professional world [16,41]. In the last 20 years, nearly every field related to science and mathematics has seen the growth of a computational counterpart. Examples include Bioinformatics, Computational Statistics, Chemometrics, Neuroinformatics, which has been recognized both by those within the STEM education communities and computer science education organizations [9,94]. Bringing computational tools and practices into mathematics and science classrooms gives learners a more realistic view of what these fields are, better prepares students for pursuing careers in these disciplines [9,37], and helps equip students to be more savvy STEM citizens.

From a pedagogical perspective, the thoughtful use of computational tools and skillsets can deepen learning of mathematics and science content [46,33,73,78,90,93,102,104,117,118]. The reverse is also true—namely that science and mathematics provide a meaningful context (and set of problems) within which CT can be applied [46,55,62]. This differs markedly from teaching computational thinking as part of a standalone course in which the assignments that students are given tend to be divorced from real-world problems and applications. This sense of authenticity and real-world applicability is important in the effort to motivate diverse and meaningful participation in computational and scientific activities [18,20,36,39]. This reciprocal relationship—using computation to enrich mathematics and science learning and using mathematics and science contexts to enrich computational learning—is at the heart of our motivation to bring computational thinking and science and mathematics concepts together.

For learners, possessing good CT skills may be a motivator for students to pursue computer science [1] and other STEM-related majors [40,106]. CT has also been linked to creativity and innovation [73,95], and it has important applications in other STEM areas [11,162].
CONSTRUCT SUMMARY

CT stems back to the constructionist work of Seymour Papert [11-12], and was first coined as a term in a seminal article by Wing [128]. She explained that CT entails “solving problems, designing systems, and understanding human behavior, by drawing on the concepts fundamental to computer science” (p. 32). As such, it represents an ability to analyze and then solve various problems—a framing that provided a fresh perspective on the relationship between humans and computers, and gave rise to a wave of research on CT.

CT in K-12

In K-12 education, CT includes several aspects, including:

- problem-solving skills and particular dispositions, such as confidence and persistence, when confronting particular problems [14];
- the ability to think with the computer-as-tool [14]; and
- using computers to model their ideas and develop programs (i.e. programming skills) [14].

The earliest work to put this idea into practice was the development of the Logo programming language [10-11]. While Logo was designed most immediately to teach mathematical concepts, its creators quickly recognized the far-reaching benefits of the skills learned through programming, arguing that “computer presence could contribute to mental processes not only instrumentally but in more essential, conceptual ways, influencing how people think even when they are far removed from physical contact with a computer” [11, p. 4].

EDUCATOR'S NOTE: Extensive research over the last three decades has focused on issues related to teaching and learning skills, concepts, and practices relevant to computational thinking [13], and though several frameworks and guidelines for bringing computational thinking into K-12 education have emerged, there is no one agreed-upon model [10]. This map focuses on just one of those prominent models. If the reader is interested in exploring additional frameworks, please contact jgroff@media.mit.edu.
CONSTRUCT SUMMARY

Building competency in CT means development in a range of sub-competencies, including Data Literacy, Modeling & Simulation practices, Programming and Problem-Solving Skills, and Systems Thinking.

Sub-Concepts

There are five cognitive processes with the goal of solving problems efficiently and creatively:

I. Decomposition: Dissect a complex problem/system into manageable parts. The divided parts are not random pieces, but functional elements that collectively comprise the whole system/problem.

II. Abstraction: Extract the essence of a (complex) system. Abstraction has three subcategories:
   (a) Data collection and analysis: Collect the most relevant and important information from multiple sources and understand the relationships among multilayered datasets;
   (b) Pattern recognition: Identify patterns/rules underlying the data/information structure;
   (c) Modeling: Build models or simulations to represent how a system operates, and/or how a system will function in the future.

III. Algorithms: Design logical and ordered instructions for rendering a solution to a problem. The instructions can be carried out by a human or computer. There are four subcategories:
   (a) Algorithm design: Create a series of ordered steps to solve a problem;
   (b) Parallelism: Carry out a certain number of steps at the same time;
   (c) Efficiency: Design the fewest number of steps to solve a problem, removing redundant and unnecessary steps;
   (d) Automation: Automate the execution of the procedure when required to solve similar problems.

IV. Debugging: Find and fix errors after building up particular models, including to Detect and identify errors, and then fix the errors, when a solution does not work as it should.

V. Iteration: Repeat design processes to refine solutions, until the ideal result is achieved.
This competency model integrates three sub-concepts, tracked across 8 development levels. Within each, four sub-concepts are identified as well—see the following notation identified throughout each:

I. DE = Decomposition II. AB = Abstraction III. AL = Algorithmic Thinking IV. EV = Debugging
<table>
<thead>
<tr>
<th>Competency</th>
<th>Description</th>
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<tbody>
<tr>
<td>DE = Decomposition</td>
<td>Designs a solution that depends on solutions to smaller instances of the same problem (recursion) (AL) (DE) (AB)</td>
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<tr>
<td>AB = Abstraction</td>
<td>Understands that some problems cannot be solved computationally (AB)</td>
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<tr>
<td>AL = Algorithmic Thinking</td>
<td>Recognizes that the design of an algorithm is distinct from its expression in a programming language (which will depend on the programming constructs available) (AL) (AB)</td>
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<td>EV = Debugging</td>
<td>Evaluates the effectiveness of algorithms and models for similar problems (AL) (AB)</td>
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<td>Recognizes where information can be filtered out in generalizing problem solutions (AL) (AB)</td>
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<td>Uses logical reasoning to explain how an algorithm works (AL) (AB) (DE)</td>
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<td>Represents algorithms using structured language (AL) (DE) (AB)</td>
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<td>Understands a recursive solution repeatedly applies the same solution to smaller instances of the problem (AL)</td>
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<td>Recognizes that some problems share the same characteristics and use the same algorithm to solve both (AL)</td>
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<td>Understands the notion of performance for algorithms and appreciates that some algorithms have different performance characteristics for the same task (AL) (EV)</td>
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<td>Understands that iteration is the repetition of a process such as a loop (AL)</td>
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<td>Recognizes that different algorithms exist for the same problem (AL)</td>
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<tr>
<td></td>
<td>Represents solutions using a structured notation (AL) (AB)</td>
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<tr>
<td></td>
<td>Can identify similarities and differences in situations and can use these to solve problems (pattern recognition)</td>
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<td>Shows an awareness of tasks best completed by humans or computers (EV)</td>
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<td></td>
<td>Designs solutions by decomposing a problem and creates a sub-solution for each of these parts (DE) (AL) (AB)</td>
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<td></td>
<td>Recognizes that different solutions exist for the same problem (AL) (AB)</td>
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<td></td>
<td>Designs solutions (algorithms) that use repetition and two-way selection i.e., if, then and else (AL)</td>
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<td></td>
<td>Uses diagrams to express solutions (AB)</td>
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<td></td>
<td>Uses logical reasoning to predict outputs, showing an awareness of inputs (AL)</td>
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<td></td>
<td>Understands that algorithms are implemented on digital devices as programs (AL)</td>
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<td></td>
<td>Designs simple algorithms using loops, and selection i.e., if statements (AL)</td>
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<tr>
<td></td>
<td>Uses logical reasoning to predict outcomes (AL)</td>
</tr>
<tr>
<td></td>
<td>Detects and corrects errors i.e., debugging, in algorithms (AL)</td>
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<tr>
<td></td>
<td>Understands what an algorithm is and is able to express simple linear (non-branching) algorithms symbolically (AL)</td>
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<tr>
<td></td>
<td>Understands that computers need precise instructions (AL)</td>
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<tr>
<td></td>
<td>Demonstrates care and precision to avoid errors (AL)</td>
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</tbody>
</table>
COMPETENCY MODEL

I. DE = Decomposition  II. AB = Abstraction  III. AL = Algorithmic Thinking  IV. EV = Debugging

1. Executes, checks and changes programs (AL)
2. Uses logical reasoning to predict the behavior of programs (AL)
  Detects and corrects simple semantic errors i.e., debugging in programs (AL)
3. Declares and assigns variables (AB)
  Uses post-tested loop e.g., 'until', and a sequence of selection statements in programs (AL)
4. Uses a variable and relational operators within a loop to govern termination (AL)
5. Has practical experience of a high-level textual language, including using standard libraries when programming (AB) (AL)
   Selects the appropriate data types (AL) (AB)
6. Knows the difference between, and uses appropriately, if and if then else statements (AL)
7. Uses nested selection statements (AL)
   Appreciates the need for, and writes, custom functions including use of parameters (AL) (AB)
8. Designs / writes nested modular programs that enforce reusability utilizing sub-routines wherever possible (AL) (AB) (DE)
   Understands the difference between 'While' loop and 'For' loop, which uses a loop counter (AL) (AB)
   Understands and uses two dimensional data structures (AB) (DE)
   Appreciates the effect of the scope of a variable (e.g., a local variable can't be accessed from outside its function) (AB) (AL)
9. Understands and applies parameter passing (AB) (DE)
   Understnads the difference between, and uses, both pre-tested e.g., 'while', and post-tested e.g., 'until' loops (AL)
   Applies a modular approach to error detection and correction (AB) (DE)
10. Uses nested selection statements (AL)
    Appreciates the need for, and writes, custom functions including use of parameters (AL) (AB)
11. Knows the difference between, and appropriately uses if and if then else statements (AL)
12. Uses a variable and relational operators within a loop to govern termination (AL)
13. Detects and corrects syntactical errors (AL)
14. Designs, writes and debugs modular programs using procedures (AL) (DE) (AB)
    Knows that a procedure can be used to hide the detail with sub-solution (AL) (DE) (AB)
15. Creates programs that implement algorithms to achieve given goals (AL)
16. Declares and assigns variables (AB)
   Uses post-tested loop e.g., 'until', and a sequence of selection statements in programs (AL)
17. Uses arithmetic operators, if statements, and loops, within programs (AL)
18. Uses logical reasoning to predict the behavior of programs (AL)
   Detects and corrects simple semantic errors i.e., debugging in programs (AL)
19. Able to create a simple program in an environment that does not rely on text (e.g., programmable robots) (AL)
20. Understands that programs execute by following precise instructions (AL)
21. Has practical experience of a high-level textual language, including using standard libraries when programming (AB) (AL)
22. Selects the appropriate data types (AL) (AB)
23. Knows the difference between, and appropriately uses if and if then else statements (AL)
24. Uses a variable and relational operators within a loop to govern termination (AL)
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54. Uses logical reasoning to predict the behavior of programs (AL)
   Detects and corrects simple semantic errors i.e., debugging in programs (AL)
55. Able to create a simple program in an environment that does not rely on text (e.g., programmable robots) (AL)
56. Understands that programs execute by following precise instructions (AL)

<table>
<thead>
<tr>
<th>I. DE = Decomposition</th>
<th>II. AB = Abstraction</th>
<th>III. AL = Algorithmic Thinking</th>
<th>IV. EV = Debugging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performs operations using bit patterns e.g. conversion between binary and hexadecimal, binary subtraction etc. (AB) (AL)</td>
<td>Knows what a relational database is, and understands the benefits of storing data in multiple tables (AB) (DE)</td>
<td>Knows the relationship between data representation and data quality (AB)</td>
<td>Knows that digital computers use binary to represent all data (AB)</td>
</tr>
<tr>
<td>Understands and can explain the need for data compression, and performs simple compression methods (AL) (AB)</td>
<td>Knows the relationship between binary and electrical circuits, including Boolean logic (AB)</td>
<td>Understands how and why values are data typed in many different languages when manipulated within programs (AB)</td>
<td>Knows that computers transfer data in binary (AB)</td>
</tr>
<tr>
<td>Knows how numbers, images, sounds and character sets use the same bit patterns (AB)</td>
<td>Knows how bit patterns represent numbers and images (AB)</td>
<td>Understands the relationship between resolution and color depth, including the effect on file size (AB)</td>
<td>Performs simple operations using bit patterns e.g. binary addition (AB) (AL)</td>
</tr>
<tr>
<td>Performs more complex searches for information e.g. using Boolean and relational operators (AL) (EV)</td>
<td>Defines data types: real numbers and Boolean (AB)</td>
<td>Distinguishes between data used in a simple program (a variable) and the storage structure for that data (AB)</td>
<td>Knows that digital computers use binary to represent all data (AB)</td>
</tr>
<tr>
<td>Analyses and evaluates data and information, and recognizes that poor quality data leads to unreliable results, and inaccurate conclusions (AL) (EV)</td>
<td>Queries data on one table using a typical query language (AB)</td>
<td>Knows the difference between data and information (AB)</td>
<td>Knows why sorting data in a flat file can improve searching for information (EV)</td>
</tr>
<tr>
<td>Understands the difference between data and information (AB)</td>
<td>Performs more complex searches for information e.g. using Boolean and relational operators (AL) (EV)</td>
<td>Knows why sorting data in a flat file can improve searching for information (EV)</td>
<td>Uses filters or can perform single criteria searches for information (AL)</td>
</tr>
<tr>
<td>Recognizes different types of data: text, number (AB)</td>
<td>Appreciates that programs can work with different types of data</td>
<td>Recognizes different types of data: text, number (AB)</td>
<td>Recognizes that digital content can be represented in many forms (AB)</td>
</tr>
<tr>
<td>Appreciates that programs can work with different types of data</td>
<td>Recognizes that data can be structured in tables to make it useful (AB) (DE)</td>
<td>Recognizes that data can be structured in tables to make it useful (AB) (DE)</td>
<td>Distinguishes between some of these forms and can explain the different ways that they communicate information (AB)</td>
</tr>
</tbody>
</table>
A number of genres of tools have been helpful in supporting the development of CT skills, including programming, robotics, and game design. Each one of these areas emphasizes various CT components. For instance, writing computer programs requires the analysis of the problem (e.g., determining the goal to achieve), and then breaking the problem down to its constituent processes (e.g., identifying sub-goals and associated steps to achieve the goal). Writing efficient programs requires abstraction and generalization. For instance, if one step needs to be repeated four times, an efficient solution involves looping the step rather than writing the same code four times. Additionally, part of the programming code may be reused within similar problems, with minor adjustments, rather than rewriting a new program from scratch. To test the correctness and efficiency of a program, debugging is necessary. That is why programming is frequently used to promote CT skills.

Similarly, robotics provides learners with tactile experiences to solve problems via CT skills. Learners need to identify the general problem/goal for the robot, then decompose the problem (e.g., figuring out the number of steps or sub-goals to accomplish the goal). Towards this end, learners develop algorithms for the robot so that it can follow the instructions and act accordingly. When the robot does not act as expected, debugging comes into play. Debugging requires the iterative processes of systematic testing and modifying.

Finally, as with programming and robotics, game design and gameplay entail various goals for players to solve. These can be smaller goals represented within levels of the game, and larger goals represented by boss levels and/or part of the narrative. To succeed, players need to derive solution plans, and if a plan fails, then a modified plan is developed. By systematically testing various plans, players find the most effective strategy to overcome challenges in the game. Moreover, skillful players are able to adopt strategies used before to solve new problems. Thus, problem decomposition, systemic testing and debugging, generalization, and iteration are skills required in gaming and are important components of CT.
Due to its close relationship with computing and programming, CT skills appear to be improved via computational tools, such as Scratch. The strength of Scratch is to help young people learn to think creatively, reason systematically, and work collaboratively, and thus is suitable to facilitate CT. It is easy to use with its drag-and-drop programming method, and provides a meaningful learning environment where learners engage in specific contexts. A number of research projects have shown that Scratch enhancing CT and programming knowledge, skills.

Alice (Carnegie Mellon University, 1999) functions similarly to Scratch, equipped with ready-made code blocks. Compared with Scratch, it focuses on creating 3D programming projects. It also can be utilized to train CT.
The CTSiM platform was designed to integrate ecology and CT learner for 6th graders, supporting concepts such as sequencing, loops, and variables, iteration, problem decomposition, abstraction, and debugging. CTSiM uses a virtual agent when students fail a given task 3-5 times, scaffolding from the agent is triggered. In that case, the virtual agent provided conversation prompts, and students answered by choosing one of the options, which in turn triggered a response from the agent.

Program Your Robot

This "serious game" aims to teach programming and computational thinking concepts. It is an Adobe Flash game called "Program your robot" in which players must help a robot escape from a series of platforms using a "solution algorithm". Players construct this "solution algorithm" by giving various commands (split into action & programming commands) to the robot. It is similar to LightBot and Robozzle but the authors claim that those games aren't designed for learning, but fun, whereas theirs is. Although lacking empirical evidence they feel that their game encompasses the following CT skills: algorithm building, conditional logic, tracking a simulation, debugging, and student responses supported this.
### Lego Mindstorms

Lego Mindstorms series of kits contain software and hardware to create customizable, programmable robots. They include an intelligent brick computer that controls the system, a set of modular sensors and motors, and Lego parts from the Technic line to create the mechanical systems. Mindstorms kits are sold both commercially and to be used as an educational tool, originally through a partnership between Lego and the MIT Media Laboratory. Solving robot programming problems revealed students' CT skills, which were measured via rubrics related to the quality of problem-solving performance.

### TangibleK Robotics Curriculum

How early can children learn CT skills? The TangibleK Robotics curriculum included 20 hours of instruction and one final project to measure students’ development of CT in terms of debugging, sequencing, loops, and conditionals. TangibleK teaches CT concepts in a way that is suitable for students' developmental stages.
AgentSheets is an authoring tool that uses game design to teach CT, as well as to promote students' interest and skills in computer science. AgentSheets provides a low entry bar for inexperienced students, yet does not restrain students with advanced abilities from creating complex game systems. In one study, teachers and community college students in two summer workshops learned how to animate interactions among objects via programming, using five AgentSheets design tasks.

GameBlox is a game editor that uses a blocks-based programming language to allow anyone to make games. It's free and no downloads are required. You can make games online that you can play both on this site and on your mobile device.
Pandemic is a cooperative board game based on the premise that four diseases have broken out in the world, each threatening to wipe out a region. In data collected on first year undergraduate students playing the game, looking at the CT concepts being used, they found that distributed computation (which they describe as rule based action) was the most common found during all three sessions, and believe that players had to 1) internalize a set of rules and 2) optimize behavior and strategies based on these rules and they believe CT concepts are in play across various strategic board games.

CS Unplugged is a collection of free learning activities that teach CS through engaging games and puzzles that use cards, string, crayons and lots of running around. Developed by the University of Canterbury, New Zealand, so that young students could interact with computer science, experiencing the kinds of questions and challenges that computer scientists experience, but without having to learn programming first. It includes:

- Videos of different activities
- Making bracelets coded in binary
- Competitions
- Shows
- Adapting CS Unplugged activities to different themes
- Outdoor activities
ASSESSMENTS

Research-supported assessments to support ST:

Dr. Scratch - Competency Assessment

An online tool that can evaluate your Scratch projects in a variety of computational areas. You can upload an sb2 file or just provide the project url, avoiding the need to previously download the project to your computer. By analyzing your projects with Dr. Scratch, you can easily check your Computational Thinking Score.

Dr. Scratch uses the Progression of Early Computational Thinking Model (ECoT), a framework to assess CT skills of primary students by analyzing Scratch projects.
### RELATED CONSTRUCTS

The obstacle on the way that someone finds to reach the intended purpose is called Problem. If someone meets with some obstacles while endeavoring to reach a certain purpose or intellect, it means there is a problem for that person (Menti 2004). When solving a complex problem in any domain, one should generate and test hypotheses systematically to understand how the system works. It is impossible to test all possibilities, so selecting the right parameters to test is important.

According to [13], critical thinking has been defined as "the use of cognitive skills or strategies that increase the possibility of the desired behaviors." When the literature is examined, it could be observed that one of the most criticized issues of our educational system is rule learning that is the result of the traditional understanding [13].

Requires one to solve problems by thinking as a designer [9]. CT and design thinking both focus on problem solving. Design thinking, like engineering, focuses on product specification and the requirements imposed by both the human and the environment (i.e., practical problems). Again, CT is not limited by physical constraints, enabling people to solve theoretical as well as practical problems.

Although both involve understanding and modeling systems, CT is broader than ST, which focuses on identifying and understanding the workings of a system as a whole. CT aims to solve problems efficiently and effectively, going beyond modeling and understanding to include algorithmic design, automation, and generalization to other systems/problems—and is a broader competency that contains a number of

Involves the application of math skills to solve math problems, such as equations and functions [19]. Mathematical thinking consists of three parts: beliefs about math, problem solving processes, and justification for solutions. The main commonality between CT and mathematical thinking is problem solving processes [19]. See figure...

CT skills are not the same as programming skills [9], but along with problem-solving, these competencies are very closely related and being able to program is one benefit of being able to think computationally [9].

Involves skills needed to build or transform things in the world in order to construct better lives [9] as well as "applied science and math, solving problems, and making things" [9]. The overlap between CT and engineering includes problem solving, along with understanding how complex systems work in the real world [15]. However, unlike engineering, CT is intended to help humans understand complex phenomena through simulations and modeling, which can transcend physical constraints [15].
This is an unpublished prototype of the LearningGraph project.
Please do not distribute without consent.

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REFERENCES


