Chapter 27
Personalized Mastery-Based Learning Ecosystem:
A New Paradigm for Improving Outcomes and Defying Expectations in Early Childhood

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ABSTRACT

Children differ greatly in what they know and are ready to learn when they enter school. However, when their individual needs are assessed and addressed, even very young children can learn and can greatly surpass grade-level expectations. This chapter discusses the partial implementation of a research-based personalized mastery-based learning ecosystem (PMLE) that uses My Math Academy, a games-based learning program and personalized teacher resources to deliver learning outcomes for young children at scale. The implementation of the My Math Academy PMLE with nearly 1000 prekindergarteners at a high-need school district resulted in significant learning gains, including gains beyond grade level, despite large learner variability in students' prior knowledge and learning progress. Teachers also felt empowered to deliver differentiated instruction, building on the personalized learning students experienced through My Math Academy. Results showed that the PMLE framework can help close equity gaps and help children excel in ways that defy expectations.

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INTRODUCTION

Learner Variability

Although children develop through relatively predictable stages, as environmental influences interact with individual genetic variation and developmental timing, there is great individual variation in how children learn and acquire skills (Rose, Rouhani, Fischer, 2013; Rose, 2016; Pape, 2018). This learner variability means that children of precisely the same age can be at different developmental levels in different domains, learning different things at different rates. Each responds differently to adversity and support; each also demonstrates their learning differently and varies in their needs for instruction, support, and enrichment.

A challenge in early education is addressing learner variability at the onset of formal schooling. Consider the fact that many children enter kindergarten with gaps in their learning foundation that make it difficult for them to learn successfully in school—gaps that only widen as children move on to successive grades (Duncan et al., 2007; Duncan & Magnusen, 2011; Seigler, 2009). This affects certain subgroups of children more than others, as children of color and children from low SES homes have been found to fall behind in disproportionate numbers when compared to their more advantaged peers (deBrey et al., 2019).

The recent COVID-19 pandemic has exacerbated the problem of learner variability. Near the end of the 2019-2020 school year, millions of children who had been attending school in person were suddenly expected to learn in virtual or hybrid environments due to the COVID-19 pandemic. During the 2020–2021 school year, many of these children who had been learning remotely gradually returned to in-person schooling. Differences in school districts' approaches to remote or hybrid learning, as well as varying family and home environments had a pronounced impact on the performance of these children. By the end of the 2020-2021 school year, students were, on average, found to be four to five months behind in math and reading (Dorn, Hancock, Sarakatsannis, & Viruleg, 2020), and while many students had substantial amounts of unfinished learning for their grade level, the greatest amount was concentrated among Black, Indigenous, and Persons of Color (BIPOC; Kuhfeld et al., 2020; Meckler & Natanson, 2020; Renaissance Learning, 2020). Though schools struggled to meet the needs of students prior to the emergence of COVID-19 (deBrey et al., 2019), the pandemic has been a catalyst for deeper examination of the challenge of addressing learner variability—requiring us to consider the ways in which traditional models of schooling have fallen short, and how we might better design programs that leverage all the inputs in a young child's life (e.g., home, parents, school, community, technology, etc.) to ensure that their learning needs are met.

The notion that there is a preponderance of "average" children in our school system, for whom all instruction can be designed and delivered, is a myth (Rose, 2016; Rose, Rouhani, & Fischer, 2013). No two children are alike, nor do they have the same developmental or academic needs – each child's developmental path is uniquely individual. Traditional instruction that provides the same instruction at the same pace to children of the same age not only fails to nurture the potential of each child, but may actually do harm by subjecting children to the negative long term academic effects that result from diminished or non-existent opportunities to master critical core content and competencies in early childhood (Claessens & Engel, 2013; Duncan et al., 2007; Nguyen et al., 2016). While "individualizing the curriculum" is a common refrain heard throughout education, the meaning behind this phrase is often unclear (Wormeli, 2005). There are many ways to tailor the learning to the individual, including adapting content scope and sequence, pace, and pedagogy. However, if standardized measures of student achievement are any indication (deBrey et al., 2019), adapting learning experiences across these different dimensions, simultaneously, for all students in a classroom is impossible in present educational paradigms. Teachers have tried to make this work, often by creating small groups of children who generally would benefit from similar instruction. However, it remains incredibly challenging for a teacher to discern in a group of 20-30 children—at any given moment—the prior knowledge that each child brings to bear, what they are learning, how well they are mastering the targeted content, and where their misconceptions might be developing, much less effectively address their needs. As Bloom (1968, 1971) pointed out in his pioneering work on mastery learning, it is possible for an expert educator in a one-to-one setting with a student to do this, but nearly impossible for a teacher in a traditional whole class or small group setting to do the same. Yet, to provide every child with an equal opportunity to succeed, we must attend to the variability present among learners.

Addressing learner variability requires a systematic approach that involves various key inputs in the child's life. According to Bloom (1984), the four main "objects of change," through which the child's learning may be impacted, are the child, the teacher, the materials, and the environment. Adapting the learning experience to the individual *Child* means understanding the prior knowledge of the child, the child's strengths, misconceptions, learning approaches and pacing needs. Though Bloom did not describe it this way, we would also suggest that this means designing experiences that are highly engaging and that can motivate the child's interest in the topic and desire to learn it. Leveraging the design of the curriculum *Materials* means designing curriculum scopes and sequences that are explicit, granular, and able to be flexibly adapted to the child's needs—giving intentional consideration to what the child knows, what they don't know, and what they are most ready to learn next. Leveraging the *Teacher* refers to empowering educators with the critical knowledge (both content area and pedagogical) needed to understand and deliver differentiated instruction, based on best practices a child's unique needs and learning trajectories. Lastly, leveraging the *Environment* means recognizing that learning does not only occur in school environments, but that learning takes place in the home prior to the onset of formal schooling and has the potential to continue once the child has begun formal schooling, and that for parents and caregivers who want to help and support their children, better guidance and support is needed (Betts, 2021; Clements & Sarama, 2014; Sonnenschein et al., 2005). When all "objects of change" are systematically mobilized to meet the unique needs of the individual child, these "objects" are transformed into "agents of change" that can drive the acceleration and durability of learning outcomes (Betts, Thai, & Gunderia, 2021).

In the field of biological science, the term *ecosystem* refers to the complex relationships and interactions between living things and their environment that ensures the survival (or not) of an organism (Merriam Webster, 2021). In this kind of ecosystem, everything in the system is impacted by everything else, and adaptivity and responsiveness are key ingredients in the success of individual living things. Similarly, complex relationships and interactions between learners, other individuals, and their environment define a learner's *Learning Ecosystem.* The interconnectedness and interdependency of learners with their environment has been described in the work of many educational theorists, including Vygotsky, Bloom, Bronfenbrenner, and others. Vygotsky (1986) wrote extensively about the importance of "more knowledgeable others" in the child's learning environment (i.e., parents, older siblings, caregivers, etc.), as well as teachers. Bloom (1984) described relationships between the four objects of change (discussed previously) which, when properly leveraged, could increase the learner's ability to learn. Bronfenbrenner(1986, 1992, 1999) expanded upon these learning ecosystem frameworks and models to describe the complexity of the relationships contained there in more detail, positioning the child at the center of several ever-expanding layers of influence, from proximal (e.g., parents, family), to distal (e.g., education policy, societal views on education, etc.). As these scholars and theorists have pointed out, this *ecosystem can be leveraged to ensure the successful learning of the child* through the empowerment of all the stakeholders in the child's learning sphere to work together to respond to and impact the child's learning.

In this chapter, we posit that at school entry in preschool or prekindergarten, many 3- and 4-year-olds are more capable than conventional wisdom leads us to believe or that common frameworks for early learning would suggest (e.g., Headstart Early Outcomes Learning Framework, U.S. Department of Health and Human Services, 2015), and we ask the reader to consider the notion that conventional preschool through kindergarten paradigms may, in fact, actually limit the learning that young children are capable of when their individual learning needs in a content area are effectively addressed. The question at hand: how do we identify, reinforce, and build upon the knowledge, understandings, skills and capabilities that already exist in children, and the adults that support them, as a basis for *systematic* growth? In this chapter, we propose the design and implementation of a Personalized Mastery-Based Learning Ecosystem (PMLE) framework for early mathematics learning as a scalable solution, grounded in Bloom's four objects of change and Bronfenbrenner's ecological systems theory that addresses learner variability. We know that expertly designed mastery-based personalized learning systems afforded by advances in technology and the availability, collection, and analysis of meaningful data, have the potential to address learner variability and its impact on achievement at scale (e.g., Betts, Thai, Jacobs, & Li, 2020; Bang, Li, & Flynn, in press; Owen & Hughes, 2019; Thai, Bang, Li, 2021). Additionally, when provided with actionable data, research-based strategies, and resources to meet the needs of each child, educators and caretakers are effectively empowered to deliver personalized instruction to diverse learners from a wide range of backgrounds and levels of prior knowledge. We further present findings from an implementation of a portion of that PMLE framework during the 2020/2021 COVID-19 pandemic when schooling was significantly disrupted. The mobilization of the child's personal learning ecosystem ensured that pre-kindergarteners enter kindergarten with competencies needed for later success. Results also suggest that innovations with PMLEs enabled by research, technology, and data can accelerate student learning beyond grade-level expectations and ensure equitable instruction for every child.

BACKGROUND

The Situated Learner

Learners do not learn in a vacuum, but rather are situated within unique contexts, relationships and experiences that influence their individual learning needs (Bronfenbrenner, 1986, 1999, 2005). Decades of research in human learning and development have shown that key to effective learning and healthy development is a whole child approach to education, one that begins with a nurturing family environment and positive school climate that affirm and support the child's varying strengths, needs, and interests as they engage in learning (for summaries, see Cantor, Osher, Berg, Steyer, & Rose, 2018; Osher, Cantor, Berg, Steyer, and Rose, 2018). Children actively construct knowledge based on these relationships, experiences, and social contexts. They learn best when they are actively engaged with *more knowledgeable others* (Vygotsky, 1986) who can guide the learning of concepts and knowledge and connect them to the learner's lived experiences and prior knowledge. Thus, effective teachers—whether they be parents or caregivers in the home environment, professional educators in the school environment, or other significant people in the child's life—do not "deliver" information to students. Rather, they are guides and mentors that lead or draw forth the child's development by setting appropriately challenging tasks in the child's zone of proximal development (ZPD), watching and guiding the child's efforts, and offering feedback and guidance as needed to help the child progress forward (See Fig. 1; Vygotsky, 1986).

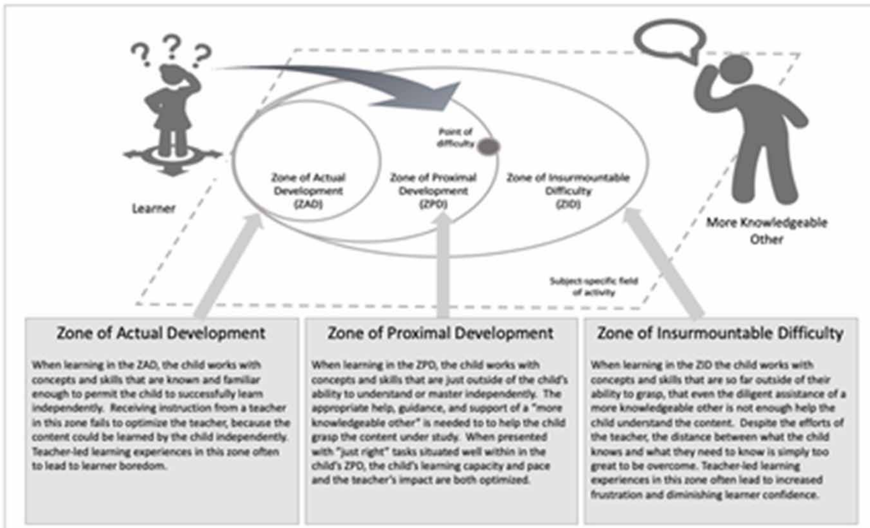
Furthermore, human relationships are catalysts for healthy development and learning (Center on the Developing Child, 2016). For example, the supportive and responsive interactions children have with caring adults who understand their needs have a huge impact on language development (Romero et al., 2018), can buffer potentially negative effects of childhood adversity (Shonkoff, 2012; 2011), can promote the development of positive attitudes and behaviors in children, build their confidence as learners, and help address the impacts of inequality (e.g., Gay, 2010). Such research and wisdom of practice offer insights for educators, policy makers, and product developers about how to develop such environments. The challenge is, how do we systematically leverage an ecosystems approach that can synergize and empower the whole "village" – the entire community of people surrounding the learner – to work together to support the conditions necessary for a child's successful learning? Even more importantly, how do we do this on a wide scale for *every* child?

Optimizing Learning through Personalized Instruction

Decades of research on learning and instruction have provided us with guidelines for practice and design for effective learning (e.g., Clark & Mayer, 2003; Bransford, Brown, & Cocking, 2000; Bransford et al., 2005; Bjork & Yan, 2014; Pashler et al., 2007; Hirsh-Pasek et al., 2015). Furthermore, the design of a curriculum, along with the pedagogy used to deliver that curriculum, can be used to optimize learning by building on each child's prior knowledge and experiences, connecting those to the big ideas within and across disciplines, and designing tasks that are not only engaging and relevant, but are appropriately challenging for the child's level of learning readiness (e.g., Appleton, Christenson, & Furlong, 2008; Betts, Appleton, Reschly, & Christenson, 2010; Finn & Zimmer, 2012; Vygotsky, 1986). Providing opportunities for children to take risks, set goals, and monitor their own work can encourage them to become more self-confident, independent learners (McGuire & McGuire, 2015). Taken together, these are necessary ingredients to challenge and support children to perform at the best of their abilities, help them transfer knowledge and skills to new contexts and new content areas, and achieve.

According to Vygotsky (1986), optimal learning occurs through a partnership between the learner and a *more knowledgeable other* who has the capacity to guide, lead, and help the learner progress in ways that would be difficult for the learner to accomplish on their own. For example, a learner of any age, who already knows how to play checkers, may have some difficulty independently learning the game of chess, even though there are some similarities (e.g., turn-taking game, same game board, some pieces move similarly, etc.). The learner will learn faster with a guide who is more expert at the concept or skill to be learned—someone who not only explains the rules of the game, but who can play together with the learner, scaffolding the game itself to the learner's level while slowly ramping up the difficulty, and offering guidance and strategies just as the learner is ready to understand and practice applying them. Vygotsky identified three "zones" that learners move through as they become more competent (See Fig. 1). Of the three, the zone of proximal development (ZPD) describes the area where the most learning can occur. When learning in the ZPD, the learner tackles, in partnership with a more knowledgeable other, tasks and learning challenges that are just beyond what the learner can do on their own. The more

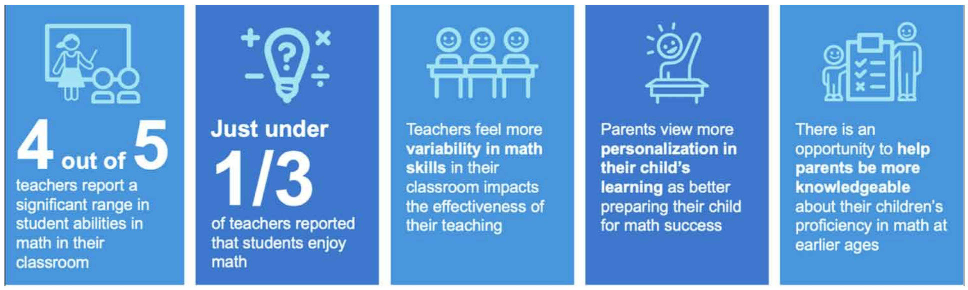
Figure 1. Understanding of the zone of proximal development (Based on Zaretskii's (2009) interpretation of Vygotsky). This figure demonstrates how the learner performs the action of acquiring experience (assimilating content knowledge and skills).



knowledgeable other acts as a guide, stretching the understanding and skills of the learner, and challenging them while providing support, so that the learner may succeed in the most expeditious way possible. In this manner, the learner learns faster than if they were attempting to learn content on their own.

To help a child progress in the most efficient way possible, ensuring mastery, durability, and transferability of knowledge and skills, three things must be known about the child at any given moment: what the child already knows, what they do not yet know, and what they are *most ready* to learn next (e.g., Betts, 2019; Bloom, 1984; Vygotsky, 1986; Roll, Russell, & Gasevic, 2018; Sottilare, Graesser, Hu, & Holden, 2013). In response to that information, the child must be provided with (1) just-right activities that are in their ZPD, (2) a more knowledgeable other (e.g., parent, coach, tutor, teacher, intelligent tutor, software, etc.) who can recognize the child's growing and developing understanding (or misunderstanding) of content and provide just-in-time feedback and guidance, and (3) the ability to adapt or tailor the learning experiences, both individual activities as well as learning trajectories, to the child's needs. Through these mechanisms, the child does not spend time learning content that is already known, but rather is directed to activities and experiences that are more likely to lead to faster growth. Unfortunately, children in school often spend a substantial amount of time exposed to content they either already know and have mastered which leads to boredom, or to content that is so far beyond their ability level that they become frustrated and confused while trying to learn. Due to pervasive learner variability, it is rare in a classroom that the learning content is presented at the "just right" level for all the learners. The content will inevitably be too easy for some, just right for others, and too difficult for still others. Consider a recent study conducted by Age of Learning, Inc., which found that 80% of teachers reported *significant* ranges of abilities in their math classrooms, such that the effectiveness of their teaching was negatively impacted (see Fig. 2; Sheehan & Rothschild, 2020). In sum, traditional classroom paradigms do not personalize learning sufficiently to effectively address learner variability.

Figure 2. Findings of a survey with 600 parents and 600 teachers on their sentiments about learner variability and personalized learning (Sheehan & Rothschild, 2020)



Using Technology to Address Learner Variability

With the availability of technology and internet access, learning can happen anywhere, anytime—which allows for a rich collection of data, that when analyzed, can provide meaningful insights about learner engagement and performance. Betts and colleagues (2020) have discussed the powerful opportunity education stakeholders and technology developers have in leveraging advances in technology to collect data about, inform, and improve the education of our children. Educational systems that are designed to collect meaningful data about children's learning performance and behaviors in the environment, and to analyze that data and offer real-time support in response to that data, are poised to disrupt and transform traditional place-based education paradigms that struggle to meet the individual needs of students. Information systems can be designed to communicate data to schools, parents, children, and connect them in ways that have not previously been possible (Betts, Thai, & Gunderia, 2021). With the accumulating research on what works and how to help children best learn, research-based recommendations based on this data can provide actionable insights to teachers and caretakers in real-time, thereby enhancing their ability to further personalized instruction to address learner variability.

Personalized learning is not a new concept (e.g., Bloom, 1984), and has recently garnered increased attention through the lens of *Smart Learning* (Betts et al., 2020; Hoel and Mason 2018; Kinshuk et al. 2016; Owen et al. 2019; Roberts-Mahoney et al. 2016). Kinshuk and colleagues (2016) defined Smart Learning as the "fusion of technology and pedagogy to create an *ecosystem* that *involves active participation of teachers, parents and others in the learners' learning process*" (p. 562). More specifically, personalization in the age of Smart Learning means merging technology, curriculum, and pedagogy, to create synergies between the child, the materials, and significant individuals in the child's learning sphere, so that the child's immediate learning needs are known and met by all in real time.

The engine that drives this personalized (smart) learning, is an Adaptive Instructional System (AIS) that includes dynamic mechanisms to deliver instruction, provide corrective feedback, and adjust learning trajectories based on the learner's performance in the moment (Sottilare, Graesser, Hu, & Holden, 2013; Betts, 2019; Betts et al., 2020; Hoel and Mason 2018; Kinshuk et al. 2016; Owen et al. 2019; Roberts-Mahoney et al. 2016; Thai & Tong, 2019). For example, during any given interactive learning activity on a touchpad device, the AIS evaluates each tap and drag interaction by the learner and determines the degree of scaffolding needed to foster learner success, the learner's level of understanding and demonstration of content and skills mastery, and so on. As learners' competencies are assessed during learning activities, the system not only adjusts levels of feedback and scaffolding within the activity itself, it further dynamically adjusts the learning trajectory of future activities. The system accomplishes this by determining whether the learner should stay in the current activity for more practice on the present learning objective, move forward to a new activity with a successive learning objective, or revisit a previous or adjacent activity designed to strengthen and review prior or related competencies. In this manner, the system creates and adapts individualized learning trajectories (i.e., pathways) through the learning content for each learner (Betts, 2019).

It is important to note here that the efficacy of such AISs in driving mastery and durability of learning depend largely on the strength and granularity of the scope and sequence of content that powers the system. Consider, an adaptive system can only be as strong or effective as the content upon which is it mapped. If the curricular content is too broad, or unclear, the efforts of an AIS in such a context will not result in meaningful or lasting student learning, regardless of how strong the adaptive system is. Many AISs, while claiming to be adaptive and personalized, may fail to achieve meaningful learning outcomes for students because the curriculum content that underpins the system is not sufficiently granular or properly sequenced. For an adaptive instructional system to effectively ensure durable and lasting learning—free from gaps and misconceptions—content area concepts and skills must be extensively unpacked and mapped (i.e., precursor, successor, and correlational relationships identified) to ensure that everything a learner could potentially know, understand, or be able to do is identified, addressed, and mastered. An effective adaptive instructional system then uses this extensive knowledge map to drive decision-making around dynamically adjusting learning trajectories to the individual's needs (Betts, 2019).

In sum, the components of an effective mastery-based, personalized AIS that ensures meaningful outcomes for the learner must include the following:

1. Baseline, or diagnostic testing to ensure that the learner's prior knowledge is assessed so that the learner may be appropriately placed in their ZPD within the system and that there are successive iterations of the learner's ZPD
2. Clear, discrete, granular learning objectives, organized and mapped according to precursor, successor, and correlational relationships, that are sequenced into educational units of increasing difficulty so that learning may build without gaps
3. Engagement in educational units (e.g., deliberate skills practice, calculations, data interpretation, reading) that are focused on achieving or demonstrating proficiency with or mastery of the target learning objectives
4. A set minimum passing standard (e.g., criterion assessment score) for each learning activity or experience
5. Formative assessment to gauge activity completion at a preset minimum passing standard for mastery
6. Advancement to the next educational unit given measured achievement at or above the mastery standard
7. Continued practice or study on an educational unit until the mastery standard is reached.

(e.g., Betts, 2019; McGaghie, 2015; Sottilare & Brawner, 2018)

Driven by the interactions between the learner and an AIS with the components listed above, the system moves the learner through an iterative cycle of instruction, application, and practice, promoting the mastery of new concepts and skills. Such personalized learning approaches have proven very promising in ensuring that individual needs are being met and learning outcomes are achieved (e.g., Betts, Thai, Jacobs, & Li, 2020; Bang, Li, & Flynn, in press; Owen & Hughes, 2019; Thai, Bang, & Li, 2021).

An AIS-Powered Personalized Mastery-Based Learning Ecosystem Framework

The field of Smart Learning for our youngest learners (e.g., preschool through kindergarten) is largely uncharted territory, as the process of designing digital adaptive instructional systems for very young children is hampered by interaction design challenges (Thai et al., In Press), as well as ongoing concerns about young children and screen time (Council on Communications Media, 2016; World Health Organization, 2019). The AIS-powered Personalized Mastery-Based Learning Ecosystem discussed in this chapter is designed to drive scaled impact for young children. Through the PMLE, the unique needs of each learner are addressed by capturing individual learner data from the adaptive instructional experiences and materials in the digital space to empower the adults around them with (1) critical, real time information about the learning of the child, (2) actionable insights and recommendations for supporting, fostering, and building the child's immediate learning, and (3) fostering relationships between the child, parents and caregivers, and educators to better personalize learning experiences for the child (Betts, Thai, & Gunderia, 2021).

The Personalized Mastery-Based Learning Ecosystem is a framework with a complex adaptive instructional system at its core (see Fig. 3). In the specific PMLE discussed here, the AIS at the center is called the Personalized Mastery-Based Learning System or PMLS (Dohring et al., 2020). The PMLS includes all the interactive materials that when used by the child, collect the important data to drive not only the interactions within the PMLS, but all the interactions throughout the entire PMLE framework.

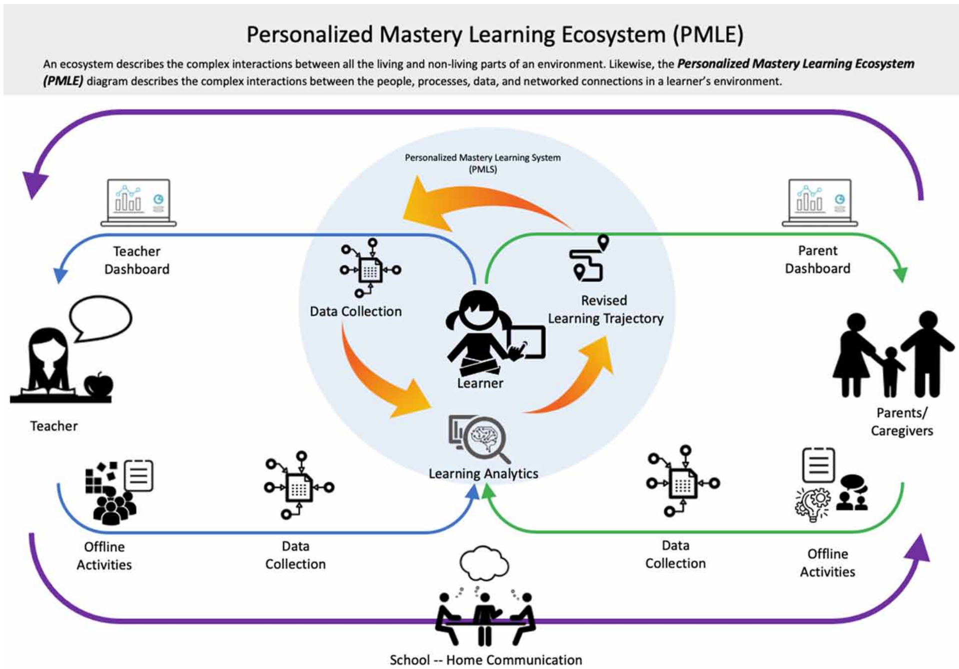
A metaphor here is perhaps useful: the PMLS is the engine, and the PMLE is the vehicle. The engine (PMLS) is what allows the vehicle (PMLE) to work and accomplish its goals. The PMLE includes all components that exist outside of the child-facing adaptive learning system, including all the people (e.g., the child, peers, teachers, parents, caregivers, etc.), and the materials that comprise or guide offline activities (e.g., worksheets, projects, teacher-led lessons, parent-child math talks, etc.). In other words, the child-facing system, or PMLS, is one component (albeit a critically large one) of the broader PMLE framework. The Personalized Mastery-Based Learning Ecosystem shown in Figure 3 places the learner at the center and describes the complex interactions among the learner, all people, processes, data, and networked connections in the learner's environment (Betts, Thai, & Gunderia, 2021).

CASE STUDY: THE DESIGN AND IMPLEMENTATION OF MY MATH ACADEMY PMLE WITH 3- AND 4-YEAR-OLDS

The My Math Academy PMLE for Early Mathematics Instruction with Young Children

The My Math Academy PMLE consists of three complementary components for child learning: learning supported by adaptive algorithms using child performance data, parent-supported learning, and teacher-supported learning. All three components are designed to work together, leading to increases in and acceleration of children's mastery of early math skills and knowledge, as well as their motivation, confidence, and persistence in learning math.

Figure 3. Personalized Mastery Learning Ecosystem framework (PMLE) with the Personalized Mastery Learning System (PMLS) at the core (Betts, Thai, & Gunderia, 2021)



The goal of My Math Academy is to help all children develop a solid foundation of number sense and operations using adaptive, digital, games-based interactions. At the time of this writing, the child-facing My Math Academy app features 98 games consisting of over 300 activities, covering concepts and skills for pre-kindergarten through second grade. The patented Personalized Mastery Learning System™ underlying My Math Academy is an AIS that uses initial diagnostic assessments to measure each child's prior knowledge and determine where they are best placed within the program (Dohring et al., 2020, 2021). As the student plays and progresses through various activities and levels in My Math Academy, evidence of learning on each discrete learning objective is collected and analyzed. The work of generating in-game learning evidence is based on the model of Evidence Centered Design (ECD), a canonical approach to evidence-based design in educational contexts (Mislevy, Almond, & Lucas, 2003) that enables rigorous translation of game interactions into competencies of learning objectives (Shute & Kim, 2014). The PMLS' adaptive system uses the learner's performance to recommend learning games at a specific level of difficulty, based on a predetermined knowledge map of granular learning objectives and their prerequisite relationships (Betts, 2019). My Math Academy games present children with a series of well-ordered problems and provide just-in-time feedback to support mastery (Gee, 2005). Each game includes up to six Learning Activities at varying difficulty levels, including an in-game mastery assessment called the "boss" level. Students master boss levels to demonstrate their skills and understanding, indicating that they are ready to move to the next game. Within each leveled activity, performance data is used to provide and adjust levels of appropriate scaffolding, difficulty, and formative feedback in real-time to the learner. Formative assessment enables ongoing feedback cycles and customized learner difficulty levels (Shute & Kim, 2014); the just-in-time feedback may change behaviors that are fed into the next round of formative feedback (e.g., Ke, Shute, Clark, & Erlebacher, 2019). These methods align with Bloom's theory that meaningful feedback helps children recognize what they have learned well, reinforces key concepts, and identifies the specific concepts upon which children need to spend more time. These methods also align with research in learning and memory that retrieval practice and formative feedback are some of the most effective ways to enhance long-term memory (e.g., Bjork, 1994; Butler, Karpicke, & Roediger, 2008). When such feedback is accompanied with targeted lessons designed to unpack and address any misunderstandings, children can effectively learn and move forward (Guskey, 1997). For more info about My Math Academy, see Betts (2019), Owen & Hughes (2019), as well as Betts, Thai, Jacobs, & Li (2020).

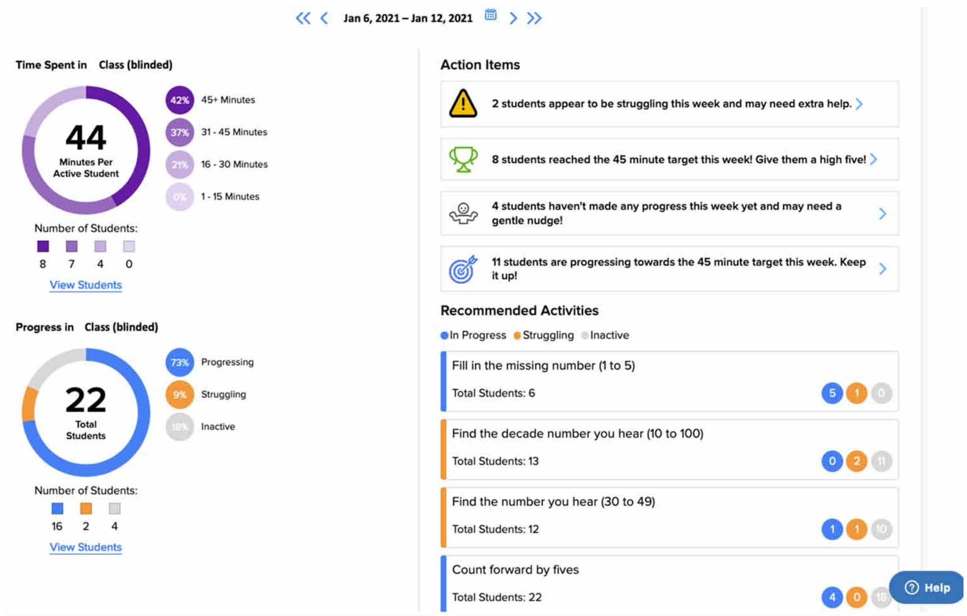
My Math Academy Teacher-Support Features

As previously discussed, the data collected from the My Math Academy games are analyzed to provide actionable insights and individualized activity recommendations to the teacher as well as parents or caregivers. For the teacher, these recommendations may range from ideas for small group instruction to independent offline activities or personalized enrichment for students. Each recommendation is generated by the data collected about the student and targeted toward the student's zone of proximal development. In this manner, the role of the PMLS in the broader PMLE is to act as a "vigilant, automated, teaching assistant with its eye constantly evaluating the progress of learners, while providing both detail and evidence of that learning to teachers" (Betts, Thai, & Gunderia, 2020, p. 37) for every child. This intelligent assistant records and analyzes the learner's interactions, and provides the adults in the learner's life with a comprehensive picture of the learner's progress, as well as what the learner is most ready to learn next. The teacher-reporting features provide critical information that allows for more immediate, tailored, data-driven instruction—regardless of how many students are in the classroom—empowering teachers to individualize the curriculum for all. To parents and caregivers, the PMLS provides meaningful information about the child's progress in accessible language, recommendations for parent-child shared math activities, and even modeling of "math talks" to help parents and caregivers better understand how to communicate with their children about numeracy (Susperreguy & Davis-Kean, 2016).

While the My Math Academy PMLE is designed to provide comprehensive support for both teachers' instructional decision making as well as interactions between the child and parent or caregiver in the home environment, only the development and implementation of the teacher support features are discussed in the present chapter. More information about parent and caregiver support features can be found in Betts, Thai, & Gunderia (2020).

Information and insights are provided to teachers through the Teacher Portal, which includes a dashboard of real-time student progress data and supplemental materials based on each student's progress. The primary purpose of the dashboard is to provide teachers with critical real-time data and insights that can be used by the teacher to differentiate instruction according to individual student needs (see Figs. 4, 5). The reporting features of the dashboard enable the teacher to monitor students' progress individually or as a whole class, and can also be filtered into teacher-created groups. Usage (i.e., time spent in game and learning activities) and progress (i.e., learning activities mastered) are displayed for whole class and for individual students. This snapshot view provides teachers with a quick overview of students' status (e.g., inactive, in progress, etc.), as well as how they are performing on specific in-system learning objectives. Teachers can also view data about each student's progress against common standards frameworks (e.g., Common Core State Standards, state standards, etc.), understand how

Figure 4. Sample dashboard display of usage and progress for whole class and for individual students. This snapshot view provides teachers with a quick overview of students' status (e.g., inactive, in progress), how they are doing on their respective Learning Objectives, overall usage across classrooms, and recommended activities for individual or groups of students, and other key items that require teacher attention.

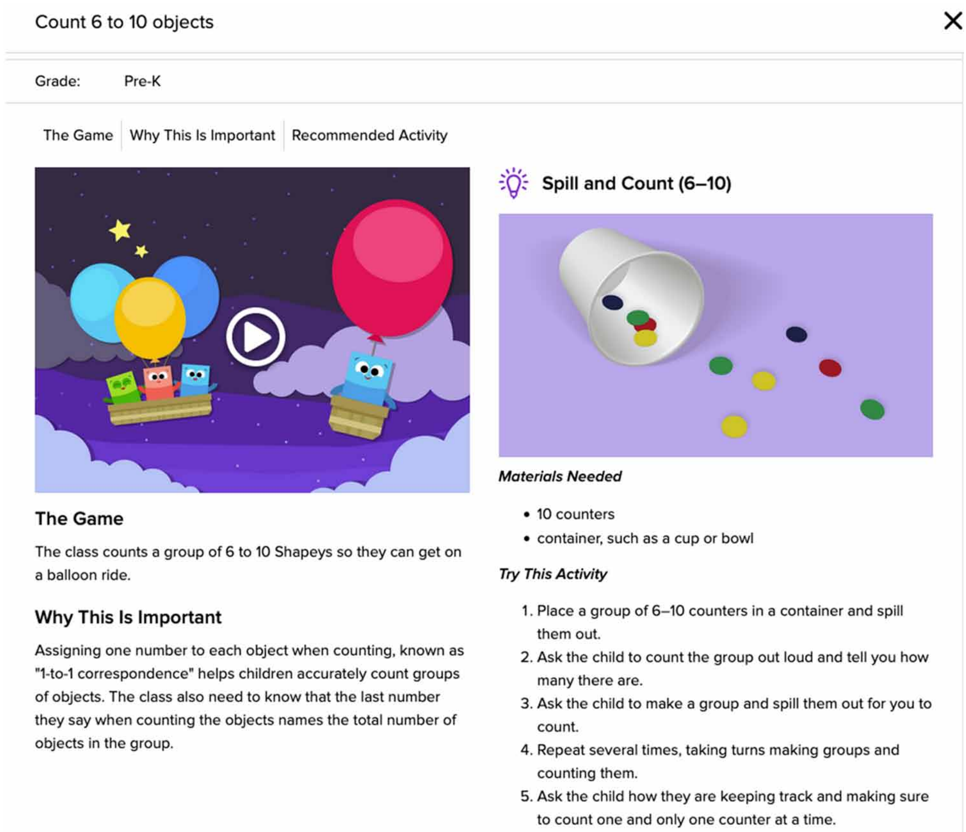


students are performing with respect to grade-level expectations, and can access recommendations for grouping students at similar levels based on their in-system performance (i.e., ready to learn, need for review, reinforcement, or intervention). More importantly, the dashboard provides actionable insights to the teacher in the form of recommended topics and activities of high value for individual and/or small groups of students, as well as detailed guidance for how these activity recommendations may be flexibly integrated into classroom instruction (Fig. 5).

Developing Teacher Content Area Knowledge and Pedagogical Expertise

Teachers' knowledge of mathematics content and pedagogy are known to be directly correlated with student learning gains (Baumert et al., 2010; Hill, Rowan, & Ball, 2005; Opperman, Anders, & Hachfeld, 2016). However, many preschool and prekindergarten teachers are lacking not only the required mathematics content and pedagogical knowledge, but also the confidence and self-efficacy needed to effectively teach critical early mathematics competencies to their students (Copley, Clements, and Sarama, 2004). In many countries, preschool and prekindergarten teachers are not even required to engage in special training designed to develop their mathematics content knowledge, pedagogical expertise, or to increase teacher confidence in teaching early childhood mathematics. Teachers often rely solely on their own experiences in learning mathematics as a guide (Ginsberg et al., 2008; Sarama & Dibiase, 2004). Consequently, it is common for many early childhood teachers to avoid the explicit teaching of mathematics, instead preferring to only employ informal instructional strategies for mathematics instruction, or to place more focus on the development of their students' literacy knowledge and skills (Copley & Padron,

Figure 5. Sample view of the teacher dashboard that provides details about specific lessons a student is current working on, and recommended offline activities that teachers can do with the student, aligned with what that student is currently learning in My Math Academy learning games.



1998, Lee & Ginsberg, 2007). In other cases, many early childhood educators place more emphasis on whole child pedagogy that develops social-emotional competencies, rather than the explicit teaching of mathematics content and skills (Jenkins et al., 2018).

Given the correlation between teachers with deep mathematics content area and pedagogical knowledge and student achievement, and the fact that many teachers possess limited expertise in this area, a key purpose of the Teacher Portal is to build teacher mathematics knowledge and pedagogical expertise. To build teachers' mathematics content area knowledge, the My Math Academy Teacher Portal provides explicit detail on each granular learning objective to be mastered. To support and develop teachers' pedagogical knowledge, the dashboard provides explainers for each activity that describe and model how the concept or skill is being taught in the system, why it is being taught in a particular way, and how the design of the activity works to eliminate the formation of misconceptions and strengthen learners' conceptual understanding. The dashboard further provides individualized recommended offline activities that teachers can do with a single student or group of students, based on their immediate needs as assessed in real-time by the adaptive system. These recommendations provide further explanation designed to not just help the teacher deliver differentiated and targeted instruction, but to additionally help the teacher understand *why* the instruction should be delivered in the suggested manner. Because the system provides real-time, specific, detailed information about the immediate needs of each student in the classroom, the Teacher Portal—by design—increases teacher capacity to meet the individual needs of every student in the classroom, simultaneously and dynamically. As a result, students who need remediation, reinforcement, or enrichment, receive it just as such instruction is likely to make the most impact. Furthermore, students who are capable of moving forward more quickly are not held back to established grade level expectations that may be inadvertently limiting their achievement. Rather, they too receive individualized opportunities for acceleration that keep them in their respective zones of proximal development.

Through the information, recommendations, supports, and scaffolds that these dashboard features provide, teachers are also positioned as "learners in the system," professionally developing and growing their expertise as they work with their students. In sum, the PMLE framework not only meets the individual learning needs of students, it also helps teachers become more expert at teaching early childhood mathematics. This increase in teacher expertise has the potential to benefit all children in the classroom, as well as students the teacher will teach in the future.

The Implementation Pilot of My Math Academy PMLE with Harlingen Consolidated Independent School District, Texas

The purpose of this pilot was to evaluate the extent to which the My Math Academy PMLE can empower and accelerate early math instruction for children ages 3 and 4 from low SES families in real learning contexts. The child-facing system and teacher support components were the focus of this pilot. Future research will focus on testing the parent/caregiver-facing component and the ecosystem as a whole.

Over the course of the 2020–2021 school year, many of the millions of children who were learning remotely due to the COVID-19 pandemic gradually returned to in-person schooling. In anticipation of the extraordinary challenges that characterized the 2020–2021 school year, many educators and administrators across thousands of districts in the United States searched for effective educational resources to support learning and teaching. One such district was the Harlingen Consolidated Independent School District (HCISD) in Texas. Harlingen is a city (population ~86,000) where 82% of the population are identified as Hispanic or Latino, and about 33% of the families have income below the poverty level (US Census Bureau, 2019). About 80% of the students in the district are eligible to participate in the free and reduced-price meal program (McFarland et al., 2019), and in fall of 2020, 61% of children in pre-K were classified as "at-risk," meaning that they did not perform satisfactorily on a readiness test or an assessment administered during the school year.

Given the crucial role of early mathematics skills and knowledge in later academic success (Watts, Duncan, Clements, & Sarama, 2018) the early childhood education administrators in Harlingen specifically sought resources that could address the following needs: 1) inspire a love of math in their youngest learners (ages 3–4), 2) equitably strengthen these young children's foundational math knowledge, and 3) equip educators with insights about each learner's strengths and weaknesses as well as tools to provide personalized instruction for each student. They identified Age of Learning's My Math Academy as the resource that could address their needs, as it was found to be effective in helping young learners (Thai, Bang, & Li, 2021; Bang, Li, & Flynn, in press; "Age of Learning", 2022). Harlingen piloted My Math Academy in 77 early childhood education classrooms during the 2020–2021 school year. Like many school districts across the country, Harlingen began the school year with all students learning remotely, and teachers worked with individual students' families to ensure that each child could log in to the program from home. By the end of the school year, approximately 67% of the students had returned to in-person instruction while 30% continued in remote schooling.

Nearly 1000 pre-K students used My Math Academy as supplemental mathematics instruction during this pilot. A subgroup of 129 three-year-old children were enrolled in a program partially funded by the U.S. Department of Health and Human Services' Head Start program (pre-K3). The remaining (847) children were 4-year-olds in regular prekindergarten program (pre-K4). While all pre-K students had access to the program for the entire school year, they began using the program at different times during the school year, with 8% starting in September and the majority starting between October and December of 2020. Teachers were asked to encourage each student to use My Math Academy for 45 minutes per week over multiple days (e.g., 15 minutes per day for three days a week). Each student had access to a district-issued iPad that had My Math Academy installed, and students used their individual accounts to log in, either at school or at home.

Prior to the start of implementation, teachers received a two-hour live virtual training on My Math Academy, which included video introductions (3–9 minutes each) of how My Math Academy works, the students' first-time user experience, and an overview of the Teacher Portal (student account management, exploring Dashboards, and how to get started). In between the videos, teachers participated in short virtual breakout rooms or answered reflection questions. During the implementation period in November, teachers participated in another one-hour virtual webinar to gain a more in-depth understanding of students' initial placement into the My Math Academy system, develop their skills in making effective use of the Teacher Portal, and gain facility in interpreting the Student Stats Dashboard in the Teacher Portal. Teachers also gained access to resources outlining how My Math Academy correlates with the Texas Essential Knowledge and Skills (TEKS) curriculum standards used by the district.

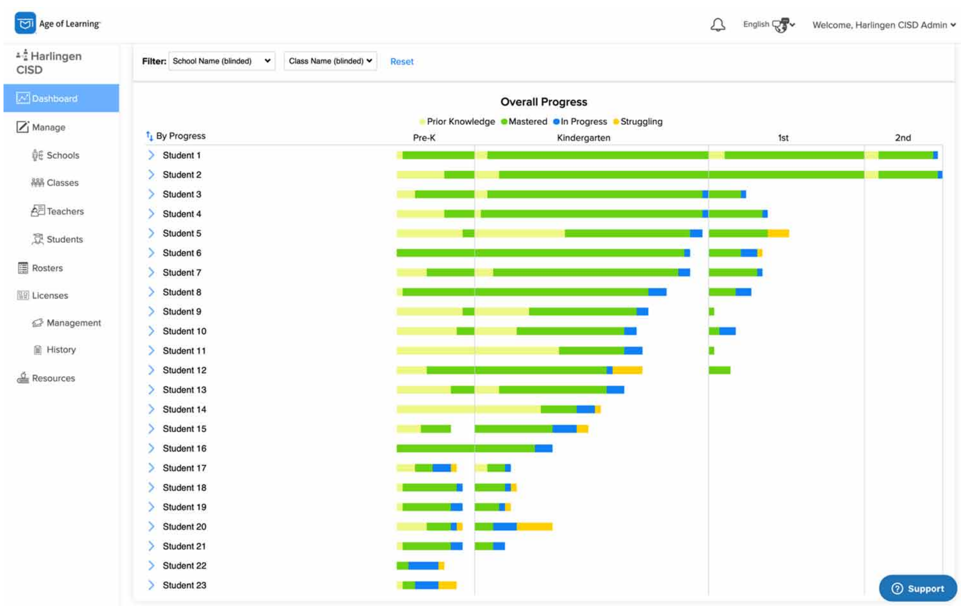
General Results

Learner Variability in Prior Knowledge

Children differed greatly in their prior knowledge at the onset of the school year. Consider a single classroom of 24 4-year-olds at HCISD in which students were of similar socio-economic background (Fig. 6). Their progress in mathematics – as measured by My Math Academy – varied widely across four grade levels from preschool to second grade. This learner variability poses a huge challenge for any teacher who wishes to meet each child's needs. To fully support each child's academic progress, teachers must first understand the ways in which learners vary. This challenge is exacerbated by the fact that the depth and breadth of this information about what children know and do not know at 3 and 4 years of age is not usually available. Furthermore, when assessed, learners are typically measured against grade level standards in school settings, in which a fixed range of knowledge/skills that children should acquire at each age and grade is assumed.

Across the pre-K cohort at HCISD, in-system measures showed that 26% of students started the My Math Academy program having already mastered all pre-K skills and were already working at the kindergarten or first grade level. Of the remaining 74% of students who had not, 54% had none or very few foundational math skills, 13% had some pre-K skills, and 7% had mastered nearly all pre-K skills enabled these observable, verifiable data obtained by *My Math Academy* about what students know and can do freed teachers from subjective impressions about student behaviors and enable them to fully understand each child's needs and to leverage each child's strengths to support their learning without grade level or curriculum limitations. As we built teachers' capacity to effectively support learner variability in their classrooms, it is crucial that we supply them with reliable, granular measures to understand each child's

Figure 6. Example of learner variability in prior knowledge and progress made by students in a pre-K4 classroom at the end of the school year. Skills students came in knowing – as measured by the initial placement diagnostic assessments embedded within My Math Academy – are represented in yellow bars (Prior Knowledge). Skills students acquired – as measured by embedded assessments within My Math Academy – are represented in green (Mastered). Skills that students were currently working on are in blue (In Progress), and those that students may be struggling with (i.e., students fail back to an earlier skill in the program) are in orange.



learning progress, including what each could do, was ready to learn, and was making current progress with, as well best practices and strategies specifically designed to address each child's strengths and weaknesses.

Learning Gains Defy Expectations

Toward the end of the school year, some children transitioned to in-person schooling while others remained learning from home. Children who were learning from home spent significantly less time with My Math Academy, which expectedly impacted their ability to progress in the program. On average, pre-K students used My Math Academy for 30.09 weeks (SD = 7.18) over the course of the 2020–2021 school year. They spent on average 15.18 hours (SD = 11.19) and completed an average of 201.02 Learning Activities (SD = 142.54).

Results showed that with usage, pre-K3 and pre-K4 students demonstrated substantial increases in their math knowledge over the course of the school year during which they used My Math Academy.

Most notably, many children demonstrated gains beyond their grade level. In the classroom illustrated in Figure 7, by the end of the school year, two pre-K4 students in this example class completed or nearly completed the second-grade content, of which the benchmark skill was to perform three-digit subtraction with regrouping using the standard algorithm. Additionally, half of these students had started on first grade content, and nearly all were able to complete the pre-K content.

Across the district, data from My Math Academy indicated that pre-K3 and pre-K4 students tripled and doubled their skills, respectively. Students made significant progress on their grade-level standards as well as on standards beyond their assigned grade levels. By the end of the school year, 71% of pre-K4 students had demonstrated mastery beyond pre-K skills. Most notably, 51% of them were working on content at the kindergarten level, and 20% were on first or second grade level (17% at first grade and 3% at second grade levels). For the pre-K3 students, 37% had demonstrated mastery on all pre-K skills, with 34% of them working on kindergarten content and 3% were working on first grade content. This placed an average pre-K4 student at the middle of K level and an average pre-K3 student at the beginning of K level on number sense and operations, suggesting that the pre-K students were advancing nearly a year beyond their grade level by the end of the school year. It is worth pointing out that these tremendous gains were seen in a year when many students across the United States were falling a year or more behind grade level expectations (Dorn, Hancock, Sarakatsannis, & Viruleg, 2020; Kuhfeld et al., 2020; Meckler & Natanson, 2020; Renaissance Learning, 2020).

These gains seen in My Math Academy aligned with district measures of achievement. During the school year, the district administered the CIRCLE (Center for Improving the Readiness of Children for Learning and Education) Progress Monitoring assessment three times to pre-K students (beginning, middle, and end of school year). The CIRCLE assessment is a screening and progress monitoring tool with well-established reliability and validity when used with 3- and 4-year-olds in that it relates to other tests and predicts child outcomes (Landry, Assel, Williams, Zucker, Swank, & Gunnewig, 2014; Assel et al., 2020). Results from the CIRCLE assessment confirmed that students who regularly used *My Math Academy* were highly likely to be "on track" for their grade level in math at the end of the school year. More specifically, 89% of students who used My Math Academy (and 98% of students who used it regularly, who averaged 40 minutes per week and mastered at least 15 skills in My Math Academy) were on track on overall math skills at the end of the school year, as compared to 77% of students who did not use My Math Academy who were considered to be "on track."

Encouragingly, these learning gains persisted over the summer. During fall of 2021, the pre-K students (then kindergarteners) took the NWEA MAP Growth assessment, a validated adaptive interim assessment that measures whether a student performs on, above, or below grade level in K-12 subjects against the national average (NWEA, 2020). This was the first time the district administered this assessment. Results showed that the now kindergarteners performed above the national average in mathematics. 49% of them scored above the 60th percentile; 27% scoring above 80th percentile. They also have the greatest percentage of students performing above the national average compared to any other grade levels within the district, who did not use My Math Academy. Contrast this with fall 2020, where 62% of the same children (then in PreK) were classified as "at-risk."

This result is remarkable considering that the COVID-19 pandemic has generally led to decline in scores elsewhere, especially for disadvantaged students (e.g., Kuhfeld et al., 2020). Considering also that disadvantaged children are at risk of entering kindergarten behind their more advantaged peers, and that this learning opportunity gap has been consistently observed to persist through later schooling and into adulthood (e.g., Duncan et al., 2007), results from HCISD suggest that when students' learning needs are met, disadvantaged children can defy expectations and succeed—not only in meeting, but in transcending established grade-level expectations.

Teacher Feedback on Implementation

Survey and interview data collected from teachers confirmed the learning gains shown by in-game progress. Teachers reported that students learned a great deal from My Math Academy, and their feedback remarked on how often we underestimate children's ability:

When they start off in pre-K, we don't know what they can and cannot do, and we are so set in our own ways in teaching, like, this is what they need to know. Yet with your program [My Math Academy], we could see seven students [at my school] who excelled higher than we could ever have imagined. And we would not have known without this program.

Teachers also found the data and resources in My Math Academy empowering, enabling them to gain a deeper understanding of individual students' math progress and to effectively tailor instruction to individual students:

The data is so useful. I can level my students right, in tiers. I can see the lessons that they are doing or see what lessons they're struggling [with]. I would write down those lessons and try to get them in interventions, one-on-one practice with them. And I really liked the examples, like "oh, use counters to help students . . ." And it works, so definitely, it did help me differentiate my instruction with my students.

This feedback emphasized that differentiated instruction must be built on what students already know, which serves as the foundation upon which to increase their math knowledge, each at their own pace. To do so, teachers must understand what each student is capable of and have the resources needed to provide students with individualized support. Because the resources provided by My Math Academy empowered teachers to address learner variability, they found that the program provided students an equal chance of experiencing academic success in a school year disrupted by the pandemic (see survey results in Figure 7 below).

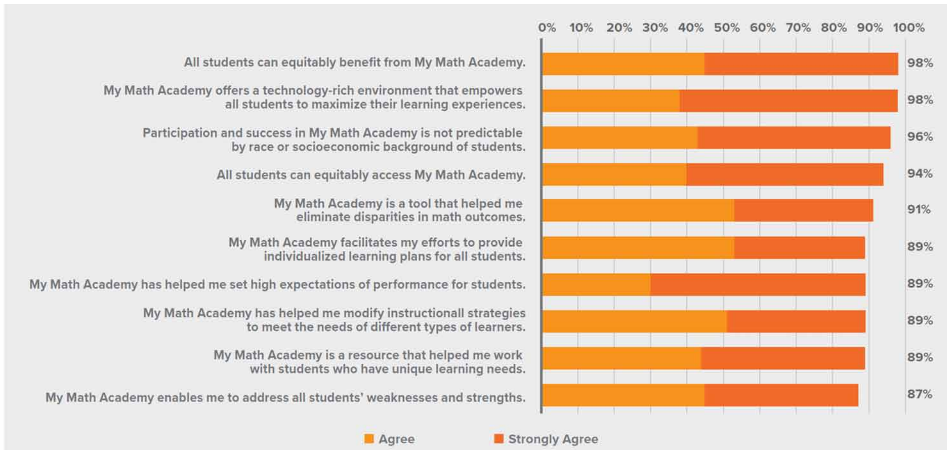
They described how the My Math Academy program helped them close the gaps exacerbated by the COVID-19 pandemic:

The app was great because it allowed students to move forward at their own level, so my [higher level] students were able to move forward and allowed my slower students to really practice their skills without being rushed to the next skill.

What I like about My Math Academy is that it builds on their knowledge, and it goes up from what they know as an individual… It works for any kid. [As] long as they're playing it on a daily basis, you can see the growth.

For such a program to be effective, the program must also be able to support educators in creating learning environments that promote the well-being of children and fosters students' positive attitudes toward learning. Over 90% of teachers reported that My Math Academy had a "positive" or "very positive"

Figure 7. Teacher ratings in response to "Please select one answer choice per statement that best represents you and your students?" on a scale from 0-3 (0 = strongly agree, 1 = agree, 2 = disagree, 3 = strongly disagree). N = 51.



impact on students' attitudes and behaviors that facilitate their participation and enhance their chances of academic success (DiPerna & Elliott, 2002). They reported that My Math Academy increased students' interest, enjoyment, and self-confidence in learning math, and that it improved students' engagement in learning math and their focus and attention during math lessons. Beyond targeting each child's unique needs, teachers mentioned that My Math Academy's design features, including how math is situated in relatable scenarios with lovable characters, helped children remain engaged with the learning process. For example, one remarked:

My Math Academy got some of my reluctant math learners to be excited about practicing math.

Key Findings

First, teachers found the data and resources in My Math Academy empowering, enabling them to tailor instruction and gain a deeper understanding of individual students' math progress. Second, teachers indicated that My Math Academy is a tool that enables them to equitably provide every child with an equal chance of success. Third, teachers reported that My Math Academy had a significant positive impact on students' interest, enjoyment, and confidence in learning math. In addition, teachers and administrators were surprised to see so many of their students not only on track for their grade level, but to observe a number of students greatly surpass conventional expectations for this age group. Carmen Alvarez, the Director of Early Childhood Education for Harlingen explained,

The teachers were surprised by what the children were able to do. The skill that really comes to mind is the skill of addition and subtraction with regrouping. That's usually a skill that's not introduced until late second grade, early third grade, and our pre-k students, about 20 of them, were able to do that skill. The teachers were very surprised. I think sometimes we limit what our children can do, but My Math Academy is really opening their eyes to the potential of the math skills that some children [have]… but *we had no way of knowing that until we started looking at the data that My Math Academy provided for us. (Alvarez et al., 2021, June 17)*

Both the data and the anecdotal evidence from Administrators and teachers showed when all of the children's individual mathematics learning needs were met, remarkable outcomes could be achieved. Harlingen CISD now has a new problem: preparing for incoming kindergarteners that are either on track or ahead of grade level expectations—a problem they have not encountered before. In a district where many students are considered "at risk," teachers spend much of the kindergarten year remediating for concepts and skills that children need, but do not have. Not so for the kindergarten class of 2021-22. According to Alvarez, "this is going to be a different challenge for us this next school year. I know we hear a lot about the academic slide, but that's obviously not happening here at Harlingen. Kindergarten math for next year is going to look totally different because the children are coming with a very different skillset – not only with the skills, but what they can do with their math" (Alvarez et al., 2021, June 17). Based on this success, the Harlingen school district now has 5,200 students and 300 teachers using My Math Academy and the PMLE framework (Alvarez, 2022).

The idea that conventional early childhood education paradigms may be *limiting* the achievement of our youngest learners is a new one. More often, concerns (understandably) have largely focused on children who enter early school without the critical prior knowledge needed to take advantage of the academic learning that takes place in school. Additionally, concerns over children who struggle to master critical core competencies in these early years have centered on what schools and teachers should or could be doing to address this problem. As a result, classroom instruction may focus more on these emerging math skills, even if not all students require or benefit from it. Yet, the implementation of My Math Academy in Harlingen shows that even children designated as "at risk" were capable of defying conventional expectations for their age and developmental level. All children deserve to have their needs met – whether their needs arise from gaps in their foundation, or the need for more exposure to core concepts, more time to learn, more practice to develop fluency, or *more acceleration*. By the end of the school year, 20% of four-year-olds and 34% of three-year-olds in Harlingen were already at least a grade level beyond their assigned grade level in number sense and operations, defying the grade-level expectations we as educators and policy makers have set. This suggests that we may be under-valuing the potential of our students.

SUMMARY AND CONCLUSION

Given that learner variability exists and has intensified in light of the recent COVID-19 pandemic, accepting it as a normal and predictable part of teaching means that we must proactively plan for and even celebrate variations in children. As we look forward, we need to work toward solutions to unlock the potential of every child and ensure that each child achieves proficiency in basic skills. This means access to high-quality research-based and data-informed instructional systems, universal access to devices and bandwidth to access such systems, and importantly, the development and support for ecosystems that build capacity among parents before formal education and for teachers after that. Results from the pilot of the My Math Academy PMLE at Harlingen CISD has shown us that when provided with personalized instruction that meets the immediate needs of individual learners, even the youngest students are able to exceed conventional grade-level expectations. We must learn to think differently about how to educate our children, meet their needs, and challenge our own age-based and grade-based assumptions about what children are capable of when their needs are fully met—before and after formal schooling begins.

As we develop greater understanding of what children are capable of in the earliest grades, it will also be critical to understand the ways in which digital programs can provide learning solutions at scale. The PMLE framework has shown incredible promise in meeting the challenge of learner variability. We know that our education system needs to foster a positive school climate and supportive instruction and services that provides settings designed to foster strong relationships, family engagement, and meaningful instruction that targets the needs of the whole child. In this chapter, we describe an approach that uses research-based and data-informed practices to create an ecosystem in which the child is at the center. A well-designed adaptive instructional system aimed at collecting meaningful data, dynamically adapting personalized learning trajectories, scaffolding in real-time to meet individual needs, with well-designed reporting and recommendation systems for teachers, driven by student performance and behavioral data, can empower learning growth and positive connections to mathematics in children. Teacher resources that provide real-time data about the learner and actionable insights that can be delivered to the teacher in the moment, just when the child needs it, as well as help grow the teachers' knowledge and skills, building teachers' awareness of key misconceptions, and how to address them. This approach leverages the potential of big data and related advances in machine learning and learning analytics to identify trends and patterns in children's learning and behavior to help us better understand how kids learn math, what learning trajectories promote the most growth, and at what developmental ages children are most capable of learning various content.

This chapter has discussed a framework for a PMLE with My Math Academy and the implementation of part of the ecosystem (the student and teacher components). Other models should also be considered and evaluated, such as the usage of edtech to increase parents and caretakers' capacity to support the child prior to the onset of formal schooling, especially in low-SES and non-English speaking environments, non-school childcare settings, or in rural areas where formal preschool is not available (i.e., Shamir et al., 2019). Family resource portals can deliver real-time data about the child, provide parents with tailored recommended activities to do with the child, foster positive associations with math through meaningful interactions between kids and parents/caregivers. Such home-based interactions are an essential component of the PMLE framework, as research has shown that the home learning environment and parental engagement are critical for children's development of early math skills (Epstein & Sanders, 2002; Fantuzzo, McWayne, Perry, & Childs 2004 ; Jeynes, 2012; 2017) and for children's positive connections to math and self-confidence around math (e.g., Garcia & Weiss, 2017). Future research will need to include the home environment and the synergies among all components within the ecosystem (i.e., including home-school connection, offline interactions, etc.).

Investing in early childhood is more important than ever before (Heckman, 2012; Omidyar Network, 2019; also see Chapters 1-3 of this volume). As research has shown, early math success predicts not only later academic achievement, but outcomes well into adulthood, including the likelihood of graduating from high school and college completion (Duncan et al., 2007; Duncan & Magnuson, 2011, 2013, etc.). When we ensure children succeeds early, we positively change the trajectory of their entire lives. When we harness the power of science, technology, and design for scale, we can pave the way for innovative early childhood solutions that positively impact a new generation of early learners.

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KEY TERMS AND DEFINITIONS

Adaptive Instructional Systems: A class of software that is used to optimize instruction for a learner or groups of learners by tailoring instruction and recommendations to the learner or learners' needs, goals, and/or preferences in a specific learning domain.

Learner Variability: The individual variations that occur among learners due to the naturally differentiated development of young children, their family background, the environment they grow up in, and the experiences they have. These variations impact how children learn and acquire skills.

Mastery Learning: An approach to instruction proposed by Benjamin Bloom (1984) that requires students to acquire knowledge and demonstrate mastery of a skill before moving on to successive ones, and that delivers instruction through appropriately individualized scaffolds, feedback, and enrichments.

Objects of Change: A term coined by Benjamin Bloom (1984) in his seminal paper referring to the four factors that when modified or enhanced would have the greatest potential to increase student achievement. The four objects of change are the learner, the instructional materials, the teacher quality and methodology, and the learner's environment (at home, school, and socially).

Personalized Learning: An approach to instruction that aims to customize instruction for each student based on each student's unique skills, abilities, preferences, background, and experiences.

Personalized Mastery-Based Learning Ecosystem (PMLE): The PMLS plus all components that exist outside of the PMLS, including all the people (e.g., the learner, peers, teachers, parents, and caregivers, etc.) and offline materials (e.g., worksheets, projects, teacher-led lessons, parent-child interactive content, etc.). The PMLE encompasses and is driven by and informs the PMLS (Betts, Thai, & Gunderia, 2021).

Personalized Mastery-Based Learning System (PMLS): An adaptive instructional system developed by Age of Learning that includes the instructional design, data collection, analytics, and information delivery mechanisms (i.e., through dashboards) to assess in real-time what the learner already knows, doesn't know, and most ready to learn next, and deliver appropriate instruction and scaffolding at a granular skill level (Dohring et al., 2020, 2021).