The goal of my research is to develop novel computing systems that optimize student learning for any environment. I work at the intersection of human-computer interaction (HCI) and educational technology, exploring how personalized data-driven systems can adapt to meet the unique needs of each student, teacher, and classroom. Recent data shows that only one in four high school graduates in the United States are prepared for college in core areas, and student test scores have remained stagnant since the 1970s. While technology has advanced massively during that time, computing systems have had little impact on how we learn. In my research, I harness the potential of educational technology by tackling the complex factors that influence learning. I believe that interactive systems such as online tools and educational games can capture unprecedented information about the learning process. This data can provide insights into student motivations, misconceptions, and mental processes. Most importantly, we can move beyond data analytics to create interventions that optimize learning for each student, teacher, and classroom.

My research approach combines techniques from HCI, game design, data mining, and artificial intelligence to (1) understand the factors that impact learning, (2) design and build novel technical systems that maximize learning given these factors, and (3) evaluate the resulting systems through large-scale online and classroom experimentation. In my dissertation research, I have used this approach to design systems that increase student motivation, generate personalized scaffolding, and support formative assessment. This work presents a core set of technical challenges focused on quantifying student behavior, modeling learning domains, and adapting interventions automatically. However, designing solutions for real-world classrooms also requires addressing deep social and motivational challenges. Throughout my PhD, I have collaborated with experts in educational psychology and the learning sciences to tackle these inherently interdisciplinary problems. My interventions have been used by over 100,000 students online, adopted by companies, and used in classrooms throughout the Seattle area. My work demonstrates that personalized data-driven systems can transform how we teach, assess, communicate, and collaborate in learning environments.

Current Research
My PhD research explores the design of computing systems to support learning in a variety of contexts. I have studied educational game design through large-scale online experimentation [1, 9, 11, 12, 13], explored novel techniques for capturing and analyzing student behavior [6, 12, 14], developed new paradigms for automatically generating personalized content [8, 10, 15], and measured the usage of educational tools through classroom and online experiments [5, 7]. As part of this work, I have created an incentive structure that promotes the growth mindset in an educational game, developed new frameworks for generating instructional scaffolding, and evaluated a personalized learning system that visualizes student data in real-time for classroom teachers. I survey these three projects here.

Growth Mindset Incentive Structures for Educational Games
Educational games have great potential to engage students in educational settings. Incentive structures, the systems of rewards given to successful players, have elicited particular attention for their motivational potential. However, the effects of in-game rewards on motivation and learning are not well understood. Stanford psychologist Carol Dweck and her colleagues have studied student motivation extensively, and have found that some praise can have negative effects in educational settings. Praising a student’s inherent abilities promotes the fixed mindset, or the belief that intelligence is unchangeable, while praising strategies and effort promotes the growth mindset, or the belief that intelligence can grow. The growth mindset is associated with high motivation and academic achievement. However, most video games reward students for their performance and speed, rather than their strategies and effort. It is therefore possible that traditional game incentives could inadvertently harm student motivation and learning.

I collaborated with Carol Dweck to explore whether growth mindset praise could be incorporated into a game. We designed a novel “brain points” incentive structure for the educational game Refraction that rewards players for their effort, use of strategy, and incremental progress. To implement this idea, we developed a set of behavioral metrics that capture student actions in real time, detecting when they try new hypotheses, restart levels, and solve sub-problems. These analytics allow us to immediately reward and encourage productive behaviors at a micro-level, an approach that fundamentally differs from previous interventions that praise students after activities are completed.

To date, over 100,000 students have participated in online studies evaluating the brain points intervention. To recruit students, I partnered with the educational website BrainPOP and the homeschooling company K12. In our initial study on BrainPOP, we measured the effectiveness of growth mindset Refraction compared to a control version of...
the game that rewarded level completion. We found that children in the brain points condition persisted longer and used more strategy [12], confirming the benefits of rewarding growth mindset behaviors. However, we were curious to see if brain points are effective simply because children enjoy earning points during gameplay rather than at the end of each level. We designed a follow-up study that compared the brain points design to a modified version that awarded brain points randomly. Our results confirmed that brain points are successful specifically because they reward strategy and effort; rewarding children at random times was significantly less effective [9]. We replicated our original findings with a different population of students on K12 [11], and have discovered in ongoing work with K12 that growth mindset Refraction encourages many more struggling students to complete the game.

The success of our research has led the non-profit company Enlearn (founded by Zoran Popović) to adopt the brain points incentive structure in their educational software. It is also being incorporated into the Voyager curriculum for math and language arts, which will be delivered to thousands of students in the near future. Carol Dweck discusses this joint work in her 2014 TED talk, which has been viewed over 3.5 million times.

**Automatic Generation of Instructional Scaffolding**

Not all students learn at the same pace; some may need ten times more practice than others to master a concept. Great teachers support multiple learning pathways by personalizing instruction. However, it is hard for teachers to adapt content in real-time, especially in large classes. This is an area where educational technology has great potential to augment traditional classroom learning. In domains such as K-12 mathematics, we would like to provide massive banks of example problems, along with step-by-step explanations and real-time feedback to scaffold students as they practice. Authoring this content by hand at the scale required to support all students is infeasible. As a result, my collaborators and I chose to explore new methods for automatically generating problems and scaffolding.

We first tackled this problem in the domain of procedural knowledge [10]. Procedures appear in many contexts, particularly in STEM fields. Some procedures are simple, but others require choosing the steps to execute using features of the problem. For example, to solve a subtraction problem, a student must decide whether to borrow by comparing the digits in a column. Our key insight was to encode the problem-solving thought process as an algorithm, using conditional statements and loops to model these decision points. My collaborator Erik Andersen developed a method for generating problems from these models [2]. However I also wanted to generate step-by-step demonstrations for all problems solved by a procedure. We noted that the steps used to solve a given problem can be identified by walking through the algorithm line-by-line for that problem. To translate the lines into explanations, we use mappings between code constructs and visual objects in the user interface. This approach allows us to generate explanations for all 55 million unique four-digit subtraction problems using one 25-line model of the subtraction procedure.

This solution naturally supports many types of interactive scaffolding. We developed techniques for repurposing step-by-step content to generate just-in-time feedback and tutorial progressions that gradually fade between explanations and independent problem solving [10]. An evaluation with fifth-grade students showed that our generated tutorials produce similar learning gains to those of a human teacher [10]. This research led to a collaboration with Stuart Reges to develop scaffolding for the introductory programming courses at UW. We worked with thirteen undergrad RAs who adopted this modeling approach to build tools that are currently in use by over 300 students in CSE142.

After developing methods for generating content in procedural domains, my collaborators and I extended our approach to the open-ended domain of algebraic equations [8]. Intelligent tutoring systems demonstrate robust meth-
ods for responding to student actions in such domains. However, previous research did not provide a method for generating both problems and scaffolding from a single underlying domain model. To facilitate problem generation, we modeled algebraic problem-solving in the logic programming language answer set programming (ASP). The if-then production rules defined by our model are similar to those used in intelligent tutoring systems, however we are able to generate problems and all valid solutions automatically using existing answer set solvers. The solutions provide the sets of operations that can be applied to solve a given equation. We note step-by-step explanations can be generated directly from these rules. We use the preconditions defined in the rule body to explain why an operation can be applied, and use the rule name to describe how to apply the operation. Through a proof-of-concept implementation, we show how to generate problems, problem ontologies, step-by-step explanations, responses to misconceptions, and faded tutorial progressions using this approach [8]. Furthermore, our user study demonstrates that people solve problems more accurately and efficiently after practicing problems with our explanations and hints [8].

**Personalized Learning for the Classroom Ecosystem**

Although personalized learning systems have great potential, they are rarely used in classrooms. This lack of adoption highlights the importance of evaluating systems not just in terms of their technical contributions, but also in terms of their impact on behavior in the classroom. To study classroom integration, I partnered with the non-profit company Enlearn [7]. Enlearn grew out of our research at UW, with the goal of creating adaptive learning solutions for the classroom. Their tablet-based platform includes an adaptive problem-solving application for students and a teacher application that visualizes student progress in real time. We recruited four fifth-grade math teachers in the Seattle area, and observed and logged behavior in classes that used traditional paper materials and the tablet-based software. Over 200 students in eleven math classes participated in this study over the course of ten weeks. We found that students in tablet-based classes completed up to six times more problems than those in paper-based classes, and performed better on assessment problems [7]. Teachers also assisted three times more students in classes where they had access to real-time data [7]. However, we discovered that classroom factors such as teacher organization and student behavioral issues impacted the effectiveness of the system, highlighting the importance of considering the entire classroom ecosystem in the design and evaluation of educational technologies.

**Future Research**

I am driven to empower students, teachers, and communities through technologies that provide high-quality educational support. Looking forward, I will continue to explore how personalized data-driven systems can transform how we teach, assess, communicate, and collaborate in learning environments. This research will present a broad range of technical challenges spanning areas as diverse as game design, data science, and artificial intelligence. I will approach my work by (1) understanding the factors that impact learning, (2) designing and building novel technical systems that maximize learning given these factors, and (3) evaluating the resulting systems through large-scale online and classroom experimentation. Interdisciplinary collaboration has been essential to my research success thus far, and I will continue to partner with experts in educational psychology and the learning sciences to achieve my research goals. While there are many research directions that interest me, I outline a few concrete examples here.

**Data Visualizations for Students, Teachers, and Parents** – Most existing data collection systems focus on aggregating student data for the benefit of administrators and policy-makers. I believe the rich data collected through educational technologies could have a profound impact when appropriately communicated to students, teachers, and parents. My work has already shown how teacher behavior changes when student progress is communicated in real time [7]. However, deep advances in data mining and visualization are needed to effectively reduce behavioral data into actionable information that can be used by stakeholders. I am particularly interested in empowering students by teaching them to reflect on their progress using data. Education research shows that meta-cognitive planning can have a strong impact on student performance. I will combine ideas from metacognition theory and growth mindset theory to develop targeted visualizations that encourage students to take ownership over their own progress.

**Personalization for Learning Disabilities** – My research thus far has focused on personalizing instruction using metrics that capture student performance and productive struggle in real time. In the future, I plan on extending this approach using richer historical data. I am particularly interested in developing systems that can detect and address learning disabilities such as dyslexia. I plan on exploring new technical methods for automatically detecting common learning disabilities directly from behavioral data. I believe games would be a great tool for collecting this targeted information. I also plan on developing interventions that leverage student models and growth mindset theory to automatically adapt content and help students develop techniques for overcoming educational obstacles. Tackling these hard problems will require advances in both student modeling and interactive interface design.
Learning Technologies for Developing Countries – Many of the technical approaches I have explored could be extended to support learning in low-resource settings, particularly in developing countries. Teachers in these contexts are often faced with high student-to-teacher ratios and diverse levels of student ability, so automation and personalization systems could have an important impact. I completed my masters research in the area of Information and Communication Technologies for Development (ICTD), studying mobile solutions to global health challenges [3, 4]. Although this research tackled problems in a different domain, it taught me about the unique challenges that arise in low-resource settings and provided me with experience conducting fieldwork outside of the United States. Combining this background with my current expertise in learning systems, I plan to explore the many open problems in this area, with a particular focus on providing personalized scaffolding through low-cost mobile devices.

My research interests are not limited to these examples, and will likely span a wide range of technologies, approaches, and application areas. Many of the data-driven techniques that I apply to problems in educational domains could be extended to target human-centered challenges in areas such as machine learning, software engineering, and personalized health. I anticipate collaborating with researchers in many sub-fields of computer science in the future.

References