Using Adaptive Learning Technologies to Personalize Instruction: The Impact of Interest-Based Scenarios on Performance in Algebra

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Abstract: Context personalization refers to the idea of adapting learning activities based on students' interests and experiences. While new learning technologies make such innovations feasible, little research supports whether and how context personalization may mediate important learner outcomes, especially in mathematics. Here, we present results of a experimental study of Algebra I students (N = 145) receiving context personalization within an intelligent tutoring system, Cognitive Tutor Algebra. Results suggest that personalization allowed students to form more accurate and meaningful *situation models* of story problems, facilitating algebraic symbolization. Interest-based interventions may allow learners to make critical connections between personally relevant scenarios and abstract representational systems. Adaptive learning environments that personalize instruction by leveraging interests are an important future direction for advanced learning technologies.

Introduction

Collins and Halverson (2009) in the book *Rethinking Education in the Age of Technology* describe a compelling vision for how technology could change the nature of schooling. Among the key strengths that technology-based interactive learning environments could bring to educational practice is customization of learning. New technology innovations allow learning to be personalized to students' interests, abilities, and preferences, in order to provide assistance when needed, and present instruction that is understandable, engaging, and situated in the context of what is important to leaners. Such technologies are timely, given the pressing problems with motivation that face schools today (Hidi & Harackiewicz, 2000), especially in secondary mathematics (Mitchell, 1993; Loveless, Fennel, Williams, Ball, & Banfield, 2008).

One powerful way to adapt instruction using technology that is relatively widespread in mathematics education is intelligent tutoring systems (ITS; Koedinger & Corbett, 2006). These systems build a cognitive model of a learner's current knowledge, and use these models to adapt problem selection, track mastery, and provide just-in-time feedback and hints. However, beyond adapting instruction to students' knowledge, recently these systems have begun to consider a new and potentially important form of personalized learning – presenting instruction in the context of students' *interests* (Hidi & Renninger, 2006; Renninger, Ewen, & Lasher, 2002). Carnegie Learning's new ITS *MATHia* personalizes middle school mathematics problems to different topics of student interest, such as sports, art, and music (Carnegie Learning, 2011). Here, we refer to this type of adaption based on topic interest as "context personalization," or, for simplicity, "personalization."

While many stakeholders in education, including teachers (Fives & Manning, 2005), believe such interventions support learning, there is little evidence of their effectiveness, especially in secondary mathematics. Further, little research exists that confirms or provides an explanation as to why personalization could support learning in more abstract domains such as high school algebra, which has been framed as a gatekeeper to higher-level mathematics (Kaput, 2000) with significant implications for equity and access (Moses & Cobb, 2001). Here, we present the results of a context personalization intervention within the Cognitive Tutor software that was carried out in Algebra I classes. We explore at how such technology-based innovations have the potential to mediate learning outcomes by matching instruction to student interests.

Literature Review

Interest

Personalization, as conceptualized here, has the potential to enable productive pathways to learning by activating *topic interest (*Ainley, Hidi, & Berndorff, 2002). Interest is defined as "the psychological state of engaging and the predisposition to re-engage with particular classes of objects, events, or ideas over time" (Hidi & Renninger, 2006, p. 112). Topic interest has components of both *situational interest*, activated by surprising, salient, or evocative features of the environment, and *individual interest*, a learner's enduring preferences towards particular topics, activities, or objects (Mitchell, 1993; Hidi & Renninger, 2006). Individual interest is assumed to have both knowledge-related and value-related components, meaning that it is associated with both learners' feelings of value for and knowledge of the topic (Renninger et al., 2002). In some cases, when learners are presented with a topic they are interested in, their familiarity with and connection to the particular scenario may allow for the knowledge and value components of individual interest to be activated. In other cases, even though a problem is personalized to a general topic that interests the student, their connection with the particular story might not be very strong. In this case, an affective reaction from the situational interest spurred by topic familiarity may be more likely (Ainley et al., 2002). Thus topic interest is influenced by both individual and situational factors, and may be an important support for learning, as research has demonstrated that interest mediates attention, persistence, and engagement (Ainley, Hidi, & Berndorff, 2002; Durik & Harackiewicz, 2007; Hidi, 2001; McDaniel et al., 2000; Renninger & Wozinak, 1985).

Prior studies on personalization in mathematics have shown mixed results, suggesting that there is a need to better understand how personalization can impact learner outcomes. Several studies have found learning gains for personalization (Anand and Ross, 1987; Cordova & Lepper, 1996; Chen & Liu, 2007), while others have not (Bates & Weist, 2004; Cakir & Simsek, 2010; Ku & Sullivan, 2000). In previous work (Walkington & Maull, 2011) we hypothesized that these mixed results are due to the fact that in order for personalization to be effective, the difficulty of the problems being personalized must be at the edge of learners' abilities. This makes the ITS system used in the present study an especially interesting platform to study personalization, as it intelligently selects problems based on a cognitive model of performance. In addition to the mixed results in the literature, all of the previous studies have been conducted with elementary school students, and few look at personalization during the actual course of instruction where issues of interest and motivation would be most salient. Here, we present an ITS-based study of personalization during the course of algebra instruction.

Algebraic Reasoning

The present study focuses on algebra story problems (Figure 1), specifically the skill of writing of symbolic expressions from story problems. Koedinger and Nathan (2004) found that algebra story problems were easier to solve than matched symbolic equations, and attributed this to difficulties students have learning the language of algebra. Indeed, a number of studies have shown that algebraic expression-writing is a challenging skill (Walkington, Sherman, & Petrosino, 2012; Bardini, Pierce, & Stacey, 2004; Koedginer & McLaughlin, 2010; Clement, 1982; Stacey & MacGregor, 1999). Students may have a tendency to conceptualize a symbolic equation as a string of calculations rather than a statement about equality, and may assign variables multiple or shifting values (Clement, 1982; Stacey & MacGregor, 1999). Students may also have difficulty combining different parts of symbolic expressions (Koedinger & McLaughlin, 2010; Heffernan & Koedinger, 1997).

Nathan, Kintsch, and Young (1992) proposed a model of algebra story problem solving where learners negotiate three levels of representation: (1) a *propositional textbase* containing the information given in the story in propositional form, (2) a *situation model* representing a qualitative understanding of the actions and relationships in the story, and (3) a *problem model* which includes formal mathematical operands, variables, and equations. They found that when students were given support in forming situation models through computer animations, they were better able to write equations from stories. Similarly, in a pilot study of 24 students solving normal and personalized algebra story problems, we found that personalization supported students in forming more detailed and accurate situation models of problem scenarios. Students were more likely to attempt personalized problems, reported that personalized problems easier to solve and more related to their lives, and were more likely to use informal strategies on that closely mirrored the problem's action (Walkington et al., 2012). Here, we investigate this idea of supporting learner's situation models on a larger scale, during the course of actual classroom instruction with an intelligent tutoring system.

Research Question

In previous work (Walkington, 2012) we found that personalization of algebra story problems promotes performance and learning gains for algebraic symbolization. However, it is not clear from our previous studies precisely *why* this result occurred. Here, we engage in a deeper investigation of the positive performance effect for personalization, in order to try to uncover how personalization supports learning. Thus our research question is: How and under what circumstances does personalization of algebra story problems support learning pathways? To investigate this question, we will examine the interaction between the context of a story problem and the impact of personalization, the effect of the readability level of the problem on the impact of personalization, and the impact of personalization on student mistake patterns.

Methods

This study took place during instruction as 145 9th grade Algebra I students used the Cognitive Tutor Algebra software. Cognitive Tutor is an intelligent tutoring system for Algebra I that individualizes instruction through adaptive problem selection and feedback (Koedinger & Corbett, 2006). Participants used Cognitive Tutor two days per week, most students spent several sessions working through the unit examined in this study, Unit 6. Participants were from a suburban school in the Northeastern United States that was majority Caucasian (96%), with 18% of students eligible for free/reduced lunch and 71% proficient in math on the 11th grade assessment.

Participants were randomly assigned to two conditions when they entered Unit 6, which contained algebra story problems on linear functions. The control group received the standard problems for the unit, while the experimental group received problems matched to their topic interests through a computer survey administered to both conditions. The survey asked students to rate their level of interest in (i.e., "liking of") 9 topic areas: sports, music, movies, games, TV, computers, food, art, and shopping. Personalized problems corresponding to each topic were written based on prior surveys ($N = 60$) and interviews ($N = 29$). Although the *topic* of each problem was matched to students' interests at the individual level, there is no measure in this study of whether the specific *story* in each problem was relevant to individual students' experiences with that topic. However, our prior survey, interview, and observational work revealed a great deal of overlap in the individual experiences and preferences high school students typically had in relation to each of the 9 topics.

There were 27 problems in the original unit, and 4 variations on each problem were written to correspond to the interest topics (Table 1). For each problem, students filled in different cells in a spreadsheet as they solved *result* and *start unknowns*. In result unknowns (questions 1-2, Figure 1), students solved for the y variable in a linear function given a specific x value, which involves directly applying the described operations. For start unknowns (questions 3-4, Figure 1), students solved for the x variable in a linear function given a y value, which may require working backwards. Students also wrote algebraic expressions from story scenarios.

Table 1: Example of four personalized variations on original algebra story problem from Unit 6

Original Problem	One method for estimating the cost of new home construction is based on the proposed square footage of the home. Locally, the average cost per square foot is estimated to be $46.50.
Sports	You are working at the ticket office for a college football team. Each ticket to the first home football game costs $46.50.
Music	You are helping to organize a concert where some local R&B artists will be performing. Each ticket to the concert costs $46.50.
Art	You have been working for the school yearbook, taking pictures and designing pages, and now it's time for the school to sell the yearbooks for $46.50 each.
Games	You work for a Best Buy store that is selling the newest Rock Band game for $46.50.

An open pit copper mine is 1,550 feet deep, and the company estimates that it is getting deeper at the rate of seven feet per month. Assume the number of feet below the surface is a negative number.
How deep was the mine one decade ago?
How deep will the mine be in two years?
If you have not already done see, please fill in the expression row with an algebraic expression for the depth.
3. In how many months will the mine by 1,564 feet deep?
4. How long ago was the mine started according to this algebraic model?

Quantity name	The digging time	The depth of the mine
Unit	month	Foot
Expression	X	-1550-7X
Question 1	-120	-710
Question 2	24	-1718
Question 3	2	-1564
Question 4	-1550/7	0

Figure 1. Example of normal story problem scenario - upper text shows result and start unknown questions posed, while lower table displays correct responses to each problem part

The data were analyzed using hierarchical logistic regression (Snijders & Bosker, 1999), where problem parts were nested within students who were nested within teachers. Random intercept terms were included for which story problem the student was working on, and what linear function (i.e., $y=-1550 - 7x$) or "item" was being described in the story problem. The dependent variable was whether the student got the problem part correct on the first attempt. Fixed effects included which condition the student was in (experimental group - personalized problems or control group - normal problems), the difficulty of the *knowledge component* being assessed in the problem part, and the interaction between condition and knowledge component difficulty. A knowledge component (KC; Koedinger & Aleven, 2007) is a skill that is tracked for mastery by Cognitive Tutor, and KCs were classified as easy, medium, or hard based on student performance data. Hard KCs included writing algebraic expressions with slope and intercept terms, while medium KCs included solving result and start unknowns, working with different types of numbers, and writing expressions with only a slope. Easy KCs included identifying independent and dependent units and entering given values.

Results and Discussion

The output from the regression model of performance in Unit 6 is shown in Table 2. Personalization increased performance when students were solving problem parts with hard KCs (odds = 1.5228, $p < .001$) and easy KCs (odds = 1.5228*.9368 = 1.4266, $p < .001$). The effect of personalization on medium KCs did not quite reach significance (odds = 1.5228*.7689 = 1.1709, $p = 0.0601$). Personalization supported students' algebraic expression-writing for linear functions that had both a slope and intercept term (hard KCs), and also facilitated the solving of less mathematically-relevant portions of the problem, like identifying units (easy KCs).

Table 2: Output for hierarchical logistic regression model of performance within Unit 6

	Raw Coeff	Std. Error	Exp(Coeff)	z value	Sig
(Intercept)	-0.27378	0.22707	0.7605	-1.21	
Condition-Control	Ref.				
Condition-Experimental	0.42053	0.11134	1.5228	3.78	***
KC-Hard	Ref.				
KC-Medium	1.32951	0.05986	3.7792	22.21	***
KC-Easy	2.17917	0.06105	8.8390	35.69	***
Condition-Exp:KC-Medium	-0.26276	0.08255	0.7689	-3.18	**
Condition-Exp:KC-Easy	-0.06528	0.08484	0.9368	-0.77	

Note. Significance codes: '***' 0.001, '**' 0.01, '*' 0.05

Although it is not included here for brevity, analyses of students' work in a future unit of Cognitive Tutor showed that personalization not only increased performance on hard KCs within Unit 6, it significantly increased performance on hard KCs in the subsequent unit, after the personalization intervention had been removed (Walkington, 2012). This suggests that the performance boost associated with personalization in Unit 6 facilitated students' learning of the concept of algebraic expression-writing. Thus we determined that it is critical to engage in a deeper investigation of what promoted or caused the performance differences seen in Unit 6, in order to better understand why personalization ultimately impacted students' long-term learning.

Problem Cover Stories

We begin by examining which of the story problems in Unit 6 benefitted most from being personalized. This may indicate classes of story problems for which personalization is particularity helpful. To do this, we added a condition by item random slope to the model shown in Table 3. This term essentially shows how the condition (personalized versus non-personalized) interacted with each base story problem to impact student performance. We concentrated on two groups of problems for this analysis. First, we looked at problems with random slopes indicating that personalization *reduced* the odds of getting the problem correct, corresponding to odds values of 0.7 to 0.9. Second, we looked at problems with random slopes indicating that personalization *increased* the odds of getting the problem correct, corresponding to odds values of 1.1 to 1.4. The results are shown in Table 3.

Table 3: The impact of personalization on performance for selected story problems in Unit 6

Topic of Original Problem	Linear Function	Personalization's Impact on Odds	Personalization…
Cell phone service	y = 60-5x	0.73	Reduced performance
Getting raise at work	y = .04x	0.74	Reduced performance
Pay from work	y = .72x	0.75	Reduced performance
Selling paintings	y = 64-6x	0.82	Reduced performance
Mail-order shopping	y = x -.025x+10	0.85	Reduced performance
Sending cards to friends	y = 55-.5x	0.86	Reduced performance
Paying cell phone bill	y = -.23x+7.87	0.86	Reduced performance
Making wages at work	y = 10.50x	0.87	Reduced performance
Nitrogen in an asteroid	y = 90-2x	1.13	Increased performance
Home square footage	y = 46.50x	1.13	Increased performance
Taking pictures with film	y = 36-6x	1.15	Increased performance
Installing carpet	y = 12.95x	1.19	Increased performance
Trading wampum shells	y = 80-6x	1.22	Increased performance
Taking vitamins	y = 50-2x	1.22	Increased performance
Breaking crayons	y = 24-2x	1.39	Increased performance

Several trends are apparent from Table 3 that provide insight into how personalization may support learning. First, personalization was not particularly helpful when the problem's topic was already relevant to students' lives and interests – like paying for their cell phone or getting paid at work. In these cases, the original problem could actually be slightly easier for students to solve than the personalized versions. Most of the problems where personalization was not beneficial dealt with money. High school students already have strong familiarity with doing calculations with money, especially in the context of work and shopping (Walkington et al, 2012), thus it makes sense that personalizing such a problem is unlikely to further improve performance. The instances in Table 3 where personalization increased performance are also revealing – high school students are not likely to have direct experience with calculations relating to nitrogen in an asteroid or installing carpet, thus personalization of these problems was particularly beneficial. Taken together, these results suggest that personalization supports performance when irrelevant story contexts become more situated within students' experiences and interests, and the ways in which they encounter numbers in their everyday life. Thus personalization may be effective in supporting learners in forming detailed and comprehensible *situation models* (Nathan et al., 1992) of problem scenarios, allowing them to leverage their prior knowledge of familiar contexts.

Readability Level

One reason why personalization may increase performance is that personalized problems are easier for students to read and interpret. This is supported by the data shown in the previous section, which suggested that personalization had the largest impact when it was used on problems with contexts that were not familiar or relevant to students' experiences. To examine this hypothesis, we added the readability level (Flesch, 1948) of the story scenario to the hierarchical model as a predictor. Readability level is an index used to measure comprehension difficulty, and uses indicators such as number of words, number of sentences, and syllables. Each story problem was classified as "below grade level" if the Flesch-Kincaid grade level test predicted its readability was appropriate for grades 4-7, "at grade level" if it was appropriate for grades 8-10, and "above grade level" if it was appropriate for grades 11-15. This addition also allowed us to check whether differences in performance for personalized problems were being driven solely by systematic differences in readability level.

Results show that personalization still had a significant positive effect on performance on easy (odds = 1.397, $p < .001$) and hard (odds = 1.489, $p < .001$) KCs when controlling for readability level. The model also showed a significant interaction between readability level and condition ($\chi^2(2) = 6.364$, $p < .05$), and readability level and knowledge component difficulty ($\chi^2(4) = 39.532$, $p < .001$). The results are summarized in Figure 2. For both easy and hard KCs, when a problem was easy to read (below grade level) the personalization condition had higher performance. However, the advantage of the personalization condition became even *greater* as the problems became more difficult to read. So, for example, if a student was presented with normal problem that was difficult to read, and a personalized problem that was also difficult to read, their performance would be considerably higher on the personalized problem. Whereas different readability levels did not seem to impact performance on personalized problems, increasing grade level readability had a considerable negative effect on performance on normal problems. The model showed that personalization had significantly greater positive impact on performance when the text of the problem was above grade level, for both hard and easy KCs (odds = 1.424, $p < .05$), compared to performance on these KCs on below grade level texts.

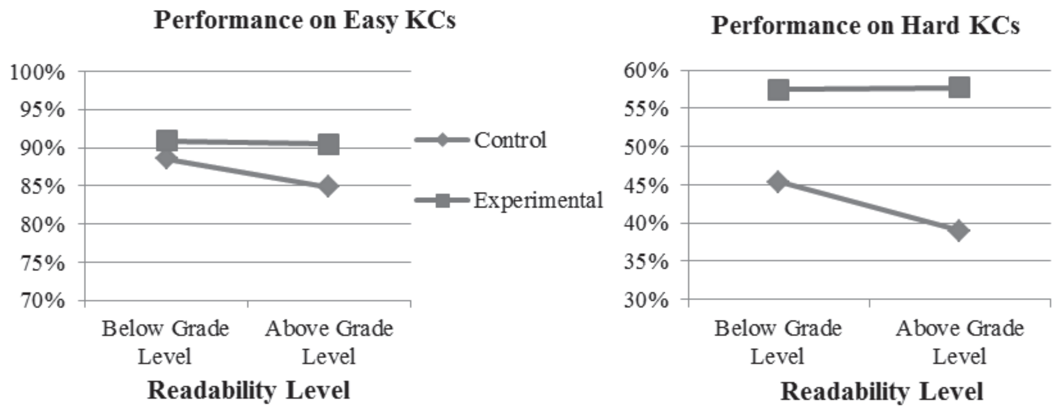

Figure 2. The impact of readability level on problem-solving performance for control (normal problems) and experimental (personalized problems) groups, separated by Easy KCs (left) and Hard KCs (right)

These results suggest that personalization allows students to better interpret difficult verbal scenarios of complex mathematical situations, and that this effect is especially large when students are asked to write algebraic expressions from story scenarios. The students' familiarity with personalized story contexts, due to the connection with their interests, may allow students to better understand the relationships within a story scenario with a complicated verbal structure, facilitating the formation of detailed and accurate situation models that support expression-writing. Thus personalization may allow learners to better move from their propositional textbase to an elaborated understanding of the story's actions and relationships.

Analysis of Mistakes

Personalization had an important positive impact on performance and learning for hard KCs, when students were writing symbolic equations from story scenarios. The analyses above suggest that successfully writing a symbolic equation from a story is tied to the students' verbal comprehension of the text and their ability to draw on their prior knowledge to form a situation model of the actions and relationships being described. We conducted an analysis of students' interactions with the tutor when solving hard KCs in order to see if the situation model support provided by personalization allowed students to avoid certain kinds of mistakes. As can be seen from Table 4, when students were presented with personalized problems, they were more likely to write an algebraic expression successfully on their first attempt, were less likely to initially ask for a hint, and were less likely to make a mistake and write the expression incorrectly. Results of the HLM analysis presented at the beginning of the section show that the difference in correct answers for the control group (42.6%) versus the experimental group (51.6%) is a statistically significant ($p < .001$) trend.

Table 4: Student performance on Hard KCs

Outcome	Control	Experimental
First Attempt Correct	42.6%	51.6%
First Attempt Hint	8.2%	4.9%
First Attempt Incorrect	49.2%	43.4%

As can be seen from Table 5, there are also differences in mistake patterns that may account for the greater success of the experimental group in writing algebraic expressions. The experimental group was equally likely to make simple sign reversal errors on either the slope or the intercept term. However, the experimental group was less likely to mix up the slope and intercept parameters or use incorrect signs for both the slope and intercept. The experimental group was also slightly less likely to not include a slope coefficient (i.e., use a slope of 1), not include an intercept term, or leave out both the slope term and the independent variable. Generally, this seems to imply that personalization assists students in remembering to include the appropriate parameters and variables in their expression, while also helping them make sense of how these parameters should be combined. This suggests that personalization reduces the likelihood of large conceptual misspecifications of the functional relationship by supporting students' situation models. In this way, personalization may allow students to meaningfully create a mathematical model for a situation, allowing them to coordinate their understanding of the story with a formal symbolic representation. This is contrasted with a purely procedural or syntactic construction of an algebraic expression, where situational understanding is not well connected to symbolic reasoning. Such approaches may be more prone to major conceptual errors, as shown by research on *direct translation* strategies when solving arithmetic word problems (Hegarty, Mayer, & Monk, 1995).

Table 5: Mistakes made by students when writing symbolic expressions from story scenarios

Write Equation Mistake	Control	Experimental
Entered slope of 1	111	103
Mixed up slope and intercept	57	39
No intercept	146	136
Only intercept	16	9
Intercept wrong sign	166	165
Slope wrong sign	116	114
Wrong sign, slope and intercept	104	118

Summary and Conclusion

In previous work, we found that personalization to students' interests mediates performance and learning in potentially powerful ways, supporting students in navigating the abstract representational systems in algebra. Here, we took a closer look at the data from our studies in order to investigate why such an effect occurs. We conclude that personalization may support students' formation of more detailed, accurate, and meaningful situation models of problem scenarios. This is evidenced by findings that the effect of personalization is largest when it makes an irrelevant problem relevant to students' experiences and when it makes the actions and relationships in a complex verbal scenario more easily read and interpreted. Personalization also seemed to allow students to make fewer large conceptual mistakes when specifying the relationships in a story, suggesting that personalization supports coordination of situation and problem models.

Rather than creating a general motivational effect that was seen throughout learners' problem-solving, the impact of topic interest on performance was targeted. Interest facilitated performance when students were working directly with the scenario, naming quantities and units and formulating a symbolic equation of the relationships. When students wrote equations, interest seemed to support understanding of the deeper, quantitative structure of the story. This suggests that for algebra story problems, the effectiveness of interest-based interventions lies in their ability to allow productive connections between situational contexts and formal models of situations. As the context becomes more comprehensible and connected to prior experience, students are better able to coordinate their situation and problem models in the process of problem-solving.

We hypothesize that personalization could be considered a form of *grounding* (Goldstone & Son, 2005; Koedinger, Alibali, & Nathan, 2008) that allows for abstract formalisms to be coordinated with concrete everyday experiences. Here, we presented evidence that the grounding provided by personalization becomes more effective as the story scenarios become more related to the interests, language, and activities the students are familiar with. Further, we described how in related work (Walkington, 2012) providing such grounding not only facilitated performance on personalized problems, but also allowed for robust learning of underlying algebraic ideas. This suggests that grounding interventions based on topic interest are not simply a crutch for learners to lean on when they struggle or become disengaged – they are a scaffold that has the potential to allow learners to come to understand powerful systems of representation.

With the rise of advanced learning technologies, the potential to connect instruction to both students' interests and to their current level of understanding has become a reality. It is critical that we understand how this technology impacts students' cognition and problem-solving, such that it can be leveraged in schools to enable productive pathways to learning. Here, we show how interest-based interventions can mediate students' situational understanding of mathematical relationships in story problems, fostering critical connections between personalized scenarios and abstract representational systems. It is both surprising and promising that such a simple alteration to instructional materials to make them more adaptive had an important impact on both performance and long-term learning of difficult concepts in secondary mathematics. As learning technologies advance, we thus propose that an important future direction is designing environments that can adapt to student background and preferences in a deeper and more meaningful manner, by leveraging the interests that drive and motivate students in authentic and powerful ways.

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