QUANTIFIED CLOSED-LOOP INTERNALIZATION OF MATHEMATICS

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Approaches to education that use New Media often focus on the front-end, which is presenting interactive material to the student. To complete the learning approach using such media, it is essential to integrate the back-end, which includes (i) assessing and tracking the student's internalization of a concept, (ii) tracking each teacher's attainment of learning outcomes for her students, and (iii) realigning the content using the tracking information. Our approach has done this, and has been tested on over 20,000 students for over 5 years. This paper presents our closed-loop method, the issues encountered and resolved, as well as quantified results that this approach yields.

INTRODUCTION

Over the past 20 years, there have been several approaches that use technology to enable learning. Connecting students and instructors across locations has been studied (Welsh et al., (2003; Johnson, Hornick and Salas, 2008). The time element is addressed by web-based approaches (Sendall, Ceccucci & Peslak, 2008; Chester & Gwynne, 2006) as well as applications on personal devices (Tremblay, 2010; Terras & Ramsay, 2012). Broadcasting the same material to an entire class in conjunction with a teacher is solved using classroom technology such as Oliver, Osa and Walker (2012), and increasing engagement via gamification of learning is an approach used extensively (De Castell, 2011). There are approaches to enable a teacher to connect with a student either individually (Sharma & Hannafin, 2007; Rekkedal & Qvist-Eriksen, 2003) or as a Massive Open On-line Classroom (MOOC) (Hu, 2013), and there is peer-to-peer learning (Courts & Tucker, 2012; Tarasowa et al., 2013). While the above mentioned approaches focus on delivery of content, there are others that focus on testing and assessment, which could be either assessment of a student using technology (Eisenberg, 2008), or assessment of the technology itself (Fletcher, 2013).

While current approaches focus on one aspect of education chain, technology offers the scope of addressing the complete problem of creating an engaging action space, presenting material integrated with the curriculum, assessing internalization, tracking student progress, tracking teacher efficacy, tracking efficacy of the tool itself, and finally making necessary adjustments and going back to the first step. A recommendation for an adaptive learning system has been made by the U.S. Department of Education (U.S. Department of Education, 2012). Such a closed loop system is a powerful use of Information and Computer Technology (ICT) in the educational space, enabling an experiential and constructivist approach with quantifiable learning across students of different backgrounds (age, gender, economic level, rural/urban, etc) (U.S. Department of Education, 2012; Warschauer & Matuchniak, 2010). Moreover, there is an increasing recognition that continuous feedback and re-orientation is needed for the teacher as well (Harris, Mishra & Koehler, 2009; Hattie, 2009). The general realm of

cognitive psychology and how it influences instructional design has been considered (de Jong, 2010), and needs to be complemented with various other factors to ensure long-term learning happens (Termos, 2012).

The focus of our study was to implement some of the recommendations made by the U.S. Department of Education (2012) as well as take into consideration some of the suggestions offered by other researchers (Johnson et al., 2011; Siemens & Baker, 2012). While most of the problem is solved using technology, human factors also play a small but pivotal role (Cobb, Yackel & Wood, 2011).

The study was conducted in several small groups of 8 learners of varying ages working under the supervision of a teacher, with each learner having an individual laptop. Data collected was used to refine the content and pedagogy and the system itself, to make learning more effective.

TECHNOLOGY AND THE STUDENT

Overview

While developing technology for learning, we need to first understand what the inhibitors to e-learning are (Muilenbeurg & Berge, 2005). Factors influencing learning in school children include level of engagement, learner motivation, social interaction (Vygotsky, 1978), academic skills and support for individual needs (McCombs & Miller, 2008). Further, for e-learning, accessibility and ease of use are also to be considered. Adoption of new media for learning is slow also because many students still prefer traditional ways of learning using pen-paper, as well as time with a teacher (Gorra et al., 2010). It is not often clear to the instructor whether the student got the answer right by guessing or 'romancing' the answer (Piaget, 1973), by memorization, or by applying mathematical principles. Further, when a student needs more questions of a particular type, the instructor is often limited by the questions provided in the text book. The pitfall is that the student tends to retain the answers in memory, and finds it difficult to have an unbiased view towards the question the second time over. Finally, when a student struggles at a particular question, it is not clear to an instructor why the student is struggling. Johnson et al have reported the usefulness of 'Learning Analytics' to monitor and predict student performance, hence spot potential issues early and take appropriate corrective measures (Johnson et al., 2011).

Dependencies across Years

Mathematical concepts covered by the student in the current year depend on concepts covered in earlier years (see figure 1). If a brick at the bottom of the pyramid is loose, cementing the top does not help. It is essential to identify which brick is loose and to fix it. This requires the content to be very fine-grained and tagged with appropriate dependency requirements. It also presents two requirements to the technology: identification of weak areas and remedy for the weaknesses.

In all of the content developed for this system, at most one new concept is introduced at each level. Moreover, at the point where a new concept is introduced, numbers are kept very simple, with a focus on first internalizing the concept (see the section on "Measuring Internalization"). Once the new concept is internalized, the next level introduces larger numbers with the same concept. The next stage is to expose the student to questions that

combine this new concept with other concepts already internalized so that the learner is able to construct a connection between concepts (Ausubel, 1967).

Technology Interaction

The interaction of the technology with the student is illustrated in figure 2. The computer first decides what level this particular student is at, then explains a concept to the student, and presents questions associated with the concept explained. The student works on the questions, and the computer both grades his work as well as times how long he has taken. In addition, the system computes a quantified metric for internalization of concepts, and decides what should be done next.

If the concept is not yet internalized, the system continues to expose the student to questions at the current level. Once the concept is internalized, the student's level is incremented, and the system moves the student up to viewing the explanation of a new concept, and starting questions in that concept. In addition to interaction with the student, the technology is also used to give feedback to the teacher as well as the content developer. This concept is also illustrated in figure 2, where two outputs of the system are later used.

Measuring Internalization

Our empirical approach measures internalization of a concept using three parameters: Accuracy, Speed, and Consistency. Clearly, the student has to solve the problem accurately, and correctness of his solution is essential. Having solved the problem correctly, it is necessary that he accomplishes this within the stipulated time.

Getting the problem correct and within average time is not sufficient. The student has to exhibit *consistency* which ensures that accuracy has not been achieved by fluke. This additional requirement is that the student exhibits accuracy and speed, 9 *times in a row*. This is shown in figure 3. The student started with low percentage and high time, and after attempting it several times, finally got the timing to less than 2 minutes and percentage above 90%. Long-term retention is also measured.

Constrained Randomization

One issue that invariably arises when using a text book is that the student is able to memorize the answers to a particular question. A patented method of constrained randomization (Moni, & Moni, 2012) has been employed to ensure that the student is presented with the same question but with different numerical values, until the concept is internalized. Problems based on various concepts are presented in random order to the student, coaxing the student to apply thinking and reasoning skills.

All teachers agree that mastering mathematics requires practice. Our system has automated the creation of questions at that exact nuance of the topic in that precise level. In many specific topic-level combinations, many millions of questions can be generated. Thus, even if the student needs 50, 100, or 200 distinct questions to master a particular idea, these questions are readily generated for the student.

Note that in figure 4, all questions are exactly the same, except the numerical values vary. Moreover, the variation of numerical values, in this case, has been constrained to be at most 2 digit. Additionally, the coefficient of "x" in any of the expressions is constrained to be non-zero. A further constraint that has been imposed is that the answer is an integer. This is somewhat of a deep constraint, since we need to work backward from the answer to formulate

a question that meets these requirements. The details of this approach may be seen in Moni and Moni (2012). In figure 5, the theme of the problems are the same but the problems use different operations. These appear in random order when a child is working on word problems.

Binary Search for Incomplete Internalization

Automatic identification of weak areas is done using a binary search method. If a student exhibits consistent weak performance in a particular level, the system takes him/her down a notch, and introduces questions in levels that are dependencies of the weak level. For example, Decimal Multiplication depends on Multiplication and Decimal Addition. If the student exhibits consistent weakness in Decimal Multiplication, then the required levels of Integer Multiplication and Decimal Addition will appear.
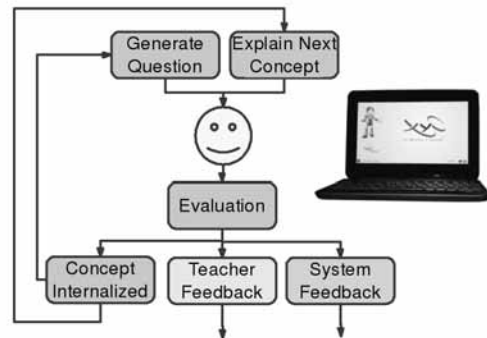

Figure 1: Math of the current year depends in on topics earlier years.

Figure 2: The flow chart to ensure covered internalization of concepts.
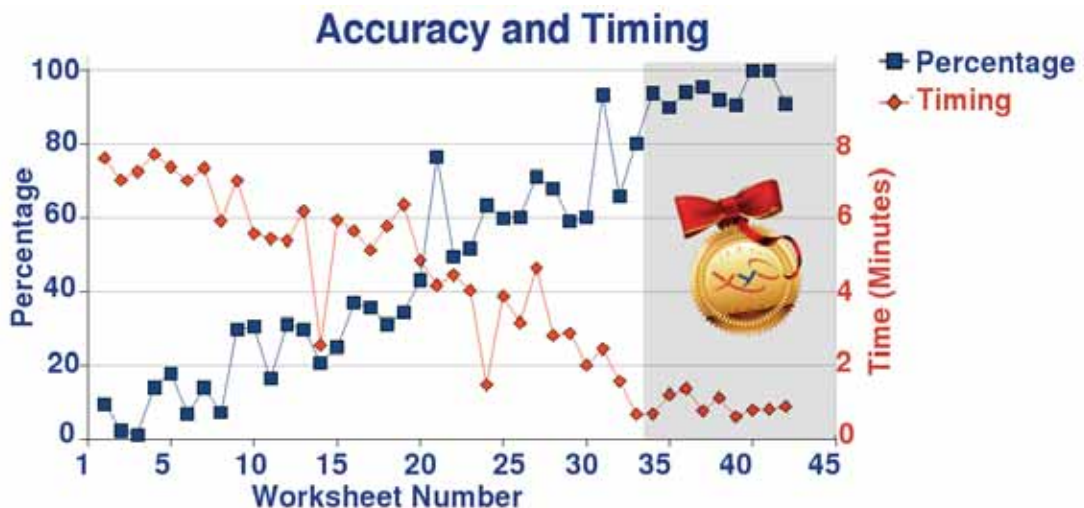

Figure 3: Internalization of a concept requires consistent work, meaning, a high percentage together with a low timing, exhibited 10 times consecutively. This is depicted in the highlighted yellow area along with a virtual medal.
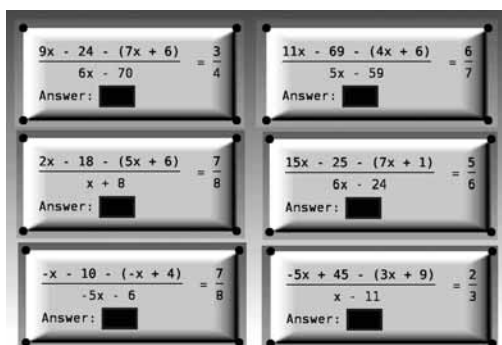
Figure 4: Constrained randomization is used to generate an unlimited number of questions in any topic-level combination.

Figure 5. Mixed word problems

TECHNOLOGY AND THE TEACHER

Feedback and formative assessment are essential for constant improvement in the instruction process (William & Leahy, 2007; Shepard, 2008). An example of such feedback is given in figure 6. As seen in the figure, the teacher knows how many hours the student has worked, and the "Work Quotient" (time used for mathematical problem-solving divided by login time). The report includes average percentage, number of questions attempted per hour, as well as snapshot of coverage of topics. There is also a per-student report (not shown in the figure) that gives information on the students, work quotient, time spent on each problem type, time spent "dreaming" (wrong answer, long duration), concepts internalized as well as which problems / concepts were difficult for students to comprehend.

Name	Class	Subject	Login Hours	Work Quotient	Num Questions	Avg	Questions per hour	Coverage Below Class	Coverage At Class	Coverage Above Class
student1	1	Olymp1	17	0.82	701	94	49	61% (52/84)	34% (8/23)	16% (2/12)
student3	3	Olymp3	46	0.73	3058	80	91	72% (91/126)	58% (33/56)	35% (11/31)
student5	5	Olymp5	31	0.71	2030	87	93	76% (92/120)	79% (38/48)	38% (33/85)
student7	7	Olymp7	27	0.86	1699	80	74	55% (66/120)	9% (8/83)	10% (10/100)
student9	9	CBSE_9_SAI	17	0.26	489	97	109	86% (13/15)	48% (58/120)	0% (0/0)

Figure 6: Summary of performance sent to the teacher.

Technology enables feedback to be given to the teacher immediately at the end of each session of work. Considering what teaching methodology works best (Petty, 2009) while taking into consideration individual students' strengths and weaknesses (Black & William, 1998) makes for better teaching methodology. The use of technology in formative assessment leads to instruction which is better aligned to student needs (Johnson et al., 2011; Davis & McCowen, 2007). Our system quantitatively directs this individualistic approach to instruction with optimal support from the teacher.

TECHNOLOGY AND THE CONTENT

Analyzing data on which levels take maximum time for students to master enables the development of required pedagogical content to make comprehension easier. Figure 7 illustrates some of the data used to refine the content. Often students "Skip" a question (get it incorrect in less than 5 seconds). Some of the highest percentage of skipping is seen in certain

introductory topics. Although a topic like Addition Word Problems may have 30 to 40 levels in our content, the data indicates which levels encounter frequent resistance and need to be further refined.

Name of topic and level	Percentage Skip	Avg Attempts to Internalization
Intro to Add WP	15.48	54
Intro to Mul WP	15.22	42
Ratio Prop Simple Prob	13.58	55
Area Vol: Perimeter	7.93	29

Figure 7: Example of quantitative metrics used to refine the content.

CONCLUSION

Using technology, it is possible to integrate the front-end (presenting material to the student) as well as the back-end, which is (i) assessing and tracking the student's internalization, (ii) tracking each teacher's effectiveness, and (iii) refining the content using the feedback. This closed-loop approach greatly enhances learning, improves efficiency of the teacher, and creates a productive learning environment where time spent is fruitfully utilized. Using this technology, each student's progress can be tracked and instruction tailored to his need, as if he were the only student in the class. The overall effectiveness of the teacher is significantly enhanced because the technology precisely isolates the problem areas. The long term effectiveness of the system is continuously increasing, since the technology is used to give quantified feedback to improve the technology itself, as well as the content.

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