Intuitions Aren't Good Enough: The Essential Marriage of Learning Theory, Scientific Assessment, and "eLearning" for a Brighter Future for Education

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I. Introduction

Educational interventions (from classroom teaching to textbooks to eLearning tools) make shockingly little use of what is in fact the best information available to improve education: scientific results from research studies in the learning sciences. We act as though the ***intuitions*** of educators and educational software developers are sufficient *on their own* to produce effective instructional environments. They are not. The general failure to apply research-based theory and to do scientific assessments of educational interventions is starkly illustrated by a single study found at the Department of Education's excellent web resource, the "What Works Clearinghouse." [http://www.whatworks.ed.gov/]

Currently, on the front page of that web site, you will find a report on middle school math curricula. The study's authors state its purpose as providing a review of "the available evidence from research conducted since 1983 on the effectiveness of curriculum-based interventions for improving mathematics achievement for middle school students." Remarkably, a fundamental conclusion of the report is: "Only 5 of the more than 40 middle school math interventions known to be available for adoption have any studies of their effectiveness that meet the WWC evidence standards."

One must ask: How can we responsibly promote the use of educational interventions that offer *no* scientific evidence of their effectiveness? An alternative to direct assessment that could justify use, would be designs grounded in well-confirmed research-based theories from the learning sciences. There are many reasons to believe that, especially in higher education, very few educational practices are grounded in what we have learned from these sciences in the last few decades about how people learn. My contention is:

> **Unless we first design teaching and learning environments using well-confirmed theories from the learning sciences, and second regularly test the efficacy of those interventions through sound scientific assessments, we will not improve the future of education.**

II. eLearning Environments Can Play a Major Role in Achieving these Desiderata

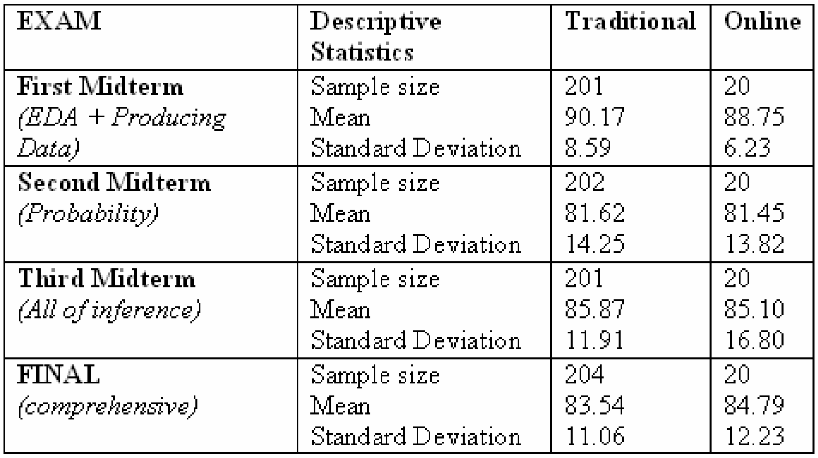
eLearning presents us a major opportunity here: digital learning environments offer us an opportunity to meet both desiderata -- but not unless we change how they have been and still are still being developed. I will describe for you a project at Carnegie Mellon University, funded by The William and Flora Hewlett Foundation, designed to use the development and application of web-based learning environments to produce measurably better learning outcomes by:

- Basing course design on proven theories about how people learn.
- Iteratively improving courses through routine scientific assessments and appropriate modification based on those assessments.
- Using a team of content experts, cognitive scientists, human-computer interaction experts, and information technologists as the “author” of every course.

The project I refer to is called the “**Open Learning Initiative**,” (OLI). [http://www.cmu.edu/oli] It has produced exemplars of what we call “cognitively informed” online courses (which can also serve as “interactive textbooks” for traditionally taught courses) and provides those an open educational resource for any learner with access to the Internet. The educational materials in the Open Learning Initiative currently include complete, self-contained online courses in statistics, economics, formal logic, causal reasoning, chemical stoichiometry, and substantial portions of courses in physics and biology. We are currently developing courses in calculus, mechanical engineering, research methods, French and Chinese.

These materials are completely different in kind and have a completely different purpose than those available at MIT’s OpenCourseWare site. The Open Learning Initiative courses are not a compilation of course materials used in traditionally taught courses at Carnegie Mellon, the OCW model. Rather they provide the ***complete enactment of instruction*** online. Although we believe OLI courses are more effective when used as an “interactive textbook” along with traditional instruction (indeed the very kind of textbook we project will dominate future educational settings), students can complete an entire course in one of these subjects using *only* the online instruction. The option of having no instructor is precisely the reason that the OLI courses *must* be informed by the best current knowledge from the cognitive sciences and iteratively developed, using formative studies of student use in order to make them effective. This development philosophy and process is what makes the OLI courses so different from the hundreds of computer-based courses the have been hyped over the last few decades, but failed miserably in use. OLI courses are exemplars of online instruction *that works.*

Departing from the national norm, the Carnegie Mellon statistics department has worked for years with cognitive scientists at the university to study and improve their traditional introductory course. During fall 2005, we conducted a formal experiment using IRB-approved methods to assess the effectiveness of the OLI statistics course. A random sample of students took the instructor-free version of the OLI online statistics course in place of the traditional statistics course for the entire semester. The results of the study are shown here:



EXAM	Descriptive Statistics	Traditional	Online
First Midterm *(EDA + Producing Data)*	Sample size	201	20
	Mean	90.17	88.75
	Standard Deviation	8.59	6.23
Second Midterm *(Probability)*	Sample size	202	20
	Mean	81.62	81.45
	Standard Deviation	14.25	13.82
Third Midterm *(All of inference)*	Sample size	201	20
	Mean	85.87	85.10
	Standard Deviation	11.91	16.80
FINAL *(comprehensive)*	Sample size	204	20
	Mean	83.54	84.79
	Standard Deviation	11.06	12.23

As you can see, the students in the sample who used *only* the OLI online instruction performed just as well as students in a (very high quality) traditional statistics course that involved: attendance at three small lecture sections per week, one additional computer lab per week, regular consultation with faculty, weekly graded homework assignments and traditional assessments. ***The resources necessary to deliver the online course were far fewer than those needed to deliver the traditional course.*** Of course, the resources that went into the development of the OLI course were far greater than those that go into a typical post-secondary statistics course.

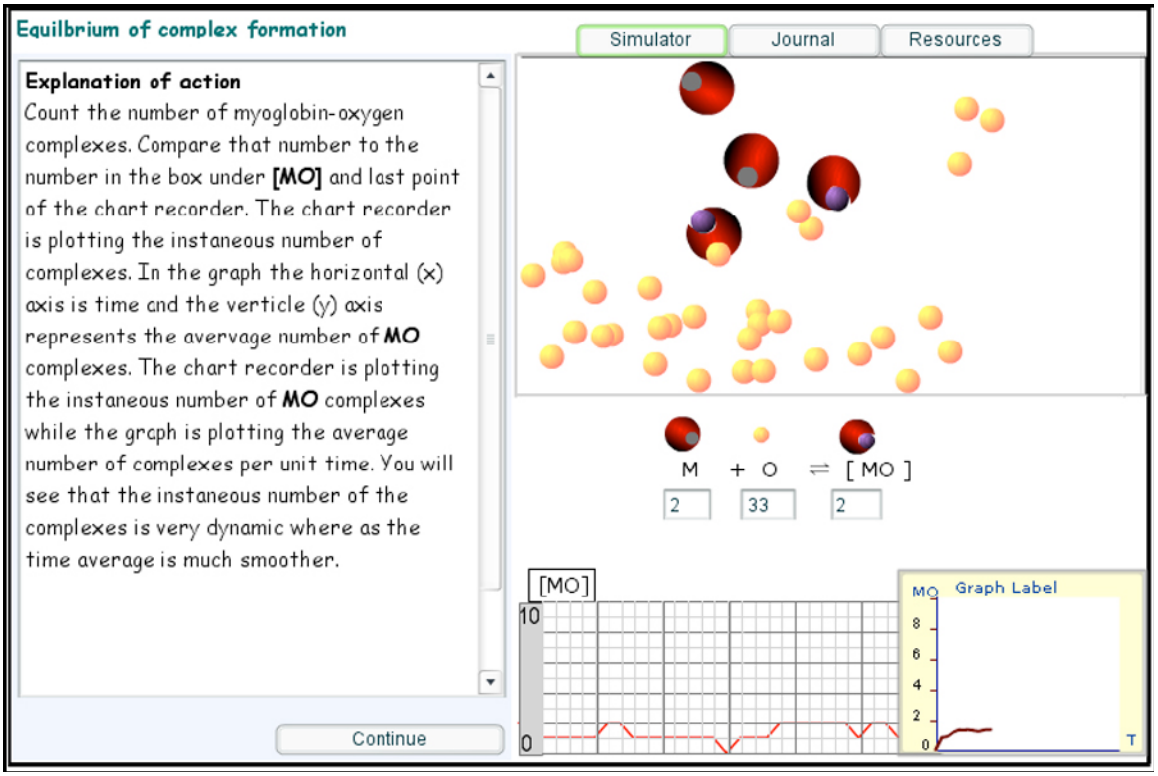
If the OLI course were adopted either as a stand-alone online course *or* as an interactive textbook by a large number of colleges and universities, the cost of instructional delivery per student across all students would be substantially reduced. ***Moreover, the use of this eLearning, interactive textbook would provide a curriculum and associated educational interventions for all introductory statistics courses which were designed from research-based principles and which have evidence they actually work to produced desired learning outcomes.*** Major findings from studies that have investigated use of *StatTutor*, part of the OLI statistics course, as supplement to traditional instruction include that students are better able to identify the appropriate statistical analysis for given problems and make more valid inferences from data. (Chang, Koedinger, & Lovett, 2003; Lovett & Greenhouse, 2000; and exhibit article: Lovett & Meyer, 2002) ***Digital learning environments can be a way to broadly disseminate truly effective educational interventions.***

In fall 2005, we also conducted a formal 5 week experiment using IRB-approved methods to assess the effectiveness of the OLI biology course. Two sections of the course, totaling over 300 students, were given the same introductory material in lecture and online in week one. Then, one section spent weeks 2 and 3 continuing to use the online course as their mode of instruction while the other section covered the same material in a traditional three lecture per week format. In weeks 4 and 5, the sections reversed roles and all students took the same midterm at the end of week 5. Although there are many more results than this, here are several representative findings:

- Observations of the two sections revealed more active participation in class discussions among students when they were using the online course.

- An exam given at the end of the 3rd week showed an advantage for the online section
- Detailed analyses of the data logs showed a positive and significant association between students' time spent working on particular activities and performance on quiz questions testing the corresponding topics.

The design process of the OLI biology course, as in all OLI courses, begins by identifying the key learning objectives for each topic and then includes interspersing interactive feedback and assessment activities (e.g., mini-tutors, simulator environments, animations, low-stakes comprehension questions) into the instructional content. In particular, the detailed animations of complex biological processes depict each process with a high level of scientific accuracy while minimizing the likelihood they would engender student misconceptions. A sample simulation from the OLI biology course looks like this:



Explanation of action

Count the number of myoglobin-oxygen complexes. Compare that number to the number in the box under **[MO]** and last point of the chart recorder. The chart recorder is plotting the instaneous number of complexes. In the graph the horizontal (x) axis is time and the verticle (y) axis represents the avervage number of ***MO*** complexes. The chart recorder is plotting the instaneous number of **MO** complexes while the graph is plotting the average number of complexes per unit time. You will see that the instaneous number of the complexes is very dynamic where as the time average is much smoother.

Figure 1. Integrated environment with linked representations. This simulator represents a highly magnified view of a test tube containing a protein (red balls) and its ligands (yellow balls). As the simulation runs, the number of bound proteins changes. These numbers are captured and displayed as part of the reaction equation as well as in two different graph formats. Students manipulate the system and practice making connections between different representations of the concept of equilibrium

All Open Learning Initiative courses undergo formative assessment as part of their design and development. We have either completed or are in the process of completing summative assessments of the kind described above for all the courses. [See exhibit article: (Scheines, et. al., 2005)] Moreover, the fact that these courses live in a digital delivery environment allows us to "instrument" them to provide course designers specific feedback about the effectiveness of individual interventions used in the courses. For example, we can (with students' permission) track what strategies students employ to solve problems in a virtual chemistry lab or in structuring a statistical analyses or in drawing causal hypotheses from statistical data.

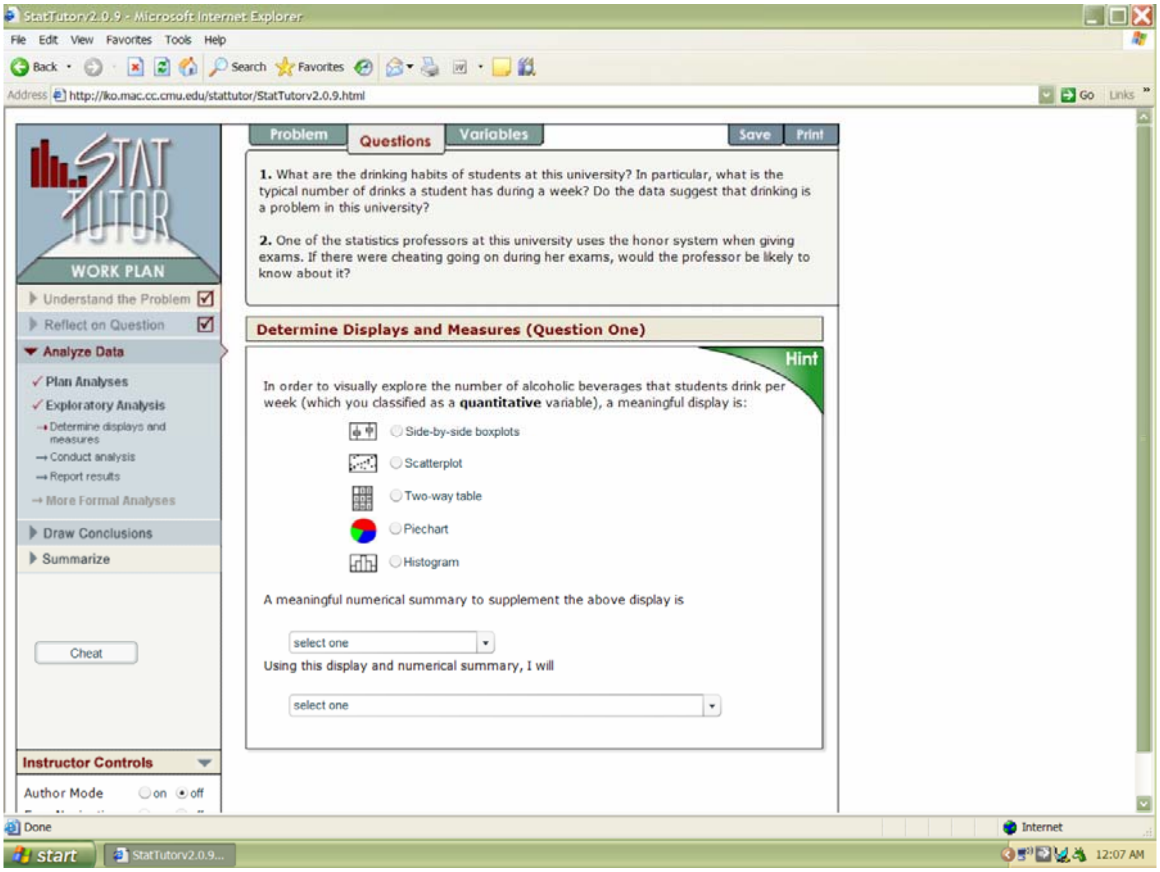
The same instrumentation that provides meaningful feedback to course designers also allows us to develop mechanisms for providing feedback to instructors who are using the courses to support their instruction. ***One of the great assets of eLearning environments is their unique capabilities to deliver instruction while simultaneously gathering data on what is and what is not working in the environment to improving student learning***. We are developing tools that connect diverse data sources in the OLI courses on student work to provide meaningful feedback to the instructor of their students' progress in real time. Based on this feedback, instructors can review areas of difficulty, assign additional work or move on to the next topic.

The results from the learning sciences have informed a wide range of instructional interventions in the OLI courses. For example, a fundamental result of many scientific studies in learning is:

> **Educational interventions should provide instruction in the problem-solving context and give immediate feedback on errors.**

OLI courses are designed to provide the most effective feedback possible. We have benefited from some of the best work done in the area of intelligent tutoring systems at Carnegie Mellon which has produced some of the most effective commercial educational interventions in K-12 mathematics available today – the CarnegieLearning CognitiveTutor curriculum [See exhibit articles: (Anderson, Koedinger, et. al., 1997) and (Aleven and Koedinger, 2002)]. Many OLI courses feature Cognitive Tutors and "mini-tutors" to give students feedback directly in the problem solving context. A Cognitive Tutor is a computerized learning environment whose design is based on cognitive principles and whose interaction with students mimics that of a human tutor—i.e., making comments when the student errs, answering questions about what to do next, and maintaining a low profile when the student is performing well. (Anderson, Corbett, Koedinger & Pelletier; 1995). "Mini-tutors" provide directed scaffolding and hints as well as immediate feedback to students as they work through steps of a specific problem. A full Cognitive Tutor is based on cognitive models created from extensive recording of both expert and novice paths in problem solution.

Traditional computer aided instruction gives only didactic feedback on student answers, such as "correct" or "try again". The Cognitive Tutors and "mini-tutors" do something very different. They provide context specific assistance during the problem solving process, such as in the statistics course "you appear to be confusing a categorical with a continuous variable, review the definitions". StatTutor (Lovett, 2001; Meyer & Lovett; 2002). is a Cognitive Tutor that is embedded in the OLI Statistics course. Statistical data-analysis problems presented in StatTutor appear at various points in the OLI Statistics course to support students as they practice the skills and concepts they are learning. The interface looks like this:



1. What are the drinking habits of students at this university? In particular, what is the typical number of drinks a student has during a week? Do the data suggest that drinking is a problem in this university?

2. One of the statistics professors at this university uses the honor system when giving exams. If there were cheating going on during her exams, would the professor be likely to know about it?

Determine Displays and Measures (Question One)

In order to visually explore the number of alcoholic beverages that students drink per week (which you classified as a **quantitative** variable), a meaningful display is:

○ Side-by-side boxplots
○ Scatterplot
○ Two-way table
○ Piechart
○ Histogram

A meaningful numerical summary to supplement the above display is

select one

Using this display and numerical summary, I will

select one

Figure 2. StatTutor, an intelligent tutoring system developed at Carnegie Mellon that facilitates understanding of statistical ideas and analytical techniques by helping students construct useful knowledge representations and thereby develop effective problem-solving skills.

Cognitive scientists have long recognized the problem of "inert knowledge." This refers to cases where the ideas and techniques acquired by students in an instructional setting are not transferred by the student to real world contexts. Our goal in all OLI courses is to promote the relevance and coherence of the domain of knowledge. Promoting relevance means teaching students how the skills and formal systems transfer to real world situations outside the context of instruction. Promoting coherence means teaching students how the discreet skills they are learning fit together in a meaningful big picture.

Much of college level chemistry is often taught out of context as a set of abstract mathematical skills. Students employ learning strategies to solve typical text book problems and perform well on traditional chemistry exams but often fail to see either the relationship between the mathematical procedures and the chemical phenomena those procedures represent or the relationship between the chemical phenomena and the real world. The OLI chemistry course is designed to address both of these educational challenges. We address the challenge of connecting the mathematical procedure to use in chemistry by replacing traditional textbook problems with problems to be constructed and solved in the virtual chemistry lab. We use the virtual chemistry lab to create learning environments with ill-structured, ambiguous problems that require flexible application of procedural knowledge.

For example, a typical textbook problem would be given as: “When 10ml of 1M A was mixed with 10ml of 1M B, the temperature went up by 10 degrees. What is the heat of the reaction between A and B?” A student can solve this type of problem by searching through his or her textbook, matching the question to a similar equation, filling the values into the found equation and producing a correct answer mathematically without understanding the chemistry. The resulting knowledge is usually “inert.”

The equivalent problem in the Virtual Lab would be given as: “Construct an experiment to measure the heat of reaction between A and B?” To solve the equivalent problem in the virtual lab, the student must understand the relationship between the mathematical equation and chemistry. Rather than a page with equations, the setting for chemistry homework in the OLI course is this:

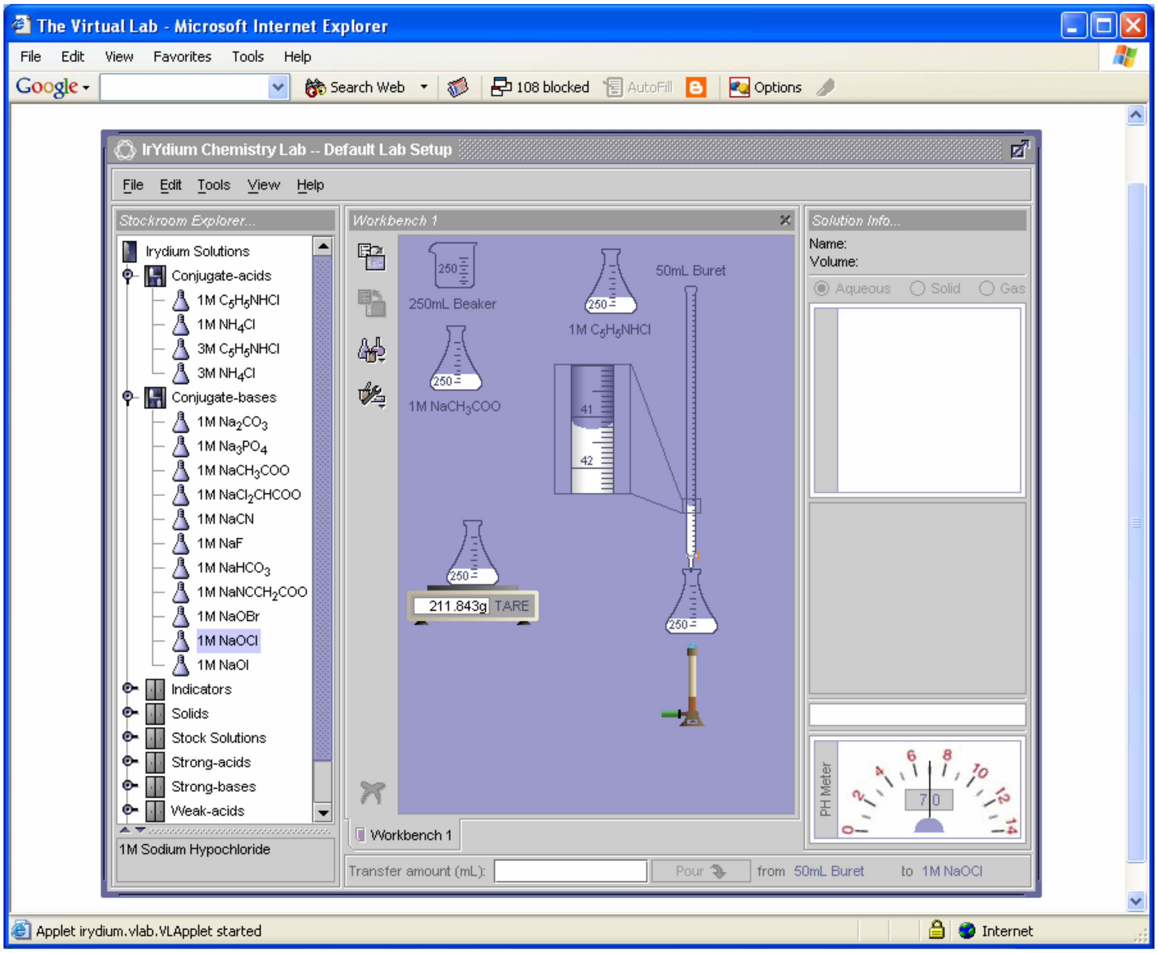


Figure 3. The Virtual Chemistry Lab, a learning environment that presents students with ill-structured, ambiguous problems that require flexible application of procedural knowledge.

We address the second challenge of connecting the procedures of chemistry to the real world by employing scenario based learning. The OLI introductory Chemistry course situates the learning of stoichiometry in a real world problem of arsenic contamination of the water supply in Bangladesh.

It should be clear by now that the ***Open Learning Initiative courses work because we incorporate research from multiple literatures, including cognitive psychology, education, educational technology, and science education and take very seriously the notion that research-based theories and assessment practices must be used to develop effective eLearning***.

III. A Major Reason Intuitions About Learning Alone Aren't Enough

The fact is that surprisingly few eLearning materials are currently developed using an OLI-like model. Why should they be? Why aren't the intuitions of good teachers about presenting material good enough for designing all educational interventions, including those delivered by computers? There is a research-based answer: the "expert's blind spot."

One of the most serious problems that confronts both traditional and online education is the well-documented phenomenon of the "expert's blind spot." Experts have biases that can lead to inaccurate conclusions about student difficulty in learning. Simply stated, as we become more expert in any discipline, it becomes harder for us to see the difficulties encountered by the novice learner. A study done by Nathan and Koedinger illustrates the problem in the domain of high school algebra. (Nathan & Koedinger, 2000). They used actual student performance in answering a number of high school mathematics problems to establish the varying difficulty of those problems. They then asked three different groups: high school mathematics instructors (the most expert), middle school mathematics instructors, and elementary school mathematics instructors (the least expert) to rank the problems according the degree of difficulty they believed high school students would have with each problem. The results show the "expert's blind spot."

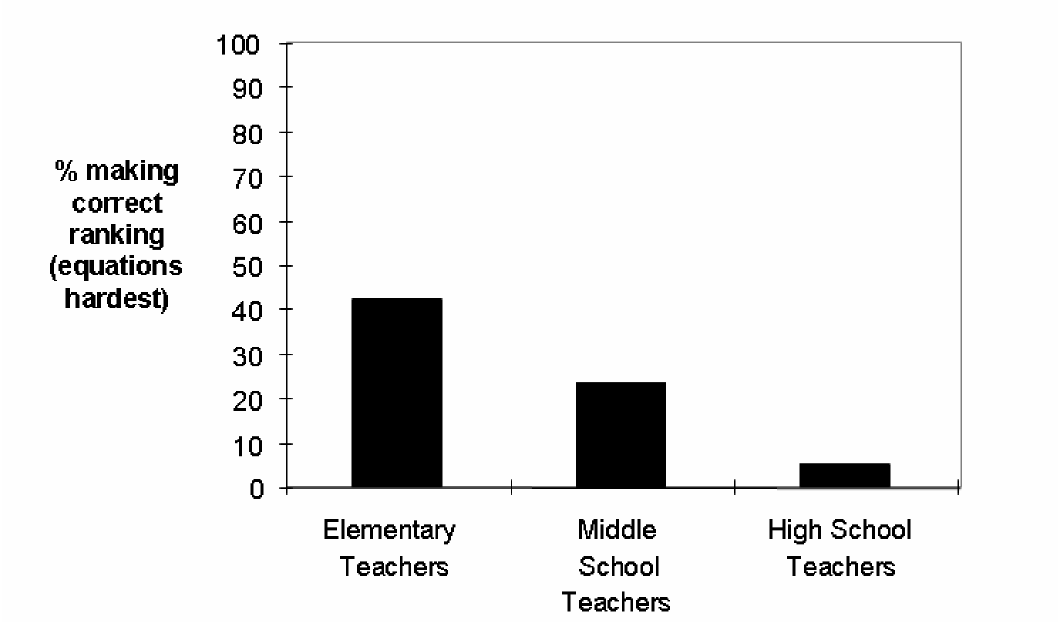


Figure 4. Nathan, M.J. & Koedinger, K.R. (2000). Teacher's and researchers beliefs of early algebra development. Journal of Mathematics Education Research, 31(2), 168-190

By far, the high school instructors were the least able to recapture the novice's perspective. This fact has profound implications for how we prepare instruction. Specifically, it means that, as we become more and more expert in a subject, we can less and less afford to depend on our intuitions about the ways in which novices understand that same knowledge. In small classroom traditional instruction, the problem of the expert's blind spot is mitigated by the instructor getting immediate feedback from the students that they need more help or that they are lost or confused. When we move from traditional small class room instruction to large lecture halls or to online instruction, the need for an effective design strategy to overcome the expert's blind spot is more profound. This is because in large lectures and in online environments the remoteness of the student can impoverish the feedback loops instructors have for knowing when students are learning the material and when they are lost.

In the OLI project, we employ several design strategies to mitigate the expert's blind spot. One such strategy is having design teams comprised of people with varying levels of domain expertise. For example our OLI chemistry team has a senior faculty member, a graduate student, an undergraduate, a high school chemistry teacher and a novice who all collaborate on how to present the material.

Another strategy is to use cognitive science and human computer interaction methods to gather data from novices as they attempt to solve problems in the domain. This data can be quantitative experimental data such as difficulty factor assessments or parametric experiments or qualitative data from classroom observations, contextual inquiry, think aloud studies or examining examples of student work. For example in designing our OLI statistics course, we reviewed hundreds of mid-term and final exams of first year statistics students and spent many hours conducting think aloud studies with novice statistics students as they solved data analysis problems. In designing our OLI Logic course learning scientists observed classroom discussions to document the processes through which students and instructors worked through misunderstandings.

Most importantly, once we have an initial design, we observe students as they attempt to learn the material and collect data traces of their learning processes to inform the next iteration of the course.

Practitioners in the field of Human Computer Interaction (HCI) are taught the mantra "the user is not like me" to remind them that they cannot use their own bias to design effective systems for other people. In the OLI project we use a modification of that mantra, we say to ourselves: "the student is not like me" and we are committed to using cognitive and human computer interaction methods to find out what students are like and how they learn.

IV. Conclusions

The bottom line conclusions for the future of education, especially as it involves eLearning as a significant element are fairly straightforward:

- **Cognitively-informed design and scientific assessment processes should become the norm in education. We must recognize that solely intuitively-informed designs suffer weaknesses including the expert's blind spot.**

- **Educational treatments, especially eLearning treatments, that can't provide scientific evidence for their efficacy, should not be used**

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- **Digital eLearning environments provide an unprecedented opportunity to widely propagate demonstrably effective, cognitively-informed educational interventions.**

- **Educational institutions should encourage the adoption of cognitively-informed eLearning treatments (interactive textbooks, online courses, learning objects, etc.), recognizing that these kinds of treatments will be developed by the few for use by the many, like textbooks.**

- **The potential for eLearning environments to gather performance data to inform individual students, educators, and instructional designers about what works and what doesn't should be a high priority in criteria for funding development of eLearning and purchasing decisions for eLearning tools.**

In the final analysis, it's always a quote by Herbert Simon, the Nobel Laureate polymath who spent most of his career with us at Carnegie Mellon, that summarizes the necessary marriage of learning sciences and technology to make effective eLearning tools: "If we understand the human mind, we begin to understand what we can do with educational technology."

References:

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Lovett, M. (2001). A collaborative convergence on studying reasoning processes: A case study in statistics. In S. Carver, & D. Klahr (Eds.) <u>Cognition and Instruction: 25 Years of Progress</u>. Mahwah, NJ: Erlbaum.

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