Studying and achieving robust learning with PSLC resources

LearnLab
Pittsburgh Science of Learning Center
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HCI & Psychology
CMU Director of PSLC

6th Annual Pittsburgh Science of Learning Center Summer School

- 10th overall
  - ITS was focus in 2001 to 2004
- Goals:
  - Learning science & technology concepts & tools
  - Hands-on project => poster on Fri

Vision for PSLC

- Why? Chasm between science & practice
  - Indicators: Ed achievement gaps persist,
    Low success rate of randomized controlled trials
- Underlying problem: Many ideas, too little sound scientific foundation
- Need: Basic research studies in the field

=> PSLC Purpose: Identify the conditions that cause robust student learning
  - Field-based rigorous science
  - Leverage cognitive & computational theory, educational technologies

Builds off past success: Intelligent Tutors Bringing Learning Science to Schools!

- Intelligent tutoring systems
  - Automated 1:1 tutor
  - Artificial Intelligence
  - Cognitive Psychology
- Andes: College Physics Tutor
  - Replaces homework
- Algebra Cognitive Tutor
  - Part of complete course
Tutors make a significant difference in improving student learning!

- **Andes: College Physics Tutor**
  - Field studies: Significant improvements in student learning

- **Algebra Cognitive Tutor**
  - 10+ full year field studies: improvements on problem solving, concepts, basic skills
  - Regularly used in 1000s of schools by 100,000s of students!

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**Overview**

- **PSLC Background**
  - Intelligent Tutoring Systems
  - Cognitive Task Analysis

- **PSLC Methods & Tech Resources**
  - *In vivo* experimentation
  - LearnLab courses, CTAT, TagHelper, DataShop

- **PSLC Theoretical Framework**

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**President Obama on Intelligent Tutoring Systems!**

"we will devote more than three percent of our GDP to research and development. .... Just think what this will allow us to accomplish: solar cells as cheap as paint, and green buildings that produce all of the energy they consume; learning software as effective as a personal tutor; prosthetics so advanced that you could play the piano again; an expansion of the frontiers of human knowledge about ourselves and world the around us. We can do this."

*How close to this vision are we now? What else do we need to do?*

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**Cognitive Tutor Approach**

- **Cognitive Psychology**
- **Artificial Intelligence**
- **Curriculum Content**
  - Math Instructors
  - Math Educators
  - NCTM Standards

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**Research base**

**Cognitive Tutor Technology**

**Cognitive Tutors**

- Algebra I
- Equation Solver
- Geometry
- Algebra II
Cognitive Tutor Technology

- Cognitive Model: A system that can solve problems in the various ways students can

  Strategy 1: IF the goal is to solve a(bx+c) = d
  THEN rewrite this as abx + ac = d

  Strategy 2: IF the goal is to solve a(bx+c) = d
  THEN rewrite this as bx + c = d/a

  Misconception: IF the goal is to solve a(bx+c) = d
  THEN rewrite this as abx + c = d

Cognitive Tutor Technology

- Cognitive Model: A system that can solve problems in the various ways students can

  If goal is solve a(bx+c) = d
  Then rewrite as abx + ac = d

  3(2x - 5) = 9
  6x - 15 = 9
  2x - 5 = 3
  6x - 5 = 9

  If goal is solve a(bx+c) = d
  Then rewrite as abx + c = d

  3(2x - 5) = 9, 2x - 5 = 3, 6x - 5 = 9

- Model Tracing: Follows student through their individual approach to a problem -> context-sensitive instruction

Cognitive Tutor Technology

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Cognitive Tutor Course Development Process

1. Client & problem identification
2. Identify the target task & “interface”
3. Perform Cognitive Task Analysis (CTA)
4. Create Cognitive Model & Tutor
   a. Enhance interface based on CTA
   b. Create Cognitive Model based on CTA
   c. Build a curriculum based on CTA
5. Pilot & Parametric Studies
6. Classroom Evaluation & Dissemination
Cognitive Tutor Approach

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Curriculum Content

Cognitive Tutors
Algebra I
Equation Solver
Geometry
Algebra II

Difficulty Factors Assessment:
Discovering What is Hard for Students to Learn

Which problem type is most difficult for Algebra students?

Story Problem
As a waiter, Ted gets $6 per hour. One night he made $86 in tips and earned a total of $81.90. How many hours did Ted work?

Word Problem
Starting with some number, if I multiply it by 6 and then add 66, I get 81.90. What number did I start with?

Equation
\[ x \times 6 + 66 = 81.90 \]

Algebra Student Results:
Story Problems are Easier!

Percent Correct

<table>
<thead>
<tr>
<th>Problem Representation</th>
<th>Percent Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Story</td>
<td>70%</td>
</tr>
<tr>
<td>Word</td>
<td>61%</td>
</tr>
<tr>
<td>Equation</td>
<td>42%</td>
</tr>
</tbody>
</table>

Expert Blind Spot:
Expertise can impair judgment of student difficulties


"The Student Is Not Like Me"

- To avoid your expert blind spot, remember the mantra:

  "The Student Is Not Like Me"

- Perform Cognitive Task Analysis to find out what students are like

Prior achievement:
Intelligent Tutoring Systems bring learning science to schools

A key PSLC inspiration: Educational technology as research platform to generate new learning science

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- PSLC Methods & Tech Resources
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- PSLC Theoretical Framework
PSLC Statement of Purpose

Leverage cognitive and computational theory to identify the instructional conditions that cause robust student learning.

What is Robust Learning?

- Robust learning is achieved through the development of both:
  - conceptual understanding & sense-making skills
  - procedural fluency with basic skills
- Robust Learning is measured by
  - transfer to novel tasks
  - retention over the long term, and/or
  - acceleration of future learning

PSLC Statement of Purpose

Leverage cognitive and computational theory to identify the instructional conditions that cause robust student learning.

In Vivo Experiments
Principle-testing laboratory quality in real classrooms
**In Vivo Experimentation Methodology**

Methodology features:
- What is tested?
  - Instructional solution vs. causal principle
- Where & who?
  - Lab vs. classroom
- How?
  - Treatment only vs. Treatment + control
- Generalizing conclusions:
  - Ecological validity: What instructional activities work in real classrooms?
  - Internal validity: What causal mechanisms explain & predict?

**What is tested?**
- Lab experiments

**Where?**
- Classroom
- Lab

**In Vivo learning experiments**

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**LearnLab**

A Facility for Principle-Testing Experiments in Classrooms
LearnLab courses at K12 & College Sites

- 6\(^{+}\) cyber-enabled courses: Chemistry, Physics, Algebra, Geometry, Chinese, English
- Data collection
  - Students do home/lab work on tutors, vlab, OLI, ...
  - Log data, questionnaires, tests → DataShop

PSLC Technology Resources

- Tools for developing instruction & experiments
  - CTAT (cognitive tutoring systems)
    - SimStudent (generalizing an example-tracing tutor)
  - OLI (learning management)
  - TuTalk (natural language dialogue)
  - REAP (authentic texts)
- Tools for data analysis
  - DataShop
  - TagHelper

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KLI Framework: Designing Instruction for Robust Learning

The conditions that yield robust learning can be decomposed at three levels:

- Knowledge components
- Learning events
- Instructional events

Get framework report at learnlab.org

KLI Event Decomposition

- Decompose temporal progress of learning
- Observe/control instructional & assessment events
- Infer learning events & changes in knowledge

What's the best form of instruction? Two choices?

- More assistance vs. more challenge
  - Basics vs. understanding
  - Education wars in reading, math, science...
- Researchers like binary oppositions too. We just produce a lot more of them!
  - Massed vs. distributed (Pashler)
  - Study vs. test (Roediger)
  - Examples vs. problem solving (Sweller, Renkl)
  - Direct instruction vs. discovery learning (Klahr)
  - Re-explain vs. ask for explanation (Chi, Renkl)
  - Immediate vs. delayed (Anderson vs. Bjork)
  - Concrete vs. abstract (Pavio vs. Kaminski)
  - ...
An example of some PSLC studies in this space

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Learn by doing or by studying?

- Testing effect (e.g., Roediger & Karpicke, 06)
  - "Tests enhance later retention more than additional study of the material"
  - Paas and van Merrienboer (1994), Sweller et al. (1998), van Gerven et al. (2002), van Gog et al. (2005a, 2005d), Sweller et al. (1999), Ayres (2006), Treffon & Reiser (2003), Renki and Atkinson (2003), ... the list goes on...

- Worked example effect
  - "a worked example constitutes the epitome of strongly guided instruction [aka optimal instruction]"
  - Kirschner, Sweller, & Clark (2006), Why minimal guidance during instruction does not work... failure of... problem-based... teaching.

- Theoretical goal: Address debate between desirable difficulties, like "testing effect", and direct instruction, like "worked examples"

- Limitation of past worked example studies have weaker control, untutored practice
  - PSLC studies compare to tutored practice

Derivation:
> 15 instructional dimensions
> 3 options per dimension
> 2 stages of learning
=> 315777 options

205,891,132,094,649
"Big Science" effort needed to tackle this complexity
Cumulative theory development
Field-based basic research with microgenetic data collection
Worked Example Experiments within Geometry Cognitive Tutor
(Alexander Renkl, Vincent Aleven, Ron Salden, et al.)

- 8 studies in US & Germany
  - Random assignment, vary single principle
  - Over 500 students
  - 3 in vivo studies run in Pittsburgh area schools
- Cognitive Science 08 IES Best Paper Award

Ecological Control = Standard Cognitive Tutor
Students solve problems step-by-step & explain

Lab results
- 20% less time on instruction
- Conceptual transfer in study 2

In Vivo
- Adaptively fading examples to problems yields better long-term retention & transfer
Worked example effect generalizes across domains, settings, researchers

- Geometry tutor studies
- Chemistry tutor studies in vivo at High School & College (McLaren et al)
  - Same outcomes in 20% less time
- Algebra Tutor study in vivo (Anthony et al)
  - Better long term retention in less time
- Theory: SimStudent model (Matsuda et al)
  - Problems provide learning process with negative examples to prune misconceptions
- Research to practice
  - Influencing Carnegie Learning development
  - New applied projects with SERP, WestEd

Processes of Learning within the KLI Framework

The conditions that yield robust learning can be decomposed at three levels:

Knowledge components

Learning events

Instructional events

Learning Events in the Brain & reflected in Dialogue

- Fluency building
  Memory, speed, automaticity
- Refinement processes
  Classification, co-training, discrimination, analogy, non-verbal explanation-based learning
- Sense-making processes
  Reasoning, experimentation, explanation, argument, dialogue

Some PSLC Examples

- ACT-R models of spacing, testing effects & instructional efficiency (Pavlik)
- SimStudent models of learning by example & by tutoring
  - Inductive logic programming, probabilistic grammars (Matsuda, Cohen, Li, Koedinger)
- Transactivity+ analysis of peer & classroom learning dialogues (Rose, Asterhan, Resnick)

Knowledge components carry the results of learning

- Knowledge component = a unit of cognitive function or structure that can be inferred from performance on a set of related tasks.
- Used in broad sense of a knowledge base
  - From facts to mental models, metacognitive skills
Kinds of Knowledge Components

<table>
<thead>
<tr>
<th>Task Features</th>
<th>Response</th>
<th>Relationship</th>
<th>Rationale</th>
<th>Labels</th>
</tr>
</thead>
<tbody>
<tr>
<td>constant</td>
<td>constant</td>
<td>implicit</td>
<td>no</td>
<td>association</td>
</tr>
<tr>
<td>constant</td>
<td>constant</td>
<td>explicit</td>
<td>no</td>
<td>fact</td>
</tr>
<tr>
<td>variable</td>
<td>constant</td>
<td>implicit</td>
<td>no</td>
<td>category</td>
</tr>
<tr>
<td>variable</td>
<td>constant</td>
<td>explicit</td>
<td>no</td>
<td>concept</td>
</tr>
<tr>
<td>variable</td>
<td>variable</td>
<td>implicit</td>
<td>no</td>
<td>production, schema, skill, rule</td>
</tr>
<tr>
<td>variable</td>
<td>variable</td>
<td>explicit</td>
<td>no</td>
<td>principle, rule, model</td>
</tr>
</tbody>
</table>

- Other kinds of KCs
  - Integrative, probabilistic, metacognitive, misconceptions or "buggy" knowledge

Example KCs with different features
- Chinese vocabulary KCs: const->const, explicit, no rationale
  - If the Chinese pinyin is "lao3shi1", then the English word is "teacher"
  - If the Chinese radical is "L", the English word is "sun"
- English Article KCs: var->const, implicit, no rationale
  - If the referent of the target noun was previously mentioned, then use "the"
- Geometry Area KCs: var->var, implicit & explicit, rationale
  - If the goal is to find the area of a triangle, and the base <B> and the height is <H>, then compute 1/2 * <B> * <H>
  - If the goal is to find the area of irregular shape made up of regular shapes <S1> and <S2>, then find area <S1> and <S2> and add

Knowledge components are not just about domain knowledge
- Examples of possible domain-general KCs
- Metacognitive strategy
  - Novice KC: If I'm studying an example, try to remember each step
  - Desired KC: If I'm studying an example, try to explain how each step follows from the previous
- Motivational belief
  - Novice: I am no good at math
  - Desired: I can get better at math by studying and practicing
- Social communicative strategy
  - Novice: When an authority figure speaks, remember what they say.
  - Desired: Repeat another's claim in your own words and ask whether you got it right

Can these be assessed, learned, taught? Broad transfer?

Learning curves: Measuring behavior on tasks over time
- Data from flash-card tutor
- Tasks present a Chinese word & request the English translation
- Learning curve shows average student performance (e.g., error rate, time on correct responses) after each opportunity to practice

Dataset: Chinese Vocabulary Spring 2007
Sample size: All Data

Integrated KCs for mental models, central conceptual structures, strategies & complex planning

6 secs

3 secs
Empirical comparison of KC complexity

Example KC types
- Chinese vocabulary KCs: const->const, explicit, no rationale
- English Article KCs: var->const, implicit, no rationale
- Geometry Area KCs: var->var, implicit/explicit, rationale

Time
- 6 -> 3 secs
- 10 -> 6 secs
- 14 -> 10 secs

Which instructional principles are effective for which kinds of knowledge components?

Prompted self-explanation studies across domains

- Physics Course - field principles
  - Better transfer than providing explanations

- Geometry Course - properties of angles
  - Better transfer than just practice despite solving 50% fewer problems in same time

- English Course - article use
  - Pure practice appears more efficient; self-explanation may help for long-term retention & for novices

- Cross-domain hypoth: Type of KC determines when self-explanation will be effective.

Summary

- Obama: "learning software as effective as a personal tutor"
- How close to this vision are we now?
  - Many fielded Intelligent Tutors
  - Students learn as much or more
- What else do we need to do?
  - Expand to more areas => CTAT
  - More sophisticated interaction => CSCL
  - Use tutors to advance science & improve educational practice => In Vivo & EDM

In other words ...

Take the PSLC Summer School!