Simulated Students and Classroom Use of Model-Based Intelligent Tutoring

by

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Simulated Students & Classroom Use of Model-Based Intelligent Tutoring Systems

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Modeling & simulation to enhance education

- Two paths:
  1. Students create models & use simulations
  2. Researchers create models of learners to guide materials development

- #1 is great way to *potentially* enhance learning, however,

- Understanding student learning (#2) is critical to effective design & use
Real World Impact of HCI & Learning Technologies

Algebra Cognitive Tutor

- Based on computational models of student thinking & learning
- Course used nationwide
  - Over 4000 schools, 35 states, 475K students use for 80 minutes per week

Spin-off: Carnegie Learning™

Intelligent tutoring goes to school in the big city.
Overview

• Background: Cognitive Tutors
  – Simulating tutoring
  – Data crucial to create accurate model

• Pittsburgh Science of Learning Center
  – Generalizing learning science & technology

• Examples of advanced modeling efforts
  – Simulating student learning
  – Modeling metacognition, help-seeking
  – Machine learning detectors of student engagement
An experimental aircraft has sunk off the coast of South Africa at a depth of 12,700 feet. The military have located the aircraft and are in the process of raising it to the surface. It is currently 7625 feet below the surface and is being raised at the rate of 185 feet per hour. (Hint: Consider the direction above sea level to be positive)

1. How deep was the aircraft five hours ago?
2. How deep will the aircraft be five hours from now?
3. When did the military start raising the aircraft?
4. When will the aircraft reach the surface?

To write an expression, define a variable for the time from now and use this variable to write a rule for the depth of the aircraft.

Use table, spreadsheet

<table>
<thead>
<tr>
<th>Time</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>HOURS</td>
</tr>
<tr>
<td></td>
<td>-7625+185H</td>
</tr>
<tr>
<td>1</td>
<td>-5</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>-27.018</td>
</tr>
</tbody>
</table>

Use equations, symbolic calculator

-7625+185H = -12790
Add 7625
185H = -5,165
Divide by 185
H = -1,033/37
Multi-Disciplinary Approach

Research base
Cognitive Psychology
Artificial Intelligence

Cognitive Tutor Technology

Curriculum Content
Math Instructors
Math Educators
NCTM Standards

Cognitive Tutors
Algebra I
Equation Solver
Geometry
Algebra II
Cognitive Tutor Technology:
Use ACT-R theory to individualize instruction

- 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: Use ACT-R theory to individualize instruction

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

\[ 3(2x - 5) = 9 \]

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

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

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

\[ 6x - 15 = 9 \quad 2x - 5 = 3 \quad 6x - 5 = 9 \]

- Model Tracing: Follows student through their individual approach to a problem -> context-sensitive instruction
Cognitive Tutor Technology:
Use ACT-R theory to individualize instruction

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

\[ 3(2x - 5) = 9 \]

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

Hint message: "Distribute \( a \) across the parentheses."

Known? = 85% chance

\[ 6x - 15 = 9 \]
\[ 2x - 5 = 3 \]
\[ 6x - 5 = 9 \]

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

Bug message: "You need to multiply \( c \) by \( a \) also."

Known? = 45%

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

- Knowledge Tracing: Assesses student's knowledge growth -> individualized activity selection and pacing
Multi-Disciplinary Approach

Research base

Cognitive Psychology

Artificial Intelligence

Cognitive Tutor Technology

Curriculum Content

Math Instructors
Math Educators
NCTM Standards

Cognitive Tutors

Algebra I
Equation Solver
Geometry
Algebra II
What prior knowledge do algebra students have?

Which problem type is most difficult for beginning Algebra students?

Story Problem
As a waiter, Ted gets $6 per hour. One night he made $66 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!

Practical & Theoretical Implications of Surprising Results

- Guided Cognitive Tutor Algebra design
  - Success due in part to smoothly bridging from students' existing common sense

- Inspired basic *cognitive modeling* work to explain these results
  - Coded student solutions for alternative strategies & errors
  - Model could generate both & fit student data on frequency of both
Cognitive Tutor Algebra Course

- Integrated tutor, text, and teacher training
- In computer lab 2 days/week, classroom 3 days/week
- Learn by doing:
  - Project-based
  - Student-centered
  - Cooperative learning
  - Teacher as facilitator
Original Field Study Results

- Full year classroom experiments with comparison classes
- Replicated over 3 years in urban schools
- In Pittsburgh & Milwaukee

- Results:
  50-100% better on problem solving & representation use.
  15-25% better on standardized tests.

Many other studies of Cognitive Tutor Algebra

- 11 study reports available
  - From 1994 to present, 11 different districts
  - More than 8000 students in these studies
  - Most run independently of Carnegie

- Significant positive results in all but 1 case (which was a tie)

- See www.carnegielearning.com/results/reports
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Transition to Pittsburgh Science of Learning Center

Past Success:
- Cognitive Tutors as delivery vehicle
  - Bring *existing* Learning Science to classroom

New Goal:
- Cognitive Tutors as research platform
  - Create *new* Learning Science & Technology
- 5 year, $25 million research center:
Generalizing Cognitive Tutor Approach

Research base

Cognitive & Educational Psychology
Artificial Intelligence

Learning Science & Technology

Curriculum Content

University Instructors & Professors

Technology-Enhanced Courses

Statistics Philosophy Economics Chemistry ...

...
Pittsburgh Science of Learning Center (PSLC)

- **Problem**: Inadequate theory to engineer courses to be provably effective in raising student achievement
- **Solution**: PSLC’s theory & facility development
  - Theory: Unified effort toward *robust learning* theory
  - Facility: *LearnLab’s* courses, technology, DataShop

- **Scientific merit & broad impact**
  - Advance a practical learning theory, evidence-based education, fast & natural dissemination
PLSC Focus on Robust Learning

• Other Intelligent Tutoring Systems yield better learning on immediate post-tests
  – Woolf, Graesser, VanLehn, ours ...
• Push to address robust learning
  – Transfer beyond isomorphic probs
  – Long term retention
  – Preparation for better future learning
• Address both sides of ed wars
  – Basic fluency & deep conceptual understanding
• Tutor at meta-cognitive level
PSLC’s Resources

• 7 Technology-enhanced courses where researchers can run studies
  - Algebra, Geometry, Chemistry, Physics, French, Chinese, English

• Data Shop
  - A repository of student learning data sets
  - Reporting, export, & analysis tools

• Tools for authoring tutors ...
LearnLab: 7 testbed courses open for studies

- Technology-enhanced courses:
  - 2 math, 2 science, 3 language courses
- Tutors, simulations, video, chat rooms, multimedia ...

A 2000-kg car in neutral at the driveway 20.0 m long slips its parking brake and rolls down. Assume that the driveway is frictionless.

What is the magnitude of the velocity of the car when it hits the garage door?

Answer: 

[Diagram showing a car on a driveway with angles and distances labeled]
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Cognitive Tutor Authoring Tools (CTAT)

- Easier authoring of Tutoring Systems
  - Non-programmer methods
  - General plug-and-play architecture
- Tutors created in a variety of domains:
  - Chemistry, Thermodynamics, Genetics, Law, French culture ...

http://ctat.pact.cs.cmu.edu

CTAT Cognitive Tutor Authoring Tools
Software that enables you to author intelligent tutor behavior

Cognitive Tutors have been successful in raising students' math test scores in high school and middle-school classrooms, but their development has traditionally required considerable time and expertise. With the Cognitive Tutor Authoring Tools (CTAT),...
Aids for Building Cognitive Tutors

- Iterative design-&-test for GUI
  - Building, testing, and modifying a prototype
  - Cycling quickly and easily

- Cognitive Modeling
  - Generating a cognitive model without programming
  - Human friendly testing & debugging
Solution

- Integrated intelligent authoring environment
  - CTAT: Cognitive Tutor Authoring Tools
  - Simulated Student: Machine learning agent that learns cognitive skills
CTAT: Cognitive Tutor Authoring Tools
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SimStudent

- Work with Noboru Matsuda & William Cohen
- Learn production rules by demonstration
- 3 parts: What, how, and when
  - What to operate on
  - How to operate
  - When to do it
Structure of a Production Rule

If

such and such constraints hold

When

among this and that GUI elements

What

Then

do actions with the GUI elements

How

Left Hand Side (LHS)

Right Hand Side (RHS)
Structure of a Production Rule

(defrule trans-lr-lhs

  (?problem <- (problem (interface-elements ?table1 ? ? ?)))
  (?table1 <- (table (columns ?column1)))
  (?column1 <- (column (cells $?m1 ?cell0 $?)))
  (?cell0 <- (cell (value ?val0 &-nil)))

  (?table2 <- (table (columns ?column2)))
  (?column2 <- (column (cells $?m2 ?cell1 $?)))
  (?cell1 <- (cell (value ?val1 &-nil)))

  (?column1 <- (column (cells $?m3 ?cell2 $?)))
  (?cell2 <- (cell (name ?selection) (value ?input)))

  (test (consecutive-row ?cell0 ?cell2))
  (test (same-column ?cell0 ?cell2))
  (test (distinctive ?cell0 ?cell2))
  (test (consecutive-row ?cell1 ?cell2))
  (test (same-column ?cell1 ?cell2))
  (test (distinctive ?cell1 ?cell2))

  (test (polynomial ?val0))
  (test (not (has-var-term ?val1)))

  =>

  (bind ?input (first-var-term ?val0))
  (modify ?cell2 (value ?input)))
Learning Techniques

(defrule trans-lr-lhs
  ?table1 <- (table (columns ?column1))
  ?column1 <- (column (cells $?m1 ?cell0 $?))
  ?cell0 <- (cell (value ?val0&-nil))

  ?table2 <- (table (columns ?column2))
  ?column2 <- (column (cells $?m2 ?cell1 $?))
  ?cell1 <- (cell (value ?vall&-nil))

  ?column1 <- (column (cells $?m3 ?cell2 $?))
  ?cell2 <- (cell (name ?selection) (value ?input))

  (test (consecutive-row ?cell0 ?cell2))
  (test (same-column ?cell0 ?cell2))
  (test (distinctive ?cell0 ?cell2))
  (test (consecutive-row ?cell1 ?cell2))
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  =>

  (bind ?input (first-var-term ?val0))
  (modify ?cell2 (value ?input))

  Brute Force Search

  Focus of attention

  Working Memory Element (WME)

  WME path

  LHS

  Topological constraints

  WME conditions

  FOIL

  Feature constraints

  RHS
SimStudent demo ..
SimStudent Goals & Progress

• Improving tutor authoring
  - Works in multiple domains
    • Past: Multi-column addition & multiplication, Tic-Tac-Toe, fraction addition
    • Current: Equation solving, Stoichiometry
    • Future: Scientific reasoning

• Simulating human learning
  - Studies varying:
    • Alternative curriculum sequences
    • Human-like memory limitations
  - Surprising result: Hard-to-easy curriculum sequence better than easy-to-hard
A model good student help-seeking behavior

- Production system implementation
- About 50 rules
- Use same model tracing technique
- But at the "metacognitive" level
  - In addition to geometry tutor at cognitive level
Tutoring Help-Seeking

- **Goal:** Foster long-term *learner independence*
- **Model of desired learning & help-seeking behaviors**

- Provide tutoring relative to this model
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Another example of using ML
Adapting to When Students
Game an Intelligent Tutoring
System

Former Phd student Ryan Baker
Gaming the System

"Attempting to get correct answers and advance in a curriculum by taking advantage of the software's help or feedback, rather than by actively thinking through the material"

For instance

- Systematic Guessing
  (cf. Mostow et al 2002)
- Drilling through Hints
  (cf. Wood & Wood 2000, Aleven 2001)
"Scooter the Tutor"

- A tutor agent
- Uses a *machine learning* "detector" to recognize student gaming behavior
- Intended to reduce gaming & negative consequences for learning
Gaming detector construction

1. Collect data
   - Observe students in computer lab
     • Code off-task behaviors
   - Get tutor interaction log data from same sessions

2. Train a machine learning system using data
   - Techniques: Fast correlation-based filtering, forward selection on log data variables & interaction terms
   - Generalized & cross-validated across four tutor domains
Samantha is trying to find out what brand of dog food her dog Champ likes best. Each day she feeds him a different brand and sees how many bowls he eats. But then her mom says that maybe her dog just eats more on days when he exercises more.

Please draw a scatterplot to show how many bowls the dog eats, given the dog's level of exercise that day.
During the Student's Tutor Use

- Scooter responds to gaming in two ways
  - Emotional expressions
  - Supplementary exercises
Emotional Expressions

- If the student never games, Scooter looks happy
Emotional Expressions

- If the student appears to be gaming, Scooter looks increasingly displeased and becomes redder and redder
Supplementary exercises

- Multiple Levels
- If a student is wrong, receives another question

Why do we need to know the largest value of height in this part of the problem?

- To help pick a scale for the axis
- To help pick the last label of the axis
- To help pick the first label of the axis
- To help pick which point to plot first
Scooter demo video ...
Scooter results

- Reduces gaming behavior
- Supplementary exercises increase learning
- Emotional responses do not

Baker et al. (2006). Adapting to When Students Game an Intelligent Tutoring System (Best Paper at ITS06)
Two kinds of student modeling approaches

1. Rational approach
   - Analyze domain & code model that "makes sense"
   - Example: Help-seeking model

2. Empirical approach
   - Collect human data driven & use statistical machine learning to learn model
   - Example: Gaming detector

- Remember PSLC's resources
  - One is DataShop
  - It provides data needed for empirical approach
DataShop: Get data to build or test models of learning!

- Microgenetic log data of student learning over semester
- Data from math, science, language courses
Conclusions
Summary

- Two educational uses of models & simulations
  1. Students create models & use simulations
  2. Researchers create models of learners to guide development of reliably effective materials
- Cognitive Tutors simulate & support tutoring
  - Data is crucial to create effective model
- Pittsburgh Science of Learning Center
  - Resources for modeling, authoring, experimentation
  - Repository of data & theory
- Examples of advanced modeling efforts
  - SimStudent learns rule-based model
  - Help-seeking model: Tutors metacognition
  - Scooter uses machine learning detectors of student engagement
Pittsburgh Science of Learning Center opportunities

- Propose a classroom study or attend summer school
- Analyze student data
  - TagHelper: Verbal data coding software
  - DataShop: Data sets, reporting & analysis tools
- Author a tutor or on-line activity
  - Cognitive Tutor Authoring Tutors
  - TuTalk: Authoring tutorial dialog
  - Open Learning Initiative
  - On-line assessments