Educational Technologies
WS2008/9

Intelligent Tutoring Systems - Cognitive Tutors

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28.10.2008 Introduction and overview

04.11.2008: Intelligent tutoring systems (1) - Cognitive Tutors

11.11.2008: Intelligent tutoring systems (2) – ActiveMath

18.11.2008: Student modeling

25.11.2008: Pedagogical components, instructional planning

02.12.2008: Meta-cognitive support (1) – Help

09.12.2008: Error diagnosis and feedback

16.12.2008: Meta-cognitive support (2)

13.01.2009: Collaborative learning technologies

20.01.2009: Multi-Media Learning principles

27.01.2009: Web-based systems

03.02.2009: Educational data mining

10.02.2009: Project presentations by students
Today’s Lecture

- Brief Introduction to the Concept of Intelligent Tutoring Systems
- The Behavior of Intelligent Tutoring Systems
- Cognitive Tutors - Description
- Cognitive Tutor Demo
What is an Intelligent Tutoring System (ITS)?

- A kind of educational software
  - Supports “learning by doing” with step-by-step guidance
- Uses artificial intelligence techniques to
  - Provide human tutor-like behavior
  - Be more flexible, diagnostic & adaptive
- Computer-based instructional system that separates content (what) from strategy (how)
- Usually makes inferences about what the student “knows”, i.e., Contains a model of domain, strategy, and/or student
- Typically have a mixed-initiative approach in which students can ask questions and have more control over their learning
Problem Solving: Andes Physics Tutor
(VanLehn et al)

Presentation of problem and place to provide an answer

Help provided to students when they ask intelligent tutor to “explain further”
Diagnosis and Simulation: Sherlock (Lesgold et al)

Avionics troubleshooting tutor

Simulation of the actual control panel of an F15 test station

Presentation of problem; control of tutor

Schematic of F15 component under diagnosis
Learning French Culture (Ogan et al.)

Now that you've seen the result...

Was your prediction correct?

Student views clip of French cultural scene

Student is asked questions about the clip

In this clip from the end of the school year, the two oldest students are about to hear the results of their exams and whether they will move on to middle school the following year.
Learning Science with Dialogue (Graesser et al.)

- Talking head
  - Gestures
  - Synthesized speech

- Presentation of the question/problem

- Dialog history with
  - tutor turns
  - student turns

- Student input (answers, comments, questions)

- The sun exerts a gravitational force on the earth. The earth moves in its orbit around the sun. Does the earth pull equally on the sun? Explain why.
Problem Solving: Stoichiometry (McLaren et al.)

Stoichiometry Tutor |  Help

Problem Statement
Suppose the WHO recommended limit for arsenic in drinking water is equal to 0.000014 grams of arsenite (AsO2−) / L solution. To determine the concentration of arsenite in a solution sample that is safe, one needs to check it against the WHO recommendation. How many grams of arsenite (AsO2−) / L solution are in a sample with 0.58 moles of arsenite (AsO2−) in 100 kiloliters (100 kL) of solution? The result should have 2 significant figures. (Hint: the molecular weight of arsenite (AsO2−) is 108.8 g AsO2− / mol AsO2−.)

Hint: The goal is to convert the amount of substance in moles to grams by using molecular weight.

Student solves equation; correct answers in green, incorrect answers in red

Presentation of the question/problem

Student can ask for hints
For What Domains are Intelligent Tutor Systems Relevant?

- Complex, multi-step problem solving
  - Not simple single step question & answer

- Can develop & worth developing
  - It is expensive! Worth it when e.g.,
    - large number of students, importance of topic, lack of other alternatives

- Can interpret student actions
  - Natural language is not necessary
  - Or can be handled with menus or NL tech
What are ITSs used for?

- Classroom Learning: Algebra Cognitive Tutors
- Distance (i.e., e-Learning): ActiveMath
- Learning Science Studies
- Quick Case Study: Stoichiometry Tutor

- How do students learn with worked examples vs. tutors vs. unsupported problem solving?
- Does it matter how feedback is provided?
  - Polite language vs. Direct language
  - Audio feedback vs. Text feedback
Interesting Learning Questions Connected with Intelligent Tutors

▶ “Gaming the system”
  ▶ Are students more likely to game systems than to game human tutors?

▶ Should we have bottom-out hints?
  ▶ Do bottom-out hints encourage hint abuse?
  ▶ Should (computer) tutor let students out of a problem when they struggle?
  ▶ What do human tutors do? Delay bottom-out hint?
  ▶ Put a cap on the number of bottom-out hints?

▶ If students know that the tutor is assessing them, would it influence their behavior with the tutor?
  ▶ Will they “game” the assessment?
  ▶ Hide the assessment algorithm?
ITS Architecture: Simplified

Components of the ITS architecture

- Tutoring Model
- Student Model
- Domain Model
- Interface
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The “loops” of Intelligent Tutors


▶ The “Outer Loop”

▶ Focused on the *problems*, i.e., which problems to present to the student

▶ The “Inner Loop”

▶ Focused on *steps* of a problem and what to do at each step
The nested loops of conventional teaching

For each chapter in curriculum

- Read chapter
- For each exercise, solve it
- Teacher gives feedback on all solutions at once
- Take a test on chapter
The nested loops of Computer Aided Instruction (CAI)

For each chapter in curriculum

▶ Read chapter

▶ For each exercise
  ▶ Attempt answer
  ▶ Get feedback & hints on answer; try again
  ▶ If mastery is reached, exit loop

▶ Take a test on chapter
The nested loops of Computer Aided Instruction (CAI) – Only Outer Loop

What is the value of x?

\[ x = 25 \]

Answer
The nested loops of Intelligent Tutoring Systems

For each chapter in curriculum
  ▶ Read chapter
  ▶ For each exercise
    ▶ For each step in solution
      ▶ Student attempts step
      ▶ Get feedback & hints on step; try again
    ▶ If mastery is reached, exit loop
  ▶ Take a test on chapter
What is the value of $x$?

Step 1: $40° + 30° + y° = 180°$

Step 2: $70° + y° = 180°$

Step 3: $y° = 110°$

Step 4: $x° + 45° + 110° = 180°$

Step 5: $x° + 155° = 180°$

Step 6: $x° = 180° - 155°$

Step 7: $x° = 25°$

Answer: $x° = 25°$
Error specific feedback: How?
Usually the first few hints of a hint sequence

What is the value of $x$?

$40 + 30 + y = 180$

$y = 250$

Oops! Check your arithmetic.
What is the value of $x$?

$40 + 30 + y = 180$

$y = 250$

You seem to have made a sign error.
Hints segue from error specific feedback to next-step hinting

What is the value of $x$?

$$40 + 30 + y = 180$$

$y = 250$

Try taking a smaller step.

Source: Bruce McLaren, Eric Melis, Vincent Aleven, Ken Koedinger, Kurt Van Lehn
Next-step hints become more specific

What is the value of x?

40 + 30 + y = 180

y = 250

Try doing just one arithmetic operation per step.
Def: A **bottom-out hint** is the last hint, which tells the student what to enter.

What is the value of $x$?

```
40 + 30 + y = 180
y = 250
```

Enter $70 + y = 180$, and keep going from there.
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Kinds of Computer Tutors

Tutoring systems

Intelligent tutoring systems
  e.g., Sherlock, ActiveMath

Constraint-based tutors
  e.g., SQL Tutor

Model-tracing tutors
  e.g., Andes

Cognitive tutors
  e.g., PAT

CAI e.g., Math Success 2006
An ITS Success Case

Cognitive Tutor Algebra (aka Pump)

- Most widely used ITS
  - 2500+ schools across North America
  - Marketed by Pittsburgh company Carnegie Learning

- “Exemplary Curriculum” by US Dept of Ed

- Most cited Journal of AI-Ed paper

Researchers

Teachers

Source: Bruce McLaren, Eric Melis, Vincent Aleven, Ken Koedinger, Kurt Van Lehn

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**Cognitive Tutor Math:**
2007-08: 2600 Schools, 500,000 Students
Pedagogical Approaches

Cognitive Tutors support “guided learning by doing”
- ACT-R: procedural knowledge is acquired by doing

Other approaches:
- (Guided) discovery learning, simulations
- Critiquing of solutions
- Post-hoc reflection
- Dialog
- Support for self-explanation, example-studying
More Details: Pedagogical Approach in Cognitive Tutors

- Problem selection by system
- Mastery learning based on student model
- Immediate feedback
- On-request help, with progressively more specific hints
- Proactive help on repeated errors
- Bug messages
- “Scaffolding” in the interface
Algebra Cognitive Tutor

Analyze real world problem scenarios

A rock climber is currently on the side of a cliff 67 feet off the ground. She can climb on the average about 2 one-half feet per minute.

1. When will she be 92 feet off the ground?
2. In 20 minutes, how many feet above the ground will she be?
3. In 75 seconds, how far above the ground will she be?
4. Ten minutes ago, how far above the ground would she have been?

For the formula, define a variable for the climbing time, and use this variable to write an expression for her height above the ground.

Use table, spreadsheet

<table>
<thead>
<tr>
<th>UNIT</th>
<th>TIME</th>
<th>HEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINUTE</td>
<td>FEET</td>
<td></td>
</tr>
<tr>
<td>FORMULA</td>
<td>X</td>
<td>2.5X+67</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>92</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>117</td>
</tr>
<tr>
<td>3</td>
<td>1.25</td>
<td>70.125</td>
</tr>
</tbody>
</table>

Use graphs, graphics calculator, symbolic calculator

Tutor learns about each student

Tutor follows along, provides context-sensitive Instruction
Evaluation Contrast

|^ Gold standard: The “2 sigma” effect of human 1 on 1 tutoring.  
  > Individual tutors improve upon classroom instruction by 2 standard deviations. (Bloom, 1984)

|^ Effectiveness of educational technologies
  > Computer-aided instruction = 0.3-0.5 sd (meta-analysis of 100s of studies)
  > Cognitive Tutor technology = 1 sd
Early Demonstrations of Cognitive Tutor Effectiveness

▶ Students learn faster (Programming)
  ▶ Cognitive tutor for LISP programming language
  ▶ Experimental group 3 times faster & better scores than control

▶ Students learn better (Geometry Proof)
  ▶ Cognitive tutor for geometry proof design
  ▶ Two classroom studies: experimental group 1 sd better
  ▶ Key lesson: Pay attention to social context. Curriculum integration, teacher training, follow standards


Cognitive Tutor Development – From Idea to the Classroom

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 Use & Dissemination

Not stages. Iterate!
Remember this slide from the Intro Lecture?

Technology Enhanced Learning (TEL)

- AI
- Computational Linguistics
- Cognitive Psychology
- Web-Technology Multimedia
- Pedagogy
- Content
Here’s Another Variation – Specific to Cognitive Tutors

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

Source: Bruce McLaren, Eric Melis, Vincent Aleven, Ken Koedinger, Kurt Van Lehn
Project-Based Learning by Doing

Features of Class Activities

Cell Phone Problem

• Read realistic contexts:

“You are told that tomorrow you are to order cellular phone service for all the officers in your company. Your boss tells you that she will be providing you with the necessary information ...”

• Compare alternatives:

  Economy Service: $19.95 per month and $0.31 per minute.
  Silver Service: $40.95 per month and $0.16 per minute.
  Gold Service: $80.95 per month with no per minute charge.

• Analyze using multiple representations:

  “... include equations, tables, graphs, points of intersection”

• Create a model and write a report:

  … include the range of airtime for which each plan is the cheapest
  … present your report and decision to the President of the company
Mantra #1

The Teacher Is Not Like Me
Combining Theory & Practice

Research base
Cognitive Psychology
Artificial Intelligence

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Simple, But Effective, Instructional Design Principles

► Instruction is most effective when it builds on what students already know

► Sequence instruction from easy to hard (also called “Mastery Learning”)
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!

Expert Blindspot:

Expertise can impair judgment of student difficulties

Mantra #2:

The Student Is Not Like Me

- To avoid your expert blind spot

- Use Cognitive & HCI methods to find out what students are like
Kinds of Cognitive Analysis & HCI Methods

▶ Theory
  ▶ ACT-R cognitive modeling

▶ Quantitative Experimental data
  ▶ Difficulty Factors Assessments
  ▶ Parametric experiments with system alternatives

▶ Qualitative data
  ▶ Think alouds, tutor-student log files
  ▶ Classroom observations, contextual inquiry

▶ Participatory Design
  ▶ Practitioners (teachers) are paid team members, 50% teaching + 50% on design team
Kinds of Cognitive Task Analysis

- **Approaches**
  - *Empirical*: Based on observation, data, exp.
  - *Analytical*: Based on theory, modeling.

- **Goals**
  - *Descriptive*: How students *actually* solve problems. What Students need to learn.
  - *Prescriptive*: How students *should* solve problems. What Students need to know.
Combining Theory & Practice

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ACT-R: A Cognitive Theory of Learning and Performance

- Big theory … key tenets:

  - Learning by doing, not by listening or watching

  - Production rules represent performance knowledge:

    These units are: Instruction implications:
    - modular           isolate skills, concepts, strategies
    - context specific  address "when" as well as "how"

**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

  - 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 $bx+c = d/a$

  - $3(2x - 5) = 9$

  - $6x - 15 = 9$

  - $2x - 5 = 3$

  - $6x - 5 = 9$

- **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

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

  Hint message: “Distribute $a$ across the parentheses.”

  Known? = 85% chance

  $3(2x - 5) = 9$

  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%

  $6x - 15 = 9$

  $2x - 5 = 3$

  $6x - 5 = 9$

- **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

*Source: Bruce McLaren, Eric Melis, Vincent Aleven, Ken Koedinger, Kurt Van Lehn*
Combining Theory & Practice

- **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
AI Production Rules – A Means to Implement ACT-R Rules

- Working memory -- the database
- Production rule memory
- Interpreter that repeats the following cycle:
  1. Match
     - Match “if-parts” of productions with working memory
     - Collect all applicable production rules
  2. Conflict resolution
     - Select one of these productions to “fire”
  3. Act
     - “Fire” production by making changes to working memory that are indicated in “then-part”
English

ADD
IF
The goal is to do \texttt{?problem}, a single-column addition problem
And no result has been found yet
And the first addend is \texttt{?num1}
And the second added is \texttt{?num2}
THEN
Set \texttt{?sum} to the sum of \texttt{?num1} and \texttt{?num2}
Write \texttt{?sum} as the result

Jess

(defrule add
 ?problem <-
 (1column-addition-problem
  (result nil)
  (first-addend ?num1)
  (second-addend ?num2))
=>
 (bind ?sum (+ ?num1 ?num2))
 (modify ?problem (result ?sum)))
Knowledge Representation

- Representing “memory” of:
  - The “ideal” cognitive model
  - The student‘s activities
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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
Replicated Field Studies

- Full year classroom experiments
- 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.

Why do Cognitive Tutors (and ITSs more generally) work? (some of many possible answers)

- For task domains where knowledge is a set of relatively independent pieces, like productions, the production rules are just what students need to learn.

- Tutors reduce the grain size of interaction, enabling students to more quickly detect & repair flaws.

- Tutors are like worked examples in which the student gets to guide the way the example is presented.

- — more research needed!
THE END