Cognitive Science and Education

ACT-R and the PUMP Tutor

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Material in this slide based on Ken Koedinger's invited talk at the 2001 Artificial Intelligence in Education Conference, and Christian Lebiere's ACT-R tutorial.

Education: A great domain for Cognitive Science

- Model students' reasoning:
  - To give the right feedback, at just the right moment.
- Create flexible, easy to use environment:
  - Expressive, rich, multi-modal interaction.

Intelligent tutoring systems are the textbooks of the future

- *Pervasive* as textbooks are today
- *Not replacement* for teachers, textbooks
- More dynamic, interactive, & effective model of learning than textbooks
  - Influences teaching practice
  - Support for lifelong learning

Koedinger (2001). Cognitive tutors as modeling tool & instructional model. In Forbus & Feltovich (Eds.) *Smart Machines in Education: The Coming Revolution in Educational Technology*.

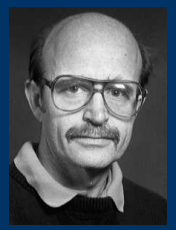
Consequence:

ITSs will revolutionize education

An ITS Success Case

Cognitive Tutor Algebra (aka Pump)

- Most widely used ITS
  - 50,000 students in 00-01 school year
  - 200,000+ projected
  - 1700 Schools (From the 2004 NYT article)
- "Exemplary Curricula" by US Dept of Ed
- Most cited IJAIED paper in past 4 yrs!
  - Koedinger, Anderson, Hadley, & Mark (1997). Intelligent tutoring goes to school in the big city.

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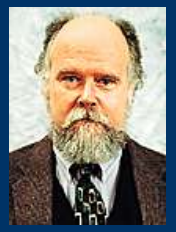
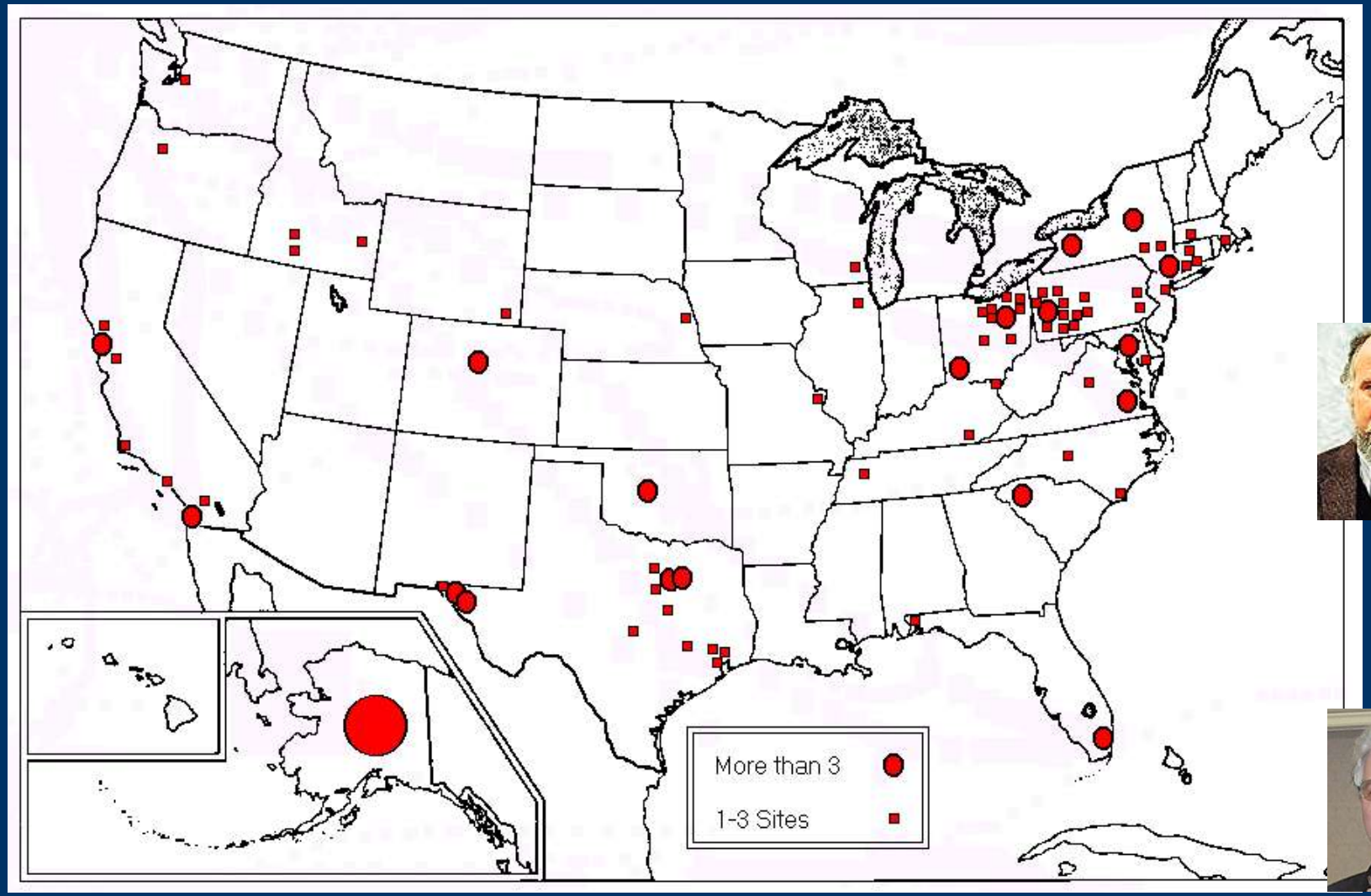
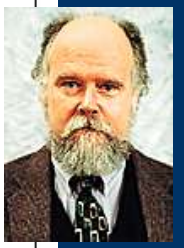
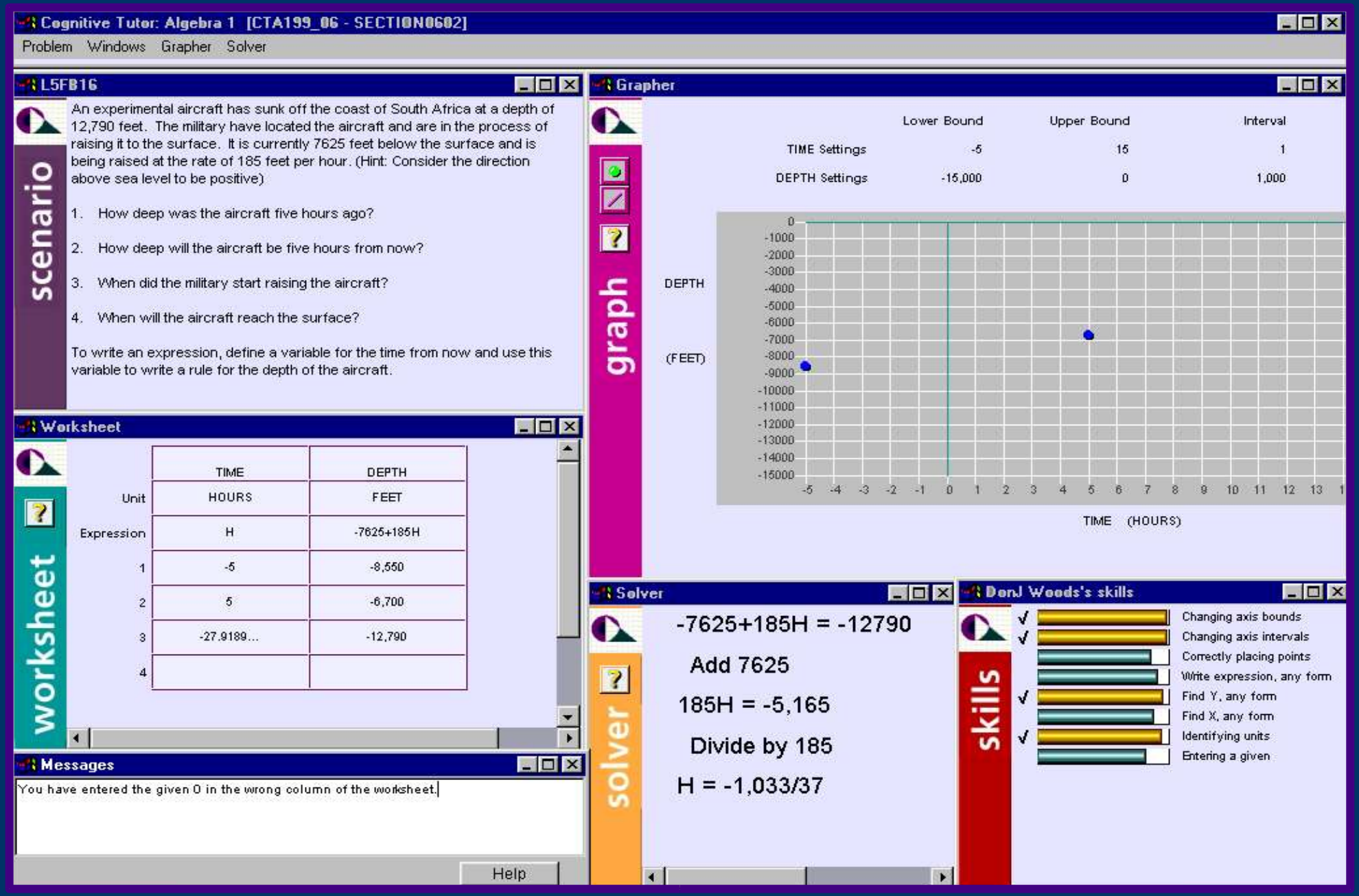



300+ Schools in 2000-01





Algebra Cognitive Tutor



Cognitive Tutor Technology

Use ACT-R theory & empirical studies of learners to create ...

- Cognitive Model: Incorporates multiple strategies & typical student misconceptions

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

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

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

- Model Tracing: Follows student through their individual approach a problem -> context-sensitive instruction
- Knowledge Tracing: Assesses student's knowledge growth -> individualized activity selection and pacing

ACT-R: A unified theory of cognition

Desiderata for a unified theory of cognition

- **Philosophy:** Provide a unified understanding of the mind.
- **Psychology:** Account for experimental data.
- **Education:** Provide cognitive models for intelligent tutoring systems and other learning environments.
- **Human Computer Interaction:** Evaluate artifacts and help in their design.
- **Computer Generated Forces:** Provide cognitive agents to inhabit training environments and games.
- **Neuroscience:** Provide a framework for interpreting data from brain imaging.

Representational Assumptions of ACT-R

- Declarative Knowledge: Chunks
  - Schema/ Frame like structure
  - Has slots for various , and an isa pointer for category membership
- Procedural Knowledge: Production rules
  - Conditions, variables, actions.

Main claims of ACT-R

1 There are two long-term memory stores, declarative memory and procedural memory.

2 The basic units in declarative memory are chunks.

3 The basic units in procedural memory are production rules.

Declarative-Procedural Distinction

- Declarative knowledge
  - Includes factual knowledge that people can report or describe, but can be non-verbal
  - Stores inputs of perception & includes visual memory
  - Is processed & transformed by procedural knowledge
  - Thus, it can be used *flexibly*, in multiple ways
- Procedural knowledge
  - Is only manifest in people's behavior, not open to inspection, cannot be directly verbalized
  - Is processed & transformed by fixed processes of the cognitive architecture
  - It is more specialized & *efficient*

Chunks: Example 1

(CHUNK-TYPE NAME SLOT1 SLOT2 SLOTN)

(FACT3+4

isa ADDITION-FACT

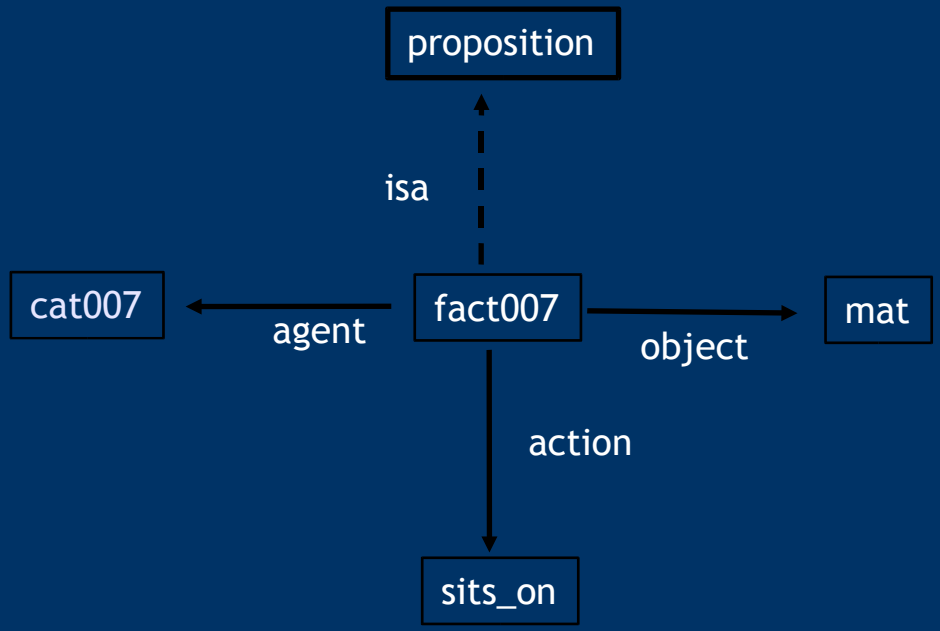
ADDEND1 THREE

ADDEND2 FOUR

SUM SEVEN)

Chunks: Example 2

Fact: The cat sits on the mat.



A Production is

1. A 50 millisecond step of cognition.

2. The source of the serial bottleneck in otherwise parallel system.

3. A condition-action data structure with "variables".

4. A formal specification of the flow of information from cortex to basal ganglia and back again.

Production Rules Describe How People Use Declarative Rules in their Thinking

Declarative rule:

Side-side-side theorem

IF the 3 corresponding sides of two triangles are congruent (≅)

THEN

the triangles are ≅

Production rules describe thinking patterns:

Special condition to aid search

IF two triangles *share a side* AND
the other 2 corresponding sides are ≅

THEN the triangles are congruent (≅)

Using rule backward

IF *goal*: prove triangles ≅ AND
2 sets of corresponding sides are ≅

THEN *subgoal*: prove 3rd set of sides ≅

Using rule heuristically

IF two triangles look ≅

THEN try to prove any of the corresponding sides & angles ≅

~ 100 Published Models in ACT-R 1997-2002

I. Perception & Attention
1. Psychophysical Judgements
2. Visual Search
3. Eye Movements
4. Psychological Refractory Period
5. Task Switching
6. Subitizing
7. Stroop
8. Driving Behavior
9. Situational Awareness
10. Graphical User Interfaces

II. Learning & Memory
1. List Memory
2. Fan Effect
3. Implicit Learning
4. Skill Acquisition
5. Cognitive Arithmetic
6. Category Learning
7. Learning by Exploration and Demonstration
8. Updating Memory & Prospective Memory
9. Causal Learning

III. Problem Solving & Decision Making
1. Tower of Hanoi
2. Choice & Strategy Selection
3. Mathematical Problem Solving
4. Spatial Reasoning
5. Dynamic Systems
6. Use and Design of Artifacts
7. Game Playing
8. Insight and Scientific Discovery

IV. Language Processing
1. Parsing
2. Analogy & Metaphor
3. Learning
4. Sentence Memory

V. Other
1. Cognitive Development
2. Individual Differences
3. Emotion
4. Cognitive Workload
5. Computer Generated Forces
6. fMRI
7. Communication, Negotiation, Group Decision Making

Visit http://act.psy.cmu.edu/papers/ACT-R_Models.htm link.

How Production Systems Fit into Cognitive Tutors

- The main step in developing a Cognitive Tutor is to develop a cognitive model.
  - Decompose the skill to be taught into small knowledge units.
  - We use “production rules” to represent these knowledge units.

- A production system combines:
  - A set of *if-then production rules* that transform data in *working memory* as directed by a procedure called the *interpreter*.

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

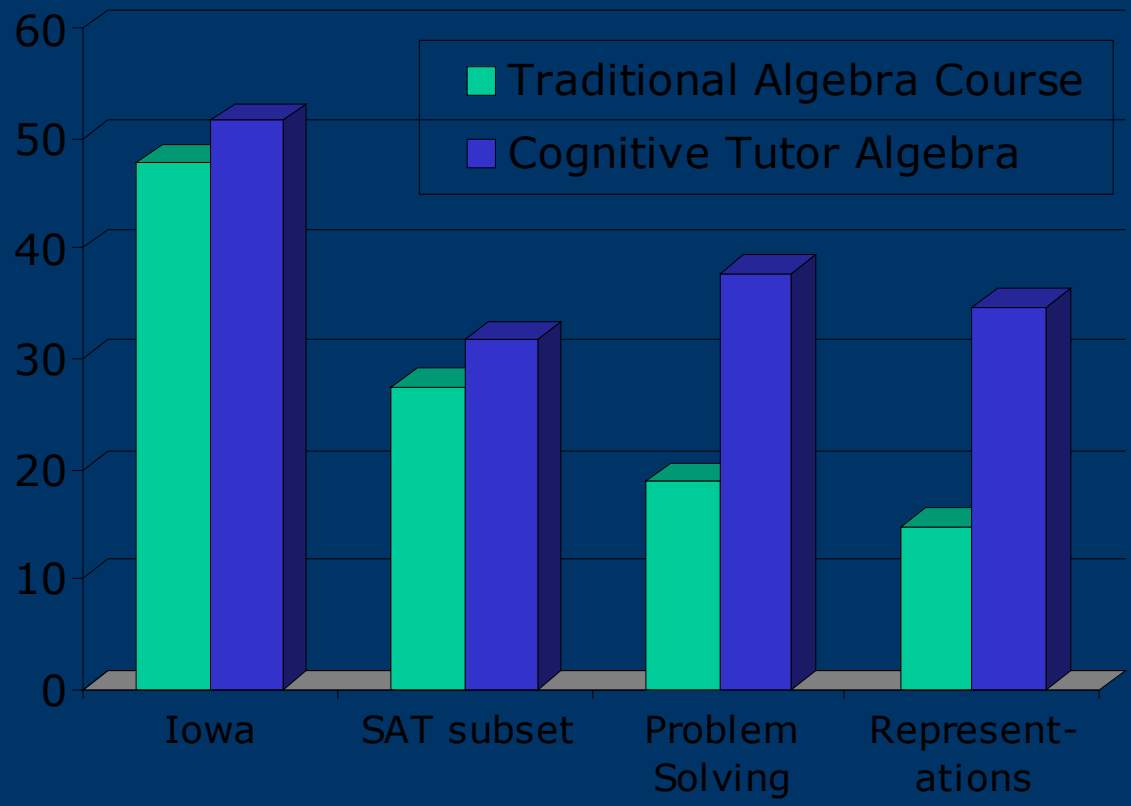
Replicated Field Studies

- Controlled, 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.



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Three Mantras
You Should Repeat Day & Night

- The Student Is Not Like Me
- The Teacher Is Not Like Me
- I Am Not Like Me

The Student Is Not Like Me

Difficulty Factors Assessment: Which Problem Type is Hardest?

Story Problem

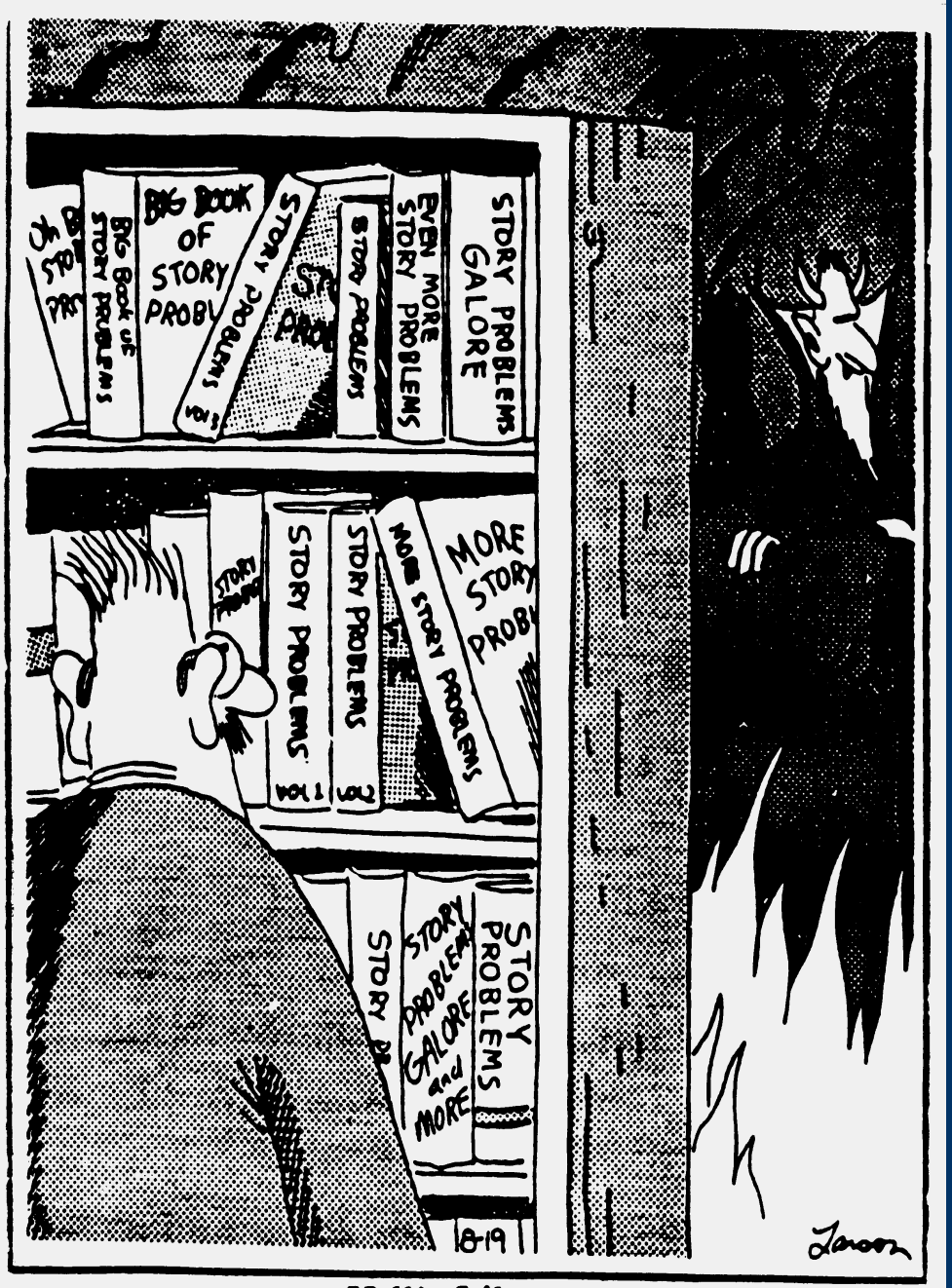
As a waiter, Ted gets $6 per hour. One night he made $66 in tips and earned a total of $81.90. How many hours did Ted work?

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?

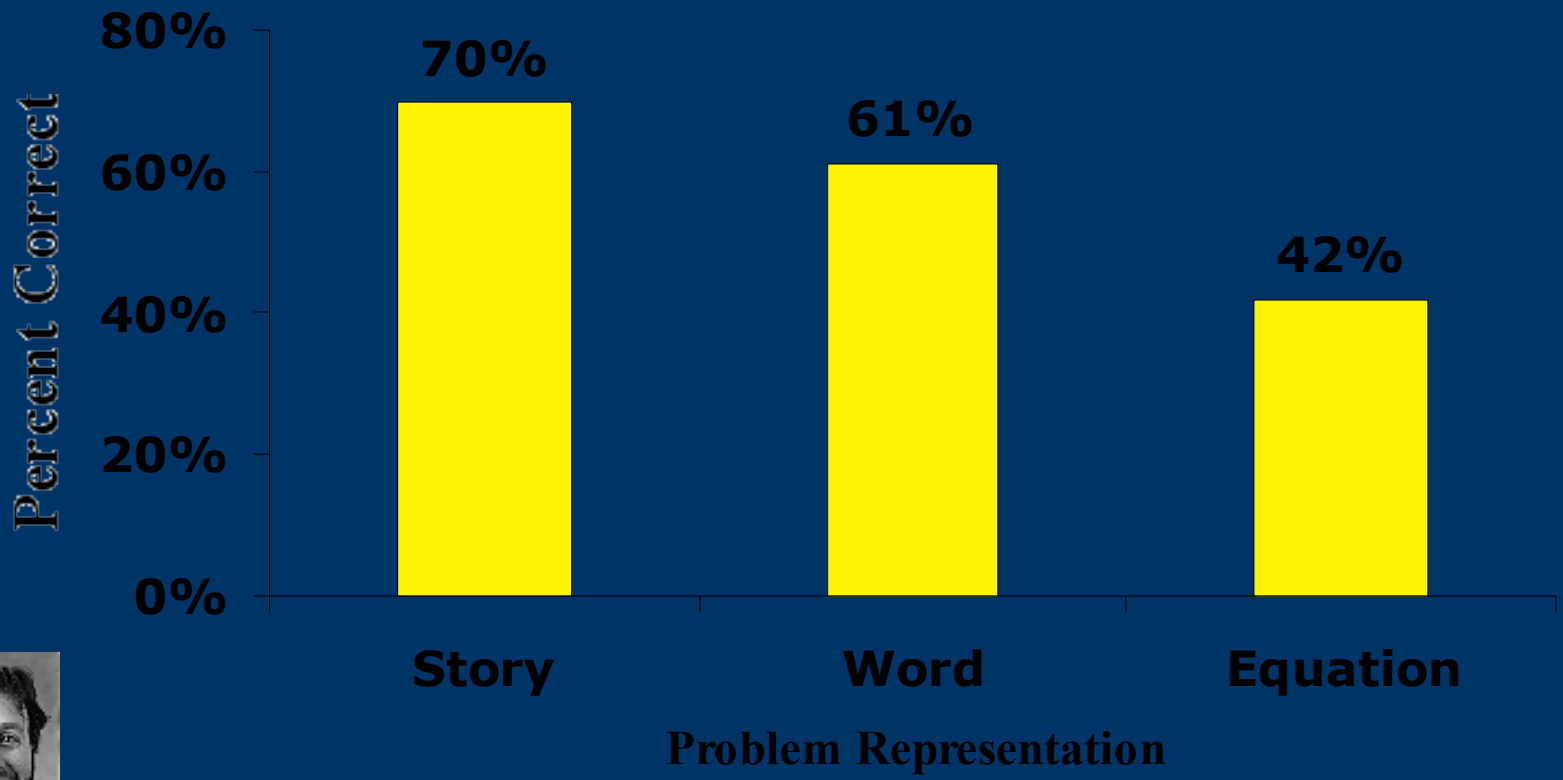
Equation

$x * 6 + 66 = 81.90$



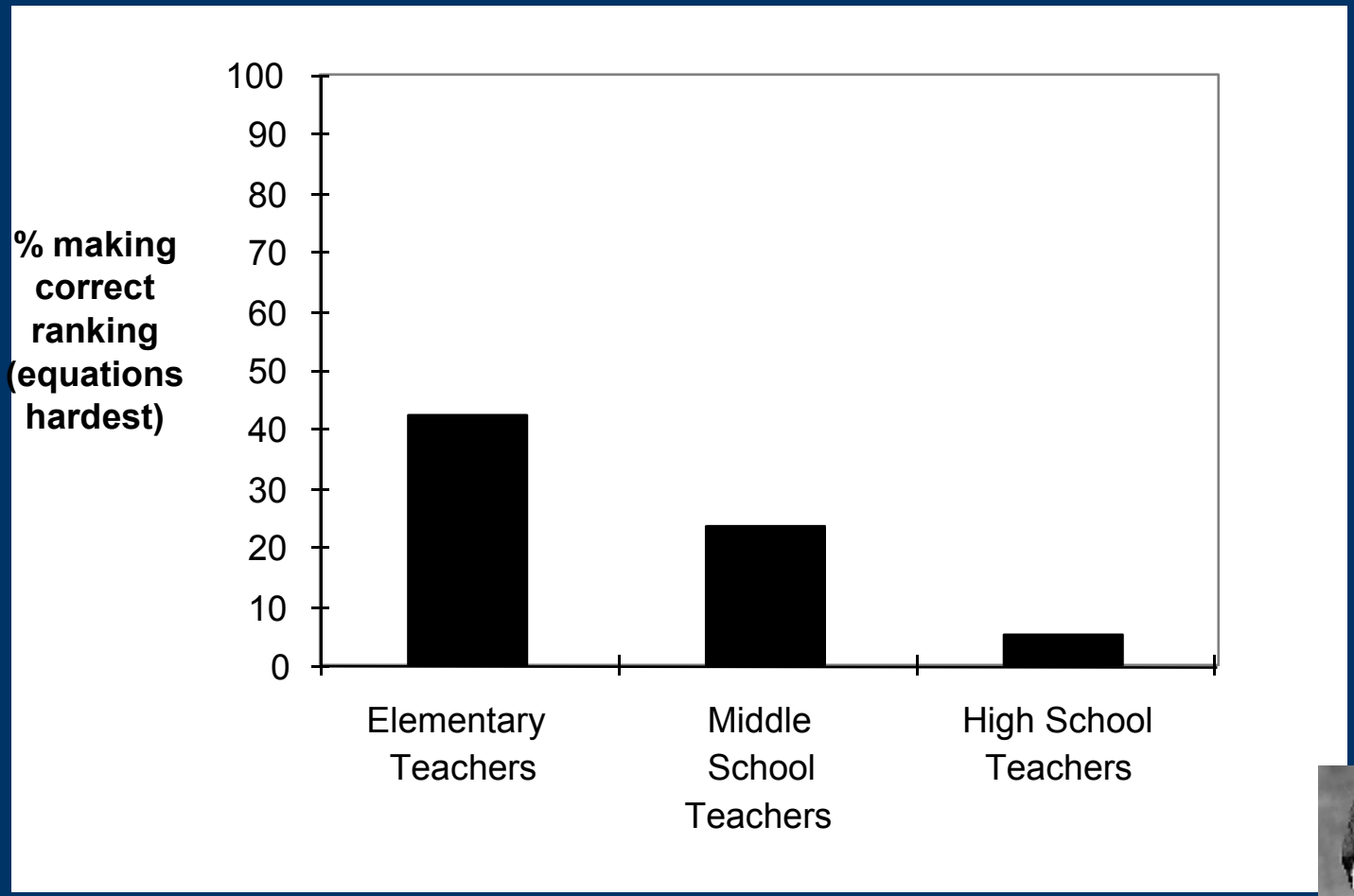
Hell's Library.

Algebra Student Results: Story Problems are Easier!



Koedinger, K. R. & Nathan, M. J. (2001). The real story behind story problems: Effects of representations on quantitative reasoning. Submitted for peer review.

Expert Blindspot:
Expertise can impair judgment of student difficulties



Nathan, M. J. & Koedinger, K. R. (2000). An investigation of teachers' beliefs of students' algebra development. *Cognition and Instruction, 18*(2), 207-235

Expert Blindspot

- Experts' judgments are biased by self-assessing their own performance
- Sources of bias in expert judgment:
  - Under-estimate novice's intuitive, concrete modes of thinking
  - Over-estimate ease in acquiring formal, abstract modes of thinking
- Result: Inaccurate evaluations, poor design choices

What is the Student Like?

- To avoid your expert blindspot, remember:

  "The Student Is Not Like Me"

- Use Cognitive & HCI methods to find out what students *are* like

I Am Not Like Me

- Your knowledge of your own knowledge is limited
  - Much of what we know is implicit
  - Much of our learning is implicit learning
  - Learning by inducing from experience, not by being told
  - Examples:
    - Language learning
    - Reber grammar, Broadbent simulation control

Implications of "I Am Not Like Me"

- Should not trust self-reports of learning
  - Anecdotes are nice, but can be misleading
  - Introspection can lead you astray …
- Need to assist students in both implicit and explicit modes of learning
  - Visual & verbal, examples & rules, situated & abstract, how & why

Implicit Knowledge We Need to Model

- Knowledge students bring with them
  - Informal representations & strategies
  - Partial knowledge
  - Unarticulated procedural knowledge

- "Hidden skills" students need to learn
  - Representational syntax & semantics
  - Perceptual knowledge
  - Metacognitive skills