Chapter 7: Adaptive Instruction (CS-411)

Tanja Käser

November 4, 2025

09.09	–	Overview of learning technologies	P. Dillenbourg & T. Käser
16.09	Experimenting PS-I Defining learning goals	Human cognition	Pierre Dillenbourg
23.09	Designing learning activities	Designing experiments	Chris Petrie
30.09	Designing learning activities	Piaget, microworlds & simulations	Pierre Dillenbourg
07.10	Designing learning activities	Inferential statistics (part 1)	Patrick Jermann
14.10	Implementing learning activities	Inferential statistics (part 2)	Patrick Jermann
~~21.10~~	*Break*		
28.10	Implementing learning activities	Skinner, Bloom & mastery learning	Pierre Dillenbourg
04.11	Statistics	Student modeling, Adaptive Ed.	Tanja Käser
11.11	Statistics	Bayesian Knowledge Tracing	Tanja Käser
18.11	Running Experiments	Vygotsky, social cognition	Pierre Dillenbourg
25.11	Running Experiments	GenAI for Education	Tanja Käser
02.12	Running Experiments	GenAI for Education	Tanja Käser
09.12	Analyzing data	AR & VR For education	Pierre Dillenbourg
16.12	Finalizing projects	Synthesis & project presentation	P. Dillenbourg & T. Käser

Learning Theories

Measuring Learning

AI in Education

Personalized & Generative Approaches in Digital Education

1. Foundations of Adaptive Instruction
   - Principles and history of adaptive learning systems
2. Learner Modeling
   - How we represent the learner to drive adaptive instruction
3. Generative AI in Education
   - Understanding generative models and their implications for teaching and learning
4. Designing AI-Enhanced Learning Experiences
   - Bridging adaptive instruction and generative AI

Personalized & Generative Approaches in Digital Education

1. **Foundations of Adaptive Instruction**
   - *Principles and history of adaptive learning systems*
2. Student Modeling
   - How we represent the learner to drive adaptive instruction
3. Generative AI in Education
   - Understanding generative models and their implications for teaching and learning
4. Designing AI-Enhanced Learning Experiences
   - Bridging adaptive instruction and generative AI

What if the learning activity that you have designed does not work well for Tanja?

The learner adapts

If you don’t understand the video, play it again, but slower

The teacher adapts

If students do not understand a concept, re-explain the concept

The systems adapts

If students do not master a skill, select a more effective learning activity

Your Experience

Think of a digital tool that you have used:

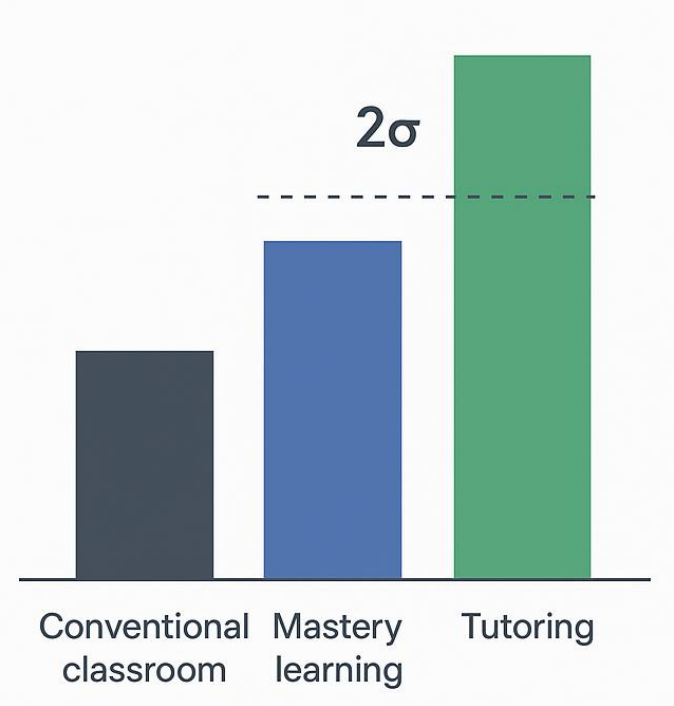
What does it adapt for you?

How does it know what to change?

Adaptive Instruction - Definition

Adaptive instruction is the systematic tailoring of learning experiences in response to a learner's needs, abilities, and progress, using data and algorithms.

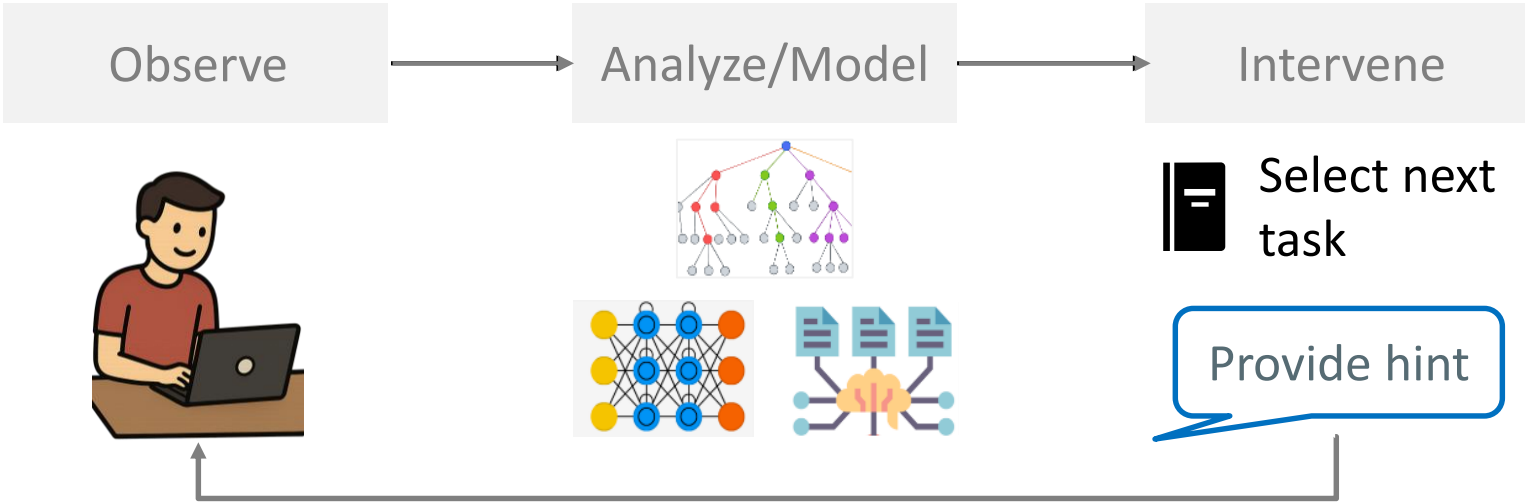
Why it matters - Bloom's Two-Sigma Problem



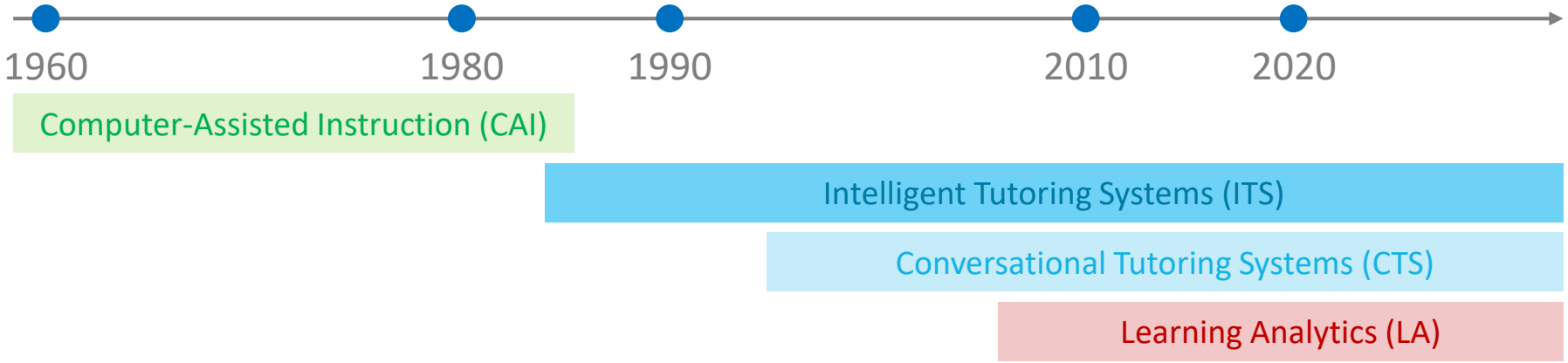
How can we approximate one-on-one tutoring at scale?

Bloom, B. S. (1984). The 2 Sigma Problem: The Search for Methods of Group Instruction as Effective as One-to-One Tutoring. *Educational Researcher*, *13*(6), 4–16.

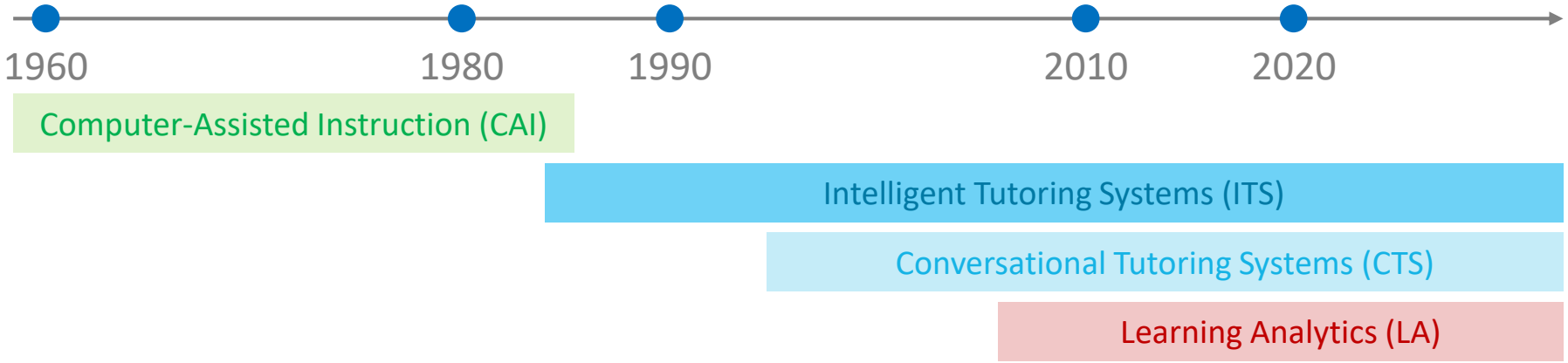
How it works – The learner modeling loop



Evolution of adaptive instruction



Evolution of adaptive instruction



Static Branching | Symbolic Adaptivity | Machine Learning | Deep Learning | Generative AI

Evolution of adaptive instruction

1960 1980 1990 2010 2020

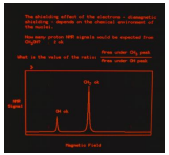
Computer-Assisted Instruction (CAI)

Intelligent Tutoring Systems (ITS)

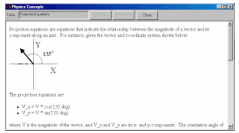
Conversational Tutoring Systems (CTS)

Learning Analytics (LA)

Cognitive Tutor



PLATO

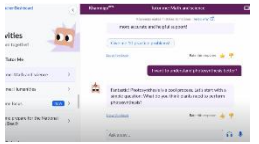


Andes

AutoTutor

Squirrel Ai Learning

Squirrel AI



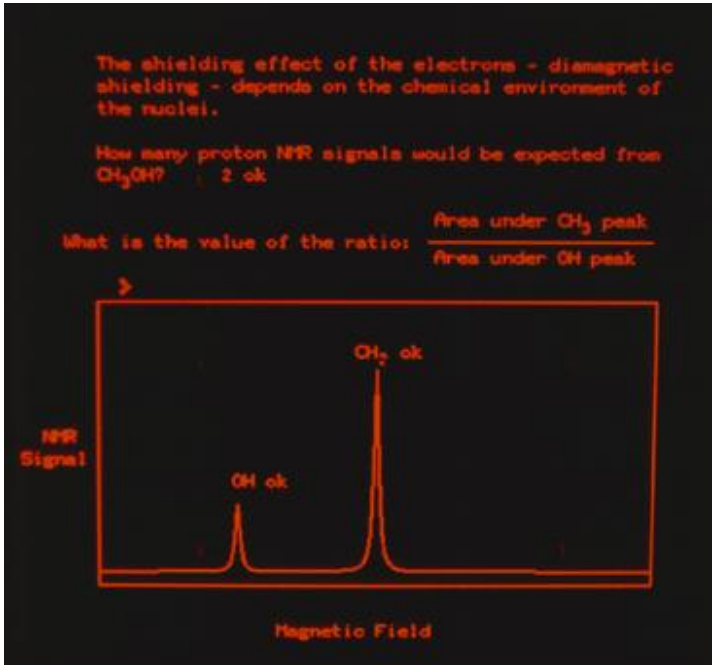
Khanmigo

Static Branching | Symbolic Adaptivity | Machine Learning | Deep Learning | Generative AI

CAI

The PLATO Project

- **P**rogrammed **L**ogic for **A**utomatic **T**eaching **O**perations

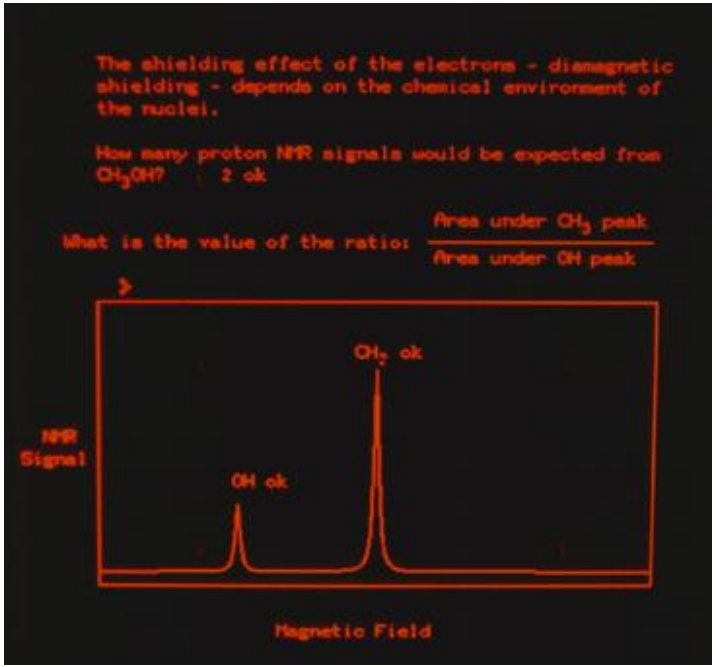


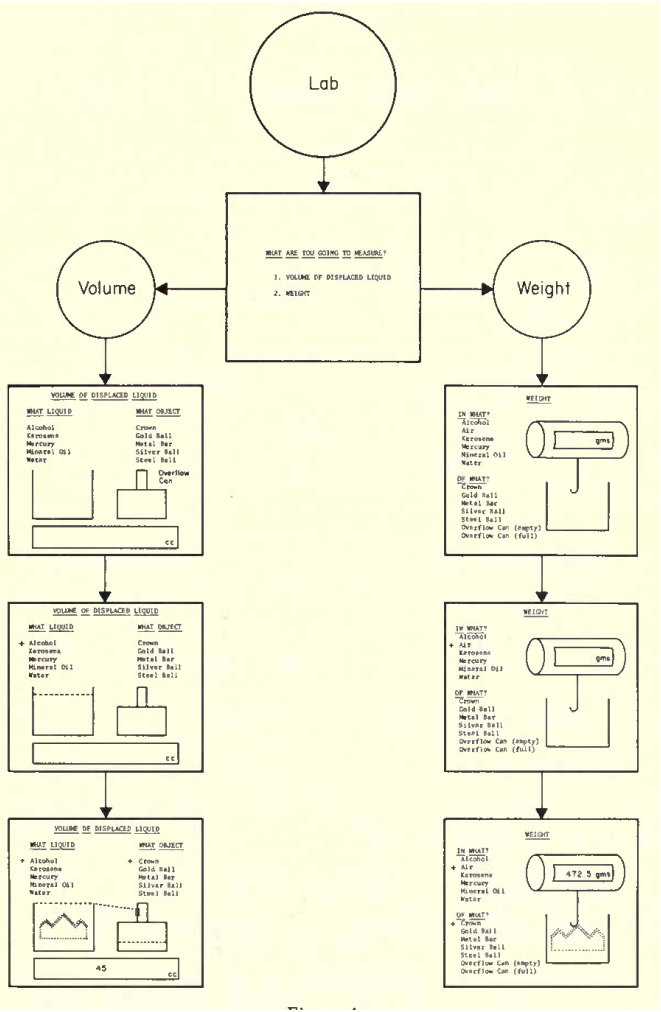
Bitzer, D.L., Lyman, E.R., & Easley, J.A. (1965). The Uses Of Plato: A Computer Controlled Teaching System.

CAI

The PLATO

- **P**rogrammed **L**ogic for **A**utomatic **T**eachi

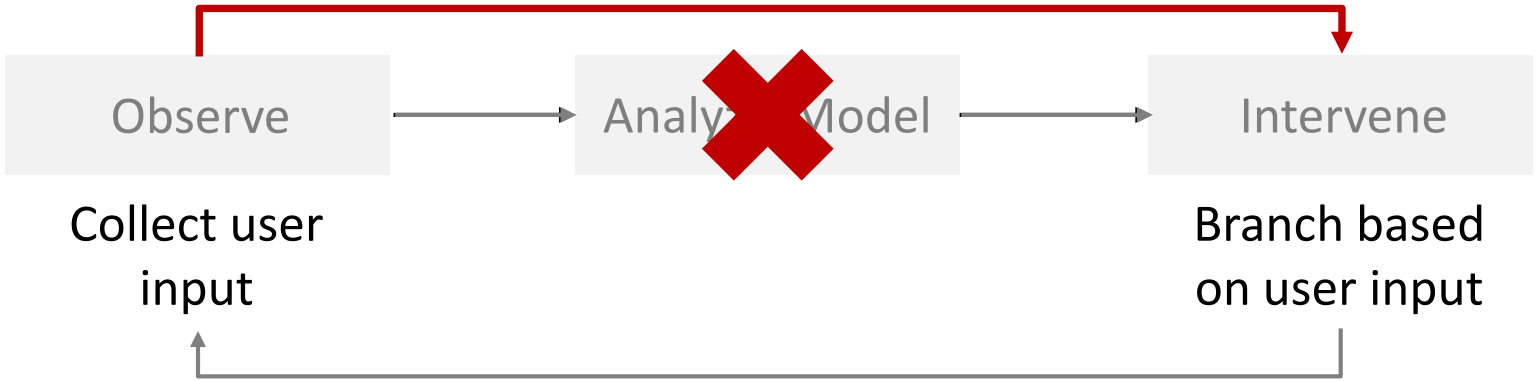




Bitzer, D.L., Lyman, E.R., & Easley, J.A. (1965). The Uses Of Plato: A Computer Controlled Teaching System.

The PLATO Project

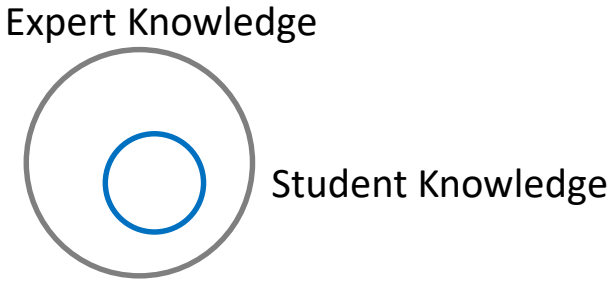
- **P**rogrammed **L**ogic for **A**utomatic **T**eaching **O**perations



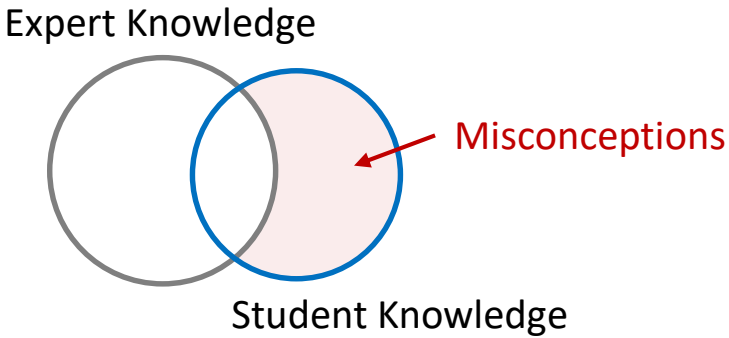
Bitzer, D.L., Lyman, E.R., & Easley, J.A. (1965). The Uses Of Plato: A Computer Controlled Teaching System.

ITS

First Modeling Paradigms



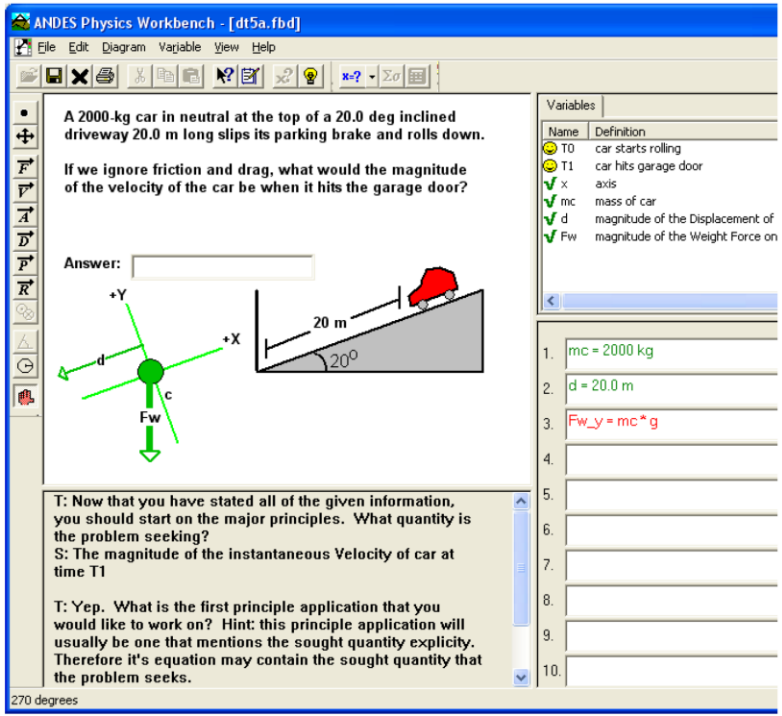
Overlay Model



Buggy Model

ITS

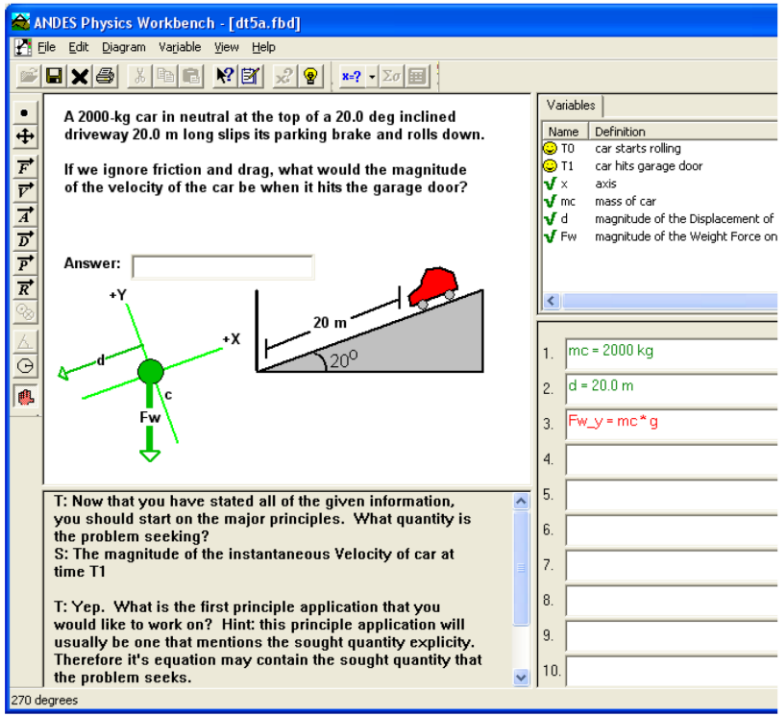
Symbolic Adaptivity: Andes



Schulze, K. G., Shelby, R. N., Treacy, D. J., Wintersgill, M. C., VanLehn, K., & Gertner, A. (2000). Andes: An Intelligent Tutor for Classical Physics. *Journal of Electronic Publishing*, 6(1)

ITS

Symbolic Adaptivity: Andes



Observe → **Model** → **Intervene**

User Input

- *Model Tracing*: Expert Rules
- *Buggy Library*: Misconceptions

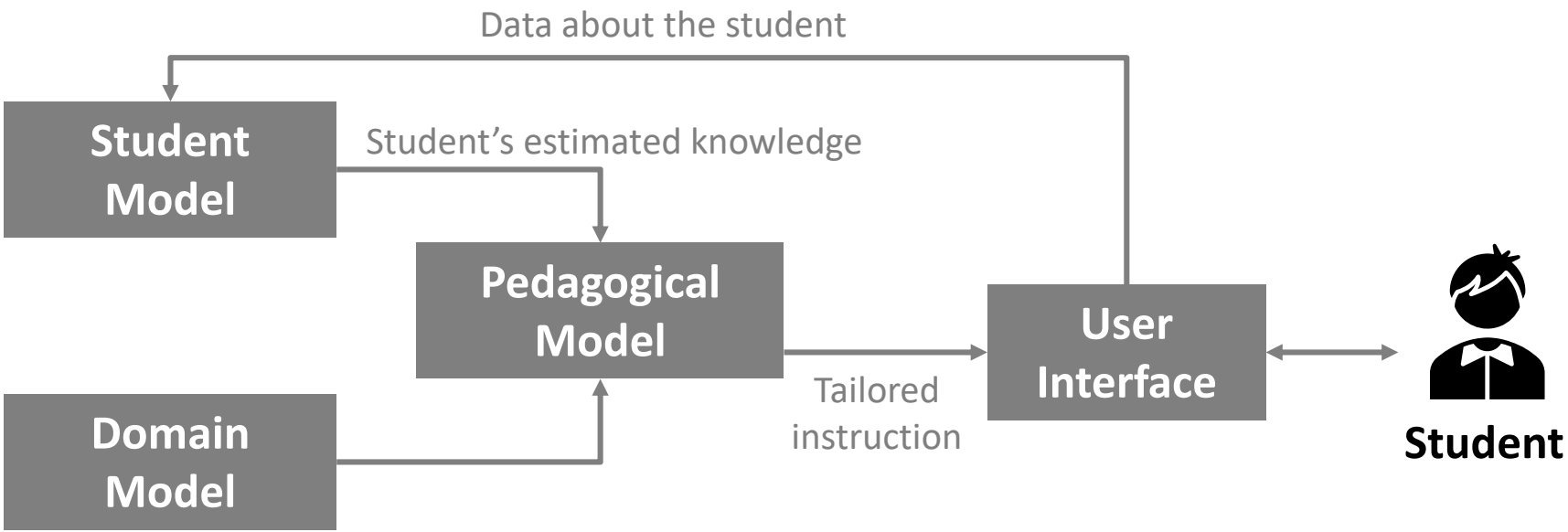
Buggy Model

Correct: green
Wrong: red
→ Hint or remediation for misconception

Schulze, K. G., Shelby, R. N., Treacy, D. J., Wintersgill, M. C., VanLehn, K., & Gertner, A. (2000). Andes: An Intelligent Tutor for Classical Physics. *Journal of Electronic Publishing*, 6(1)

ITS

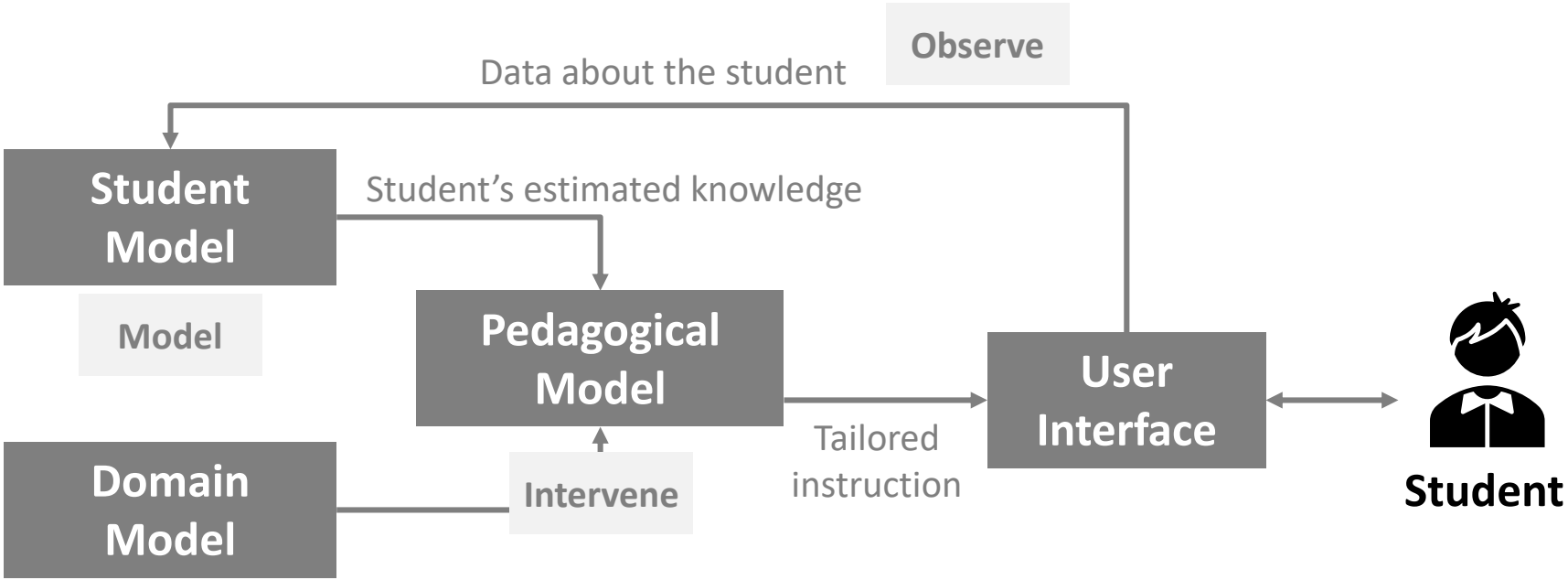
Advanced Modeling Paradigm



Shute, V. J., & Psotka, J. (1996). Intelligent Tutoring Systems: Past, Present, and Future. In *Handbook of Research on Educational Communications and Technology,* 570-600

ITS

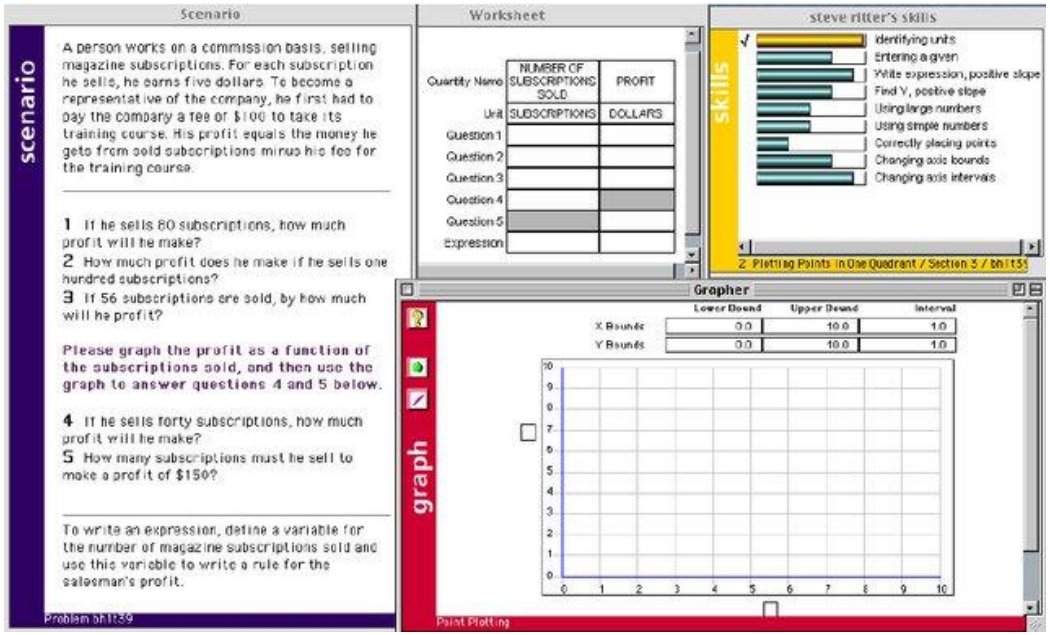
Advanced Modeling Paradigm



Shute, V. J., & Psotka, J. (1996). Intelligent Tutoring Systems: Past, Present, and Future. In *Handbook of Research on Educational Communications and Technology,* 570-600

ITS

Probabilistic Model: Cognitive Tutor

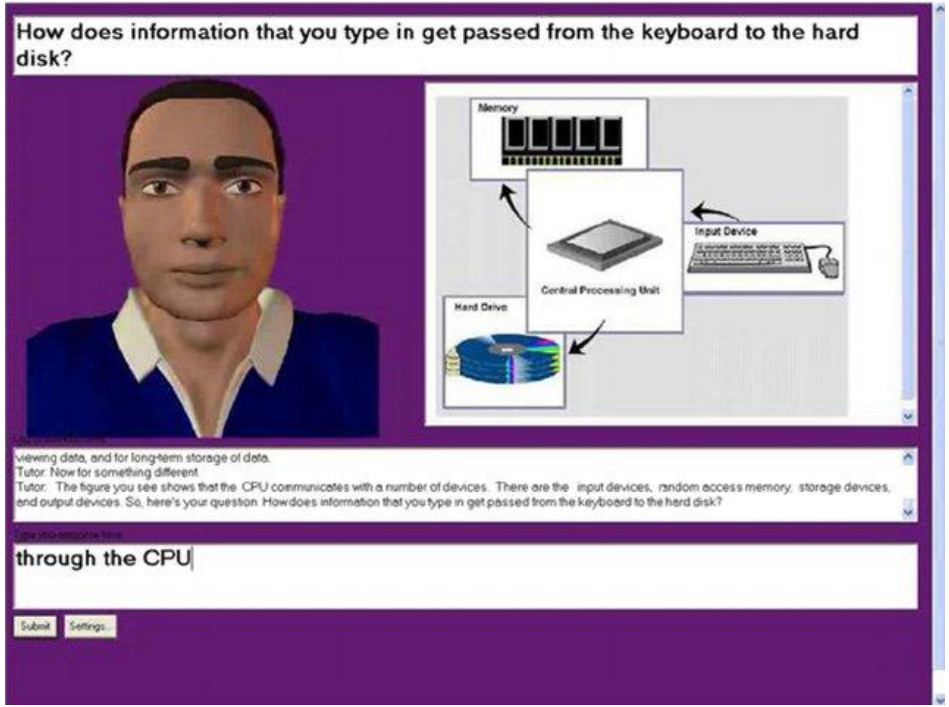


- *Domain Model*: skills for math word problem-solving
- *Student Model*: probabilistic model (knowledge tracing, next week)
- *Pedagogical model*: mastery learning, advance when skill is learned

Anderson, J. R., Corbett, A. T., Koedinger, K. R., & Pelletier, Ray. (1995). Cognitive Tutors: Lessons Learned. *Journal of the Learning Sciences*, 4(2), 167–207.

CTS

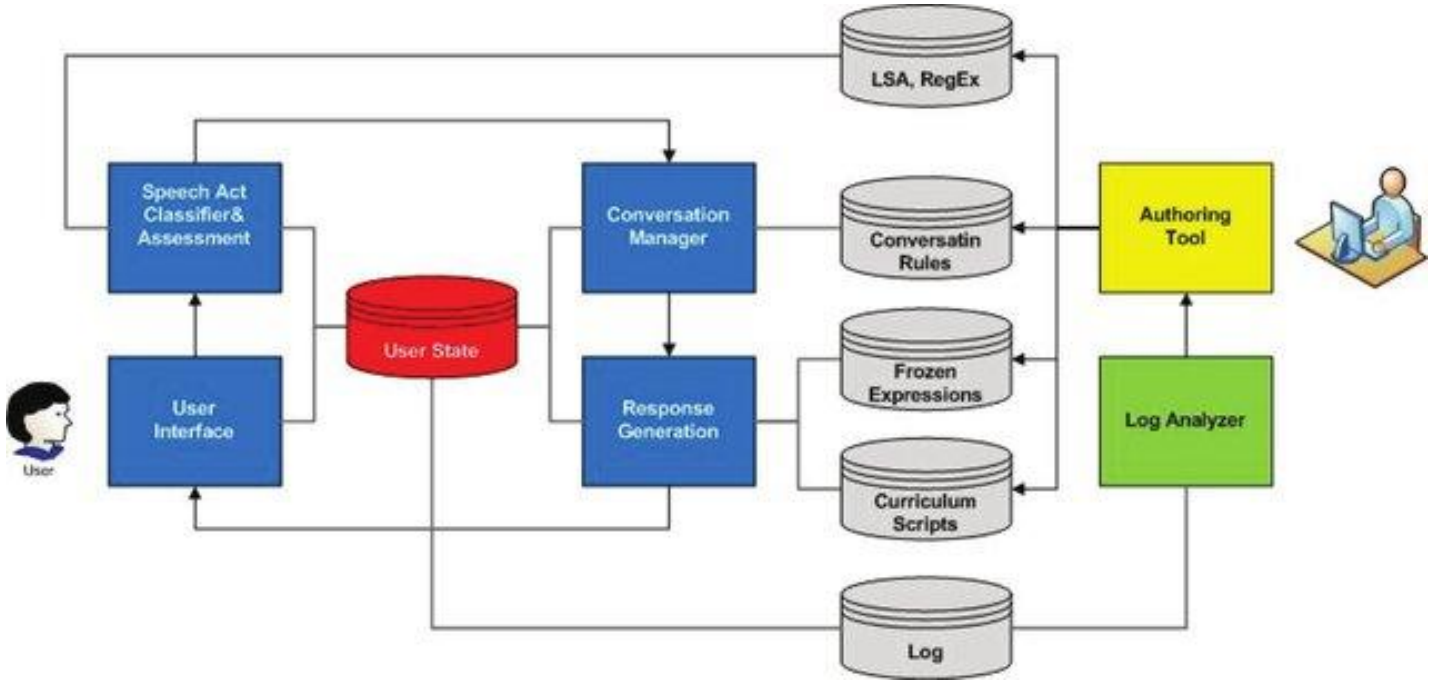
ML-Based: AutoTutor



A. C. Graesser, S. Lu, G. Tanner Jackson, H. H. Mitchell, M. Ventura, A. Olney & Max M. Louwerse (2004). AutoTutor: A tutor with dialogue in natural language. *Behavior Research Methods, Instruments, & Computers* 36, 180–192

CTS

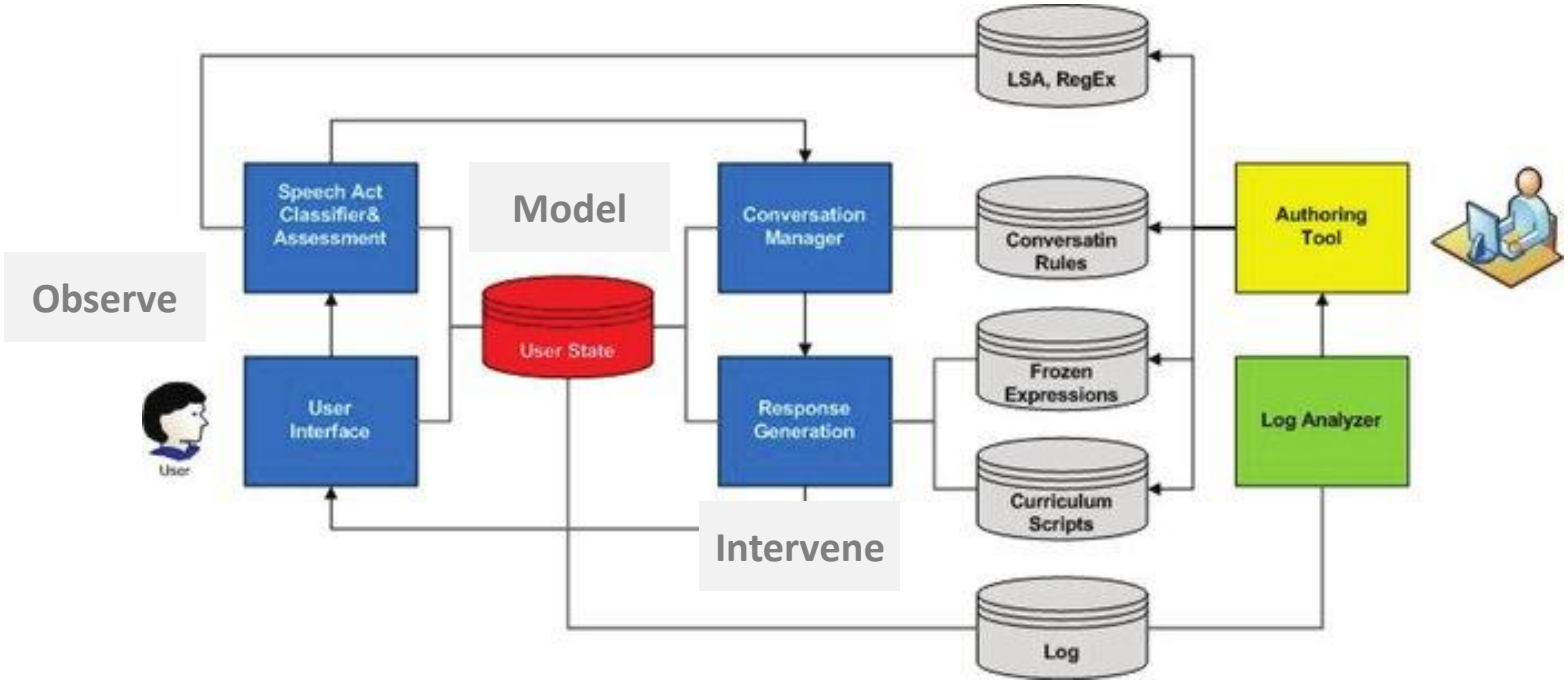
ML-Based: AutoTutor



A. C. Graesser, S. Lu, G. Tanner Jackson, H. H. Mitchell, M. Ventura, A. Olney & Max M. Louwerse (2004). AutoTutor: A tutor with dialogue in natural language. *Behavior Research Methods, Instruments, & Computers* 36, 180–192

CTS

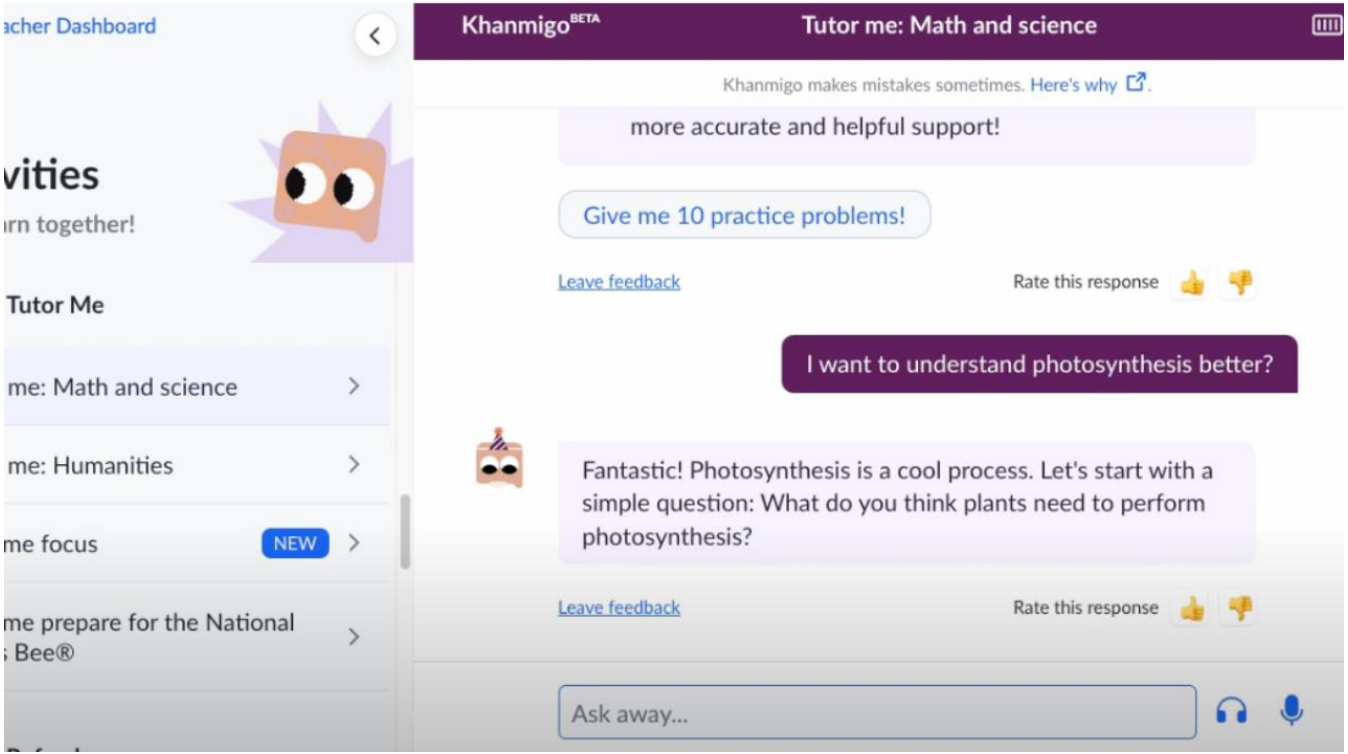
ML-Based: AutoTutor



A. C. Graesser, S. Lu, G. Tanner Jackson, H. H. Mitchell, M. Ventura, A. Olney & Max M. Louwerse (2004). AutoTutor: A tutor with dialogue in natural language. *Behavior Research Methods, Instruments, & Computers* 36, 180–192

CTS

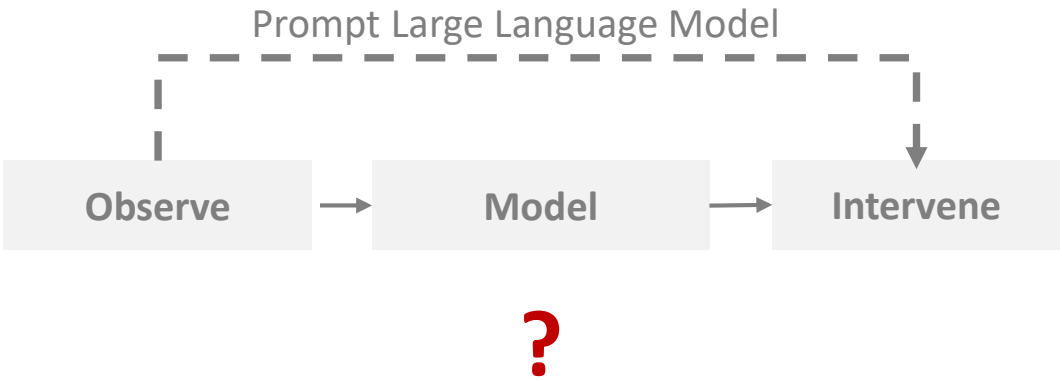
Khanmigo– Generative AI



https://www.khanmigo.ai/

CTS

Tutoring by large language model



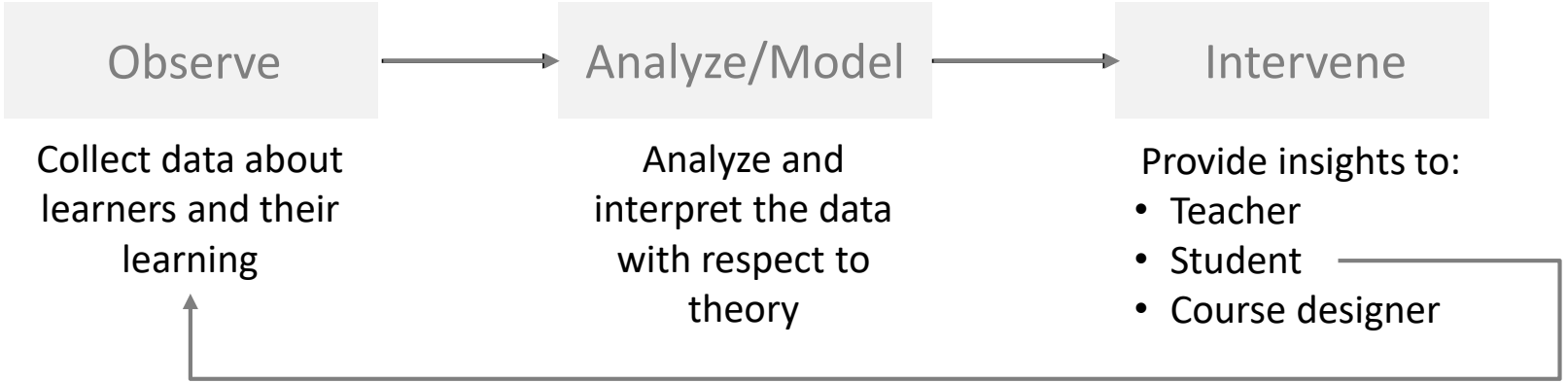
LA

Definition

Learning analytics is the *collection, analysis, interpretation and communication of data about learners* and their learning that provides theoretically relevant and actionable *insights to enhance learning and teaching.*

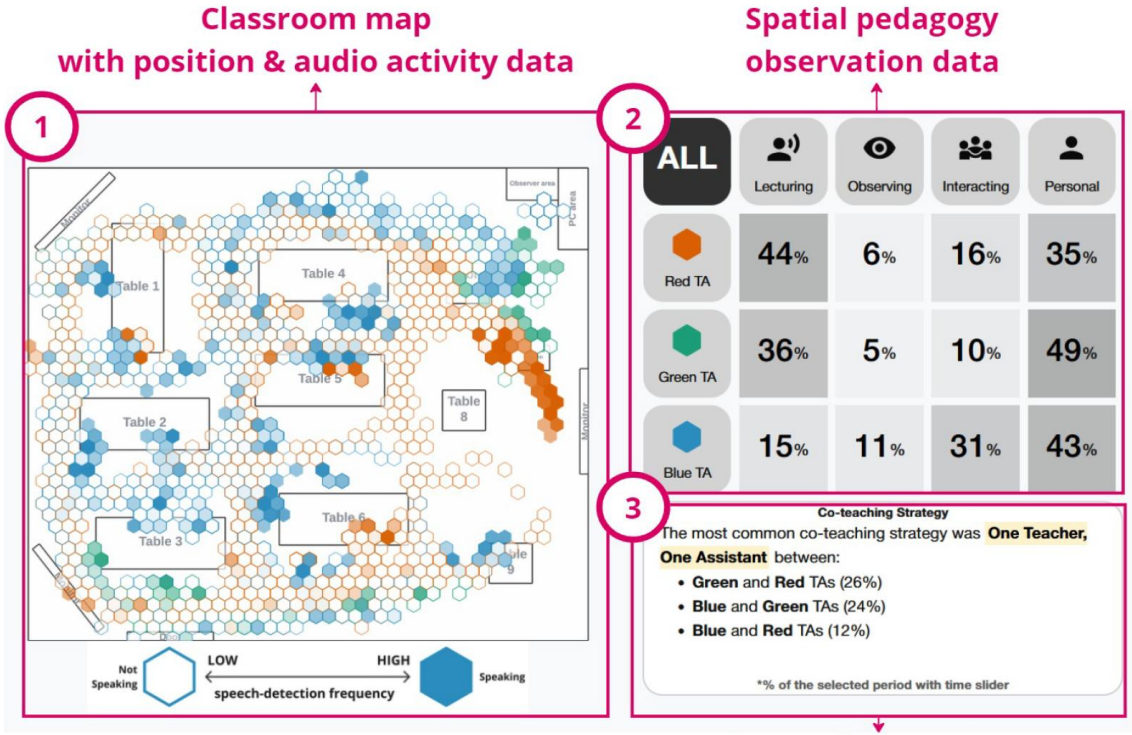
Definition

Learning analytics is the *collection, analysis, interpretation and communication of data about learners* and their learning that provides theoretically relevant and actionable *insights to enhance learning and teaching.*



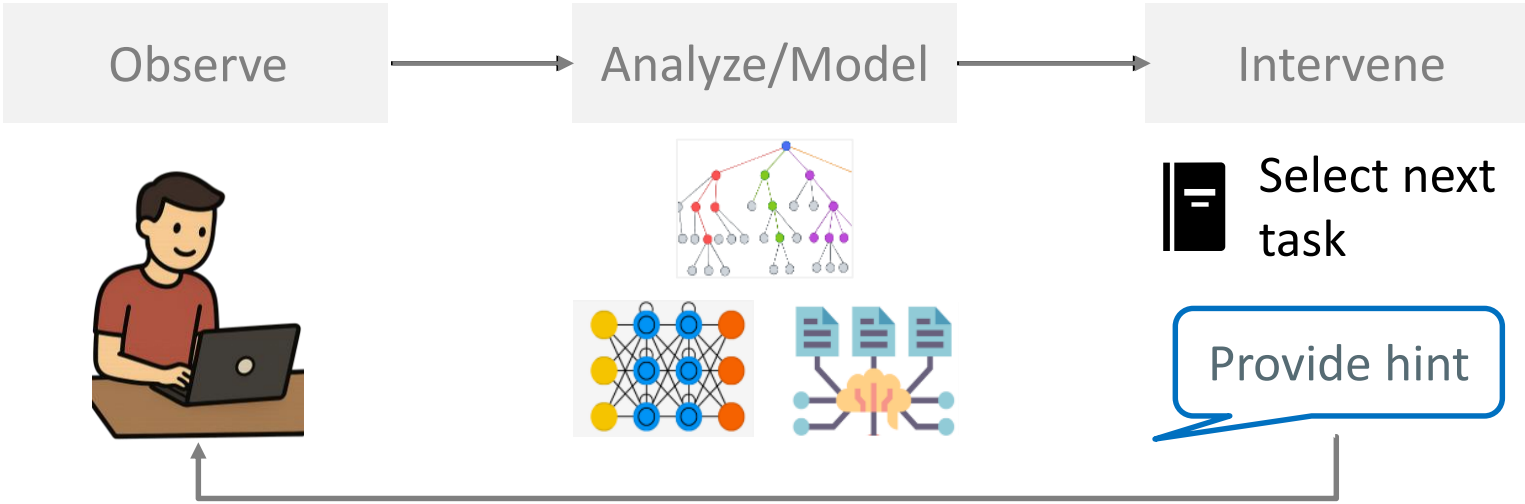
LA

Student-Facing Dashboard: TeamTeachingViz



R. Alfredo, P. Mejia-Domenzain, V. Echeverria, D. Rahayu, L. Zhao, H. Alajlan, Z.Swiecki, T. Käser, D. Gašević, and R. Martinez-Maldonado (2025). TeamTeachingViz: Benefits, Challenges, and Ethical Considerations of Using a Multimodal Analytics Dashboard to Support Team Teaching Reflection. *Proceedings of LAK*

How it works – The learner modeling loop



Intervene – what can we adapt?

Intervene – what can we adapt?

What? What does the learner need to learn (content)?

When? When do they see the content?

How? How do they engage with the content?

Dimensions of Adaptivity

WHAT
(Content)

- Topic/skill/concept
- Difficulty

WHEN
(Timing & Sequence)

- Sequence/order of material
- Pace/repetition
- Spaced practice/review

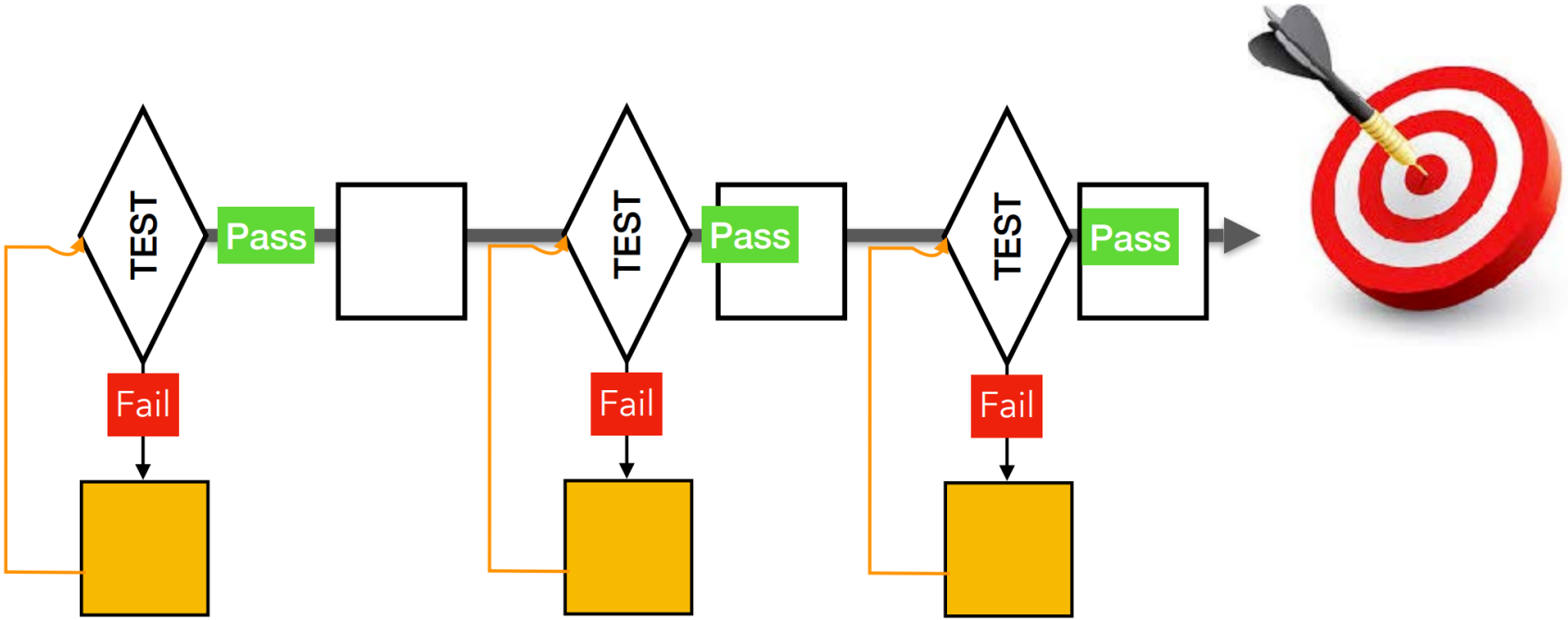
HOW
(Presentation & Interaction)

- Task format
- Support type: feedback, hint
- Modality: text, video, VR simulation
- Instructional strategy

Case Study - Duolingo

Pedagogical Foundations

Mastery Learning



Pedagogical Foundations

Core Mechanism	Theoretical Basis	Cognitive process supported	Adaptive implication	Example
Mastery Learning (Bloom)	Learning as progression through mastery of components	Consolidation of knowledge before new learning	Systems adapt *pacing and feedback loops* until mastery threshold is met.	*Cognitive Tutor*

Vigotsky - Intro

- Russian psychologist
- Worked to create theories of cognitive development
- Conducted research & writing during the same time as Piaget (1920's & 1930's)

Vigotsky – The big ideas

- Different than Piaget's image of the individual constructing understanding alone
  - Everything is social
- Vygotsky saw cognitive development as depending more on interactions with people & ***tools*** in the child's world.
  - *Tools* are *real*: pens, paper, computers;
  - or *Tools* are *symbols*: language, math systems, signs

Vigotsky – The big ideas

Explained complex learning through **Guided Participation**

- Explained things that are taught rather than discovered (reading, writing etc.)
- a way to “share the thinking load”
- Helping a novice accomplish a complex task
- Assistance can be physical or mental & come from adults or peers
- **Scaffolding:** where the more knowledgeable other provides some type of structure.

Vigotsky – The big ideas

Vygotsky developed the theory of the **Zone of proximal development** (ZPD)

- The distance between where a learner is at developmentally on their own & where a learner could be with the help of a *more knowledgeable other.*
- A *more knowledgeable other* can be an adult or a peer, helping a learner in this way is to *scaffold* their learning. Scaffolding occurs through the process of internalization, mediated by language and thought.

Vigotsky - Example

A mother is sitting with her toddler singing, *“Baa, baa black sheep have you any wool, yes sir, yes sir ….”* at this point the mother pauses and the child sings loudly, *“THREE BAGS FULL!”*.

– How is this guided participation?

Pedagogical Foundations

Core Mechanism	Theoretical Basis	Cognitive process supported	Adaptive implication	Example
Mastery Learning (Bloom)	Learning as progression through mastery of components	Consolidation of knowledge before new learning	Systems adapt *pacing and feedback loops* until mastery threshold is met.	*Cognitive Tutor*
Zone of Proximal Development (Vigotsky)	Learning occurs when supported just beyond independent ability	Guided performance within cognitive stretch	Systems adapt *task difficulty, hint level*, or *help type* (scaffolds).	*Assistments*

Spaced Repetition

How do you learn vocabulary?
What strategies do you use?

Spacing effect

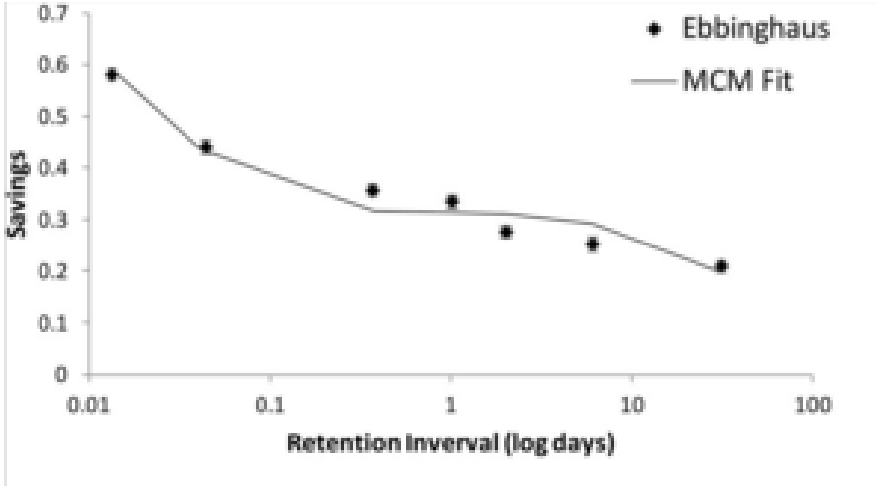
Learning is more effective when study sessions are spaced out.

- Humans can store information much better in their long-term memory with spaced study sessions which repeat information, also known as **spaced repetition** or **spaced presentation** than massed presentation ("**cramming**").

But how do we repeat this information?
Is there a way to design how we can repeat information for best memorization?

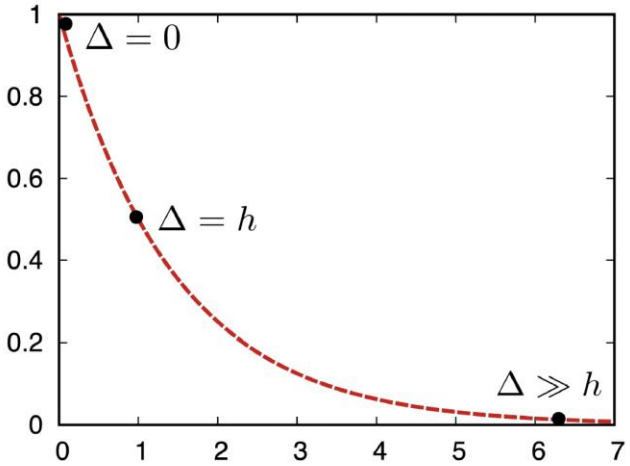
Ebbinghaus's experiment

Hermann Ebbinghaus studied memorization of nonsense syllables, such as "WID" and "ZOF" (CVCs or Consonant–Vowel–Consonant) by repeatedly testing himself after various time periods and recording the results.



Savings = **Retention rate** = Relative number of items still remembered in later recollection trials.

Ebbinghaus's expt. → Power law of Vocab learning



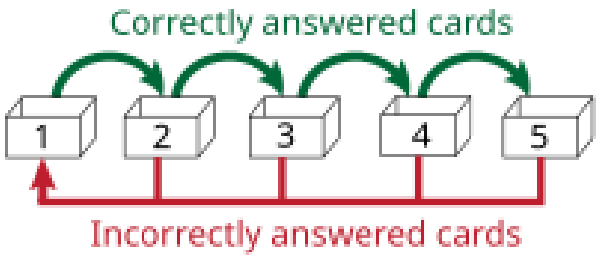
$$p = 2^{-\left(\frac{\Delta}{h}\right)}$$

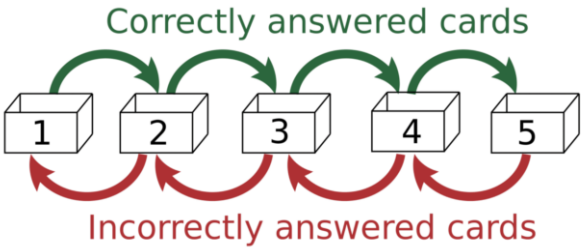
p = Probability of recalling an item

Δ = Time elapsed since the item was reviewed

h = Half-life of the item

Common Vocab Learning Systems: Leitner System





- Flashcards are sorted into **groups** according to how well the learner knows each one
- The learners try to recall the solution written on a flashcard.
  - If they succeed, they send the card to the next group.
  - If they fail, they send it back to the first/previous group.

Each succeeding group has a longer period before the learner is required to revisit the cards.

Duolingo's half life regression model

A data-driven improvement based on the idea of the forgetting curve

Skill bars: an estimation of the probability of correct recall

Duolingo's half life regression model

A data-driven improvement based on the idea of the forgetting curve

Estimation of the half-life of an item via linear regression

$$\hat{h}_\Theta = 2^{\Theta \cdot \boldsymbol{x}}$$

Θ := weight vector

$\boldsymbol{x}$:= feature vector

Burr Settles and Brendan Meeder. 2016. A Trainable Spaced Repetition Model for Language Learning. *Proceedings of ACL*, pp. 1848–1858

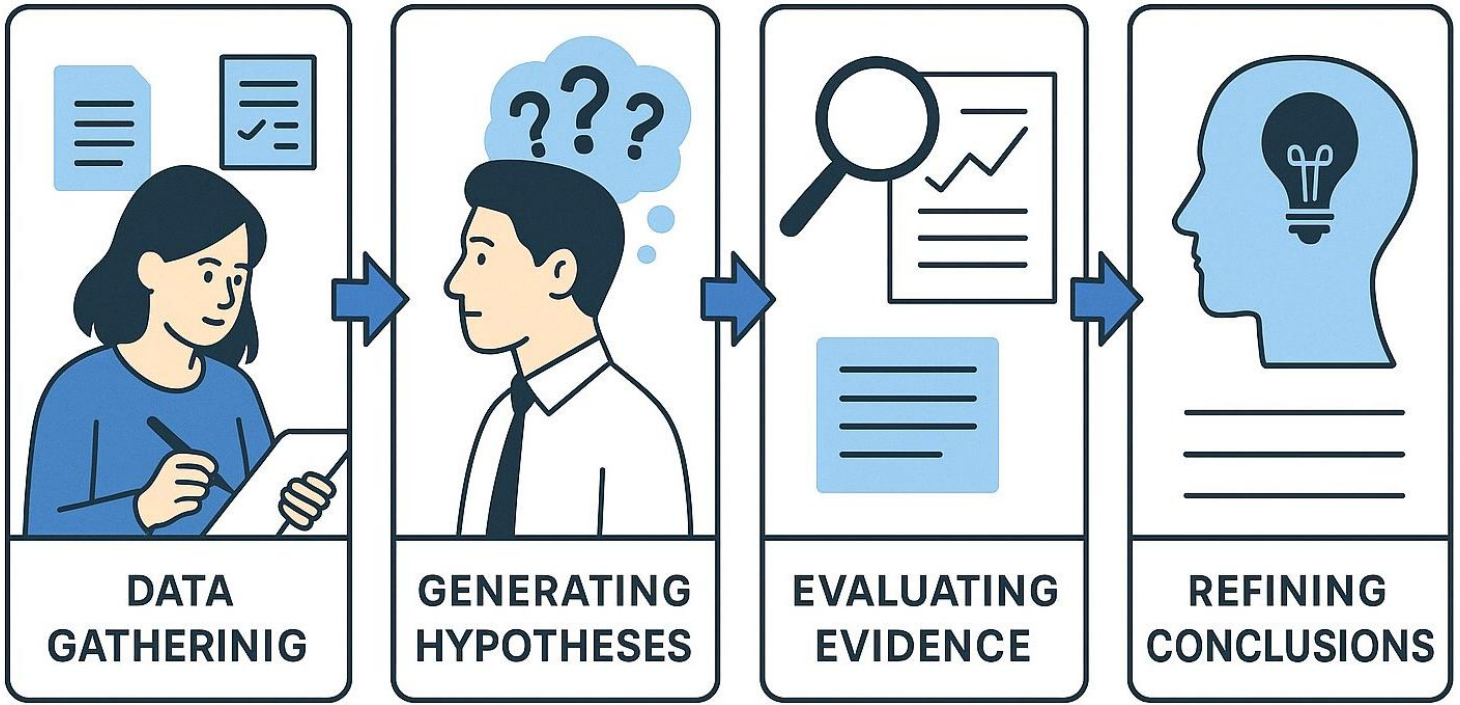
Pedagogical Foundations

Core Mechanism	Theoretical Basis	Cognitive process supported	Adaptive implication	Example
Mastery Learning (Bloom)	Learning as progression through mastery of components	Consolidation of knowledge before new learning	Systems adapt *pacing and feedback loops* until mastery threshold is met.	*Cognitive Tutor*
Zone of Proximal Development (Vigotsky)	Learning occurs when supported just beyond independent ability	Guided performance within cognitive stretch	Systems adapt *task difficulty, hint level*, or *help type* (scaffolds).	*Assistments*
Spaced Repetition (Ebbinghaus)	Memory decays predictable; recall strengthens retention	Long-term memory consolidation	Systems adapt *review intervals* based on learner's *retention probability*.	*Duolingo*

What about adaptive instruction in PS-I?

Explore | Consolidate | Apply

Diagnostic Reasoning in a Pharmacy



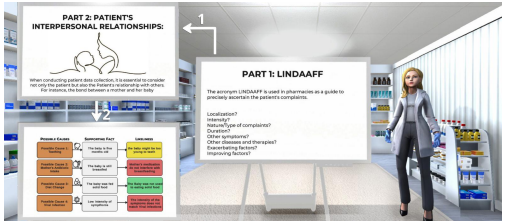
PharmaSim – Virtual Pharmacy

PharmaSim – PS-I Sequence

Explore

Father of a baby with diarrhea

Consolidate



Adaptive Instruction

Apply

Another father of a baby with diarrhea

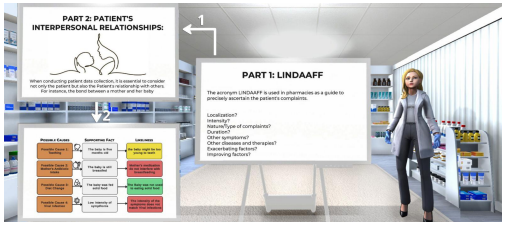
Mother with breastfeeding issues

PharmaSim – PS-I Sequence

Explore

Father of a baby with diarrhea

Consolidate



Adaptive Instruction

Apply

Another father of a baby with diarrhea

Mother with breastfeeding issues

Observe

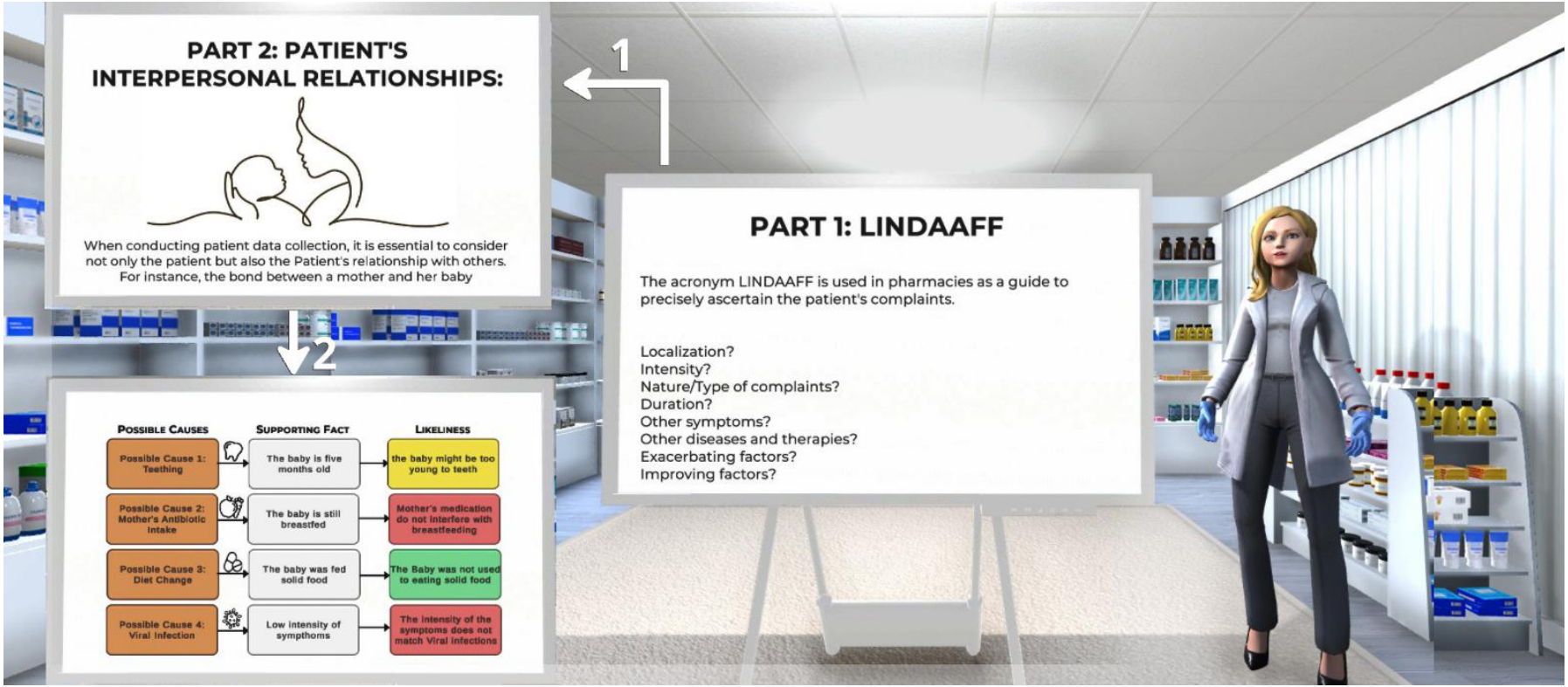
Questions

Model Tracing

Missing Information

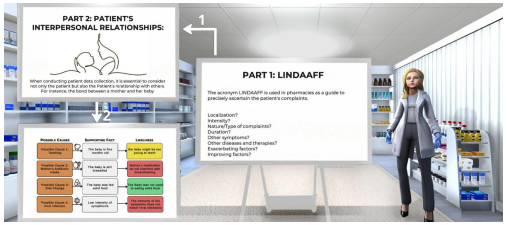
Intervene

Adaptive Instruction



Control – I-PS sequence

Instruction



Worked Example

Problem-Solving

Father of a baby with diarrhea

Transfer

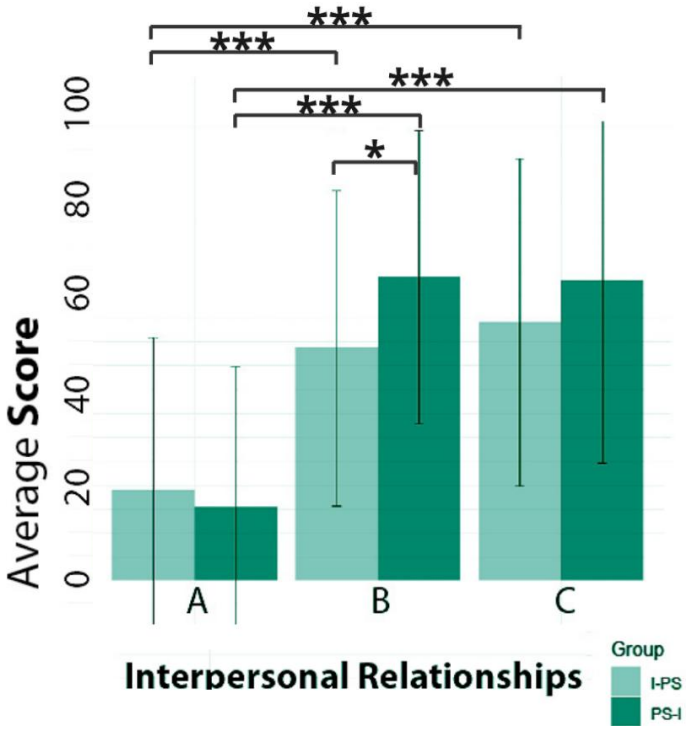
Another father of a baby with diarrhea

Mother with breastfeeding issues

Evaluation

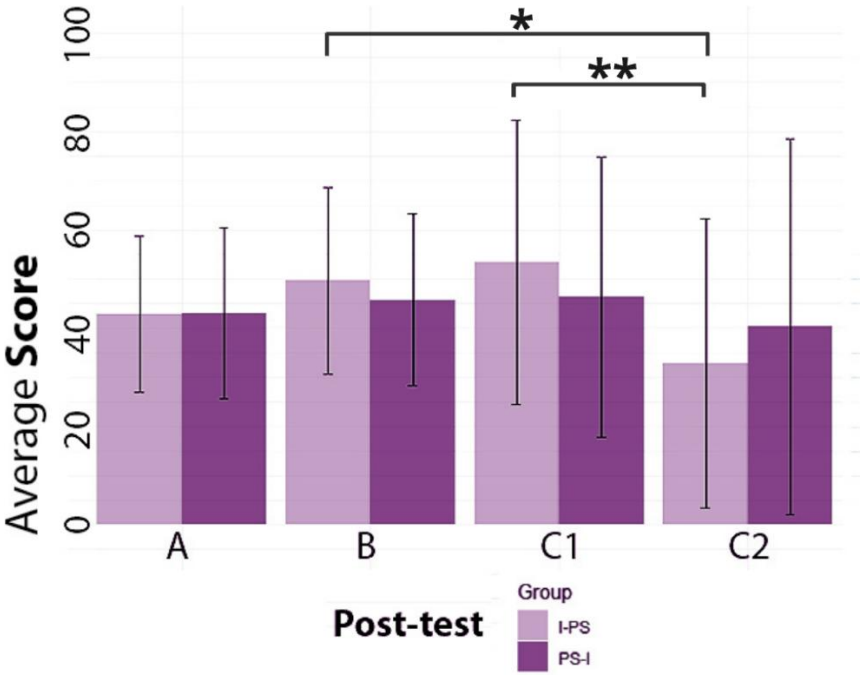
- Measure application of strategies across scenarios:
  - Checklist
  - Interpersonal Relationship
  - Systematically assessing causes

PS-I apply interpersonal relationships more



Güreş, F.B., Nazaretsky, T., Radmehr, B., Rau, M., Käser, T. (2025). How Instructional Sequence and Personalized Support Impact Diagnostic Strategy Learning, *Proceedings of AIED*

PS-I transfers data interpretation strategy better



Güreş, F.B., Nazaretsky, T., Radmehr, B., Rau, M., Käser, T. (2025). How Instructional Sequence and Personalized Support Impact Diagnostic Strategy Learning, *Proceedings of AIED*

Summary – Adaptive Instruction

We have seen today:

- *What* it is (definition)
- *How* it works (learner modeling loop)
- *How* it has evolved (history)
- *Where* it applies (dimensions of adaptivity)
- *Why* it works (pedagogical foundations)