

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	<i>Break</i>		
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:

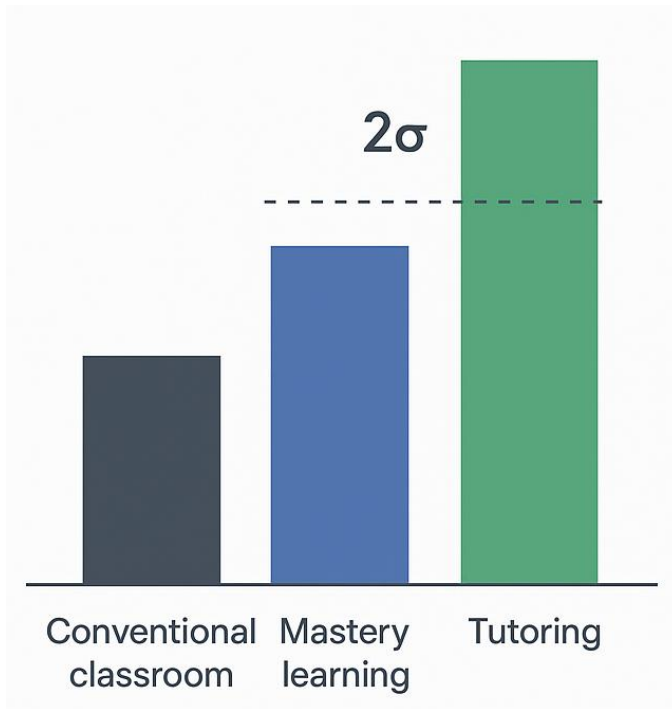
What does it adapt for you?

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**.

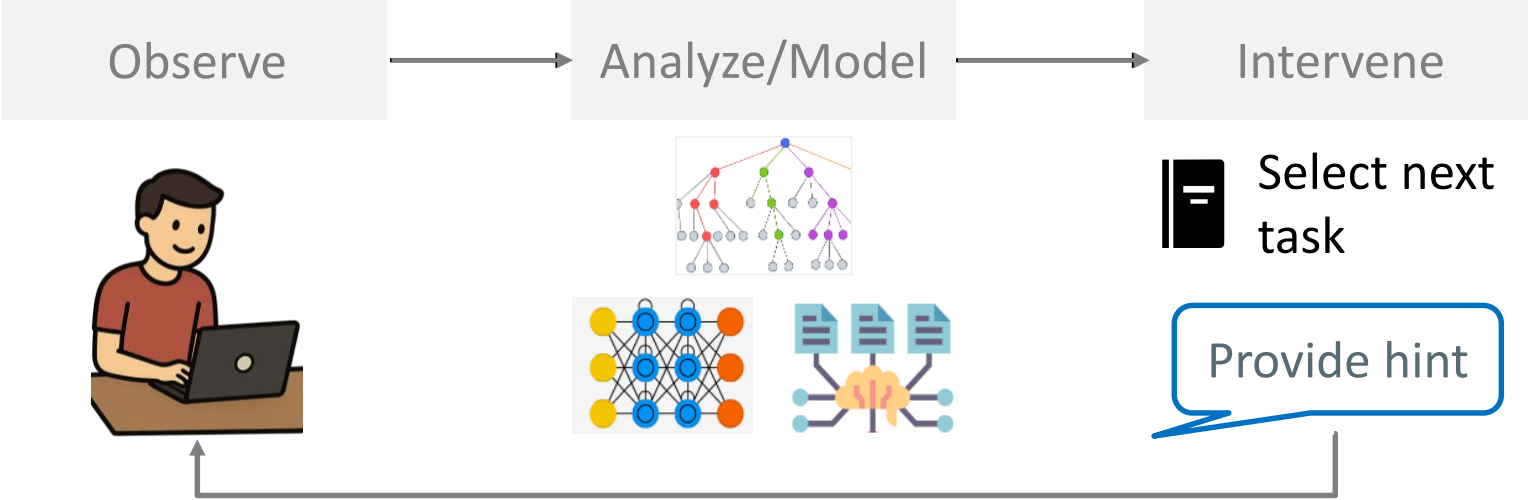
Why it matters - Bloom's Two-Sigma Problem



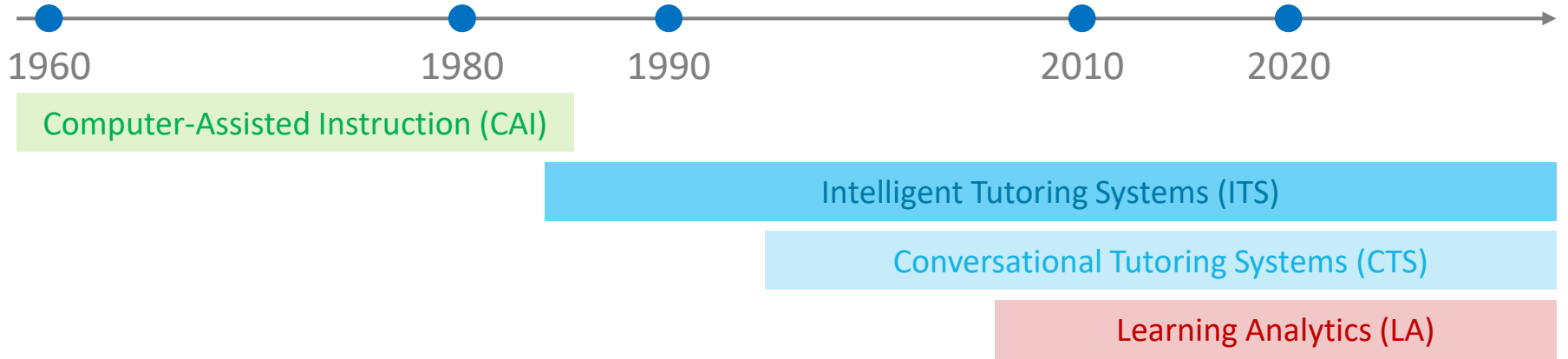
How can we approximate one-on-one tutoring at scale?

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.

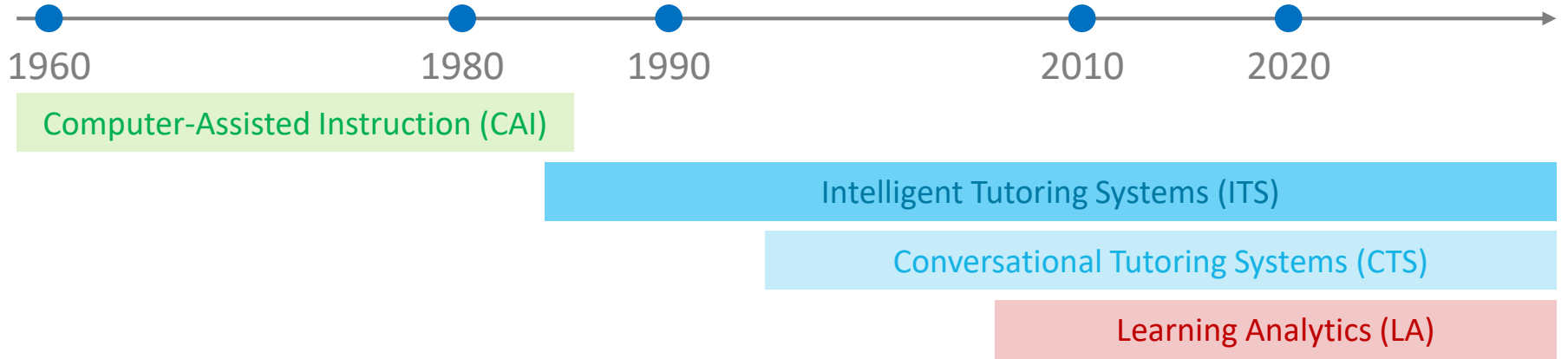
How it works – The learner modeling loop



Evolution of adaptive instruction



Evolution of adaptive instruction



Static Branching

Symbolic Adaptivity

Machine Learning

Deep Learning

Generative AI

Evolution of adaptive instruction



Computer-Assisted Instruction (CAI)

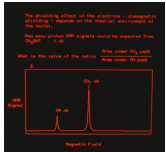
Intelligent Tutoring Systems (ITS)

Conversational Tutoring Systems (CTS)

Learning Analytics (LA)

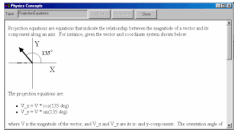


Cognitive Tutor



PLATO

Static Branching



Andes

Symbolic Adaptivity



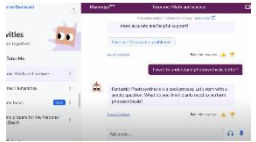
AutoTutor

Machine Learning



Squirrel AI

Deep Learning

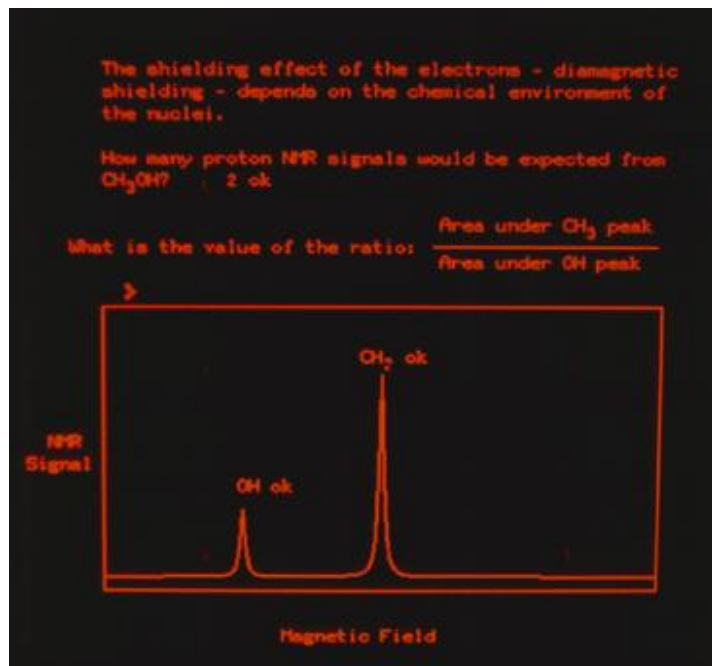


Khanmigo

Generative AI

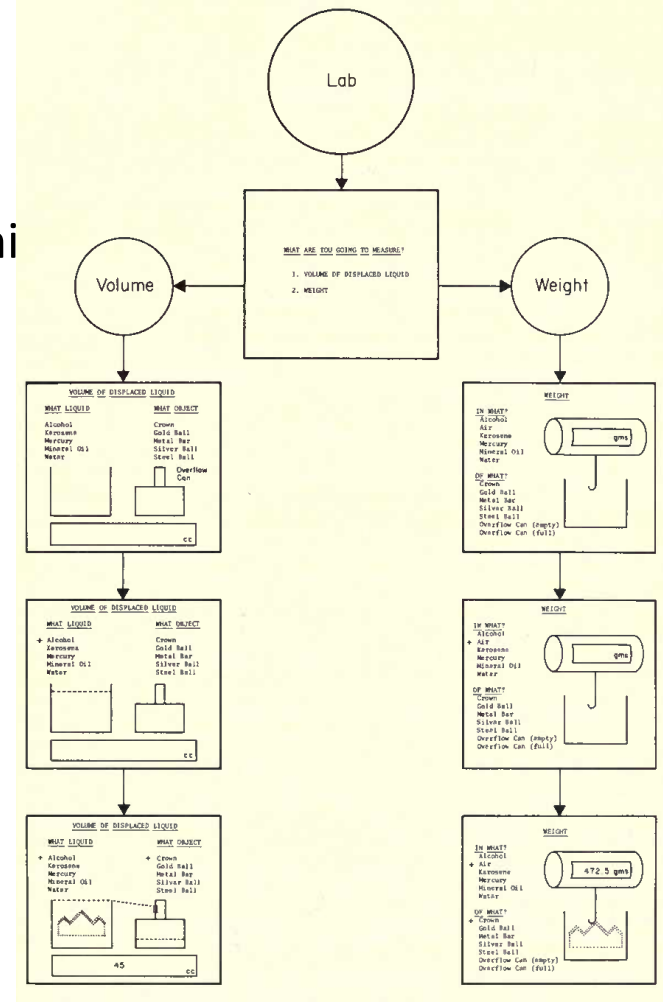
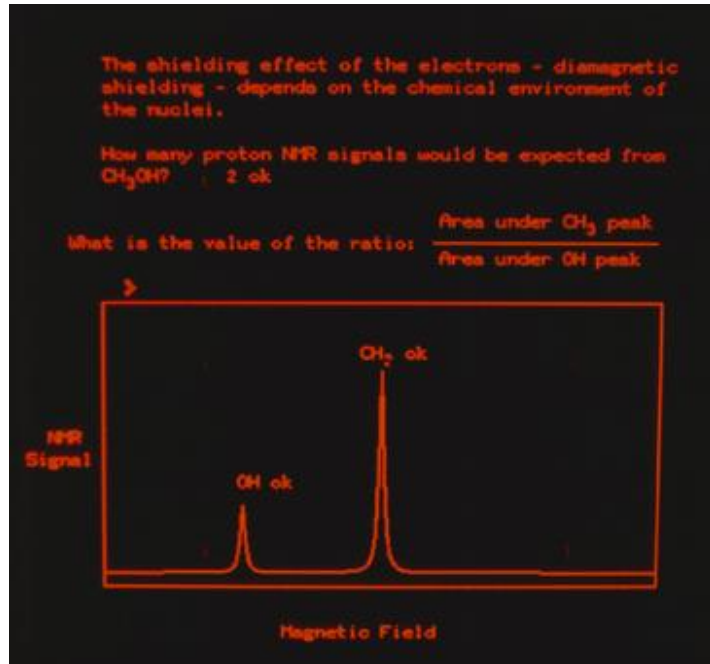
The PLATO Project

- Programmed Logic for Automatic Teaching Operations



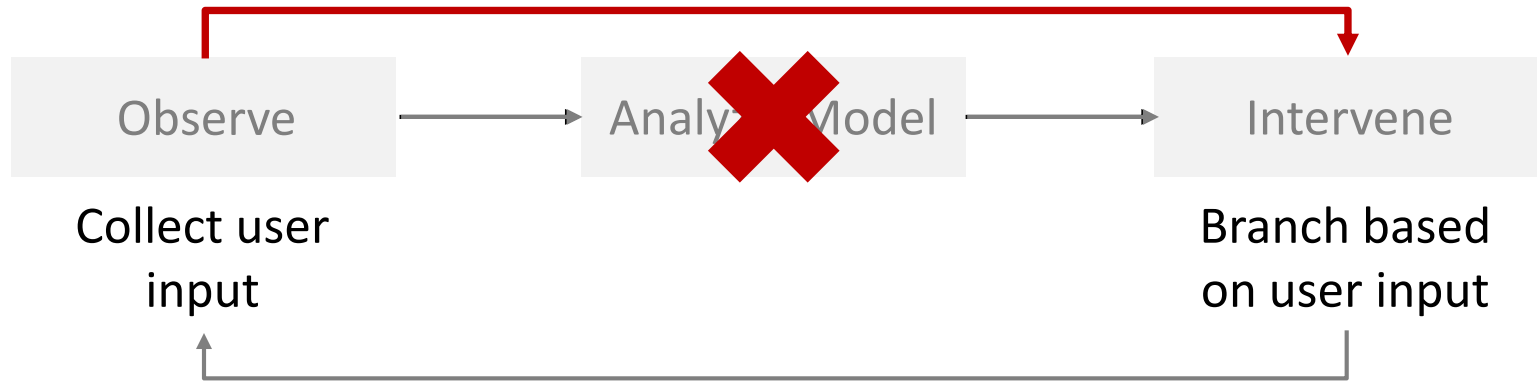
The PLATO

- Programmed Logic for Automatic Teaching



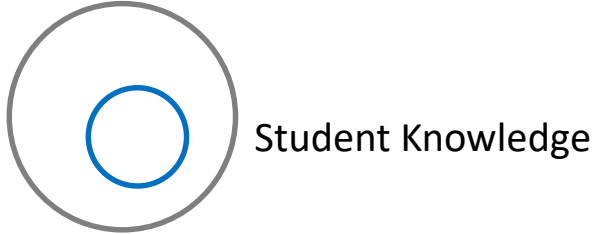
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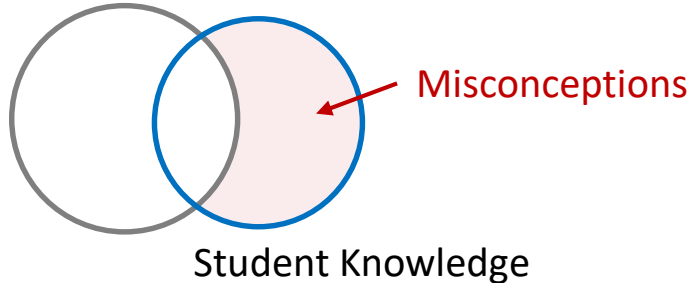
First Modeling Paradigms

Expert Knowledge



Overlay Model

Expert Knowledge



Buggy Model

Symbolic Adaptivity: Andes

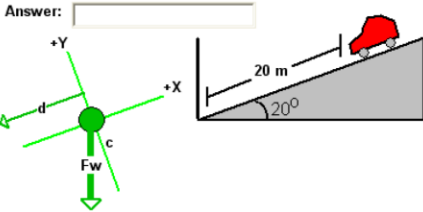
ANDES Physics Workbench - [dt5a.fbd]

File Edit Diagram Variable View Help

A 2000-kg car in neutral at the top of a 20.0 deg inclined driveway 20.0 m long slips its parking brake and rolls down.

If we ignore friction and drag, what would the magnitude of the velocity of the car be when it hits the garage door?

Answer:



Variables

Name	Definition
T0	car starts rolling
T1	car hits garage door
x	axis
mc	mass of car
d	magnitude of the Displacement of
Fw	magnitude of the Weight Force on

1. $mc = 2000 \text{ kg}$

2. $d = 20.0 \text{ m}$

3. $Fw_y = mc * g$

4.

5.

6.

7.

8.

9.

10.

T: Now that you have stated all of the given information, you should start on the major principles. What quantity is the problem seeking?

S: The magnitude of the instantaneous Velocity of car at time T1

T: Yep. What is the first principle application that you would like to work on? Hint: this principle application will usually be one that mentions the sought quantity explicitly. Therefore it's equation may contain the sought quantity that the problem seeks.

270 degrees

Symbolic Adaptivity: Andes

ANDES Physics Workbench - [dt5a.fbd]

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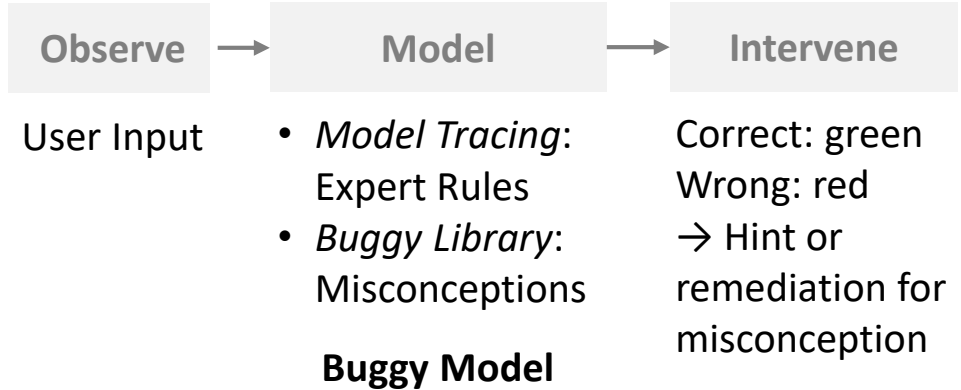
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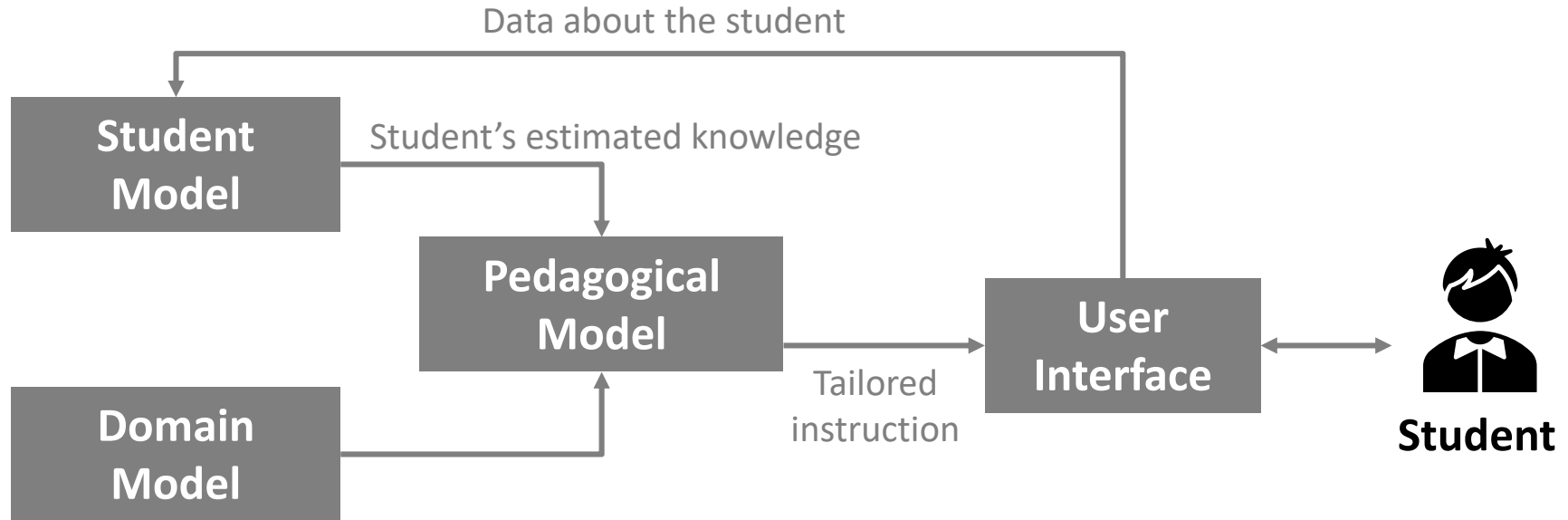
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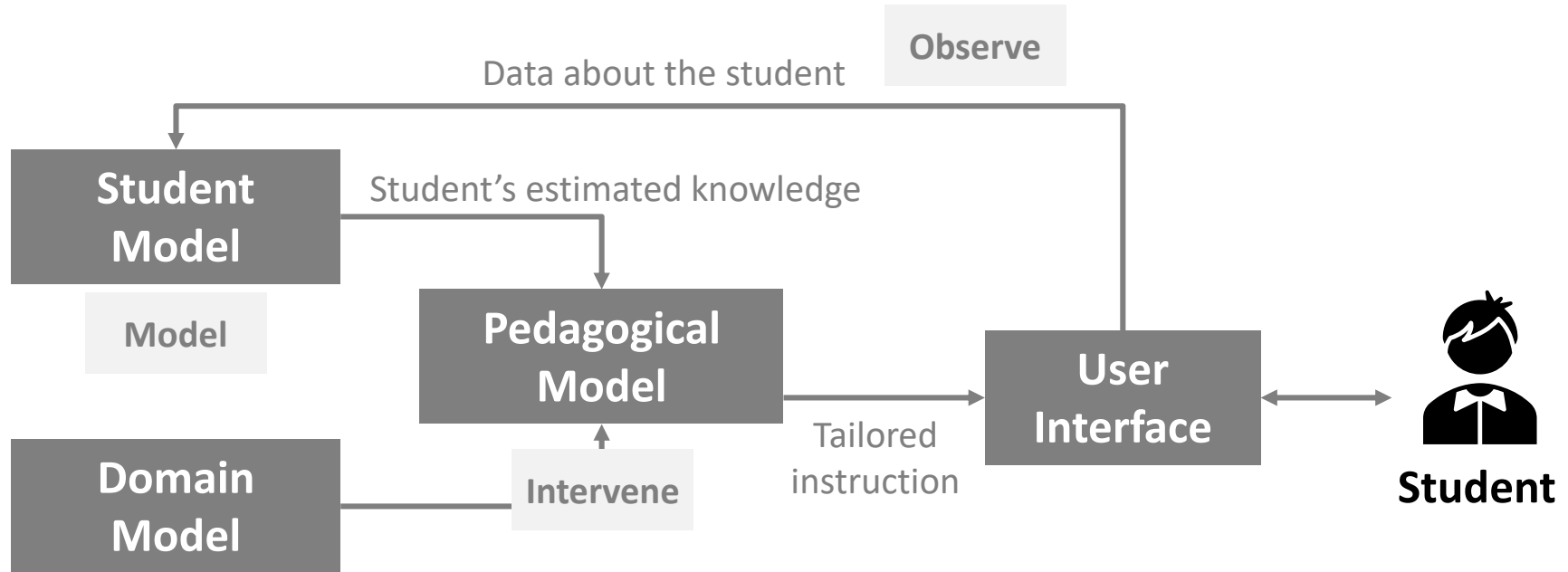
270 degrees



Advanced Modeling Paradigm



Advanced Modeling Paradigm



Probabilistic Model: Cognitive Tutor

The screenshot displays the Cognitive Tutor interface with four main components:

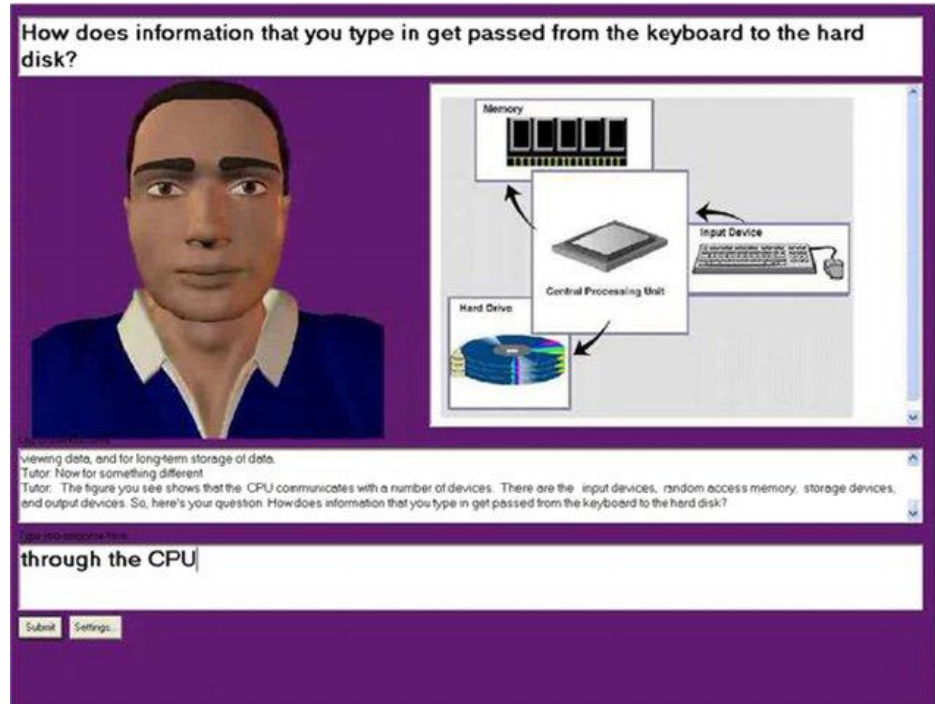
- Scenario:** A text-based problem about a person selling magazine subscriptions on a commission basis. It includes five numbered questions and instructions for graphing and writing expressions.
- Worksheet:** A table for recording student answers.

Quantity Name	NUMBER OF SUBSCRIPTIONS SOLD	PROFIT
Unit	SUBSCRIPTIONS	DOLLARS
Question 1		
Question 2		
Question 3		
Question 4		
Question 5		
Expression		
- Skills:** A horizontal bar chart titled "steve ritter's skills" showing proficiency levels for various math skills. The skills listed are: identifying units, entering a given, Write expression, positive slope, Find V, positive slope, Using large numbers, Using simple numbers, Correctly placing points, and Changing axis intervals.
- Grapher:** A window for plotting a graph. It includes a coordinate plane with axes from 0 to 10. Above the graph is a table for setting axis bounds:

	Lower Bound	Upper Bound	Interval
X Bounds	0.0	10.0	1.0
Y Bounds	0.0	10.0	1.0

- *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

ML-Based: AutoTutor



How does information that you type in get passed from the keyboard to the hard disk?

Memory

Input Device

Central Processing Unit

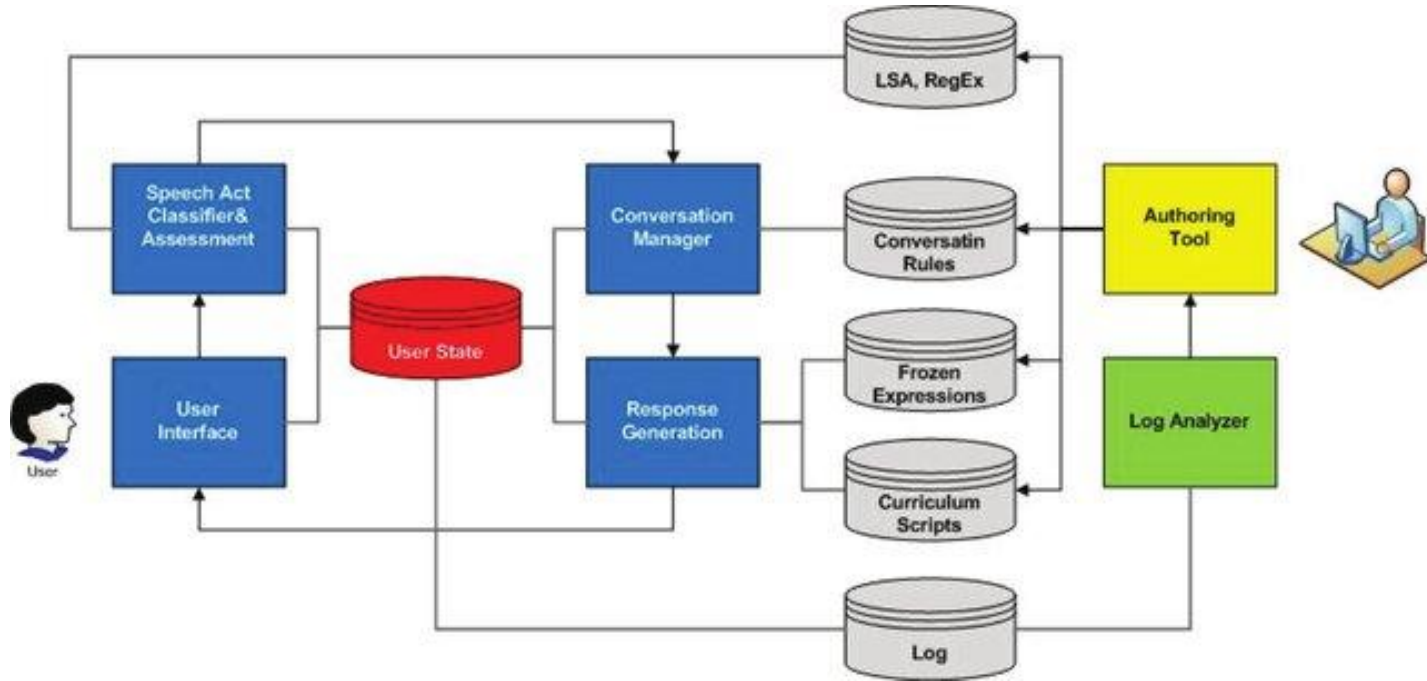
Hard Drive

viewing data, and for long-term storage of data.
Tutor: Now for something different
Tutor: The figure you see shows that the CPU communicates with a number of devices. There are the input devices, random access memory, storage devices, and output devices. So, here's your question. How does information that you type in get passed from the keyboard to the hard disk?

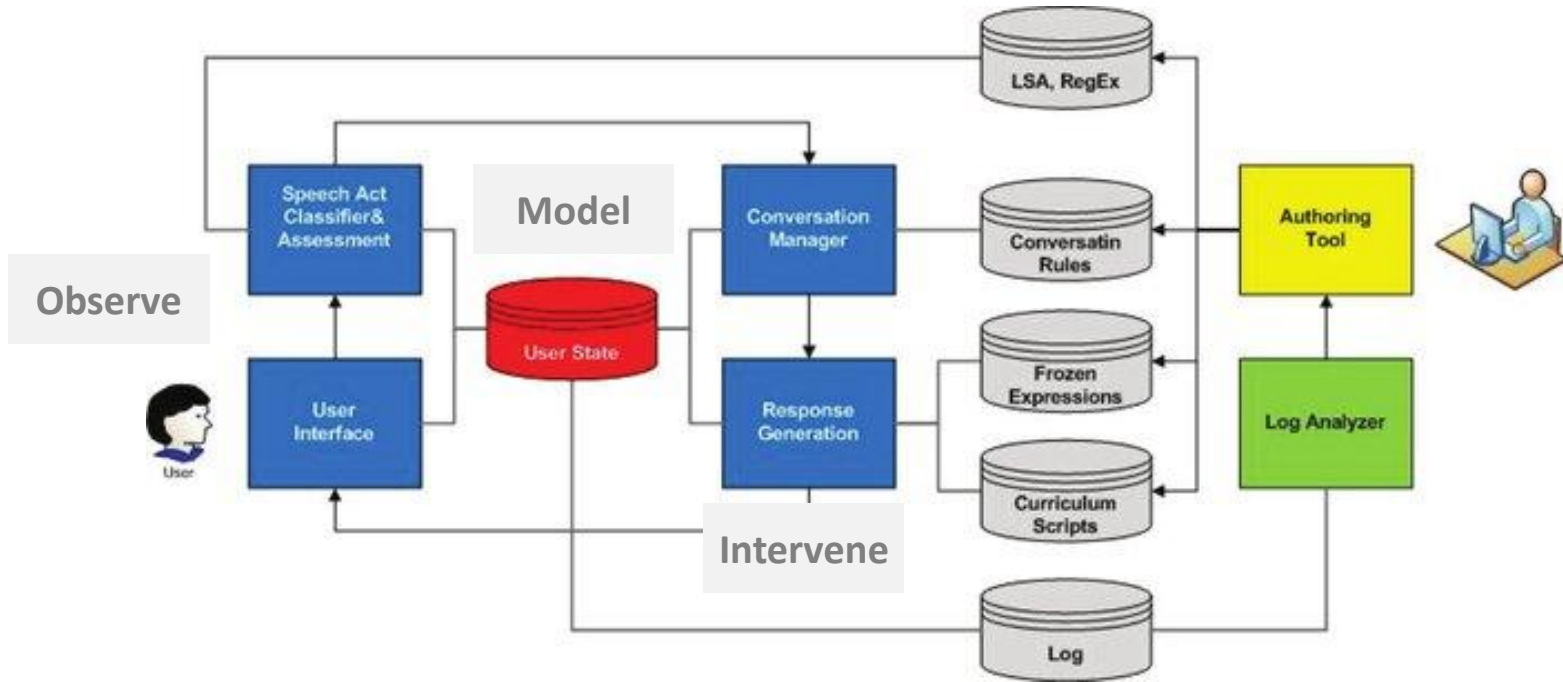
through the CPU

Submit Settings

ML-Based: AutoTutor



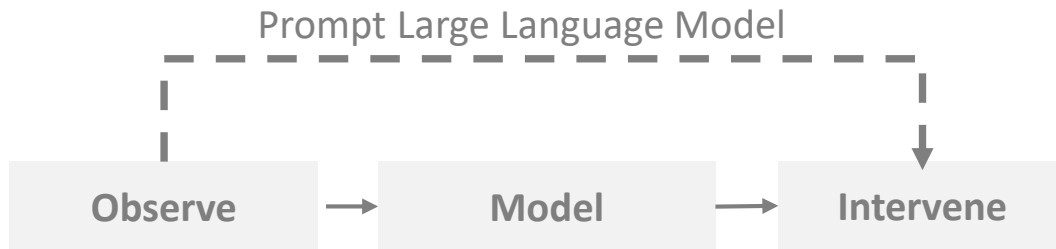
ML-Based: AutoTutor



Khanmigo— Generative AI

The screenshot displays the Khanmigo AI tutor interface. On the left is a sidebar with navigation options: "Teacher Dashboard", "Activities", "Tutor Me" (with a sub-option "Tutor me: Math and science"), "Tutor me: Humanities", "Tutor me focus" (marked "NEW"), and "Tutor me prepare for the National Bee®". The main chat area has a purple header "Khanmigo BETA Tutor me: Math and science". A message from the AI says "Khanmigo makes mistakes sometimes. Here's why" and "more accurate and helpful support!". A user input bubble says "Give me 10 practice problems!". The AI responds with "Leave feedback" and "Rate this response" (thumbs up/down). A user input bubble says "I want to understand photosynthesis better?". The AI responds with "Fantastic! Photosynthesis is a cool process. Let's start with a simple question: What do you think plants need to perform photosynthesis?" and "Leave feedback" and "Rate this response". At the bottom is an input field "Ask away..." with a microphone icon.

Tutoring by large language model



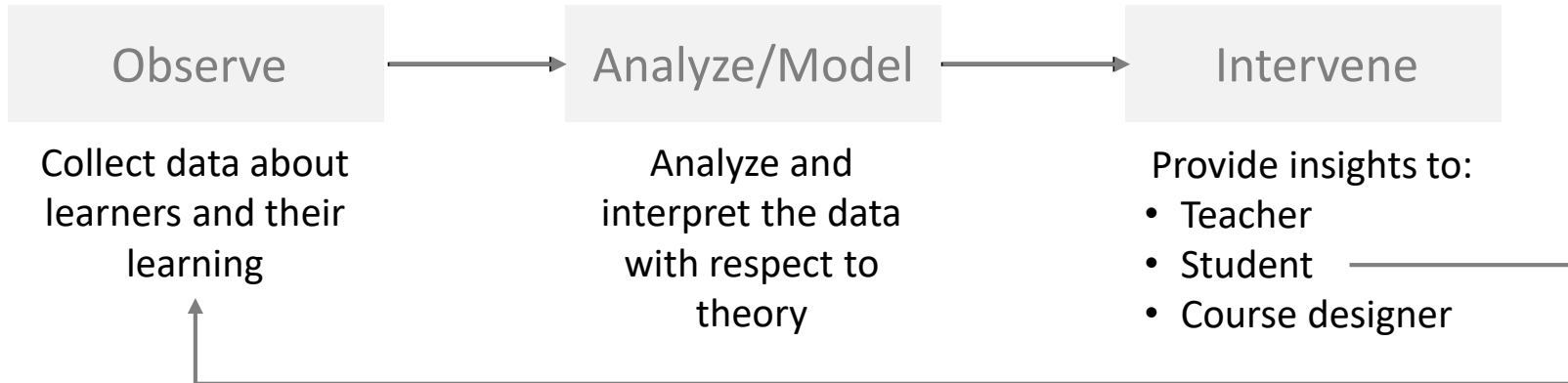
?

Definition

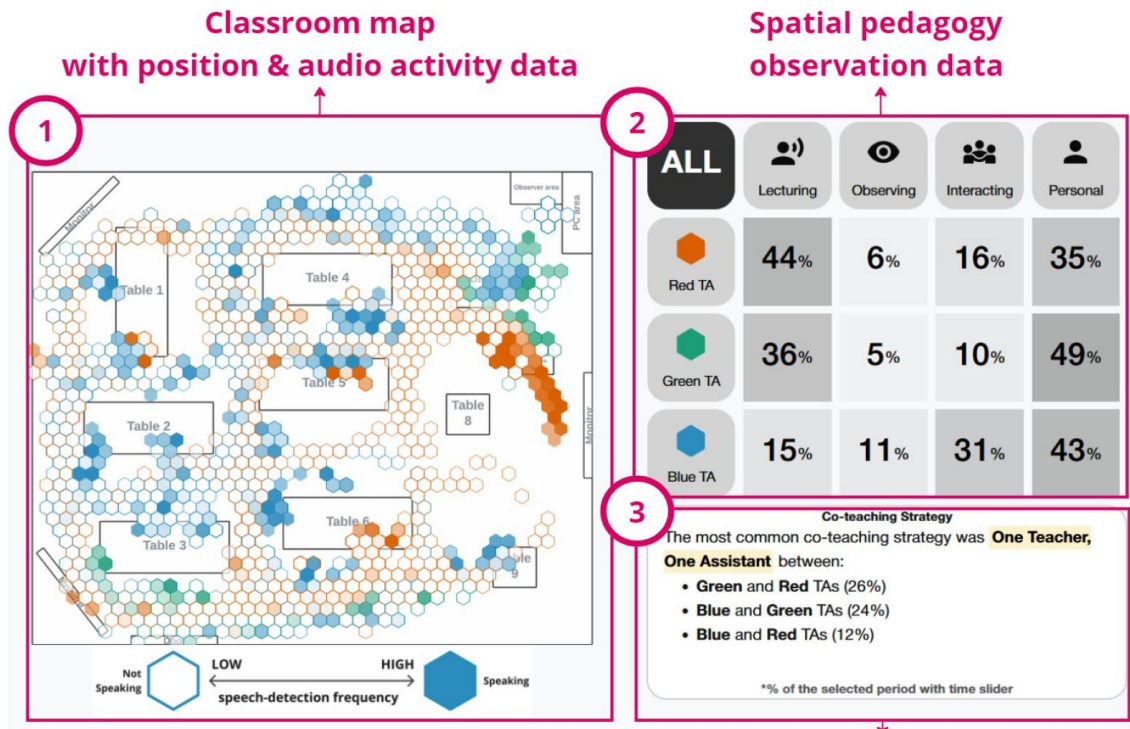
Learning analytics is the *collection, analysis, interpretation and communication of data about learners* and their learning that provides theoretically relevant and actionable *insights to enhance learning and teaching*.

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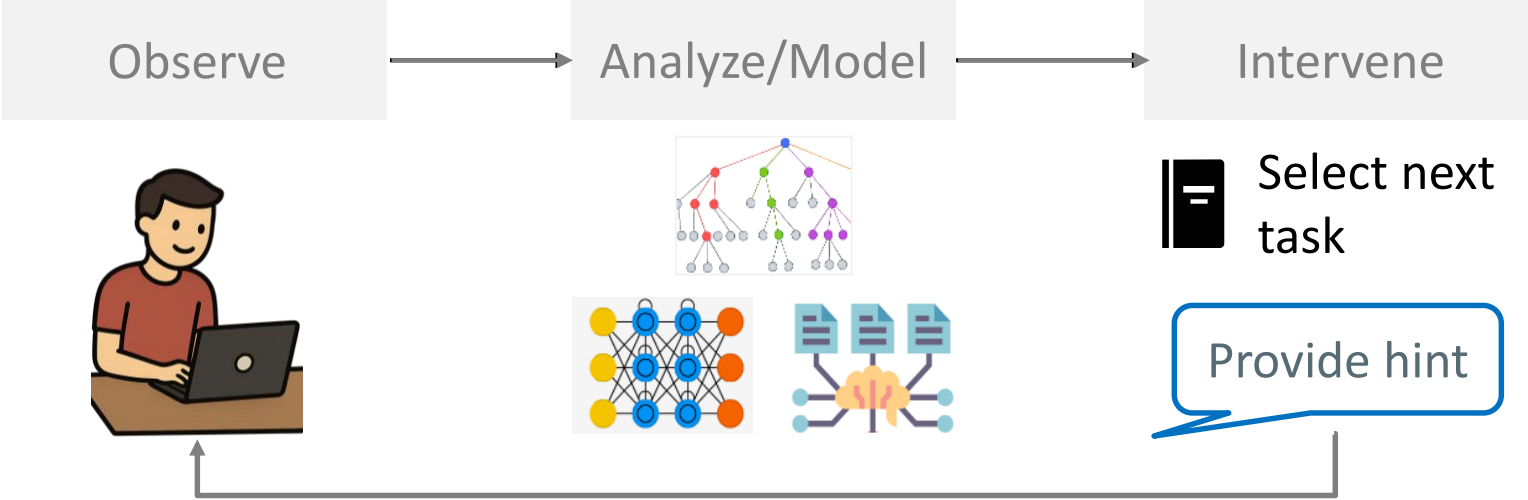
Student-Facing Dashboard: TeamTeachingViz



Co-teaching strategy descriptive data

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)

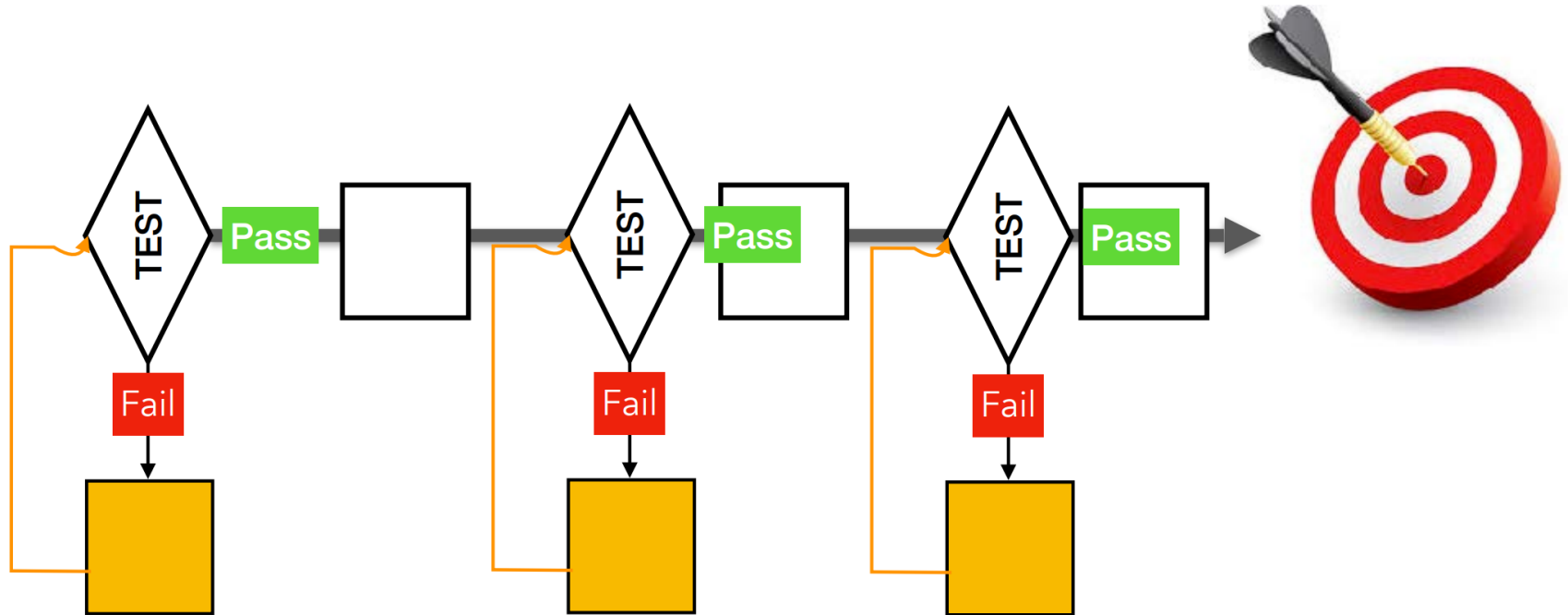


- Task format
- Support type: feedback, hint
- Modality: text, video, VR simulation
- Instructional strategy

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 <i>pacing and feedback loops</i> until mastery threshold is met.	<i>Cognitive Tutor</i>



Vygotsky - Intro

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

Vygotsky – 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.

Vygotsky – 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?

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Zone of Proximal Development (Vigotsky)	Learning occurs when supported just beyond independent ability	Guided performance within cognitive stretch	Systems adapt <i>task difficulty, hint level, or help type</i> (scaffolds).	<i>Assistments</i>

Spaced Repetition

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

Spacing effect

Learning is more effective when study sessions are spaced out.

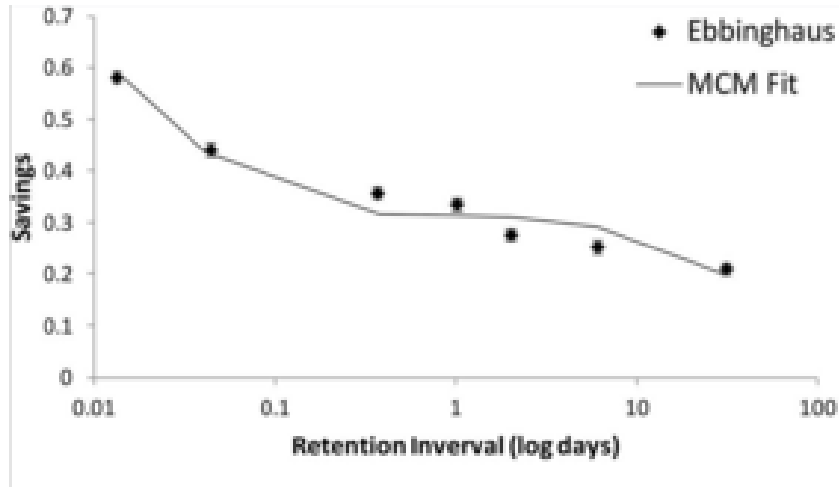
- Humans can store information much better in their long-term memory with spaced study sessions which repeat information, also known as **spaced repetition** or **spaced presentation** than massed presentation ("cramming").

But how do we repeat this information?

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

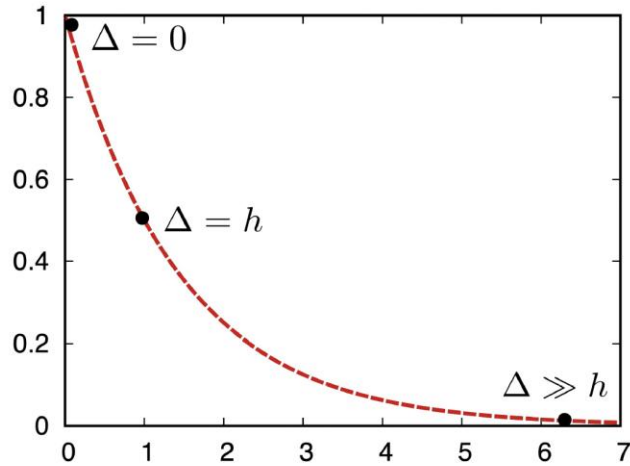
Ebbinghaus's experiment

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



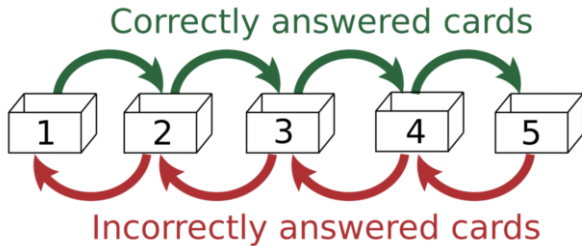
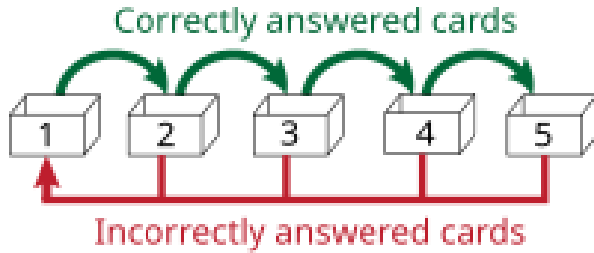
$$p = 2^{-\left(\frac{\Delta}{h}\right)}$$

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

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

Θ := weight vector

x := feature vector

Pedagogical Foundations

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Spaced Repetition (Ebbinghaus)	Memory decays predictable; recall strengthens retention	Long-term memory consolidation	Systems adapt <i>review intervals</i> based on learner's <i>retention probability</i> .	<i>Duolingo</i>

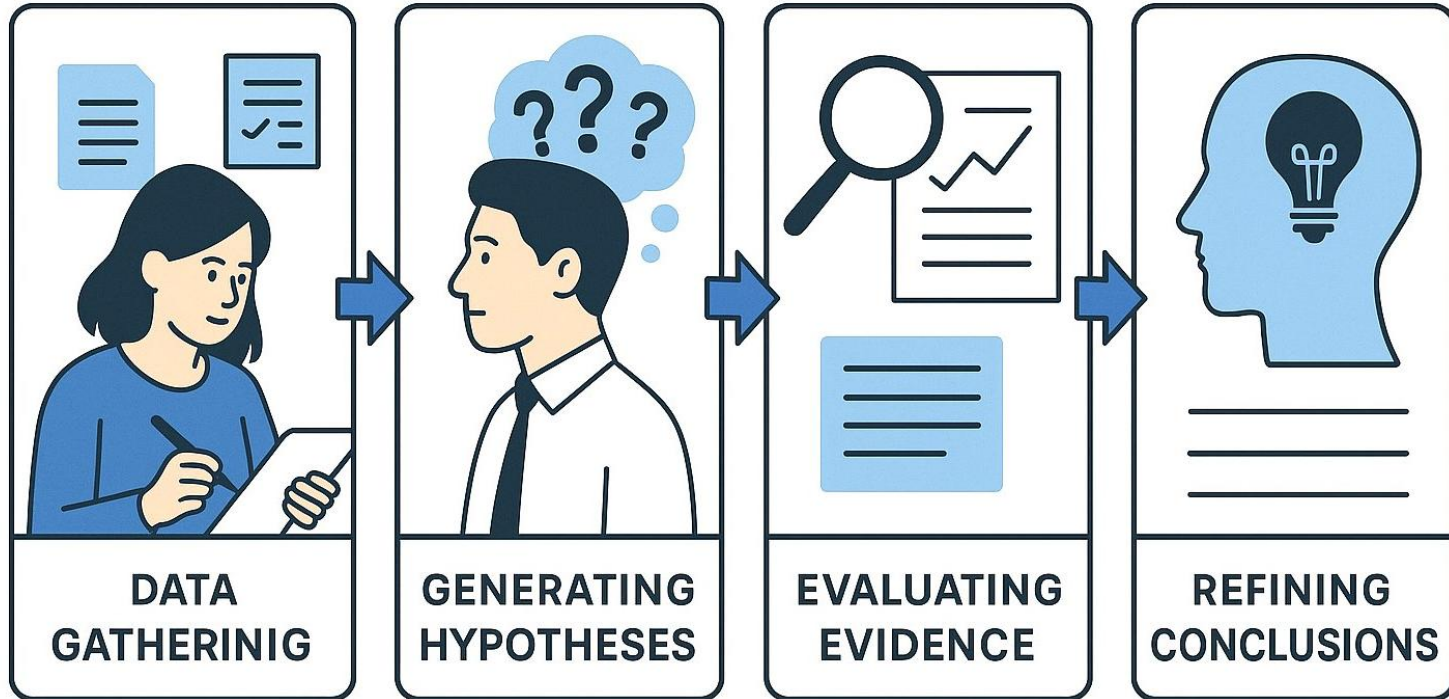
What about adaptive instruction in PS-I?

Explore

Consolidate

Apply

Diagnostic Reasoning in a Pharmacy



PharmaSim – Virtual Pharmacy



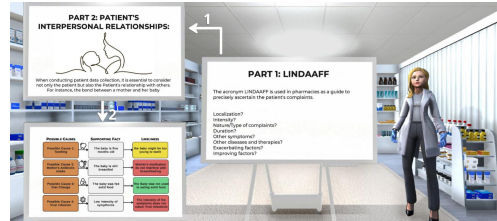
PharmaSim – PS-I Sequence

Explore



Father of a baby with diarrhea

Consolidate

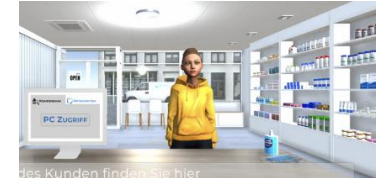


Adaptive Instruction

Apply



Another father of a baby with diarrhea



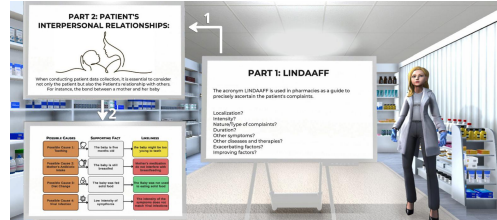
Mother with breastfeeding issues

PharmaSim – PS-I Sequence

Explore



Consolidate



Apply



Father of a baby with diarrhea

Adaptive Instruction

Another father of a baby with diarrhea

Mother with breastfeeding issues

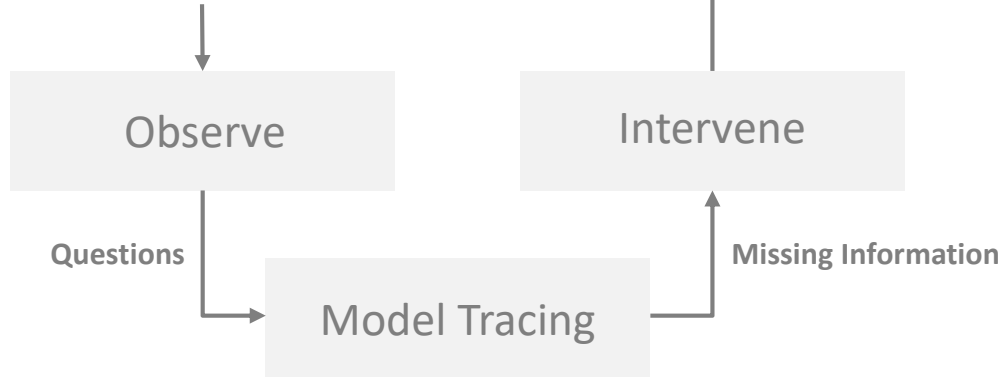
Observe

Intervene

Questions

Missing Information

Model Tracing



Adaptive Instruction

PART 2: PATIENT'S INTERPERSONAL RELATIONSHIPS:

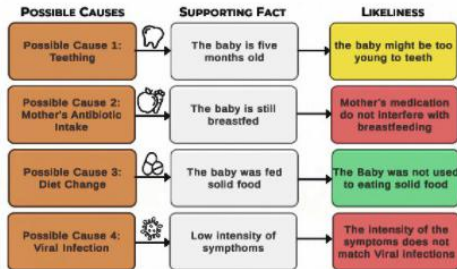


When conducting patient data collection, it is essential to consider not only the patient but also the Patient's relationship with others. For instance, the bond between a mother and her baby

PART 1: LINDAAFF

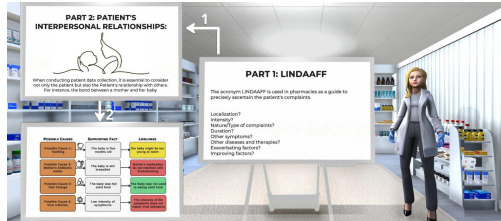
The acronym LINDAAFF is used in pharmacies as a guide to precisely ascertain the patient's complaints.

Localization?
Intensity?
Nature/Type of complaints?
Duration?
Other symptoms?
Other diseases and therapies?
Exacerbating factors?
Improving factors?



Control – I-PS sequence

Instruction



Worked Example

Problem-Solving



Father of a baby with diarrhea

Transfer



Another father of a baby with diarrhea

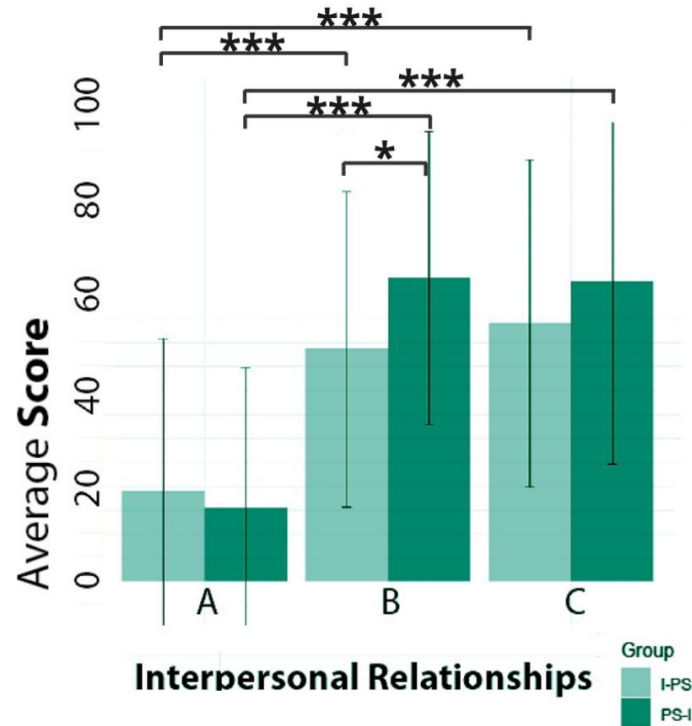


Mother with breastfeeding issues

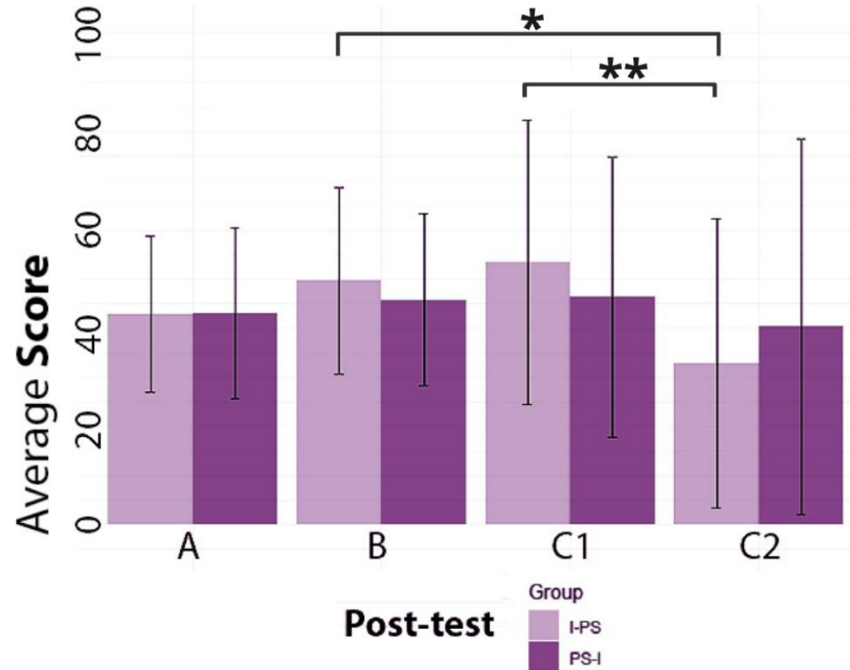
Evaluation

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

PS-I apply interpersonal relationships more



PS-I transfers data interpretation strategy better



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)