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Development of a Prototype Simulation-based AI System to Support Physics Inquiry Learning : Easy Physics

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Motivation

- **Challenges in learning Physics**
 - Physics is hard...
 - Students experience repeated failures in applying abstract concepts and problem-solving → **learning abandonment**
 - Mismatch on scientific concept with students' preconception (Lim & Lee, 2015)
 - Gap between physics concepts and real world (Angell et al., 2004)
- **Constructivist view about WHY Physics is difficulty**
 - **Thinking models** which are formed in daily experience contexts **not easily modified** (Ausubel, 1968).
 - Physics learning is a process of **reconstructing existing thinking models** through cognitive conflict and accommodation

Research Gap

- **Technology-assisted attempts to promote conceptual change**
 - ① **ITS (Intelligent Tutoring System)**: Customized feedback (VanLehn et al., 2007)
 - ② **Simulation**: Manipulable activities in contextualized situations (Jonassen & Easter, 2012)
- **Limitations of existing research**
 - ① **ITS**
 - Insufficient consideration of scientific concept formation process
 - Lack of pre-concept **dissatisfaction** + Text-based feedback only available (Posner et al., 1982)
 - ② **Simulation**
 - Limited representation scope of scientific modeling
 - Only pre-fixed variables can be manipulated → **Constraints on thinking externalization**
(Jonassen & Easter, 2012)

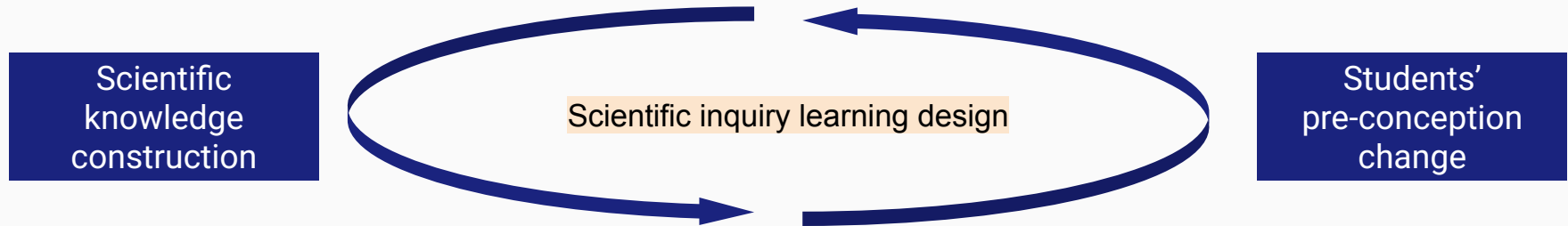
Need for Research

- **Potential of Learning Cycle model**

- Constructivist-based learning cycle models in science education: **POE model** (White & Gunstone, 2014), **5E model** (Duran & Duran, 2004)

- **Learning Cycle Model**

- General procedure: **(1) Exploration - (2) Concept introduction - (3) Application**



- **Scientific inquiry learning design** (Bybee et al., 2006; Lawson, 2001)

- Dissatisfaction with pre-concept based on experimental results → Scientific concept provision through teacher intervention → Recognition of scientific concepts' usefulness

Need for Research

- **Technology-enhanced scientific inquiry learning**
 - **POE model + Computer simulation:** effectively promotes student conceptual change & generalization (Tao & Gunstone, 1999)
 - **5E model + Computer simulation:** improves physics achievement & attitudes (Sari et al., 2017)



Effectiveness of technology-enhanced learning environment applying **Learning Cycle Model**

- Potential of integrating simulation-based Learning Cycle Model + **AI in Education**
 - **Large Language Model (LLM)**'s excellent **code generation capability** (Austin et al., 2021)
 - Generate physics simulation code applying 'natural language' prompts (Ali-Dib & Menou, 2024)
 - **LLM**'s excellent **ICL (In-Context Learning) capability** (Brown et al., 2020)
 - Develop a customized feedback chatbot using prompt engineering (Stamper et al., 2024)

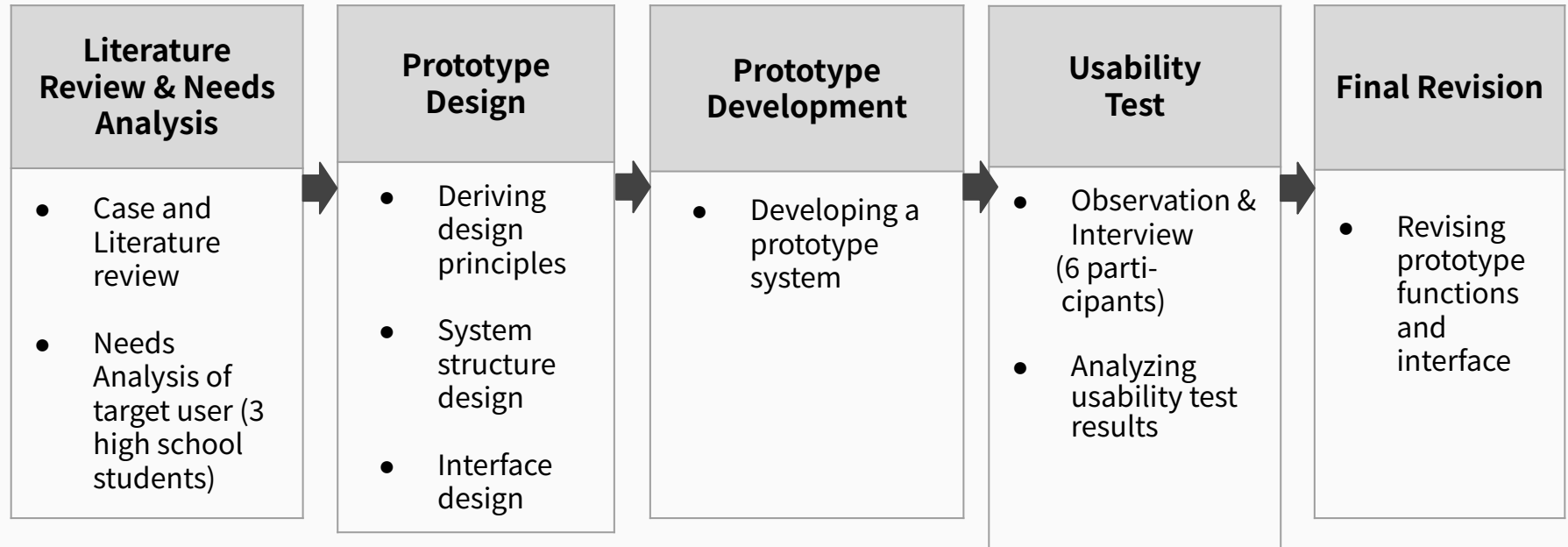
Research Objectives

- **Research Purpose**
 - Integration of **LLM-generated code-based simulation** into 5E learning cycle model
 - Scaffolding by **LLM-based AI tutor with specialized roles** for each learning cycle

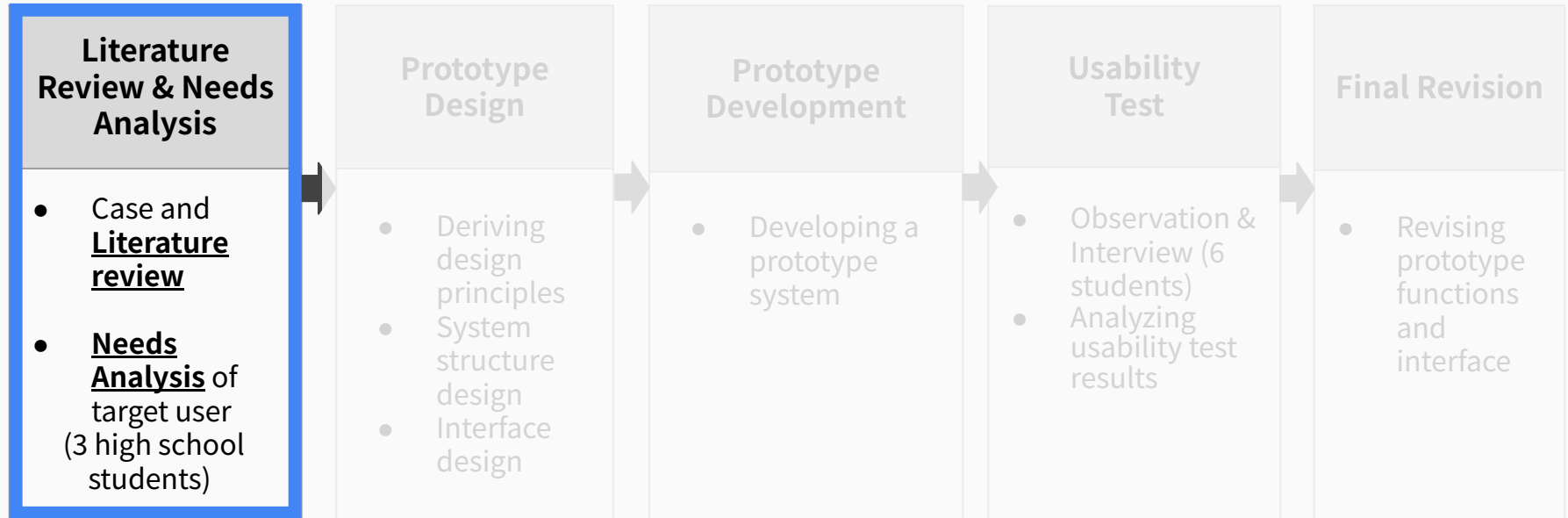
- **Research Questions**
 - 1) How is a simulation-based AI system prototype designed and implemented to support students' physics inquiry process?
 - 2) What are user responses to the simulation-based AI system prototype supporting students' physics inquiry process?

Research Procedure

- Richey & Klein (2014) Design and Development Research (DDR), Type 1

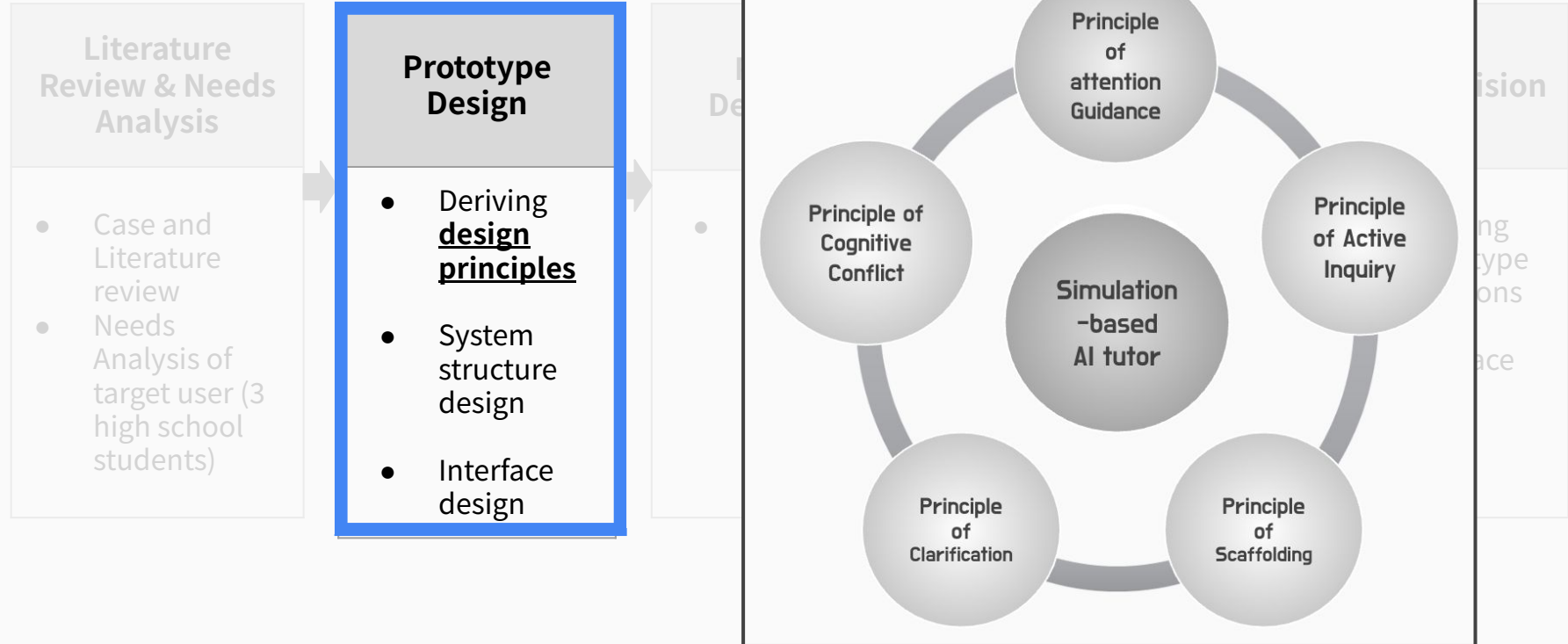


Research Procedure

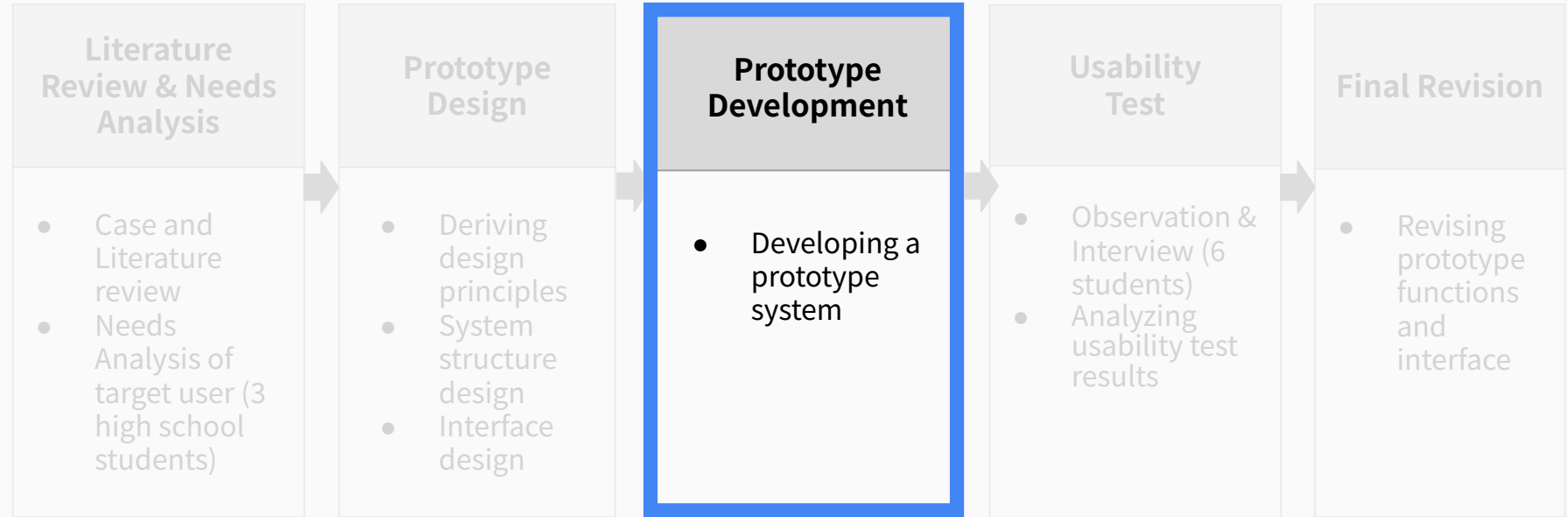


- **(Literature Review)** 'AI tutor', 'physics simulation', 'scientific thinking' and 'conceptual change in science'
- **(Need Analysis)** Conducted in-depth 1:1 interviews with three high school seniors. Observed their process of solving problems related to the concept of <force and acceleration>.

Research Procedure



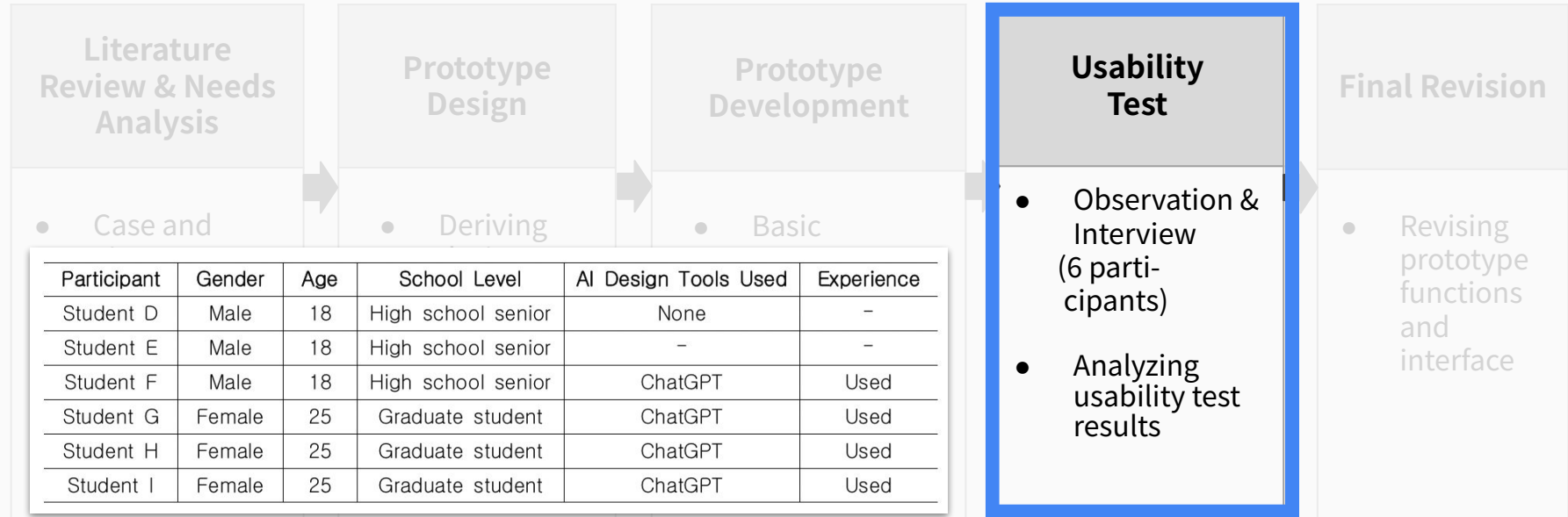
Research Procedure



- (Overall Application Architecture Design) **Streamlit**
- (AI Prompting Chain Development Tools) **OpenAI's GPT-4o API** in combination with **LangChain**

- (Retrieval-Augmented Generation Tools) **FAISS** vector DB to implement RAG
- (Simulation Visualization Tools) **Plotly**

Research Procedure

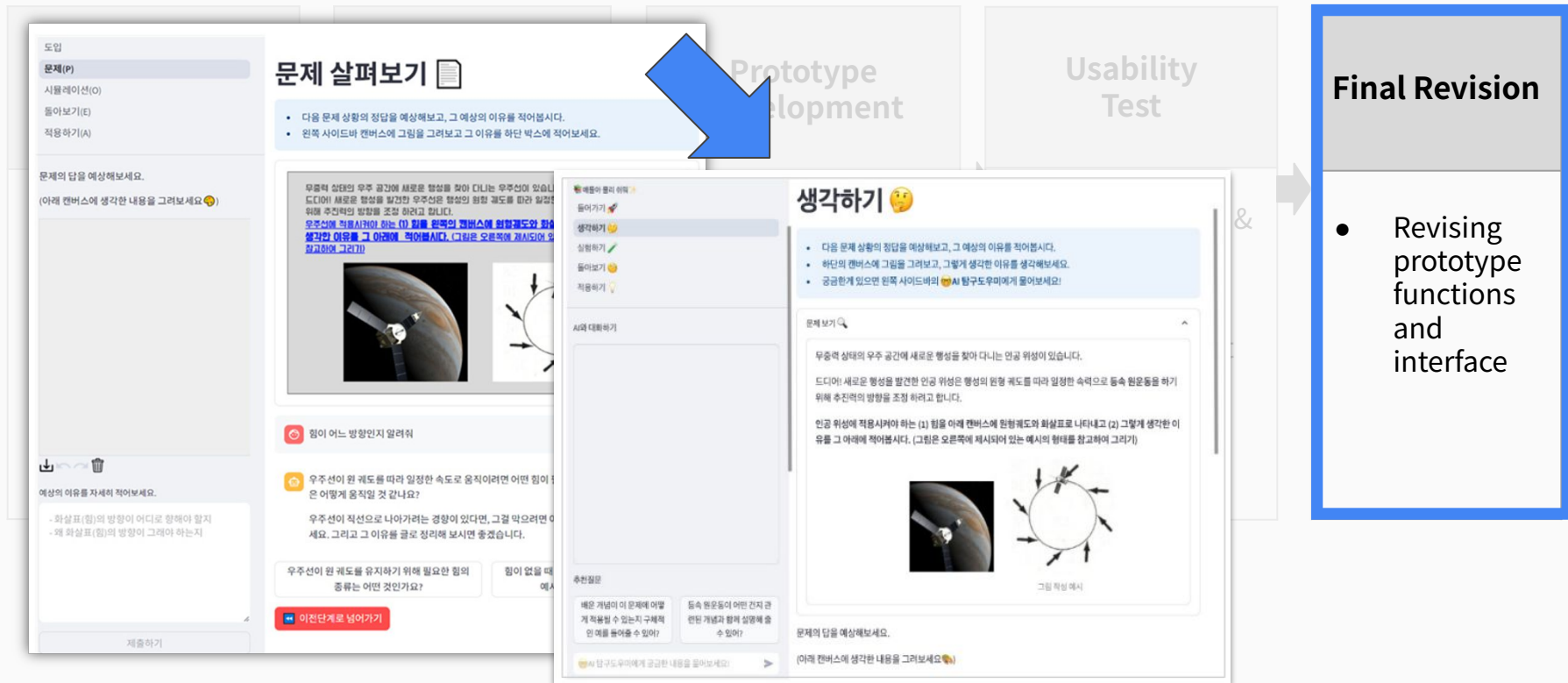


Research Procedure

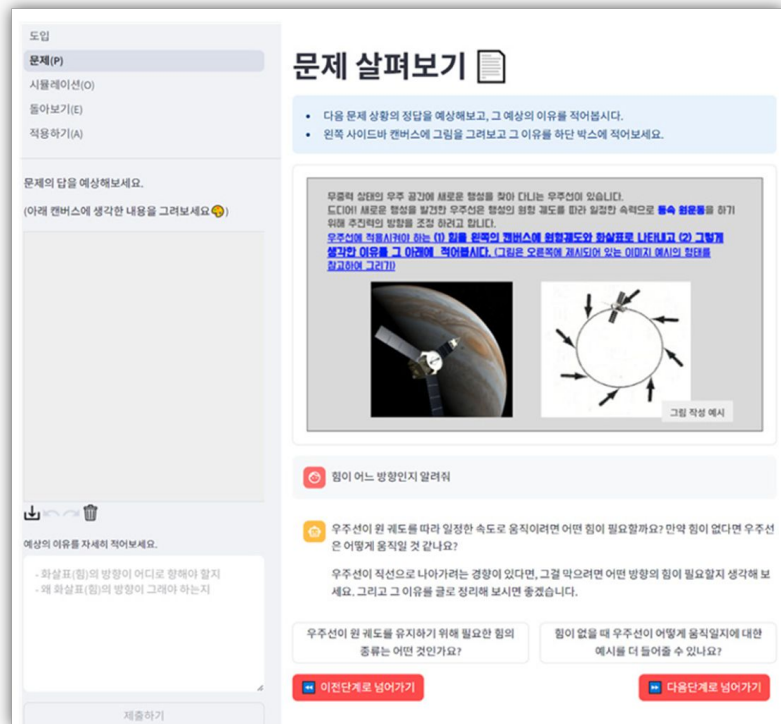


- User study protocol
 - 1. Presented 3 prior knowledge questions related to the concept of 'force' to assess students' preconceptions
 - 2. Observed participants using the prototype while employing the "Think Aloud" method
 - 3. Conducted a usability survey and interviews (Yoon & Yunus, 2022; Morville, 2005)

Research Procedure

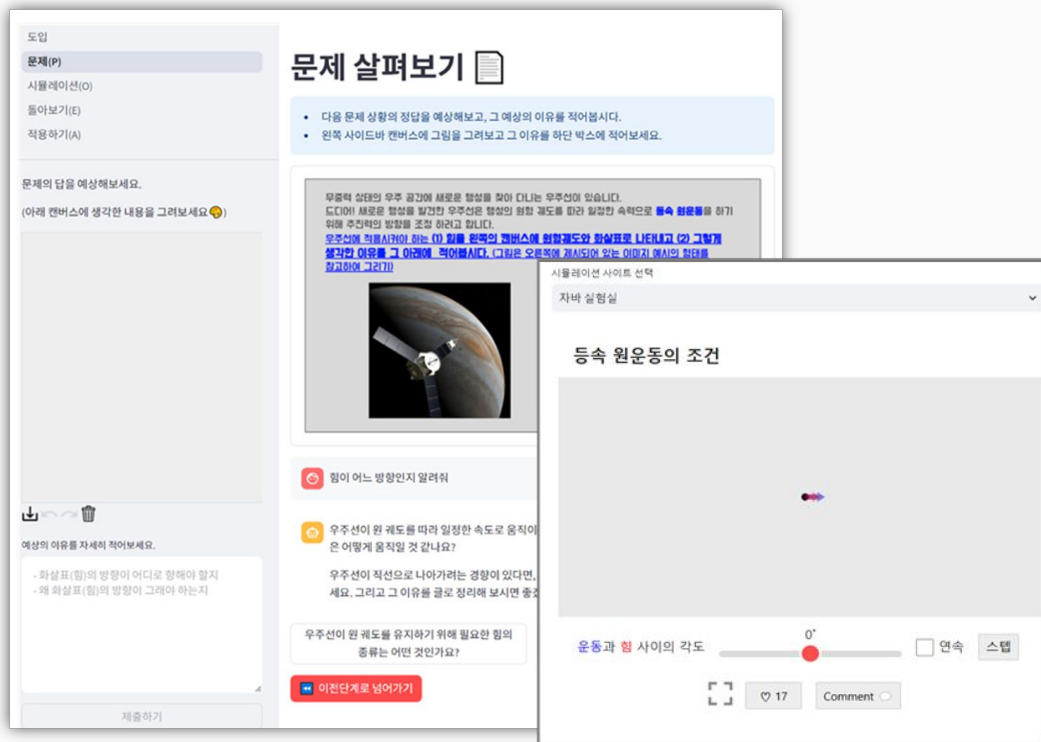


Initial Prototype



- **Learning contents and activities**
 - Physics subject, solving problems of 'Mechanics and Energy' Chapter **'Circular Motion' topic**
- **Basic structure of screen**
 - **Main window** on the right, learning contents with learning activities window
 - **Sidebar** on the left, drawing canvas and writing answer
- **AI tutors in every steps**
 - Adapted with Retrieval Augmented Generation(RAG) technology
 - Adaptive feedback based on physics textbook and students answers

Initial Prototype



Learning stage following POE-A model

- (**P**rediction) Provide a problem related to circular motion and predict an answer with AI tutor based on the **principle of scaffolding**
- (**O**bservation) Manipulate pre-defined simulation and making simulation by prompts based on the **principle of cognitive conflicts**
- (**E**xplanation) Solve the problem again reflecting the simulation results based on the principles of **principle of active inquiry**
- (**A**pplication) Transfer concepts by solving new problems based on **principle of clarification**

Usability Evaluation

- **Results**
 - Participants generally felt that the prototype was useful and interesting for learning physics
 - **Usability: $M=4.72$, $SD=0.57$**
 - **Usefulness: $M=4.36$, $SD=1.17$**
 - **Attractiveness: $M=4.39$, $SD=1.04$**
- **Advantage of prototype**
 - **P1:** “Simulations provide a visualization of laws of physics to help students understand concepts”
 - **P2:** “Feedback from AI tutors is adaptive and helpful along the learning levels”
- **Disadvantage and improvements of prototype**
 - Difficulty recognizing where students are in the learning stage due to unclear distinctions
 - → **Add explanations about each stage** or **change name more intuitively**
 - Hard to know AI tutor's location because it changes depending on the stage
 - → **Pin the AI Tutor window** in a fixed position
 - Difficulty understanding the difference between the two simulations and not being able to utilize them for the intended purpose
 - → The purpose of each simulation, specific manipulatives, and student roles are **explained by the AI tutor or detailed in the activity instructions**

Final prototype of AI system(1)

Stage	5E Learning Cycle Model	Student learning activity	Role of AI tutor
1. Introduction 🚀	Engage	- Review Physics concepts relevant to the problem (presented in 2nd stage) - Activate background knowledge	- Provide feedback based on preset answers and hints

Sidebar
: AI tutor

🚀 들어가기 물리 쉬워!

들어가기 🚀

생각하기 🤔

실험하기 📏

들어보기 📺

적용하기 📌

AI와 대화하기

🗨️ AI 탐구도우미에게 궁금한 내용을 물어보세요!

들어가기 진행률: 25%

들어가기 🚀

오늘 배운 물리 개념은?

- 먼저 (힘과 운동) 소단원에서 배운 내용을 복습해봅시다!
- 궁금한게 있으면 왼쪽 사이드바의 🗨️ AI 탐구도우미에게 물어보세요!

🗨️ 안녕하세요! 저는 오늘 여러분과 함께 공부할 AI 튜터입니다.

먼저 오늘 배운 기본 개념부터 다시 떠올려볼까요?

공을 발로 찰 때처럼 한 사람이 힘을 작용하기도 하지만 줄다리기처럼 여러 사람이 함께 힘을 작용할 때도 있죠. 이처럼 한 물체에 여러 힘이 동시에 작용할 때, 이 힘들과 같은 효과를 나타내는 하나의 힘을 무엇이라고 할까요? (초성 힌트: ㅇㅁㅎ)

📌 알짜힘!

🗨️ 정확합니다! 알짜힘은 물체에 작용하는 모든 힘을 하나로 합친 것이예요. 예를 들어, 줄다리기에서 양쪽에 서 당기는 힘들을 모두 고려한 최종적인 힘이 바로 알짜힘이죠.

이제 알짜힘의 다른 이름에 대해 알아보까요?

🗨️ 알짜힘은 다른 말로도 부르는데요, 그 용어가 무엇인지 아시나요? (초성 힌트: ㅇㅁ)

🗨️ AI 튜터의 질문에 대한 답변을 작성해주세요.

Main window
: Learning activities

3. Results

Final prototype of AI system(2)

Stage	5E Learning Cycle Model	Student learning activity	Role of AI tutor
2. Prediction 🤔	Explore	- Look at the problem for the first time - Anticipate what is the answer and why	- Support for connecting problem to physics concepts - Suggest scaffolding how to solve problem (NOT direct answer)

Suggested questions

The screenshot shows the AI system interface for a physics problem. The main section is titled '생각하기' (Thinking) and contains a question about orbital velocity. Below the question is a '추천질문' (Recommended questions) section with two suggested questions. To the right of the main section is a 'Drawing Canvas' for drawing a diagram. Below the canvas is a 'Reason for answer' section for explaining the answer. The interface is in Korean.

Drawing Canvas

Reason for answer

Final prototype of AI system(3-1)

Stage	5E Learning Cycle Model	Student learning activity	Role of AI tutor
3. Experiment 	Explore	- Observe simulation result while manipulating it - Find the differences between their prediction and simulation	- Provide instructions on simulation procedures and operation methods

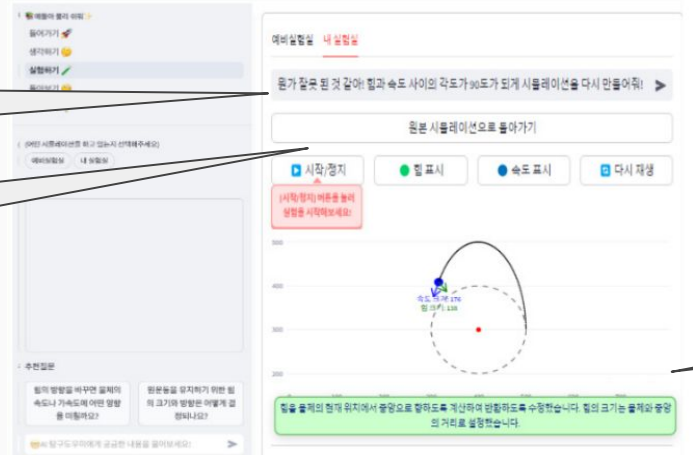


3-1. Preliminary LAB

Simple manipulation less freely but easily

Final prototype of AI system(3-2)

Stage	5E Learning Cycle Model	Student learning activity	Role of AI tutor
3. Experiment 	Explore	- Observe simulation result while manipulating it - Find the differences between their prediction and simulation	- Support students to create and modify simulations as they intended



AI chat box

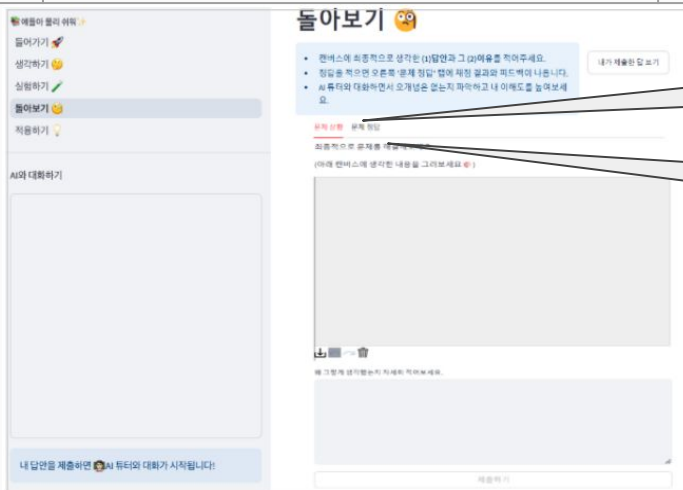
(Apply my submitted answer) button

3-2. My LAB

More customized manipulation more freely but not that easily

Final prototype of AI system(4)

Stage	5E Learning Cycle Model	Student learning activity	Role of AI tutor
4. Explanation 🤔	Explain	- Look at the problem again - Explain differences between predictions and observations in their own words	- Support concept formation by explaining correct answer and reasons



Problem scenario

Correct answer and reasons

Final prototype of AI system(5)

Stage	5E Learning Cycle Model	Student learning activity	Role of AI tutor
5. Application 💡	Elaborate, Evaluate	- Apply learned content to new situations to extend and refine concepts.	- Offer concrete evaluation and feedback on the application and extension

Expert's modeling
in answer

배움터 물리 실험

물어가기
생각하기
실험하기
들어보기
적용하기

AI와 대화하기

공전 궤도가 뭐지...?

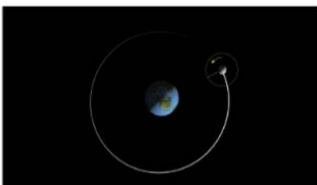
공전 궤도는 천체가 다른 천체 주위를 도는 경로를 말합니다. 예를 들어, 지구는 태양 주위를 공전하고 있는데, 이때 지구가 따라가는 경로가 바로 공전 궤도입니다. 공전 궤도는 일반적으로 타원 모양이지만, 특정 조건에서는 원에 가까운 형태가 될 수도 있습니다.

혹시 공전 궤도에 대해 더 궁금한 점이 있거나, 관련된 다른 개념에 대해 알고 싶으신가요?

만약 궁금증도 물어봐주세요 궁금한 내용을 물어보세요!

적용하기 💡

- 배운 내용을 새로운 상황에 적용해보며 개념을 더 깊게 이해해보세요.
- 지구 주위를 도는 달의 운동을 관찰해보고 그 이유를 설명해보세요.



지구 주위를 도는 달의 모습

등속 원운동

운동을 방향만 변하는 운동 놀이공원에서의 회전하는 관동차, 지구 주위를 도는 인공위성, 시계의 바늘 등은 일정한 속도로 원을 그리며 운동하는데, 이러한 운동을 등속 원운동이라고 합니다. 등속 원운동하는 물체는 속력이 변하지 않고 운동 방향만 변합니다. (교과서 16쪽)

다시 등장한 AI 보조교사입니다! 매직으로, 배운 내용을 새로운 상황에 적용해보세요!

위 그림과 같이 달이 공전 궤도를 유지하면서 계속 지구를 돌 수 있는 이유는 무엇일까요?

New open-ended
question

Discussions

- **LLM-Generated Code-based Simulation for Conceptual Change**
 - (1) **Imagined situations** into **simulations** → (2) **Visual representation** of preconceptions → (3) Meets Posner et al. (1982) **dissatisfaction + plausibility** conditions → (4) Promotes conceptual change
- **LLM-based AI Tutor's Dual Role**
 - **Customized AI tutors with different roles** for each learning stage
 - **'Engage' stage:** Activating learner's prior knowledge + Providing related Q&A
 - **'Explore' stage:** Guiding simulation procedures and operation methods
- **Multimodal AI-powered Customized Feedback**
 - **Multimodal AI:** Integrates and processes text, image, audio data altogether
 - (1) Physics concepts difficult to express verbally → (2) AI system processes **drawing(image) with reason(text)** → (3) Provides customized feedback based on student's physics representations

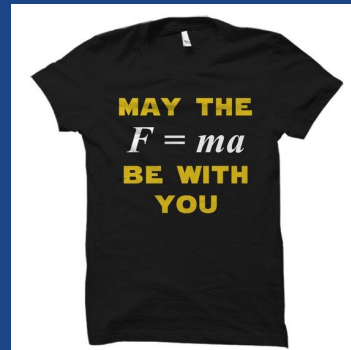
Considerations

- **Student Interest and Motivation Should be Considered**
 - Most students successfully completed tasks and conceptual change occurred in simulation-based POE instruction → **Delayed post-test results showed many students regressed to preconceptions** (Tao & Gunstone, 1999)
 - AI system needs connection to **continuous learning, not one-time use**
- **Human Teacher-AI System Collaboration Should be Considered**
 - Concerns about **increased AI dependency** and **decreased interaction with teachers and peers** in usability test
 - Student task performance ability affects dependent-collaborative interaction patterns with AI (Kim et al., 2023)
 - (1) Teacher's AI demonstration and metacognitive strategy guidance → (2) **Reduced AI dependency** → (3) Enhanced student AI competency (Kim & Cho, 2023)

Implications and Conclusions

- **Theoretical implications**
 - Combination of learning theory + cutting-edge AI technology
- **Practical implications**
 - Using new tools to help students better grasp Physics concepts and improve their scientific inquiry
 - Satisfaction on highly customized feedback in usability test
- **Research Limitations and Future Directions**
 - **Sample limitations:** Needs analysis N=3, Evaluation N=6 → Need to expand subjects & contexts
 - **Prototype stage yet:** Field application and long-term learning effects unverified → Field application research needed

May the Physics be with you:)



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Literature Review and Need Analysis to Prototype Design

- **(Literature Review)** Searched keywords such as 'AI tutor', 'physics simulation', 'scientific thinking' and 'conceptual change in science'
- **(Need Analysis)** Conducted in-depth 1:1 interviews with three high school seniors. Observed their process of solving problems related to the concept of force and acceleration.
- **Deriving design principles for Prototype Development**
 - Provide experiences that induce cognitive conflict and scientifically reconstruct preconceptions.
 - Support concretization of abstract physics concepts through visual and manipulative learning methods.
 - Implement step-by-step scaffolding to promote conceptual understanding and application before problem-solving.

