AI-Driven Interactive Hierarchical Concept Maps for Digital Learning Environments and Intelligent Textbooks

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Concept Maps

- Each node in a concept map represents a single idea or concept. These are connected by labeled arrows that define the relationships.
- They were introduced by Joseph Novak in the early 1970s and were inspired by the work of educational psychologist David Ausubel. The key idea is that learners grasp new concepts better when they can anchor them to what they already know.

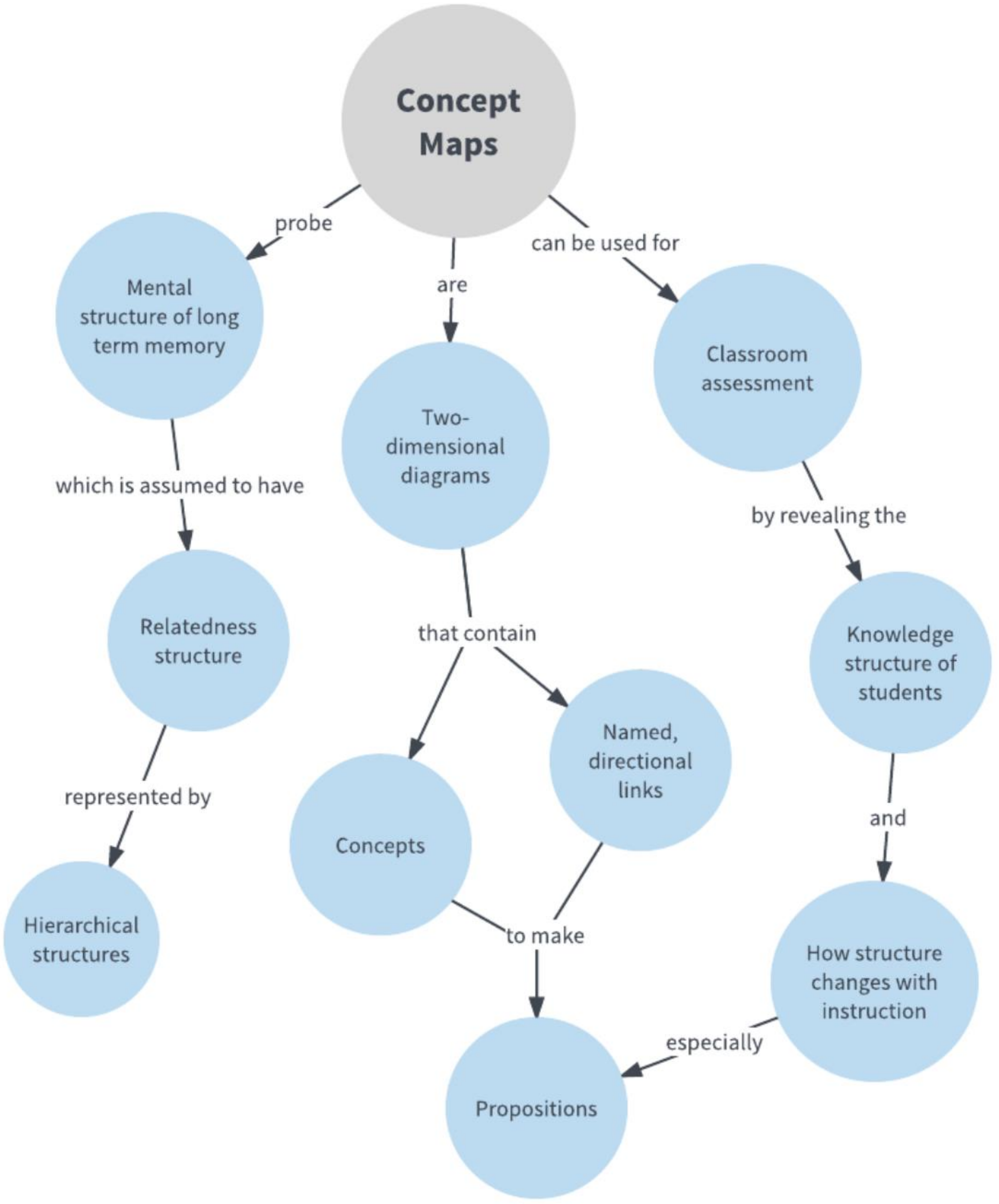
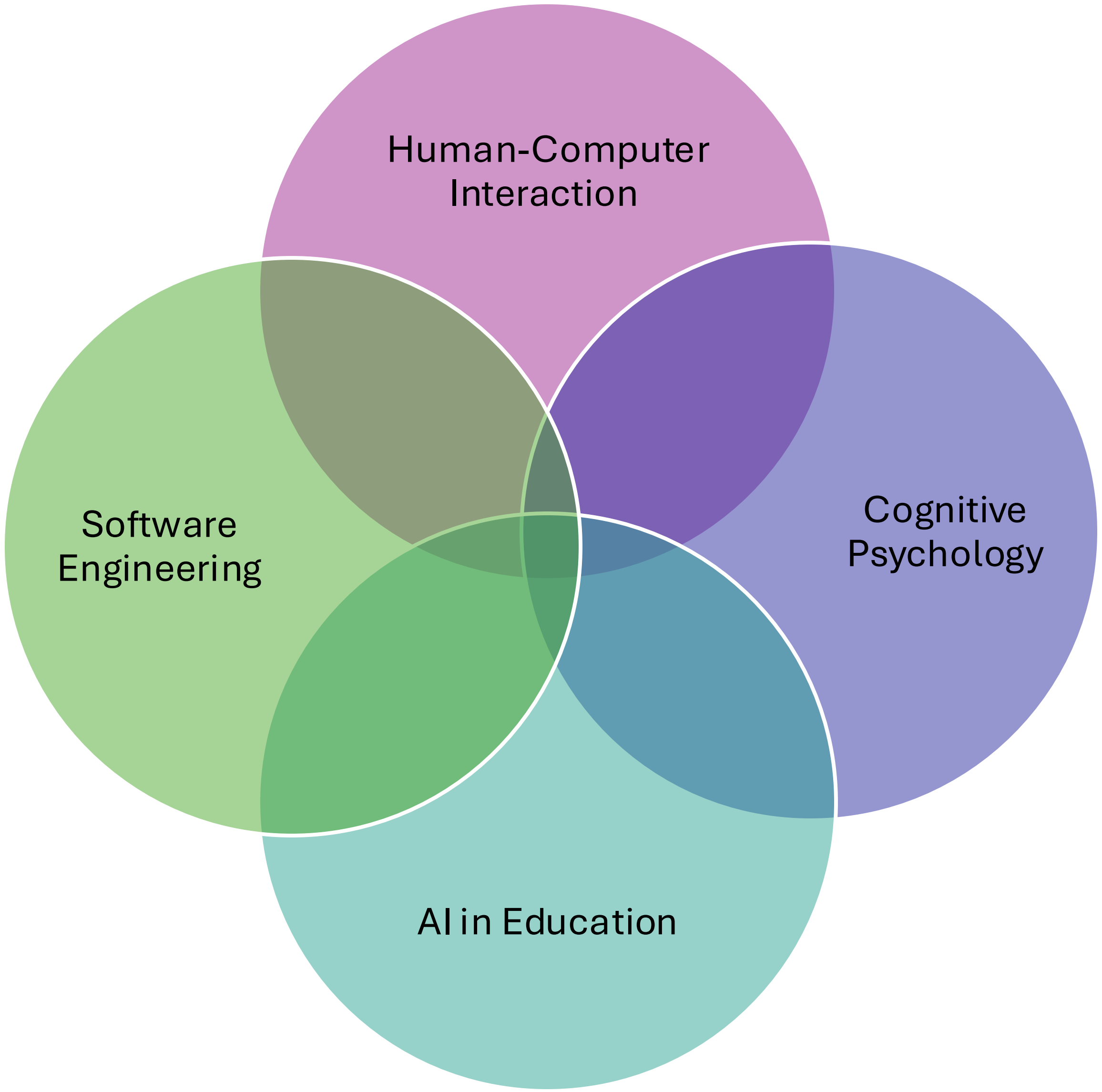


Image: https://www.lucidchart.com/pages/tutorial/concept-map

Graph-based knowledge representation

Approach(es)	Key Contributor(s)	Applied Area	Purpose
Semantic Networks & Conceptual Graphs	R. Quillian (1966), J. F. Sowa (1984)	AI, cognitive modeling, natural language understanding	Represent knowledge as interconnected concepts and relations; enable logical inference
Concept Maps & Mind Maps	J. D. Novak (1972), T. Buzan (1970s)	Education, learning science, personal productivity	Visualize and organize conceptual knowledge to support understanding and recall
Ontologies, RDF, OWL & Topic Maps	W3C (1999, 2004), ISO (2000)	Semantic Web, ontology modeling, linked data	Enable machine-readable web knowledge representation and reasoning
Knowledge Graphs & Property Graphs	Google (2012), Neo4j, Amazon Neptune and others	Search, recommendation systems, enterprise knowledge	Structure and link diverse data for semantic search, recommendations, and analytics

Research Areas



Digital Concept Maps in iTextbooks

1. Improved comprehension and retention	*Concept maps help visualize and organize knowledge, making it easier for students to understand and remember complex material.*	*Schroeder et al., 2018 [1], Bolatli & Bolatli, 2024 [13]*
2. More engaging and motivating learning experience	*Interactivity (clickable nodes) increases student motivation and encourages deeper exploration.*	*Elgendi & Shaffer, 2020 [14]; Schwab et al., 2017 [15]*
3. Support for self-regulated and personalized learning	*Learners can navigate topics in their own order and depth, promoting autonomy and exploration.*	*Barria-Pineda et al., 2017 [9], Schwab et al., 2017 [15] M. L. Hollingsworth, N. H. Narayanan [8]*
4. Efficient review and structured recall	*The hierarchical layout helps learners revisit materials with context and structure, not just isolated facts.*	*Bolatli & Bolatli, 2024 [13], Schwab et al., 2017 [15], Puntambekar et al., 2003 [6]*

Types of Concept maps

Teacher-created maps

- Teacher-created concept maps **present structured knowledge** and show key concept relationships. Paper versions are used in lectures and handouts, while digital maps offer interactivity and multimedia. They support content navigation and fit well into e-learning environments.

Student-created maps

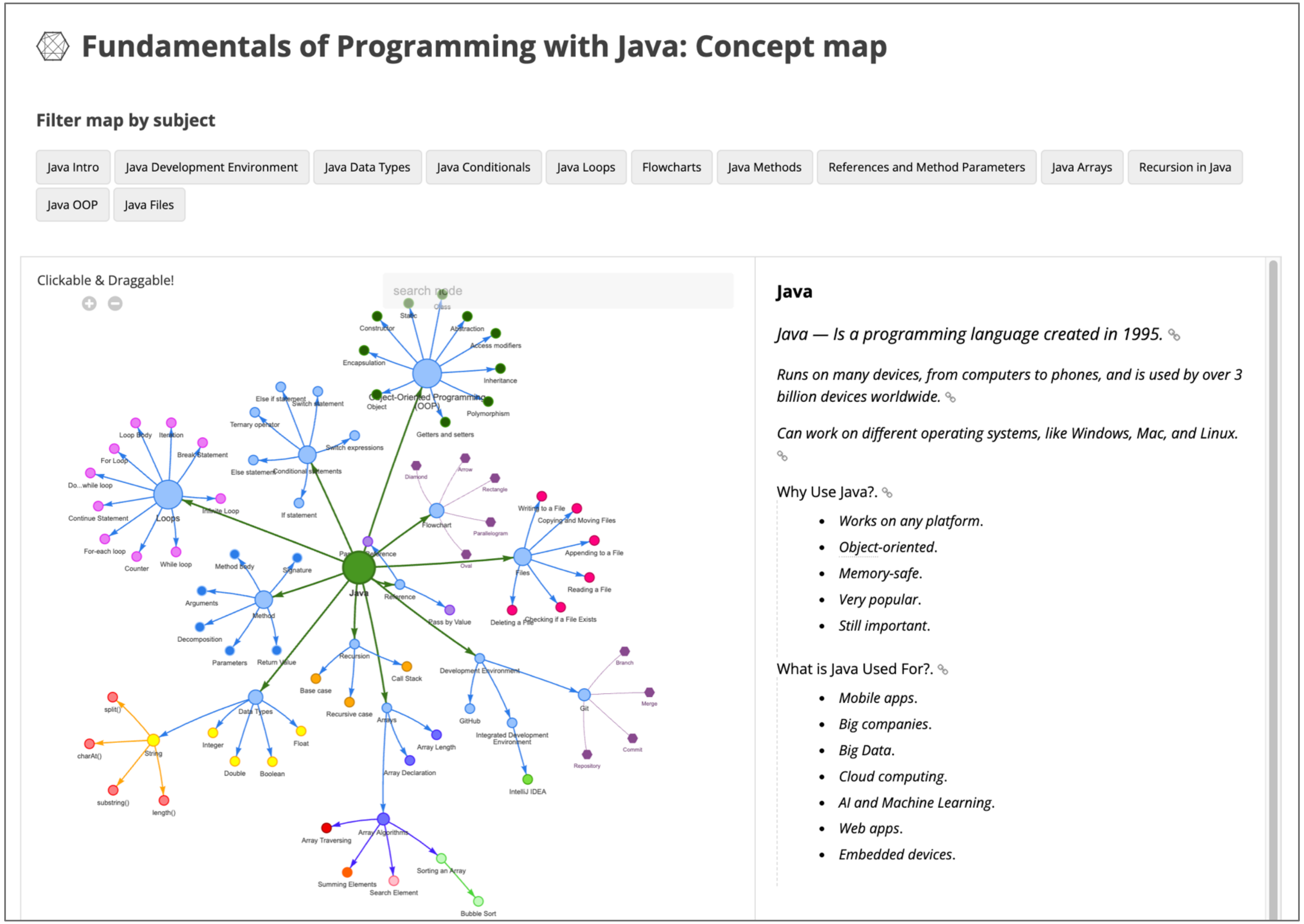
- Serve as a **tool for active learning** and **assessment**. Students build maps to articulate their understanding and reveal misconceptions.

Collaborative maps

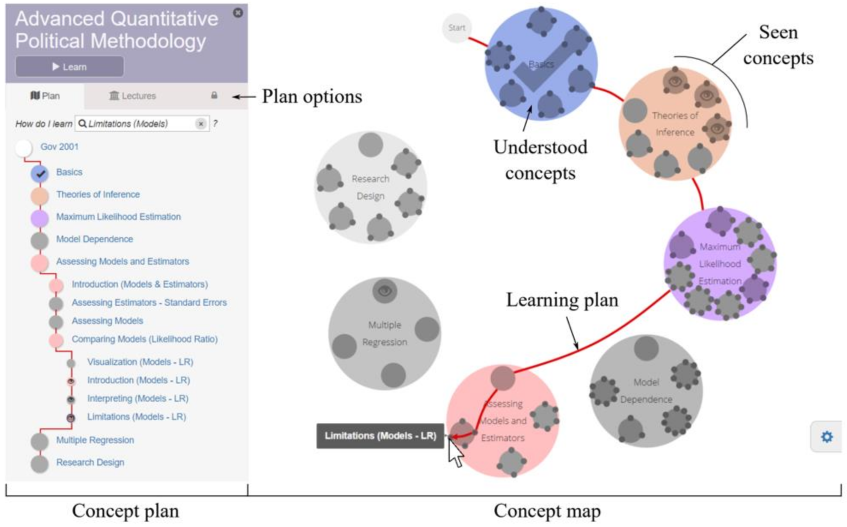
- Created by **groups of students**, fostering shared understanding, discussion, and co-construction of knowledge. Common in project-based or social constructivist settings.

Interactive Digital Concept Map Example

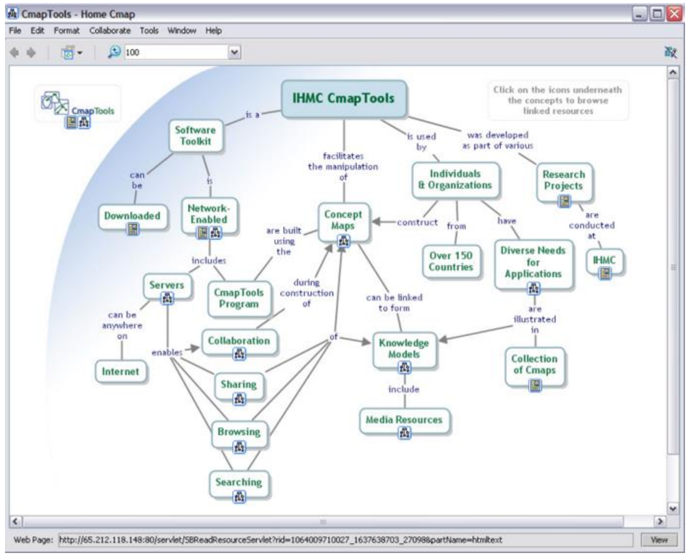
Author's example – Semantic Portal: http://semantic-portal.net/java-fundamentals/summary



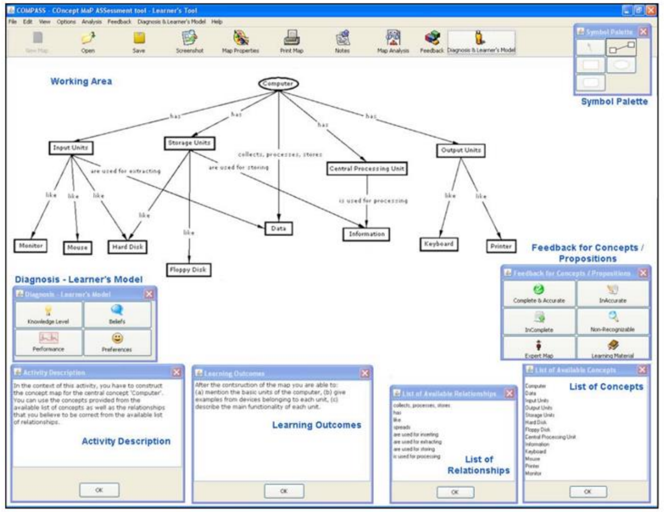
Digital Concept Map Examples



booc.io



CmapTools



COMPASS

1. Schwab, M., Strobelt, H., Tompkin, J., Fredericks, C., Huff, C., Higgins, D., … & Pfister, H. (2016). *booc.io: An education system with hierarchical concept maps and dynamic non-linear learning plans*. IEEE Transactions on Visualization and Computer Graphics, 23(1), 571–580. https://doi.org/10.1109/TVCG.2016.2598446
2. Gouli, E., Gogoulou, A., Alexopoulos, A., & Grigoriadou, M. (2008, September). *Exploiting COMPASS as a tool for teaching and learning*. In Proceedings of the 3rd International Conference on Concept Mapping (pp. 383–390).
3. Cañas, A. J., Hill, G., Carff, R., Suri, N., Lott, J., Gómez, G., Eskridge, T. C., Arroyo, M., & Carvajal, R. (2004). *CmapTools: A knowledge modeling and sharing environment*. In Proceedings of the First International Conference on Concept Mapping (Vol. 1, pp. 125–133).

Approaches to Automated Concept Map Generation

Approach	Key Techniques	References
Ontology/Knowledge-Base Driven	Generates concept maps from predefined semantic models or ontologies using structured relationships between concepts.	Dicheva & Dichev (2006) [11]; Kluga et al. (2019) [19] Tytenko (2019) [4]; Elgendi & Shaffer (2020) [14]; Shimada et al. (2017) [10]
Text/NLP-Based Extraction	Uses rule-based or statistical NLP techniques to extract concepts and links directly from educational texts or textbooks.	Wehnert et al. (2024) [20];
Hypermedia/Navigation-Based	Builds concept maps from structural metadata (e.g. course outlines or hyperlinks) to support interactive navigation in e-learning environments.	[6]; Schwab et al. (2017) [15]; Shimada et al. (2017) [10]; Puntambekar et al. (2003) [6]
Large Language Model (LLM)-Based	Applies LLMs (e.g. GPT) to extract and link key concepts from segmented e-book content based on deep language understanding.	Ma & Chen (2025) [18] Perin et al. (2023)

Shortcomings of Current LLM-Based Concept Map Generation Approaches

Perin et al. (2023)
Ma & Chen (2025)

1. **Lack of Interactivity**
   - Generated concept maps are presented as static structures without support for user interaction, exploration, or adaptive navigation.
2. **High Cost of Fine-Tuning**
   - Fine-tuning large language models [Perin et al. (2023)] is computationally expensive and time-consuming, limiting scalability and real-time adaptability in diverse educational settings.
3. **Absence of Hierarchical Structuring**
   - Maps are typically flat or shallow, lacking multi-level hierarchical views that are essential for reducing cognitive load and supporting structured knowledge exploration.
4. **Limited Human-in-the-Loop Refinement**
   - Both approaches provide minimal or no mechanisms for instructor oversight, manual correction, or iterative refinement of the generated maps.
5. **No Generation of Pedagogical Content**
   - Concept nodes are not accompanied by structured descriptions, examples, or learning materials, reducing the pedagogical utility of the maps in instructional contexts.
6. **Lack of Educational Validation and Usability Design**
   - Existing solutions do not address the use of such maps in real educational contexts, lack production-ready interactive UI/UX design, and overlook the cognitive overload caused by large, flat maps

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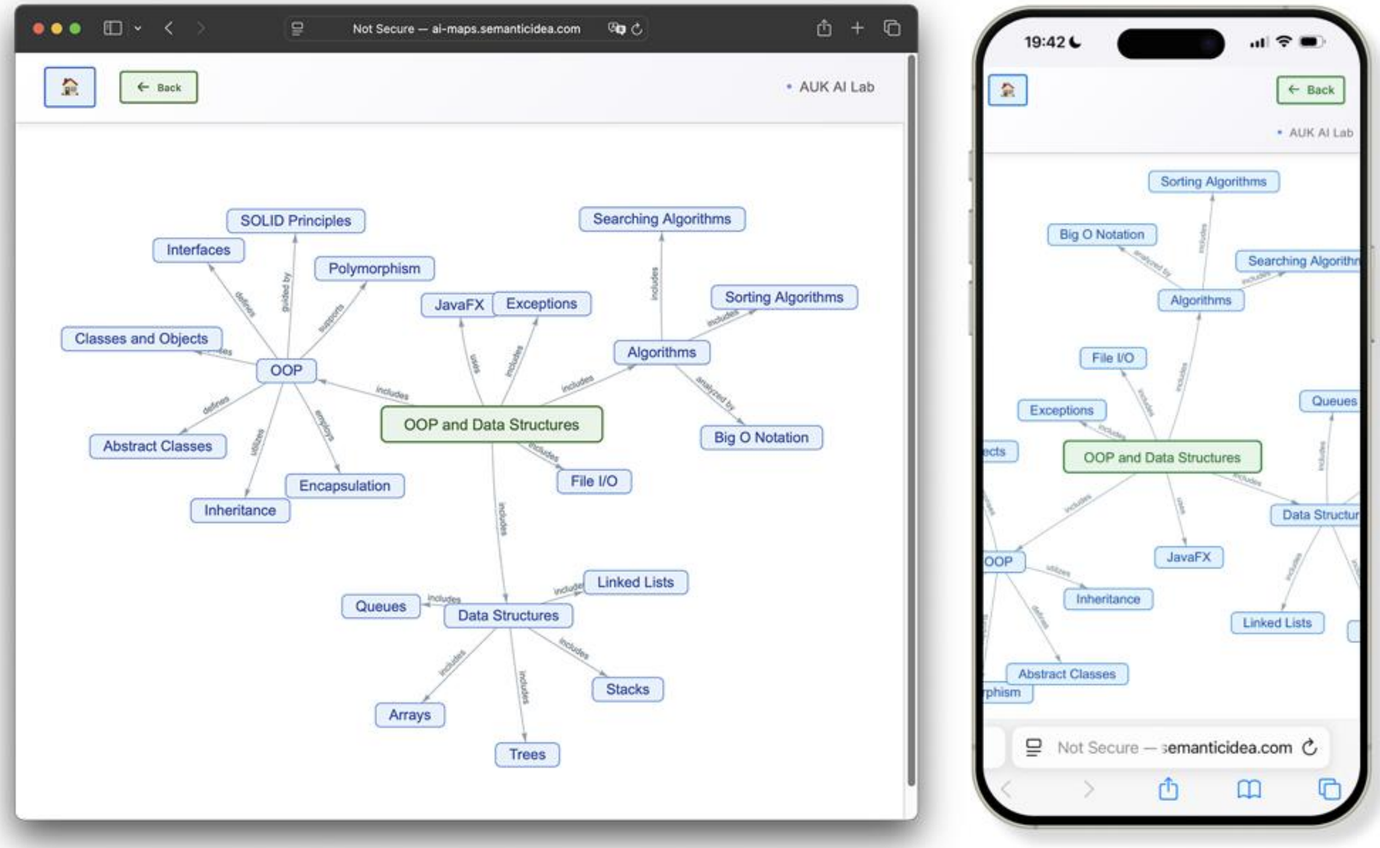
An AI-Driven Concept Map System



http://ai-maps.semanticidea.com/course/sdt101/course-map

Research Objectives

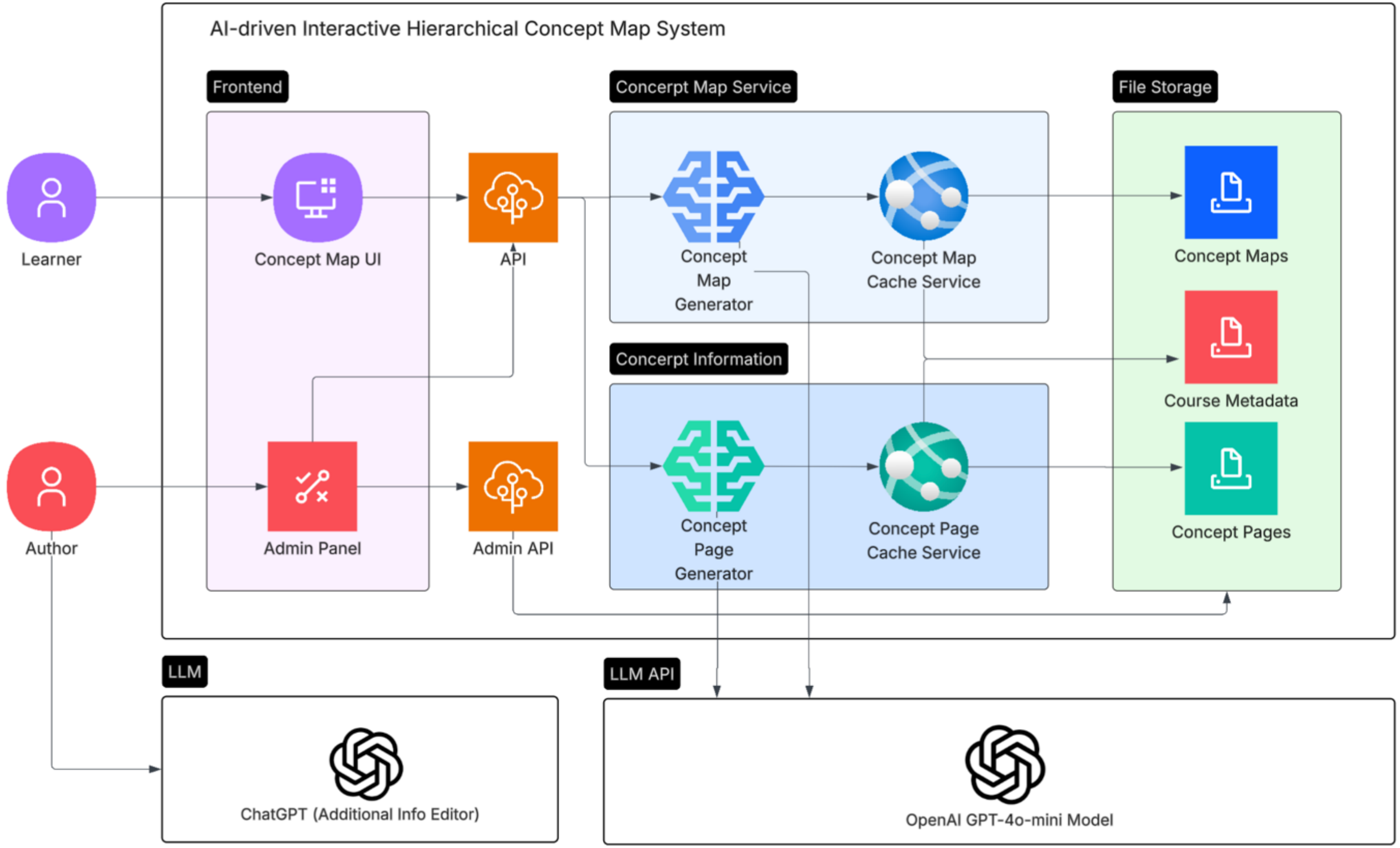
Objective 1: Enable Interactive Exploration
Develop AI-generated concept maps that support clickable navigation, drill-down views, and on-demand access to concept descriptions

Objective 2: Implement Hierarchical View and Navigation
Introduce multi-level mapping to reduce cognitive load and enhance structured understanding

Objective 3: Integrate Human-in-the-Loop Workflow
Allow instructors to refine, rephrase, and regenerate concept maps and node content

Objective 5: Evaluate Educational Effectiveness
Collect and analyze student feedback on usability, clarity, and learning impact to validate the system in real-world courses.

aimaps system design



- Frontend (Vis.js + JS/HTML)
- Backend (Python API)
- LLM Integration (GPT-4o-mini)
- Data Storage (Filesystem: JSON, txt)
- Deployment: AWS Elastic Beanstalk

Workflow Summary

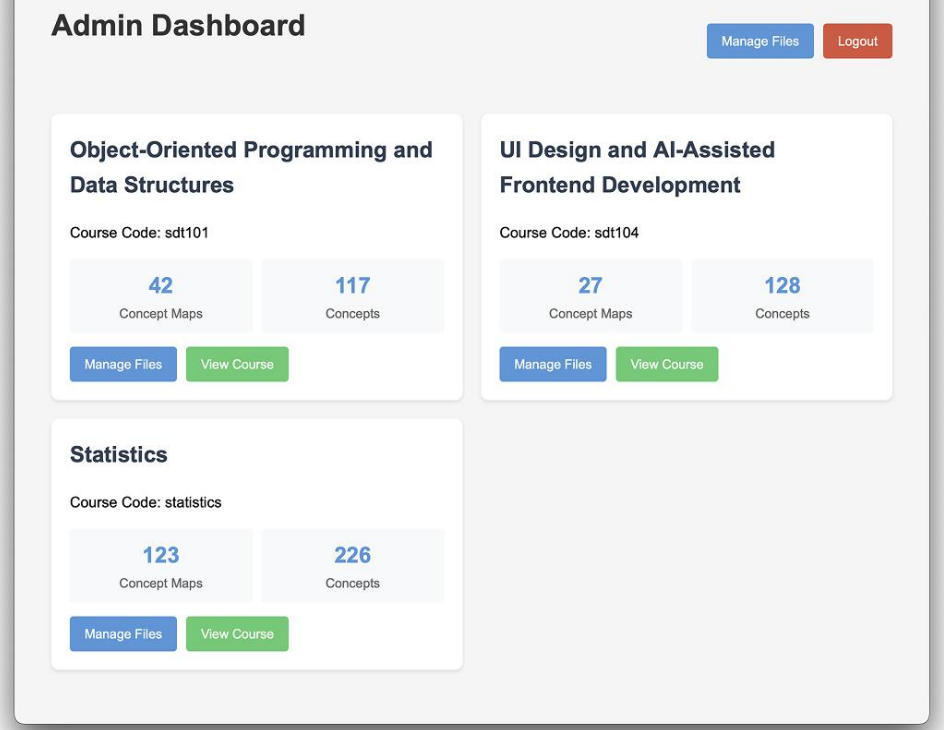
Instructor creates a course

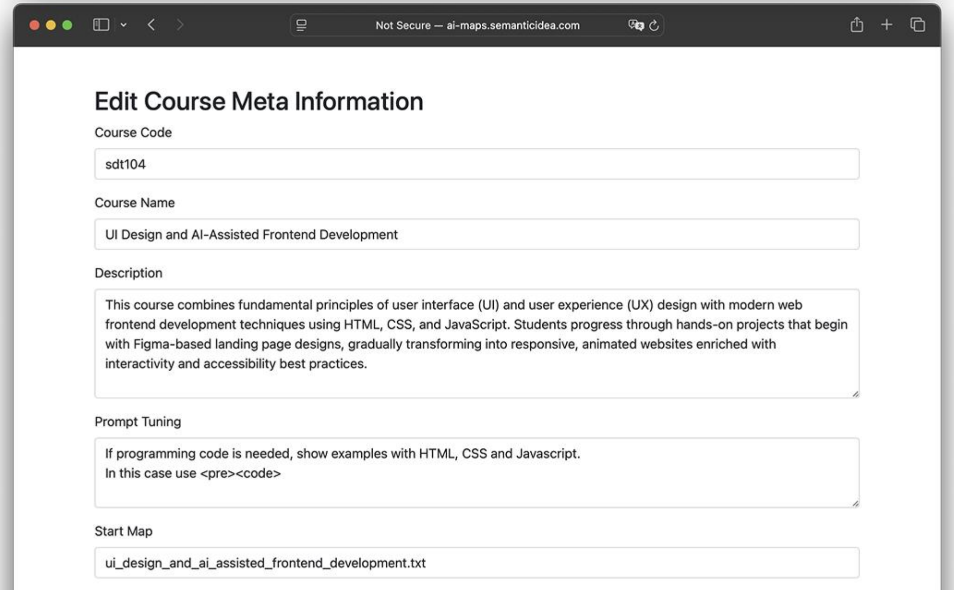
AI generates root map

Instructors refine nodes/pages (via LLMs)

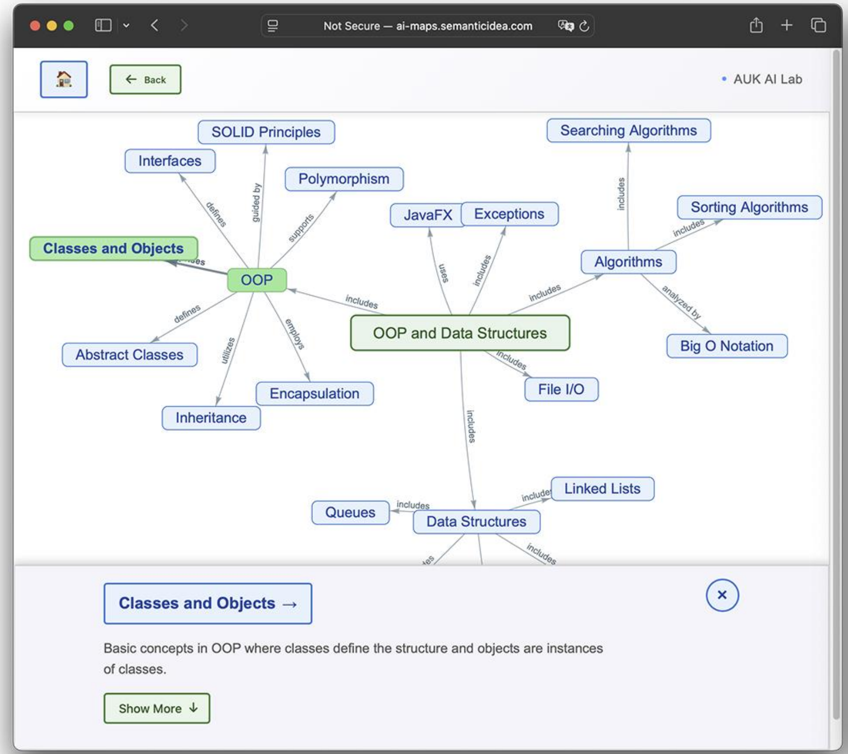
Drill-down to child maps

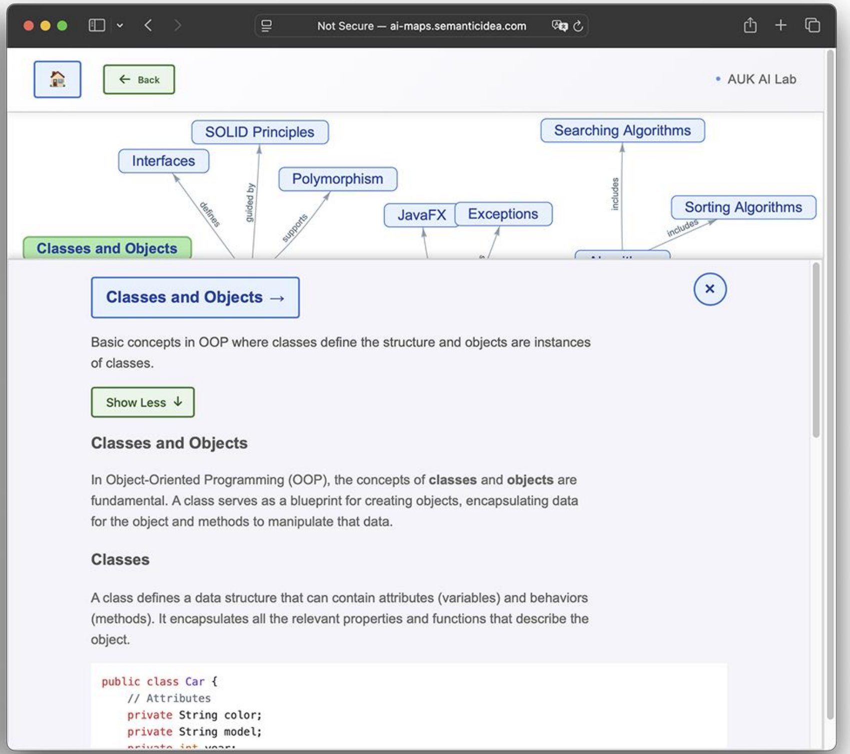
Infinite expansion via AI

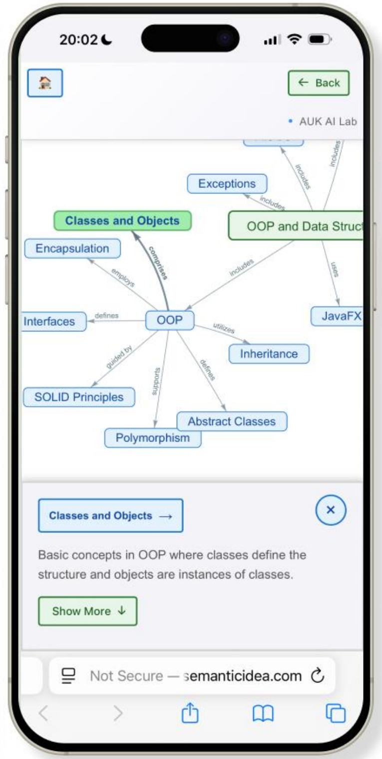


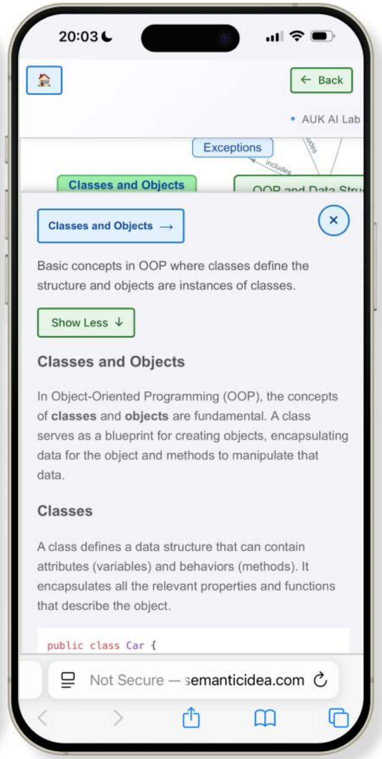


Interactive Nodes Provide Access to Concept Descriptions



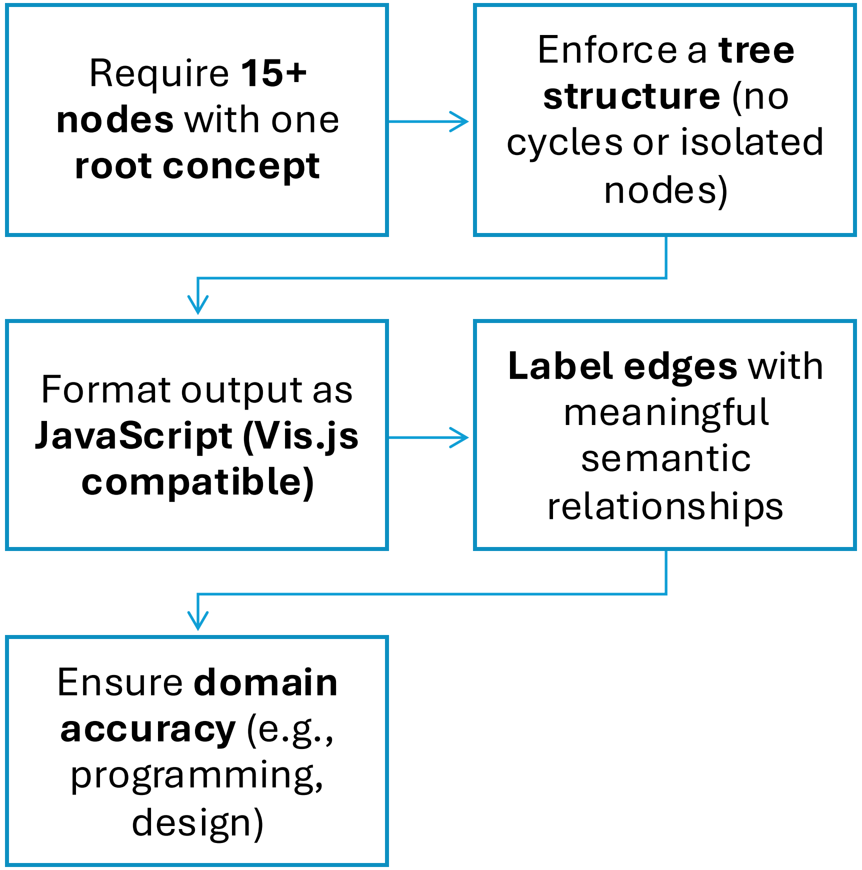




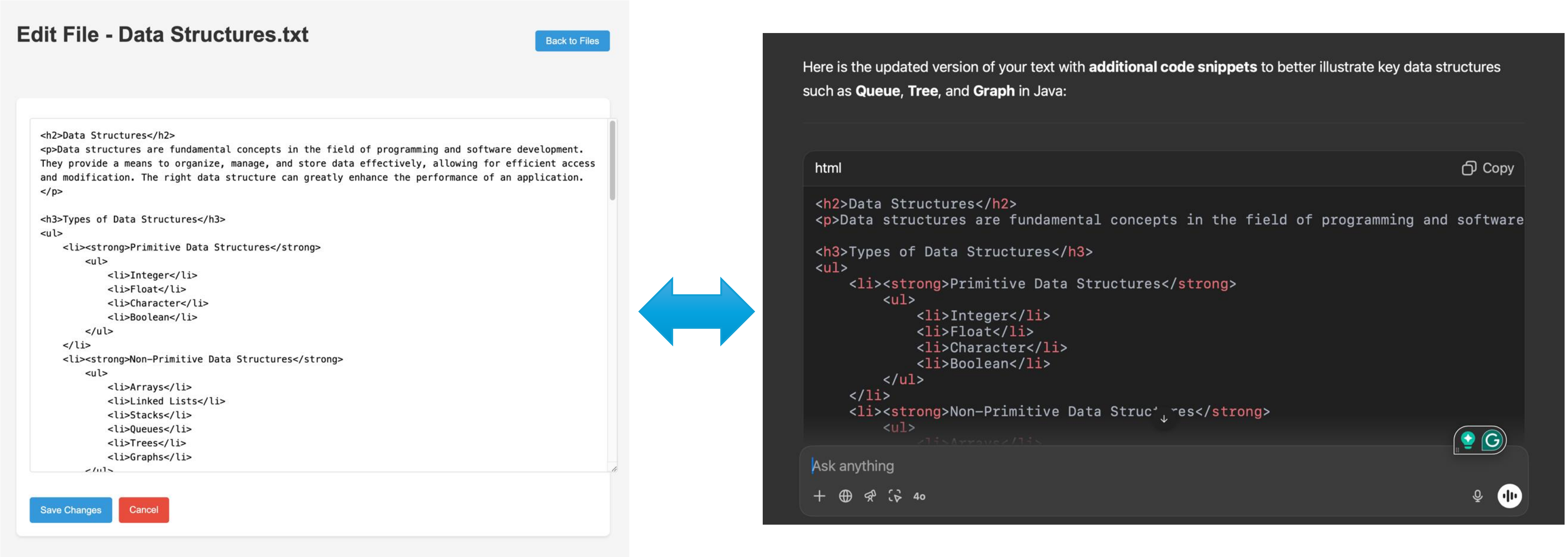


Generate and Navigate Hierarchical Subtopic Maps

Prompt Engineering for Concept Map Generation




```
prompt = f"""
    give me Concept Map for topic '{question}' {description} as data for Vis.js. {prompt_ad
    {programming_prompt_tuning}
    There must be not less than 15 nodes.
    There should be no dangling nodes. I want to have edges titled. Your answer must consis
    markdown.
    The graph must be acyclic and hierarchical. The graph must be tree-like.
    Do next:
    1)  Set the root concept.
    2)  Create Hierarchy of levels (general → specific).
    3)  Do Tree-like structure (no cycles or cross-links).
    4)  Make two-level mind map and present it in the format of Vis.js.

    Format Example for topic AI:

    // Define nodes
    const nodes = new vis.DataSet([
        // Root
        {{ id: 1, label: "JavaScript", description: "Programming language for creating dyna

        // First-level topics
        {{ id: 2, label: "Syntax and Variables", description: "The rules for writing JavaSc
        {{ id: 3, label: "Functions and Scope", description: "Reusable blocks of logic and
        {{ id: 4, label: "Arrays and Objects", description: "Data structures for grouping v
        {{ id: 5, label: "DOM Manipulation", description: "Changing content and structure o
        {{ id: 6, label: "Advanced JavaScript Concepts", description: "More powerful constr
        behavior." }},

        // Syntax and Variables children
        {{ id: 11, label: "let, const, var", description: "Different ways to declare variab
        {{ id: 12, label: "Data types", description: "Primitive and complex types like stri
        {{ id: 13, label: "Variable scope and hoisting", description: "Rules determining vi
        declarations." }},

        // Functions and Scope children
        {{ id: 14, label: "Function declarations vs expressions", description: "Two styles
        {{ id: 15, label: "Scope chain", description: "Hierarchical access to variables." }
        {{ id: 16, label: "Parameters and return values", description: "Passing data to and
```



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External LLM

Instructor-Guided Human-in-the-Loop Refinement

Case Studies

AI-powered interactive concept maps were piloted in two first-year undergraduate courses at American University Kyiv.

Purpose: Evaluate the effectiveness, usability, and student perception of system-generated maps for course review and conceptual understanding.

Course 1: SDT 101 Object-Oriented Programming & Data Structures

42 maps, 117 concept pages

24 student responses

Course 2: SDT 104 UI Design and AI-assisted Frontend Dev

27 maps, 128 pages

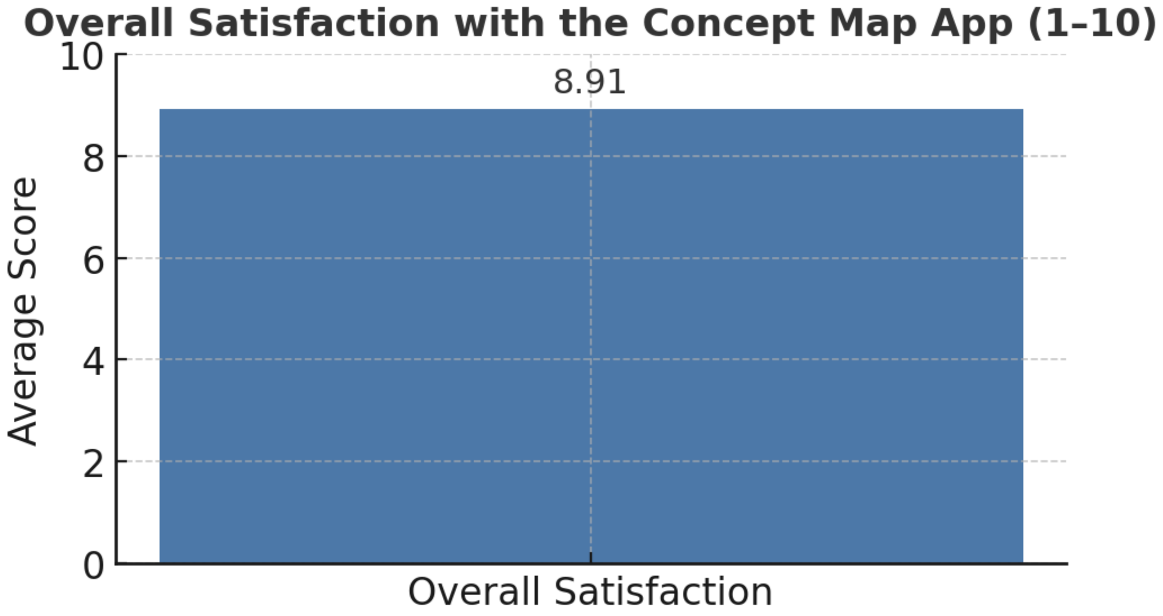
11 student responses

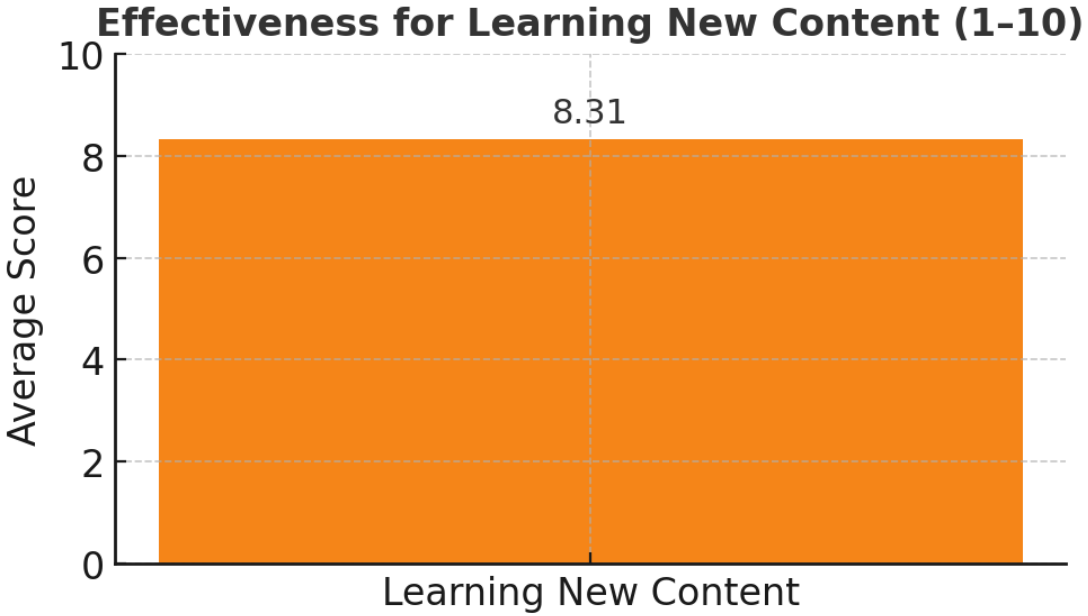
Course instructors: Roman Tymoshuk, Andrii Tsabanov, Ivan Danilov, Sergiy Tytenko

Survey Questions

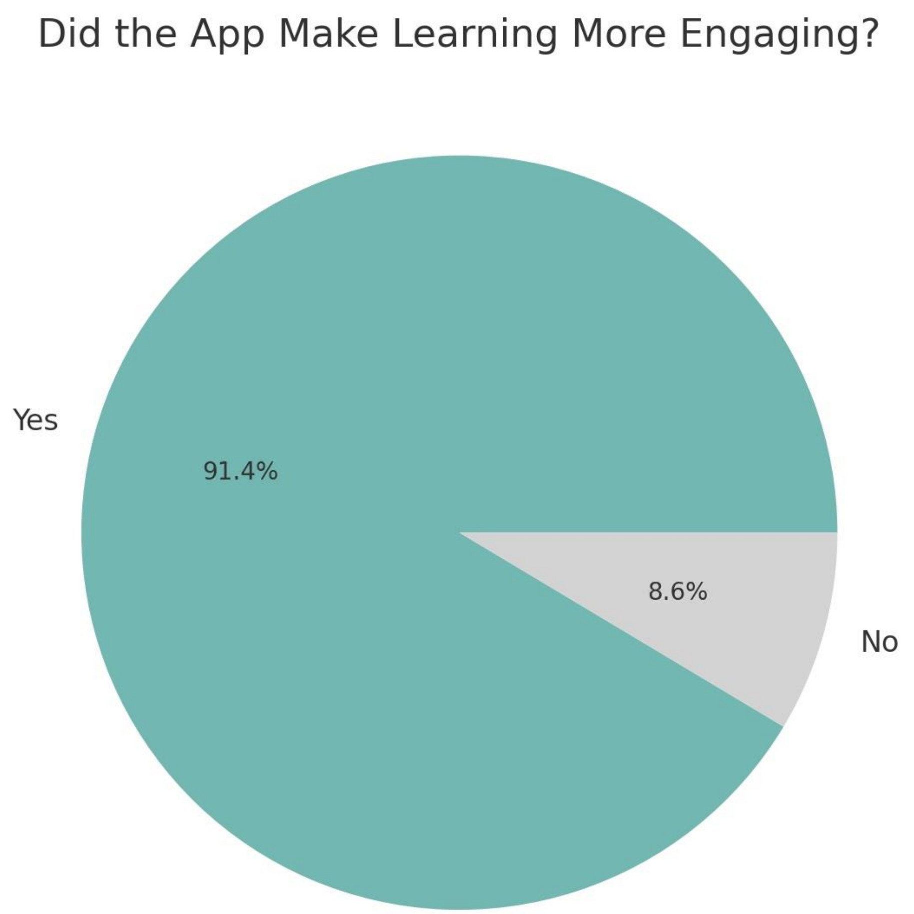
Satisfaction (1–10)	• *“How satisfied are you with your learning experience using the concept map app?”*
Engagement and Enjoyment	• *“Did the app make learning more engaging or enjoyable?”*
Preferred Review Method *(Text, Interactive Concept Maps, Both)*	• *“Which format was more effective for reviewing and recalling course content?”*
Effectiveness for Learning New Content (1–10)	• *“How effective is the Concept Map tool for learning new content?”*
Usefulness of Drill-Down Navigation	• *“Was the ability to click on a concept and explore subtopics useful?”*
Most Useful Features	• *“What features of the app did you find most useful?”*
Suggestions for Improvement	• *“What features do you think should be improved or added?”*

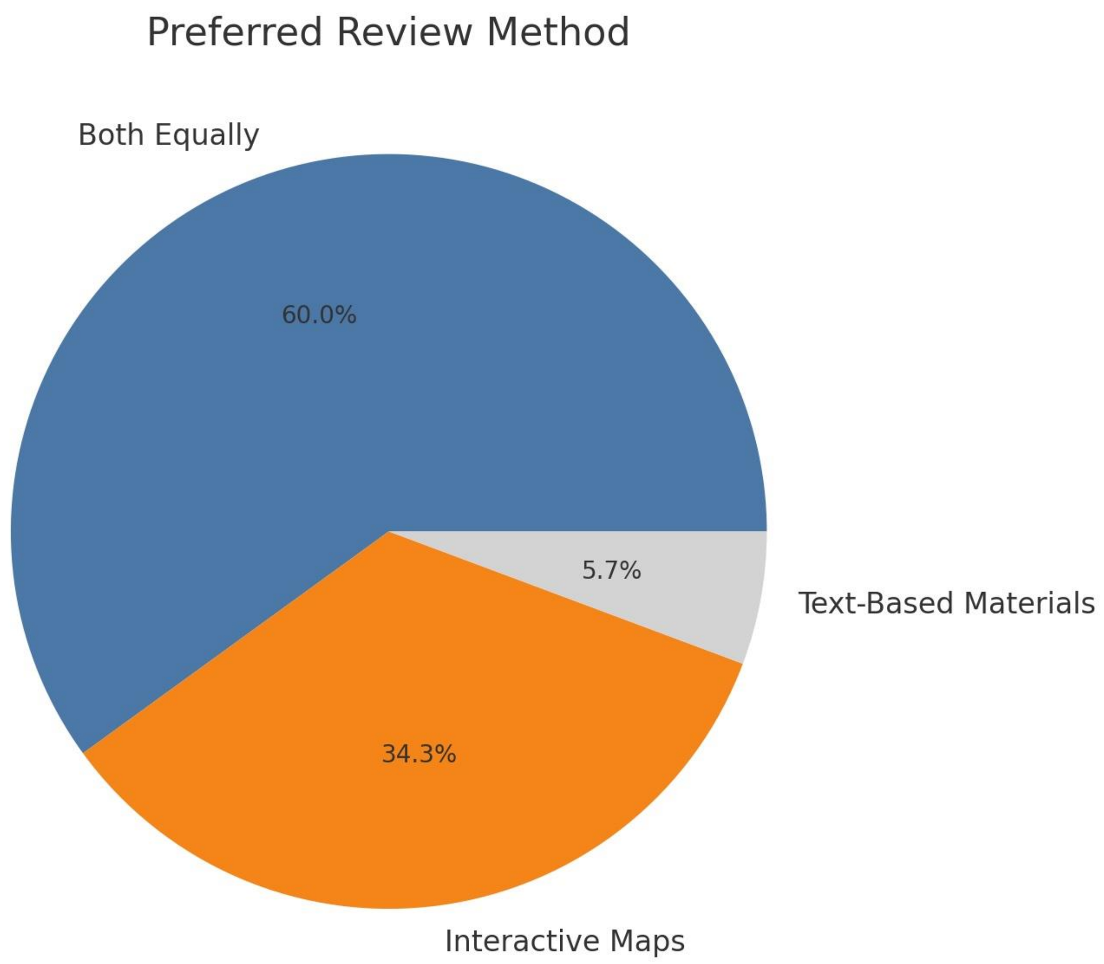
Satisfaction and Perception of Effectiveness for Learning New Content





Engagement and Preferred Review Method

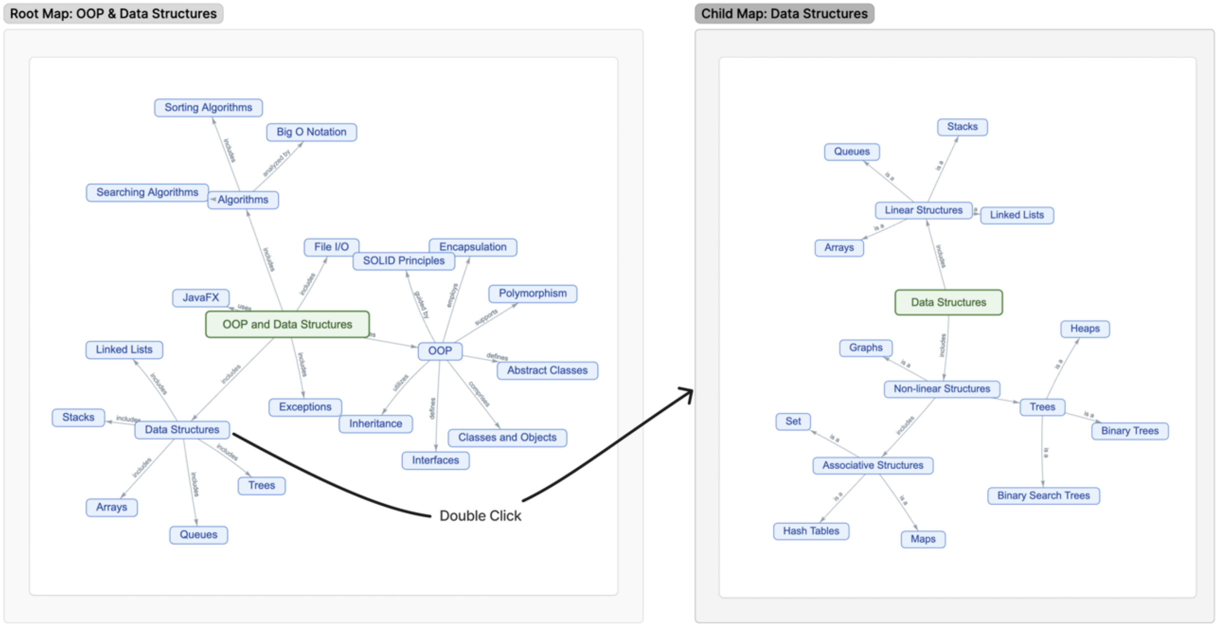




100%

Usefulness of Drill-Down Navigation

- 100% of students confirmed that the ability to click on concept names and navigate through nested maps was helpful, reinforcing the effectiveness of the interactive hierarchical concept map approach.



Most Valued Features – Student Feedback

Clickability & Depth Navigation (11 students)

"I can click and read info about a topic or go further and find more details."

"Double-clicking to go to a deeper level of the topic."

Visual Structure & Concept Relationships (9 students)

"It is interactive, has nice and clear structure."

"It's easy to see which concepts are related — this helps me memorize."

"All topics you need are in one place — great for reviewing."

Suggestions for Improvement – Student Feedback

No Changes Needed (7 students)	“Everything is perfect”, “Nothing to improve”
UI Design (8 students)	Visual tweaks, better layout, dark theme
Interaction (6 students)	Smoother graph navigation, remove “Show more”
Additional Features	Collaboration, comments, quizzes, Q&A

Current Approach Limitations

Metadata-Based Generation:

The first version of concept map materials is generated directly by the LLM, based solely on the course title and metadata, without explicit input materials.

This approach works well for traditional or well-established subjects, but may become a bottleneck when applied to more specialized or rapidly evolving domains where nuanced or cutting-edge knowledge is required.

Infinite Drill-Down Navigation

Disorientation: Users may get lost in nested layers of information, losing track of the main structure.

Topic Drift: Without sufficient contextual constraints, the LLM may generate content that diverges from the core subject area, leading to unintended transitions into unrelated domains.

Submap Consistency

Since submaps are generated automatically and independently, structural inconsistency may occur. A concept node that appears in multiple maps might lead to different or incomplete subgraphs, causing missing child nodes in some contexts or breaks in conceptual continuity.

Future work

Concept Map Generation from Course Materials

Integrate wide context window and RAG methods to improve concept map accuracy using actual course materials.

Instructor-Centric Editing Tools

Integrate concept map and page refinement directly into the instructor UI for seamless, in-platform editing.

Enhanced Admin Dashboard

Expand dashboard functionality for easier course management and map customization.

Cross-Domain Validation

Evaluate the system's effectiveness in broader subjects such as mathematics, management, and postgraduate software engineering.

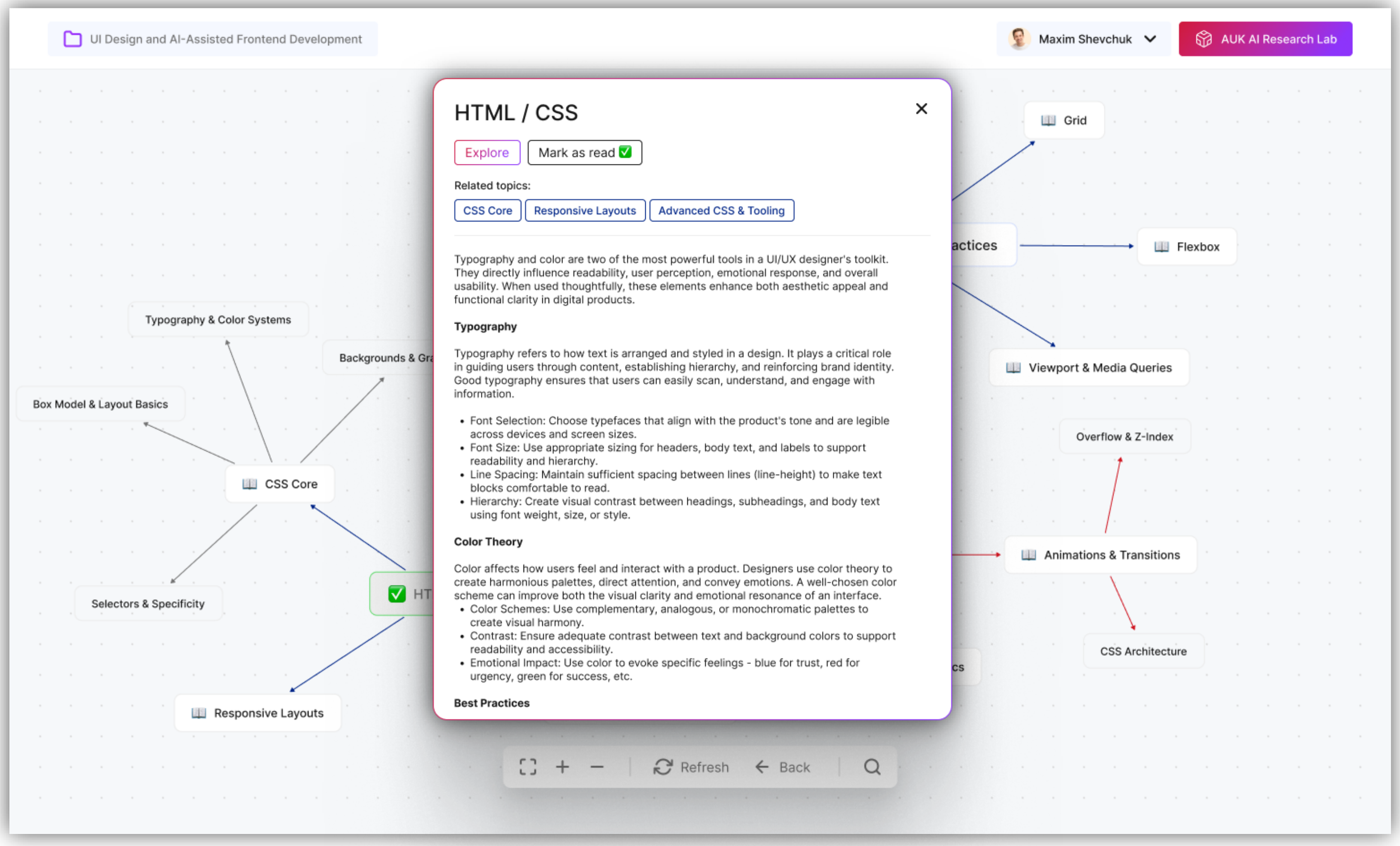
Agentic AI Workflows

Explore AI agents capable of coordinating multi-step concept map generation and iterative refinement.

New Version of the System – KnowledgeMaps AI

AI Research Lab Team

- Sergiy Tytenko
- Serhii Artymovych
- Vladyslav Saniuk
- Andrii Tsabanov
- Yehor Papkovych
- Oleksandr Vasyliev
- Mariia Zhak



We invite instructors to pilot the new version of the interactive concept map system as part of their courses starting from the upcoming fall semester.

Conclusions

1. **AI-powered interactive concept maps** improve students' ability to review and navigate course content more effectively than traditional materials.
2. **The aimaps system** addresses limitations of current LLM-generated maps:
   - Adds interactivity and hierarchical structure
   - Provides pedagogical content per node
   - Enables instructor-led refinement
3. **Student feedback confirms**:
   - High satisfaction and engagement
   - Strong preference for drill-down navigation
   - Concept maps seen as more effective or equally effective compared to text
4. **Experimental findings** support the **pedagogical value** of concept maps in computer science education.
5. **The new version KnowledgeMaps AI** introduces refined instructor tools, improved UI, and capabilities for content generation based on uploaded course materials laying the foundation for broader academic use.

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