

USING KNOWLEDGE GRAPHS TO STRUCTURE AND SUMMARIZE INSTRUCTION IN STEM CLASSROOMS

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Abstract

In the context of 21st-century STEM education, knowledge graphs (KGs) have emerged as powerful pedagogical tools for structuring, visualizing, and summarizing complex instructional content. These structured visual representations map relationships between concepts, enabling learners to navigate abstract domains such as mathematics and computer science with greater clarity and depth. Contemporary pedagogical models position knowledge graphs not only as cognitive scaffolds but also as epistemological organizers that reflect the internal logic of STEM disciplines, thereby supporting meaningful learning and disciplinary fluency. A pilot study conducted at Kaye College of Education and Achva Academic College in Israel examined the integration of knowledge graphs into STEM instruction. At Kaye, the focus was on pre-service secondary school teacher education (N=5), where graphs were used to support pedagogical analysis and conceptual development in a Numerical Analysis course. At Achva, knowledge graphs were embedded in a Data Structures course, helping first-year undergraduate computer science students (N=9) visualize algorithmic relationships and consolidate their learning during summary lectures. Across both institutions, the instructional model emphasized four instructional principles derived from research on meaningful learning and visual knowledge representations: 1) Conceptual Organization – Structuring content around central ideas and their interrelations. 2) Cognitive Visibility – Making abstract relationships tangible through visual mapping. 3) Comparative Reasoning – Highlighting similarities and differences between concepts. 4) Reflective Integration – Using graphs to summarize and reinterpret knowledge. Preliminary findings from both colleges indicate positive effects on students' engagement, understanding, and perceived ability to articulate conceptual connections. Students reported that knowledge graphs clarified abstract ideas and supported deeper reflection. From the instructor-researcher perspective, the graphs appeared to support more focused classroom dialogue by providing a shared reference for comparison. Knowledge graphs, therefore, offer a promising framework for organizing and summarizing instruction in STEM classrooms.

Keywords: Knowledge graphs, STEM education, epistemic representations, comparative reasoning, meaningful learning.

1. Introduction

In STEM education, students and instructors frequently encounter knowledge domains whose internal organization is not immediately evident. Courses in mathematics and computer science are typically presented as sequences of topics. In contrast, the relational structures that confer coherence upon the discipline, including dependencies, abstractions, implementation hierarchies, and alternative solution paths, often remain implicit. Consequently, learners may acquire isolated techniques without developing an integrated understanding of how ideas interrelate, thereby constraining transfer and disciplinary reasoning (Ausubel, 1968; Marton, 2015). One way to address this challenge is to make the structure of the subject explicit through visual representations such as concept maps. Research indicates that making conceptual relationships visible improves integration and achievement in STEM (Wang et al., 2025).

Knowledge graphs (KGs) extend this idea by representing entities and explicitly typed relations grounded in a semantic schema or ontology (Gruber, 1993; Hogan et al., 2021; Paulheim, 2017). Unlike informal diagrams, they encode types of concepts and relations in ways that support both human interpretation and computational processing, making hierarchies, dependencies, alternatives, and constraints explicit and open to inspection (Berners-Lee, Hendler, & Lassila, 2001). In educational contexts, such graph-structured representations can expose and reorganize the conceptual architecture of a domain, enabling learners to engage more directly with relationships among ideas. Recent reviews indicate that knowledge graph approaches can support curriculum design, concept instruction, and personalized learning in higher education (Abu-Salih & Alotaibi, 2024; Qu, Li, Wong, Wu, & Liu, 2024). In learning technologies, KGs are also used to model domain knowledge and learner state for adaptive feedback and

prerequisite tracing (Dang et al., 2021; Wang, Burke, Poulos, Iqbal, & Lee, 2024), consistent with research emphasizing that well-structured knowledge representations support transfer and problem solving (Bransford, Brown, & Cocking, 2000).

Although KGs are formally graphs in the mathematical sense, the present study does not treat them primarily as computational structures. Rather, they are employed as structured pedagogical representations that make conceptual relationships explicit within classroom practice. In this respect, they resemble concept maps in their instructional function while maintaining explicitly typed relations characteristic of knowledge graph representations. This relational explicitness enables KGs to function not only as visual summaries but also as shared classroom artefacts that support comparison, explanation, and disciplinary reasoning. However, much of the existing literature positions KGs primarily as computational infrastructures or instructional planning tools, and far less attention has been given to their role as participatory classroom artefacts that shape discourse, comparison, and disciplinary reasoning during instruction.

Consequently, the present study investigates how instructor-constructed KGs function in regular STEM classrooms as epistemic representations that make disciplinary structure explicit and accessible to inquiry. We report a mixed-methods pilot study conducted at two Israeli institutions, Kaye College of Education and Achva Academic College, in which KGs were integrated into a Numerical Analysis course for pre-service mathematics teachers and a Data Structures course for computer science undergraduates. The instructional design was guided by four core principles informed by research on meaningful learning, conceptual organization, and visual knowledge representations: conceptual organization (structuring content around central ideas and their interrelations); cognitive visibility (making abstract relationships tangible through visual mapping); comparative reasoning (highlighting similarities and differences between concepts); and reflective integration (using graphs to summarize and reinterpret knowledge) (Ausubel, 1968; Novak & Gowin, 1984; Ainsworth, 2006; Linn, 2006).

The study asked: (1) How do students perceive instructor-constructed KGs as tools for organizing disciplinary knowledge? (2) How do knowledge graph representations support students in articulating conceptual relationships and comparing alternative solutions?

2. Research design and methodology

2.1. Methodology and context

This study employed a mixed-methods convergent parallel design (Creswell & Plano Clark, 2017). Qualitative and quantitative data were collected concurrently, analysed separately, and integrated during interpretation. The quantitative strand consisted of a researcher-developed questionnaire comprising 27 Likert-type items rated on a five-point scale (1 = very little extent, 5 = very great extent). The qualitative strand consisted of open-ended questionnaire responses analysed using thematic analysis, focusing on how participants described the role of KGs in organizing concepts and supporting comparison (Shkedi, 2011).

The study involved two sources of evidence: (a) the instructor-constructed knowledge graphs used as pedagogical artefacts; and (b) a questionnaire administered during a summary lecture in each course, including both structured Likert-type items and open-ended questions focusing on students' experiences with the knowledge graph activities.

The first context was a Numerical Analysis course for third-year pre-service secondary school mathematics teachers (N=5) at Kaye College of Education, a teacher-education institution in Israel. The course introduces foundational numerical methods (e.g., root-finding, numerical integration, iterative methods) and the associated concepts of complexity, convergence, error, and stability. It enrolls advanced undergraduates preparing for secondary school teaching. The second context was a Data Structures course for first-year computer science undergraduates (N=9) at Achva Academic College, which covered asymptotic analysis, basic algorithms (searching and sorting), linear data structures (linked lists, stacks, queues), and non-linear data structures (graphs, trees, heaps). In both settings, the instructor was a member of the research team and designed knowledge graph-based activities as part of regular course instruction.

The study was conducted in accordance with international ethical standards. The questionnaire was anonymous, ethical approval was obtained from the Institutional Ethics Committees of Achva Academic College and Kaye College of Education, and all participants provided informed consent.

2.2. Research design

In both courses, instructor-constructed knowledge graphs (KGs) were integrated into planned lectures (a summary lecture in Numerical Analysis; recurring topic lectures in Data Structures) to make the relationships among key course concepts explicit. The graphs were constructed based on the conceptual structure of the course syllabus and the instructional materials used in teaching, including lecture notes and the central topics addressed in the lectures. Content validity was established through expert review by two computer science and mathematics education experts, and minor revisions were implemented to improve clarity and precision. Concepts were selected to represent core entities within each unit (e.g., numerical methods, data structures, and abstract data types), while labeled relations represented meaningful

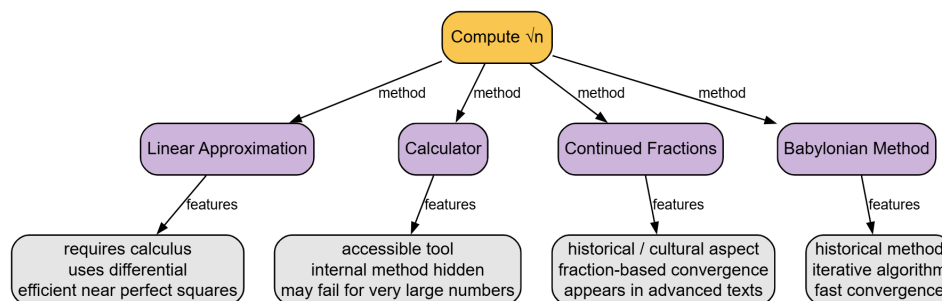
disciplinary connections such as *implements*, *depends on*, *generalizes*, and *is-a* (Zhitomirsky-Geffet & Avidan, 2022).

The design of the graphs was guided by four instructional principles underlying the study. Conceptual organization guided the selection of central concepts and their hierarchical relationships. Cognitive visibility shaped the visual representation of dependencies and conceptual groupings. Comparative reasoning was supported by including relations that allowed different methods, structures, or approaches to be examined within the same representation. Reflective integration was addressed by connecting graphs across units to support a broader conceptual view of the course.

In the Numerical Analysis course, a global KG was presented during a summary lecture to represent conceptual relationships among major course topics, including convergence, accuracy, stability, and computational cost. The graph served as a visual framework for discussing how different numerical methods relate to one another and for comparing alternative approaches to solving numerical problems. During the lecture, students were invited to interpret the graph, identify conceptual dependencies between methods, and discuss similarities and differences among numerical methods.

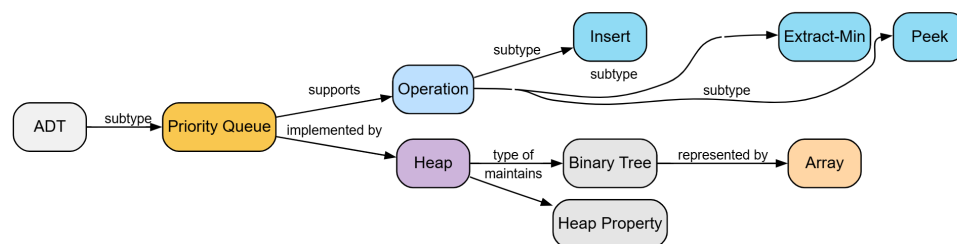
The knowledge graphs were created using *Graphviz*, an open-source graph visualization software, with structures defined using the DOT graph description language.

Figure 1. Part of the global KG from the Numerical Analysis summary lecture, showing a comparison between four methods of computing the square root (irrational number) of a natural number.



In the Data Structures course, instructor-constructed KGs were integrated throughout, with each graph corresponding to a major topic in the syllabus. These graphs represented relationships between abstract data types, concrete data structures, and associated operations. At the beginning of each thematic unit, a local KG was introduced to provide an overview of the topic's conceptual organization.

Figure 2. Local unit KG from Data Structures lecture, showing an abstract data type - priority queue.



As instruction progressed, new concepts were incorporated into the graphs, and the relationships among them were discussed explicitly in class. At the end of each unit, the local graphs were connected to form an evolving course-level representation. This cumulative graph presented during the summary lecture allowed students to situate newly introduced concepts within a broader conceptual framework and to support discussion of implementation choices and complexity trade-offs across different data structures.

3. Findings and discussion

Quantitative analysis was based on Likert-type items assessing perceived clarity, structural organization of course content, support for comparison, and the overall usefulness of the graphs for understanding the course material. Due to the small sample size, quantitative results are presented using descriptive statistics and interpreted alongside the qualitative findings. Figures 3–4 provide illustrative distributions: most participants reported limited prior familiarity with KGs, and students in both courses rated the visual presentation of a KG as more beneficial than presenting concepts in written text.

Figure 3. Responses for the following question, both courses. Extent of prior familiarity with a knowledge graph before the course.

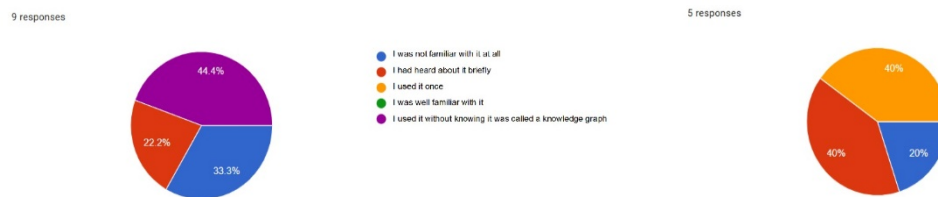
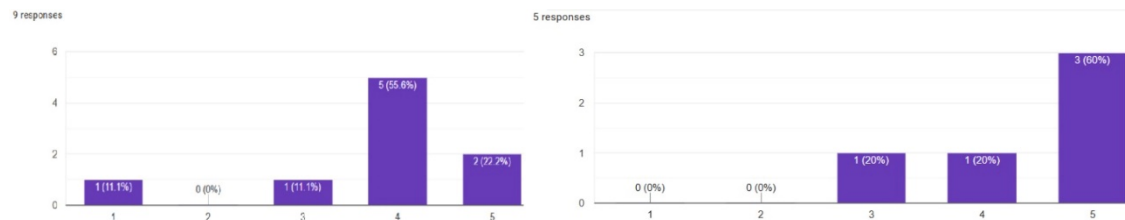


Figure 4. Responses for the following question, both courses. To what extent is a visual presentation of a knowledge graph in lectures and in the summary session more beneficial than presenting concepts in written text?



Qualitative analysis of open-ended questionnaire responses used thematic analysis to identify recurring perceptions of how KGs supported understanding, comparison, and integration (Shkedi, 2011).

Across both the Numerical Analysis and Data Structures courses, students reported that the KGs supported their understanding of complex relationships among course concepts and helped them integrate material more holistically. In the Numerical Analysis course, participants described the graphs as tools for “seeing the big picture”. In response to the question: “*What, in your opinion, is the main added value of using a KG in a Numerical Analysis course?*” one participant wrote:

“The ability to organize knowledge in a hierarchical and interconnected way, making it easier to understand the dependencies between topics.”

The visual structure also helped students identify which ideas served as prerequisites and which represented more advanced or derived concepts, thereby supporting both study planning and exam revision. From the instructor-researcher perspective, the graphs served as shared reference points during whole-class discussions, particularly when comparing numerical methods or examining error behavior and convergence conditions.

Similar patterns emerged in the Data Structures course. Students indicated that progressively integrating topic-specific graphs into a global course-level representation helped them perceive the syllabus as a connected conceptual landscape rather than a sequence of discrete chapters. The global graph was used to position newly introduced structures, such as heaps, relative to earlier material on lists, trees, and graphs, and to reason about alternative implementation strategies for design problems. Some students reported tracing paths through the graph to compare solution strategies, such as array-based versus linked-list-based structures. In response to the question: “*How did integrating the KG improve your ability to explain complex course concepts to others?*” one participant explained:

“Integrating a knowledge graph allows me to map the relationships between key concepts visually. In a course like Data Structures and Algorithms, which includes abstract ideas (such as lists, trees, graphs, sorting, and complexity), presenting the connections between them as a knowledge graph can illustrate what depends on what, what builds on what, and how the ideas relate to one another. This enables a more intuitive explanation, not just a technical one.”

Finally, a joint analysis integrating quantitative questionnaire results and qualitative responses was conducted to identify convergences across the data sources and strengthen the interpretation of the findings. Across the two courses, several cross-cutting themes aligned with the study’s four design principles. First, the graphs supported conceptual organization by making prerequisites, thematic clusters, and relationships among topics explicit. Second, they enhanced cognitive visibility, helping students clarify misunderstandings and structure their revision. Third, they supported comparative reasoning by enabling students to juxtapose alternative methods, structures, or strategies within a shared representation. Fourth, they supported reflective integration by allowing students to situate new concepts within an evolving conceptual framework. Taken together, the results indicate that when conceptual dependencies and relationships are made explicit, students engage with course content as a network rather than a linear sequence of topics. Across both courses, students described locating new concepts within the evolving graph and tracing relational paths to compare alternatives, suggesting that knowledge graphs can support classroom reasoning by making conceptual relationships visible.

4. Conclusions and implications

Our findings answer both research questions by showing that students perceived instructor-constructed KGs as effective tools for organizing disciplinary knowledge and that these representations supported their ability to articulate relationships among concepts and compare alternative methods or solution strategies. Students reported that KGs helped them visualize dependencies among concepts and understand the broader conceptual structure of the course, reinforcing their role as tools for making relational and hierarchical aspects of STEM content explicit.

Future research could expand the number of participants, enabling more robust statistical analysis and improving the generalizability of the findings. Another direction is to investigate participatory models in which students contribute to the construction or revision of KGs, thereby deepening engagement with disciplinary structure. Overall, the findings suggest that knowledge graphs have the potential to serve as powerful pedagogical representations that make the structure of STEM knowledge explicit and accessible to inquiry.

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