Pedagogy Insights
An International Peer reviewed Journal of Multidisciplinary research

Vol. 1, Issue 3, October 2026, 100–114
ISSN: 3139-843X
DOI: https://doi.org/10.5281/zenodo.24186276

Mind Mapping Techniques as Cognitive Catalysts in Science Education: Evaluating Pedagogical Affordances Across Diverse Digital Software Tools

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DOI: https://doi.org/10.5281/zenodo.24186276

Abstract

Technology is very basic and important in the modern age. The National Education Policy 2020 highlighted the role of technology in Section 23 of this document. By incorporating new technologies in education, there would be a revolution in both what students learn and how they learn. The NEP calls for innovative teaching methods that change teacher-led education to student-centered education. This enables learners to acquire knowledge through a constructivist approach and helps shift away from the long-standing misconception of rote memorization. With this aim, the researcher tries to explore how the mind mapping technique acts as a cognitive catalyst for the development of science education by evaluating its pedagogical affordances with the available different mind mapping software. The mind map technique, which is a spatial visualization method for organizing ideas, has been widely recognized as an instructional approach in science learning. It functions on cognitive load theory, dual coding theory, constructivist theory, and Asubel's meaningful learning theory. It involves connecting the main ideas via nodes to encode the information actively. The review suggests that using various digital mind-mapping software improves science learning outcomes. The selection of a digital mind-mapping tool shapes the experiential learning by providing real-time collaboration; support for embedding multimedia files, and different types of exporting options. Affordances pedagogically include organizing science concepts, conducting inquiry tasks, and making metacognitive reflections. However, there are still limitations in these studies despite their positive outcomes: sample sizes are small; study designs are inconsistent; and they focus primarily on measuring short-term memory gains through quasi-experimental designs. It would be better if future research focused on conducting large-scale randomized controlled trials across different types of science content. The research reflects how mind-mapping digital tools can be used as brainstorming tools for collaborative, real-time engagement and creative learning, helping uphold the concept through visually connected ideas and nodes. The research would benefit learners and teachers in the creative teaching-learning process and for assessment purposes across different levels of education. Articles published in leading journals, conference proceedings, and online websites have been referred for review purposes.

Manuscript Information
- **Received:** 31-10-2026
- **Accepted:** 05-11-2026
- **Published:** 12-11-2026
- **MRR: 1(3);** 2026: 100-114
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- **Plagiarism Checked:** Yes
- **Peer Review Process:** Yes

How to Cite this Article
Tyagi, J., Mind Mapping Techniques as Cognitive Catalysts in Science Education: Evaluating Pedagogical Affordances Across Diverse Digital Software Tools, *Pedagogy Insights*, 1(3), 100–114.
https://pedagogyinsights.com/index.php/files/issue/view/3

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ISSN: 3139-843X

Keywords:
Mind Mapping Technique, Digital Software Tools, Science Education, Cognitive catalyst and Pedagogical Affordances

Introduction

Science deals with the limitations of linear note taking and lecture based instructional methods that overload working memory. Traditionally, science pedagogy has relied heavily on expository textbooks, linear verbal lectures, and passive note-taking. Cognitive psychologists and science educators have demonstrated that linear textual formats poorly represent complex, dynamic, and non-linear physical systems (Kozma, 2003; Mayer, 2009). To cope up this gap, learning via constructivist pedagogical approach is supported to ease science concepts understandable. According to Naturalism Philosophy learning is done with the more engagement of sensory motor skills to support this, visual-spatial representations have become foundational to constructivist pedagogy. Beginning with the pioneering work of Tony Buzan on associative mind mapping and Joseph Novak on hierarchical concept mapping, visual knowledge organizers have served as external cognitive scaffolds (Buzan & Buzan, 1996; Novak & Gowin, 1984). In scientific education, the mapping method requires learners to come up with the central ideas, arrange them in a hierarchical order in concept mapping, and connect them with other keywords in mind mapping through propositions.

Mind maps are one type of graphical organizer that involves the use of a central idea from which branches are drawn that represent sub-ideas related to the central concept (Buzan, 1995; Tyagi & Kishor, 2024). Tony Buzan in the 1970s, introduce the concept of mind maps that leverage the brain's visual and associative capacities ("right-brain" that functions logically) to encode information more richly. For science education, which requires students to connect information, concepts and process, it is suggested that mind mapping should enable the learners to construct knowledge rather than merely taking notes passively (Buzan & Buzan, 2006). Mind maps can be developed via paper or pen or on blackboard manually but with the availability of digital advancement tools and creating more interactive meaningful engagement of today's science learners digital mind mapping tools become popular. Not all concepts can be fully grasped through notetaking or simple memorization, but through organizing them meaningfully (Goodnough & Long, 2007). Mind maps offer a non-linear approach for making such connections, while the linear approach offered by paper imposes limitations on reorganizing ideas. Moving hierarchies around on paper involves erasing and redrawing, which is a source of extra friction and discouragement from restructuring (Canas et al., 2005). In contrast, digital tools offer a limitless space and enable the creation of non-linear connections among ideas with easy restructuring, hyperlinks, and multimedia simulations. This paper examines the mind mapping technique through theoretical lenses (cognitive and learning theories) how it acts as a cognitive catalyst, synthesize empirical evidence on its effects in science education contexts, compare key digital mind-mapping tools, and derive best practices for teachers in science classrooms.

Theoretical Framework

The pedagogical mechanism of mind mapping intersects across the following foundational educational and cognitive theories.

Cognitive Load Theory and Dual Coding Theory

According to Cognitive Load Theory (CLT), human working memory has time and capacity limits on handling new information (Sweller et al., 1998, 2019). Cognitive architecture divides mental burden into intrinsic (complexity of content and element interactivity of the scientific material), extraneous (how information is presented), and germane (schemas construction means productive mental capacity dedicated to constructing, refining, and automating long-term schemas). The use of mind maps can assist CLT in reducing unnecessary load through organization and visual aids since mind maps organize information in branches and hierarchical

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order to form schemas similar to those in LTM in which information is stored. Color and images contribute to offloading of the working memory by using colors on branches and symbols that use sensory memory (visual sketchpad in Paivio's theory) to encode the information through dual channels. The Dual Coding Theory by Paivio (1986) supplements CLT by showing that humans have two independent channels of processing linguistic and spatial-visual information. Digital mind mapping software directly optimizes this dual-channel capacity. Thus, mind maps impose an organized structure that aligns with Miller's rule to keep cognitive load manageable (Mayer,2009).

Ausubel's Meaningful Learning Theory, Novakian Constructivism and Schema Theory

According to constructivist learning theory, new knowledge is learned through connections to previous knowledge. The use of mind maps helps in this regard as it highlights the structural relationships between concepts. The hierarchical structure (i.e., primary branches and sub-branches) provides for clear categorization and delimitations, consistent with the development of schema. The "uniqueness" of each individual's mind map represents this constructivist view of learning. Therefore, the use of mind maps can be viewed as a way of constructing personal knowledge, where students categorize scientific information based on their cognitive schema. According to David Ausubel (1968), meaningful learning involves connecting new, unknown concepts with cognitive schemas. This happens through three cognitive processes: **Subsumption (**Subordinating specific phenomena under broader principles), **Progressive Differentiation (**Gradually elaborating concepts to reveal greater detail, nuance, and specificity) and **Integrative Reconciliation (**Recognizing cross-links and resolving cognitive dissonance across previously disconnected conceptual domains). Ausubel's theory was developed in practice by Novak and Gowin in 1984 through visual mapping. For scientific education, the scientific proposition is the unit of currency. The student creates a digital proposition, making their internal mind map visible.

Metacognition and Self-Regulation

Mind mapping also encourages metacognitive processes. Creating a mind map requires learners to plan (decide on main ideas), organize (decide where branches go), and evaluate (add or remove details) – all reflective activities. D'Antoni et al. note that mind maps "engage learners at a metacognitive level" similar to concept maps (D'Antoni et al.,2009). Keyword selection and idea condensing is the process that fosters self-monitoring, as students have to weigh ideas for their importance and their interrelations. Finally, the map created by students will be the instrument of self-regulation and will help them reveal the presence of weaknesses and misunderstandings. Moreover, usually good mind maps feature a number of connections and even coloring, which means that the process of mental work is quite intensive. In other words, mind mapping combines theoretical and practical elements, as it fits the framework of CLT, dual coding, schemata formation, and self-reflection.

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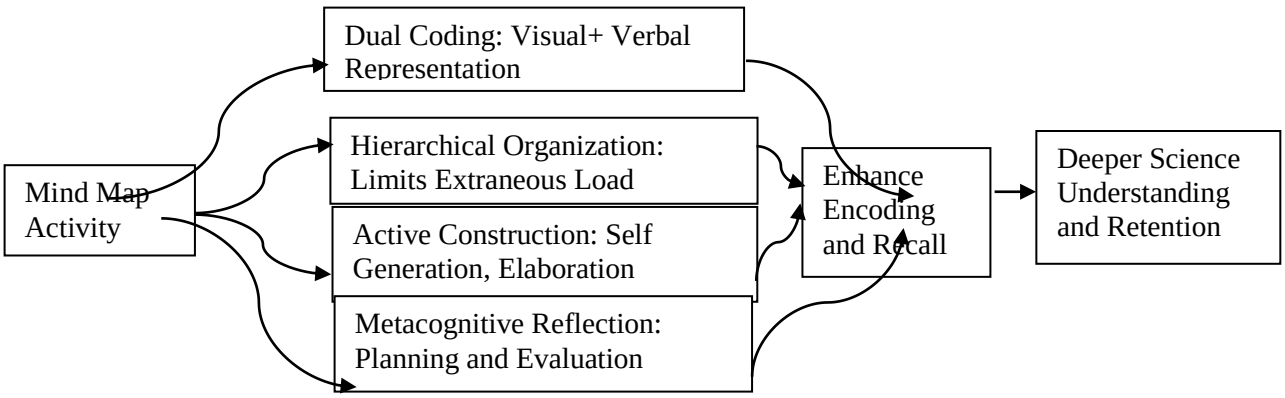


Figure 1: How mind maps facilitate cognitive processing while learning scientific concepts. The use of two channels, structure imposition, and active construction for better understanding and retention.

The TPACK Integration Matrix

According to Technological Pedagogical Content Knowledge (TPACK) theory introduced by Mishra & Koehler (2006), technology should not be implemented within instructional context in isolation. Integration of technology happens at the point where Content Knowledge (CK), Pedagogical Knowledge (PK) and Technological Knowledge (TK) meet (Tyagi, 2024).

With respect to science instruction, the use of TPACK would imply that software is not used only as a digital alternative to poster boards. Rather, teachers would take advantage of certain functionalities within the software (TK) like collapsible branches, live links to external simulation tools, and multiple user history revisions in order to teach through inquiry (PK).

Objective of the Study

1. To investigate various theoretical perspectives of mind mapping through the use of technology in science classrooms.
2. To investigate various digital software tools for mind mapping.
3. To explore the affordances and challenges of using digital mind mapping software's tools in class practices.

Research Methodology

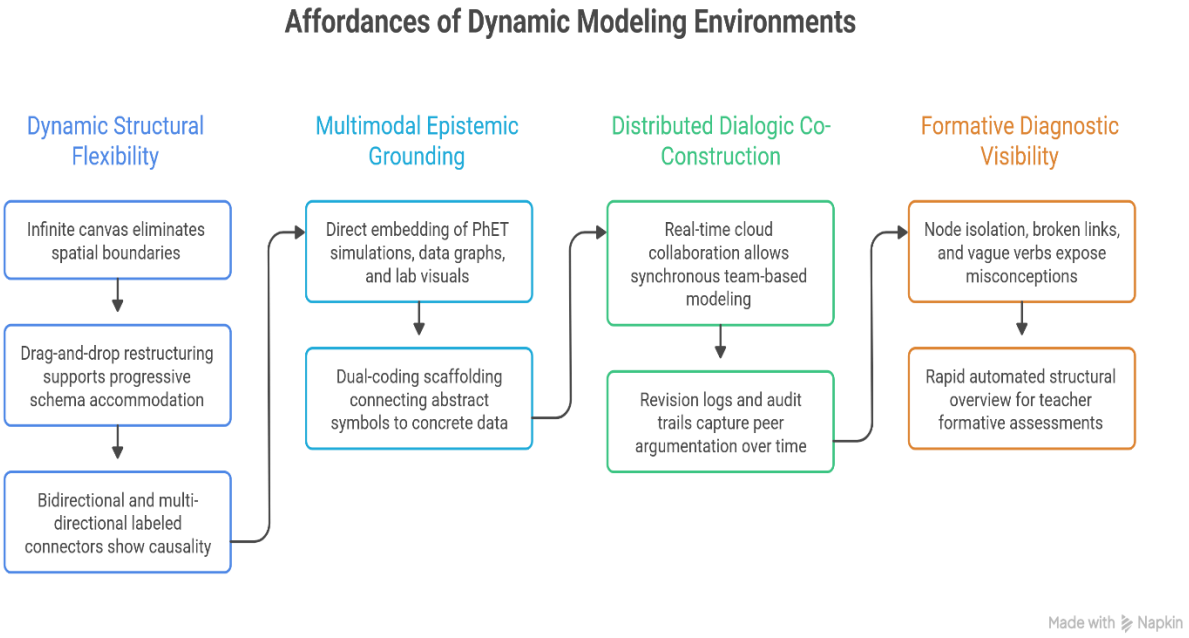
This research study makes use of a qualitative approach with a document analysis. The researcher gathered data from both primary sources: NCF 2005, NCF 2023 and NEP 2020 policy document and secondary sources such as websites, magazines, journals, conference proceedings and e-content. The data were collected from Google Scholar, ResearchGate and PubMed database. The search was limited to science education, article document types, English language publications, and journal articles as source types. After reviewing the remaining papers, on such criteria the researcher removed duplicates and selected 54 articles to meet the study's inclusion criteria for the final review. Review employs a structured framework, such as Cognitive Load Theory, Dual Coding Theory, Ausubel's Meaningful Learning Theory, Novakian Constructivism and Schema Theory, Metacognition, Self-Regulation and TPACK, allowed for identifying Pedagogical Affordances of Digital Mind Mapping Software, offering analytic rigor. Image generation is done with the help of Napkin ai.

Pedagogical Affordances of Digital Mind Mapping Software

For a fair assessment of digital technologies, their technical characteristics should be translated into educational affordances. This means that an affordance is not a feature of a particular technology, but rather the relationship between the technical characteristic and its pedagogical use in education (Gibson, 1977; Wang et al., 2010).

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Pedagogical Affordance Matrix for Science Education



Unlike the traditional linear note-taking and static chalkboard writing, dynamic structural and relational flexibility of Digital Mind Mapping software allows learners to freely restructure the relationship between concepts according to their changing conceptual understanding to facilitates cognitive accommodation (Piaget, 1971; Canas et al., 2005); multimodal grounding will help students ground abstract conceptual definitions with concrete examples (Kozma, 2003). Modern digital mapping tools allow students to anchor abstract text nodes to external multimedia, including: Interactive simulations (PhET models), High-resolution microscopy captures and real-time laboratory data plots and Web-based scientific literature links; In Distributed and Dialogic co-construction Cloud-based mapping platforms transform from an isolated exercise into an active collaborative environment. Students work in groups and are engaged in synchronous argumentation (Driver et al., 2000; Vygotsky, 1978).

Diverse Digital Mind Mapping Software Tools

Dimension/ Features	**XMind**	**Coogle**	**Miro**	**Free mind**
Collaboration	Real time co-editing team workspace	Real time editing with multiple collaborators	Real time white board collaboration	None Local only
Templets/ Layouts	Multiple layouts (Mind map, fishbone, matrix, pitch); Zen mode	Flowchart shapes and multi-root; basic styling	Built-in mind-map templates (concept, problem); canvas shapes	Basic mind-Map only
Multimedia Support	Insert images, notes, attachments (PDF, audio); AI-assisted graphics	Drag-and -drop unlimited images; text labels	Embed images, PDFs, Google Sheets or Excel on canvas	Only static Nodes (text only)
LMS/Tool Integration	Import/export Office (Word/PPT); no LMS plugin	No LMS; Embeds by link	Embeds into Conflu -ence/ Notion/Teams (Slack, Jira, etc.)	None

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Pricing	Freemium; Pro & Business tiers; student discount	Freemium and Paid version	Freemium and Paid version	Free (open-source)
Accessibility	Desktop, Web, Mobile & cloud sync	Web-only	Web app; mobile apps; Infinite canvas	Desktop (Java); no mobile
Export Formats	PNG/SVG/PDF/Office (Word/Excel/ PowerPoint)/ Markdown/OPML	PDF, PNG/ JPEG, text	PDF, PNG/JPEG; CSV (via add-on); embed/ share links	PNG, HTML, XML, PDF, or printed output

Mindjet (Mind Manager): Mindjet is a popular commercial mapping software originally developed by Mike and Bettina Jetter in 1998 and later acquired by Corel in 2016. This software helps us to plan, operate and handle our ideas with visual frameworks in terms of Mind maps, concept maps, flowcharts, organization charts and gantt charts. Available at different platforms across windows, macOS, iOS, Android and Web-based browsers (Corel Corporation,2024).

Mindomo: It's a web-based freemium software developed by Expert Software Applications, released in 2007. Mindomo utilizes different features of AI-powered tools, offers live two-way synchronization with real time collaboration, users can embedded YouTube, web images, local/cloud files, notes, icons, and LaTeX math formulas and Accessible via web browsers, desktop apps, and mobile apps with offline editing and syncing (Expert Software Applications, 2024).

MindMup: Mindmup is a free, open-source mind mapping application based on JavaScript. It assists us in creating unlimited maps on the web without installing any software locally, with features such as argument visualization, Google Workspace Integration, and document outlining (Sauf Pompiers Ltd., 2024).

TheBrain: It's a digital mind mapping tool developed by TheBrain Technologies. Originally it was launched in 1996, functioning as an N-dimensional database where any idea or file can be linked, having dynamic network, via relative links: Parent thoughts, child thoughts, siblings and jump thoughts and featured of Cerebro AI Integration (TheBrain Technologies LP, 2024).

Padlet: Padlet is a digital cloud-based mind mapping software that allow people to collaborate, developed by Wallwisher, Inc. (operating as Padlet). It allows users to add content, feedback and make real-time improvements including text, images, hyperlinks, documents, audio clips, and video recordings-onto dynamic virtual boards (Wallwisher, Inc., 2024).

Ayoya: The development of Ayoa (DropTask) was associated with Tony Buzan, having the capabilities of mind maps, neuro-inclusivity, and brainstorms. The interface has been specifically designed for people with dyslexia, attention deficit hyperactivity disorder, autism, and others cognitive functions (OpenGenius Ltd., 2024).

Smartdraw: SmartDraw originally established in 1994 as an alternative to Microsoft Visio. SmartDraw is simpler to use than the G Suite and Microsoft Office's standard drawing tools. It can be worked on any device or phone. it provides rule-based automatic formatting for mind mapping, cause-and-effect (fishbone) diagrams, flowcharts, structural equation modeling layouts, and organizational frameworks (SmartDraw Software, LLC, 2024).

LucidChart: Lucidchart is a HTML-5 web-based intelligent diagramming, flowcharting, and visual collaboration platform developed by Lucid Software Inc. which provides real time collaboration. It is easily combined with MS office, G suite, Atlassian office, etc (Lucid Software Inc., 2024).

Edraw Mind Map: EdrawMind (MindMaster or Edraw Mind Map) is a cross-platform application for creating mind maps, brainstorming ideas, and visually organizing knowledge designed by Wondershare Technology Co., Ltd. through its subsidiary EdrawSoft. (Wondershare Technology Co., Ltd., 2024).

Freeplane: Freeplane is the free and open-source software that generates and analyses mind maps, concept maps, and knowledge management written in Java. Freeplane is running

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ISSN: 3139-843X

on every Java version of any operating system, we can execute it through a USB device if we don't want to download it (Polivaev et al., 2024).

WiseMapping: It was originally created by Paulo Veiga and maintained by the WiseMapping open-source development community. The software is Java based and offers both a public and a private workspace. Users will have different mind maps and shared maps with teams. It supports Windows, Linux, Mac and is also available in cloud version (Veiga & WiseMapping Community, 2024).

MindMapper: Mind mapper is one of the types of flexible project management tools with interactive dashboard and planner created by SimTech Systems, Inc. and SIMTECH USA. (SimTech Systems, Inc., 2024).

Novamind: A visual mind mapping and brainstorming software application developed by NovaMind Pty Ltd (founded by Gideon King in Australia). It enables user to imagine and coordinate their plans through innovative production and brainstorming (NovaMind Pty Ltd., 2014).

GitMind: GitMind is a web-based tool used to make visual diagrams, concept maps, and mind maps using AI technology provided by Wangxu Technology (HK) Co., Limited (Apowersoft). (Wangxu Technology Co., Ltd., 2024).

iMindMap: The official mind-mapping software suite developed by Chris Griffiths in direct partnership with Tony Buzan under ThinkBuzan Ltd (later rebranded as OpenGenius Ltd). This iMindMap is a workspace that helps us to catch ideas, to organize, to create, to gather knowledge in a single hub, to play with our opinions, to implement them, to make ideas a reality. (ThinkBuzan Ltd., 2018).

Microsoft Word: Microsoft Word is popularly used free and open-source software for the development of digital mind maps. This is more versatile than pen and paper (Microsoft Corporation, 2024).

There are also some other digital mind mapping softwares like Semantik, Compendium, MindView, iMindQ, Creately, Visio, Cacoo, Drakonhub, Mindly, Docear, Openmind, Bubbl.us, Mind Genius, Venngage, Mind42, ConceptDraw MindMap and others used to prepare digital mind maps.

Studies related to science Education

Several experimental studies have investigated mind mapping in K–12 science classes. Abi-El-Mona and Abd-El-Khalick (2008) randomly assigned 62 eighth-graders to either a mind-mapping condition or a traditional note-taking condition during a science unit. After intervention, those who were involved in creating mind maps achieved better grades in a test of science achievement than control students, means there is improvement in conceptual understanding. Jordan, Bawaneh (2020) has compared "Mind Maps Teaching Method" with conventional method using 10th grade physics students (N=111) as for the knowledge of electric energy concepts. Those participants who had used mind maps performed better in both post and retention tests compared to control groups ($p<.05$). Both studies prove the possible positive effect of mind mapping on the process of learning. However, some research findings on K-12 do not demonstrate such positive outcomes as far as mind mapping is concerned. For example, Wickramasinghe et al. (2010) conducted research on the combination of mind mapping technique for underprepared secondary school students and found no statistical significance in their short-term results. Farrand et al. (2002) performed a randomized trial on a sample of medical students (n=50). The subjects learned text-based information through drawing mind maps and conventional reading of notes. After one week, students who used mind maps remembered on average 10% more material than the control group (average recall score: 85% vs. 75%, the results were favorable for mind maps.

The research conducted by Ismail et al. (2010) on the instruction in computer science involved a quasi-experimental design (n=127, university students). Three types of instruction were used in the course on programming: Mind Mapping combined with Cooperative Learning (MMCL), Cooperative Learning (CL), and Traditional lecture (T). The group of students who received MMCL instruction performed significantly better in programming and demonstrated greater knowledge of metacognition compared to the traditional group ($p<.05$). The group receiving CL instruction performed better in comparison with the control group in some cases as well.

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Table 1. presents important empirical literature in relation to science. Effect sizes were infrequently reported in primary literature. Liu et al. (2014) in their meta-analysis of 6 mind mapping studies reported a standardized mean effect size of ~0.75 in terms of achievement. Similarly, Batdi (2015) reported a very large effect (d~1.06) on achievement with 15 studies, whereas Li et al. (2018) meta-analysis (60 studies) reported an average effect of ≈0.76.

Table 1. Summary of Empirical Studies on Mind Mapping in Science Education

Study	Participants (Grade/ Discipline)	Design (Control)	Intervention	Outcome Measure	Results
Farrand et al. (2002)	50 medical students	RCT (Mind map vs. conventional study)	Mind map study	Content recall test (1 week later)	Mind map group recalled 10% more over control.
Abi-El-Mona & Abd-El-Khalick (2008)	62 eighth-graders (middle school science)	RCT (Mind map vs. note summary)	Mind map training + map creation	Science achievement test	Mind-map group scored significantly higher ($p<.05$) than control.
Deanship (2020)	111 tenth-graders (high school physics)	Quasi-exp (Mind map vs. traditional)	Mind Maps Teaching Method	Physics concepts test (pre/post)	Mind-map group > control on immediate achievement & retention ($p<.05$).
Ismail et al. (2010)	127 undergrad CS majors (college)	Quasi-exp (MMCL vs. CL vs. trad.)	Mind map + Coop Learning (MMCL)	Programming performance score & metacog knowledge	MMCL group significantly outperformed traditional in programming & metacog ($p<.05$).
Shi et al. (2022) (Meta-analysis)	21 studies (K–college, various STEM)	Meta-analysis (vs. traditional)	Mind-mapping instruction (various)	Academic achievement (cognitive outcomes)	Overall positive effect favoring mind-map instruction; stronger in STEM subjects

Cognitive Catalysis: Transforming Science Learning in Practice

Digital mind mapping tools act as cognitive catalysts by accelerating and supporting three core intellectual processes:

Visualization of Abstract and Intangible Phenomena: There has always been one of the most difficult aspects for secondary science teachers known as the "chemical triplet," a phrase coined by Johnstone (1991), which refers to the simultaneous ability to deal with three distinct levels: the macroscopic level, submicroscopic level, and symbolism. Digital mind mapping makes connections across all three levels easy to make; One central point represents the macroscopic observation, like a piece of metal rusting; The first branch represents the submicroscopic depiction of electron movement; The second branch represents the balanced chemical equation

with an accompanying ΔH notation.

Exposing and Remediating Alternative Misconceptions: Science misconceptions such as mixing up respiration and ventilation and thinking that mass is lost when combustion takes place have often remained prevalent owing to the nature of assessments carried out through traditional means, which mainly involve multiple choice questions and memorizing of definitions without addressing any causal structure (Treagust, 1988). The alternative conceptions become readily apparent by using digital mind maps.

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ISSN: 3139-843X

Fostering Systems Thinking Across Disciplinary Silos: Modern day educational models like the Next Generation Science Standards (NGSS) of the US and the NEP 2020 of India focus on cross-cutting themes and cross-pollination of ideas across disciplines. Such as in Physics: Radiative forcing and albedo effect; Chemistry: Ocean acidification and carbon dioxide balance; Biology: Coral bleaching and metabolism changes; and Sociology / Economics: Carbon pricing and emissions from factories.

Students can then be able to represent all of this on their infinite digital whiteboard without the constraints imposed by conventional discipline-based learning.

Pedagogical Implementation: The 5E-Mapping Model

In order to keep digital mind mapping from becoming an exercise in chaos, technology should be systematically applied to pedagogically proven learning sequences. The following framework is a combination of digital mind mapping and the proven 5E Instructional Model (Bybee et al., 2006):

Engage sequence corresponds to Diagnose Pre-Mapping. Prior to direct teaching, students work in small teams on the cloud-based canvas (Coggle) to build a quick map centered around a single question. The teacher assesses the live mind maps available in the central dashboard.

Explore Phase for lab experiments or computer models, learners will make use of tablets or laptops in order to fill in their mind maps with data. It will also entail adding photos through smart phones, linking up spreadsheets, or embedding a table of data into the concept maps.

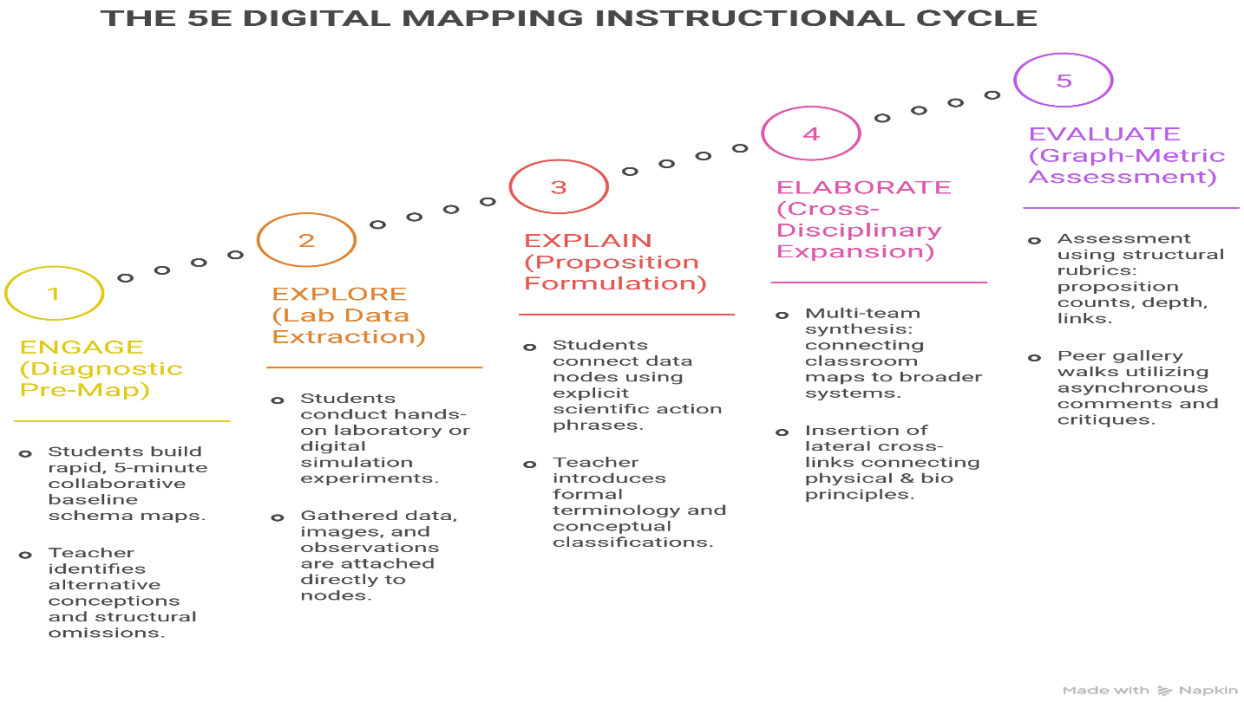
Explain Phase, after collecting empirical data by the students, the instructor will tell them to connect their empirical observations with scientific theories. Here accuracy becomes the key; that is, the students will use scientific verbs when making connections.

Elaboration stage learners expand their maps laterally by connecting their laboratory insights to wider systemic phenomena. A biology map exploring *Enzymatic Activity* connects directly to physics principles (*Kinetic Theory and Temperature*) and chemical foundations (*Activation Energy Barriers*).

Evaluation stage assessment moves away from rote testing toward evaluating structural schema metrics (Novak & Gowin, 1984; Yin et al., 2005). The teacher evaluates the students' maps on the basis of quantifiable and structural measures: Propositional Validity; Structural Depth; and Cross-link Density.

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ISSN: 3139-843X



Pedagogical Affordances and Constraints

Mind mapping offers several pedagogical affordances aligned with common learning objectives in science:

Conceptual Organization: By structuring topics into branches, mind maps make relationships explicit, helping students see “big picture” connections (e.g. linking ecosystem components or steps in a process).

Active Learning: Creating a mind map requires students to actively process information-sorting main ideas and details, which promotes deeper cognitive engagement (elaboration and self-explanation).

Multimodal Learning: Mind maps allow incorporation of images, colors, and symbols, catering to visual learners and enhancing memory (dual coding).

Collaboration and Communication: Digital maps enable group brainstorming and sharing.

Reflection and Metacognition: The resulting map itself becomes an artifact of comprehension, where students can check whether critical links are present or not.

Scaffolding: Educators have options for scaffolding increasing levels of difficulty.

Digital mind-mapping tools clearly provide several cognitive benefits, however, their use in the classroom presents actual instructional issues:

The "Aesthetic Wandering" Dilemma

One main area where digital map-making classes fail is when critical thinking is replaced by surface-level design tasks (Kirschner et al., 2006). In the early use of sophisticated tools, students waste time selecting personalized branch colors, exploring icons, and setting up their fonts instead of focusing on developing their propositions. Thus, the use of Styling should be minimized in the previous stage. Students must make use of only monochrome or basic template designs when creating their ideas initially.

Cognitive Overload from Complex Software Interfaces

For novice learners, navigating complex software interfaces can introduce considerable extraneous cognitive load. If a student struggles to figure out how to add a cross-link or adjust an arrow's direction, those interfaces frustrations compete directly with the working memory needed to process scientific concepts (Sweller et al., 2019). Addressed it by

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taken digital tool adoption slowly. Teachers need to start with partially completed "skeleton maps" of experts, and only ask students to fill in the remaining linking verbs and subordinate nodes, before finally creating their own maps from scratch.

Infrastructure Inequity and the Digital Divide

The cloud-based dynamic map-making tools are extremely reliant upon personal computer technology, consistent internet connection speed, and active software subscriptions through institutions. Within under-resourced public schools, lack of access to devices. To overcome these schools must choose simple, platform-independent tools which facilitate offline storage and cross-platform synchronization.

Time and Training: Needs instruction in map standards (such as keyword usage and color).

Suitability of Content: Linear or procedural subject matter (like math proofs) might not be as easily adapted to radial maps. Even so, there are many linear scientific processes that can still be conceptualized.

Challenges in Assessment: The evaluation of such a wide range of creative works such as mind maps is subjective, unlike test scoring. Using these affordances in relation to learning goals, teachers can assign mind maps for activities like summing up a unit of study, creating experiments, and making projects. A well-tested rubric known as the Mind Map Assessment Rubric (MMAR) is used to score mind maps along the lines of concept-linking, cross-links, hierarchical levels, examples, pictures used, and colors (D'Antoni et al., 2009).

Implementation Guidelines for creating mind maps

For the effective use of mind maps teachers must use them in their lessons intentionally. Recommended techniques for using mind maps efficiently include:

1. **Introduce Mind Map**: Teach learners how to create a map by highlighting the concept of central themes, branch hierarchy, and keyword usage.
2. **Define Clear Objectives**: Construct mind maps for a particular purpose.
3. **Use Digital Tools for Interaction**: Employ collaborative software (MindMeister, Miro) for group activities. For example, assign small teams to co-construct branches on a shared map in real-time, then merge maps to form a class-wide concept map.
4. **Scaffold Complexity**: Novice students may begin by building upon an existing partially completed map that is made by an expert.
5. **Integrate Across Curriculum**: Apart from the scientific information, mind maps can be used for note taking. According to the ACS RISE website, one should employ sequential overlapping maps when connecting related concepts.
6. **Allow Creative Expression**: Get them to use icons and color, even doodling where possible.
7. **Iterate and Revise**: Treat maps as living documents. Students can refine or expand maps after group discussion or feedback.
8. **Present and Explain**: Apply the use of the presentation mode of maps that are possible within software to explain their thought process to peers.

Conclusion

Education in science should transcend the boundaries of rigid text learning to prepare individuals for the dynamic variables of the 21st-century world. NEP 2020 and NGSS, developing scientific temperament and critical thinking demands pedagogical approaches that enable the testing of systems thinking. The combination of Novakian theory and modern software makes these tools genuine cognitive catalysts. The software applications cannot alone make the difference in education; they need to be adopted through instructional approaches like the 5E-Mapping approach, which is based on teachers' competency of TPACK.

Mind maps possess great potential to act as a catalyst to cognition in scientific instruction. The use of mind maps can be as a teaching aid in the sense that it promotes active, visual, and collaborative interaction with knowledge and is consistent with curricular objectives such as concept building and inquiry-based learning.

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In order to achieve this, instructors should offer guidelines (on CLT-based mind-mapping design principles) and ensure alignment between the activity and its objectives. Mind-mapping assessment can use rubrics to reflect on the distinct nature of its products. Future research should broaden beyond achievement to include attitudes, problem-solving, and higher-order thinking. Integrate **Generative AI and Automated Semantic Scaffolding** based Mind mapping technique, Large Language Models (LLMs); **Learning Analytics and Epistemic Network Analysis (ENA)**. With proper planning and reflection, mind mapping will not be seen merely as a gimmick, but rather as an effective tool for deep learning.

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