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Prompt Engineering as a 21st Century Learning Competency: A Conceptual Framework for Science and Mathematics Education

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Abstract

Artificial Intelligence (AI), particularly generative AI powered by Large Language Models (LLMs), is reshaping science and mathematics education. While prior studies have emphasized AI literacy, digital competence, and teacher preparedness, comparatively little attention has been given to the learner competencies required for effective interaction with AI through prompt engineering. This conceptual paper positions prompt engineering as a twenty-first-century learning competency that fosters inquiry, reasoning, critical thinking, communication, and self-regulated learning. Using a conceptual research design, the study synthesizes contemporary literature and educational theories to develop a learner-centred perspective on prompt engineering. Four complementary theories constructivist learning, self-regulated learning, cognitive load theory, and inquiry-based learning provide the foundation for two proposed frameworks. The Prompt Engineering Learning Competency (PELC) Framework identifies six domains essential for AI-supported learning, while the Prompt Engineering Competency Model (PECM) explains learners' progression from novice users to expert prompt engineers. The paper argues that prompt engineering should be recognized as an educational competency rather than merely a technical skill, with implications for curriculum design, classroom practice, teacher education, learner assessment, and future research in science and mathematics education.

Keywords: prompt engineering, artificial intelligence, science education, mathematics education, AI literacy, stem education, learning competency.

1 Introduction

Artificial Intelligence (AI) is rapidly transforming education, particularly in science and mathematics, where inquiry, reasoning, and problem-solving are central to teaching and learning. Generative AI powered by Large Language Models (LLMs) has introduced new opportunities for learners to interact with knowledge through conversational interfaces capable of supporting explanation, exploration, and problem-solving. While much of the existing scholarship emphasizes AI literacy, digital skills, and teacher preparedness, comparatively less attention has been given to the learner competencies required to interact effectively with AI systems through purposeful prompt design. Prompt engineering is the practice of crafting purposeful inputs to guide AI responses is emerging as an important competency in AI-supported learning. It extends beyond technical optimization to encompass inquiry, communication, metacognition, critical evaluation, and ethical engagement. In science and mathematics education, where learners are expected to formulate hypotheses, solve complex problems, analyse evidence, and justify conclusions, prompt engineering provides opportunities to strengthen higher-order thinking and collaborative knowledge construction through meaningful interaction with AI.

Existing frameworks on AI literacy primarily focus on responsible AI use, digital competence, and teacher readiness. Although these perspectives are essential, they provide limited guidance on the specific competencies learners require to engage effectively with generative AI in educational settings. Consequently, prompt engineering is often presented as a technical strategy for improving AI outputs rather than as a learner-centred educational competency that supports inquiry, reasoning, reflection, and disciplinary learning. This paper addresses this conceptual gap by positioning prompt engineering as a twenty-first-century learning competency for science and mathematics education. Drawing on constructivist learning, self-regulated learning, cognitive load theory, and inquiry-based learning, it proposes two complementary conceptual models: the Prompt Engineering Learning Competency (PELC) Framework and the Prompt Engineering Competency Model (PECM). The PELC Framework identifies six interrelated domains that characterize effective prompt engineering in AI-supported learning, while the PECM describes learners' developmental progression from novice to expert prompt engineers. Together, these models provide a theoretical foundation for curriculum design, classroom practice, teacher education, learner assessment, and future research in science and mathematics education.

2 Literature Review/Theoretical Framework

Artificial Intelligence (AI) in education has evolved from early applications such as automated grading and intelligent tutoring systems to adaptive learning platforms, learning analytics, and generative technologies. Holmes et al. (2019) and Luckin (2018) highlighted AI's potential to personalize learning, improve assessment, and support adaptive instruction, while Kasneci et al. (2023) and Lo (2023) emphasized the transformative role of generative AI in reshaping learners' interaction with knowledge. These developments have shifted AI from being primarily an instructional support tool to becoming an interactive learning partner capable of facilitating inquiry, problem-solving, and knowledge construction. Generative AI tools such as ChatGPT, Gemini, Claude, and Microsoft Copilot enable conversational learning, problem-solving, content generation, and personalized feedback. Scholars caution that AI should complement rather than replace teachers (Luckin, 2018; Holmes et al., 2019). Frameworks for twenty-first-century learning consistently highlight critical thinking, creativity, communication, and collaboration as essential learner competencies (Trilling & Fadel, 2009; Dede, 2010). Recent scholarship has increasingly recognised prompt engineering as a critical competency for effective interaction with generative artificial intelligence in educational settings. Studies by Federiakin et al. (2024) and Lee and Palmer (2025) highlight the importance of prompt design in enhancing learning outcomes, while Qian (2025) further synthesises emerging evidence and demonstrates that structured prompt engineering supports learners' problem-solving, critical thinking, and responsible AI use across educational contexts.

Constructivist approaches emphasize scaffolding and social interaction as foundations for meaningful learning (Bruner, 1960; Vygotsky, 1978, p. 87), while Cognitive Load Theory underscores the importance of managing learners' mental effort during complex tasks. Sweller observed that "Cognitive load during problem solving affects learning" (1988, p. 257). Similarly, self-regulated learning frameworks highlight learner autonomy, planning, monitoring, and reflection. Zimmerman noted that "Self-regulation refers to self-generated thoughts, feelings, and actions that are planned and cyclically adapted" (2000, p. 14). Schraw et al., (2006) further argued that "Promoting self-regulation in science education requires metacognition as part of a broader perspective on learning" (2006, p. 111). Collectively, these perspectives suggest that effective interaction with AI requires learners to think critically, monitor their understanding, and refine their approaches throughout the learning process.

Kolb's experiential learning perspective, which states that "Learning is the process whereby knowledge is created through the transformation of experience" (1984, p. 38), further situates prompt engineering within continuous cycles of inquiry, experimentation, reflection, and improvement. Rather than accepting AI-generated responses uncritically, learners engage in repeated interactions that involve questioning, evaluating evidence, revising prompts, and constructing deeper understanding. This iterative process reflects the characteristics of inquiry-based learning commonly promoted in science and mathematics education. Global organizations have increasingly emphasized AI literacy as an essential educational priority. UNESCO (2024) and OECD (2024) advocate competency frameworks that prepare teachers and learners for AI-driven societies, while NCTM (2023) and NSTA (2024) encourage the responsible integration of AI into mathematics and science education. These initiatives recognize the importance of ethical AI use, digital competence, and responsible innovation. However, they provide limited attention to the specific learner competencies required for effective interaction with generative AI through prompt engineering.

Although recent studies acknowledge prompt engineering as an emerging skill in AI-assisted learning (Federiakin et al., 2024; Lee & Palmer, 2025), the existing literature largely focuses on improving AI performance or generating better outputs. Comparatively little attention has been devoted to understanding prompt engineering as a learner-centred educational competency that develops inquiry, communication, metacognition, disciplinary reasoning, and ethical engagement. This conceptual gap provides the rationale for the development of the Prompt Engineering Learning Competency (PELC) Framework and the Prompt Engineering Competency Model (PECM) proposed in this paper. Prompt engineering is conceptualized in this study as a multidimensional learning competency grounded in four complementary educational theories: Constructivist Learning Theory, Self-Regulated Learning Theory, Cognitive Load Theory, and Inquiry-Based Learning. Individually, each theory explains an important dimension of learning; collectively, they provide a comprehensive foundation for understanding how learners can effectively interact with generative AI in science and mathematics education.

2.1 Constructivist Learning Theory

Constructivist learning theory emphasizes that learners actively construct knowledge through interaction with their environment rather than passively receiving information. Vygotsky's principle that "What the child can do in cooperation today he can do alone tomorrow" (1978, p. 87) highlights the importance of scaffolding and guided learning, while Bruner (1960) emphasized discovery learning and active engagement in knowledge construction. Within AI-supported learning, prompt engineering reflects these constructivist principles by enabling learners to formulate questions, seek explanations, test ideas, and refine understanding through iterative interaction with AI systems. Rather than replacing learners' thinking, AI serves as a scaffold that supports deeper conceptual understanding.

2.2 Self-Regulated Learning Theory (SRL)

Self-Regulated Learning Theory explains how learners plan, monitor, evaluate, and regulate their own learning processes. Zimmerman described self-regulation as "self-generated thoughts, feelings, and actions that are planned and cyclically adapted" (2000, p. 14). Prompt engineering closely reflects this cyclical process. Learners begin by identifying learning goals, formulate prompts, evaluate AI-generated responses, recognize gaps or misconceptions, and revise their prompts to obtain more meaningful outcomes. Consequently, effective prompt engineering requires not only technical interaction with AI but also metacognitive awareness and reflective learning.

2.3 Cognitive Load Theory (CLT)

Cognitive Load Theory provides additional justification for prompt engineering by explaining how instructional design influences learning efficiency. Sweller's observation that "Cognitive load during problem solving affects learning" (1988, p. 257) suggests that poorly structured interactions may overload learners' working memory. Well-designed prompts help organize information, reduce unnecessary cognitive demands, and direct learners' attention toward relevant concepts. Consequently, prompt engineering supports meaningful learning by minimizing extraneous cognitive load while promoting deeper conceptual processing, particularly in science and mathematics where learners frequently encounter abstract and complex concepts.

2.4 Inquiry-Based Learning (IBL)

Inquiry-Based Learning emphasizes questioning, investigation, evidence evaluation, and reflective thinking. Kolb's experiential learning perspective that "Learning is the process whereby knowledge is created through the transformation of experience" (1984, p. 38) aligns closely with the iterative nature of prompt engineering. Learners continuously generate questions, interpret AI-generated responses, compare evidence, refine prompts, and construct new understanding. This repeated cycle of inquiry and reflection positions prompt engineering as an active learning process rather than a simple method for obtaining information from AI systems.

2.5 Integration of the Four Theories

Although each theory explains a distinct aspect of learning, together they provide a coherent theoretical foundation for prompt engineering as a learner-centred competency. Constructivism explains how learners actively construct knowledge through interaction with AI; Self-Regulated Learning explains how learners plan, monitor, and refine their engagement; Cognitive Load Theory explains how effective prompt design supports efficient information processing; and Inquiry-Based Learning explains the iterative processes of questioning, investigation, and reflection. Collectively, these perspectives establish prompt engineering as a multidimensional competency that integrates communication, inquiry, metacognition, disciplinary reasoning, and ethical responsibility. Guided by these complementary theories, this paper proposes two conceptual models. The Prompt Engineering Learning Competency (PELC) Framework identifies six interrelated competency domains required for effective AI-supported learning, while the Prompt Engineering Competency Model (PECM) explains learners' developmental progression from novice to expert prompt engineers. Together, these models provide a theoretical foundation for understanding prompt engineering as a twenty-first-century learning competency in science and mathematics education.

3 Materials and Methods

This study adopted a conceptual research design to develop a theoretical framework for understanding prompt engineering as a twenty-first-century learning competency in science and mathematics education. Conceptual research synthesizes existing theories, scholarly literature, and policy documents to generate new theoretical perspectives and conceptual understanding (Dede, 2010; Jaakkola, 2020). Unlike empirical research, conceptual studies integrate existing knowledge to develop new frameworks and theoretical propositions that advance scholarly discourse.

Data sources included peer-reviewed journal articles, books, and policy documents from UNESCO (2024), OECD (2024), ISTE, NCTM (2023), and NSTA (2024). Literature searches were conducted across Scopus, Web of Science, ERIC, Google Scholar, and ScienceDirect using keywords such as Artificial Intelligence in Education, Generative AI, Prompt Engineering, AI Literacy, and STEM Education. Inclusion criteria focused on literature addressing AI in education, science and mathematics education, prompt engineering, competency-based learning, AI literacy, and educational theories relevant to learner development. Studies that focused exclusively on technical AI programming, software engineering, or commercial AI applications without educational relevance were excluded.

The selected literature was reviewed comparatively to identify recurring concepts, theoretical perspectives, and competency dimensions associated with effective AI-supported learning. Particular attention was given to areas of convergence across constructivist learning, self-regulated learning, cognitive load theory, inquiry-based learning, and contemporary AI literacy frameworks. These recurring themes informed the conceptual development of the Prompt Engineering Learning Competency (PELC) Framework, which identifies six interrelated learner competency domains, and the Prompt Engineering Competency Model (PECM), which describes learners' developmental progression from novice to expert prompt engineers. Trustworthiness was enhanced by grounding the proposed frameworks in established educational theories (Vygotsky, 1978; Zimmerman, 2000; Sweller, 1988; Kolb, 1984), synthesizing evidence from multiple scholarly sources and international policy frameworks, and maintaining consistency with APA 7th edition scholarly reporting standards. As a conceptual study, the credibility of the proposed models depends on the coherence of the theoretical synthesis rather than empirical validation.

4 Results

The analysis revealed that although Artificial Intelligence is increasingly integrated into science and mathematics education, there is no comprehensive learner-centred framework that explicitly conceptualizes prompt engineering as a learning competency. Existing studies primarily emphasize AI literacy, digital competence, and the optimization of AI outputs (Kasneci et al., 2023; Lo, 2023). Comparatively less attention has been given to the competencies learners require to engage effectively, critically, and ethically with generative AI in educational contexts. To address this gap, this study developed two complementary conceptual models: the Prompt Engineering Learning Competency (PELC) Framework and the Prompt Engineering Competency Model (PECM).

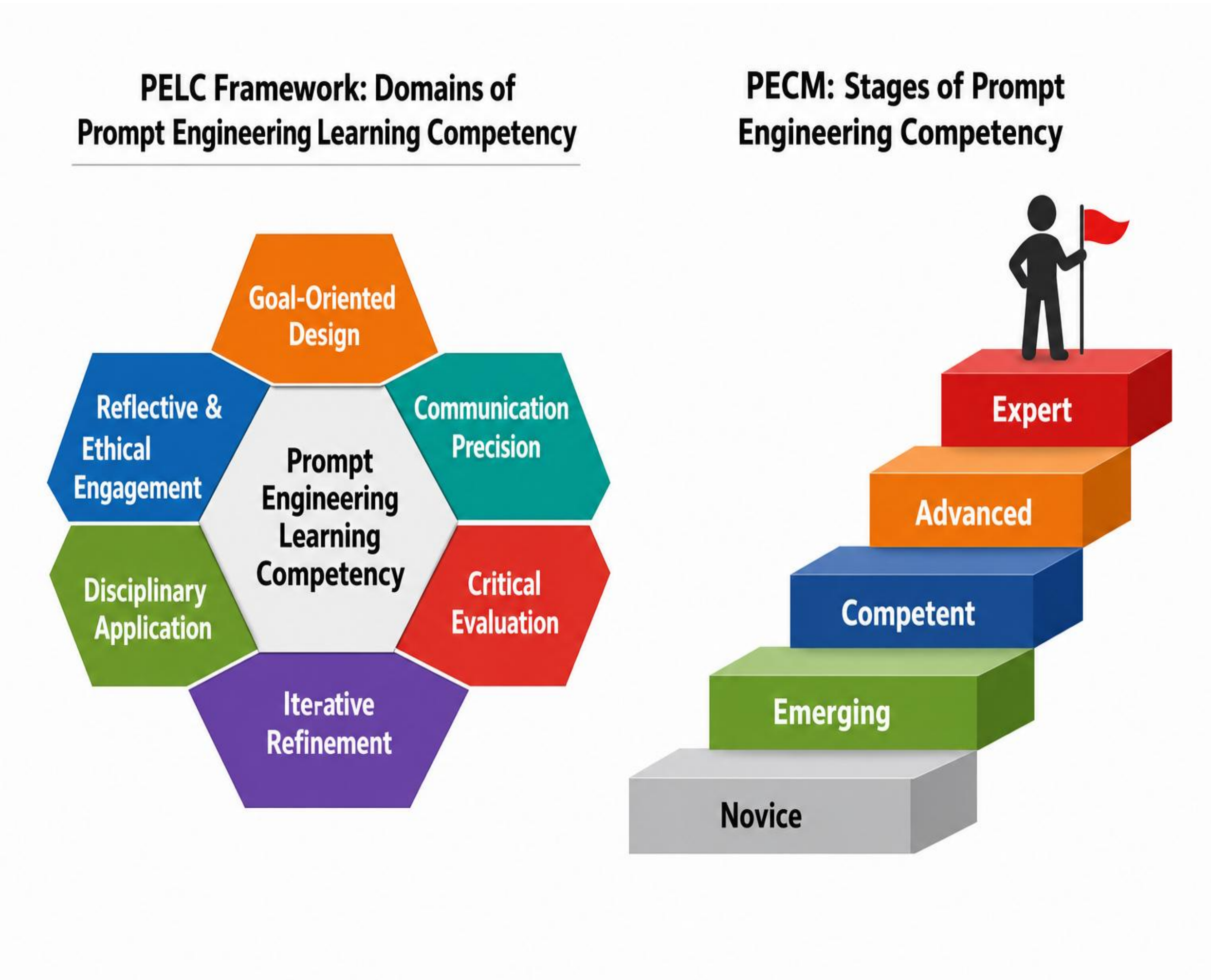
The Prompt Engineering Learning Competency (PELC) Framework identifies six interrelated competency domains that underpin effective AI-supported learning: goal-oriented design, communication precision, critical evaluation, iterative refinement, disciplinary application, and reflective and ethical engagement. Rather than functioning as isolated skills, these domains operate interactively throughout the learning process. Learners begin by defining clear learning goals, communicate effectively with AI through purposeful prompts, critically evaluate AI-generated responses, refine prompts based on reflection and feedback, apply new knowledge within disciplinary contexts, and engage responsibly with AI in ways that promote ethical and informed decision-making.

The Prompt Engineering Competency Model (PECM) complements the PELC Framework by describing learners' developmental progression from novice to emerging, competent, advanced, and expert prompt engineers. The model emphasizes that competency develops progressively through experience, reflective practice, increasing metacognitive awareness, and purposeful engagement with AI-supported inquiry. Advancement across the five levels reflects growth not only in technical proficiency but also in learners' ability to think critically, communicate effectively, solve disciplinary problems, and use AI responsibly.

Together, the PELC Framework and PECM provide a conceptual foundation for curriculum development, instructional practice, learner assessment, and teacher education by positioning prompt engineering as a multidimensional educational competency rather than merely a technical procedure (see Figure 1).

Figure **1**

Prompt Engineering Learning Competency (PELC) Framework and Prompt Engineering Competency Model (PECM).



The PELC Framework illustrates the six learner competency domains required for effective AI-supported learning, while the PECM Model depicts learners' developmental progression from novice to expert prompt engineers. The PELC Framework (left) presents six interrelated competency domains: Goal-Oriented Design, Communication Precision, Critical Evaluation, Iterative Refinement, Disciplinary Application, and Reflective & Ethical Engagement. The PECM (right) illustrates learners' developmental progression from Novice to Expert, demonstrating increasing autonomy, metacognitive awareness, disciplinary reasoning, and ethical engagement in AI-assisted inquiry. Figure 1 presents the conceptual relationship between the Prompt Engineering Learning Competency (PELC) Framework and the Prompt Engineering Competency Model (PECM), illustrating both the competency domains and learners' developmental progression in AI-supported learning.

5 Discussion

The findings of this study position prompt engineering as a learner-centred educational competency that extends beyond the technical optimization of AI-generated responses. Unlike existing AI literacy frameworks, which primarily emphasize digital competence, ethical AI use, and responsible technology integration (UNESCO, 2024; OECD, 2024), the proposed PELC Framework and PECM Model emphasize the competencies learners require to engage meaningfully with generative AI in science and mathematics education. This perspective reinforces the view that effective AI-supported learning depends not only on access to AI technologies but also on learners' ability to formulate purposeful prompts, evaluate AI-generated information critically, refine their interactions, and apply knowledge within disciplinary contexts. The findings are consistent with constructivist learning theory, which views knowledge as actively constructed through interaction and guided inquiry (Bruner, 1960; Vygotsky, 1978). Prompt engineering enables learners to engage in purposeful questioning, test ideas, receive immediate feedback, and refine their understanding through iterative dialogue with AI. Rather than replacing learner thinking, AI functions as a scaffold that supports deeper conceptual understanding and independent learning.

Similarly, the proposed models align with Self-Regulated Learning Theory. Zimmerman (2000) described self-regulation as a cyclical process involving planning, performance, monitoring, and reflection. The iterative refinement of prompts represented within both the PELC Framework and the PECM Model reflects this process by requiring learners to establish learning goals, evaluate AI-generated responses, identify misconceptions, and modify subsequent prompts. Consequently, prompt engineering promotes learner autonomy, metacognitive awareness, and reflective practice. The findings also support Cognitive Load Theory. Sweller's (1988) observation that cognitive load influences learning suggests that well-structured prompts can reduce unnecessary mental effort while directing learners' attention to essential concepts. In science and mathematics education, where abstract reasoning and complex problem-solving are common, purposeful prompt design may assist learners in organizing information more effectively, thereby supporting meaningful learning.

Furthermore, Inquiry-Based Learning provides an important lens for interpreting the findings. Consistent with Kolb's (1984) experiential learning cycle, learners engage in repeated cycles of questioning, investigation, interpretation, reflection, and refinement while interacting with AI systems. This iterative process strengthens inquiry, evidence-based reasoning, and disciplinary understanding, all of which are fundamental goals of science and mathematics education. A significant contribution of this paper is the reconceptualization of prompt engineering from a technical procedure to a multidimensional learning competency. While previous studies have acknowledged prompt engineering as an emerging AI skill (Federiakin et al., 2024; Lee & Palmer, 2025), they have generally focused on improving AI performance rather than explaining how learners develop prompt engineering competence. By proposing the PELC Framework and PECM Model, this study provides a conceptual foundation for understanding prompt engineering as an educational process that integrates communication, inquiry, critical thinking, metacognition, disciplinary application, and ethical engagement.

The proposed models have practical implications for science and mathematics education. They provide educators with a conceptual guide for designing AI-supported learning activities, assist curriculum developers in integrating prompt engineering into AI literacy initiatives, and offer researchers a theoretical foundation for future empirical validation. As generative AI becomes increasingly embedded within educational practice, recognizing prompt engineering as a learner competency may contribute to more effective, responsible, and meaningful human–AI collaboration.

6 Educational Implications

The findings of this study have several implications for science and mathematics education. First, curriculum developers should integrate prompt engineering into AI literacy initiatives as a learner competency that supports inquiry, reasoning, communication, and ethical decision-making rather than treating it solely as a technical AI skill. Second, teacher education programmes should prepare pre-service and in-service teachers to design learning activities that encourage learners to formulate effective prompts, critically evaluate AI-generated responses, and use AI responsibly within disciplinary contexts. Third, classroom assessment practices should extend beyond evaluating factual knowledge to include learners' ability to communicate effectively with AI, refine prompts through reflection, and demonstrate critical judgement when interpreting AI-generated information. Finally, the proposed PELC Framework and PECM Model may serve as conceptual guides for policymakers, curriculum developers, and educational researchers seeking to integrate prompt engineering into future AI literacy frameworks and STEM education initiatives.

7 Limitations and Future Research

This study is conceptual in nature and therefore does not provide empirical evidence to validate the proposed frameworks. The PELC Framework and PECM Model should be viewed as theoretically informed models that require empirical testing across diverse educational contexts, learner populations, and science and mathematics disciplines. Future research should examine the validity, reliability, and educational effectiveness of these models using qualitative, quantitative, and mixed-methods approaches. Longitudinal studies may also investigate how learners progress across the developmental stages proposed in the PECM Model and how prompt engineering competencies influence inquiry, problem-solving, critical thinking, and AI literacy in authentic classroom settings.

8 Conclusion

This paper reconceptualizes prompt engineering as a twenty-first-century learning competency that extends beyond the technical optimization of Artificial Intelligence (AI) systems. Drawing on constructivist learning, self-regulated learning, cognitive load theory, and inquiry-based learning, the study proposes two complementary conceptual models: the Prompt Engineering Learning Competency (PELC) Framework and the Prompt Engineering Competency Model (PECM). Together, these models provide a theoretical foundation for understanding how learners can engage effectively, critically, and ethically with generative AI in science and mathematics education. By positioning prompt engineering as a learner-centred educational competency rather than merely a technical skill, this study contributes to the growing discourse on AI literacy and STEM education. The proposed frameworks offer practical guidance for curriculum design, classroom practice, teacher education, learner assessment, and educational policy, while also providing a foundation for future empirical research. As generative AI continues to transform teaching and learning, preparing learners to interact thoughtfully and responsibly with AI will become increasingly important. Embedding prompt engineering within science and mathematics education has the potential to strengthen inquiry, critical thinking, communication, problem-solving, and self-regulated learning, thereby enabling learners not only to use AI effectively but also to collaborate with it in meaningful and responsible ways. Ultimately, recognizing prompt engineering as a learner-centered educational competency offers a pathway for preparing future learners to engage critically, creatively, and responsibly with Artificial Intelligence in an increasingly digital world.

9 Ethics Statement

This study did not involve human participants, animals, or primary data collection. As a conceptual investigation, it relied exclusively on published literature and policy documents. Consequently, formal ethical approval was not required. The study adhered to the principles of academic integrity by accurately representing existing scholarship, acknowledging intellectual contributions, and citing all sources in accordance with APA 7th edition guidelines. No external funding was received for this study.

10 Conflict of Interest Statement

The author declares that there are no financial, professional, institutional, or personal relationships that could be construed as potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author conducted the study independently and reports no competing interests.

11 Author Contributions

The author solely conceived and designed the study, conducted the literature synthesis, developed the Prompt Engineering Learning Competency (PELC) Framework and the Prompt Engineering Competency Model (PECM), interpreted the findings, and prepared the manuscript for publication

12 References

Bruner, J. S. (1960). *The process of education.* Harvard University Press.

Dede, C. (2010). *Comparing frameworks for 21st-century skills*. In J. Bellanca & R. Brandt (Eds.), 21st century skills: Rethinking how students learn (pp. 51–76). Solution Tree Press.

Federiakin, D., Molerov, D., Zlatkin-Troitschanskaia, O., & Maur, A. (2024). Prompt engineering as a new 21st-century skill. *Frontiers in Education*, *9*, Article 1366434. https://doi.org/10.3389/feduc.2024.1366434

Holmes, W., Bialik, M., & Fadel, C. (2019). *Artificial intelligence in education: Promises and implications for teaching and learning.* Center for Curriculum Redesign.

International Society for Technology in Education. (2024). *Artificial intelligence in education: Educator guidance.* ISTE.

Jaakkola, E. (2020). Designing conceptual articles: Four approaches. *AMS Review*, *10*(1–2), 18–26. https://doi.org/10.1007/s13162-020-00161-0

Kasneci, E., Sessler, K., Küchemann, S., Bannert, M., Dementieva, D., Fischer, F., Gasser, U., Groh, G., Günnemann, S., Hüllermeier, E., Krusche, S., Kutyniok, G., Michaeli, T., Nerdel, C., Pfeiffer, F., Poquet, O., Sailer, M., Schmidt, A., Seidel, T., Stadler, M., ... Kasneci, G. (2023). ChatGPT for good? On opportunities and challenges of large language models for education. *Learning and Individual Differences*, *103*, 102274. https://doi.org/10.1016/j.lindif.2023.102274

Kolb, D. A. (1984). *Experiential learning: Experience as the source of learning and development.* Prentice-Hall.

Lee, D., & Palmer, E. (2025). Prompt engineering in higher education: A systematic review to help inform curricula. *International Journal of Educational Technology in Higher Education*, *22*, Article 7. https://doi.org/10.1186/s41239-025-00503-7

Lo, C. K. (2023). What is the impact of ChatGPT on education? A rapid review of the literature. *Education Sciences*, *13*(4), 410. https://doi.org/10.3390/educsci13040410

Luckin, R. (2018). *Machine learning and human intelligence: The future of education for the 21st century.* UCL Institute of Education Press.

National Council of Teachers of Mathematics. (2023). *Artificial intelligence and mathematics education.* NCTM.

National Science Teaching Association. (2024). Artificial intelligence for science education. NSTA.

Organisation for Economic Co-operation and Development. (2024). *OECD digital education outlook 2024: Towards equitable and responsible AI in education.* OECD Publishing.

Qian, Y. (2025). Prompt engineering in education: A systematic review of approaches and educational applications. *Journal of Educational Computing Research*, *63*(7–8), 1782–1818. https://doi.org/10.1177/07356331251365l8

Schraw, G., Crippen, K. J., & Hartley, K. (2006). Promoting self-regulation in science education: Metacognition as part of a broader perspective on learning. *Research in Science Education*, *36*(1–2), 111–139. https://doi.org/10.1007/s11165-005-3917-8

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, *12*(2), 257–285. https://doi.org/10.1207/s15516709cog12024

UNESCO. (2024). *Artificial intelligence competency frameworks for teachers and learners.* UNESCO.

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes.* Harvard University Press.

Zimmerman, B. J. (2000). *Attaining self-regulation: A social cognitive perspective.* In M. Boekaerts, P. R. Pintrich, & M. Zeidner (Eds.), Handbook of self-regulation (pp. 13–39). Academic Press.

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