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From Dialogue to Depth: A Conceptual Model of Generative Artificial Intelligence Mediated Learning in Physics Education

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Abstract

The rapid uptake of generative artificial intelligence (GenAI) in science education calls for theoretical frameworks that explain how AI-mediated interaction shapes learning processes, rather than merely whether particular tools are effective. This conceptual paper proposes the Dialogue-to-Depth model as a theory-building framework for understanding how GenAI can support complementary epistemic functions in physics education. The model conceptualises learning as a pedagogical movement from dialogic exploration, in which learners externalise intuitive ideas, negotiate meaning, and engage in explanatory questioning, toward analytic consolidation, in which emerging conceptions are stabilised through formal representations, canonical explanations, and disciplinary language. Drawing on constructivist and sociocognitive perspectives, engagement-oriented theories, productive

failure, and contemporary work on AI literacy, the model positions generative AI as an epistemic mediator whose pedagogical role is enacted through instructional framing and teacher orchestration rather than determined by platform-specific affordances. The paper articulates theoretical implications for conceptual change research and AI-in-education, derives design-oriented principles for AI-supported physics pedagogy, and outlines a research agenda for empirical validation of the proposed trajectory across topics and learner populations. By offering a coherent conceptual vocabulary linking dialogue to depth, the model aims to support principled integration of GenAI into physics classrooms in ways that preserve learner agency, foster critical engagement with AI-generated explanations, and promote deep conceptual understanding.

Keywords: Generative Artificial Intelligence, Physics Education, Dialogic Learning, Conceptual Change, AI Literacy

Introduction

Generative artificial intelligence (GenAI) has rapidly entered educational practice, reshaping how learners seek explanations, test ideas, and produce disciplinary discourse. Large language models can sustain multi-turn dialogue, reformulate student ideas in scientific language, and generate worked explanations, thereby functioning not merely as information sources but as interactional partners that structure the epistemic flow of inquiry. Despite accelerating adoption, research on GenAI in education remains largely tool-centred and outcome-oriented, with comparatively fewer theory-building accounts that explain how AI-mediated interaction participates in conceptual development. Recent reviews and empirical studies highlight both promise and risk: conversational agents can scaffold explanation and reflection, yet they can also foster overreliance and the uptake of rhetorically fluent but conceptually shallow accounts, underscoring the need for theoretical models that foreground epistemic processes rather than performance alone ^[1, 2]. These tensions are particularly salient in physics education, where learning depends on coordinating intuitive reasoning with formal representations and causal principles through iterative articulation, challenge, and refinement of explanations ^[3, 4].

Existing learning theories offer partial resources for interpreting AI-mediated learning but do not yet fully conceptualise GenAI as an epistemic participant in classroom discourse. Constructivist and sociocognitive traditions emphasise dialogue, cognitive conflict, and guided participation as mechanisms of conceptual change ^[5, 6], while engagement-oriented models such as ICAP link interactive and constructive activity to deeper learning ^[7]. Complementary perspectives, including productive failure and cognitive load theory, highlight the pedagogical value of sequencing exploratory struggle before analytic consolidation and of managing representational demands during formalisation ^[8]. In parallel, emerging work on AI literacy stresses the epistemic work required to evaluate machine-generated claims and to calibrate trust in probabilistic systems,

especially when outputs appear authoritative [9, 10]. Together, these strands suggest the need for a unifying conceptual framework that situates GenAI within the epistemic ecology of physics learning, clarifying how dialogic sense-making and analytic consolidation are differentially supported within designed activity systems.

This conceptual paper advances the Dialogue-to-Depth model to address this theoretical gap. The model conceptualises AI-mediated learning as a pedagogical movement from dialogic exploration toward analytic consolidation. In the exploratory phase, AI-supported dialogue can catalyse the externalisation of intuitive ideas, prompt why/how questioning, and generate productive cognitive conflict that supports metacognitive reflection and conceptual reorganisation. In the consolidation phase, analytically structured AI support can stabilise emerging conceptions through formal definitions, symbolic representations, and disciplinary precision, aligning students' explanations with canonical physics models. Importantly, the model does not attribute these functions to particular platforms; rather, it interprets dialogic and analytic interaction as pedagogical roles enacted through instructional framing, prompting practices, and teacher orchestration within inquiry-oriented physics classrooms [11, 12].

The purpose of this paper is to articulate the Dialogue-to-Depth model as a theory-building contribution that integrates insights from constructivist and sociocognitive perspectives, engagement theory, and contemporary work on AI literacy. The paper positions GenAI not simply as a tool but as an epistemic mediator whose interactional form can differentially support exploratory sense-making and formal conceptual alignment. By offering a conceptual vocabulary that links dialogic inquiry to analytic consolidation, the model aims to guide instructional design and generate testable propositions for future empirical research on conceptual change, engagement, and explanation in AI-supported physics education.

Theoretical Foundations

Contemporary accounts of learning in science education converge on the view that conceptual understanding emerges through active sense-making, dialogic negotiation of meaning, and the progressive coordination of intuitive ideas with formal representations. Constructivist and sociocognitive traditions frame learning as a process of knowledge construction mediated by interaction, discourse, and guided participation, in which learners externalise ideas, encounter cognitive conflict, and reorganise their conceptual structures through socially supported activity [3, 4]. In physics education, these processes are especially salient because students' everyday intuitions about motion, force, and energy frequently diverge from canonical models, necessitating instructional designs that foreground articulation, challenge, and refinement of explanations [13]. Empirical research on students' misconceptions in thermal physics further illustrates the persistence of alternative conceptions even at the university level [14]. Within this tradition, dialogue functions not merely as a vehicle for transmitting information but as an epistemic practice through which learners appropriate disciplinary ways of reasoning, including causal explanation, evidentiary justification, and conditional reasoning.

Engagement-oriented perspectives complement constructivist accounts by theorising how observable learning activities relate to underlying cognitive processing. The ICAP framework distinguishes interactive and constructive forms of engagement, which are associated with deeper learning, from active and passive forms that tend to support more superficial processing [7]. This distinction is consequential for theorising AI-mediated learning because generative systems can either invite dialogic co-construction of meaning or promote procedural uptake of authoritative explanations, depending on how interaction is framed. Productive failure further refines this engagement perspective by arguing that initial exploratory struggle, when followed by structured consolidation, can enhance transfer and conceptual coherence [15]. Cognitive load theory adds an information-processing lens, emphasising the need to manage representational demands during formalisation so that learners can integrate multiple elements into coherent schemas without excessive extraneous load [8]. Together, these perspectives motivate a sequenced view of learning in which dialogic exploration and analytic consolidation perform complementary epistemic functions.

The incorporation of conversational agents into learning environments extends these theoretical commitments by introducing a non-human participant into the classroom's dialogic ecology. Research on intelligent tutoring systems and pedagogical conversational agents has shown that mixed-initiative dialogue, why/how prompting, and contingent feedback can support conceptual understanding and metacognitive reflection, particularly when interactions are designed to surface and repair misconceptions [11, 16]. However, generative AI differs from earlier tutoring systems in its breadth of linguistic competence and its capacity to produce fluent, domain-appropriate discourse across topics. This amplifies longstanding epistemic concerns in science education regarding the authority of explanations and the risk that learners may appropriate canonical language without reconstructing causal relations. Recent analyses of large language models in education underscore the dual potential of such systems to scaffold explanation and to foster overreliance or uncritical acceptance, thereby heightening the importance of instructional designs that cultivate epistemic vigilance and reflective judgement [17]. Finally, the emerging literature on AI literacy foregrounds the epistemic competencies required to learn with generative systems, including the ability to interrogate sources, evaluate the plausibility of explanations, and calibrate trust in probabilistic outputs that may appear rhetorically authoritative [9]. From this perspective, learning with AI entails not only disciplinary sense-making but also meta-epistemic work oriented to the status and limitations of machine-generated knowledge claims. Integrating constructivist and sociocognitive theories with engagement models, productive failure, cognitive load theory, and AI literacy yields a coherent theoretical basis for conceptualising AI-mediated learning as a dynamic movement between dialogic exploration and analytic consolidation. This synthesis provides the theoretical grounding for the Dialogue-to-Depth model developed in this paper, situating generative AI as an epistemic mediator whose interactional form can differentially support sense-making and formalisation within physics learning.

Generative AI as Epistemic Agent in Physics Learning

The growing presence of generative artificial intelligence in classrooms necessitates a reconceptualization of the epistemic landscape of learning, particularly in disciplines such as physics where knowledge claims are tightly coupled to causal explanation, formal representation, and evidentiary justification. Unlike earlier educational technologies that primarily delivered content or scaffolded practice, large language models participate in interactional sequences by producing explanations, posing questions, and modelling disciplinary discourse. In doing so, they occupy an epistemic position within classroom activity systems, shaping what counts as a plausible explanation, how problems are framed, and which forms of reasoning are made salient. Recent analyses of generative AI in education emphasise that these systems function as epistemic mediators rather than neutral tools, influencing learners' sense-making trajectories through the conversational affordances and rhetorical authority of their outputs [1]. This shift raises foundational questions about authority, agency, and the distribution of epistemic work across human and artificial participants in physics learning.

In physics classrooms, where students' everyday intuitions often conflict with formal models, dialogic interaction plays a crucial role in externalising and revising ideas. Research on pedagogical conversational agents and intelligent tutoring systems has shown that mixed-initiative dialogue, contingent feedback, and why/how prompting can support conceptual change by eliciting learners' reasoning and confronting misconceptions in situ [18, 19]. Complementary research in physics education also highlights the pedagogical importance of carefully designed instructional activities and demonstrations that help students visualise and reason about abstract thermal concepts [20]. Generative AI extends these affordances by enabling open-ended dialogue across a wide range of physics topics, potentially supporting iterative cycles of hypothesis generation, critique, and refinement. However, the same conversational fluency that makes generative AI engaging also amplifies epistemic risks. Learners may attribute undue authority to AI-generated explanations, particularly when responses are linguistically polished and align with canonical formulations, even when underlying causal relations are incompletely understood. Recent empirical and critical accounts caution that such dynamics can foster epistemic outsourcing, in which responsibility for sense-making is tacitly transferred to the system, undermining the productive struggle central to conceptual development [17, 9].

The epistemic positioning of generative AI is further shaped by instructional framing and classroom norms. When AI is framed as a conversational partner that invites questioning and revision, it can function as a catalyst for dialogic exploration, prompting learners to articulate intuitions, confront inconsistencies, and engage in metacognitive reflection. Conversely, when AI is framed as an authoritative source of correct answers, interaction tends to privilege analytic consolidation, with students adopting formal definitions and procedures with limited discursive negotiation. Studies of human tutoring and intelligent tutoring systems suggest that the learning benefits of dialogue depend less on the mere availability of explanations than on the extent to which interactions are designed to elicit learner-generated reasoning and to make discrepancies between expectation and canonical models

salient [19]. Contemporary work on AI-driven pedagogical strategies similarly highlights the importance of teacher orchestration in positioning AI within classroom discourse in ways that sustain epistemic agency and critical engagement [12].

Finally, the epistemic role of generative AI intersects with the development of AI literacy and critical information practices. Physics learners must not only engage with disciplinary content but also evaluate the provenance, plausibility, and limitations of AI-generated claims. The capacity to interrogate sources, cross-check explanations, and calibrate trust in probabilistic outputs is increasingly recognised as a core component of scientific literacy in digitally mediated environments [10]. From this perspective, generative AI becomes a site for meta-epistemic learning, where students practice discerning the boundaries of authoritative knowledge and the conditions under which explanations warrant acceptance or further scrutiny. Conceptualising generative AI as an epistemic agent thus foregrounds both its potential to scaffold dialogic sense-making in physics and the necessity of pedagogical designs that preserve learner agency and cultivate critical epistemic judgement.

The Dialogue-to-Depth Model

The Dialogue-to-Depth model is proposed as a conceptual framework for theorising how generative artificial intelligence mediates complementary epistemic functions within physics learning, particularly in inquiry-oriented classroom contexts. The model conceptualises learning as a pedagogical movement from dialogic exploration to analytic consolidation, reflecting a dynamic sequence through which learners externalise intuitive ideas, negotiate meaning, and progressively align their reasoning with disciplinary norms. This movement is not conceived as a fixed instructional script but as a recurrent trajectory that can unfold across activities and lessons, shaped by task design, teacher orchestration, and the interactional affordances of AI systems. Contemporary accounts of science learning emphasise that conceptual development is iterative and distributed across discourse, representations, and social mediation, rather than a linear transition from misconception to correct conception [4, 3]. The Dialogue-to-Depth model situates generative AI within this distributed process by articulating how different interactional forms can support distinct phases of sense-making and formalisation.

In the dialogic exploration phase, generative AI can function as a conversational catalyst that prompts learners to articulate prior conceptions, pose "why" and "how" questions, and encounter productive cognitive conflict. Dialogic interaction supports the externalisation of tacit intuitions and the negotiation of meaning through iterative questioning and reformulation, processes that are central to constructivist and sociocognitive accounts of conceptual change [5, 6]. Engagement-oriented models further suggest that interactive and constructive dialogue affords deeper cognitive processing by requiring learners to generate inferences and coordinate perspectives [7]. When positioned as a dialogic partner rather than an authoritative source, generative AI can scaffold these processes by modelling disciplinary questioning practices, offering counterexamples, and inviting reflection on inconsistencies between everyday reasoning and formal physics principles. Such dialogic scaffolding aligns with evidence from mixed-

initiative tutoring systems showing that why/how prompting and expectation-driven feedback can elicit conceptual revision in physics learning ^[11, 19].

The analytic consolidation phase involves the stabilisation and formalisation of emerging conceptions through structured explanations, canonical definitions, and symbolic representations. From an information-processing perspective, consolidation requires integrating multiple conceptual elements into coherent schemas, a process sensitive to cognitive load and representational clarity ^[8]. Instructional models such as productive failure further argue that the pedagogical value of exploration is realised when learners subsequently encounter explicit organisation of concepts and procedures that enable them to reframe and systematise their prior struggle ^[15]. Within the Dialogue-to-Depth model, analytically structured AI support can contribute to this consolidation by providing formal derivations, precise terminology, and coherent representational links that align students' emergent explanations with disciplinary standards. However, the model emphasises that analytic consolidation is most epistemically productive when it follows, rather than replaces, dialogic exploration, preserving the learner's agency in reconstructing understanding rather than merely adopting authoritative formulations.

Crucially, the Dialogue-to-Depth model does not attribute dialogic or analytic functions to specific AI platforms as inherent properties. Instead, it conceptualises these functions as pedagogical roles enacted through instructional framing, prompting practices, and classroom norms that position AI within the learning ecology. Generative AI can be orchestrated to invite exploratory dialogue or to provide analytic consolidation, and these roles may alternate within a single lesson or learning sequence. This perspective aligns with sociocultural accounts of mediation, which view tools as acquiring pedagogical meaning through use within activity systems rather than through intrinsic features alone ^[6]. By foregrounding the movement from dialogue to depth as a designable trajectory, the model offers a conceptual vocabulary for interpreting how AI-mediated interaction can support complementary epistemic functions in physics learning and for guiding the design of hybrid pedagogical sequences that balance inquiry with formalisation.

Positioning the Model Within Existing Pedagogical Frameworks

The Dialogue-to-Depth model can be situated within, and differentiated from, established pedagogical frameworks in science education that conceptualise learning as a progression through phases of exploration, sense-making, and formalisation. Inquiry-oriented models, including learning cycles and the 5E framework, emphasise the sequencing of engagement, exploration, explanation, elaboration, and evaluation as a means of supporting conceptual development through iterative interaction with phenomena and representations. Empirical and theoretical work grounded in these traditions underscores the pedagogical value of beginning with learner-generated ideas and experiences before introducing formal explanations, thereby fostering conceptual change through cycles of cognitive conflict and resolution ^[3]. The Dialogue-to-Depth model aligns with these principles in its emphasis on dialogic exploration preceding analytic consolidation, but it extends them by explicitly theorising the epistemic role of

generative AI as a mediator of both phases, rather than treating exploration and explanation as exclusively human-facilitated processes.

Comparisons with productive failure further clarify the distinctive contribution of the Dialogue-to-Depth model. Productive failure argues that initial failure during unguided or minimally guided exploration can prepare learners to benefit more deeply from subsequent instruction, as prior struggle sensitises learners to key problem features and conceptual structures ^[15]. The Dialogue-to-Depth model resonates with this logic by conceptualising dialogic AI-supported exploration as a preparatory phase that surfaces intuitions and gaps in understanding, thereby rendering analytic consolidation more meaningful. However, whereas productive failure has been primarily operationalised in terms of task sequencing and problem design, the Dialogue-to-Depth model foregrounds the interactional form of mediation, emphasising how dialogic versus analytic modes of AI support shape the epistemic character of exploration and consolidation. This interactional emphasis responds to recent calls to attend more closely to discourse and mediation in theorising the mechanisms through which productive struggle contributes to learning ^[7].

The model also intersects with engagement-oriented frameworks, particularly ICAP, which differentiates learning activities by the generativity of learner engagement. The dialogic exploration phase corresponds to interactive and constructive engagement, in which learners co-construct meaning through dialogue and generate inferences beyond provided information, while the analytic consolidation phase is often associated with more structured activity that may involve active manipulation of representations or guided reception of formal explanations. While ICAP provides a powerful analytic lens for categorising engagement modes, it does not specify pedagogical sequences or design trajectories. The Dialogue-to-Depth model complements ICAP by offering a design-oriented account of how different engagement modes can be orchestrated over time to support conceptual development in AI-mediated environments, thereby bridging analytic classification and pedagogical design ^[7].

Finally, the Dialogue-to-Depth model can be positioned relative to contemporary frameworks for technology-enhanced learning and intelligent tutoring systems. Prior research on human tutoring and ITSs indicates that the effectiveness of instructional support depends not only on the accuracy of feedback but also on the dialogic quality of interaction, including the extent to which systems prompt learners to articulate reasoning and confront inconsistencies ^[19]. The present model extends these insights to generative AI by conceptualising dialogic and analytic interaction as complementary pedagogical roles that can be dynamically orchestrated within inquiry-based physics instruction. In doing so, the Dialogue-to-Depth model contributes a conceptual bridge between established pedagogical sequences in science education and emerging forms of AI-mediated interaction, offering a framework for interpreting and designing learning trajectories that integrate exploratory dialogue with formal consolidation in ways that preserve learner agency and epistemic rigor.

Design Principles for AI-Supported Physics Pedagogy

The Dialogue-to-Depth model implies a set of design-oriented principles for integrating generative artificial

intelligence into physics pedagogy in ways that preserve epistemic rigor while leveraging the dialogic and analytic affordances of AI-mediated interaction. Central to these principles is the recognition that the pedagogical value of AI does not reside in the provision of immediate correct answers, but in how interaction is structured to elicit learner-generated reasoning and to support the progressive alignment of intuitive conceptions with disciplinary models. Research on inquiry-based science education consistently indicates that instructional designs that foreground articulation, questioning, and explanation are more likely to promote conceptual change than designs that prioritise efficient transmission of canonical knowledge [3]. In AI-supported contexts, this entails framing AI as a partner in sense-making rather than as an authoritative oracle, thereby positioning dialogic interaction as a primary resource for conceptual exploration.

A second design implication concerns the deliberate sequencing of dialogic exploration and analytic consolidation. Theoretical and empirical work on productive failure and engagement-oriented learning suggests that learners benefit from opportunities to grapple with problems and articulate partial explanations prior to encountering formalised instruction, as such struggle sensitises them to underlying structures and enhances the meaningfulness of subsequent consolidation [15]. Within AI-mediated physics learning, this implies designing tasks and prompts that encourage students to first articulate intuitions and hypotheses through dialogue with AI, followed by structured opportunities to compare these emergent ideas with canonical representations and principles. Such sequencing can mitigate the risk that AI-generated explanations prematurely close down inquiry, while still leveraging AI's capacity to support formalisation when learners are prepared to integrate more structured accounts. Teacher orchestration remains a critical design consideration in AI-supported pedagogy. Studies of intelligent tutoring systems and classroom-based technology integration indicate that the learning value of digital supports is contingent on how teachers frame their epistemic role, regulate interactional norms, and connect AI-mediated activity to broader curricular goals [11]. In physics classrooms, teachers play a central role in positioning AI within the activity system, signalling when AI-generated explanations should be treated as hypotheses to be scrutinised rather than authoritative conclusions to be adopted. This orchestration includes designing prompts, modelling epistemic questioning, and facilitating reflective discussion that connects AI-mediated dialogue to experimental evidence, representations, and formal derivations. Recent analyses of AI-driven pedagogical strategies further emphasise the importance of equity-oriented design and accessibility considerations, ensuring that AI-supported activities do not exacerbate existing disparities in participation or epistemic agency [12].

Finally, the integration of generative AI into physics pedagogy necessitates explicit attention to AI literacy as an instructional objective. Learners must develop the capacity to critically evaluate AI-generated claims, recognise the probabilistic and fallible nature of machine outputs, and triangulate explanations with empirical evidence and disciplinary sources [10, 21]. Contemporary research on digital and AI literacies underscores that such epistemic competencies are not ancillary but central to scientific

literacy in digitally mediated learning environments [22]. Embedding opportunities for source evaluation, cross-checking, and reflective judgement within AI-supported physics tasks aligns with the Dialogue-to-Depth model's emphasis on preserving learner agency and epistemic responsibility across both dialogic exploration and analytic consolidation. By foregrounding these design principles, the model provides a theoretically grounded basis for developing AI-supported instructional sequences that harness the affordances of generative AI while safeguarding the epistemic integrity of physics learning.

Theoretical Implications and Research Agenda

The Dialogue-to-Depth model carries several theoretical implications for research on learning with generative artificial intelligence, particularly within physics education and the learning sciences more broadly. First, the model reframes AI-mediated interaction as an epistemic process rather than a mere instructional aid, thereby extending constructivist and sociocognitive accounts of learning to encompass non-human participants in dialogic sense-making. By conceptualising generative AI as an epistemic mediator that can differentially support dialogic exploration and analytic consolidation, the model contributes to emerging theoretical discussions about distributed cognition and the reconfiguration of agency in digitally mediated learning environments. Recent scholarship in AI-education has argued that learning with generative systems entails a redistribution of epistemic work across learners, teachers, and algorithmic agents, with important implications for how responsibility for sense-making is conceptualised [23]. The Dialogue-to-Depth model provides a conceptual vocabulary for articulating this redistribution in terms of complementary epistemic functions enacted through interactional form rather than tool-specific features. Second, the model offers a theoretical bridge between engagement-oriented frameworks and conceptual change research. Engagement models such as ICAP have demonstrated that interactive and constructive activities are associated with deeper learning outcomes, yet they remain largely descriptive regarding pedagogical sequencing. By embedding dialogic engagement within a broader trajectory that culminates in analytic consolidation, the Dialogue-to-Depth model specifies a temporal organisation of engagement that aligns with evidence from productive failure research, which emphasises the pedagogical value of initial exploration prior to formal instruction [15]. This temporal articulation suggests new theoretical questions about the optimal orchestration of engagement modes in AI-mediated environments, including how transitions between dialogic and analytic interaction can be designed to maximise conceptual integration without overwhelming learners' cognitive resources [8].

Third, the model foregrounds the epistemic dimension of AI literacy as integral to disciplinary learning, rather than as an ancillary digital skill. The capacity to interrogate AI-generated explanations, evaluate evidentiary support, and calibrate trust in probabilistic outputs becomes a constitutive component of physics learning when generative systems are embedded in inquiry activity. This reframing aligns with contemporary accounts of scientific literacy that emphasise critical evaluation of sources and claims in digitally mediated information ecologies [9]. The Dialogue-to-Depth model thus invites theoretical integration between research

on conceptual change and emerging frameworks of AI literacy, suggesting that epistemic vigilance toward AI outputs may be a precondition for the productive alignment of dialogic exploration with analytic consolidation.

In terms of a research agenda, the model generates several testable propositions and directions for empirical investigation. One line of inquiry concerns the conditions under which dialogic AI-supported exploration leads to greater conceptual reorganisation than analytically structured AI support provided prematurely, and how this relation varies across physics topics with differing representational demands. Another direction involves examining how teacher orchestration and classroom norms mediate the epistemic positioning of AI and the sequencing of dialogic and analytic interaction, with implications for equity and participation in AI-supported inquiry. Longitudinal research is also needed to investigate whether sustained engagement with Dialogue-to-Depth-informed designs fosters durable changes in students' explanatory practices, epistemic beliefs, and reliance on AI over time. Methodologically, mixed-methods designs that integrate discourse analysis, artifact-based reasoning measures, and learning analytics can provide the evidentiary basis for refining the model and evaluating its theoretical claims [24, 23].

Collectively, these theoretical implications and research directions position the Dialogue-to-Depth model as a generative framework for organising inquiry into AI-mediated learning processes. By linking dialogic engagement, analytic consolidation, and AI literacy within a coherent conceptual architecture, the model contributes to ongoing theoretical work on how generative AI reshapes the epistemic conditions of physics education and offers a foundation for programmatic research that integrates theory, design, and empirical validation.

Limitations of the Model

Although the Dialogue-to-Depth model offers a coherent conceptual framework for theorising generative AI-mediated learning in physics education, several limitations delimit its current scope and suggest directions for refinement. First, the model is theory-building in nature and has not yet been subjected to systematic empirical validation across diverse educational contexts. Conceptual frameworks gain explanatory power through iterative cycles of empirical testing and theoretical revision, and the present articulation should therefore be understood as a heuristic rather than a definitive account of how AI-mediated dialogue and analytic consolidation function in practice. Prior research on pedagogical sequencing, including productive failure and inquiry-based learning, indicates that the efficacy of exploration-consolidation trajectories is sensitive to domain characteristics, task design, and learner prior knowledge [3]. It follows that the Dialogue-to-Depth model may not generalise uniformly across physics topics with differing representational demands or across learner populations with varying levels of disciplinary preparedness.

A second limitation concerns the abstraction level at which the model operates. By design, the Dialogue-to-Depth framework focuses on interactional form and epistemic function rather than on the technical affordances of specific AI systems. While this abstraction supports portability across platforms, it may obscure important micro-level features of AI interfaces, prompting mechanisms, and

response styles that shape learners' engagement and interpretation of explanations. Research on intelligent tutoring systems and conversational agents demonstrates that subtle design features, such as feedback timing, question framing, and the balance between initiative and responsiveness, materially influence learning processes [11]. As generative AI systems continue to evolve, future iterations of the model will need to account more explicitly for how interface and interaction design mediate the enactment of dialogic exploration and analytic consolidation.

Third, the model foregrounds epistemic processes but does not explicitly integrate motivational, affective, and identity-related dimensions of learning with AI. Recent studies in AI-in-education suggest that learners' trust in AI, perceptions of competence, and affective responses to conversational agents can shape engagement patterns and willingness to persist in inquiry, with implications for conceptual development over time [17]. The Dialogue-to-Depth model currently treats dialogic exploration and analytic consolidation primarily as cognitive-epistemic functions, leaving under-theorised how affective and motivational dynamics may facilitate or constrain movement along the proposed trajectory. Integrating insights from motivational theories and socio-emotional learning with the model would enhance its explanatory reach and better reflect the complexity of classroom learning ecologies.

Finally, the model assumes a pedagogical environment in which teacher orchestration and curricular framing actively regulate the epistemic role of AI. In less structured or informal learning contexts, where learners interact with generative AI outside of teacher-guided activity systems, the dialogic-analytic trajectory may unfold differently or collapse into patterns of epistemic outsourcing. The growing prevalence of out-of-school AI use underscores the need to examine how the Dialogue-to-Depth model operates beyond formal classroom settings and how learners' AI literacy mediates the epistemic consequences of such interactions [9, 10]. Addressing these limitations through empirical investigation and theoretical integration will be essential for strengthening the model's validity and for clarifying the boundary conditions under which Dialogue-to-Depth provides a useful account of AI-mediated physics learning.

Conclusion

This conceptual paper has advanced the Dialogue-to-Depth model as a theoretical framework for understanding how generative artificial intelligence mediates complementary epistemic functions in physics education. By conceptualising learning as a pedagogical movement from dialogic exploration toward analytic consolidation, the model provides a vocabulary for interpreting how AI-mediated interaction can support the externalisation of intuitive ideas, the negotiation of meaning, and the subsequent formalisation of emerging conceptions in alignment with disciplinary standards. In doing so, the paper responds to calls in the AI-in-education literature for theory-building work that moves beyond tool-centric evaluation toward principled accounts of how generative systems participate in learning processes and reshape the epistemic conditions of classroom inquiry.

The Dialogue-to-Depth model contributes to ongoing theoretical integration across constructivist and sociocognitive traditions, engagement-oriented frameworks,

and contemporary perspectives on AI literacy. By foregrounding the interactional form of mediation rather than platform-specific affordances, the model conceptualises generative AI as an epistemic mediator whose pedagogical role is enacted through instructional framing, prompting practices, and teacher orchestration. This perspective preserves learner agency and situates AI within a broader activity system in which responsibility for sense-making is anchored in human participation. At the same time, the model highlights the epistemic risks associated with the rhetorical authority of AI-generated explanations and underscores the necessity of designing for critical engagement and reflective judgement when AI is embedded in physics learning environments.

Beyond its immediate conceptual contribution, the Dialogue-to-Depth model offers a generative research programme for future work on AI-mediated learning. The framework invites empirical testing across physics topics, learner populations, and instructional designs, as well as methodological innovation that can trace transitions between dialogic exploration and analytic consolidation over time. By articulating a designable trajectory that links inquiry to formalisation, the model aims to realise the pedagogical potential of generative AI while safeguarding the epistemic integrity of physics education. Ultimately, developing theoretically grounded accounts of how AI reshapes learning processes is essential for ensuring that the integration of generative technologies in classrooms supports not only efficiency and access but also deep conceptual understanding and scientific ways of knowing.

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