

Ontology-driven Semantic Retrieval for Human-Centred Interdisciplinary Curriculum Design in Secondary Education

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Abstract

Secondary education faces two pressures at once: generative AI has entered classrooms faster than schools can manage it, and the questions that shape informed citizenship (climate and energy, bioethics, the societal role of AI) cannot be explained through a single subject. Schools are poorly equipped for the second task because teacher expertise is organized along disciplinary boundaries. This paper introduces KNOTS (Knowledge Networks for Ontology-driven Teaching Systems), a two-year project that treats the two as one problem: an environment in which teachers co-design interdisciplinary learning pathways with an AI system whose knowledge base they own and validate. The architecture couples an open-weight local model with a semantic layer of domain ontologies, one per discipline, connected through explicitly typed cross-disciplinary relations rather than merged into a single schema. Retrieval is graph-constrained, so every proposed connection between subjects is traceable to its source passages and to the graph path that justified it, and no link enters the graph unless the teachers of both subjects approve it. The project runs a human-in-the-loop cycle over two school years: an AI competence framework and teacher training, collaborative design of an interdisciplinary Civic Education module on AI, and classroom piloting through action research. Expected outcomes are a reusable tool for schools, evidence on whether graph-constrained retrieval outperforms dense retrieval on cross-subject design, and a transferable model of school-AI convergence.

Keywords

Interdisciplinary curriculum design, Retrieval-Augmented Generation, Ontologies, Open-weight local LLMs, AI literacy, Human-in-the-loop

1. Introduction

KNOTS starts from two needs that are usually addressed separately and are better addressed together. The first is pedagogical. To make sense of the issues that fill public debate today (the energy transition, bioethical dilemmas, changes in international relations, AI itself) students need conceptual tools that no single school subject can give them, and schools are at a disadvantage: teaching is organized by subject and teachers are trained as specialists. The second is that generative AI is already in the classroom, on the students' side, and mostly without supervision. Banning it cannot be enforced and mainly pushes its use out of sight; accepting it passively means giving up the idea that formal education still sets the terms of learning. What is left is the harder option, critical and constructive at once, and it requires teachers who understand these systems well enough to mediate between them and their students. KNOTS uses the second need to address the first. If the obstacle to interdisciplinary teaching is that each teacher's expertise only goes so far, a system that proposes defensible connections between subjects addresses a real problem. Two conditions cannot be given up in a school: content must be reliable and traceable, since a convincing but invented statement in a curriculum is not a small matter, and personal data must

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stay under the school’s control. These push the design towards teacher-curated material, open-weight models running locally, and an explicit semantic layer rather than a general-purpose chat-bot.

2. Background and Related Work

2.1. Governance frameworks

Research on generative AI in schools is held back less by technical problems than by the lack of stable rules to refer to. UNESCO’s guidance [1] was followed by competence frameworks for students [2] and teachers [3]; at European level the updated guidelines on the ethical use of AI in teaching [4] sit alongside the AI Act [5], whose obligations for high-risk systems in education apply from August 2026, and the OECD–European Commission AILit framework [6]. The Italian reference document is the 2025 ministerial guidelines [7]. Reviews of these documents [8] find agreement on four points (protecting data, tracking how content is produced, keeping humans in charge, training teachers on the technical and ethical side) and say very little about how schools should actually do this. Without practical guidance, generative AI in schools comes down to adopting platforms for small tasks with no wider curricular reason, while teachers are left with the rest. KNOTS is placed in that gap: it treats the four points as requirements on the architecture rather than as policy statements.

2.2. Grounding, locality, and semantic structure

Retrieval-Augmented Generation is the usual answer to worries about reliability [9]: restricting the generator to a checked corpus reduces invented content and makes output traceable, and surveys of educational uses report both the promise and the recurring problems [10]. Running the model locally handles data protection, and recent work shows that fairly small models on the institution’s own hardware are already good enough for producing teaching material and supporting assessment [11]. Pedagogical quality is the hardest thing to measure, which has led to rubric-based, multi-metric evaluation of LLM output [12]. On interdisciplinary design in particular, ARCHED [13] puts transparency and teacher control at the centre of AI-assisted instructional design, co-design studies report on AI-supported interdisciplinary projects [14], an LLM-augmented framework for curriculum innovation has been applied to digital public infrastructure education [15], and work on AI literacy across subjects [16, 17] shows that AI can be studied as an interdisciplinary topic and not only used as a tool.

These systems all retrieve by embedding similarity, which works when the answer sits inside a passage and much less well when the task is to connect two bodies of knowledge that never appear in the same document: two texts about energy, by a physicist and by an economist, can be far apart in wording and close in meaning in a way that matters for teaching. Structured knowledge helps. Knowledge graphs make relations explicit and inspectable [18], ontologies state the main concepts of a domain in machine-readable form [19], and graph-based retrieval outperforms purely dense pipelines on multi-hop and global questions [20, 21]. KNOTS follows this direction with one constraint: no single unified ontology of school knowledge, because interdisciplinary teaching is useful only if the subjects stay distinguishable.

2.3. Positioning and contribution

KNOTS shares with ARCHED [13] the commitment to teacher control and transparency, and with the LLM-augmented framework of Lusi et al. [15] the use of an LLM to support interdisciplinary curriculum innovation. In both, however, the knowledge the system draws on is either the model’s own or a flat document collection. The specific claim of KNOTS is representational: disciplines are modelled as separate ontologies that are never merged, and what they share is expressed as typed relations between them, so that a cross-disciplinary suggestion is not a fluent sentence but a path in a graph that a teacher has approved and can inspect. Two consequences follow that a dense pipeline cannot deliver: retrieval can reach material that shares no vocabulary with the request, because structure rather than embedding

decides relevance; and a proposal can be contested on disciplinary grounds, because the relation type states what kind of contact is claimed. The primary contribution is this architecture and the evidence on whether it works (RQ1); the competence framework and the classroom study are the instruments through which it is put to work in a real school.

3. Research Questions

The project is organized around four research questions: RQ1 on the system and the representation it is built on, RQ2 and RQ4 on the human and organizational conditions of its use, RQ3 on its effect on students.

1. Can a generative AI system with ontology-grounded semantic retrieval give teachers usable support in designing interdisciplinary pathways in upper secondary education, and does graph-constrained retrieval outperform purely dense retrieval on this task?
2. Which competences do teachers and students need in order to use these systems responsibly, and how do they map onto the UNESCO and AILit frameworks?
3. What is the effect of AI-supported interdisciplinary teaching on students' learning outcomes, motivation, and capacity to interpret complex real-world phenomena?
4. Under what organizational conditions can teachers work together on AI-supported interdisciplinary design without losing pedagogical control?

RQ2 and RQ4 rest on the same evidence but keep different units of analysis, the individual and the organization, and they come apart when a well-trained teacher works in a school that gives no shared design time. Effects on disengagement, early school leaving and career guidance are a motivating horizon rather than a question the project can answer in two years; what the pilot can observe is covered by RQ3, and Section 7 states the limit.

4. What We Mean by Interdisciplinary

Three terms circulate in curriculum policy and they are not interchangeable; which one is meant has consequences for the technical design. A *multidisciplinary* approach looks at a problem from several points of view without putting them together, as when specialists each give an opinion on a case. An *interdisciplinary* approach makes those points of view talk to each other in order to build a single account: neuroscience does not place biology, psychology and computer science side by side, but builds one explanatory model out of them. A *transdisciplinary* approach goes further and dissolves the disciplinary boundaries themselves. KNOTS aims at the second and deliberately stops short of the third. Interdisciplinary teaching is instructive only as long as the subjects stay distinguishable, because what the student has to learn is precisely that the same object looks different from two methodological standpoints. This is a requirement on the semantic layer. The premise is that disciplines are ways of constructing reality from a point of view, each with its own concepts and methods, and Bruner's account of the structure of the disciplines [22] adds that what is worth teaching is a subject's organizing ideas rather than its accumulated content. Modelling a domain therefore means making a disciplinary point of view explicit, and so open to discussion: the artifact that supports retrieval is also one that supports reflection on how knowledge is built.

5. Architecture

A language model can be made trustworthy for schools either by training one from scratch on teaching material or by constraining how an existing one generates. The first is out of reach on any realistic school budget; the second gives up control over pre-training but recovers it where content actually reaches teachers and students. KNOTS takes the second route, in five layers under a human-in-the-loop

control layer whose decisions feed back into the first three. The design follows the AI Act [5], the European guidelines for educators [4] and the Italian ministerial guidelines [7], and keeps human supervision at every stage, from the upload of materials to the classroom pilot.

Curated corpus. Teachers choose the sources (textbook sections, legal and policy texts, scientific articles, datasets, media items) for the thematic areas they consider useful, and provenance is kept on upload, so any later suggestion traces back to a document and a passage. This is what makes the reliability requirement real rather than declared: the model has nothing else to work with.

Semantic layer. For each subject and thematic area, a lightweight ontology holds the main concepts, their properties and the relations between them, using standard vocabularies (OWL, SKOS) at a level of detail closer to a structured concept map than to a formal reference ontology. Construction is bootstrapped: concepts and candidate relations are extracted from that subject's curated corpus by an LLM-based pipeline which returns, for each candidate, the passages it was drawn from and a placement in the hierarchy. The teacher who owns the subject validates, accepting, renaming, merging or discarding, and every accepted concept keeps its provenance. Two checks follow before release, consistency with an OWL reasoner and review by an external disciplinary expert, and versions are kept, so a later disagreement about a concept traces back to the moment it entered the model. The ontologies are deliberately not merged: the notion of energy used by a physicist, an economist and an environmental scientist is kept as three distinct concepts.

Alignment layer. Contact between subjects is expressed through thematic hubs (bioethics, the environmental crisis, civic education, AI itself) and through typed relations between concepts belonging to different ontologies. Rather than asserting that two concepts are the same, a relation states what kind of contact holds: same referent seen from different standpoints, prerequisite, evidence, similarity of method, or open disagreement between two disciplinary accounts. Candidates come from lexical and structural ontology matching, from co-occurrence of concepts in documents contributed to the same hub, and from the model itself, which must return a relation type, a justification and the supporting passages. Validation is bilateral, since a cross-disciplinary link makes a claim about two disciplines at once: the teachers of both subjects must approve it, and rejections are kept as negative examples for the matching step. The last relation type matters most for teaching, because disagreement between subjects is where interdisciplinary work becomes instructive, and it is the one students are asked to reconstruct in the final task.

Hybrid retrieval. A design request is written in pedagogical terms: topic, target class, subjects involved, learning objectives, constraints. The system turns it into a starting set of concepts, walks the graph across the hubs to extract the relevant subgraph, and runs dense retrieval only on the passages linked to it. Structure decides what is relevant, embeddings decide which passage says it best, and that order is what lets the system connect two documents sharing no vocabulary: a request on automated decision-making anchored in *classification threshold* reaches a legal commentary on indirect discrimination through a typed *same referent, different standpoint* link, which no lexical overlap would have retrieved.

Local generation. An open-weight model runs on the institution's own hardware, so no student or teacher data leaves the school. It receives the subgraph with the retrieved passages and produces structured output rather than free text: a module outline, connection cards (subjects, relation type, justification, sources), objectives mapped onto the reference frameworks, and candidate assessment items.

Human-in-the-loop control. Teachers accept, edit or reject each element, and every decision is logged. Rejections and edits are as informative as acceptances, since they improve the ontologies and

Table 1

Teacher training: the five competence areas, with objectives (in italics) and contents.

Area	Objectives and contents
1. Human-centred mindset	<i>Understand the relation between people and AI in the design and use of models, and agree on the teacher's role in AI-supported teaching.</i> Syntax and semantics in text production; computation, creativity and empathy; supervised learning and the exploitation of human labour; case studies on teacher supervision in instructional design
2. Ethics of AI	<i>Understand the ethical principles that should guide the design of AI models and their use in teaching.</i> Discrimination, bias, environmental cost, manipulation, copyright, privacy and data protection; national and international rules; documents on the ethical use of AI in education; the alignment debate
3. Foundations and applications	<i>Define AI and tell it apart from earlier ICT tools; judge how reliable a system is; choose tools that fit a teaching need.</i> History of AI; training methods; neural networks; generative AI, LLMs and SLMs; running models in the cloud and locally; automatic, semi-automatic and human evaluation metrics
4. Pedagogy of AI	<i>Use AI to develop students' critical thinking and keep it instrumental to the aims set by the Italian Constitution and school regulations.</i> Pedagogical foundations; AI for inclusion, design, personalization and assessment; risks of uncritical use for teachers' own thinking; prompt engineering
5. AI for professional development	<i>Treat the didactic use of AI as part of the profession and use it for shared design and peer learning.</i> Challenges and prospects; AI tools for continuing teacher education; support for group work and peer training; the professional profile of teachers, rights and duties

the link set: designing the curriculum also builds knowledge for the system. Explainability holds on two levels by construction, the sources and the graph path, and this is what lets a teacher disagree with the system on the merits instead of simply not trusting it.

6. Methodology and Project Plan

KNOTS runs for two years, over the 2026–27 and 2027–28 school years, and follows an action-research design. It targets upper secondary education, where subjects are most specialized and where students use AI tools the most and question them the least. We plan to involve one class per school (two or three schools), preferably a fourth-year class: the class council is settled, the students are old enough for the reflective part, and the final examination is not yet putting pressure on them. The Department for Social Policies and Education of the Campania Region takes part as an institutional partner, with a remit covering early school leaving, transversal and orientation competences, and cooperation between universities and schools.

Training. Training has two tiers. A general tier, open to all interested teachers in the participating schools, covers basic AI literacy and classroom applications; a specific tier, for the teachers in the trial, covers pedagogical models of interdisciplinarity, hands-on use of the platform, and the criteria for preparing the materials that will feed the module. Content is aligned with the UNESCO teacher framework and the European guidelines [4], and sits between the acquisition and deepening levels, since each teacher will realistically reach different levels in different areas. Table 1 summarizes the five competence areas; as UNESCO notes they overlap and depend on each other, so the course is organized across them rather than one after the other. Delivery is blended, and materials are shared through the project platform itself, so that teachers get used to the tool by using it. Questionnaires administered beforehand survey prior knowledge and use of AI and the topics teachers want to cover.

Co-design. The module is designed in two phases: objectives, contents and assessment strategy are set by the teachers of the class councils involved, then the materials are loaded into the platform. The object of the module is AI, in its scientific, technical, legal, economic, environmental, social and cultural implications: it is a genuine interdisciplinary object, and it makes the module an occasion of AI literacy on the questions that matter most in this shift. Student objectives are indexed to the AILit framework [6], which we take as the main reference on the student side because it gathers the indications of the other international documents, including the UNESCO ones. Each transversal and subject-specific objective is stated as an AILit item, and each item is attached to the instrument that

will assess it; teacher competences are indexed the same way to the five UNESCO areas of Table 1. This is what makes the teacher framework, the student framework and the evaluation plan a single chain rather than three parallel lists. Within this frame the teachers also select the materials to upload, the timing and the mode of delivery.

Piloting. The pilot runs in the second school year, in ways agreed with the teachers and consistent with the school’s educational plan. Students are active participants and know the aims from the start: what is at stake is not only acquiring knowledge but questioning habits in the use of AI that are already established and comfortable, especially where study effort is concerned, and that does not happen unless students see the value of the experiment. Difficulties feed back into the model while the pilot is running rather than after it. The phase has two objectives: checking the added value of semantic integration for design, and testing a form of active AI literacy for students.

7. Evaluation and Expected Results

Evaluation works on three levels. At the *system* level we measure retrieval quality and grounding against a dense-only RAG baseline on the same corpus and the same requests. This is the direct test of RQ1: if the semantic layer does not produce connections a dense pipeline misses, the cost of building the ontologies is not justified, and we would rather find that out early. At the *design* level, disciplinary experts and the teachers involved score the generated pathways with a rubric covering curricular relevance, disciplinary fidelity, depth of integration, age suitability and coherence of assessment, with inter-rater agreement reported [12]; interaction logs add acceptance rate and extent of revision, which are harder to influence than ratings and indicate how much work the system saved. At the *learner* level, pre/post instruments assess gains on the module topic while questionnaires and reflective writing address motivation and the perceived relevance of school subjects, compared across school contexts and across the two cohorts. We keep three kinds of result apart. *Technical outcomes*: a working platform, the ontologies and the alignment set for the disciplines involved, and measured evidence on graph-constrained versus dense retrieval. *Educational outcomes*: an AI competence framework for teachers and students with an assessment instrument attached to each item, a piloted Civic Education module on AI, and evidence on teacher effort and on student learning and motivation. *Long-term impacts*: effects on early school leaving, on career guidance, and on the convergence between school practice and AI. The last group is a horizon and not a result: a two-year pilot on two or three classes cannot measure it, and what the project can contribute is the protocol and the conditions under which those effects could later be tested, which is also the part that could feed into regional guidelines.

8. Conclusion

KNOTS treats the arrival of generative AI in schools and the division between subjects as one problem rather than two. It gives teachers a system whose knowledge base they own, whose suggestions are traceable to their sources and to an explicit conceptual path, and whose semantic layer respects the fact that each subject looks at the world from its own standpoint. Generative AI here supports the teacher’s judgment rather than replacing it, and the architecture is built so that this holds in practice and not only on paper.

Declaration on Generative AI

During the preparation of this work, the authors used Claude Opus 5 in order to: grammar and spelling check and improve writing style. The tool was used exclusively for English language editing of text written in full by the authors: author-written passages were submitted to the tool to correct grammatical and spelling errors and to obtain suggestions for clearer and more fluent phrasing, without adding, removing, or altering any scientific content. No section or paragraph of the paper was generated by the

tool. The research idea, methodology and the structure and content of the manuscript are entirely the work of the authors. Every suggestion produced by the tool was individually reviewed by the authors, who accepted, modified, or discarded it; the authors take full responsibility for the publication's content.

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