How AI can help learners to develop conceptual knowledge in digital learning environments

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Abstract— **Self-paced learning engenders flexibility, individuality and autonomy, allowing learners to acquire knowledge at their convenience. Learners, in fact, increasingly seek flexible and personalized learning experiences. They require systems that not only accommodate but also enhance their learning journeys. This paper presents the combination of artificial intelligence (AI) features and the design of interaction and communication in a learning format that fosters learners' acquisition of comprehensive and sustainable knowledge. The primary focus of our approach is on individuals who are new to the course subject or possess limited prior knowledge. Recognizing the importance of structured and coherent content, our learning format emphasizes uniformity in both appearance and language across text and quiz pages. Such consistency is crucial for building a stable conceptual framework, which facilitates a deeper understanding of the subject matter. By minimizing extraneous cognitive load, we enable learners to concentrate on the intrinsic elements of the content, thereby enhancing their learning experience. A significant aspect of our design is the strategic use of natural language. Consistent language aids in the formation of domain-specific conceptual frameworks, which are essential for sustainable knowledge acquisition.**

Self-paced learning; conceptual framework; large language models;

I. Introduction

Self-paced learning is an essential part of modern education, offering learners flexibility and autonomy in their learner journeys. It empowers learners to engage with course materials at their own pace, anytime and anywhere. This flexibility not only accommodates diverse learning styles and workplace and living circumstances but also fosters a sense of ownership and responsibility in learners. However, while self-paced learning holds immense promise, it also poses significant challenges, particularly in terms of managing learners' study efforts and ensuring the retention of knowledge over a long period of time. The goal is for learners to sustainably adopt knowledge, extending far beyond mere information retention. Learners need to organize and integrate this knowledge into their long-term memory effectively. An abstract representation of the knowledge to be learned can serve as a scaffold for organizing individual knowledge items into a comprehensive and consistent whole. Building up the conceptual framework of the subject matter can provide such an abstract knowledge representation. This process is incremental by nature and varies from to learner. The learning environment, thus, needs not only to guide the learners along their learning journey but also to support them in building up their individual language representation of the conceptual framework.

The approach outlined here addresses in particular beginners, or those new to a course subject. They often lack a clear understanding of the scope and structure of the knowledge they want or need to acquire. The conceptual framework reflecting the course content in an abstract way can guide these learners through their educational journey. This helps learners integrate new information with their existing knowledge, fostering a comprehensive understanding and retention. Without such guidance, learners are often not in the position to plan and arrange their individual learning journey.

Chat-based learning environments are very popular nowadays. They have proven to be effective tools for interactive learning, engaging students in conversation and providing responses. Their efficacy, however, largely depends on the learners' ability to pose relevant questions and steer the conversation effectively. Successful interaction with a chatbot generally presupposes a decent foundational knowledge of the subject matter. Without this, learners may struggle to ask appropriate questions and guide the dialogue to effectively support their learning needs. Additionally, unlike more structured digital learning platforms, chatbots often lack the visual cues that help to clarify and organize the knowledge structure for learners.

Structured digital learning environments can provide a clear picture of the scope and structure of the knowledge to be learned. They can, thus, clearly indicate the effort the learners should dedicate to studying the subject matter at any stage of their learner journey. However, they also require thoughtful implementation of support structures to help learners effectively manage their educational journey and achieve sustainable mastery of the subject matter.

Self-paced learning should aid learners in developing a conceptual framework. This requirement significantly impacts the design of digital learning materials, influencing everything from human-computer interaction design to the automated development of semantic content representations, where AI-based text analysis plays a crucial role.

The insights presented in this paper are the result of a research project aimed at designing new digital learning formats

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tailored for both academic and vocational education. The target audience consists of learners seeking to acquire knowledge that is entirely new to them. Therefore, digital learning materials must ensure that the audience comprehends the subject matter fully, including the complete scope and all its ramifications. The prototype of the learning format presented here is currently used to teach about 250 Bachelor students at the Schmalkalden University in three different subjects.

The paper first presents foundational concepts related to sustainable knowledge acquisition; a process closely linked to building a conceptual framework of the subject matter. This framework, primarily composed of natural language expressions, helps users integrate new information and reorganize existing knowledge elements. The main focus of this paper is on this natural language-based network of concepts and how a digital learning format can intelligently support learners in developing their individual mental representations of a conceptual framework. The learning format facilitates this mental formation process through carefully designed human-computer interactions and by continuously analyzing learner input to provide appropriate feedback. This language-intensive communication with the system can be significantly enhanced by AI-supported features based on Large Language Models (LLMs).

Section 3 presents the current implementation of our digital format, particularly the interaction design and highlights the role of natural language. Section 4 describes the architecture, design, and implementation of AI features that analyze learner statements and provide accurate feedback from the course content. Unlike chatbot-based systems, this feedback does not consist of auto-generated statements. Instead, the approach described here favors providing learners with text snippets from the original course content. This keeps learners aligned with the course wording and relieves them in addition to the cognitive burden of following and studying a chat dialogue. The paper concludes with an outlook on further ways to analyze the natural language conversation with the learners that engenders new possibilities to enrich the guidance of the learners on their journey through the course content.

II. LEARNING THE CONCEPTUAL FRAMEWORK

Sustainable knowledge acquisition is a critical goal in the design of digital learning environments. Expert knowledge is inherently sustainable knowledge and, in the end, we want learners to become experts using learning environments. Achieving this goal requires more than just presenting information. It requires features that help learners build a robust conceptual framework that enables them to integrate new knowledge and to re-arrange existing knowledge. This is particularly important for learning situations where the learners do not have previous knowledge of the course subject. They benefit from scaffolded instructions [1] that explain them in an abstract way layout and structure of knowledge to be learnt and propose a learning path for successful knowledge acquisition. We may consider a book's layout and chapter structure with its glossary and index, as metaphor for such scaffolded instructions. They are the learners' starting point to take ownership of the course subject, that is, to emancipate themselves from the scaffolded instructions and to build up their own structured representation of the course content. Such a representation may take the form of a semantic cluster of related key words reflecting the course content and its conceptual framework.

We do not learn about new subjects in the void; there is always pre-existing knowledge. Even when approaching entirely new subjects, we link newly acquired knowledge to what we already know, which is organized in our long-term memory. When confronted with new information, we initially study all its details. However, when learning more details, at the same time, we also gradually abstract away details to develop an overarching representation of the new knowledge. For instance, beginners in programming study a for-loop in detail to understand its concept. With more examples, they strengthen their understanding of the for-loop. As they accumulate information on various details, learners refine their abstract representation, developing a deeper understanding of how these details connect to the overarching concept [2]. Eventually, learners integrate this abstracted knowledge into their pre-existing knowledge structure, which engenders extended capacities for further reasoning within this context. For example, students learning about risk management in Project Management also study risk mitigation strategies. Later, when they explore Agile Project Management, they learn about risk mitigation in an agile context. By leveraging their conceptual framework on risk management and integrating information on agile strategies, learners can reason about the differences between agile and traditional approaches.

Abstract representations contribute to the conceptual framework that helps learners to understand the broader context of the knowledge area addressed by the learning material [3] [4] [5]. The primary goal for learners should be to establish new knowledge within their long-term memory, thereby achieving truly sustainable knowledge. Long-term memory serves as the repository for enduring knowledge [6], while the working memory is generally utilized for short-term objectives like reasoning or problem-solving [7]. Although working memory can store information temporarily, the crucial process is the "transfer" of information from working to long-term memory, essential for generating sustainable knowledge. Experts stand out not merely due to their ability to hold information in working memory, but by their capacity to retrieve information from long-term memory independently of their working memory's capacity [2].

In self-paced learning, learners have to assume particular responsibility for their learning journey. They have to actively manage their learning processes without external guidance of a personal tutor, for instance. Without such support, the degree of ownership directly impacts learners' success rates [8]. By developing their own metacognitive strategies for self-regulated learning (SRL) [9] learners can achieve the goal of creating a comprehensive and consistent conceptual framework. Metacognition enables learners to set realistic and achievable goals, monitor progress, and employ diverse techniques to comprehend and retain learning materials. In general, SRL helps learners to manage their cognitive processes, monitor their learning efforts, and regulate their thinking to enhance learning outcomes. Digital courses usually include learning controls and features to support the learners' time management. By monitoring learners' performance on these controls and the time they dedicate to the course, the learning system can provide feedback on learning performance, supporting learners in devising efficient SRL strategies. In our approach, the leading paradigm is self-paced learning. Nevertheless, we adopt some ingredients from SRL to provide the learners with the guidance they need, in particular concerning their time management.

Measuring the successful development of an individual conceptual framework is more complex. However, there are ways to assess this development. Free-text queries, for example, can ask learners to describe a specific concept, such as a particular risk mitigation strategy, or to elaborate on a practical example of the concept and identify it.

AI can play an important role in evaluating learners' ability to develop their own conceptual framework. AI-driven features can analyze learners' responses to free-text queries in order to measure their understanding and indicate gaps in their knowledge. By using text analysis techniques, AI can assess the accuracy of learners' explanations and provide tailored feedback by referring them to the course sections addressed in the free-text query.

A more challenging approach may address tracking learners' responses and free-text navigation (as described below) over time. This helps to identify areas where learners struggle with concepts and need further support. By analyzing data on how learners interact with the course content, AI-features can suggest specific course sections that can help strengthen their conceptual framework. This continuous, personalized feedback loop ensures that learners refine their understanding and better integrate new knowledge into their existing mental models.

III. SETTING THE SCENE FOR DEVELOPING A MENTAL REPRESENTATION OF THE CONCEPTUAL FRAMEWORK

Learners benefit from well-structured and consistent learning content that maintains uniformity in appearance and wording across text and quiz pages. In such an environment, learners take ownership of the material they wish to learn. Gradually, they internalize the course structure and terminology, developing their own mental representation of the content. We may take the "well-thumbed book" as an analogy, where printed learning materials become personalized through annotations, highlighted terms, and various markers after a learner successfully completes a course. These personalized modifications indicate the learner's engagement and active processing of the material, reflecting their successful ownership and understanding of the content. The consistent structure and familiar wording help learners build a stable framework, facilitating better retention and deeper comprehension of the subject matter [10].

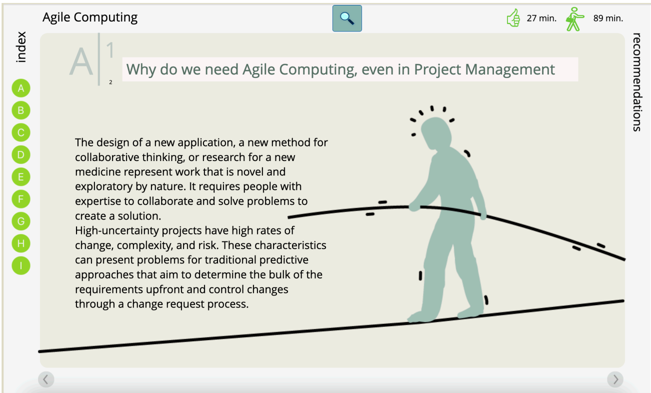


Figure 1. Minimizing the extraneous cognitive load is the leading paradigm for the design of pages displaying content.

The design paradigm of the structured learning environment outlined here prioritizes simplicity to reduce extraneous cognitive load [11] [2]. Navigating the course content and using the learning controls must be as straightforward as possible. Therefore, the courses are structured traditionally with chapters and subchapters. Learning controls, which typically conclude subchapters, consist of three to twelve questions depending on the subchapter's scope. The amount of information provided on each page is kept minimal. The basic design of text and quiz pages, as well as navigation options, remains consistent across courses. Furthermore, the use of gaming elements is limited, despite their potential to boost learner motivation (Figure 1 and 2). This design principle focuses the intrinsic cognitive load on its most important objective: integrating pieces or chunks of information to form knowledge of a higher-level top [2].

The design of digital courses must consider the broader context in which self-paced learning occurs. Digital learning environments are embedded in an ecosystem replete with distractions, including digital services, social media, games, and constant notifications. These distractions increase extraneous cognitive load and make it increasingly difficult for learners to maintain focused attention [12]. While the digital world offers unparalleled access to information and connectivity, it also presents numerous distractions that impede concentration on a particular task. Therefore, the design of digital learning environments must incorporate strategies to cultivate focused attention amidst these digital distractions.

This consideration impacts the design of each individual content page and the features that control learners' navigation. For instance, in the digital format presented here, learners are prevented from paging through the content too swiftly. They can only move to the next page after a minimum reading time has elapsed. Once a learner has read a page carefully, this time limit is lifted. Such design strategies help ensure that learners engage with the material meaningfully and maintain the focus required for effective learning.

Figure 2. The overall design is consistent with the learning controls, too. This includes consistent wording in the quizzes, which makes them easy to locate by the retrieval feature of the digital format and helps the learners build up their conceptual framework.

Each page and subchapter are meticulously titled, with content organized into manageable chunks. These titles are generated through sophisticated text summarization techniques enabled by large language models. This semantic representation allows learners to easily retrieve specific course content at any stage of their learning journey. Our platform features an AI-driven search function that enables learners to state free-text queries and locate the most relevant pages or content chunks within the course.

The initial structuring of the course content, as shown in Figure 3, reflected in the titles, serves as a guiding framework for learners by providing an index and overview of the course subject and its chapters. For novice learners, focusing on these titles offers a good starting point to grasp the surface details of the course content, such as the thematic scope and its main areas.

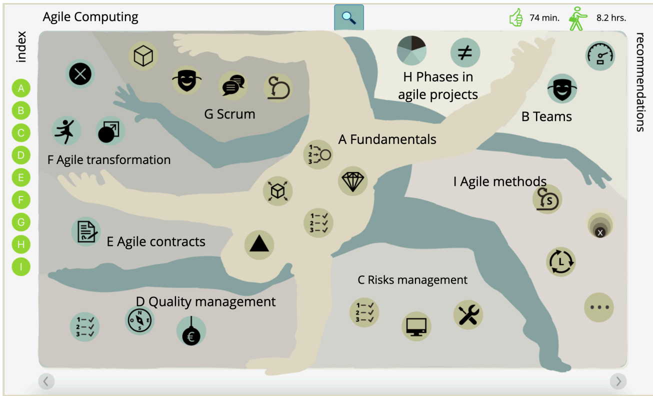


Figure 3. Overview of the course "Agile Project Management" and its structuring into chapters. In the upper right corner, the system indicates the learning effort (time) already completed by the learner and the remaining studying time.

As learners progress through the chapters and quizzes, they develop a more nuanced understanding of the subject, gradually building a more comprehensive and complex abstract representation of the content. They identify key concepts and their relationships, which become essential components of their individual conceptual framework.

The active use of the language inherent in the course content and quizzes (Figure 2), coupled with the free navigation across course pages (Figure 4), strengthens learners' conceptual frameworks. This gradual process of knowledge acquisition and the adoption of the subject's language foster the ability to form abstract representations, similar to the perspective of subject matter experts. Developing an individual abstract representation of the course content is essential for learners' sustainable adoption and organization of knowledge. Unlike chat-based learning environments, our course format prioritizes retrieving relevant text sections over generating answers to respond to learners' requests.

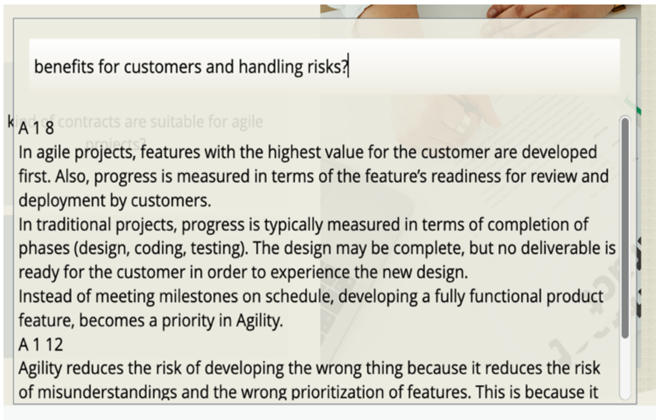


Figure 4. The learners have the possibility to retrieve selected sections from the course at any point along their learner journey. Without leaving the actual page, they can ask the system to provide them with the course content most suitable to their search query. The matching algorithm in the background uses large language models to identify the content sections that match the user query.

Consistent wording in responses and feedback is crucial because it provides contextual familiarity and stability. This consistency supports learners in understanding and internalizing the specific language of the course subject, thereby enhancing their comprehension and retention.

AI plays a crucial role in this context by providing features that help analyze learners' natural language input, interpret it accurately, and offer tailored feedback. By applying Large Language Models (LLMs), the course format can:

- Estimate the proximity of learners' statements in free-text queries to the correct answers.
- Provide learners with the most relevant extracts from the course content related to their search queries.

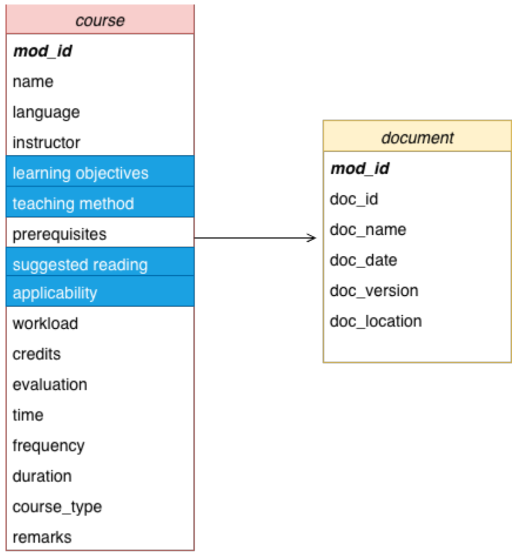
The similarity between learners' statements and the correct answers is used to calculate the points awarded for their responses in free-text queries (Figure 2). With the appropriate LLM, AI can evaluate the correctness of learners' statements based on their semantic meaning. Traditional methods, as used in classical retrieval systems—such as stopword elimination, stemming, and synonym dictionaries—were less accurate in comparing the meanings of two statements.

It is important for digital learning environments to also support the active use and training of professional language. This involves not only formulating clear statements in free-text queries but also navigating freely across the course content.

IV. AI Features Enabling Context-Related Communication

Over the past few years, Large Language Models have revolutionized the area of Machine Learning and AI, and information retrieval has not been excluded from these advances. Transformers have shown to be particularly good in capturing semantics and context, leveraging it to generate text, this feature can be exploited to enhance textual searches that are "aware" of its context. Within this work, we use LLMs as a contextual mathematical embedding that encodes language and word relationships and their semantics so that we can embed (i.e. vectorize) course content as a downstream task for searches.

Figure 6 depicts the backend abstraction of the deployed systems. Course data is usually found as semi-structured or unstructured data within MS Word documents, which are processed and stored in a database management system (DBMS). This process involves traditional parsing techniques used to recognize text, tables, and other structures. This is exemplified in Figure 5, which shows a course representation, a course document is split into two tables, one table called ***document*** that stores metadata, such as document id, document name, version, location, etc. Another table called ***course*** stores the course contents, data such as course name, language that the course is imparted, instructor's name, course duration, etc. Notice that the fields highlighted in blue are of particular importance to us. These data fields contain textual data that we use to create an embedding using an LLM through a vectorization process, aiming to enhance users´ contextual search.

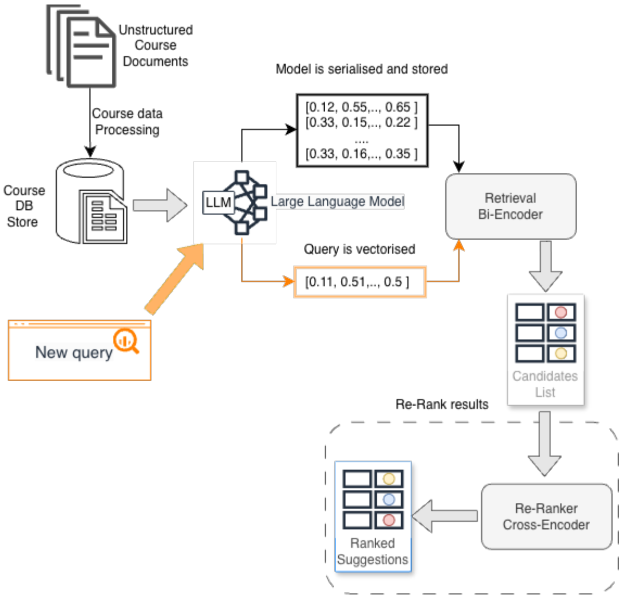


Fig, 5. Course retrieval process overview.

Notice that the vectorization of stored data is an 'offline' process, in the sense that we can take all the textual data that has been stored in the database (i.e. courses) and vectorize it so that it is ready and available for search. For instance, let us consider the field ***learning objectives*** in the table course (shown in Figure 5), this field contains the course description and objectives to be learned. Vector embeddings can be created for all ***learning objectives*** rows as shown in Figure 6, then a serialized vector set is created where the first-row vector corresponds to the first-row ***learning objective*** in the database, the vector dimension (number of columns) is given by the LLM used, typical values are 384, 768, 1536, 2048, etc.

Let us consider the case where a user creates a query, as shown in Figure 6 in orange. A new textual query is embedded using an LLM, which produces a vectorized query. Now, all necessary elements exist to create the matching against ***learning objectives***; on the one hand, we have all ***learning objectives*** vectorized. On the other hand, we have a new query vector that can be used to calculate the semantic similarity with a metric such as the cosine distance. In technical terms, this process is using a Bi-Encoder, we can match the query vector against all ***learning objective*** vectors and select the ones with greater semantic similarity. Bi-Encoders are computationally inexpensive, allowing for matching against a large set of vectors. Algorithms such as Hierarchical Navigable Small World (HNSW) and Annoy (Approximate Nearest Neighbors Oh Yeah) can be used to do approximate matching against billions of rows. Thus, Bi-Encoders are used whenever efficient vector comparison is needed, they take as input two sentences or strings and output a similarity (e.g. cosine distance). Cross-Encoders take as input two strings simultaneously to the Transformer network and produce an output value between 0 and 1 indicating the similarity between the input pair. Notice that here, a new Transformer network is used thus, this process is slower than a Bi-Encoder but tends to produce better results. Cross-Encoders do not produce an embedding thus it cannot be used as an off-line task to precompute results. The efficient way to use the encoders is to use the Bi-Encoder to compare a query against all searchable space, produce a candidate list, and then use the

Cross-Encoder over this so that the par-wise text comparison is reduced.



Fig, 6. Course retrieval process overview.

V. Conclusions

The digital learning format presented in this paper is designed to address unique challenges and opportunities of self-paced learning. By leveraging AI and the consistent design of a learning environment, we aim to enhance learners' ability to acquire comprehensive and sustainable knowledge.

The main target audience of our approach is learners who are new to the course subject or have only very little knowledge of it. One of the key aspects of our learning format is, thus, the emphasis on consistent and well-structured content. Uniformity in appearance and wording across text and quiz pages helps learners build a stable and, at the same time, comprehensive conceptual framework, fostering their understanding of the subject matter. This design principle is important when it comes to reducing extraneous cognitive load and allowing learners to focus on the intrinsic aspects of the content.

Our learning format places special emphasis on the use of natural language. The acquisition of knowledge is enhanced by providing learners with a consistent language, facilitating the development of domain-specific conceptual frameworks in their minds. Developing such a framework is crucial for acquiring sustainable knowledge. However, supporting learners' self-regulation strategies aimed at developing their individual frameworks is a complex task. We actively monitor and measure the comprehensiveness and consistency of their conceptual understanding through free-text queries that address key concepts of the course subject. In a next step, we aim to extend the analysis of language use to include free-text navigation, further supporting learners in constructing robust conceptual frameworks.

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