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Scaffolding Learning in Blockchain: From Basics to Systems Thinking in STEM Education

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Abstract

Blockchain technology has evolved rapidly and is now applied across various domains such as energy trading, finance, supply chain management, and healthcare. These applications rely on cryptographic mechanisms to ensure security and privacy, while features including decentralization, transparency, and distributed consensus extend into emerging areas like the Internet of Things (IoT), smart cities, cloud computing, and vehicular networks. In undergraduate education, blockchain strengthens cybersecurity training by introducing decentralized security models that differ from traditional centralized architectures. Through exposure to cryptographic primitives, tamper resistant data structures, decentralized identity frameworks, and transparent audit trails, students gain competencies in data integrity, authentication, and secure system design, supporting practical skill development and broadening career pathways in areas such as Web3 security and digital identity. Effective teaching can be enhanced by incorporating hands on coding, adversarial security thinking, and full stack decentralized application development spanning smart contracts, off chain services, and user interfaces. Real world case studies, cross chain technologies, and industry toolchains help students connect theory to practice, while hackathons and open source contributions provide experiential learning aligned with professional and research. This paper presents pedagogical strategies for integrating blockchain into undergraduate curricula that promote essential skills, research experience, and sustained engagement. Through systems-level thinking, collaborative learning, and structured mentorship, students explore solution pathways and address technical and research-related challenges in modern decentralized systems.

Keywords: Blockchain Technologies, Cybersecurity, STEM Education, Emerging Topics

Introduction

Blockchain technology has evolved rapidly and is now applied across diverse domains such as energy trading, finance, supply chain management, and healthcare. These applications rely on cryptographic mechanisms to ensure transactional security and privacy, while core features including decentralization, transparency, distributed ledgers, and consensus protocols extend naturally into emerging areas like the Internet of Things (IoT), smart cities, cloud computing, and vehicular networks. In undergraduate education, blockchain provides valuable cybersecurity training by introducing decentralized security models that fundamentally differ from traditional centralized architectures. Through exposure to cryptographic primitives, tamper resistant data structures, and decentralized identity frameworks, students develop competencies in data integrity, authentication, and secure system design. This preparation addresses contemporary cybersecurity challenges, supports practical skill development through laboratory activities and case studies, and broadens career pathways, and secure supply chain systems. Teaching blockchain can be further enhanced by incorporating hands on coding, adversarial security thinking, and full stack decentralized application development that spans smart contracts, off chain, and user interfaces. Additionally, integrating real world case studies, cross chain technologies, and industry grade toolchains helps students connect theoretical concepts to practical constraints. Emphasizing zero knowledge proof systems, and decentralized governance exposes learners to cutting edge research and emerging ecosystems, while hackathons, testnet deployments, and open source contributions provide authentic experiential opportunities that prepare them for blockchain related professional and research careers.

This paper presents a set of pedagogical strategies for integrating blockchain topics into undergraduate education. At the system level, students examine how individual components from foundational concepts to full architectures interoperate to achieve specified project goals. They are encouraged to explore multiple solution paths and converge on optimal system designs, enabling them to address both technical and research related challenges. The following sections analyze these strategies and their impact on student outcomes, offering educators actionable methods for promoting essential skills, authentic research experience, and sustained engagement in blockchain focused work. By emphasizing foundational concepts from foundational research papers, guiding students to realign efforts with project objectives, and combining collaborative learning with structured mentorship, these approaches foster student confidence, support independent problem solving, and build the interdisciplinary competencies needed for success in modern decentralized systems.

Challenges

Determining how to effectively connect course material to students' interests is an important instructional design consideration. Prior research[5,8] indicates that students engage more deeply with content that aligns with their interests or connects meaningfully to their prior experiences, leading to increased motivation and improved learning outcomes[7,3]. For example, presenting real-world case studies and demonstrating how blockchain technologies are applied in cybersecurity can help students recognize the practical value of the topic, a key principle of progressive and experiential pedagogy[9]. We designed theoretical module using an active learning approach, as it enables students to participate directly in the learning process through structured in-class activities rather than passive content consumption[13]. Substantial empirical evidence[16,15]indicates that active learning strategies significantly enhance student engagement, conceptual understanding, and the overall learning experience in undergraduate STEM education[6]. Collectively, these interactive pedagogical methods represent effective approaches for engaging students and reinforcing core concepts in the classroom.

To illustrate the learning outcomes supported by this pedagogical approach, we provide a representative example from the theoretical module on blockchain-based cybersecurity systems. Early in the module, students completed a formative task focused on identifying basic blockchain components (e.g., blocks, hashes, and consensus mechanisms). At this stage, student responses typically reflected a component-level understanding, with limited consideration of system interactions. Following scaffolded activities that included guided case analysis and small-group discussions, students were asked to analyze a cybersecurity scenario involving a distributed ledger used for secure data integrity verification. In their final submissions, many students demonstrated a shift toward systems-level reasoning by explicitly describing how blockchain properties such as immutability and decentralization interact to mitigate specific security threats. Qualitative feedback collected through reflective prompts indicated that students perceived the real-world case study as instrumental in helping them connect theoretical concepts to practical applications. While comprehensive assessment data are beyond the scope of the present study, these illustrative examples suggest that the progressive scaffolding strategy supports students' transition from foundational knowledge acquisition to systems thinking, aligning with the intended learning outcomes of the course.

The illustrative learning progression described above highlights a recurring instructional challenge observed in this course context: variability in students' prior knowledge. While many students entered the module with a correct understanding of foundational concepts, their existing knowledge structures were often insufficiently organized or contextualized to support higher-level systems thinking. This gap became particularly evident when students were asked to transfer isolated conceptual knowledge to complex, integrated domains. Consequently, addressing the limitations of students' prior knowledge emerged as a central motivation for the scaffolded instructional design discussed in the following section.

Challenges-I: Students' prior knowledge, it can either facilitate or impede new learning, and the ways in which they mentally organize that knowledge shape how effectively they learn and apply what they have learned. In some cases, students possess prior knowledge that is accurate but insufficient. In other words, even when students' existing understanding is correct in one specific domain and activated at the right time, it may still not be robust and ready to support more advanced learning or enable them to demonstrate a desired level of performance.

For example, a student may correctly understand basic theory related to the cryptographic primitives, such as encryption, hashing, and digital signatures, but still struggle to comprehend how these techniques are integrated into another subject, blockchain systems or Decentralized Finance. The building block of fundamental knowledge is robust, but it lacks the depth, background knowledge and contextualization scenario to support subsequent learning about Distributed ledger technology, consensus mechanisms, or smart contracts.

In addition to the accuracy and sufficiency of prior knowledge, the way students organize what they know strongly influences their learning. Knowledge that is well-organized and meaningfully connected allows students to retrieve and apply concepts more efficiently, recognize underlying patterns, and transfer learning to novel situations. By contrast, when knowledge is fragmented, loosely organized, or stored as isolated facts, students may have difficulty integrating new information, identifying relationships between ideas, or determining when certain concepts or procedures are relevant.

Furthermore, some students may possess relevant facts and concepts but lack procedural or conditional knowledge. That is, understanding how and when to apply what they know. In such cases, students are not deficient in content knowledge; rather, they struggle with transferring and utilizing that knowledge in practical or situational contexts. For example, with blockchain, students need to understand the context and evolution of blockchain technology, its benefits, key features, and how it works. With this knowledge, students are better equipped to apply blockchain concepts in real-world scenarios, such as implementing blockchain applications in healthcare.

As a result, students who lack procedural and conditional knowledge often struggle with tasks that require strategic problem-solving, or application of concepts beyond rote recall. Over time, this can lead to frustration, disengagement, and eventual loss of interest.

Solutions:

- Given the specific questions, it would be a more efficient way to assess and validate students' prior knowledge. This strategy allows the instructor to identify misunderstandings or knowledge gaps more accurately. And are able to implement the appropriate measures correctly.
- For specific chapters or components, it is helpful that the instructor briefly reviews the relevant prerequisite material to ensure that students are adequately prepared for the new content.

  For examples: *There are two main cryptographic tools frequently used in blockchain. We begin with a brief review of regular hash functions and their use in hash tables, followed by an introduction to cryptographic hash functions and their additional security properties.*
- Distributed Survey prior to the start of the course to obtain data on students' backgrounds and interests.

  For examples:
  - *Please describe any Cybersecurity projects or Information Technology experience you have completed inside or outside of an academic setting.*
  - *Please describe any significant programming projects you have completed inside or outside of an academic setting.*
  - *List any Industry Certifications that you currently hold.*

Supporting students in the transition from factual understanding to strategic application is therefore essential. Instructional approaches that help students build integrated knowledge structures, practice applying concepts in varied contexts, and receive feedback on their decision-making can strengthen their ability to transfer learning to new problems.

Personalized learning allows students to learn at their own pace and according to their background. By leveraging personalized learning techniques, this work helps students systematically understand fundamental blockchain concepts and apply the knowledge gained from coursework toward creative and improved development.

Challenges-II: Motivation Students' motivation plays a critical role in shaping their learning behavior. It determines the goals they pursue, directs their effort and attention, and sustains their engagement over time. When students are motivated, they are more likely to persist through challenges, adopt effective learning strategies, and show greater interest in exploring new concepts. Conversely, low motivation can hinder learning by reducing persistence, limiting strategic effort, and weakening overall academic performance. Facing considerable barriers, the student would easily become frustrated during the learning and training process.

Solutions:

- More running examples are introduced in the class for certain chapters, which can help students better understand real-world scenarios and stimulate their motivation and interests.
- Provide authentic and real-world tasks. For example, when discussing blockchain at the undergraduate level, the emphasis can be placed on hands-on activities that allow students to explore how blockchain works in practice. More importantly, these activities can be designed to reflect skills relevant to the cryptography and cybersecurity job markets, helping students see the professional value of what they are learning. Given job-oriented tasks, it helps students *build a career profile* aligned with their professional path. That would be of great value to their learning path. Despite considerable barriers, students were able to reduce their negative feelings through the implementation of targeted strategies. By addressing these limitations and challenges through a structured teaching approach, the findings suggest that students are more inclined to continue learning rather than becoming discouraged and frustrated by the research process. Although the training process requires additional effort, students must be prepared to step outside their comfort zones.

For examples: *Project-based active learning enables students to take initiative and work independently with limited time and concise instructions.*

Taken together, the instructional challenges described above directly informed the design of the proposed curriculum. Prior research in the learning sciences indicates that when students possess accurate but fragmented prior knowledge, learning is most effectively supported through structured scaffolding that progressively integrates concepts and contexts. Accordingly, the curricular design was intentionally structured to move students from isolated conceptual understanding toward integrated systems-level reasoning through sequenced activities, guided case analyses, and iterative reflection. This approach aligns with evidence-based instructional strategies shown to support knowledge integration, transfer, and deeper conceptual understanding in complex technical domains. Thus, the proposed design represents not only a response to observed instructional challenges, but a theoretically grounded and pedagogically justified solution.

Course Design

This course is a 4-credit course designed for undergraduate students. It integrates both algorithmic theory and software-based hands-on practice. Learners will explore core conceptual and algorithmic principles through lecture notes and reading materials, and will also have the opportunity to implement secure and efficient layered decentralized architectures by developing full-stack blockchain systems. To better organize the course, it contains three levels of progression in a hierarchical structure. We begin with fundamental concepts, proceed to Scaling Bitcoin, and then cover advanced topics related to emerging trends.

Overview of Class Content

In this subsection, the ten instructional topics covered throughout the course are summarized in Table 1. Each topic entry includes a description of its focus as well as a detailed list of associated

Table 1: Below is the list of course topics and their corresponding assigned activities, including weekly assignments and term project milestones. Note that R denotes Read, W denotes Write, D denotes Demo, and Di denotes Discussion. The term project milestones are designated as MP I (Phase I), MP II (Phase II), and MP III (Phase III). The wrap up phase includes final presentations and reports writing

Topic	**Centralized Activities** (R, W, D, Di)	**Assignments**	**Milestone**
Foundation for Understanding Bitcoin[12]	✓, ✓, ✓, ✗	Reading[12,11] -	MP-I
Cryptographic Primitives[14]	✓, ✓, ✓, ✗	Reading[14] -	
Consensus Mechanism	✓, ✓, ✓, ✗	Reading -	
Bitcoin P2P network[10]	✓, ✓, ✓, ✗	Reading[10,2] hands-on assignment	MP-II
Bitcoin System[11]	✓, ✓, ✓, ✗	Reading hands-on assignment	
Nakamoto Consensus	✓, ✓, ✓, ✗	Reading hands-on assignment	
Scaling Throughput, Scaling Latency	✓, ✓, ✓, ✗	Reading hands-on assignment	
Ethereum and decentralized applications[4]	✓, ✓, ✓, ✗	Reading hands-on assignment	
Advanced Topics I	✓, ✗, ✗,✓	Reading -	MP-III
Advanced Topics II	✓, ✗, ✗, ✓	-	**Wrap-Up**

subtopics. These subtopics highlight the relevant technical concepts, tools, hands-on exercises, and theoretical components introduced during that segment of instruction, providing a comprehensive view of the knowledge and skills students gain in the course.

- **Level I - Foundation for Understanding Bitcoin**: Review Cryptographic Primitives, hashing, and key managements and key ideas from distributed computing, including consensus algorithms.

  Learning Outcome: Students will be able to define blockchain technology and its core data structures (knowledge), identify and describe the roles of blocks, consensus protocols, and cryptographic mechanisms (comprehension), and explain how these components collectively support secure, decentralized payment transactions (application and analysis).

For example:

- What are blockchains
- Decentralized system
- Bitcoin

- **Level II - Blockchain Core architecture**: Merkle Tree, consensus mechanisms, Block Structure, Mining, Bitcoin P2P network, Ethereum and transactions UTXO;

  Learning Outcome: Students will be able to explain the foundational principles of blockchain systems, including decentralization, immutability, consensus, and distributed ledger technology. And also students can describe the core architectural components of a blockchain network such as nodes, blocks, chains, transactions, and ledgers.

- **Level III - Implementation**: Focus on permissioned blockchains (e.g., Solidity[17], Hyperledger Fabric[1]), the development of smart contracts and scripting mechanisms, and Layer-2 scalability solutions including payment channels and state channels. Smart contracts, interoperability, scaling, and governance. In this section, the instructor focuses on demonstrations and hands-on development activities, such as smart contract programming and full-stack decentralized application (dApp) development. This includes work on the on-chain layer, where students implement smart contracts in languages such as Solidity or Rust and deploy them to networks (e.g., Ethereum). It also covers the off-chain/backend layer, which handles tasks that cannot be executed on-chain, such as indexing blockchain data, providing APIs for querying blockchain information, and performing off-chain computation.

  Learning Outcome: Students will be able to design and implement secure and efficient layered decentralized architectures through hands-on coding, and build full-stack blockchain software systems. They will also be able to develop and deploy smart contracts using languages such as Solidity or Rust, and explain their execution within blockchain virtual machines (e.g., the EVM).

- **Level IV: Advanced Topics - Current Challenges and Future Work:** Scalability, proof-of-stake, blockchain privacy attacks and solutions.

  Learning Outcome: This learning goal encourages students to explore real-world blockchain case studies and critically analyze how different industries adopt and deploy decentralized technologies. Through this exploration, students will investigate contemporary blockchain research directions, including scalability, consensus design, cryptographic techniques, privacy preservation, security and formal verification, data storage, interoperability, decentralized identity, tokenomics, and governance models. The goal is to help students connect theoretical research with practical applications, recognize emerging trends, and understand how blockchain solutions are engineered for real-world constraints and opportunities.

<u>More details:</u>

- From an **INPUT** perspective, reading materials in blockchain are important because they build foundational understanding, develop analytical skills, keep learners up to date with rapidly evolving technologies, and prepare them for real-world technical and professional applications. At the same time, different levels of reading materials serve different purposes.
  - Level I materials include introductory articles and blog posts that explain core concepts, review the history and definitions of blockchain, and present case studies of real-world applications.
  - Level II materials consist of more technical resources, such as official documentation (e.g., Ethereum documentation and Solidity) and intermediate tutorials.
  - Level III materials cover specialized blockchain topics, such as security analysis, distributed systems, and protocol design.
- From an **OUTPUT** perspective, to address gaps in current curricula caused by the rapid development of chain technologies such as blockchain and their applications across multiple industries, we designed a hands-on, project-based laboratory assignment using real-life scenarios. Following a step-by-step structure, these lab assignments can be designed at varying levels of difficulty, from beginner to advanced, and student performance is evaluated through surveys and student feedback.

Discussion and Future Work

Several promising directions emerge for future implementation and refinement of the course. One important direction is interdisciplinary expansion, broadening the curriculum to address multiple application domains over the long term. For example, blockchain concepts can be examined not only in finance, but also in healthcare, supply chain, and government services, allowing students to understand how decentralized technologies address challenges across diverse sectors. Another direction is to more tightly connect blockchain concepts with relevant theoretical foundations. For instance, when studying auctions in blockchain systems, instructors can introduce how game theory supports sealed-bid auction mechanisms. This integration helps students gain not only the hands-on experiences but also the theoretical principles that guide strategic interactions and system design. A further significant direction involves integrating emerging technologies such as artificial intelligence (AI) and large language models (LLMs). These tools can support automated analysis, intelligent tutoring, enhanced cybersecurity, and data-driven decision-making within blockchain ecosystems. By incorporating AI- and LLM-related content, courses can better prepare students for an evolving technological landscape and interdisciplinary workforce demands. Collectively, these directions highlight opportunities to broaden the scope, relevance, and future-readiness of blockchain-focused education.

Conclusion

In this paper, we focus on the key challenges and present the design and implementation process of an undergraduate blockchain course from an engineering perspective within STEM education. Specifically, we examine how to design a blockchain technology course that aligns with current motivations and STEM educational goals. Blockchain technology relies heavily on cryptography to ensure the security and immutability of on-chain transactions and updates. We explore these challenges from the perspective of instructors by examining the incorporation of blockchain education into undergraduate studies, ensuring that students acquire both theoretical knowledge and practical skills. Its rapid evolution necessitates that academia continuously update course materials to meet industry expectations and advancements in AI. More importantly, such courses should equip students with the knowledge and skills required to engage in advanced research and innovation.

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