IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 19 July 2024, accepted 5 August 2024, date of publication 12 August 2024, date of current version 21 August 2024.
Digital Object Identifier 10.1109/ACCESS.2024.3442440

RESEARCH ARTICLE

An Approach to Discover Students' Conceptions in Online Computing Education: A Case Study of Students' Understanding of Virtual Memory

SONIA PAMPLONA [1], **JAVIER BRAVO-AGAPITO** [2], **AND ISAAC SEOANE** [3]
[1]Department of Science, Social Science and Mathematics Education, Universidad Complutense de Madrid, 28040 Madrid, Spain
[2]Department of Software Engineering and Artificial Intelligence, Universidad Complutense de Madrid, 28040 Madrid, Spain
[3]Department of Telecommunications, Madrid Open University, 28400 Madrid, Spain

Corresponding author: Sonia Pamplona (spamplon@ucm.es)

This work was supported in part by the Fundación HERGAR (Improving Conceptual Understanding in Online Engineering Courses) under Project FH2017-163.

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Research and Teaching Ethics Committee of Madrid Open University.

ABSTRACT This study presents a new approach for discovering conceptions among online computer science students. The research objectives were 1) to discover students' conceptions of virtual memory, an important concept in operating systems, and 2) to provide a method for discovering students' conceptions in the field of computer science. The study participants were students taking an undergraduate course on an operating system at an online university. Eleven students were enrolled in the course, and we selected all the participants who completed the course, seven students in total. We selected a qualitative case study as our methodology as we required a thorough and in-depth analysis of each student thought processes. Study data were obtained from questions on virtual memory that were included in two written evaluation tests at the beginning and end of the course. The questions assessed conceptual knowledge and meaningful learning of the concept of virtual memory. We discovered nine accepted conceptions and seven alternative conceptions related to virtual memory. We also inferred a mental model that could be the root cause of the discovered alternative conceptions. Our study has important implications for teaching and educational research in computer science. Regarding educational implications, this study makes recommendations for teaching virtual memory based on the results. Considering the implications for future research, our contributions are seven alternative conceptions of virtual memory that had not been previously identified, and a methodology for discovering conceptions that can be applied to other computing topics in both online and face-to-face environments.

INDEX TERMS Alternative conceptions, conceptions, concept understanding, mental models, misconceptions, online education, operating systems, virtual memory.

I. INTRODUCTION

Information and Communication Technologies (ICT) have fostered different ways of teaching and learning computer science because they provide more interactivity and flexibility. Instructors use blended and completely online (CO) teaching to organize, and provide educational content to students. Moreover, face-to-face (F2F) instructors utilize these technologies to complement traditional teaching to store and provide educational content. However, none had full knowledge of the student learning process. For example, F2F instructors have physical interactions with students, whereas online instructors interact with students in an e-learning system; in either case, it is difficult to gauge students' conceptual understanding. However, this task seems more difficult for CO instructors. As learning is an interpretive, incremental,

The associate editor coordinating the review of this manuscript and approving it for publication was Mario Donato Marino.

and iterative process, students can develop a particular understanding of concepts [1]. This way of making sense of something is called a conception. We distinguish between two types of conceptions: accepted and alternative. The accepted conceptions are consistent with the current scientific models. Alternative conceptions, also known as misconceptions, are incompatible with scientific models [2]. In other words, these conceptions mismatch the desired learning that instructors try to pursue, because students are not interpreting teaching in the way they intend. In computing education, a misconception does not mean that the learner has a complete lack of knowledge but indicates partial knowledge [3]. Similarly, Swidan et al. [4] defined programming misconceptions as an incorrect understanding of a concept or set of concepts that leads to mistakes in writing or reading programs. Searching for and discovering whether these mismatches or partial knowledge are present in students is not an easy task and requires a deep analysis of students' interactions and results.

This work presents a new method to perform a deep analysis of students' results with the objective of discovering conceptions and their root causes among online computer science students. We apply this method on students taking an operating systems course. The aims of this study were as follows:

- The first aim was to discover students' conceptions of one important concept of operating systems (virtual memory), along with their potential root causes.
- The second aim is to provide a method for uncovering students' conceptions of computer science that is applicable for both face-to-face and online/blended environments.

This study contributes to the scientific community in four ways. First, it provides a complete study of the conceptions of online education, a field in which further research is needed [5]. Second, this study discovers alternative conceptions in virtual memory, a topic for which no alternative conceptions had been found until now. Third, our study presents not only discovered alternative conceptions but also provides an analysis of the root causes of these conceptions. Fourth, the method presented in this study, applicable to a wide variety of scenarios in computer science, can reveal conceptions and their potential causes. To date, uncovering conceptions in online education and examining their causes have remained unexplored in computer science. Our results revealed nine accepted conceptions and seven alternative conceptions related to virtual memory. We also infer a mental model that could be the root cause of the discovered alternative conceptions.

The remainder of this paper is organized as follows. Section II describes the context of this research. Section III contains a brief explanation of the research topic: virtual memory. Section IV explains the methods and procedures applied. Section V presents the main results and their analysis. Section VI presents the discussion.

II. RELATED WORKS

Several attempts have been made to identify and detect misconceptions. On one hand, there are studies in which the authors predefined misconceptions (seen) to detect [4], [6], [7]. On the other hand, the authors discovered misconceptions (unseen) that they did not know a priori [8], [9], [10], [11].

In relation to studies that aim to detect misconceptions known a priori, Brown and Altadmri [6] analyzed the frequencies of 18 common Java mistakes among 900,000 users. They fixed these mistakes a priori and then discovered the mistakes using a Java compiler error message, a post-lexing analysis, and a customized parser. Swidan et al. [4] explored programming misconceptions held by students aged 7–17 years. They completed a multiple-choice questionnaire with programming exercises in Scratch, which included 11 known misconceptions. They found that the most common misconceptions were the difficulty in understanding the sequentiality of statements, the difficulty in understanding that a variable holds one value at a time, and the difficulty in understanding the interactive nature of a program when user input is required. Notably, these studies did not develop a method for discovering unseen misconceptions because they knew the misconceptions a priori.

As for studies that adopt a more exploratory approach to uncover misconceptions, Haldeman et al. [8] developed a methodology to generate meaningful autograding feedback and gain a better understanding of students' errors and misconceptions. This methodology defines the concepts and skills that students must master, assignments to evaluate these concepts and skills, an output code representing the outcome of assignments, and a classifier to automatically categorize errors. They applied this methodology to computer-science courses. They did not find misconceptions, but found common errors related to the incorrect use of conditional expressions and algorithmic thinking. Mladenović et al. [9] utilized a quantitative approach based on a pre-test, post-test, and chi-square test to discover misconceptions in software programming in three programming languages: Logo, Python, and Scratch. Their results showed an association between the programming language used and problem-solving abilities for Logo and Python, but not for Scratch. They also discovered misconceptions regarding loops, but these were minimized when the students used block-based programming languages rather than text-based programming languages. Shi et al. [10] proposed quantitative and qualitative methods to discover misconceptions regarding student program codes. The quantitative approach uses a deep learning method and clustering to group the results of students, whereas the qualitative approach uses an expert to inspect each cluster and evaluate whether a shared misconception is present. They tested the method on 207 students and found seven misconceptions related to the iterations, loops, and local variables of functions. Although this study discovered misconceptions from scratch, it did not analyze their underlying causes. Svabensky et al. [11] analyzed students' use of command line interfaces to understand how students solve cybersecurity tasks. They developed a system to collect metadata about command executions and used quantitative methods to analyze these data. They evaluated this system with 50 undergraduate cybersecurity students. They discovered misconceptions about command parameters and cybersecurity methods. They also developed a proof-of-concept application to process the students' command history. It is important to note that this study discovered unseen misconceptions and analyzed their underlying causes.

Furthermore, there are very few studies that uncover or detect misconceptions in the field of operating systems [5], [12]. To the best of our knowledge, there are only seven studies. Three of them detected misconceptions that were already known [7], [13], [14], while the other four uncovered new misconceptions [15], [16], [17], [18].

Webb and Taylor [7], based on their experiences with common students' misconceptions, developed a concept inventory. The concept inventory has ten multiple-choice questions with five options (one correct option, two distractor options that are misconceptions, one incorrect option, and one option to avoid a random answer). They applied this concept inventory at the beginning and at the end of the course and detected misconceptions related to indirection, I/O, and synchronization. Çakiroglu and Öngöz [13] applied peer tutoring and learning by design to understand students' conceptual understanding of the topics of operating systems. They divided their students into nine groups, and each group worked on an operating systems topic by developing animations related to the work topic. They analyzed the quantitative and qualitative data. Quantitative data were gathered from the pre- and post-tests, and qualitative data were obtained from interviews with a sample of students.

An initial exploratory study conducted by the first author of this manuscript [16] uncovered six alternative conceptions related to interrupts, I/O operations, concurrent computing, deadlock, and semaphore concepts. In this study, a qualitative methodology is used, based on multiple-choice questionnaires and explanations to justify students' answers. The three studies described below, in addition to uncovering misconceptions, explore their possible causes. The authors of the present study uncovered misconceptions of the concept of interruption by conducting a thorough analysis of root causes [15]. Data analysis was carried out in two stages. The aim of the first stage is to identify concepts difficult for students to understand. The aim of the second stage is to discover misconceptions about the concept interrupt and their possible causes. Strömbäck et al. [17] discovered misconceptions held by students regarding concurrency and synchronization by analyzing their answers to the final exam. They analyzed these answers using a method inspired by content analysis. They annotated whether the answer was correct or incorrect and the types of mistakes. Then, the answers were categorized based on the type of mistake. They examined the percentages of correct answers and mistakes in each category. They found that three misconceptions may be the cause of these mistakes. Moreover, they suggested that three non-viable mental models could be the cause of the discovered misconceptions. Similarly, Strömbäck et al. [14] explored students' understanding of concurrency using phenomenography to gain insight into the causes of the misconceptions discovered in previous work. They interviewed 14 students and categorized their responses into six categories. Each category corresponds to a way of experiencing concurrency discerned by one or several students. Kolikant [18] has developed a method to explore students' knowledge structure on the topic of concurrency. This method also helps to understand the process of knowledge construction. The method consists of a test, an interview, and another test. The first test provides a general picture of the concept of synchronization with semaphores. The interview provides more information about one student's performance. The second test was developed to investigate whether the incomplete knowledge of the interviewed student is also found in the other students. 139 computer science students took the first test, and 99 students took the second test. It showed that the students had insufficient knowledge of the semaphore definitions and had alternative definitions for typical semaphore operations (wait and signal).

Table 1 provides an overview of the research on student misconceptions in the field of operating systems. The columns contain characteristics of each work, such as whether a work discovers misconceptions (indicated as 'seen' if seen misconceptions are detected, and 'unseen' if unseen misconceptions are discovered), whether a work identifies the causes of misconceptions, whether the study is conducted in an online or face-to-face environment (OL/F2F), and the topic covered in each work (topic). The rows indicate the first author of the paper, the year of publication, and the corresponding values for each characteristic.

The originality of our study is highlighted in Table 1. Our research uncovers previously unseen misconceptions and identifies their root causes. To date, only two studies have achieved similar results, one of which is our prior work [15]. It is also one of the few studies conducted in an online environment, alongside our earlier works [15], [16]. Additionally, our study is unique in focusing on virtual memory.

Moreover, our work proposes a new method for uncovering misconceptions and their possible causes, the contributions of which are detailed in the methodology section.

III. VIRTUAL MEMORY

In this section, we briefly describe virtual memory based on the texts of Stallings [19] and Dhamdhere [20]. This was intended to help understand the results of the study for readers from engineering fields other than computer science.

Virtual memory is a method for managing memory on a computer. The architecture of virtual memory is a memory hierarchy consisting of main memory and a disk, which enables a process to operate with only some portions of its address space in main memory. Developers and software applications have the illusion of having a larger main memory than the real one when this memory management approach is

TABLE 1. Characterization of operating systems studies.

Work	Misconceptions: seen, unseen	Discover root causes	OL/F2F	Topic
Çakiroglu, 2017 [13]	seen	N	F2F	Operating systems
Kolikant, 2004 [18]	unseen	N	F2F	Concurrency
Pamplona, 2013 [16]	unseen	N	OL	Interruption, I/O, concurrency
Pamplona, 2017 [15]	unseen	Y	OL	Interruption
Strömback, 2019 [17]	unseen	Y	F2F	Concurrency
Strömback, 2020 [14]	seen	Y	F2F	Concurrency
Webb, 2014 [7]	seen	N	F2F	Indirection, I/O

used. The kernel implements this illusion using a combination of hardware and software. According to Dhamdhere [20], we refer to a software component as a virtual memory manager (VMM). The hardware component is called a memory management unit (MMU).

The basis of virtual memory is a noncontiguous memory allocation model. The virtual address space allocated to the disk is divided into pages (memory portions of the same size). Main memory is divided into page frames, which hold pages from the disk. Notably, memory accesses are always made through main memory and that main memory is significantly smaller in size than the virtual address space allocated to the disk; therefore, only a small number of pages will remain in it.

Therefore, any page used in a process must be loaded from the disk into main memory to be accessed. After its use, the page remains in main memory and is replaced by another page, depending on the replacement policy of the virtual memory system, such as first-in, first-out (FIFO), or least recently used (LRU). Consequently, the first thing to check is whether the page is already in the main memory or needs to be fetched from the disk when a process requires a page.

Despite this apparent overhead, virtual memory can achieve good performance because of the proximity principle [21]. This principle states that the addresses used by a process within a short period are concentrated in specific parts of the address space. There are two main reasons why the processes exhibit this behavior. First, only approximately 10–20% of the instructions are branch instructions, which causes the program to jump to different parts of the code. Consequently, the process tends to access addresses in a contiguous manner. Second, processes perform similar operations on multiple elements of nonscalar data such as arrays. This behavior further contributes to the clustering of addresses within a certain range. Concerning virtual memory addresses, the address of each operand or instruction in the code is a virtual address of the form (p_i,b_i), where pi is the page number and b_i is the number of bytes defining the position inside the page. The MMU translates a virtual address into the address in the main memory of a computer system.

A page table (Figure 1) was created for each process to facilitate virtual-memory management. Because only some pages of a process may be in main memory, a bit flag is

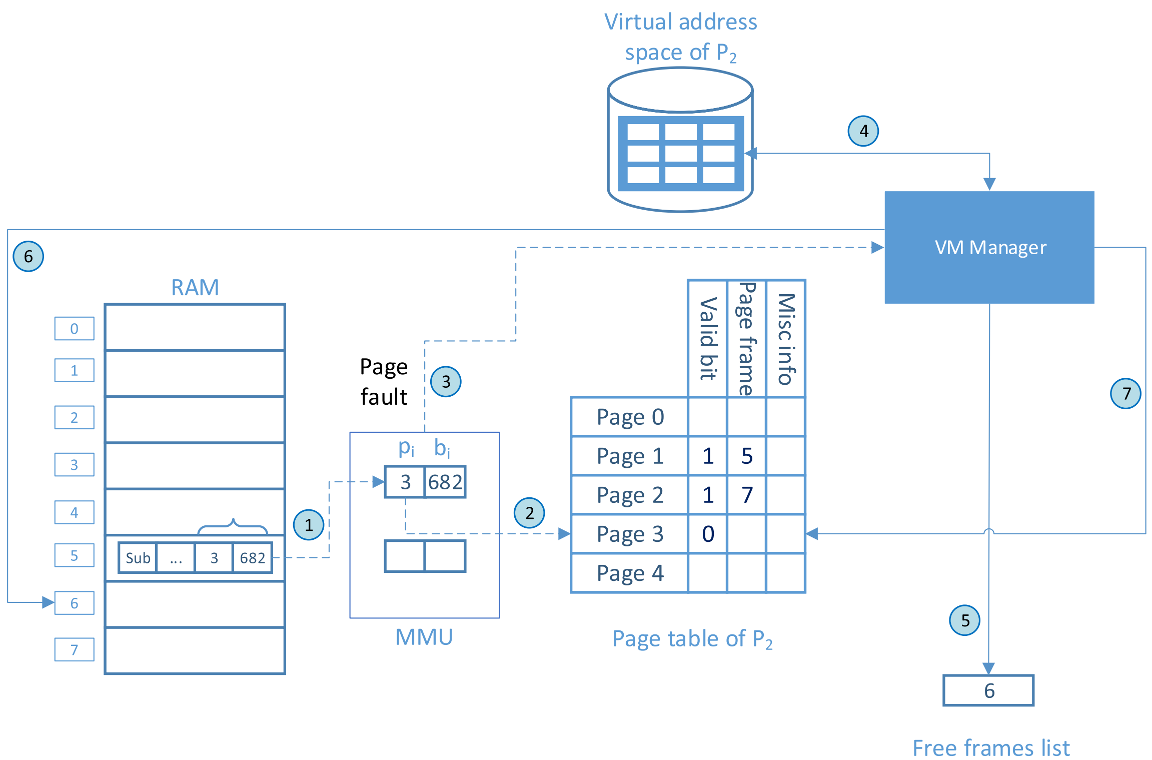

FIGURE 1. Translation of a virtual address by the virtual memory manager.

required in each page table entry to indicate whether the corresponding page is present in main memory.If the bit indicates that the page is in memory, then the entry also includes the frame number of that page.

Figure 1 shows an overview of VMM actions for the demand loading of a page. The broken arrows indicate the actions of the MMU, and the firm solid arrows indicate the actions of the VMM when a page fault occurs. The actions are labeled with numbers in circles, indicating their order of occurrence. The first action involved translating a virtual address (3, 682). Figure 1 shows that p_i is equal to 3. In the second action, the MMU searches for page 3 in the page table of P2 process. The MMU raises an interrupt called a page fault since this page is not present in the memory (valid bit = 0). This interrupt invokes the VMM with a page number that causes a page fault (Action 3 in Figure 1). The Misc information field contains the address of P2 in the virtual address space. The VMM uses this information to obtain the address on Page 3 in the swap space of P2 (Action 4). In Action 5, the VMM consults the free-frame list and finds that page 6 is currently free; then, it starts an input-output operation to load page 3 on page frame 6 (Action 6). When the input-output operation is completed, the VMM updates the page 3 entry in the page table by setting the valid bit to 1 and placing 6 in the page frame field (action 7). The final results are not shown in Figure 1.

In summary, virtual memory may be a complex concept because, as described in this section, virtual memory management involves an intricate relationship between the processor and the operating system. To fully understand how virtual memory works, it is necessary to understand at least the following concepts: memory hierarchy, virtual addresses, principle of locality, and page fault.

IV. METHOD

In this section, we describe the methods used in our study. First, an overview of the research design is provided. Second, descriptions of the researchers are provided. Third, the participants and data collection procedure are explained. Finally, the analysis and methodological integrity are discussed.

A. RESEARCH DESIGN OVERVIEW

We aimed to discover students' conceptions of virtual memory and their root causes. The problem we faced with conceptions of virtual memory was that we knew that students had trouble understanding this concept, but we did not know exactly what problems they had or the root causes of those problems. Therefore, we have no information to establish an initial hypothesis, and we cannot address the problem through a confirmatory perspective, consisting of stating a hypothesis and checking whether it has been confirmed [22].

Another perspective that is more appropriate for our problem is called the discovery perspective [22], which consists of asking questions and discovering answers based on the studied facts rather than on the researcher preconceptions. One approach that fits the discovery perspective uses ethnographic methods originally pioneered by anthropologists, particularly participant observation, and exploratory interviews.

We required students to exhibit their thinking processes to study conceptions and their root causes. Moreover, the context of our research was an online university chosen by its students because they were not available for synchronous activities, such as class attendance. Therefore, in-depth interviews were not considered as a method. On the other hand, direct observation by means of techniques, such as thinking aloud, was not possible because of the asynchronous online setting.

Therefore, we invited students to describe their reasoning processes through written assessment tests designed to promote meaningful learning. This type of assessment test compels students to perform higher cognitive processes and argue for the answers given, revealing their thinking process.

We used multiple-choice questions with open-response questions, in which students had to justify the selected answer. Open-response questions are superior to multiple-choice questions in terms of pedagogical value [23].

We need a thorough and in-depth analysis of each student thought process to discover alternative conceptions and their root causes. Considering this, we selected a qualitative case study as our methodology, which is appropriate when the purpose is to conduct in-depth research on individual cases.

A case study becomes valuable when it reveals new phenomena or suggests innovative explanations [22]. Hence, the purpose of this study is not to generalize but rather to uncover conceptions and their root causes. Accordingly, the effort of the analysis lies in the depth with which each participant is analyzed, rather than in the number of participants [24], [25].

The methodology utilized in this research is illustrated in Figs. 2, 3 and 5. To enhance the clarity and comprehension of these diagrams, the shapes used in the flow diagrams are described as follows:

- Rectangular shapes: Indicate processes that obtain or transform information.
- Pill shapes: Denote inputs and outputs within the process flow.
- Diamond shapes**:** Represent questions or decision points within the process flow.

The analysis was conducted in two stages. Figure 2 provides an overview of the complete procedure. The first stage (Fig. 3) focuses on discovering students' conceptions. The second stage (Fig. 5) involves discovering potential root causes behind the identified non-accepted conceptions.

B. RESEARCHER DESCRIPTION

The research team conducted this study consisted of three authors. The first author is an educational researcher who currently teaches STEM Education and has taught undergraduate operating system courses for 13 years at an online university. She has been a teacher in an Operating Systems course for the group under study. The second author is a computer science researcher who currently teaches web applications and

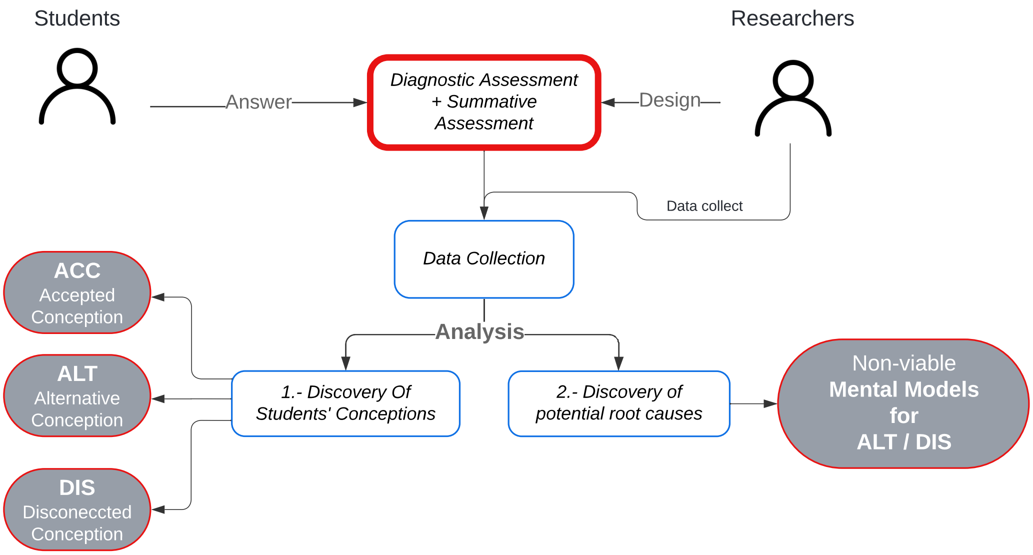

FIGURE 2. Research design overview.

has taught undergraduate compiler and artificial intelligence courses for 11 years at an online university. The third author is a telecommunications engineering teacher and researcher whose point-of-view about operating system concepts comes from a top-down approach to the topic.

C. PARTICIPANTS

The study participants were students in an Operating Systems course of a second-year undergraduate course in computer science (four years long) at an online university. Eleven students were enrolled in the course, and we selected participants who had finished the course and signed an informed consent form for the study. There were seven participants in this study (two women, five men, zero nonbinary). Their average age was 36 years and all except one had an IT-related job, although none of them worked on anything related to the design and implementation of operating systems.

D. DATA COLLECTION

The study data were obtained from questions about virtual memory included in two written evaluation tests: one taken before the beginning of the course, with a diagnostic function, and the other taken at the end, with a summative purpose. The duration of the course was 14 weeks and the duration of the evaluation tests was 90 min. The questions assessed both conceptual knowledge and meaningful learning because the purpose of our study was to elicit students' conceptions.

Accordingly, we used Bloom revised taxonomy [26] to appraise the suitability of each question. We used the knowledge dimension of Bloom revised taxonomy to distinguish conceptual knowledge from procedural knowledge, and the cognitive process dimension to distinguish between rote learning and meaningful learning.

Regarding the knowledge dimension, questions on virtual memory assess two types of knowledge: conceptual and procedural. Conceptual knowledge refers to knowledge of structures, models, and theories. Alternatively, procedural knowledge includes knowledge of algorithms, techniques, and methods, as well as knowledge of the criteria used to select which of them to apply in a particular situation.

According to these definitions, virtual memory questions that assess procedural knowledge can be solved simply by following a series of steps without us being able knowing whether a student really understands the concepts of virtual memory and page faults. A typical example of this type of question is the calculation of the number of page faults given a page-access sequence and replacement policy (LRU, FIFO, etc.). Consequently, we excluded all questions about virtual memory that assessed procedural knowledge.

Regarding the cognitive process dimension, we can distinguish between rote and meaningful learning. Meaningful learning is based on transference, which is the ability to use what has been learned to answer new questions. In contrast, rote learning is based on retention, which is the ability to remember material at a later time in the same way as it was presented during instruction [27].

Since we aimed to reveal students' thinking processes, questions about virtual memory should assess meaningful learning instead of rote learning. Therefore, according to Bloom revised taxonomy [26], we will include questions associated with higher cognitive processes: understand, apply, analyze, evaluate, create, and excluding questions associated with remember and recall.

The diagnostic assessment test comprised 23 open-ended questions. The first four questions collected information on the date of birth, computer-related jobs, computer courses, and number of times they had taken the operating system course. The remaining questions assessed knowledge about the general and specific aspects of operating systems (e.g., system calls, interrupts, virtual memory, and multitasking).

Table 2 lists the questions on virtual memory from which the data for this study were collected (Questions 1.1 and 1.2).

The summative assessment test consisted of seven questions, two open-ended questions, and five multiple-choice questions, in which students were asked to justify their answers (an example is Question 2.1 in Table 2). The questions tested knowledge of the main operating system topics (process scheduling, concurrency, memory management, and input/output management). Table 2 shows the virtual memory questions from the summative assessment from which the data for this study were derived (Questions 2.1, 2.2, and 2.3).

Diagnostic evaluation tests were the same for all students and were conducted online. However, there were two different models of summative evaluation tests, corresponding to the different dates on which students were examined. The summative tests were conducted face-to-face. Table 3 shows the questions for each summative assessment test and the students who took them.

To ensure validity of the assessment questions, we employed a multi-step validation process. First, we tested the assessment questions we designed on students who took the course in the semester prior to the study. This initial phase allowed us to identify any ambiguities or misunderstandings in the questions and to make necessary adjustments to improve clarity.

Next, we sought expert reviews from experienced educators and researchers in the field of computer science and educational assessment. These experts evaluated the questions for content validity. They also provided feedback on the appropriateness and difficulty level of the questions, as well as their alignment with the cognitive processes targeted by the revised Bloom's taxonomy.

E. ANALYSIS

The analysis was performed using ATLAS.ti [28]. First, the data were anonymized and prepared in an appropriate format for import into ATLAS.ti. Each participant in the study was identified using codes such as ST01, ST02, and ST03. After completing the data preparation process, all the study data were imported, resulting in a single ATLAS.ti document.

The analysis was conducted using the first aim of the study as a guide. The first aim has a twofold purpose: to discover students' conceptions (1) and potential root causes (2).

1) DISCOVERY OF STUDENTS' CONCEPTIONS

We distinguished between alternative conceptions (ALT), accepted conceptions (ACC), and disconnected conceptions (DIS). We considered the following definitions: an accepted conception is a conception that is consistent with current scientific models [1], an alternative conception is clearly incompatible with scientific models [2], and a disconnected conception is an isolated fragment of knowledge that students do not see as significantly linked to anything else [1].

The sequence of steps can be seen in Figure 3. The source data for this analysis were the evaluation tests taken by the students.

TABLE 2. Virtual memory questions used in the study.

Diagnostic assessment	**1.1 Virtual memory concept and operation** Do you know what virtual memory is? If you do, explain this in your own words. Do you know how does it work? Please explain this briefly
	1.2. Advantages and disadvantages of using virtual memory Do you know the advantages and disadvantages of using virtual memory? Please briefly explain them.
Summative assessment	**2.1. Virtual Memory Scenario** The virtual memory performance of an operating system is analyzed, and it is found that, under a certain workload, the CPU is used 15% of the time and the backup memory (located on disk) is used 92% of the time. Which of these actions would increase the CPU utilization percentage most? Justify your answer. A) Expand main memory. B) Increase the degree of multiprogramming. C) Change the disk used as backup memory to a disk with a larger capacity. D) Change the CPU for a faster one.
	2.2. Advantages and disadvantages of using virtual memory What are the advantages and disadvantages of using virtual memory? Please state the reasons for your responses.
	2.3. LRU Algorithm What is the purpose of the LRU algorithm? Explain how it works.

TABLE 3. Summative assessment test questions.

Model 1 Questions 2.1 y 2.2	ST01, ST02, ST04, ST05, ST06
Model 2 Questions 2.1 y 2.3	ST03, ST07

In the initial analysis, we followed this sequence of steps for each student.

• Step 1. The first author analyzed the data and selected the units of information that reflected the students' conceptions. The minimum unit of information considered was a sentence. The textual excerpts chosen at this stage of the analysis are called 'quotations' in the ATLAS.ti software. The selected quotations contained one or more sentences or even a whole paragraph. A code, that in this case represent a student conception, was created to capture the essence of each quotation [29]. The codes were not defined beforehand

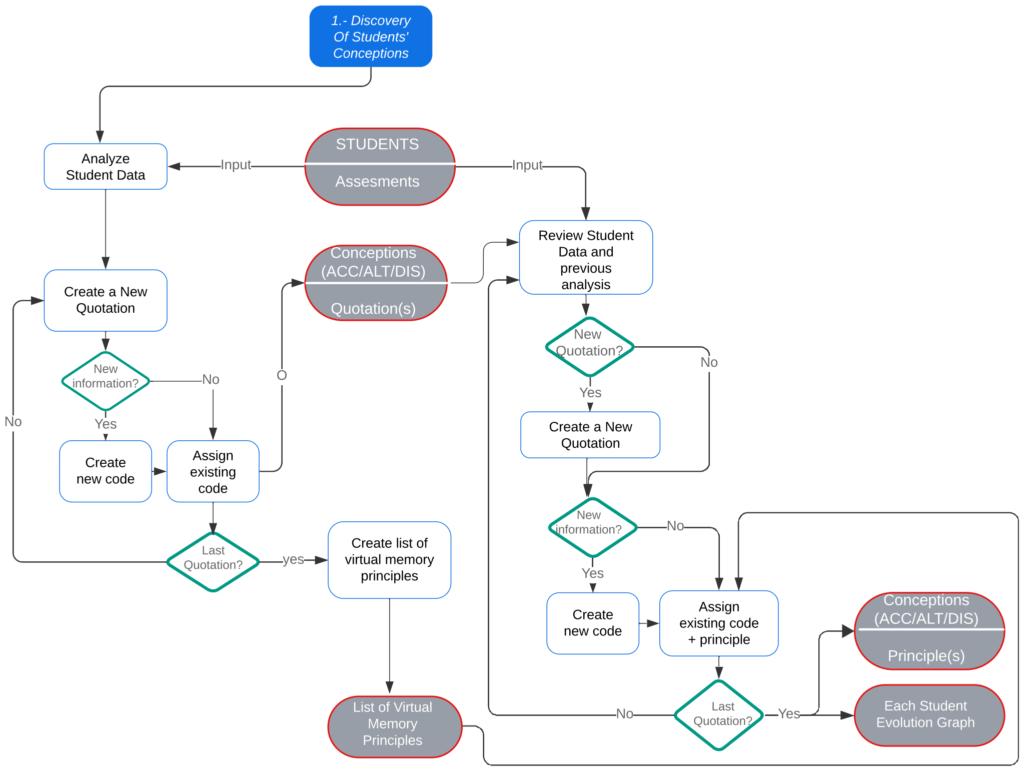

FIGURE 3. **Discovery of students' conceptions.**

but were created specifically for each quotation emerging from the data. For example, the student ST05 stated that "virtual memory consists of creating a file to store data in the case that the RAM memory becomes full" (Question 1.1. in Table 2). For this quotation, we created the code ALT6 "Virtual memory is a mechanism to increase main memory when it becomes full." After creating this code, we found that the student ST07 said that "virtual memory is a swap space on the hard disk that acts as a simulated main memory when the main memory runs out, allowing programs to continue running without crashing." This sentence was identified using the same code (ALT6) because it conveyed the same idea.

• Step 2. The three authors discussed the results obtained up to that point and reached a consensus. After completing the analysis of all student data, we grouped the codes obtained by considering the different aspects of virtual memory that emerged in the conceptions. For example, one of the aspects mentioned by the students was the structure of virtual memory and the other was the performance of virtual memory. At that point, we realized that certain aspects of virtual memory, which the students had not mentioned, were also necessary to answer the assessment questions. For example, none of the students pointed out the concept of locality of reference.

• Step 3. Accordingly, we decided to change our analysis process to allow us to record both aspects of virtual memory mentioned and those not mentioned by the students.

For this purpose, we created a list of operating principles (Table 4) of the virtual memory necessary to answer the questions in Table 2.

Once this list of principles was drawn up and agreed upon, we performed a second iteration of the analysis in which we related each of the conceptions discovered to one of these principles. A conception was associated with a principle when it was related to that principle, whether it was an accepted, alternative, or disconnected conception. The steps performed for each student in the second analysis were as follows:

• Step 1. The first author of the paper revisited the data for each student. At each iteration, new information can be uncovered because the knowledge of the researchers can change with respect to the previous iteration. At this stage, in addition to discovering conceptions and creating codes (conceptions) for each, each code was associated with one of its principles (see Table 4). For example, the code ALT6, which represents the alternative conception "virtual memory is a mechanism to increase RAM memory when it becomes full," indicates that the student is not identifying virtual memory with a memory hierarchy. The memory hierarchy is a permanent mechanism, not a temporary one as the student said, and all its levels are always in operation. In a memory hierarchy, the lowest level establishes memory capacity, and parts of the memory are loaded at the highest level to provide faster access. Therefore, we associated the conception of ALT6 with Principle 2 (memory hierarchy).

TABLE 4. Principles of virtual memory needed to answer the questions in Table 2.

Principle 1. Process execution	Virtual memory allows a process to run without being fully loaded in main memory.
Principle 2 Memory hierarchy	A machine with virtual memory supports its memory map through two levels of memory hierarchy: main memory and a backup memory that is usually a disk or part of a disk. Both the code and data for each process reside in the backup memory. Since the processor requires instructions and data reside in main memory, they are loaded into main memory from the backup memory when they are required.
Principle 3 Virtual addresses	The memory map matches the size of the secondary memory intended to be part of the virtual memory system. The processor generates virtual addresses that must be translated into main memory addresses, since all the necessary instructions and data must be located in main memory for the processor to access them.
Principle 4 Locality of reference	Program and data references within a process tend to cluster. Therefore, if we consider a short period of time, only a few pages of each process will be accessed. In other words, a page in main memory will be accessed several times before another page must be accessed.
Principle 5 Page fault	A page fault is generated when the information needed by a process is not in main memory. A page fault is a request to load a page from disk to main memory.
Principle 6 Performance	The performance of the virtual memory system depends on the number of page faults. If the page fault rate is low the performance will be acceptable.

• Step 2. The objective of this second step was to visualize the results to determine the evolution of each student knowledge. The scenario changed significantly from the first analysis as we identified six principles that relate the discovered conceptions. After considering several options, we agree with the visualization shown in Figure 4. The six ideas were represented by six zones arranged in a hexagonal form. These concepts are shown in the zone of principles with which they are associated. Accepted concepts are shown in green, and non-accepted concepts are shown in red. In addition, the initial conceptions are represented by a triangle near the center of the hexagon, and the final conceptions by a hexagon at the outer part of the hexagon.

• Step 3. The three authors discussed the results obtained up to that point and reached a consensus.

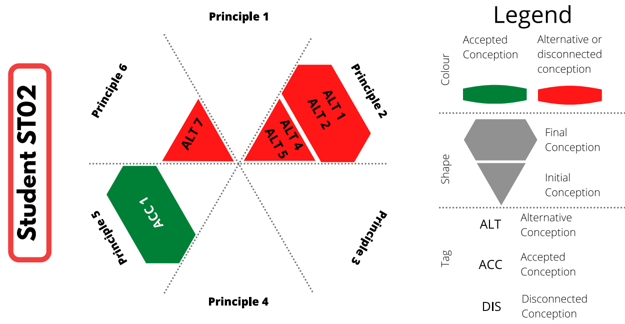

FIGURE 4. Results from student ST02 answers analysis.

2) DISCOVERY OF POTENTIAL ROOT CAUSES

We used the mental model theory to discover the causes behind the identified alternative conceptions. Mental models are the internal representations of external phenomena or systems [30]. A mental model can be conceived as an imaginary structure that corresponds to what is represented externally in terms of the spatial arrangement of the elements of the system and the relationships between them. From this perspective, a mental model of a specific domain is not just a collection of facts or beliefs, but a set of mentally perceivable elements that can be manipulated to generate predictions or explanations [31].

The procedure adopted to discover the causes of the identified non-accepted conceptions is as follows (Figure 5).

• Step 1. The starting point was a set of conceptions of virtual memory clustered by its operating principles of virtual memory (Table 4). Because of their definition, non-accepted conceptions do not agree with the virtual memory model explained in Section III of this manuscript. Therefore, for each conception, an attempt was made to infer a mental model in which the student conception fitted. The inference of the mental model was facilitated by the association of each conception with a principle of virtual memory (Table 4), performed in the previous analysis phase. For example, if a non-accepted conception is associated with the principle of 'Memory hierarchy,' the possible mental models would correspond to different forms of memory organization. Each hypothetical mental model, was agreed upon by the three authors of this study.

• Step 2. Each non-accepted conception is associated, if possible, with one of the inferred mental models.

• Step 3. When this process was applied to all non-accepted conceptions, it was cyclically repeated. The complete set of non-accepted conceptions was reanalyzed to verify and improve the fit of the inferred mental models and conceptions. As a result, hypothetical mental models were modified, merged, eliminated, or inferred to provide the best fit with the students' alternative conceptions. The analysis process was completed when the new iteration no longer provided any new information. Three iterations were performed in our case.

F. METHODOLOGICAL INTEGRITY

Our study aimed to conduct an in-depth analysis of a specific context with the goal of learning from it [32]. Therefore,

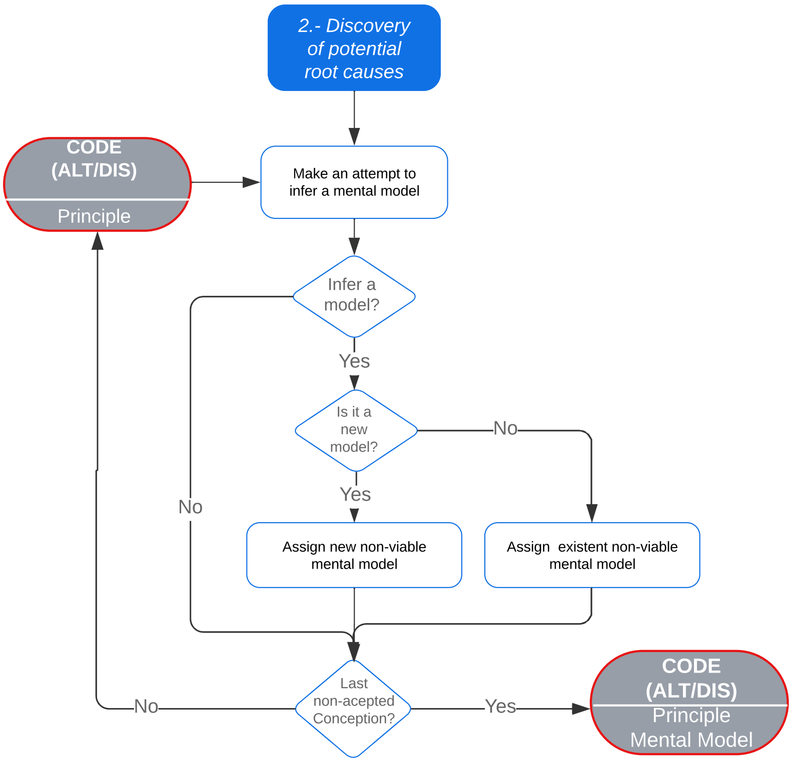

FIGURE 5. Discovery of potential root causes.

we used the trustworthiness criteria provided in [33]: credibility, transferability, dependability, and confirmability.

Techniques used to satisfy the credibility criterion include persistent observations and triangulation. The persistent observation technique provided depth information. This consists of identifying the characteristics and elements of the situation that were most relevant to the research questions and focusing on them in detail. This was performed during data analysis by iteratively applying the steps previously described.

Two types of triangulations were used: data-gathering tools and researchers. To interpret the results, information provided by different data-gathering tools was considered. Furthermore, the results were accepted by consensus among the three researchers who participated in the study, as described in the analysis section.

Regarding transferability, we provide a full description of our context, results, and contributions such that potential appliers can make transferability judgments.

Concerning dependability and confirmability, the following facts support these criteria as follows:

- Methods and procedures used in this study are described in detail.
- It is possible to follow the sequence of data collection and processing to obtain conclusions.
- The results were explicitly related to the original data.

G. ORIGINALITY OF OUR METHOD

The originality of our method is based on the following elements: the design of assessment tasks to promote higher cognitive processes using Bloom's revised taxonomy, the creation of a list of principles necessary to respond to the designed assessment tasks, and the design of a process to identify possible non-viable mental models that may be the cause of the uncovered misconceptions. To the best of our knowledge, these elements have not been used as a method for discovering conceptions and their causes.

V. RESULTS

The results align with the first objective of the article, which is to uncover students' conceptions of virtual memory and the possible causes of these conceptions. This section is divided into four subsections. The first presents the conceptions held by the students. The second exhibits these conceptions classified by principles. The third shows the potential causes of these conceptions and the inferred mental models that could be the causes. The final subsection presents the evolution of the conceptions and mental models about virtual memory.

A. STUDENTS' CONCEPTIONS

In this section, we present the total set of conceptions discovered. Table 5 shows the alternative and disconnected conceptions. In Table 5, the first column contains the code of conception, followed by the code of the students holding this conception. For example, in the second row "ALT2 (ST07)" is indicating that student ST07 held the conception coded as ALT2. The second column of the table provides the definition of the conception. For example, the definition of ALT2 is "virtual memory is a part of the secondary memory." Table 6 lists the set of accepted conceptions and follows the same notation as that in Table 5.

Below, we illustrate the analytical process of discovering students' conceptions with some examples in which we show the data excerpts and the conceptions we associated with those excerpts. Notably, students answered the Spanish questions. The authors translated the answers into English.

The student ST01 provides the following answers in the initial questionnaire.

Question 1.1 (Table 2): Do you know what virtual memory is? If you do, explain this in your own words. Do you know how does it work? Please explain this briefly.

Answer: "By definition, I understand that it is the secondary memory, reserved by the operating system, which acts as RAM. Windows uses the paging file and in Linux it is defined by the SWAP partition."

TABLE 5. Alternative and disconnected conceptions.

Alternative conceptions	
ALT1 (ST01)	Virtual memory is the secondary memory.
ALT2 (ST07)	Virtual memory is a part of the secondary memory.
ALT3 (ST01)	Virtual memory is easier to manage.
ALT4 (ST02)	Virtual memory is used only in specific cases.
ALT5 (ST02)	Virtual memory is used when the computer is low on main memory.
ALT6 (ST05, ST07)	Virtual memory is a mechanism to increase main memory when it becomes full.
ALT7 (ST01, ST02, ST07)	Virtual memory is significantly slower than main memory.
Disconnected conceptions	
DIS1 (ST03)	There is no connection between LRU algorithm and virtual memory operation.

Question 1.2 (Table 2): Do you know the advantages and disadvantages of using virtual memory? Please briefly explain these in this case.

Answer: "Advantages I imagine, among many, to prevent the operating system from crashing due to lack of memory. Disadvantages, by definition if the virtual memory is the secondary memory that acts as RAM, physically it is still linked to the laws of physics, so it is a reality that the secondary memory is much slower than RAM."

TABLE 6. Accepted conceptions.

ACC1(ST02)	There are page faults in a virtual memory system.
ACC2 (ST04, ST05, ST06)	Virtual memory allows a process to run without being completely loaded in main memory.
ACC3 (ST04)	If the main memory size is increased, disk calls decrease and CPU performance increases.
ACC4 (ST04)	It is necessary to adjust the content loaded in the main memory in order not to access the disk too much and slow down the operations.
ACC5 (ST05)	In a situation where the disk is busy and the CPU is not, the main memory acts as a bottleneck.
ACC6 (ST05)	Poor handling of page faults by the chosen replacement policy can lead to general underperformance.
ACC7 (ST06)	The process generates virtual addresses that are translated into physical addresses in the main memory.
ACC8 (ST06)	If the percentage of time that the secondary memory is occupied is very high, and the percentage of time that the processor is occupied is very low, it may be an indicator that page faults are occurring.
ACC9 (ST06)	Page faults occur when the generated physical address is not in main memory and is required to be replicated from secondary to main memory.

We inferred the following conceptions from this student statements as follows:

- The student says twice (once in each question) that virtual memory "is the secondary memory" (ALT1).
- The student claims that virtual memory "is much slower than RAM" (second question) (ALT7).

Moreover, the student ST01 provides the following answers on his final exam.

Question 2.2 (Table 2): What are the advantages and disadvantages of using virtual memory? Please state the reasons for your responses.

Answer: "Virtual memory is the part of the secondary memory where a backup of the main memory is established. Its main advantages are that much more size is available at a much lower cost. In addition, it is easier to manage. The main disadvantage of virtual memory is its speed. Being secondary memory, it is much slower than main memory."

We inferred the following conceptions from this student's statements:

- The student says that virtual memory is a "part of the secondary memory" (ALT2).
- The student states that virtual memory "is easier to manage" (ALT3).
- The student asserts that virtual memory "is much slower than main memory" (ALT7).

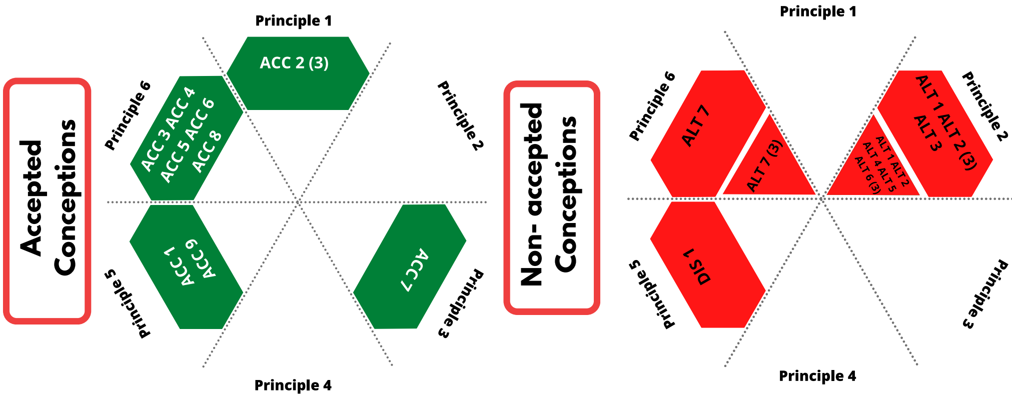

FIGURE 6. Accepted, alternative and disconnected conceptions classified by principles and by time (initial and final).

In this section, we describe the discovery process of student ST01 conceptions. We followed an analogous discovery process for the remaining students.

B. STUDENTS' CONCEPTIONS CLASSIFIED BY PRINCIPLES

In this section, we present the conceptions categorized based on the operating principles of virtual memory. Table 7 presents the accepted, alternative, and disconnected conceptions related to these principles. Each row of the table corresponds to a principle, and each conception is related to a single principle. The second column of the table shows the accepted conceptions, and the third column shows the non-accepted: alternative and disconnected conceptions. Each cell in the table contains a list of conceptions associated with each principle, indicating whether the conceptions were inferred in the initial or final stage.

Notably, we processed the results at the initial and final stages for each student, and the conceptions discovered were numbered in order of appearance, not by the number associated with each principle. Therefore, the numbers of conceptions that appear in each cell of the table are not correlated. For example, the second row of Table 7 shows the following conceptions at the initial stage: ALT1, ALT2, ALT4, ALT5, and ALT6, and ALT1, ALT2, and ALT3 at the final stage. By applying our methodology, the results in this row were obtained. First, we processed student ST01 and discovered ALT1, ALT2, and ALT3 in Principle 2. Second, we processed student ST02 and discovered ALT4 and ALT5 in Principle 2. Third, we processed ST03 and ST04 and did not discover any concepts related to Principle 2. Fourth, we processed student ST05 and we discovered ALT6 for Principle 2. Fifth, we processed student ST06 and did not discover any conception related to Principle 2. Sixth, we processed student ST07 and discovered ALT2 and ALT6, which were discovered during the processing of students ST01 and ST07. Following this process, the rows in Table 7 were created.

We draw the following conclusions regarding the analysis of Table 7 in relation to each principle:

- There is a final accepted conception of Principle 1 (ACC2) that completely coincides with the principle itself. No other conception (alternative or disconnected) indicated a lack of understanding of this principle. Therefore, there is no evidence of a lack of understanding of Principle 1.
- Principle 2 is significant in the findings because six of the seven alternative conceptions discovered are related to it. The alternative conceptions ALT1 and ALT2 directly refer to the term virtual memory. They state that virtual memory is secondary memory or a part of it. Thus, in these conceptions, students identify virtual memory only with the area of secondary memory, not with the entire memory hierarchy. On the other hand, the ALT4, ALT5, and ALT6 conceptions specify that virtual memory only comes into operation at certain times. Specifically, the ALT5 and ALT6 conceptions specify that virtual memory is used when the main memory is full. Finally, ALT3 claimed that virtual memory is easier to manage.
- Considering Principle 3, there is a final accepted conception (ACC7) and no alternative or disconnected conception. The accepted conception recognizes the existence of virtual addresses and the need to translate them into main-memory addresses.
- There were no student conceptions of Principle 4. In other words, the students did not mention the proximity principle in any of their answers. This is a remarkable result because virtual memory performance is based on this principle.
- Regarding Principle 5, there were two final accepted conceptions (ACC1 and ACC9) and one final disconnected conception (DIS1). These accepted conceptions reflect the knowledge and understanding of page fault concept. DIS1 corresponds to a student who explained a page replacement algorithm without referring to the concept of page fault even though it is precisely a page fault that triggers the execution of that algorithm. What is relevant about the conceptions of this principle is

TABLE 7. **Students' conceptions classified by principles.**

Principles	Accepted conceptions	Non-accepted conceptions: alternative and disconnected conceptions
Principle 1. Process execution	**Final conceptions** ACC2(ST04, ST05, ST06). Virtual memory allows a process to run without being completely loaded in main memory.	
Principle 2 Memory hierarchy		**Initial conceptions** ALT1. (ST01) Virtual memory is the secondary memory. ALT2. (ST07) Virtual memory is a part of the secondary memory. ALT4 (ST02). Virtual memory is used only in specific cases. ALT5 (ST02). Virtual memory is used when the computer is low on main memory. ALT6 (ST05, ST07). Virtual memory is a mechanism to increase main memory when it becomes full. **Final conceptions** ALT1 (ST02). Virtual memory is the secondary memory. ALT2(ST01,ST02). Virtual memory is a part of the secondary memory ALT3(ST01) . Virtual memory is easier to manage.
Principle 3 Virtual addresses	**Final conceptions** ACC7 (ST06). The process generates virtual addresses that are translated into physical addresses in the main memory.	
Principle 4 Locality of reference		
Principle 5 Page fault	**Final conceptions** ACC1(ST02). There are page faults in a virtual memory system. ACC9 (ST06). Page faults occur when the generated physical address is not in main memory and is required to be replicated from secondary to main memory.	**Final conceptions** DIS1 (ST03). There is no connection between LRU algorithm and virtual memory operation.
Principle 6 Performance	**Final conceptions** ACC3 (ST04). If the main memory size is increased, disk calls decrease and CPU performance increases. ACC4 (ST04). It is necessary to adjust the content loaded in the main memory in order not to access the disk too much and slow down the operations. ACC5 (ST05). In a situation where the disk is busy and the CPU is not, the main memory acts as a bottleneck. ACC6 (ST05). Poor handling of page faults by the chosen replacement policy can lead to general underperformance. ACC8 (ST06). If the percentage of time that the secondary memory is occupied is very high, and the percentage of time that the processor is occupied is very low, it may be an indicator that page faults are occurring.	**Initial conceptions** ALT7. (ST01, ST02, ST07) Virtual memory is significantly slower than main memory. **Final conceptions** ALT7(ST01). Virtual memory is significantly slower than main memory.

that some students do not even mention page faults in their descriptions and arguments about virtual memory, even though they are an essential element in this type of memory management.

- In Principle 6, we found one alternative conception (ALT7) and five final accepted conceptions (ACC3, ACC4, ACC5, ACC6, and ACC8). The alternative conception (ALT7), which is presented both at the beginning and end of the course, is related to the idea that virtual memory is much slower than main memory.

The discovered conceptions are summarized in Figure 6. In this figure, both the accepted and non-accepted conceptions can be observed at the beginning (triangles) and end (hexagons). If a conception was present in more than one student, it was indicated by parentheses and the number of students who shared that conception.

Regarding accepted conceptions, we did not discover any initially accepted conceptions related to any of the principles, but we discovered final conceptions related to four of the six principles. Thus, we did not find accepted conceptions of the proximity principle (Principle 4) or virtual memory as a memory hierarchy (Principle 2). Additionally, it could be easily observed that no student reached the complete set of accepted conceptions.

Concerning the non-accepted conceptions, there are two principles (Principles 2 and 6), of which we found both initial and final conceptions. Alternative conceptions related to Principles 2 (ALT1 and ALT2) and 6 (ALT7) persisted in the final stage. This means that the learning problems we identified were mainly related to the memory hierarchy of the virtual memory and its performance. Therefore, at the end of the course, some students did not understand that virtual memory was a memory hierarchy. On the other hand, there is a disconnected conception of page faults (Principle 5), indicating that the functioning of the LRU algorithm is understood but is not connected with the general operation of virtual memory.

C. POTENTIAL ROOT CAUSES. INFERRED MENTAL MODEL

According to the results shown in Table 7, the principle least understood about virtual memory is memory hierarchy (Principle 2). It is precisely the non-accepted conceptions around Principle 2 that have contributed the most to inferring the mental model of students who do not understand this principle might have.

The alternative conceptions associated with Principle 2 suggest that the students may have answered using a model of virtual memory architecture that differs from the virtual memory organization described in Section III. Therefore, we believe that the existence of this mismatched mental model may be the cause of these six alternative conceptions.

We then use the term "mismatch model" to refer to it, in contrast with the accepted virtual memory architecture that we will denote as the "accepted model". Next, we are going to contrast the differences between the "mismatch model", shown in Figure 7, and the "accepted model", shown in Figure 8.

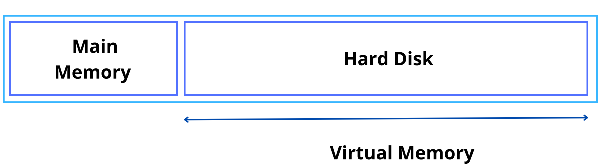

FIGURE 7. Mismatch model.

The "accepted model" (Figure 8) has a hierarchy scheme whose first level is the main memory and its second level is a reserved part of the disk. In contrast, the "mismatch model" (Figure 7) has a contiguous memory scheme where the main memory acts as the first part of the memory and the disk will be the next contiguous part, as the disk would be an extension of the main memory physical size. In the mismatch model, the disk was used only when the main memory was full. However, in the accepted model, the disk is used from the beginning, and provides a virtual address space. It is also relevant to note that the disk represented in Figures 7 and 8 does not necessarily correspond to the complete disk available in the system, but to a part of the disk reserved to manage virtual memory transactions, as described in Section III.

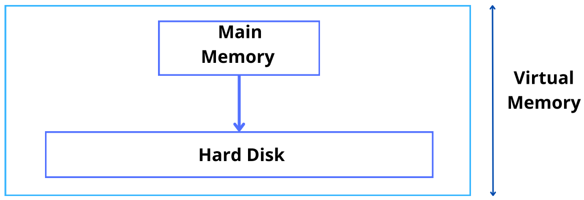

FIGURE 8. Accepted model.

Another important issue is that the meaning of the term virtual memory is different in the two models. It seems that students who used the mismatch model thought that virtual memory was only a part of the disk used to extend the main memory size, as shown in Figure 7. By contrast, in the accepted model, virtual memory is the entire memory hierarchy composed of the main memory and a part of the disk, as shown in Figure 8.

Next, we discuss each of the non-accepted conceptions discovered and their consistency with the two models presented. For this purpose, we examined Table 7, in which non-accepted conceptions are classified according to the principles. The first principle, which includes alternative conceptions (ALT1, ALT2, ALT3, ALT4, ALT5 and ALT6) is Principle 2 (memory hierarchy). The alternative conceptions ALT1 and ALT2 directly refer to the term virtual memory. They state that virtual memory is secondary memory or a part of it. Thus, in these conceptions, students identify virtual memory only in the area of secondary memory, not in the entire memory hierarchy. Therefore, the conceptions ALT1 and ALT2 are consistent with the "mismatch model" shown in Figure 7.

On the other hand, the ALT4, ALT5, and ALT6 conceptions specify that virtual memory only comes into operation at certain times. Specifically, the ALT5 and ALT6 conceptions specify that virtual memory is used when the main memory is full. These ideas are consistent with the "mismatch model," in which the main memory (first zone) and the virtual memory (second zone) are two adjacent zones. This implies that the second zone is used only when there is no available space in the first zone.

Finally, the ALT3 conception, which claims that virtual memory is easier to manage, agrees with the "mismatch model," since the management of a contiguous memory scheme is simpler than using a hierarchical memory scheme as can be seen in Section III.

Regarding Principle 5 (page fault), there is a disconnected conception (DIS1) that implies that the student does not connect the page replacement algorithm to the virtual memory operation. This conception could also have its origin in the

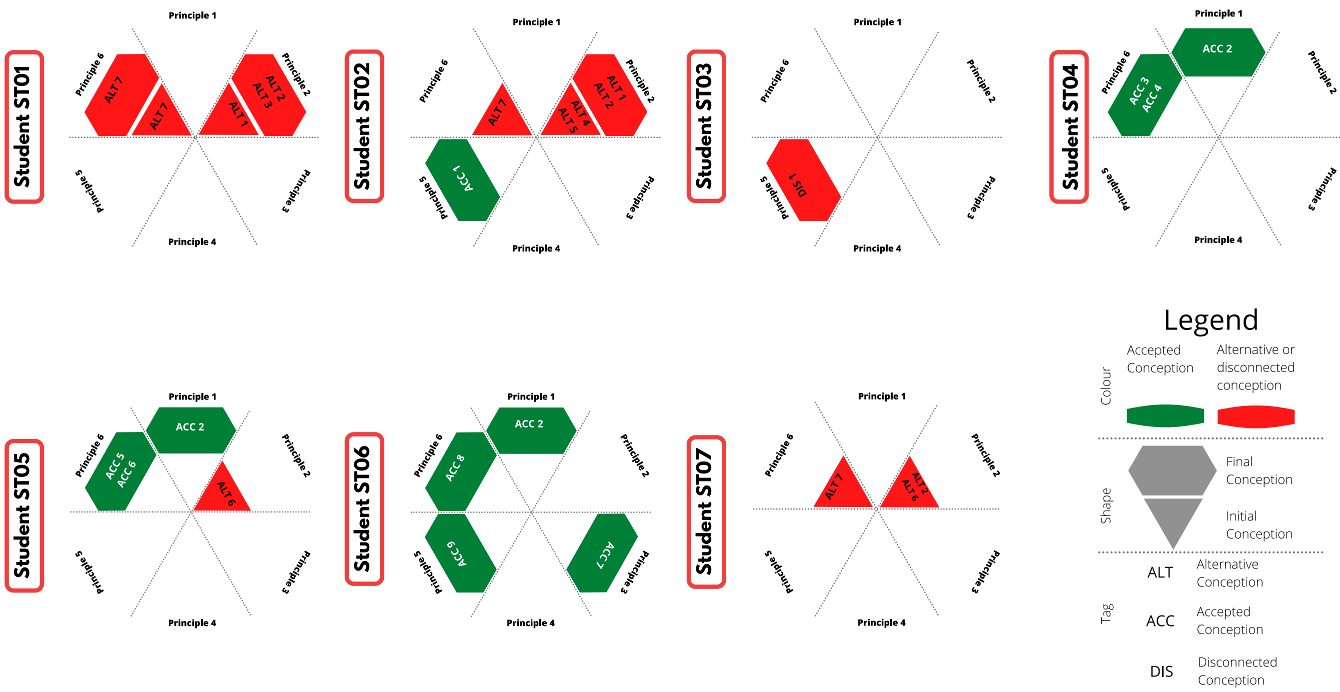

FIGURE 9. Evolution of students' conceptions.

"mismatch model", because in this model, it is not clear whether page replacement is required, which the students say is that when the main memory runs out, the disk is accessed.

Finally, we analyzed the alternative conception ALT7 associated with Principle 6 (performance). Students with this conception consider virtual memory to be much slower than main memory. This conception is congruent with the "mismatch model", in which part of the disk is used as memory when the main memory runs out. As this part of the disk is larger than the main memory itself (Figure 7), students may infer that the disk is accessed most of the time; therefore, the access speed would be much slower. Regardless of the underlying cause, students who held the alternative conception ALT7 ignore the fact that there is a memory hierarchy in which main memory contains the parts of memory most likely to be used next.

In summary, all the non-accepted conceptions that were identified aligned with the "mismatch model", suggesting that this mental model could be the underlying cause of each of them.

D. EVOLUTION OF THE CONCEPTIONS AND MENTAL MODELS ABOUT VIRTUAL MEMORY

In this section, we analyze how each student conceptions and mental models evolved during the course. Figure 9 shows a representation of the accepted and non-accepted conceptions each student held, both in the initial and final evaluations, to analyze the individual evolution in their learning process. The initial conceptions are listed inside the triangles and the final conceptions are listed in the outer hexagons.

Considering what has been described in previous section the following results can be remarked as follows:

- All the conceptions of Student ST01 entirely align with the "mismatch model". These conceptions persisted from the beginning to the end of the course, suggesting that the student initially held the mismatched model and did not experience the intended conceptual change, since they maintained the same model even after completing the course.
- Regarding Student ST02, all initial and final alternative conceptions are in line with the "mismatch model". The only accepted conception relates to page faults in virtual memory systems (ACC2). The results suggest that this student held the "mismatch model" at the beginning of the course and likely did not undergo conceptual change, as they did not exhibit accepted conceptions of the principles for which they presented alternative conceptions at the beginning (Principles 2 and 6).
- Regarding Student ST03, we have considerably small information. We know that the student had a disconnected conception by the end of the course. This conception is consistent with the "mismatch model"; however, we do not have any other data indicating that the student held this mental model.
- Student ST04 did not have any non-accepted conceptions at the beginning of the course. Therefore, we cannot infer whether they initially had any mental model. At the end of the course, the student showed accepted conceptions of Principles 1 and 6. The conceptions in Principles 6, ACC3, and ACC4 align with the accepted model and are inconsistent with the "mismatch model". Therefore, the student learned as intended during the course.

• Student ST05 had an alternative conception that was consistent with the "mismatch model" at the beginning of the course. All their conceptions were accepted by the end of the course. These results suggest that this student held the "mismatch model" at the beginning of the course and underwent a conceptual change, transforming their initial model into an accepted one.

• Student ST06 was similar to Student ST04 in that they did not have any non-accepted conceptions at the beginning of the course, and all their conceptions were accepted by the end of the course. These results suggest that the student understood the concept of virtual memory.

• Finally, Student ST07 presented two alternative conceptions at the beginning of the course that were consistent with the "mismatch model" and did not have any accepted conceptions at the end. These data suggest that this student might have held the "mismatch model" at the beginning of the course, and we do not know if a necessary conceptual change had occurred.

In summary, among the analyzed students, the following cases can be distinguished:

• Students who initially exhibit the "mismatch model" and at the end of the course this model is transformed into the "accepted model" (ST05). These students underwent a conceptual change.

• Students who exhibit the "mismatch model" both at the beginning and the end of the course (ST01 and ST02). These students did not experience a conceptual change.

• Students who did not exhibit any model at the beginning of the course but held the "accepted model" by the end of the course (ST04 and ST06).

• Students for whom we did not have sufficient information about their mental models at the end of the course (ST03 and ST07); therefore, we could not analyze the evolution of their understanding of virtual memory.

These results suggest that students who exhibited the "mismatch model" at the beginning of the course (ST01, ST02, ST05, ST07) faced more difficulties in their learning process. Only ST05 achieved conceptual change. On the other hand, students who did not exhibit a previous mental model about virtual memory at the beginning of the course (ST04 and ST06) could achieve the desired learning outcome and held the "accepted model" by the end of the course.

VI. DISCUSSION

Operating Systems courses present many difficulties to students. Particularly, many students experienced difficulties with the virtual memory concept. In this study, we analyzed the results of seven online students who took an undergraduate Operating Systems course. Each student carried out one assessment at the beginning and one assessment at the end of the course. We used qualitative methodology to analyze the results. Our analysis presents eight non-accepted conceptions and nine accepted conceptions. The contributions, limitations, and implications of our study are explained in detail in the following sections.

A. CENTRAL CONTRIBUTIONS TO COMPUTING EDUCATION

This study makes three major contributions to computer science education. The first was the discovery of eight non-accepted conceptions: seven alternative conceptions and one disconnected conception of operating systems, in particular the concept of virtual memory. To the best of our knowledge, none of these have been identified in the literature.

The alternative conceptions discovered show that there are students who claim the following statements: (i) virtual memory is secondary memory or a part of it; (ii) it is only used in specific cases; (iii) it is utilized when the main memory is depleted or scarce; (iv) it is easier to manage; and (v) it is much slower than the main memory. The discovered disconnected conception indicates that some students understand the LRU page replacement algorithm but do not connect it to the functioning of virtual memory.

The second contribution is the mental model we inferred ("mismatch model"), which could be the root cause of all the alternative conceptions we discovered and others that may arise in the future. The main characteristic of this non-viable model is that it has a continuous memory scheme instead of a hierarchical virtual memory scheme. Another feature of this mental model is that the disk, or secondary memory, is considered an extension of the main memory located after it and is only used when the memory becomes full. Finally, in this model, students believe that virtual memory is only a portion of the disk used to expand the main memory.

The third contribution is the methodology used to discover students' conceptions and infer the mental models that may be their root cause. The main aspects of this methodology are threefold: (i) the use of Bloom revised taxonomy to design assessment tests on conceptual knowledge that gauge meaningful learning; (ii) the pre-establishment of a list of principles regarding the concept to be studied; (iii) an in-depth analysis of data to elicit students' mental models. Additionally, we provide a way to visualize the evolution of conceptions, which allows us to verify whether a conceptual change have occurred among students.

Notably, this methodology is specially designed for online teaching but can also be applied to face-to-face teaching. Similarly, the methodology is applied to a specific concept in the field of operating systems (virtual memory), but it can also be applied to any concept in any area of computing science.

B. LIMITATIONS

In this study, conducted within an Operating Systems course at an online university, our objective was to uncover student conceptions. We identified seven alternative conceptions related to virtual memory, along with a mental model that explains all of them. Understanding these alternative conceptions and the associated mental model provides teachers and researchers with the opportunity to recognize them in different contexts. To determine the frequency and context-dependency of these misconceptions and mental model, further research is necessary across diverse environments (in-person, online and blended), various teaching styles, multiple instructional materials, and with varying student populations at different universities worldwide.

Regarding the methodology, the study was carried out in an asynchronous online university setting, where interviews and direct observations were not feasible. Employing these techniques in future research would offer additional methods to triangulate the results and enhance the robustness of the findings.

C. EDUCATIONAL IMPLICATIONS

The results suggest the following educational implications of the study scenario. By following the same reasoning, it is possible to obtain educational implications for scenarios that differ from ours.

The relationships among the principles considered in the analysis (Table 4) made it possible to establish their importance in the learning process. Some principles are independent, whereas others are interrelated. Principles 1 (process execution), 2 (memory hierarchy), and 4 (locality of reference) are independent. Therefore, they do not depend on any other principles. In contrast, Principles 3 (virtual addresses), 5 (page fault), and 6 (performance) are dependent on Principle 2 (memory hierarchy). This implies that these principles are a direct consequence of the virtual memory scheme as a memory hierarchy. In addition, Principle 6 (performance) is supported by Principle 4 (locality of reference).

The most important principles from the perspective of the consequences they entail are Principles 2 (memory hierarchy) and 4 (locality of reference). We have not found any understanding of Principle 4, and have discovered six alternative conceptions concerning Principle 2.

Principle 4 (locality of reference) was not pointed out by any student. This principle is the foundation of virtual memory performance and is used to design page-replacement algorithms. Moreover, we discovered a significant alternative conception of virtual memory performance: Students think that virtual memory is much slower than main memory. Therefore, it seems appropriate to introduce more educational activities into Operating Systems courses to help students understand this principle and apply it to the functioning of virtual memory.

Furthermore, locality of reference is one of the cornerstones of computer science. It was born to make virtual memory systems work well. It directly influences the design of processor caches, disk controller caches, storage hierarchies, database systems, graphic display systems, human-computer interfaces, and computer forensics [21].

The lack of understanding of Principle 2 was evident in our study. We identified six initial alternative conceptions and three final conceptions for this principle. Additionally, Principle 6 (performance) is a direct consequence of Principle 2; therefore, the seventh alternative conception discovered in our study also stems from the lack of comprehension of the memory hierarchy.

The existence of alternative conceptions regarding Principles 2 and 6 suggests that learning activities should be designed with the primary goal of understanding the operation of the virtual memory hierarchy. It is possible that many efforts are directed toward understanding isolated parts of virtual memory, such as page replacement algorithms and are not enough to comprehend the overall scheme of how virtual memory operates. In such cases, we may encounter disconnected conceptions such as those discovered in this study.

As shown in the Results section, all the alternative conceptions discovered in this study are consistent with the "mismatch model". These findings alert us that the students may have a preexisting mental model that is difficult to change before undertaking formal studies on operating systems.

This model could have been developed based on experience, as in the case of science education [34]. In the context of computing, experience comes from interactions with computers. Particularly, we believe that the installation processes of some operating systems, the concept of paging files, and some error messages regarding virtual memory could be the causes of this mental model. This can be explained by the following two examples. The first example is an error message from an operating system: "Your system is low on virtual memory. To ensure that [operating system] is working properly, increase the size of your virtual memory paging file". The second one is a text that appears in an operating system virtual memory configuration option: "A paging file is an area of the hard disk that [operating system] uses as if it were RAM."

The purpose of these messages is to facilitate the configuration of virtual memory by providing precise instructions on the actions to take. Consequently, all operational details concerning the memory hierarchy are hidden because they are not necessary in this context. However, despite their good intentions, these types of messages may be the source for the development of a mental model that is incompatible with the actual functioning of virtual memory. This model could hinder subsequent learning. Therefore, teachers should be aware of its potential existence and consider it when teaching. According to [35], teachers should elicit non-viable mental models and guide students in their modification.

D. COMPARING PRIOR THEORIES

The results of our study are consistent with findings in the field of science education. Alternative conceptions hinder the development of more elaborate and well-founded concepts [36] and are highly resistant to change [37]. Eliminating alternative conceptions is a challenging task that requires a gradual and qualitative transformation of the cognitive structure–the conceptual map that an individual uses to understand and interact with their surrounding environment [38].

E. FUTURE RESEARCH

Our study provides insights into the understanding of computer science concepts in both online and face-to-face environments. Subsequent studies can replicate our work on virtual memory by utilizing our set of principles and the discovered conceptions as a foundation. Alternatively, researchers can apply the proposed methodology to investigate different computing concepts in their studies. While our study has certain limitations (see section B), future research could address these by applying our methodology to a variety of environments (face-to-face, online, and blended), diverse teaching styles, multiple instructional materials, and with different student populations across various universities worldwide. Methodologically, future studies could incorporate interviews and direct observations, providing additional methods to triangulate the results and enhance the robustness of the findings. Furthermore, our method can be considered a proof of concept that demonstrates the usefulness of our approach. Future work could involve additional studies to explore its efficacy in other contexts and for topics within computer science beyond virtual memory, as well as providing a structured framework to support the replicability of our method.

REFERENCES

[1] K. S. Taber, "The nature of student conceptions in science," in *Science Education*, K. S. Taber and B. Akpan, Eds., Rotterdam, The Netherlands: Sense, 2017, pp. 119–131, doi: 10.1007/978-94-6300-749-8_9.

[2] I. O. Abimbola, "The problem of terminology in the study of student conceptions in science," *Sci. Educ.*, vol. 72, no. 2, pp. 175–184, Apr. 1988, doi: 10.1002/sce.3730720206.

[3] B. Du Boulay, "Some difficulties of learning to program," *J. Educ. Comput. Res.*, vol. 2, no. 1, pp. 57–73, Feb. 1986, doi: 10.2190/3lfx-9rrf-67t8-uvk9.

[4] A. Swidan, F. Hermans, and M. Smit, "Programming misconceptions for school students," in *Proc. ACM Conf. Int. Comput. Educ. Res.* New York, NY, USA: ACM, Aug. 2018, pp. 151–159, doi: 10.1145/3230977.3230995.

[5] S. Pamplona, N. Medinilla, and P. Flores, "A systematic map for improving teaching and learning in undergraduate operating systems courses," *IEEE Access*, vol. 6, pp. 60974–60992, 2018, doi: 10.1109/ACCESS.2018.2871768.

[6] N. C. C. Brown and A. Altadmri, "Novice Java programming mistakes," *ACM Trans. Comput. Educ.*, vol. 17, no. 2, pp. 1–21, Jun. 2017, doi: 10.1145/2994154.

[7] K. C. Webb and C. Taylor, "Developing a pre- and post-course concept inventory to gauge operating systems learning," in *Proc. 45th ACM Tech. Symp. Comput. Sci. Educ.* New York, NY, USA: ACM, Mar. 2014, pp. 103–108, doi: 10.1145/2538862.2538886.

[8] G. Haldeman, M. Babeş-Vroman, A. Tjang, and T. D. Nguyen, "CSF: Formative feedback in autograding," *ACM Trans. Comput. Educ.*, vol. 21, no. 3, pp. 1–30, Sep. 2021, doi: 10.1145/3445983.

[9] M. Mladenović, I. Boljat, and Ž. Žanko, "Comparing loops misconceptions in block-based and text-based programming languages at the K-12 level," *Educ. Inf. Technol.*, vol. 23, no. 4, pp. 1483–1500, Jul. 2018, doi: 10.1007/s10639-017-9673-3.

[10] Y. Shi, K. Shah, W. Wang, S. Marwan, P. Penmetsa, and T. Price, "Toward semi-automatic misconception discovery using code embeddings," in *Proc. 11th Int. Learn. Analytics Knowl. Conf.* New York, NY, USA: ACM, Apr. 2021, pp. 606–612, doi: 10.1145/3448139.3448205.

[11] V. Švábenský, J. Vykopal, D. Tovarnák, and P. Celeda, "Toolset for collecting shell commands and its application in hands-on cybersecurity training," in *Proc. IEEE Frontiers Educ. Conf. (FIE)*, Oct. 2021, pp. 1–9, doi: 10.1109/FIE49875.2021.9637052.

[12] C. M. Lewis, M. J. Clancy, and J. Vahrenhold, "Student knowledge and misconceptions," in *The Cambridge Handbook of Computing Education Research*, S. A. Fincher and A. V. Robins, Eds., Cambridge, U.K.: Cambridge Univ. Press, 2019, pp. 773–800, doi: 10.1017/9781108654555.028.

[13] Ü. Çakiroğlu and S. Öngöz, "The effectiveness of peer tutoring in remedying misconceptions of operating system concepts: A design-based approach," *Educ. Inf. Technol.*, vol. 22, no. 3, pp. 1249–1269, May 2017, doi: 10.1007/s10639-016-9490-0.

[14] F. Strömbäck, L. Mannila, and M. Kamkar, "Exploring students' understanding of concurrency—A phenomenographic study," in *Proc. 51st ACM Tech. Symp. Comput. Sci. Educ.* New York, NY, USA: ACM, Feb. 2020, pp. 940–946, doi: 10.1145/3328778.3366856.

[15] S. Pamplona, I. Seoane, J. Bravo-Agapito, and N. Medinilla, "Insights into students' conceptual understanding of operating systems: A four-year case study in online education," *IEEE Commun. Mag.*, vol. 55, no. 11, pp. 170–177, Nov. 2017, doi: 10.1109/MCOM.2017.1700362.

[16] S. Pamplona, N. Medinilla, and P. Flores, "Exploring misconceptions of operating systems in an online course," in *Proc. 13th Koli Calling Int. Conf. Comput. Educ. Res.* New York, NY, USA: ACM, Nov. 2013, pp. 77–86, doi: 10.1145/2526968.2526977.

[17] F. Strömbäck, L. Mannila, M. Asplund, and M. Kamkar, "A student's view of concurrency—A study of common mistakes in introductory courses on concurrency," in *Proc. ACM Conf. Int. Comput. Educ. Res.* New York, NY, USA: ACM, Jul. 2019, pp. 229–237, doi: 10.1145/3291279.3339415.

[18] Y. Ben-David Kolikant, "Learning concurrency: Evolution of students' understanding of synchronization," *Int. J. Hum.-Comput. Stud.*, vol. 60, no. 2, pp. 243–268, Feb. 2004, doi: 10.1016/j.ijhcs.2003.10.005.

[19] W. Stallings, *Operating Systems: Internals and Design Principles*, 7th ed., Upper Saddle River, NJ, USA: Prentice-Hall, 2011.

[20] D. M. Dhamdhere, *Operating Systems A Concept-Based Approach*. New York, NY, USA: McGraw-Hill, 2009.

[21] P. J. Denning, "The locality principle," *Commun. ACM*, vol. 48, no. 7, pp. 19–24, Jul. 2005, doi: 10.1145/1070838.1070856.

[22] B. J. Biddle and D. S. Anderson, "Theory, methods, knowledge and research on teaching," in *Handbook of Research on Teaching: A Project of the American Educational Research Association*, M. C. Wittrock, Ed., New York, NY, USA: Macmillan, 1986, pp. 230–252.

[23] S. H. K. Kang, K. B. McDermott, and H. L. Roediger, "Test format and corrective feedback modify the effect of testing on long-term retention," *Eur. J. Cogn. Psychol.*, vol. 19, nos. 4–5, pp. 528–558, Jul. 2007, doi: 10.1080/09541440601056620.

[24] S. K. Moudgalya, M. Lachney, A. Yadav, and M. A. Kuyenga, "What does the phrase 'diverse students' mean? An exploration of CS teachers' ideas of race, culture, and community in their classrooms," *Comput. Sci. Educ.*, pp. 1–29, Apr. 2024, doi: 10.1080/08993408.2024.2320004.

[25] A. Ezquerra, F. Agen, R. B. Toma, and I. Ezquerra-Romano, "Using facial emotion recognition to research emotional phases in an inquiry-based science activity," *Res. Sci. Technological Educ.*, pp. 1–24, Jul. 2023, doi: 10.1080/02635143.2023.2232995.

[26] L. W. Anderson, D. Krathwohl, and P. Airasian, *A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives, Abridged Edition*. Boston, MA, USA: Allyn & Bacon, 2000.

[27] R. E. Mayer, "Rote versus meaningful learning," *Theory Into Pract.*, vol. 41, no. 4, pp. 226–232, Nov. 2002, doi: 10.1207/s15430421tip4104_4.

[28] *ATLAS.ti*, Scientific Softw. Develop. GmbH, Berlin, Germany, 2020.

[29] J. Saldaña, *The Coding Manual for Qualitative Researchers*. Newbury Park, CA, USA: Sage, 2012.

[30] S. Vosniadou, "Mental models of the day/night cycle," *Cognit. Sci.*, vol. 18, no. 1, pp. 123–183, Mar. 1994, doi: 10.1016/0364-0213(94)90022-1.

[31] J. J. Clement, "The role of explanatory models in teaching for conceptual change," in *International Handbook of Research on Conceptual Change*, S. Vosniadou, Ed., New York, NY, USA: Routledge, 2008, pp. 417–452.

[32] B. Flyvbjerg, "Five misunderstandings about case-study research," *Qualitative Inquiry*, vol. 12, no. 2, pp. 219–245, Apr. 2006, doi: 10.1177/1077800405284363.

[33] Y. S. Lincoln and E. G. Guba, *Naturalistic Inquiry*. Newbury Park, CA, USA: Sage, 1985.

[34] H. Pfundt and R. Duit, "Bibliography, students' alternative frameworks and science education," Inst. Sci. Educ., Univ. Kiel, Kiel, Germany, Nov. 2009.

[35] M. Ben-Ari, "Constructivism in computer science education," *ACM SIGCSE Bull.*, vol. 30, no. 1, pp. 257–261, Mar. 1998, doi: 10.1145/274790.274308.

[36] M. McCloskey, "Intuitive physics," *Sci. Amer.*, vol. 284, no. 4, pp. 122–130, 1983.

[37] R. Driver, E. Guesne, and A. Tiberghein, *Children's Ideas in Science*. London, U.K.: Open Univ. Press, 1985.
[38] J. H. Wandersee, J. J. Mintzes, and J. D. Novak, "Research on alternative conceptions in science," in *Handbook of Research of Science Teaching and Learning*, D. L. Gabel, Ed., New York, NY, USA: Macmillan, 1994, pp. 177–210.

SONIA PAMPLONA received the Ph.D. degree in STEM education from the Universidad Politécnica de Madrid. She currently teaches science education with the Faculty of Education, Universidad Complutense de Madrid. She is a Computer Engineer with Universidad Politécnica de Madrid. She has participated in six R+D+i projects and seven educational projects. She has published nine articles, eight book chapters, and one book. She has also presented communications in 28 conferences. Her research interest includes neurodidactics of STEM disciplines.

JAVIER BRAVO-AGAPITO received the B.S. degree in statistics from the Universidad Complutense de Madrid (UCM), Madrid, in 2000, and the B.S. degree in computer science and the Ph.D. degree in computer science and telecommunications from the Universidad Autónoma de Madrid (UAM), Madrid, in 2004 and 2010, respectively. From 2010 to 2021, he was a Lecturer with Madrid Open University. Since 2021, he has been an Assistant Professor with the Software Engineering and Artificial Intelligence Department, UCM. He has collaborated with recognized institutions, including Telecom Bretagne, Brest, France, and the University of Pittsburgh, Pittsburgh, PA, USA. He has authored over 18 articles, two book chapters, and 23 conference papers related to e-learning and data science. His research interests include e-learning and data science.

ISAAC SEOANE received the Bachelor of Science degree in telecommunications and the Ph.D. degree in telematic engineering from the Universidad Carlos III de Madrid, Spain, in 2004 and 2012, respectively. From 2006 to 2013, he was an Assistant Professor with the Department of Telematic Engineering, Universidad Carlos III de Madrid. In 2014, he joined Madrid Open University (UDIMA), as an Associate Professor. He held several leadership roles with UDIMA, including the Director of the Telecommunications Department, from 2017 to 2021, and has been the Director of the School of Technical Sciences and Engineering, since 2021. His research interests include innovation in engineering education and the enhancement of educational practices using educational technology. He is also engaged in efforts to reduce the technology gender gap and align engineering curricula with Sustainable Development Goals (SDGs), USA.