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An Educational Setting to Improve Students' Understanding of Fundamental Computer Architecture Concepts

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Abstract. This paper presents an educational setting that attempts to enhance students' understanding and facilitate students' linking-inferencing skills. The proposed setting is structured in three stages. The first stage intends to explore students' prior knowledge. The second stage aims to help students tackle their difficulties and misconceptions and deepen their understanding of the topics under study. This is attempted through individual student engagement in suitably-designed activities and relative feedback. As recorded in previous research, students' difficulties feedback on the material development. The third stage of the educational setting exploits social interaction to help students reorganize their knowledge of the concepts under study. The web-based application of the proposed educational setting indicated improvement in first-year Computer Science (CS) students' understanding of fundamental Computer Architecture concepts and progress in students' linking-inference skills. These results encourage integration in the instructional process of interventions designed according to the proposed setting in order to support and enhance students' understanding of troublesome concepts and their interrelations.

Keywords: Introductory Computer Science courses, Computer Architecture, Data Storage, Data Manipulation, main memory, program execution, von Neumann model, curricula hard points, misconceptions, Discussion, linking-inferencing skills.

1. Introduction

It is indisputable that all CS students must know how a computer operates and not perceive it as a "black" box. All modern computers rely on the von Neumann architecture model that introduced the stored-program concept and the concept of the sequential execution of a program's instructions. The main memory plays a significant role in implementing both principles of the von Neumann model. In a stored-program computer, a program's instructions, just like data, are encoded in bit patterns and stored in successive cells of the main memory. The organization of the main memory (ordered directly-accessed addressable cells) is crucial in implementing the sequential instructions' execution concept. Thus, CS students need to clearly understand the organization and role of the main memory in program execution and its irreplaceability for a computer system. Such knowledge is essential and a prerequisite for familiarization with the computer's operation and for a greater understanding of advanced concepts that rely on other advanced subjects, such as pipelining, parallelism, virtual memory, directory systems, and pages.

Furthermore, this knowledge is fundamental and a prerequisite for acquiring programming skills, i.e., for a deeper comprehension of concepts such as arrays, lists, pointers, and loop structures. Many studies that focus on introductory programming education point out the significance of learning about the runtime dynamics of programs and the role of the computer on program execution for novice programmers (Ben-Ari, 2001; Vagianou, 2006; Sorva, 2013), both of which involve the main memory implicitly or explicitly. Other studies indicated students' problems in understanding programming concepts due to minimal memory and computer operation knowledge, among other factors (Milne and Rowe, 2002; Goldman *et al.*, 2008; Kaczmarczyk *et al.*, 2010). Studies focusing on computer architecture concepts, e.g., pipelines, and cache memory, imply students' minimal knowledge of memory-related concepts (Porter *et al.*, 2013; Grigoriadou and Kanidis, 2001).

The studies above indicated to the authors to conduct two studies investigating first-year CS students' conceptions of main memory-related topics after attending an introductory CS course. The first study focused on students' conceptions of the communication between main memory and CPU, the special-purpose registers, and the machine-language program execution. The results indicated a range of students' difficulties in understanding these concepts. By the findings, the students seemed to have superficial knowledge about these topics. In particular, they could recall knowledge and answer questions of the type "What is...?" Still, they had difficulty answering questions of the kind of *"Why…?"* or questions that required students to link these concepts and infer their interrelations when these are unstated in the course textbooks (authors, 2016). These results further motivated the second study on the students' conceptions of the role and organization of the main memory in program execution and, consequently, computer operation as defined by the von Neumann model (authors, 2022). These two studies provided insights into students' conceptions of the main memory, among other architecture topics, by documenting a list of difficulties and misconceptions that first-year CS students seem to hold. The findings of the above-mentioned studies act as feedback to the present study, which attempts to i) help students deepen their knowledge of the main memory, disk storage systems, and program execution, ii) improve students' understanding of the role and organization of the main memory in computer operation, and iii) facilitate students' linking inference process.

The student-centric pedagogy approach was adopted to design an educational setting with three stages, following active and situated-learning constructivist pedagogical principles. Efficient instruction should consider students' difficulties in comprehending the taught concepts and their possible misconceptions. Thus, the student's prior knowledge is investigated in the first stage. The second stage aims to help students enrich their knowledge and deepen their understanding of the concepts under study. This is attempted by the active engagement of the students individually in meaningful activities. The educational material and feedback used are designed appropriately to address the students' difficulties as recorded in the first stage and the previous studies. The social constructivism theory provided the basis for the third stage of the educational setting. This last stage aims to restructure the students' knowledge of the concepts under study and alter their conceptions closer to the scientific through small group discussions.

The two-stage projects or exams have already been used in programming courses of CS1 and other disciplines, positively impacting student learning. In the already used two-stage settings (two-stage programming projects), the students submit a programming assignment individually, receive the instructors' feedback, remedy any issues with their work and resubmit the job for a final grade (Szabo and Falkner, 2017), or resubmit a pair-coded version of the project after collaborating with their peers (Battestilli *et al.,* 2018). The two-stage idea is also used in Peer Instruction (PI), and recently, there has been significant research regarding the value of PI in computer science (Simon *et al.,* 2010; Porter *et al.,* 2011, 2013). In PI, students answer each question individually in the first stage, then, in the second stage, they discuss it with their peers in a small group and come up with a group answer.

This is the first study of a three-stage educational setting applied to teach Computer Architecture concepts to the best of our knowledge. The proposed educational setting is based on the two-stage idea of individual work and then collaboration in group discussions. We extended this idea by adding another stage in which students' prior knowledge is recorded. In the second stage, we grew the idea by i) adopting the activity-oriented approach, ii) developing and using educational material and tutoring feedback based on the students' difficulties and misconceptions on fundamental computer architecture concepts, and iii) grouping the activities according to the core concept they focus on and presenting each group separately, then "fusing" concepts together so as students to discern the concepts' relationships and gain a holistic feel for the "phenomenon" as is described in Marton *et al.* (2004). In the collaboration part (third stage), we took the decisions to i) form small groups of 5 to 6 students, who are chosen for their alternative opinions as expressed in the first stage, ii) use structured discussion with pre-specified initial phrases, and iii) make interventions in question-form of an expert to assist in the discussion flow.

This paper contributes to Computer Science Education by proposing an educational setting to enhance students' learning. The web-based application of the proposed setting indicated positive effects on students' linking-inferencing skills and knowledge of Fundamental Computer Architecture concepts. We consider that disseminating our proposal in the instructors' community globally may be helpful to overcome the hard points of curricula when embedded in the instructional design of CS courses.

The rest of the paper is structured as follows. The following section briefly presents previous research findings on students' understanding of the topics under study. Moreover, this section outlines the underlying theory for developing the educational material used in the activities. Then the proposed educational setting is presented. Section 3 describes the empirical web-based application of the proposed educational setting in the context of an introductory CS course. The paper concludes with further research directions and plans.

2. Background

2.1. *Previous Work: Students' Difficulties and Misunderstandings of Memory Concepts*

Research in the Department of Informatics and Telecommunications of the National and Kapodistrian University of Athens revealed that first-year students have difficulties understanding topics related to main memory and program execution. The studies showed the curricula points that seem to trouble students. In addition, the students' discomfort in linking knowledge stated in different sections of the course textbooks or taught in separate lectures became apparent. At first, the research focused on students' conceptions of the communication between main memory and CPU, the special-purpose registers, and the machine-language program execution. The data source was students' answers in the written final exams at the end of the first semester in four different academic years (Authors, 2016). In the open-ended questions posed to the students, a computer with a given word length and main memory capacity was used. Here follows a brief description of the students' difficulties as recorded after analyzing 330+ students' answers. i) Many students fail to define the address range of a given-capacity main memory due to inadequate knowledge of the binary system (they confuse binary and decimal units), ii) most of the students can describe the role of the address- and data- bus, but get confused on specifying their size in bits when the main memory capacity is given, iii) most of the students give accurate definitions of the special-purpose registers but fail to identify their size in bits when a specific computer is given (with the size of the program counter being the most troublesome to identify), iv) although most of the students are familiar with the main memory's organization, it seems that they cannot relate it with the contents of the program counter during a program's execution, and finally, v) most of the students fail to specify the contents of the special-purpose registers when they perform program tracing (particularly in the case of the JUMP command). In conclusion, although most students can recall basic knowledge on these topics, they have great difficulties applying and combining this knowledge to draw inferences.

A second study was conducted in the same department, investigating the first-year students' conceptions of the main memory's organization and its role in program execution as defined in the von Neumann architecture model (Authors, 2022). A group of students (270 students) responded to open-ended bridging-inference questions at the written final exams at the end of the semester after attending an introductory CS course. The questions challenged the students to state their opinion and justify the necessity of the main memory in computer operation. The students' answers were analyzed and formed six significant cases, which revealed the students' difficulties and misconceptions on the topics. The results of the research displayed that an adequate number of students: i) ignore or underestimate the role of main memory in computer operation, ii) disregard the role of the organization of main memory for the sequential execution of program instructions, iii) disregard the difference in structure, data storage and data access between the main memory and disk storage systems (misconception of similarity), iv) consider the volatility of the main memory or its high speed as the primary reasons for its usage in program execution, and lastly v) students seem to believe that a computer could operate when the main memory is missing, provided that the non-volatility or poor performance features of the disk storage system might be overcome in the future.

The second study's findings on students' conceptions validate the results of the first ones, asserting that most students seem to have a superficial knowledge of the concepts under study. In addition, students have significant difficulties combining this knowledge and drawing inferences. These two conclusions indicate that the students need help with the curricula themes that trouble them and to improve their linking-inferencing skills.

2.2. *Kintsch's Construction Integration Model of Text Comprehension*

Kintsch's (1988) Construction-Integration (CI) model extends pre-existing text comprehension models and is based on the notion that the comprehension process is affected by individual differences such as prior knowledge, abilities, preferences, and strategies, emphasizing mainly the role of previous knowledge.

According to this cognitive model of discourse understanding, a reader develops two distinct levels of text representation during a text comprehension process that the text base and situation models can describe. The text base model corresponds to the propositional description of a text, both at the level of the micro- and macrostructure. The situation model corresponds to the representation of the text-depicted situation, integrated with personal data (like events, actions, and persons).

Several types of measures can be used to assess a reader's text-understanding level, i.e., evaluate the extent to which the text base and situation models have been developed (McNamara *et al.*, 1996). Text base model measures are 1) free recall, when the reader is asked only to recall the text, without explanations, and 2) text-based questions, which are based entirely on the text content and the necessary information for their answer is stated in the original text and requires only a single sentence from it. Situation model measures are 1) problem-solving questions, 2) elaborative-inference questions, 3) bridging-inference questions, and 4) sorting tasks. In *problem-solving* questions, a reader is asked to apply information from the text to a novel situation, which requires a well-formed situation model. Inference questions require some type of inferring or analytical reasoning. More specifically, when a reader is asked *elaborative-inference* questions, he should combine information from the text with outside knowledge, something which can be achieved even with a nearly surface situational understanding. On the other hand, in *bridging-inference* questions, the necessary information is stated in two or more sentences in the text, and the reader should combine them and infer their text-unstated relations to answer the question, which requires a deeper situational understanding and a solid text base. In a *sorting task*, a reader is asked to relate the concepts presented in the text, which reflects the situation model, at least in part.

3. Proposed Educational Setting for Designing Learning Activities

The proposed educational setting follows a student-oriented approach and aims to help students: 1) refine and/or restructure their knowledge and 2) enhance their linking-inferencing skills. The setting interweaves instruction and assessment and has three stages (illustrated in Fig.1).

The first stage comprises the Placement Level, where students' conceptions are investigated, and topics of interest are introduced. A task that provokes students to consider the topics' interrelations is suitable for the placement level's aims.

The second stage is the Development Level, where the clarification of the topics' hard points, as reported by the literature and the placement level's results, is attempted. Here tasks deal with each topic individually, focusing on the students' difficulties

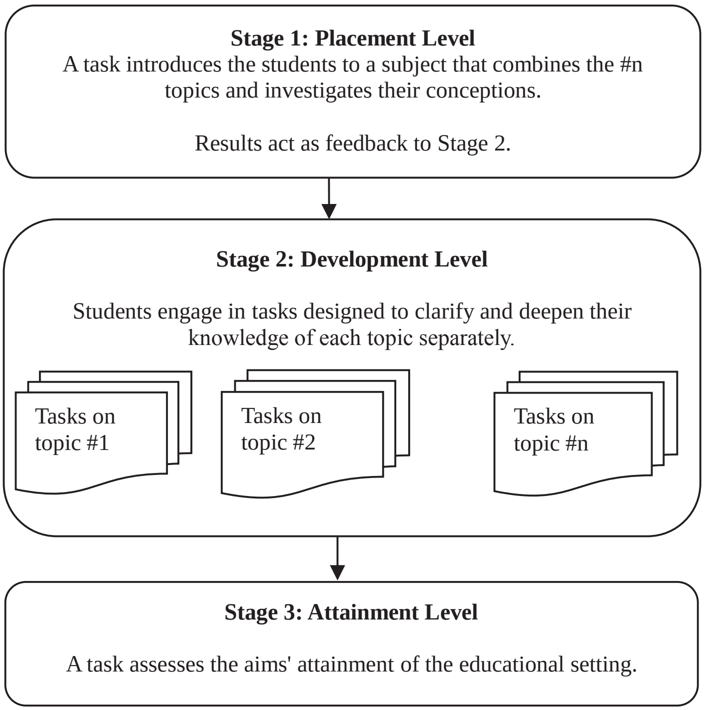

Fig. 1. The proposed educational setting.

and misconceptions. This level aims at the refinement or restructuring of students' knowledge.

Lastly, the third stage is the Attainment Level, in which assessing the students' educational attainments occurs. A task that asks students to reconsider the topics' linkage is suitable for the attainment level's aim.

The sequence of the three stages facilitates the linking-inference ability of the students.

An activity designed following the proposed setting should use educational material having the following characteristics. It should: i) correspond to the Understand and Apply cognitive processes according to Bloom's taxonomy as revised by Anderson *et al.* (2001, p. 67), ii) assess the students' text base and situation models according to Kintsch's CI model of text comprehension, iii) provoke students to make linkages and draw logical conclusions, and lastly, iv) include the curricula points of difficulty and address the students' misconceptions as known by contemporary research and the feedback on the Placement Level.

4. The Empirical Study

This study investigates whether the proposed educational setting would help students overcome their difficulties in curricula and promote their critical thinking skills. The study was conducted in the Department of Informatics and Telecommunications of the National and Kapodistrian University of Athens during the winter semester of 2016–2017 in the introductory undergraduate course "*Introduction to Informatics and Telecommunications*". The course is compulsory for all first-year students and is delivered through two-hour lectures weekly during the first semester, at the end of which students take the written examination.

The topics involved in this study are Data Storage and Data Manipulation. Data Storage covers data representation and storage within a computer, like the storage of bits, main memory's organization and capacity, mass storage, representation of information as bit patterns, and binary system. Data Manipulation covers themes related to how a computer manipulates data and communicates with peripheral devices, computer architecture basics, and machine language programming (Brookshear, 2009).

The educational material used in this introductory course is in written (text) and electronic form. Two textbooks support students learning (Brookshear, 2009; Forouzan, 2003). Electronic material is based on these books. It includes lecture notes, delivered through an LMS (eclass) and additional educational electronic material, in activities form, offered through the web-based learning environment SCALE. SCALE is adaptive, activity-oriented, and supports the knowledge-construction process by engaging students in activities that address specific learning goals (Gogoulou *et al.*, 2007). Each activity corresponds to a core concept of the course and acts supplementary to the course books. It consists of sub-activities and question items that address specific learning objectives of the Understand or the Apply level. The question items are of several difficulty levels and actively engage the students in applying their knowledge. Informative and tutoring feedback components are provided. The tutoring feedback aims to guide students either by explaining the relevant topic (i.e., with a definition or description and the correct answer) or by helping them “explore” the topic (i.e., through an image, an example, a case study, advice or a question giving hints of how to proceed). In addition, the informative feedback keeps students informed about their performance. Students navigate through the provided activities and feedback components according to their preferences. The system automatically assesses the question items.

In the course framework, students’ engagement in the activities in SCALE is optional and motivated by a pre-defined offered reward of up to one grade out of ten towards the students’ final course performance.

4.1. *Research Questions*

The study focuses on main memory structure and operations, disk storage systems, data storage and program execution, and their interrelations.

The research questions (RQ) of the empirical study were:

1. What is the impact of the educational material developed according to the proposed characteristics on students’ knowledge of the topics of interest?
2. What is the impact of the activity designed following the proposed three-stage educational setting on students’ performance?
3. What is the students’ opinion of the effectiveness of this activity in supporting their learning?

4.2. *Subjects*

The 90 students who participated in the study attended the introductory course. 28.4% of students were females while 71.6% were male students; 92% were first-year, 8% were second-year, and seniors. The students took part in an optional course project in the first semester of the academic year 2016–2017.

4.3. *Material of the Study*

The students’ difficulties and misconceptions on the topics of interest, as recorded in the previous research, guided the development of the educational material.

Intending to reach the dual goal of helping students to 1) overcome the hard points of curricula and/or their misconceptions on the topics: main memory, program execution process, disk storage systems, and data storage, and 2) infer the text-unstated relations of these topics, an activity was designed following the proposed educational setting.

The distance learning approach was considered suitable for the mass class attending the lectures. Therefore, the educational material of the first two stages of the activity was embedded in the web-based activity-oriented learning environment SCALE. The environment's activity-oriented nature, feedback provisioning capability, and the familiarization of students with it supported this decision. The Attainment level was implemented in the eclass (LMS) for its user-friendly forum interface, the students' acquaintance with it, and the mass number of students the course supported. The task of the Attainment level in the eclass involved students in online small-group discussions for learning and assessment purposes. Fig. 2 illustrates the structure of the activity.

4.3.1. *Educational Material of the Placement Level of the Activity*

Following the proposed characteristics of the educational material (see Section 3), the Placement Level task is decided to include bridging-inference open-ended questions, which are considered suitable to i) expose the subject to the students, ii) provoke students' consideration about it, and iii) act as a diagnostic tool of the students' prior knowledge.

The open-ended questions are deemed an appropriate diagnostic tool for the study's aims. Students' misconceptions become especially evident in student-generated writing as it provides richer information about students' understanding than multiple-choice questions or other forced-response assessments (Birenbaum and Tatsuoka, 1987). Moreover, the bridging-inference type of question was considered a suitable text-

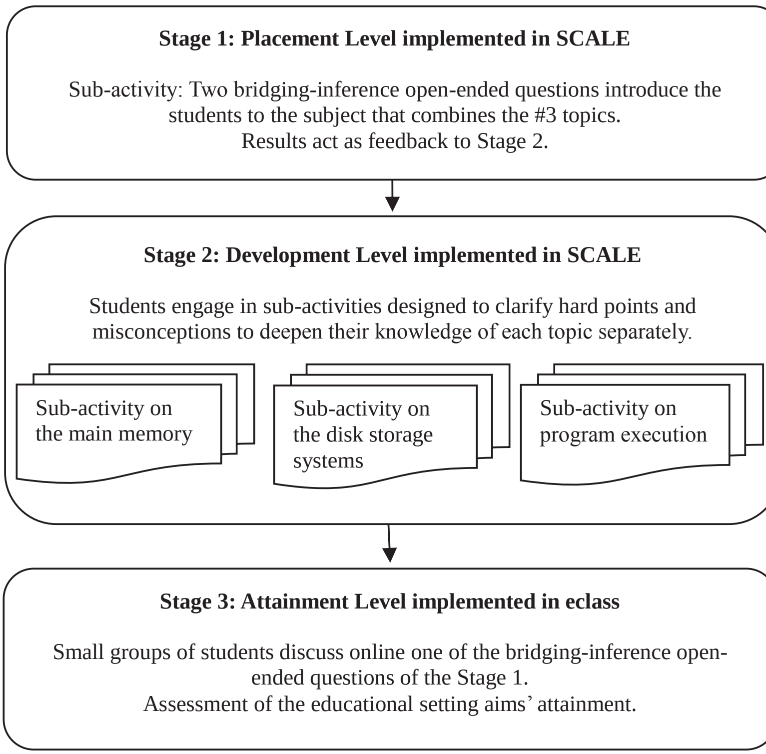

Fig. 2. The empirical application of the educational setting.

understanding measure for the research. To answer bridging-inference questions, the students should combine the necessary information stated in two or more sentences in different text parts and infer the unstated relations. According to Kintsch's CI model of text comprehension, this process requires a deeper situational understanding and a solid text base. According to the revised Bloom's taxonomy, the questions correspond to the Understand cognitive process.

The sub-activity of the Placement Level provided insights into students' thinking and consisted of two open-ended questions:

Question1: *A student with a Simple Computer wrote a program, executed it, and then stored it on the disk storage system before shutting down the computer.*

a) Describe how the program is stored on the disk storage system.

b) Another day, when the student wanted to open and edit the program, what actions would the Simple Computer take?

Question2: *Please comment on the correctness of the following suggestion and justify your answer: "A computer may run using the disk storage system when the main memory is missing."*

To answer both questions, students should have an adequate text-based understanding of the topics: i) Data Storage (the organization and operation of the main memory and disk storage systems); ii) Data Manipulation (CPU's architecture and operations, machine-language program execution), and iii) the von Neumann architecture. Additionally, students should be able to infer the text-unstated relations of the topics mentioned above and describe: 1) the reasons why the main memory and the disk storage system have this particular structure and their role in program execution; 2) the communication between the main memory and CPU; 3) the direct access of the main memory contents on cell/byte-level through their addresses and the significance of this capability for the sequential instructions' execution as is specified in the von Neumann's model, 4) the inability to access data/instructions on byte-level when stored in a disk storage system. These inferences depend on situational understanding.

4.3.2. *Educational Material of the Development Level of the Activity*

At the Development Level, students engage in tasks of the *Understanding* and *Applying* cognitive processes, according to the revised Bloom's taxonomy. The tutoring feedback clarifies the obscure points of each topic under study. The tasks are grouped according to the core concept they target. The educational material of the Development Level is supplementary to the pre-existing material embedded in SCALE. It is presented to the students in the form of three separate sub-activities. The sub-activities individually target the core concepts of main memory, disk storage systems, and program execution.

Each sub-activity consists of question items and feedback that focus on the curriculum's problematic points to students according to the relevant literature. The provided tutoring feedback is i) in question form giving hints to students to explore the topics, ii) a definition of a topic, iii) an example, iv) a case study, and v) the correct answer.

They aim to help students deepen their knowledge, overcome the issues of difficulty or misconceptions indicated by the previous research results, and construct scientifically compatible knowledge structures. In all the sub-activities of the Development Level, the distractors of the multiple-choice questions and the question items themselves correspond to the students' alternative attitudes, as recorded in the previous research (as described in Subsection 2.1). The educational material follows the characteristics outlined in Section 3.

Here follows the description of the aims of each sub-activity separately, the learning outcomes of its question items, and a few indicative question items. The system automatically assesses all the question items of the Development Level.

The **first sub-activity** aims to promote the students' comprehension of the concepts relevant to **main memory**. In particular, the topics of interest are the organization and the capacity of the main memory, the addressing of memory cells, and the communication between the main memory and CPU. The material includes six closed-ended questions (See Table 1 for a quick outline of the topics covered). The question items aim to help students realize the linkage between i) the binary system units and the calculation of the number of memory cells, ii) the number of the memory cells and the size of the address bus (in bits), iii) the direct access to a memory cell and the role of its address, iv) the memory organization and the data storage.

More specifically, two question items (Q1 & Q2) focus on the familiarization of the students with the capacity of main memory. After dealing with the questions and tutoring feedback, students are expected to be able to a) calculate the capacity of the main memory, b) convert between capacity units (binary system), and c) specify the number of cells of the main memory. The following two questions (Q3 & Q4) are relevant to the addressing system of the main memory. After engagement with the questions and feedback, students should be able to a) describe the addressing of the main memory and the direct access mechanism (Q3), b) estimate the address of the last cell, c) specify the bit-number of a cell address, and d) calculate the number of bits that the address-bus carries (Q4). The following two questions aim to help students clarify issues relevant to the internal and external organization of the main memory and its cells. After engaging with the questions and their feedback, students should be able to a) define the Most/Less Significant Bit (MSB/LSB) of a bit pattern (Q5) and b) realize the advantage of the

Table 1

Topics addressed in the questions of the first sub-activity

Questions	Topics covered in the question items.
1	Calculation of the number of cells of a given-capacity memory.
2	Calculation of the maximum number of stored bits of a given-capacity memory.
3	Organization of the memory that permits direct access to a cell.
4	Addressing a given-capacity memory, i.e., address of the last cell, the number of bits of the address of a cell, the number of bits that can be carried by the address bus.
5	Define the bit order in a cell.
6	The reason for ordering the memory cells and the bits into the cells.

combination of the bit-ordering in the cells and the cell-ordering in memory (Q6). Here follows the detailed description of two indicative questions and their feedback.

The question below (Q2) corresponds to the *Apply* cognitive process according to the revised Bloom's taxonomy. It is an *elaborative-inference* question, a measure of the students' situation model of Kintsch's theory.

Q2: Short answer question.
Fill in the blanks.
Suppose we have a 10 KBytes main memory with a cell size of 1 Byte, then:
The number of its cells is: ....
The maximum number of bits it can store is: ....

Feedback 1:
Example: Suppose we have a 1 KB main memory with cell size 16 Bytes, then the number of cells will be:1 Kbyte / 16 Bytes = 64, and the maximum number of bits it can contain is: 1 Kbyte * 1024 * 8 = 8192 bits.
Feedback 2:
Reminder: *To answer the question, you should do some unit conversions. Use whichever of the following is needed:*
1 Byte = 8 (2^3) bits
1 KByte = 1024 (2^{10}) bytes
1 MByte = 2^{20} bytes
1 GByte = 2^{30} bytes
Feedback 3:
*The **correct answer**.*

The following question (Q6) corresponds to the *Understand* cognitive process according to the revised Bloom's taxonomy and is a *bridging-inference* question that measures the students' situation model.

Q6: Multiple-choice question with one correct answer:
The stored bits in the memory cell are arranged. Also, main memory cells are organized by their address. The combination of these two arrangements permits:
1. *The access to an individual memory cell.*
2. *The definition of the most and least significant bit of a cell.*
3. *The storage of a bit pattern longer than the cell size.*

Feedback1: ***Hints*** in question form.
- Is the combination of both arrangements necessary in order to access an individual memory cell? Does the in-cell bit arrangement affect cell access?
- Is this combination necessary for arranging the in-cell bits? Is the ordering of memory cells a prerequisite for the in-cell bit order?
- Is it possible to store a 32-bit word in 4 consecutive 8-bit cells without combining the two arrangements?

Feedback2: ***Case Study:*** The case study presents how a bit pattern longer than the memory cell size is stored in memory.
Feedback3: The ***correct answer***.

Table 2

Topics addressed in the questions of the second sub-activity

Questions	Topics addressed
1	Physical characteristics of a disk storage system. Comparison between main memory and disk storage system access times. Comparison between main memory and disk storage system minimum size of accessible data
2	File storage in a disk storage system. Physical and logical records.
3	File storage in the main memory and disk storage system (picture storage). Memory cells and the disk storage system sectors.

The **second sub-activity** aims to clarify topics relevant to **disk storage systems.** Three close-ended questions comprise the sub-activity (see Table 2).

After engagement with the questions and their feedback, students are expected to be able to: a) describe the disk's structure, features, and data storage (Q1), b) recognize the differences between physical and logical records and their linkage with disk sectors (Q2), and c) realize the differences in the structure and data storage between main and secondary memory (Q3). Here follows a detailed description of two of the questions and their feedback.

The next question (Q2) corresponds to the *Apply* cognitive process according to the revised Bloom's taxonomy and is an elaborative-inference question, a measure of the students' situation model.

Q2: Multiple-choice question with one correct answer

Choose the right answer.

Suppose a 20KB file contains personal information about students. The file has eight (8) logical records and is stored on a disk system, with each sector containing 2KB.

1. *The file will consist of 8 disk sectors because it has 8 logical records and each logical record is represented as a physical one.*
2. *The file will consist of 10 disk sectors. The file is 20KB and each sector contains 2KB, so 20KB/2KB=10 sectors (file-size/sector-size=number of sectors).*
3. *The file will consist of 20 disk sectors because the sectors of all the disks have a fixed size of 1 KB.*

Feedback1: ***Definitions*** of the concepts: file, field, logical record, physical record.

Feedback2: The ***correct answer***.

The question below (Q3) corresponds to the *Apply* cognitive process according to the revised Bloom's taxonomy and is a bridging-inference question, a measure of the students' situation model.

Q3: Short answer question.

Suppose a picture is represented on a display screen by a rectangular array of 1024 columns and 1024 rows of pixels, and 8 bits were required to encode each pixel's color and intensity.

How many byte-size memory cells are required to hold the entire picture?

If each sector on a disk system contains 1Kbyte, how many sectors are required to store the entire picture?

Feedback 1: ***Hints*** in question form: *“How many pixels represent the picture?”, “How many bits are required to encode each pixel?*”
Feedback2: The ***correct answer***.

The **third sub-activity** aims to help students comprehend the **program execution** and the role and the operation of the computer components involved.

Six close-ended questions comprise the sub-activity and proceed gradually to the knowledge construction (see Table 3).

Three multiple choice question items (Q1, Q2, and Q4) and a short answer question (Q3) focus on the special purpose registers. After dealing with the questions and relevant feedback, students are expected to i) define the PC and IR correctly (Q1, Q2), and ii) realize the interrelations between memory capacity, word length, the data bus size, the program counter (PC) width, and the instruction register (IR) width (Q3), iii) specify the contents of the PC and IR during program execution in relation to the word and instruction length (Q4). Then question 5 (Q5) aims to help students i) trace a machine language program, ii) clarify the difference between the address and the contents of a cell, and between the name and the contents of a register, iii) perform the right and left shift operations and realize the effect on binary numbers, and iv) follow the flow of a JUMP instruction. Lastly, question 6 (Q6) aims to help students i) trace a machine language program, ii) clarify the difference between the address and the contents of a cell, and between the name and the contents of a register, iii) specify the contents of PC and IR, and iv) follow the flow of a JUMP instruction. Here follows the detailed description of three indicative question items and feedback.

The following two questions (Q1 & Q2) correspond to the *Understand* cognitive process according to the revised Bloom’s taxonomy. They are *text-based* questions, a measure of students’ text base model of Kintsch’s CI text-comprehension model. The distractors of Q1 and Q2 consist of students’ alternative opinions as recorded in previous research.

Table 3
Topics addressed in the questions of the third sub-activity

Questions	Topics addressed
1	Role of the program counter (PC) in program execution.
2	Role of the instruction register (IR) in program execution.
3	Size in bits of the data bus, the PC, and the IR of a given-capacity memory and word length.
4	Machine-language program tracing. PC, IR contents vs. word length and instruction length.
5	Machine-language program tracing. PC, IR contents. JUMP command.
6	Machine-language program tracing. Cell address vs. content, register name vs. content. Logical shift operation.

<u>Q1:</u> Multiple choice with one correct answer.
Choose the correct answer.
During program execution, the PC:

1. *Counts the already executed instructions.*
2. *Contains the next instruction to be executed.*
3. *Contains the address of the next instruction to be executed.*
4. *Contains the instruction being executed.*
5. *Contains the content of a cell.*
6. *Contains the address of the instruction being executed.*
7. *Is incremented by one.*

<u>Q2:</u> Multiple choice with one correct answer.
Choose the correct answer.
During program execution, the IR:

1. *Controls the order in which the instructions are executed.*
2. *Contains all the program instructions.*
3. *Contains the next instruction to be executed.*
4. *Contains the address of the next instruction to be executed.*
5. *Contains the instruction being executed.*
6. *Contains the address of the instruction being executed.*

<u>Feedback 1:</u> ***Definition*** of the PC and IR, respectively.
<u>Feedback 2:</u> A ***picture*** illustrating a simple computer's architecture and the special purpose registers' location.
<u>Feedback 3:</u> The ***correct answer***.

Lastly, the below-described question (Q4) corresponds to the *Understand* cognitive process according to the revised Bloom's taxonomy. It is an elaborative-inference question, measuring the students' situation model of Kintsch's CI text-comprehension model.

<u>Q4:</u> Multiple choice with one correct answer.
Choose the correct answer from the suggested ones.
Suppose we have the following program:

```
00 LOAD 10101110, X
01 LOAD 01010010, Y
02 AND X, Y, 11110101
```

Suppose that the first instruction of the program is loaded in the memory location 10 (value in decimal system). What are the contents of the special purpose registers during program execution?

1) *In case the program has 8-bit instructions and is executed in an 8-bit word computer,*
   a) *PC will contain the values: 10 → 11 → 12.*
      IR contains the address of the instruction being executed.
   b) *PC will contain the values: 10 → 11 → 12.*
      IR contains the instruction being executed.
   c) *PC will contain the values: 10 → 12 → 14.*
      IR contains the instruction being executed.

2) *In case the program has 16-bit instructions and is executed in an 8-bit word computer*
   a) *PC will contain the values: 10 → 11 → 12.*
      IR contains the address of the instruction being executed.
   b) *PC will contain the values: 10 → 11 → 12.*
      IR contains the instruction being executed.
   c) *PC will contain the values: 10 → 12 → 14.*
      IR contains the instruction being executed.

Feedback 1: Definitions of the word concept, the Boolean operator AND, and the LOAD instruction.
Feedback 2: Hints in question form: "How the word length interweaves with instruction length?", "How do the word and instruction length affect the values of the PC?"
Feedback 3: The ***correct answer***.

4.4. *Procedure*

An optional mid-term review project on Data Storage and Manipulation provided the context where the educational setting was applied.

A bonus reward of up to one grade motivated students to participate in the project. As a prerequisite, the participants should have attended the lectures and been engaged in the relevant topics' activities offered in SCALE, which supports the course. These conditions are intended to eliminate the lack of knowledge, ensuring that students already have studied the topics of interest and had acquaintance with the learning environment. The empirical study consisted of the following steps:

1. **Formation of the experimental group:** All students were given one week to consider whether they were willing to participate in the project. Of the 240 students enrolled in the course, 90 volunteered to join the experimental group.
2. **Placement Level of the activity – lasted one week:** The experimental group of students worked individually with the placement sub-activity embedded in SCALE. The bridging-inference open-ended questions provoked students to consider the interrelations of the topics under study. In addition, they acted as diagnostic tools for possible students' difficulties and misconceptions.
3. **Analysis of the students' answers (Dataset1) – lasted one week:** The students' responses to the open-ended questions of the Placement level were collected and analyzed to identify the students' baseline knowledge, difficulties and misconceptions. The analysis results were quite similar to and confirmed the results of previous research (see Subsection 2.1). The findings acted as feedback for the refinement (enrichment or change) of the already developed educational material. The similarity between the results of the Placement Level and the previous studies rendered the educational material suitable for the Development Level without significant additions or changes. We decided to keep the already developed educational material unchanged, even in cases where it addressed difficulties in curricula that emerged to a limited number of students in the Placement Level of this activity.

4. **Development Level – lasted two weeks:** Students were given two weeks to work on the sub-activities embedded in SCALE. Each sub-activity corresponded to one of the topics: main memory, disk storage systems, and program execution.
5. **Attainment Level – lasted five days:** Students who followed the project schedule and completed their work on the Development Level on time participated in the online small-group discussions at the eclass LMS. The guidelines of this task specified that students should enter the discussion forum by expressing their opinion on one of the bridging–inference open-ended questions already posed at the Placement Level. The collection of these initial students' messages constitutes Dataset2, used to assess the improvement of students' knowledge after the Development Level. The discussion session ended by submitting the group answers to the question under discussion. The group answers made up the Dataset3 which assessed students' attainments after completing the course project.
6. **Questionnaire:** The students completed the questionnaire by the end of the optional course project. They expressed their opinions: 1) on the impact of the educational material on their knowledge, and 2) on how the proposed educational setting affected their understanding and linking-inference skills.

4.5. *Data Collection*

The Placement and Attainment Levels provided qualitative data through written answers to investigate the research questions. Moreover, the analysis of 1) the log files automatically created by SCALE, detailing students' behavior (time, access to the available feedback components) and the length of students' working time, and 2) the questionnaires completed by the students, provided the qualitative and quantitative data.

4.6. *Data Analysis*

The students' answers to the Placement and Attainment Levels were filed, manually content-analyzed, and classified according to correctness and justification (Datasets1 and 2). One of the authors initially classified each response as correct, incorrect, and partially correct. Then the incorrect and partially correct answers were separated from each dataset. The authors and another experienced instructor from the department processed these answers in pairs to derive students' conceptions. The first couple of authors went through the answers and coded them using an open coding approach. Many student answers included several justification cases. Each case was recorded and coded with a small phrase, i.e., "ROM," "disk storage system synchronization issue," "RAM volatility," etc. Then, the second pair, which consisted of the third author and the instructor, confirmed and refined them. The cases that appeared in more than five student answers were considered frequent.

Moreover, to investigate the impact of the educational material, which was used in the Development Level, on the students' thinking, the log files of SCALE were analyzed. In particular, the length of time each student devoted to working in the sub-activities was identified. Then, the students were separated into two categories (engaged/disengaged) according to their working time length.

In addition, the students completed the evaluation questionnaire at the end of the course project. The first ten questions concerned the first and second stages (Placement and Development Levels) of the course project. They asked students to express their opinion about the impact of the material on their knowledge. Indicative items are "*The material structured in sub-activities helped in deepening my knowledge of each corresponding topic.*", "*After dealing with the educational material about the main memory, disk storage systems, and program execution, I changed my initial answers to at least one of the questions of the Placement Level,*" "*Dealing with the activity made me realize that I had incorrect conceptions about the main memory*." Students' answers could vary from 1 to 5 (one indicates "I strongly disagree," while five indicates "I strongly agree"). The means, standard deviations, and percentage of students were used to present quantitative data. The percentage of students appearing in Tables 7 and 8 corresponds to the number of students who expressed their agreement (4 for "I agree" or 5 for "I strongly agree").

4.7. *Results*

4.7.1. *Placement Level's Results*

The sub-activity of the Placement Level provided insights into students' thinking and consisted of two open-ended questions.

The correct answer to *Question1a* is that only the bit pattern of the program code is copied from the main memory (RAM) to the disk storage system, not the allocated addresses. Each pattern of 16-bit instruction is copied in sequence.

Unfortunately, none of the students responded correctly. Most of them answered that the allocated address of each instruction is copied to the disk storage system, followed by the bit-pattern of the instruction. The fixed-size 16bit instruction was neglected by most of the students.

The correct answer to *Question1b* is that the program code should be copied from the disk storage system to the main memory in order to be edited and executed.

Many students answered that the program is edible and can run from the disk storage system. Many others confuse the sequence of operations during program execution (confusion about the instruction order, the contents of the special-purpose registers, etc.)

Here follows a more detailed description of Question2 asked in the Placement Level task:

By linking all the necessary information (described in Section 4.3.1.), students should conclude that, as the von Neumann architecture defines, a computer cannot run when the main memory is missing. The correct justification is that, contrary to the structure of the disk storage system, only the main memory's organization in ordered addressable cells/bytes enables the distinct storage and fetching of a program's instructions which is essential for the machine cycle (fetching, decoding, and execution).

The students' answers were analyzed and grouped, considering correctness and justification. According to the correctness criterion, the responses are classified into 1) cor-

Table 4

Classification of students' answers (%) according to the correctness criterion

Type of answer	Placement Level	Attainment Level		
	Dataset1 (%)	Dataset2 (%)		Dataset3 (%)
		t < 50min (Disengaged students 34.4%)	t >= 50min (Engaged students 65.6%)	
Correct	3.3	0	18.6	63
Incorrect	23.9	22.6	3.4	16
Partially Correct	72.8	77.4	78	21

rect, 2) incorrect, and 3) partially correct. The answers that accepted the possibility of a computer operating without the main memory were classified as incorrect. Partially correct, answered the students suggesting that the main memory is essential in computer operation but for trivial or wrong alternative reasons. Table 4 illustrates the results of Placement Level (Dataset1) concerning this classification.

The processing of the incorrect and partially correct students' answers, considering the justification criterion, concluded in a list of cases. The most frequently-mentioned cases of students' justifications are shown in Table 5. Many students specify two or more justification cases in their partially correct answers.

The results indicated that students have superficial knowledge about the role and the organization of the main memory, i.e., easily recall that a program should be in the main

Table 5

Outline the most frequent justification cases of the incorrect and partially correct students' answers to the question posed at the Placement and Attainment Levels

Cases	Type of answer / Description of justification case	Dataset1 (%)	Dataset2 (%)
1	Incorrect Answer: When the main memory is missing, a computer may operate slower using only the disk storage system because both are similar storage systems that work at different speeds.	23.3	11.1
2	Partially Correct Answer: According to von Neumann's architecture, the main memory is one of the fundamental computer subsystems. The disk storage system communicates only with the main memory, not the CPU.	12.2	17.8
3	Partially Correct Answer: A program should be in the main memory for its execution, so the main memory is necessary for a computer's operation.	23.3	42.2
4	Partially Correct Answer: ROM is part of the main memory, so the computer cannot start up if it is missing.	41.1	46.7
5	Partially Correct Answer: The main memory is volatile and used for data storage during program execution. A disk storage system is a non-volatile system, so it would soon be out of space if it replaced the main memory no matter its capacity.	22.2	20.0
6	Partially Correct Answer: The electronic circuitry of the main memory renders its speed fast enough for synchronization with CPU circuits. A disk storage system has mechanical parts and requires a physical motion for its operation, making its speed extremely slow compared to the CPU.	7.8	11.1

memory to be executed but fail to connect and justify this fact with the main memory's organization in ordered addressable cells/bytes.

Moreover, students confuse or ignore the interrelations of the topics. In particular, the students have difficulties explaining why the main memory is irreplaceable for computer operation. They fail to relate the main memory's organization with the implementation of the sequential execution of a program's instructions, as defined in the von Neumann model. The findings in the Placement Level were close to the ones derived in the previous research (see Subsection 2.1) no matter the different experimental conditions, i.e., a group of first-year students at another academic period who answered the questions without time pressure and after having lectures delivered by another instructor.

4.7.2. *Attainment Level's Results*

The task of the Attainment Level provided insights into students' understanding after dealing with the Development Level sub-activities. The task assigned to the students asked them to discuss in eclass LMS the *Question2* of the Placement Level.

The online asynchronous structured small-group discussions lasted five days. At the end of the discussion, students should conclude with a team response to the question and submit it online. The guidelines of the assignment specified i) that the students should enter the discussion with the statement of their opinion on the subject and their justification, ii) the use of specific initial phrases to facilitate the flow of discussion, and iii) the minimum number of messages (at least five) posted by each student. The initial phrases used are: *"My opinion is…", "A better opinion is…", "I agree/disagree with…because...", "Do the group agree/disagree with…?", "My answer to…(the student) is…".*

12 out of 90 students did not continue to the Attainment level because they couldn't follow the activity schedule as the deadlines were tight. The researchers separated the 78 students who proceeded to this Level into 14 groups of five to six members. The group members were suitably chosen so that each one held at the Placement Level a different opinion.

The discussion process provided insight into students' thinking and conceptions because it required students to explicitly articulate content in their own words. Consequently, it indicated their understanding or misunderstanding since many of the students elaborated on their justifications to persuade their peers.

An expert monitored the discussion session and intervened a few times to clarify ambiguous points that troubled students, i.e., specified that the term computer means a contemporary one that follows the von Neumann architecture. Moreover, the expert intervened with questions giving hints to rekindle the discussion flow in case a group tended to form an incorrect opinion, i.e. when the group concluded that the disk storage system could not replace the main memory because it has very low performance and cannot synchronize with the CPU, the expert posed the question to the group: "*If the disk storage system was faster and could synchronize with the CPU, would the CPU run programs directly from the disk storage system?*". Such interventions urged students to rethink the theme and discuss it once again.

The screenshots of the online discussions facilitated recording the students' opinions when the task was completed. The collection of the students' first messages made up the Dataset2 used to assess their attainments after exploiting the educational material of the Development Level.

Moreover, the collection of the group answers constitutes the Dataset3 used to evaluate students' attainments after completing the activity designed following the proposed educational setting. The students' responses were collected, analyzed, and grouped, again considering the level of correctness and the justification as criteria. Table 4 illustrates the results of the Attainment Level (Datasets2 and 3) according to the correctness criterion. The most frequent justification cases of Dataset1 reappear in Dataset2 with a different frequency (Table 5).

4.7.3. I*mpact of the Educational Material on Students' Knowledge (RQ1)*

The categorization of Datasets 1 and 2 according to the correctness criterion indicates the effectiveness of the educational material of the Development Level.

The length of time (t) that each student devoted to the sub-activities of the Development Level is a significant factor that is expected to affect the impact of the educational material on students' knowledge. For this reason, an analysis of the log files of SCALE was conducted to track down the total working time of each student. Two secondary-education informatics teachers helped estimate the minimum time necessary for submitting an answer to all the activity questions. The mean of the times the two teachers spent reading and answering all the activity questions without using the available tutoring feedback was considered the shortest time a student should have devoted to the activity. This time was estimated to be 50 minutes. A comparison was made between each student's actual total working time and the estimated minimum length of time necessary for the activity. The process resulted in the division of Dataset2 into two sub-groups, as shown in Table 4. Considering the students who worked less time than the estimated as rather disengaged while working in the environment, we expected that the impact of the educational material on their knowledge and thinking would be insignificant/trivial. As can be seen in Table 4, a considerable percentage of students (34,4%) worked less time than the estimated one and probably chose to participate in the optional review project mainly for the reward on the course final score and not to support their learning process and to deepen their knowledge on the topics covered. The answers of Dataset1 and those of Dataset2 belonging to the disengaged students are similarly allocated to the three correctness categories.

On the contrary, the students that worked for a considerable time seemed to improve their knowledge. The number of incorrect answers was reduced, and 18.6% of students answered correctly. The wrong answer that the main memory may be replaced with the disk storage system without impacting the computer's operation, apart from the lower performance, indicated that students seem to hold the misconception of the similarity between the two systems. So the reduction in the incorrect answers meant that the educational material of the activity clarified the discrete nature and characteristics of the main memory and the disk storage systems and their discrete roles in program execution.

Table 6
Interrelations between the type of answer, working time means, and standard deviation of the engaged students (t > 50s)

Type of answer	Students (%)	Mean working time (s)	Standard Deviation
Correct	18.6	67.5	21.1
Partially Correct / Incompletely Justified	78	65	21.3
Incorrect	3.4	52.3	5.5

Thus, the educational material helped some students overcome the misconception of the similarity between the two systems.

After analyzing Dataset2, considering the justification criterion, the six predominant justification cases of Dataset1 appeared again in different percentages of answers. Table 5 shows the distribution of the six justification cases to Datasets 1 and 2.

Comparing each student's response in the two datasets revealed that most of the second answers were enriched with more justification cases. This fact manifests that the students improved their knowledge. Only a few of the students added in their blend of justifications the poor performance of a computer when the disk storage system replaces the main memory.

Table 6 shows the categories of the students' answers that worked more than the minimum estimated time (t > 50sec) relative to the mean working time and the standard deviation. There is no difference in the means of students' working time between the correct and partially correct answers, but the mean working time of the incorrect category is significantly lower. This result suggests a relation between the study time of the educational material of the activity and the students' knowledge.

4.7.4. *Impact of the Activity Designed Following the Proposed Three-stage Educational Setting on Students' Performance (RQ2)*

The analysis of the group answers (Dataset3) submitted at the end of the small-group discussions session indicated students' performance improvement, as shown in Table 4. The individual work at the second stage (Development Level) of the proposed educational setting clarified the content, enriched students' knowledge, and reduced incorrect conceptions. The collaborative work in the proposed educational setting's third stage (Attainment Level) dramatically improved students' performance. Although only 18.6% of students responded correctly before the discussions, 63% of the students concluded with a correct group answer. This result is indicative of the transformative power of social interaction.

4.7.5. *Students' Opinions of the Effectiveness of this Three-stage Activity in Supporting Learning (RQ3)*

Students' responses to the questionnaire completed at the end of the optional project were collected to explore students' opinions about the educational material developed and the discussion session. Indicative questions are shown in Table 7.

Table 7

Students' opinions (means, standard deviations, and percentage of students) toward the activity

	Question Items	Mean	Standard Deviation	Agreement (%)
Q1	The material structure in sub-activities helped deepen my knowledge of each related topic.	4,24	0,9	81
Q2	Engaging with the sub-activities resolved some of my queries on the above topics.	3,94	0,8	73
Q3	After dealing with the sub-activities, I reconsidered my answers to the questions of the Placement Level.	3,11	1,2	50
Q4	After dealing with the sub-activities, I dramatically changed my answers to the questions of the Placement Level.	2,46	1,2	25
Q5	I consider that discussing the topic with my colleagues was a good experience.	4.34	0.8	86
Q6	The discussion enriched my knowledge of the relevant topics.	4.00	1.1	77
Q7	The discussion made me realize the linkage between the relevant topics.	3,75	1,1	66
Q8	Before expressing an idea in the discussion, I studied the course textbooks, the web, or other sources.	4.27	0.9	86
Q9	The final group answer is more correct than my initial opinion.	4.23	1.0	76

Most students stated that the material structured in sub-activities helped deepen their knowledge of each topic separately and resolved some of their queries (Table 7, items Q1 and Q2). Although nearly 50% of the students stated that the engagement with the sub-activities helped them to realize misconceptions on the topics and made them reconsider their answers at the Placement Level (Table 7, item Q3), nevertheless only 25% of the students stated that they dramatically changed their responses to the questions at the Placement Level (Table 7, item Q4). It is interesting, though, that 90% of the students that reported a change in their answers have devoted more than 70 minutes to the sub-activities of the Development Level. This fact conforms to the results of the RQ1 and indicates that the educational material affected students' knowledge depending on the working time length.

As far as it concerns the discussion session, 86% of the students have a positive attitude toward discussion (Table 7, item Q5). 77% consider that the discussion session enriched their knowledge (Q6). 66% declare that the opinion exchange helped them link their pre-existed knowledge on the topics under discussion (Q7). 86% said the discussion motivated them to study the issues in-depth (Q8). Finally, 76% consider that the final group answer is more correct than their initial opinion (Q9).

4.8. *Threats to Validity*

This instructional intervention is promising, but some issues should be discussed.

Successful repetition of the instruction intervention to the first-year CS students at another academic year or institution would strengthen the findings and the value of the proposed three-stage educational setting.

In addition, although a large percentage of the group answers (Dataset3) were assessed as correct, it is not sure that each group student held the same idea at the end of the discussion. Furthermore, even if all the group students concluded in the same opinion, it needs investigation on the long-term knowledge retention.

Lastly, the motivated participation of the students may impact the results. If all students were asked to participate without any bonus in the final course grade, that would add more confidence to the findings.

5. Conclusion

This paper presented a three-stage educational setting for designing activities to facilitate students' learning. The web-based application of the proposed setting indicated improvement in students' performance and linking-inferencing skills.

Individual work with educational material developed suitably to cover difficulties and misconceptions proved helpful and enriched students' knowledge. The results of the discussion session show a significant impact on students' knowledge and linking skills.

Furthermore, according to students' opinions, as expressed in the questionnaires, the discussion with their peers enhanced their motivation to study the topics in-depth and search for information in the course textbooks and other sources. These are signs of intentional learning, an optative feature of an educational setting.

Thus, integrating interventions that follow the proposed educational setting in the instructional design is promising for enhancing students' understanding and, consequently, CS teaching.

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