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An Operational Approach for Building Learning Environments Supporting Cognitive Flexibility

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ABSTRACT

Constructivism is a learning theory that states that people learn by actively constructing their own knowledge, based on prior knowledge. A significant number of ICT-based constructivist learning systems have been proposed in recent years. According to our analysis, those systems exhibit only a few constructivist principles, and a critical problem related to the design and use of this kind of systems has been the lack of a practical means to facilitate the instructional design process. Our research aims to help designing truly constructivist learning environments. Our approach is based on a set of operational criteria for certain aspects of constructivism: We use these criteria as a useful pedagogical framework to provide easy-to-use tools and operational guidelines for teachers to build ICT-based constructivist learning environments. One facet often mentioned as being strongly relevant to constructivism is cognitive flexibility. This paper presents COFALE—a new, domain-independent, and open-source e-learning platform that could be used to devise learning conditions fostering cognitive flexibility—and an example of its use: the design of a course on recursion in computing science.

Keywords

E-learning, Constructivism, Instructional design, Operational criteria, Open-source platform.

Introduction

Piagetian or cognitive constructivism (Piaget, 1975) is an educational approach that "emphasizes that individuals learn best when they actively construct knowledge and understanding" (Santrock, 2001, p. 318). Constructivist learning is a process of active construction and transformation of knowledge (Bourgeois & Nizet, 1999). Bruner (1973) introduces the following example of constructivist learning:

> The concept of prime numbers appears to be more readily grasped when the child, through construction, discovers that certain handfuls of beans cannot be laid out in completed rows and columns. Such quantities have either to be laid out in a single file or in an incomplete row-column design in which there is always one extra or one too few to fill the pattern. These patterns, the child learns, happen to be called prime. It is easy for the child to go from this step to the recognition that a multiple table, so called, is a record sheet of quantities in completed multiple rows and columns. Here is factoring, multiplication and primes in a construction that can be visualized.

A counter-example of constructivist learning would be a case in which the child is given a textual definition to learn the concept of prime numbers. This situation may not foster learning, from a constructivist point of view, because it could lead to "rote" or passive learning (Chieu, 2005).

In recent years, constructivist beliefs and practices have been widely adopted, as evidenced by the appearance of a significant number of ICT-based constructivist learning systems (Kinshuk et al., 2004). Many researchers accept the central assumption of constructivism as stated by Santrock; however, they derive different pedagogical implications from the same basic principles. Driscoll (Driscoll, 2000), for instance, identifies five major facets of constructivism related to instructional design: (1) reasoning, critical thinking, and problem solving; (2) retention, understanding, and use; (3) cognitive flexibility; (4) self-regulation; and (5) mindful reflection and epistemic flexibility.

A major problem related to the design and use of constructivist learning systems has been that, while many pedagogical principles for constructivism exist, there is little *practical* advice on how to exploit advanced learning technology to exhibit constructivist principles.

In earlier work (Chieu et al., 2004; Chieu & Milgrom, 2005), we have defined and justified a set of operational criteria for cognitive flexibility, one of the important facets of constructivism. Also in earlier work (Chieu, 2006), we

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have presented a new authoring system, named COFALE, in which we provide the course designer with *easy-to-use* tools and *operational* guidelines for building ICT-based learning environments fostering cognitive flexibility. In this paper, as an extended work of (Chieu, 2006), we present and discuss more about the operational approach we have applied to help teachers *effectively* create learning conditions that facilitate and stimulate cognitive flexibility in a variety of domains. To illustrate the usefulness of our approach, we show how the course designer might use COFALE to devise conditions of learning for a problem area presented in the next paragraph: the learning of the recursion concept. We also report on a preliminary evaluation of the operational approach, which shows several encouraging results for fostering cognitive flexibility by means of ICT-based learning conditions.

The concept of recursion is very important in computing science (Bhuiyan et al., 1994). Many teachers and educational researchers consider that both teaching and learning recursion are difficult because of three main reasons (Anderson et al., 1988; Bhuiyan et al. 1994): (1) the concept is unfamiliar (students are induced to proceed by analogy from examples); (2) the concept is complex (it is hard for students to transfer from a pattern of recursion to a new one); and (3) interference may arise from knowledge of other methods of solution (e.g., iterations).

In the following sections, we first introduce necessary background on cognitive flexibility and present operational criteria for cognitive flexibility; then we show how the course designer might use the set of operational criteria as a useful pedagogical framework and COFALE as an effective technological means for creating learning conditions leading to cognitive flexibility, and we report on a preliminary evaluation of the recursion "course" handled by COFALE with actual students; finally, we present our discussion and conclusion.

Cognitive flexibility

Among the five facets of constructivism identified previously, we chose cognitive flexibility because of three main reasons. Firstly, cognitive flexibility is often mentioned by constructivist authors (Bourgeois & Nizet, 1999; Driscoll, 2000; Spiro & Jehng, 1990). Secondly, the pedagogical principles underlying cognitive flexibility reflect the basic characteristics of constructivism (Spiro & Jehng, 1990; Spiro et al., 1991). Thirdly, a significant number of examples have showed that ICT may facilitate the implementation of learning conditions fostering cognitive flexibility (Driscoll, 2000; Spiro & Jehng, 1990; Wilson, 1996).

In this section, we first define and present several examples of cognitive flexibility. Then, we present the main conditions of learning suggested by educational theorists for cognitive flexibility. Finally, we show why and how we have proposed operational criteria for cognitive flexibility.

Definition and examples of cognitive flexibility

According to Spiro and Jehng (Spiro & Jehng, 1990), cognitive flexibility is "the ability to spontaneously restructure one's knowledge, in many ways, in adaptive response to radically changing situational demands" (p. 165).

In a Piagetian point of view, cognitive flexibility, as learning, is the ability that newborns already have when they come into the world. Indeed, when an infant is born, it possesses a variety of innate reflexes, for instance, sucking, reacting to noises, focusing on objects within their view. Within a short time, it begins to modify these reflexes to adapt to the new environment surrounding the newborn, for example, sucking a finger becomes a different action from sucking a nipple. As the child develops, his or her ability to exhibit cognitive flexibility gradually matures (Driscoll, 2000).

Here are several examples of cognitive flexibility behavior we deduce from indications suggested by educational theorists (Bourgeois & Nizet, 1999; Spiro & Jehng, 1990):

- ➢ When students are faced with a new problem, they try to analyze different aspects of the problem in a systematic manner and to use different ways they have successfully used in the past to solve similar or related problems in order to find a solution as complete as possible.
- ➢ When students are confronted with a new concept, they try to perform different activities in different contexts to look further into various aspects of the new concept.

- When students discuss with peers, they try to listen and ask, in a systematic manner, questions such as “Why?”, “What is your source of information?” in an effort to understand other points of view.

The individual's cognitive flexibility is there, but in instruction we need to provide *explicitly* and *systematically* learning conditions that facilitate and stimulate students' cognitive flexibility, especially in complex and ill-structured domains, that is, the domains in which cases or examples are diverse, irregular, and complex (Spiro & Jehng, 1990; Feltovich et al., 1996). The next sub-section describes those conditions of learning.

Conditions of learning for cognitive flexibility

Advanced learning in ill-structured and complex domains such as biomedicine and literature gives rise to a difficult problem: What one has to do to attain a *deep understanding* of a complex concept (Spiro & Jehng, 1990). Deep understanding means that students are prepared to be ready to apply conceptual knowledge in a domain where the phenomena occur in irregular patterns, and to use knowledge in a great variety of ways that may be required in a rich domain.

Spiro and colleagues have shown in a number of studies that when students attempt to apply, to ill-structured domains, the strategies they have used effectively for understanding well-structured domains (e.g., in introductory learning), they make errors of oversimplification, overgeneralization, and "overreliance" on context-independent representations (Spiro et al., 1988). In the biomedical domain, for example, students who use only organicist metaphors or only the metaphor of the machine to help them understand how the body functions tend to analyze cases only partially. The point Spiro and associates make is that neither metaphor captures all aspects of body functions, although neither metaphor is wrong.

Therefore, in attempting to solve the problem of instruction in ill-structured domains, Spiro and associates have presented a new Cognitive Flexibility Theory in which they have advocated the use of multiples forms of pedagogical models, multiple metaphors and analogies, and multiple interpretations of the same information (Feltovich et al., 1996). The central metaphor of Cognitive Flexibility Theory is “learning in criss-crossed landscape”: “Revisiting the same material, at different times, in rearranged contexts, for different purposes, and from different conceptual perspectives is essential for attaining the goals of advanced knowledge acquisition” (Spiro et al., 1991, p. 28). The authors have argued that by criss-crossing a conceptual landscape in many directions, knowledge that will have to be used in many ways is acquired in many ways. If taught in this manner, medical students, for instance, would be able to examine a single case from many different vantage points and see firsthand the effect of reinterpreting a particular symptom. Examining multiple cases in different contexts will help students build new cognitive structures in order to account for new cases.

Another point of view proposed by educational theorists (Bourgeois & Nizet, 1999; Frenay & Bédard, 2004) about cognitive flexibility in adult education have stressed that teachers should encourage learners to explore new knowledge in various concrete situations, more or less different from the ones with which learners have been familiar. Those authors claim that this operation is important for knowledge transfer because it provides the chances for learning reinforcement (i.e., prior knowledge helps accounting for new knowledge). On the other hand, Bourgeois and Nizet have added, it is necessary to give means allowing learners to analyze and evaluate the new knowledge "from the outside". According to this approach, teachers are responsible for the following three activities: (1) engage learners in expressing their personal points of view, (2) organize the confrontation of learners' points of view, and (3) provide methodological tools allowing learners to treat different points of view. The point Bourgeois and Nizet make is that learners are confronted not with only one alternative point of view on a given object but with a diversity of points of view, and that learners are systematically encouraged to "come in" and "come out" different points of view with which they are confronted, and to connect those points of views one to another.

Driscoll (Driscoll, 2000) have examined the assumptions proposed by Spiro and colleagues, and identified two principal conditions of learning for cognitive flexibility: (1) *multiple modes of learning* (i.e., multiple representations of contents, multiple ways and methods for exploring contents), and (2) *multiple perspectives on learning* (i.e., expression, confrontation, and treatment of multiple points of view).

We believe that the previous indications are still too general for the course designer to be able to imagine concrete steps when he or she wants to design learning systems leading to cognitive flexibility. For instance, what has to be done with the learning contents in the recursion problem presented earlier? That is why we propose *operational criteria* for cognitive flexibility.

Operational criteria for cognitive flexibility

In earlier work (Chieu et al., 2004; Chieu, 2005), we transformed the pedagogical principles underlying Driscoll's two learning conditions for cognitive flexibility into operational criteria (Table 1) and we showed examples of their use. We followed Driscoll's conditions of learning because they appear to embody different points of view proposed by other educational theorists.

Table 1. Operational criteria for cognitive flexibility (MM = multiple modes, MP = multiple perspectives)

Learning components	Learning conditions	
	Multiple modes of learning	Multiple perspectives on learning
Learning contents	MM1: *The same learning content presenting concepts and their relationships is represented in different forms (e.g., text, images, audio, video, simulations).*	MP1: *The same abstract concept is explained, used, and applied systematically with other concepts in a diversity of examples of use, exercises, and case studies in complex, realistic, and relevant situations.*
Pedagogical devices	MM2: *Learners are encouraged to study the same abstract concept for different purposes, at different times, by different methods including different activities (reading, exploring, knowledge reorganization, etc.).*	MP2: *When facing a new concept, learners are encouraged to explore the relationships between this concept and other ones as far as possible in complex, realistic, and relevant situations.* MP3: *When facing a new concept, learners are encouraged to explore different interpretations of this concept (by other authors and by peers), to express their personal point of view on the new concept, and to give feedback on the points of view of other people.* MP4: *When facing a new concept, learners are encouraged to examine, analyze, and synthesize a diversity of points of view on the new concept.*
Human interactions	MM3: *The number of participants, the type of participant (learner, tutor, expert, etc.), the communication tools (e-mail, mailing lists, face to face, chat room, video conferencing, etc.), and the location (in the classroom, on campus, anywhere in the world, etc.) are varied.*	MP5: *During the discussion, learners are encouraged to diversify – as far as possible – the different points of view about the topic discussed.*
Assessment	MM4: *During the learning process, learners are encouraged to use different assessment methods and tools, at different times, and in different contexts for demonstrating their ability to solve different problems.*	MP6: *During the problem-solving process, learners are encouraged to confront multiple ways to solve the problem and multiple possible solutions to the problem.*

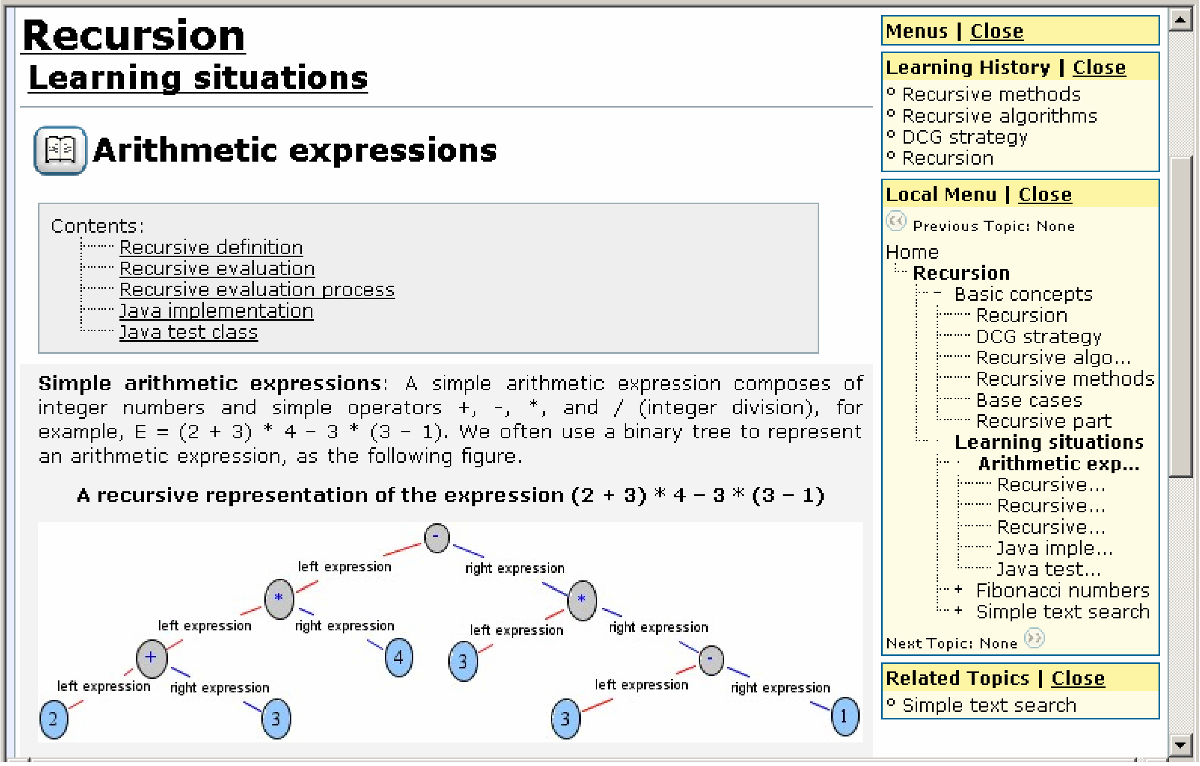
We defined an operational criterion for cognitive flexibility to be a test that allows a straightforward decision about whether or not a learning situation reflects the pedagogical principles underlying cognitive flexibility. To propose operational criteria for cognitive flexibility, we first examined many existing learning systems and identified four main components of learning systems: (1) learning contents (e.g., concept definitions); (2) pedagogical devices (e.g., tools provided for learners for exploring learning contents); (3) human interactions (e.g., means for engaging tutors and learners in exchanges); and (4) assessment (e.g., post-tests for determining whether learners have achieved learning objectives). Then, in each of the four learning components and for each of the two learning conditions for cognitive flexibility, we defined criteria that can be applied for checking the presence of the learning condition in the learning component (Table 1).

In the next section, we show how the course designer might use learning and authoring tools provided by the COFALE system to satisfy criteria for cognitive flexibility.

COFALE as a learning environment and as an authoring system

COFALE is based on ATutor (Adaptive Technology Resource Center, 2004), an open-source Web-based learning content management system. For the purpose of the discussion, we shall assume that a “novice” learner (Bob), familiar with “traditional” programming (say in the Java programming language), wants to learn recursion (i.e., to develop the ability to solve problems recursively). In this section, for each criterion for cognitive flexibility defined in the previous section, we show how a course designer (Tom) uses COFALE to present Bob with learning situations satisfying the corresponding criterion. Note that a number of learning and authoring tools are originally supported by ATutor (thus also by COFALE).

Bob needs to develop his capacity to implement recursive solutions for a variety of problems. Navigating the "Local Menu" seen on the right hand side of Figure 1, Bob reads the definition and examples of the main concepts such as recursion, recursive algorithms, and recursive methods (Figure 1: Area 1). After that, Bob is encouraged to explore a situation about arithmetic expressions (Figure 1: Area 2). We show, in the following presentation for criterion MM2, how Bob is encouraged, in COFALE, to explore situations.



Recursion

Learning situations

Arithmetic expressions

Contents:
- Recursive definition
- Recursive evaluation
- Recursive evaluation process
- Java implementation
- Java test class

Simple arithmetic expressions: A simple arithmetic expression composes of integer numbers and simple operators +, -, *, and / (integer division), for example, E = (2 + 3) * 4 - 3 * (3 - 1). We often use a binary tree to represent an arithmetic expression, as the following figure.

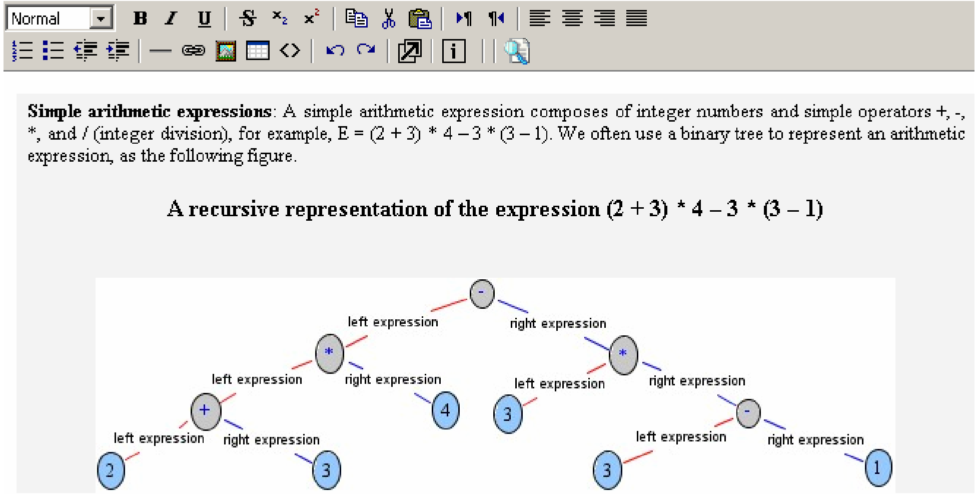
A recursive representation of the expression (2 + 3) * 4 − 3 * (3 − 1)

Figure 1. A part of Bob's learning hyperspace in COFALE

Criterion MM1

In the arithmetic expressions situation, Tom induces Bob to examine multiple representations of recursion through the use of hyperlinks presented in Area 3 or in Area 4 of Figure 1: a textual definition, two simulations, and a Java implementation.

To satisfy criterion MM1, Tom has made multiple representations available for recursion: A combination of text, images, and simulations helps Bob grasp diverse aspects of recursion better than does a single text. ATutor provides Tom with a hypermedia authoring tool (Figure 2) to create learning content objects (i.e., content pages) in different forms.



Simple arithmetic expressions: A simple arithmetic expression composes of integer numbers and simple operators +, -, *, and / (integer division), for example, E = (2 + 3) * 4 – 3 * (3 – 1). We often use a binary tree to represent an arithmetic expression, as the following figure.

A recursive representation of the expression (2 + 3) * 4 – 3 * (3 – 1)

Figure 2. Tool for creating content objects

Criterion MP1

After exploring the first situation, Bob is encouraged to explore the second one: “Simple text search”, seen at the bottom of the menu “Related Topics” offered by ATutor (Figure 1: Area 5). In this situation, Bob sees how to apply recursion to represent a text (i.e., a list of words) as a linked list and how to look up a phrase in a document.

In COFALE, we explicitly encourage Tom to prepare several situations to help Bob understand how to apply the concept of recursion in different contexts. Arithmetic expressions explain the use of recursion in binary trees in a natural way and simple text search explains the use of recursion in linked lists. Note that criterion MP1 is independent to ICT and that Tom must be versed in the subject of recursion to be able to prepare a *diversity* of learning situations for the student.

Criterion MP2

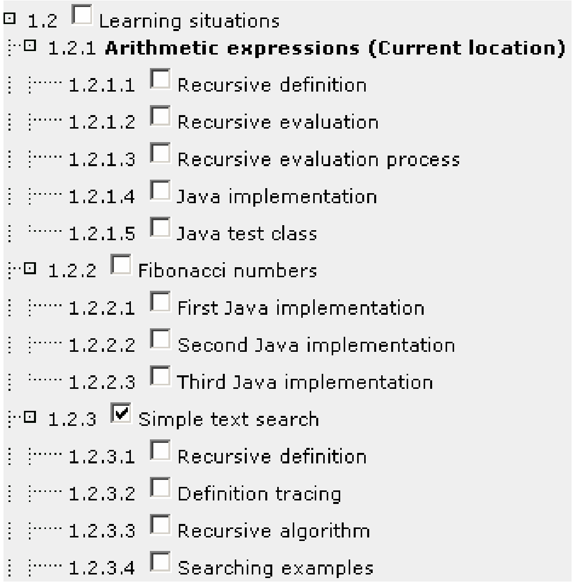
When Bob explores simple text search, Tom presents a hyperlink encouraging Bob to examine “linked lists”, an important concept related to recursion. Similarly, while exploring this concept, Bob could return to the recursion hyperspace by using one of the hyperlinks presented in “Related Topics” and “Learning History”, shown at the top right of Figure 1. The latter contains the hyperlinks of Bob’s recently visited content pages, which are generated by COFALE. The two menus also help Bob navigate intelligently to avoid getting lost in the learning hyperspace.

To satisfy criterion MP2, Tom has defined, for every discrete piece of learning content (page), the other pages related to that one: simple text search related to arithmetic expressions, linked lists related to simple text search, and so on. For instance, the tool (Figure 3) provided by ATutor allows Tom to associate “Simple text search” with “Arithmetic expressions” by selecting the checkbox next to “Simple text search”. On the basis of those associations, ATutor automatically generates the hyperlinks in menu “Related Topics”.

Criterion MM2

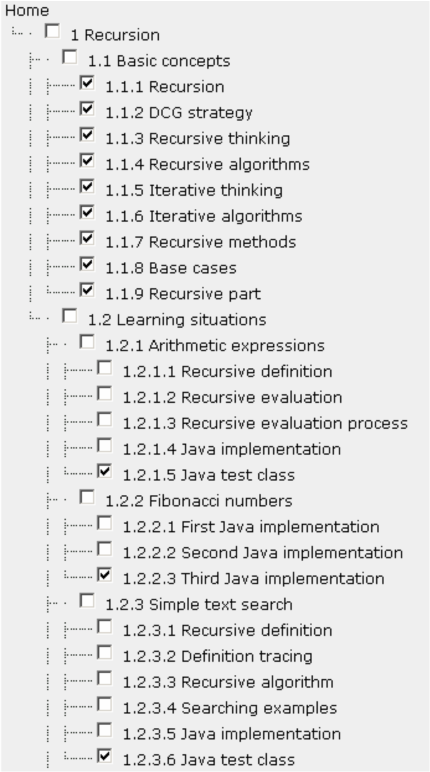
To encourage Bob to look further into the concept of recursion, Tom presents Bob with a number of learning activities at the end of each content page, for example, at the end of the final page of the situation about arithmetic expressions, Bob is invited to explore related topics, to add comments, to do tests, to discuss with peers, and so on (Figure 5).

COFALE supports a set of predefined learning activities (Figure 5), most of which are associated with a hyperlink, which allows learners to go directly to the pedagogical device(s) corresponding to the activity. To define, for each activity (e.g., “Examples & Summaries”), the content pages to which the activity is related, Tom selects the checkboxes next to the content pages he wants to associate with the learning activity (Figure 4). On the basis of those associations, at the end of each selected page, COFALE presents Bob with a hyperlink to the activity (i.e., “Examples & Summaries”).



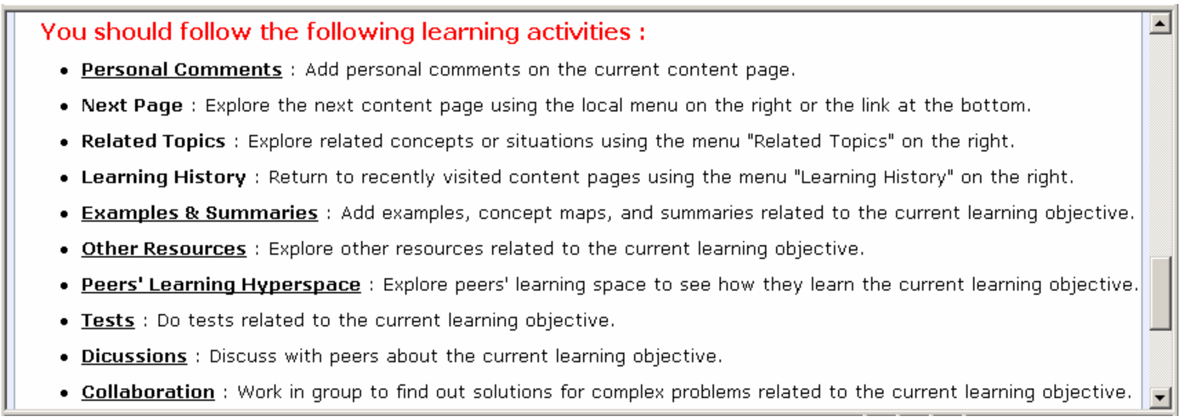
- ⊟ 1.2 ☐ Learning situations
  - ⊟ 1.2.1 **Arithmetic expressions (Current location)**
    - 1.2.1.1 ☐ Recursive definition
    - 1.2.1.2 ☐ Recursive evaluation
    - 1.2.1.3 ☐ Recursive evaluation process
    - 1.2.1.4 ☐ Java implementation
    - 1.2.1.5 ☐ Java test class
  - ⊟ 1.2.2 ☐ Fibonacci numbers
    - 1.2.2.1 ☐ First Java implementation
    - 1.2.2.2 ☐ Second Java implementation
    - 1.2.2.3 ☐ Third Java implementation
  - ⊟ 1.2.3 ☑ Simple text search
    - 1.2.3.1 ☐ Recursive definition
    - 1.2.3.2 ☐ Definition tracing
    - 1.2.3.3 ☐ Recursive algorithm
    - 1.2.3.4 ☐ Searching examples

Figure 3. Tool for defining related topics relations



Home
- ☐ 1 Recursion
  - ☐ 1.1 Basic concepts
    - ☑ 1.1.1 Recursion
    - ☑ 1.1.2 DCG strategy
    - ☑ 1.1.3 Recursive thinking
    - ☑ 1.1.4 Recursive algorithms
    - ☑ 1.1.5 Iterative thinking
    - ☑ 1.1.6 Iterative algorithms
    - ☑ 1.1.7 Recursive methods
    - ☑ 1.1.8 Base cases
    - ☑ 1.1.9 Recursive part
  - ☐ 1.2 Learning situations
    - ☐ 1.2.1 Arithmetic expressions
      - ☐ 1.2.1.1 Recursive definition
      - ☐ 1.2.1.2 Recursive evaluation
      - ☐ 1.2.1.3 Recursive evaluation process
      - ☐ 1.2.1.4 Java implementation
      - ☑ 1.2.1.5 Java test class
    - ☐ 1.2.2 Fibonacci numbers
      - ☐ 1.2.2.1 First Java implementation
      - ☐ 1.2.2.2 Second Java implementation
      - ☑ 1.2.2.3 Third Java implementation
    - ☐ 1.2.3 Simple text search
      - ☐ 1.2.3.1 Recursive definition
      - ☐ 1.2.3.2 Definition tracing
      - ☐ 1.2.3.3 Recursive algorithm
      - ☐ 1.2.3.4 Searching examples
      - ☐ 1.2.3.5 Java implementation
      - ☑ 1.2.3.6 Java test class

Figure 4. Tool for defining pages related to an activity



You should follow the following learning activities :

- **Personal Comments** : Add personal comments on the current content page.
- **Next Page** : Explore the next content page using the local menu on the right or the link at the bottom.
- **Related Topics** : Explore related concepts or situations using the menu "Related Topics" on the right.
- **Learning History** : Return to recently visited content pages using the menu "Learning History" on the right.
- **Examples & Summaries** : Add examples, concept maps, and summaries related to the current learning objective.
- **Other Resources** : Explore other resources related to the current learning objective.
- **Peers' Learning Hyperspace** : Explore peers' learning space to see how they learn the current learning objective.
- **Tests** : Do tests related to the current learning objective.
- **Dicussions** : Discuss with peers about the current learning objective.
- **Collaboration** : Work in group to find out solutions for complex problems related to the current learning objective.

Figure 5. Learning activities proposed to Bob

Criterion MP3

To satisfy this criterion, COFALE engages Bob in four learning activities: (1) add comments on the learning content proposed by the course designer (“Personal Comments” in Figure 5), for example, reformulate the main points of the definition of recursion; (2) add his own examples such as a recursive phenomenon in his life (“Examples & Summaries” in Figure 5); (3) explore external resources (“Other Resources” in Figure 5), for example, the online Java tutorial (Kjell, 2003) in which the author illustrates a great number of recursive examples; and (4) explore peers’ learning spaces (“Peers’ Learning Hyperspace” in Figure 5), for instance, log into the learning hyperspace of an “expert” learner to see and give feedback on her own recursive examples.

To support the exploration of external resources, Tom has needed to search the Internet and introduce the chosen links (e.g., the Java tutorial). The other three activities are supported by COFALE without Tom’ explicit intervention.

Criterion MP4

To satisfy this criterion, Tom engages Bob to produce summaries of the points of view of other sources and peers (“Examples & Summaries” in Figure 5). For instance, COFALE provides Bob with an empty table so that he can state his own definitions of recursion, recursive methods, and recursive problem solving, together with peers'. COFALE supports this activity without intervention of the course designer (Tom).

Criterion MM3

To satisfy this criterion, Tom encourages Bob to work with others (“Discussions” in Figure 5), sometimes with the participation of the tutor, by using multiple communication tools supported by ATutor such as e-mail, forums, chat rooms. Tom also incites Bob to use a Q&A website (Java World, 2004) to ask experts questions about recursion.

The ATutor platform supports multiple communication tools, but to engage learners to use them in COFALE, Tom has created a forum and invited Bob and his peers to confront and discuss their recursive examples that they have encountered in their everyday life.

Criterion MP5

To satisfy this criterion, for every discussion tool provided for students, COFALE attaches two dropdown lists of general and domain-specific questions that Bob could use to elicit peers’ point of view. For instance, when Bob sees an example or solution proposed by a peer, Bob can select the question “What was your source of information?” from the list of general questions to ask the peer to justify the solution.

Tom is asked to prepare a list of general questions and a list of domain-specific questions. COFALE supports a list of predefined general questions proposed by researchers in pedagogy (e.g., Wright, 1995).

Criterion MM4

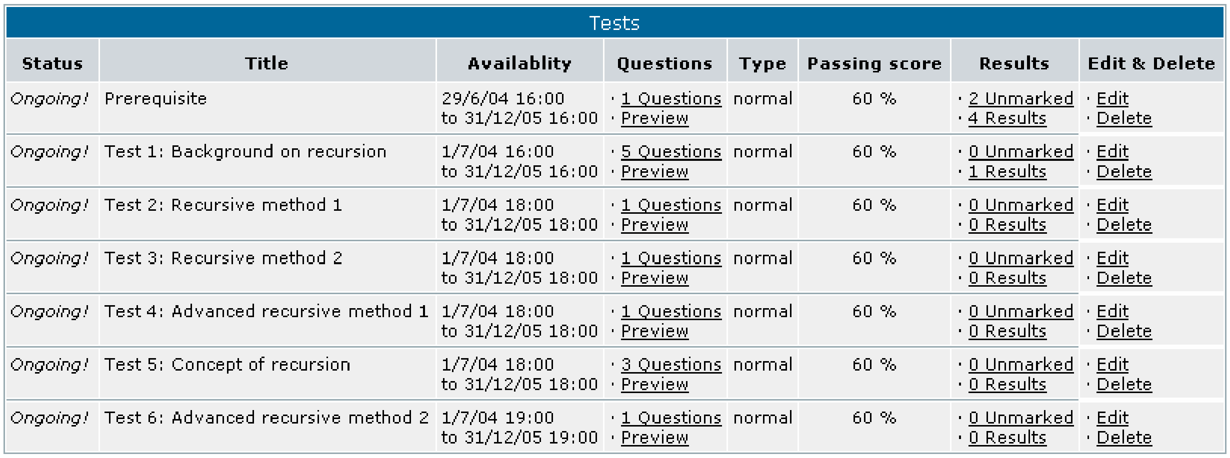
At different points in time, for example, after exploring multiple learning situations or after discussing with peers, Bob is engaged in two assessment activities: (1) individual tests in which Bob is asked to solve problems in the robot situation (e.g., a robot can walk 1 or 2 or 4 meters, computing the number of ways the robot can walk n meters and listing all the ways the robot can walk n meters where n is a positive integer); (2) work in group in which Bob and one or two other peers are asked to solve complex problems in a tree-structured file system (e.g., listing all files and sub-directories in a given directory).

COFALE provides Tom with a test manager (Figure 6) so that he can create individual tests, for example, introduce an assessment situation, a passing score, one or more questions. Presently, Tom can create three types of questions: multiple-choice, true-false, and open-ended. Furthermore, Tom can use ATutor's tools (Figure 7) to create assessment situations in groups. For instance, he can constitute small groups of learners, and present them with problems in the situation about file management and with a brief description of the class File in Java, which is useful for students to solve the given problems (Figure 7: Area 1).

Criterion MP6

In the robot situation, to compute the number of ways the robot can walk n meters, Bob is encouraged to use and compare both the iterative method and the recursive one. In the file management situation, Tom exhorts Bob and his peers to confront and compare different solutions. For example, in the "Drafting Room" (Figure 7: Area 2), Bob and Alice propose two different solutions to the given problems: Bob first lists the files and sub-directories in the given directory, then in its sub-directories, and Alice first lists the files and sub-directories in the sub-directories of the given directory, then in the given directory. Because they confront multiple solutions, they are invited to use a domain-specific tool, JDiff (JEdit, 2005), to analyze the difference between the two Java implementations.

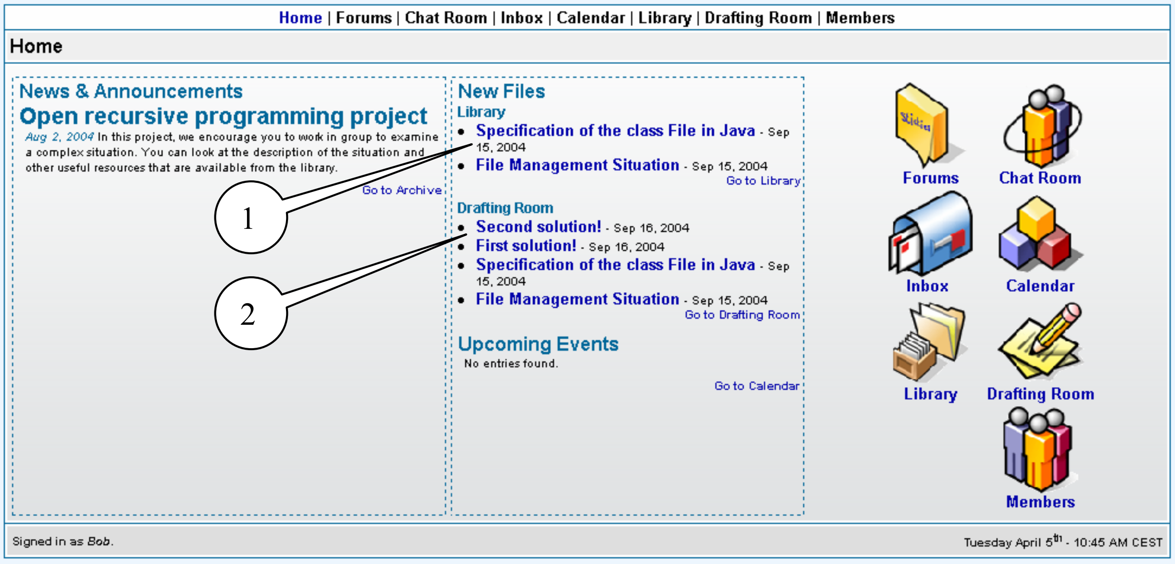
Tom must be an expert in the subject of recursion to be able to satisfy this ICT-independent criterion. For instance, Tom has proposed the file-listing assessment problem because it may evoke different solutions by students to the given problem.



Tests

Status	Title	Availablity	Questions	Type	Passing score	Results	Edit & Delete
Ongoing!	Prerequisite	29/6/04 16:00 to 31/12/05 16:00	· 1 Questions · Preview	normal	60 %	· 2 Unmarked · 4 Results	· Edit · Delete
Ongoing!	Test 1: Background on recursion	1/7/04 16:00 to 31/12/05 16:00	· 5 Questions · Preview	normal	60 %	· 0 Unmarked · 1 Results	· Edit · Delete
Ongoing!	Test 2: Recursive method 1	1/7/04 18:00 to 31/12/05 18:00	· 1 Questions · Preview	normal	60 %	· 0 Unmarked · 0 Results	· Edit · Delete
Ongoing!	Test 3: Recursive method 2	1/7/04 18:00 to 31/12/05 18:00	· 1 Questions · Preview	normal	60 %	· 0 Unmarked · 0 Results	· Edit · Delete
Ongoing!	Test 4: Advanced recursive method 1	1/7/04 18:00 to 31/12/05 18:00	· 1 Questions · Preview	normal	60 %	· 0 Unmarked · 0 Results	· Edit · Delete
Ongoing!	Test 5: Concept of recursion	1/7/04 18:00 to 31/12/05 18:00	· 3 Questions · Preview	normal	60 %	· 0 Unmarked · 0 Results	· Edit · Delete
Ongoing!	Test 6: Advanced recursive method 2	1/7/04 19:00 to 31/12/05 19:00	· 1 Questions · Preview	normal	60 %	· 0 Unmarked · 0 Results	· Edit · Delete

Figure 6. Individual tests manager



News & Announcements

Open recursive programming project

Aug 2, 2004 In this project, we encourage you to work in group to examine a complex situation. You can look at the description of the situation and other useful resources that are available from the library.

New Files

Library

- Specification of the class File in Java - Sep 15, 2004
- File Management Situation - Sep 15, 2004

Drafting Room

- Second solution! - Sep 16, 2004
- First solution! - Sep 16, 2004
- Specification of the class File in Java - Sep 15, 2004
- File Management Situation - Sep 15, 2004

Upcoming Events

No entries found.

Signed in as *Bob*.

Tuesday April 5th - 10:45 AM CEST

Figure 7. Collaboration hyperspace

All criteria

In addition to the previous learning situations proposed to Bob, at any time he may review his learning behavior or navigation history. For instance, after exploring arithmetic expressions, Bob can look again at the content pages he has viewed, the number of visits for each content page, and the total time he has used for each content page. Bob can also see the tutor's feedback on his learning behavior with respect to cognitive flexibility.

To give Bob feedback on his learning behavior, the tutor first logs into his learning hyperspace. Then, the tutor examines Bob' navigation history to see how Bob has explored the recursion hyperspace and constructed his own learning space. Finally, the tutor uses a simple text editor supported by COFALE to give comments to Bob. For example, if Bob explored only one learning situation (e.g., arithmetic expressions), the tutor may give him the following suggestion: "You should examine multiple learning situations presented in COFALE in order to try and apply recursion in diverse contexts".

Preliminary evaluation

A number of studies have showed positive results that pedagogical models proposed for cognitive flexibility help students in advanced knowledge acquisition (Spiro & Jehng, 1990). The implementation of learning conditions fostering cognitive flexibility in an e-learning platform such as COFALE, however, is relatively new. Thus, it must carry out surveys to evaluate various aspects of COFALE. For example: Do learning conditions provided by COFALE foster students' cognitive flexibility effectively? Do students follow suggestions proposed by COFALE (e.g., to explore related concepts and do learning activities presented at the bottom of each page), more specifically, do their learning processes respect criteria for cognitive flexibility? Nevertheless, the evaluation of learners' cognitive ability must be very hard (de Jong, 2005; Wilson, 1997). For the time being, we could perform only a preliminary study to answer the previous questions partly.

A 2-week-long study was performed to formatively evaluate the recursion course we designed using COFALE (Chieu, 2005). The study method is as follows: Nine first-year engineering students at the *Université catholique de Louvain*, having acquired knowledge of programming and Java in a problem-based learning approach but no knowledge of recursion, were randomly organized into two groups: four in the COFALE group and five in the control group. We organized the study into four phases: pretest, experiment, posttest, and interview. Both groups were given the same pretest, posttest, and interview questions. For the experimental phase, they were given the same

45-minute-long lecture and 2-hour-long homework. The only difference was that: After the lecture, within 1 hour the COFALE group explored the recursion course maintained by COFALE whereas the control group read a chapter about recursion of a reference book (Lewis & Loftus, 2003), both with the participation of the tutor.

Several encouraging results were reported on learning with the help of COFALE. Students in both groups mastered the concept of recursion to a significant degree. The COFALE group's learning behavior, however, seemed to be somewhat more consistent with cognitive flexibility than the control group's. For example: in the posttest, more students of the COFALE group than of the control group tried to activate their prior knowledge, in different ways, to analyze different aspects of a new problem and to propose a solution as complete as possible; in the interview, the COFALE group tried to define the concept of recursion more clearly and accurately than did the control group. The COFALE group had more learning motivation than did the control group. For instance: during the exploration of COFALE, students asked the tutor 20 questions by e-mail in comparison with 3 face-to-face questions of control group students during their reading of the book chapter; students in the COFALE group did all three exercises proposed by the tutor whereas students in the control group did only one or two among many exercises proposed by the authors of the book chapter. One of the reasons for those differences may be that criterion MP1 has not been seriously taken into account in the creation of examples and exercises in the book chapter, meaning that its examples and exercises are more or less similar in terms of instruction–they emphasize only one or two aspects of the underlying concept (we see this problem in many textbooks). Indeed, the following short extract of an interview of a student in the COFALE group could show the effectiveness of criteria MM1 and MP1 in the recursion course we designed in COFALE (the evidence is in italic):

> COFALE is good, personalized… We can work anywhere, submit exercises online … There is not much in one content page... *Many examples, they are clear and well explained, in each example they do not give the solution immediately, there is one page to explain how to think, one page to explain how to build the solution, and one page to show the solution. This helps to construct our own solution by ourselves.*

Discussion

To understand learning tools and authoring tools supported by COFALE completely, one should examine the dissertation of a researcher of ours (Chieu, 2005). To explore the COFALE open-source project (including the online course on recursion), one should visit the following website: http://cofale.info.ucl.ac.be.

COFALE is a domain-independent platform, meaning that it can be used to design “courses” in a variety of domains. Indeed, COFALE is based on ATutor, claimed to be domain-independent (Adaptive Technology Resource Center, 2004). Furthermore, the features COFALE has added on to ATutor are also domain-independent, for example, the tool shown in Figure 4 could be used in the design of any “courses”.

The course designer's workload for making a course available in COFALE is not very high (about 8 person-hours for the course on recursion) because of two main reasons. Firstly, COFALE supports many learning activities without direct intervention of the course designer. Secondly, operational criteria provide useful guidelines for the course designer.

For the implementation of COFALE, we have modified several components of ATutor and added a number of learning and authoring tools. We have selected ATutor among many open-source learning content management systems because it makes it easy to add pedagogical devices exhibiting the desired characteristics for cognitive flexibility and to create and manage fine-grained sharable content objects that are compliant with the IMS/SCORM standard (MASIE Center E-learning CONSORTIUM, 2003). This latter characteristic is useful both for the design of goal-based learning and for the personalization of learning contents (MASIE Center E-learning CONSORTIUM, 2003). Our contribution to ATutor is about 20 percent of the source code (or 5,000 lines of PHP code). It is worth to note that the development of the COFALE system has been mainly oriented to the set of criteria for cognitive flexibility: Each learning tool and each authoring tool in COFALE must have at least a *raison d’être*, that is to be present to satisfy one or more criteria for cognitive flexibility. Therefore, the workload for the design and implementation of the COFALE system could be considered as relatively low (about 6 person-months of programming work). That is why we could claim that *the operational approach we proposed is effective*.

In earlier work (Chieu et al., 2006), we analyzed several "courses" handled by existing systems, claimed to support constructivism explicitly, with respect to the criteria for cognitive flexibility: a motion course by SimQuest (de Jong et al., 2004), a Moodle features course by Moodle (Dougiamas, 2004), and a Java course by KBS (Henze & Nejdl, 2001). We also tried to use ATutor's tools to devise a course on recursion with the set of criteria for cognitive flexibility in our "mind" during the instructional design process. The result of the analysis is presented in Table 2. It is not surprising that the examples we analyzed do not satisfy all criteria for cognitive flexibility, because the authors of those learning systems may have designed those examples without any explicit ideas of cognitive flexibility in "mind".

The analysis showed the following main conclusions:

- There would be many different ways to create ICT-based learning conditions fostering cognitive flexibility. For example, we could use computer-based simulations (SimQuest) or hypermedia (Moodle, KBS, ATutor, COFALE) to satisfy criteria MM1 and MM2.
- The course designer should take into account the quality of criteria satisfaction rather than only the number of satisfied criteria, meaning that the course designer's expertise in the subject of instruction is essential. For criterion MP1, for instance, one must be an expert in the subject of recursion to be able to devise a *diversity* of meaningful instructional situations for the concept of recursion (e.g., arithmetic expressions and simple text search). The point here is that preparing a diversity of situations that emphasize different aspects or interpretations of a new concept is more important than preparing many situations that emphasize only one or two aspects of the new concept.
- In practice, it is not necessary to always satisfy all of the criteria for cognitive flexibility: In certain contexts, for example in introductory learning such as SimQuest's motion course, satisfying a half of the criteria might be sufficient enough to help students attain the learning objectives effectively. For the time being, there has been no evidence indicating that satisfying all criteria is always better than satisfying, for instance, two thirds of the set of criteria.

Table 2. Existing learning systems and cognitive flexibility

Learning components	**Criteria**	**SimQuest**	**Moodle**	**KBS**	**ATutor**
Learning contents	MM1	X	X	X	X
	MP1	X		X	X
Pedagogical devices	MM2	X	X	X	X
	MP2	X		X	X
	MP3		X		
	MP4				
Human communication	MM3		X		X
	MP5		X		
Assessment	MM4		X	X	X
	MP6				X

The important point we make here is that the set of criteria, learning tools, and authoring tools we have proposed is not exhaustive. One can surely modify them, propose new ones, or even reject part of them, according to his or her personal interpretation of learning conditions fostering cognitive flexibility.

Conclusion

Cognitive flexibility is one of the important facets of constructivism (Spiro & Jehng, 1990). It is also one of the important requirements for professional and life-long learning (Driscoll, 2000; Bourgeois & Nizet, 1999; Spiro & Jehng, 1990). From the development and validation of COFALE, a new domain-independent e-learning platform, we may conclude that our approach, based on *operational criteria*, makes the design and use of ICT-based learning environments supporting cognitive flexibility *straightforward* and *effective*. Indeed, the course designer can use the set of criteria for cognitive flexibility as a useful pedagogical framework (i.e., a checklist) and the COFALE platform as an easy-to-use technological means to create "courses" exhibiting the desired characteristics of cognitive flexibility.

We believe that our operational approach could also be used to exploit other facets of constructivism (e.g., problem solving) in order to design more completely constructivist learning environments. It should be noted that proposing criteria for the facet of problem solving must be hard because problem solving is domain-dependent (Weber & Brusilovsky, 2001).

Although a preliminary evaluation of COFALE has reported on several encouraging results, we shall conduct more long-term studies to know the full extent of how ICT-based learning conditions fostering cognitive flexibility affect how students learn, especially in life-long learning contexts. Evaluating students' cognitive flexibility, however, is very hard because it is really difficult to know what happens exactly in the "mind" of an individual when he or she is learning (Wilson, 1997). For example, during the evaluation of COFALE, it was hard for us to find pertinent questions in order to help students to express what happens to them cognitively during their learning process. For this kind of exercise, we believe that operational criteria could be very useful, in the same way that operational criteria have been used to evaluate learning conditions. Nevertheless, proposing criteria for evaluating learners' cognitive behavior is much harder than proposing criteria for evaluating conditions of learning, because conditions of learning are observable whereas cognitive behavior is not always observable. We hope that researchers in education and cognition shall contribute to figure out this problem in the future.

Besides studying COFALE's cognitive tools for learners by ourselves, we shall also collect and analyze empirical data about teachers' feedback on the use of the operational criteria and of the COFALE system for the design of their own "courses" in different teaching subjects.

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