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A Flexible Approach to Metacognitive Scaffolding in Computer-mediated Inquiry Learning

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Abstract: This paper presents a flexible approach to model and support inquiry learning processes in complex domains centered around emerging learning objects. It describes our work on applying educational process modeling techniques to provide an agenda-based tool for metacognitive scaffolding that supports students in regulative activities. A prototype has been developed as a pedagogical agent. Rather than presenting the suggested learning sequence directly, the pedagogical agent helps the students to reflect on and possibly re-plan their learning processes by monitoring and analyzing students' actions and by using a predefined process model. The pedagogical agent has been tested and the initial test results demonstrate the technical feasibility of this approach.

Keywords: inquiry learning, metacognitive scaffolding, computer-mediated learning environment, educational process modeling, pedagogical agent

1. Introduction: Scaffolding Inquiry Learning

Inquiry learning emphasizes constructivist ideas of learning. On the one hand, an inquiry learning process, rather than following a routine, is usually dynamic and unpredictable. The question/problem faced by the students is usually open-ended and ill-structured; there is no fixed target or prescribed result that the students have to achieve [16]. On the other hand, students should learn and use the scientific inquiry skills when they are engaged in inquiry. There are various models for inquiry learning introduced in educational literature (e.g., [6] and [7]). In addition, many artifacts such as problem definitions, hypotheses, and inferences emerge in inquiry learning processes [3]. Learning and producing artifacts in appropriate sequences, may improve the effectiveness and efficiency of the inquiry learning. It is implied that metacognitive scaffolding should not enforce the students to strictly follow a predefined learning path in such product-rich and ill-structured processes, but should help them to manage the science inquiry processes in a systematic way.

If students employ the inquiry strategies during a series of inquiry activities, it is likely that the students internalize these strategies from repeated uses, which allows scaffolding to be faded [12]. Pea [11] argued that effective fading mechanisms should differ between high and low achieving students. It is implied that scaffolding should be provided appropriately according to the skill levels of the students.

As Quintana et al. [13] summarized, students lack the knowledge about the activities that constitute inquiry and the procedures for performing these activities, and they lack the strategic knowledge needed to select activities and coordinate the inquiry. Specific methods should be implemented in the learning environment to foster the advancement of students' self-regulative competencies and meta-skills for regulating inquiry activities [8]. Related methods and mechanisms of metacognitive scaffolding are summarized by Hannafin, et al. [5] as: a) suggesting students to plan ahead, evaluate their progress, and determine their needs; b) modeling cognitive strategies and self-regulatory processes; and c) proposing self-regulating milestones and related monitoring. Other studies (e.g., [2] and

[10]) suggest that the learning environment should foster students to perform metacognitive tasks, such as directing students to explicitly plan their activities and justify their choices for action, or arrange the opportunities to reflect on the quality of their planning and how well they executed their plan.

This paper describes our work on devising computational scaffolding for fostering students to gain self-regulation skills. We claim that educational process modeling technologies can be applied to develop a flexible approach to developing computational metacognitive scaffolding. The challenge here lies in the fact that one cannot predict, or design in advance, the learning processes and outcomes emerging in settings that are based on participants' activities and solving of ill-structured problems [4].

2. A Flexible Approach to Computational Metacognitive Scaffolding

Based on the considerations described in the introduction, we are developing an approach to provide metacognitive scaffolding. The three sub-sections of this section present our approach on the three corresponding aspects. Note that in the rest of the paper the terms scaffolding denotes computational metacognitive scaffolding if it is not explained further.

Model-Based Scaffolding

Our approach to scaffolding is based on the knowledge captured in a learning process model. A learning process model consists of a set of hierarchically structured, typed activities such as *problem-definition*, *hypothesis-generation*, and *solution-finding*. An activity will produce an artifact such as *problem statements*, *hypotheses*, or *solutions*. Some types of activities can be refined further. For example, an *experiment* can be decomposed into activities such as *data-collection*, *data-processing*, and *data-interpretation*. An artifact will be produced by using a certain tool. For example, many types of artifacts can be produced by using a text editor. The production of some types of artifacts needs specific tools such as a simulator and a concept-mapping-tool. It is important to note that two structures should be explicitly specified in the process model for providing metacognitive scaffolding: a temporal activity structure and an artifact-dependent structure. Fig. 1 shows an example of both structures in a segment of a process model that includes seven activities (drawn in blue boxes) and their associated artifacts (drawn in red ellipses). A detailed explanation of this diagram can be found in section 3. The relation "A is *preceding* B" (drawn as a dashed blue arrow) means that it is usually preferred to do A before B. It is different from the semantics "the completion of A will trigger the start of B", which is widely used in process modeling. It is just a suggested activity sequence for achieving better results or/and to improving learning efficiency in a normal situation. For example, students would better *reflect on important criteria* before *filling the criteria weight table*. However, the student can decide to accept the suggestion, to do something else in between these two activities, or to *fill the criteria weight table* without *writing the reflection on important criteria*. The second structure is based on the dependence between artifacts. The relation "A is *dependent* on B" (drawn as a dashed red arrow) means that the content of A is affected by the content of B. For example, the *criteria final table* is dependent on the *criteria table* and the *criteria weight table*. If one or both of them are changed, the *criteria final table* should be changed accordingly. These two structures have similarities but are not identical. For example, *reflecting on important criteria* is preceding *filling the criteria weight table*, but there is no dependence between two artifacts of these two activities. *Creating my favourite pizza* is indirectly preceding *creating my first healthy pizza*, but the former is not directly and indirectly dependent on the later. Both structures, in theory, are directed acyclic graphs (DAGs).

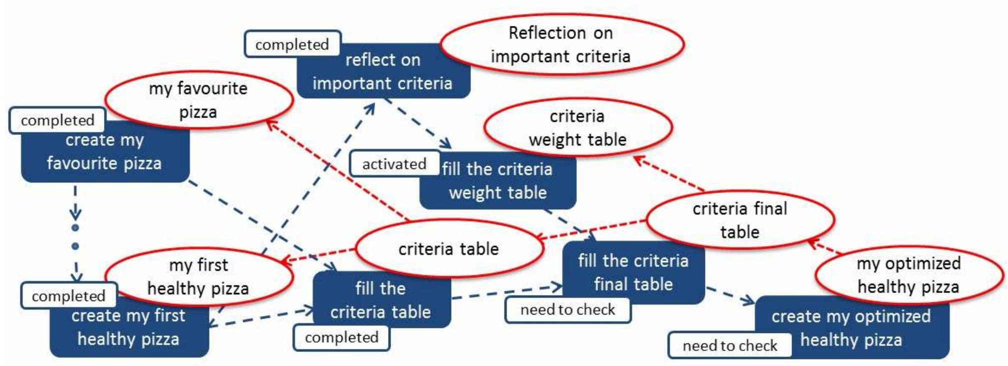

Fig. 1: Examples of Activity-temporal Structure and Artifact-dependent Structure

A process model can be instantiated as an execution (or called instance) for a student at runtime. In order to execute an ill-structured and open-ended process, as shown in Fig. 2, an activity dynamic model is defined with four states: *enabled*, *activated*, *need_to_check*, and *completed*. These four activity states correspond to the four states of the associated artifact: *expected*, *in progress*, *need_to_check*, and *finished*. A student can explicitly declare the completion of an activity (causing the event *complete*) when the student thinks that the associated artifact is *finished*. Unlike a typical task-driven or object/artifact-driven process model in which the finish of an activity/artifact will trigger the start of the next activity, our model enables the student to start to do an activity at any time. S/he can also perform a *completed* activity to modify a previously *finished* artifact, because the inquiry learning is open-ended and cyclic in nature. The student can directly manipulate the associated artifact without the need to explicitly declare *start* and *modify*. For each artifact we define several thresholds, the volume (e.g., the size of text for a text-editor and the numbers of node and links for a concept-mapping-tool) and execution time of the artifact will be traced at the runtime. Thus, the events *start* and *modify* will be detected through monitoring and analyzing student's actions on the artifact. For example, when it is captured that the student has worked on an artifact and the volume and execution time have reached to the thresholds, an event *start* occurs. Note that the state change of one activity may result in the state transitions of other activities if they have artifact dependences. As illustrated in Fig. 2, when the student has made changes to a *finished* artifact (e.g., *criteria weight table*) to some extent (specified by thresholds), the student will be asked to confirm whether s/he is making a substantive change. If it is confirmed to make a substantive change, the event *modify* occurs. This event not only changes its state to *activated*, but also changes the state of those activities into *need_to_check*, which artifacts (e.g., *criteria final table* and *my optimized healthy pizza*) depend on the artifact of this activity. The following sub-section will describe this situation continually.

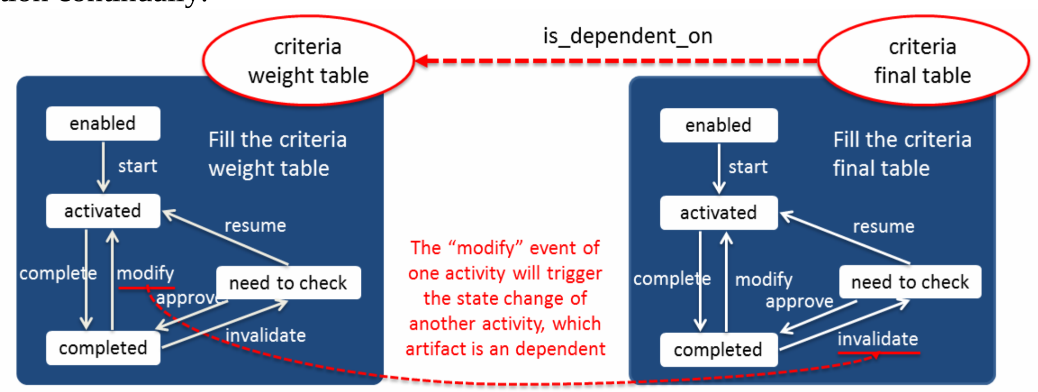

Fig. 2: State-transition Diagrams of Two Activities

Three Levels of Scaffolding

In our approach, scaffolding will be provided in three situations:

1. When a student expresses the need by clicking a special button, the scaffolding tool will be presented to the student on demand.
2. When a student implies the need by clicking the *complete* button in the tool to perform an activity, the student will think about strategic plan and determine what to do as the next step in order to approach the learning goal. Opening the scaffolding tool at this time can help the student to move out from a cognitive activity to a high level reasoning process about a tactical or/and strategic plan to achieve a milestone or/and the overall learning goal.
3. When a student is not aware of the need, but s/he is doing something without complying with the artifact-dependent structure. The reason why the student does so is either being unfamiliar with the inquiry process or starting a new cycle of inquiry. There are two cases in such a situation. a) When the student *start* to work on an *expected* artifact (e.g., *my optimized healthy pizza*) without finishing its depended artifacts (e.g., *criteria weight table* and *criteria final table*), the student will be suggested to work on the depended artifacts first and then start to perform this activity. b) As described in the last sub-section, when the student has confirmed that s/he is *modifying* a *finished* artifact (e.g., *criteria weight table*) after finishing its affected artifacts (e.g., *criteria final table* and *my optimized healthy pizza*), the states of the effected artifacts and their associated activities become *need_to_check*. Then the student will be asked to check whether to resume those activities. If s/he confirms by expressing *resume*, the state of this activity will become *activated*. If the student is not going to change an effected artifact, s/he can choose *approve*.

Based on these three situations, we define three levels of scaffolding for the students who have different levels of metacognitive skills. A novice student can choose the high level of scaffolding and will be supported in all three situations. For an intermediate student the actively provided scaffolds are not necessary anymore. S/he can choose the medium level of scaffolding in which the third situation is excluded. As a skilled student the scaffolding on demand is enough. The more the student's skill increases, the less s/he may use it although scaffolding remains available.

An Agenda Form of Scaffolding

Our approach to provide metacognitive scaffolding is using an additional tool to the main workspace that provides entries of all activities in a hierarchical structure. In order to foster regulative activities, our scaffolding tool is provided in a form of agenda.

The agenda tool (see Fig. 4) consists of two parts. The first part is used to verbally present feedback, explanations, and suggestions. The second part is a list of activities with the states and completion times. The student can monitor the work progress by viewing the sequentially structured activities. The *need_to_check* activities are marked and the student can choose *resume* or *approve*. The list can include either all activities or a subset of activities that are related to the currently focused activities. It stimulates the student to reflect on the overall process or recent work progress. The list also supports the student to evaluate work progress by enabling to attach a short note to each activity and to write evaluation about the overall process as well. Activities can be listed in a suggested sequence or an actual work sequence. The student can change the suggested learning sequence according her/his concrete situations. If a change causes conflicts to the definitions in activity-temporal structure or artifact-dependent structure, the student will be informed. The student can decide to withdraw or insist the change.

3. Implementation of a Metacognitive Scaffolding Agent

By adopting the presented approach, a prototype has been implemented as a Metacognitive Scaffolding Agent (MSA) and integrated into the SCY inquiry learning environment. SCY[1] is a European research project on learning in science and technology domains. SCY uses a flexible and adaptive pedagogical approach to learning based on "emerging learning objects" (ELOs), i.e., artifacts created by the learners during the learning process [3]. Learners work on missions [15] (e.g., the "Pizza Mission" to learn about healthy food and the "ECO Mission" to learn about ecosystems) in the SCY learning environment called SCY-Lab using various tools on ELOs individually or collaboratively with support from pedagogical agents. When a student starts a mission, a mission execution (or called runtime) will be instantiated from the learning process model that is formally described as the mission specification. The SCY environment is implemented as a client-server architecture. The SCY server hosts multiple services like the Repository of Open Learning Objects (RoOLO), a communication and collaboration platform, the logging and notification facilities and last but not least the pedagogical agent framework [17]. The pedagogical agent framework integrates all pedagogical agents in SCY and provides common mechanisms to share data, access user log data and ELOs, and finally send notifications back to the user. The framework is based on a blackboard architecture using a TupleSpace implementation called SQLSpaces [17], i.e., the different agents only communicate over the shared platform (the "blackboard") and not directly with each other. By monitoring and changing the contents on the platform, each agent contributes to solving a problem according to its specification.

Fig. 3 shows a brief overview of the SCY architecture. SCY-Lab stores and retrieves user created learning objects and mission runtime information from RoOLO. The pedagogical agent framework provides access to the same data for agents through the "RoOLO Accessor Agent". All user actions (e.g., load/save an ELO with a tool, insert/delete text in text-editor, add/remove a node/link in concept-mapper, set a value in a simulator) are logged into the TupleSpace and are accessible for all interested agents. For example, a concept map agent monitors students' progress while using the SCYMapper tool by analyzing users' actions on concept maps. If necessary, scaffolding on developing a concept map will be sent to the client through the notification service. The MSA is also implemented as such a pedagogical agent. It monitors and measures students' overall work progresses by analyzing actions performed by the students from the actions space and provides process guidance if necessary using the commend space and the notification service in SCY-Lab (see Fig. 3).

When a student starts to execute a mission, the MSA will search for the document that specifies the process model of the mission from the RoOLO (via the RoOLO Accessor Agent). If the mission model is new, the MSA will extract the document and create the process model. Meanwhile, the MSA will create a mission execution for the user and store the mission execution in the guidance space (GS). When the student starts to perform an activity, the MSA will create an activity instance and store related information in the GS. As the student operates on the ELO with the appropriate tool, the ELO evolves and the activity changes its state. The tuple about the activity and the ELO will be updated in the GS. If a specific event is detected according to the specification of

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[1] SCY – "Science Created by You" is an EU project of the 7th Framework Programme, see http://www.scy-net.eu (last visited in Sep 2011).

the process model (e.g., the student *completes* an activity or *modifies* the ELO of a *completed* activity), the MSA will analyze the work progress of the student and provide metacognitive scaffolding to the student through the notification facility.

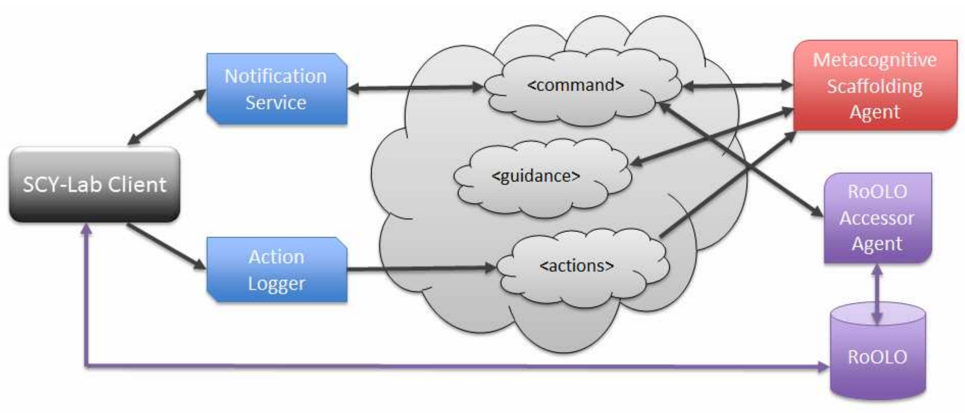

Fig. 3: Implementation Architecture

The MSA has been implemented and tested to scaffold the "Pizza Mission" (see [15], p. 110). The mission aims at actively engaging students in the right choice of food products through creating a healthy pizza. In this mission, a virtual pizza is an artifact created using a pizza simulation tool to represent a solution to a societal and personally relevant problem. 31 activities and their associated artifacts are modeled and a part of activity-temporal structure and artifact-dependent structure are depicted in the Fig. 1. Briefly describing, after creating the first pizza *my favorite pizza*, the students are introduced to the concept of nutrients and compare their own diet with the daily nutritional needs of the human body. Further on, they learn about the digestive system, and its function, and look at the consequences of an unhealthy diet. Then they return to the pizza simulation tool and create a second pizza *my first healthy pizza*. All ingredients of both pizzas combined serve as items in the *criteria table*. After assigning weights to each of the criteria *criteria weight table*, there will be a table with final scores *criteria final table*, so that students may select the healthiest pizza ingredients for their last pizza *my optimized healthy pizza*. Finally, they compare their pizzas with those of their peers and write reports.

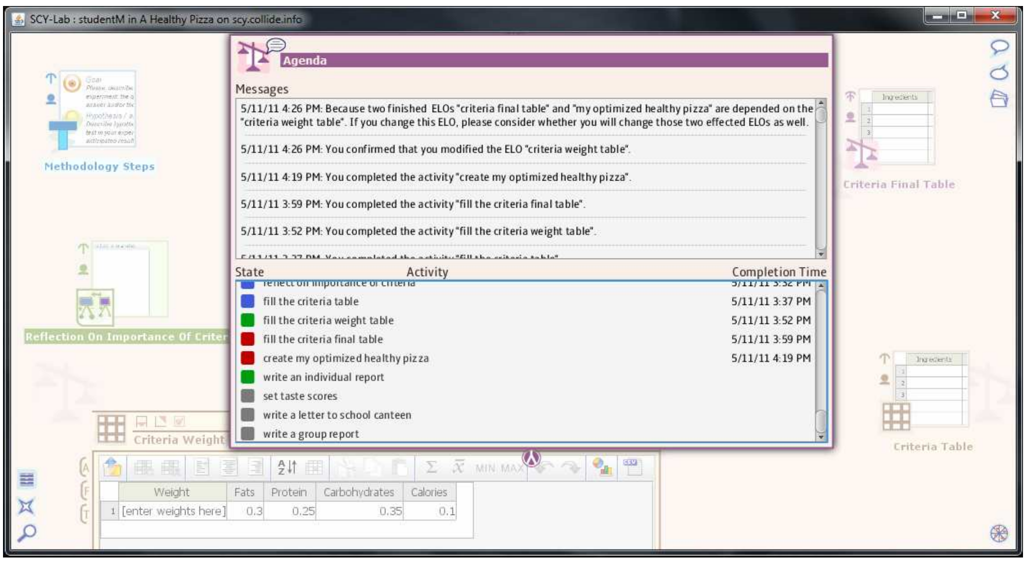

Fig. 4: A Screenshot of the Scaffolding Tool That Is Embedded in SCY-Lab.

Fig. 4 shows a screenshot of the metacognitive scaffolding tool that is embedded in SCY-Lab. Related activities are organized in a learning activity space. An activity can be opened by clicking the icon of its associated ELO in the space. According to the type of an ELO, an appropriate tool will be opened. The student can perform an activity by manipulating the associated ELO. In certain situations, the scaffolding tool will fall down like a curtain. The screenshot captures the UI of the tool after the student has confirmed that s/he is *modifying* the previously finished *criteria weight table.* As described in the last section and depicted in Fig. 1, the state of this activity became *activated* (marked in green). The two activities with effected, dependent artifacts *criteria final table* and *my optimized healthy pizza* became *need_to_check* (marked in red). The student can choose *resume* or *approve* from the button menu and then the color of the button will change to green or blue accordingly.

4. Discussion

In order to scaffold inquiry process management, there are two broadly different approaches to decompose activities: unordered and ordered activity decompositions [14]. Many inquiry learning environments such as Symphony [13] and Process Coordinator [10] have been developed by adopting an unordered activity decomposition approach. These systems provide a set of unconnected entries for activity possibilities, so that students can access the possible activity spaces freely. Our approach emphasizes the ill-structured and open-ended nature of inquiry learning, but provides less strict process guidance. Some other systems such as KIE [1] explicitly describe the learning path. The students have to complete one activity and then can start the next one. This approach guides students, at least novice and intermediate students, to use scientific inquiry process skills and improve learning efficiency. However, this approach restrains students, in particular skilled students, to think and decide on their own strategic plan. In fact, there is an additional approach in between these two extremes. The decomposed activities are displayed as a list as done in WISE [9] or connected as lines/arrows in the main work space. On the one hand, the explicitly provided learning sequence is not used to control the work process; on the other hand it provides hints for the students to take a suggested learning path to achieve the learning goal. Although this approach meets the two conflict requirements to some extent at the same time, it provides insufficient support for regulative activities. Our approach can be regarded as an extension to the third approach described above. In the main workspace, a set of connected activities are presented as the entries to enter the activity spaces. Students can select and perform activities freely. However, for the students with different levels of self-regulation skills, an additional scaffolding tool will be presented to the students in certain situations. The tool provides rich information about the work progress captured by monitoring and analyzing users' operations. In addition, the tool aids students to think and to make an action plan by using process knowledge specified in the process model. Obviously, our scaffolding mechanisms are not embedded in the basic functionalities of the learning environment. When students change their own plans, such changes have no effect on the system's functions. Due to the use of educational process modeling technologies, the same scaffolding mechanisms can be reused to support various inquiry learning strategies and different knowledge domains. In summary, our approach is generic and flexible.

5. Conclusions and Future Work

In this paper, we have identified requirements to develop metacognitive scaffolding mechanisms for flexibly structured inquiry learning processes. The approach can be characterized by the following features: 1) the scaffolding is based on knowledge captured in the process model such as activity-temporal structure, artifact-dependent structure and an activity-artifact dynamic model; 2) the scaffolding has three levels for the student with different levels of self-regulation skills; and 3) the scaffolding provides rich information and functions to engage students in regulative activities. Based on this approach, a prototype has been implemented and tested in the SCY-Lab environment. In comparison with other approaches, our approach is flexible and provides a new way to computational metacognitive scaffolding.

Scaffolding can be differentiated by mechanisms and functions. Mechanisms emphasize the methods through which scaffolding is provided, while functions emphasize the purposes served [5]. This paper focuses on an approach to develop the mechanisms. So far our evaluation work has been restricted to the test of the prototype and the test results demonstrate the technical feasibility of the approach. The future work in this direction is to evaluate the functions of such scaffolding in real learning settings and improve the approach according the feedback from evaluations.

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