The foundations of a theory-aware authoring tool for CSCL design

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A R T I C L E   I N F O

Article history:
Received 19 January 2009
Received in revised form 3 September 2009
Accepted 3 September 2009
Available online xxxx

Keywords:
Ontology
Intelligent authoring system
CSCL
Collaborative learning design

A B S T R A C T

One of the most useful ways to enhance collaboration is to create scenarios where learners are able to interact more effectively. Nevertheless, the design of pedagogically sound and well-thought-out collaborative learning scenarios is a complex issue. This is due to the context of group learning where the synergy among learners’ interactions affects learning processes and, hence, the learning outcome. Although many advances have been made to support the designing of collaborative learning scenarios through technology, a more systematic approach is lacking. With the limitations of the current designing methods and tools, it is difficult to develop intelligent authoring systems that can guide users in order to produce more effective collaboration. One of the main difficulties with creating a more consistent (computer-understandable) approach to designing collaboration is the necessity of proposing better ways to formalize the group learning processes. In this paper, we present an innovative approach that uses ontologies and concepts from learning theories to create a framework that represents collaborative learning and its processes. Ontologies provide the necessary formalization to represent collaboration, while learning theories provide the concepts to justify and support the development of effective learning scenarios. Such an approach contributes to establish the foundations for the design of the next generation of intelligent authoring systems referred to as theory-aware systems. To verify the viability and usefulness of our proposed ontological framework in the context of systematic design, the development and use of an intelligent authoring tool for CSCL design is presented. This system is able to reason on ontologies to give suggestions that help users to create theory-compliant collaborative learning scenarios. We carried out several experiments with teachers in a geometry drawing course and the results indicate that the system helps teachers to create and interchange their scenarios more easily and facilitates the selection of important pedagogical strategies that influence positively the designing and effectiveness of group activities.

1. Introduction

For many years researchers and practitioners have been doing research on computer-supported collaborative learning (CSCL) to improve the development of computational programs that can increase learning outcomes, and support collaboration in classrooms and e-learning environments (Dillenbourg, 1999; Stahl, Koschmann, & Suthers, 2006). Among the many topics related to CSCL, one of the most important is the design of group activities.

Through the design of CL activities, a teacher/designer can define, for example, the overall learning goals for each learner and for the entire group, establish the relationship between learning goals and the group structure, and form groups in an appropriate way enabling learners to obtain more benefit from interacting with their peers. Without a well-thought-out design for CL scenarios the chance of having an effective collaboration decreases considerably. This conclusion is based on the fact that many researchers have reported that the inadequate design of CL scenarios is one of the main causes of unsuccessful group learning (Dillenbourg, 2002; Fiechtner & Davis, 1985).

In spite of the importance of CL design, researchers in the field have noted problems with the lack of a more systematic approach (computer-understandable approach) that can be used by humans and computers to support pedagogically sound group formation and the satisfactory design of CL activities (Hernandez-Leo et al., 2006; Isotani, Inaba, Ikeda, & Mizoguchi, 2009; Strijbos, Martens, Jochems, & Broers, 2004). One of the reasons for this is the difficulty of creating models that formally represent the CL processes, the interactions between learners, and the impact of these interactions on the learners’ development (Inaba, Ohkubo, Ikeda, & Mizoguchi, 2002; Strijbos, Martens, & Jochems, 2004).

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0360-1315/$ - see front matter © 2009 Published by Elsevier Ltd.
doi:10.1016/j.compedu.2009.09.010

Please cite this article in press as: Isotani, S., et al. The foundations of a theory-aware authoring tool for CSCL design. Computers & Education (2009),
doi:10.1016/j.compedu.2009.09.010
According to Dillenbourg (2002) and Suthers, Dwyer, Medina, and Vatrapu (2007), the key to comprehending collaborative learning is to gain an understanding of the wealth of the interactions between individuals. The next step is to use this understanding to help with the design of CL scenarios. Hernandez-Leo et al. (2006) and Inaba, Ikeda, and Mizoguchi (2003) emphasize that what is needed is the development of better ways of formalizing the flow of collaborative learning processes. In order to provide an effective CL scenario is essential to establish appropriate parameters (goals and tasks) for each learner and to structure the group appropriately. To achieve this we need understandable models to represent CL activities which are based on the interactions between individuals.

Numerous learning theories have been developed and evaluated extensively to facilitate an in-depth understanding of collaborative learning and the impact of interactions in group activities. Some examples of this are: Legitimate Peripheral Participant – LPP (Lave & Wenger, 1991), Anchored Instruction (CTGV – Cognition & technology group at Vanderbilt, 1992), and Cognitive Apprenticeship (Collins, 1991). Although learning theories are not complete in terms of their ability to describe learning, and the different viewpoints sometimes contradict each other, they can provide and explain some essential conditions in which learners are able to learn more effectively. In order to explain the learning process, usually a learning theory gives information about what happens inside the learner’s mind. This process, whether explicitly or implicitly, provides the context, learning activities, group structures, learning objects, target goals (knowledge/skills), and various other parameters that affect learning. These parameters described in learning theories are essential for structuring the group and designing pedagogically sound CL scenarios.

Nevertheless, the selection of an appropriate theory to design CL scenarios for specific situations is a difficult and time-consuming task. One of the reasons for this is the difficulty in understanding the theories due to their complexity and ambiguity. Each theory offers a different point of view, level of aggregation, perspective, and emphasis. Furthermore, they are written in natural language and, as a result, there is no common vocabulary to describe their characteristics. Thus, to systematically design effective CL scenarios based on learning theories it is necessary to extract the essential concepts of the theories and create models/frameworks to represent them formally and explicitly.

Through the use of ontologies and ontological engineering, many interesting results have been obtained which can help to organize the conceptual knowledge of learning theories (Ikeda, Go, & Mizoguchi, 1997; Inaba & Mizoguchi, 2004). An ontology is a system of fundamental concepts semantically represented in a computer-understandable manner (Mizoguchi, Hayashi, & Bourdeau, 2007). The use of ontologies allows for the creation of conceptual frameworks and models that describe theories, taking into consideration their similarities and differences. Furthermore, it also helps in the development of sharable and reusable knowledge that can be incorporated into a wide variety of intelligent systems and applications. In this work we present the collaborative learning ontology (CL ontology) that our group has developed to date. We demonstrate how it can be used to propose useful models to clarify the relationships between desired interaction patterns, the learner’s knowledge acquisition process, and the skills development process in CL sessions. Through the clarification of concepts and the development of models based on ontologies, we intend to aid in the design of effective and pedagogically sound CL scenarios. Finally, we will explore some of the challenges to develop a prototype of an authoring system that exemplifies how the next generation of intelligent systems, referred to as theory-aware systems, can be created and used to help the design of collaborative tasks with educational purposes.

In the following sections we initially contextualize our work, showing some of the achievements and limitations of the current research on CSCL design. Then we introduce our previous work about the CL Ontology, placing emphasis on concepts that help to understand the interaction process and the learner’s development. Next, an ontology-based model referred to as CMIP is presented which clarifies the relationship between interactions and the learner’s growth, offering a formal way to explain the learning development process through a set of collaborative learning activities. Finally, we present the development and utilization of an authoring tool that support the designing of theory-based CL scenarios.

### 2. Related work on CSCL design

Free collaboration does not always produce satisfactory learning outcomes (Dillenbourg, 2002). One of the main reasons highlighted by Fiechtner and Davis (1985) and Isotani et al. (2009), is that an unstructured collaboration often leads to CL sessions being filled with meaningless interactions. Such interactions can be defined as those that interfere with the good “health” of the group and the progress of collaboration among group members. Some examples of the large number of meaningless interactions are: arguments between members; long discussions without any concrete results; “off-topic” discussions; abrupt interruptions while effective collaboration is taking place; and excessive participation (of one member) or lack of it. In order to avoid these problems and enhance the probability that meaningful interactions occur during collaborative learning processes (such as conflict resolution, explanation, and mutual regulation); it is necessary to form groups properly and to propose CL activities that foster the occurrence of desired interactions among learners (Tchounikine, 2008).

To facilitate the design of effective CL sessions, the CSCL community has put a great deal of effort into defining CSCL scripts. These scripts are guidelines that help to support structured collaboration by facilitating the description of collaborative tasks. Through the use of scripts, it is possible to describe collaboration and CL processes, including their different components (variables/conditions) and mechanisms (Miao, Hoeksema, Hoppe, & Harrer, 2005). According to Kobbé et al. (2007) the main components to describe scripts are:

(a) **Participants** – meaning the total number of participants (e.g. two students per group) and the participant characteristics (e.g. different knowledge or opinions).

(b) **Activities** – a list of activities forming a hierarchical structure in which any coarse-grained activity can be decomposed into more fine-grained activities and vice versa.

(c) **Roles** – allow/foster a participant to behave in a certain manner that helps him to achieve his/her goal while supporting other participants to achieve their goals as well (e.g. tutor and tutee roles).

(d) **Resources** – learning objects that can be used by participant to support the learning process.

(e) **Groups** – a set of participants which are grouped according to the participants’ characteristics, activities, constraints, and the available learning objects. Usually groups form a hierarchical structure whereby the larger groups are composed of smaller ones.

Concerning script mechanisms, Kobbe et al. emphasize three of them:

(a) **Task distribution** – provide learners with specific tasks in order to foster the appearance of positive interactions.

(b) **Group formation** – principles used to compose groups considering the parameters presented in the script components.

(c) **Sequencing** – temporal structure for interactions that specify the order in which events and activities should take place (activities workflow).

A script allows for the improved design of an instructional plan that uses collaborative learning to facilitate knowledge generation through meaningful interactions (Stegmann, Weinberger, & Fischer, 2007). Another interesting characteristic of scripts is the possibility of having different levels of granularity. These levels are referred to as macro- and micro-scripts. On one hand, macro-scripts aim to show the flow of activities without considering the specific sequences of interactions that may occur during collaboration. On the other hand, micro-scripts try to provide a more detailed description of each interaction and its impact on learning development. Both are quite important for understanding and designing more effective CL sessions. This is because a broad view (macro-level) of CL allows for a better comprehension of the CL process as a whole, which in turn facilitates the identification of patterns and similarities between instructional plans; while a more detailed view allows for the identification of specific interactions that can support the achievement of desired learning goals in a specific situation.

CSCL scripts are quite flexible and powerful in supporting collaboration (Tchounikine, 2008). Nevertheless, to use them appropriately while enjoying their benefits is a difficult task, especially for people without the expertise in designing CL activities. For example, it is not clear how to choose a task to achieve a specific goal. Also, when creating a script, a designer/teacher needs to create the constraints regarding the roles that can be played by learners: *Can any role be played by any learner, in any activity?* Besides these questions, many others arise when creating scripts or combining their components and mechanisms.

To facilitate the use of scripts, it is necessary to have some support from expert designers, or some intelligent guidance that can help novices to propose well-thought-out CL scenarios. Therefore, the ability to have interaction patterns (guidelines to propose interactions in CL scenarios) that can be described using scripts is highly sought after in order to enhance the design of potentially effective and pedagogically sound CL scenarios (Hernandez-Leo et al., 2006). Such patterns act as recipes for designing collaboration that can be used to promote meaningful interactions, and to enhance the effectiveness of CL activities.

Usually, a pattern in CSCL describes a problem (or a goal) which occurs many times in classrooms or CSCL environments. Besides that, it also describes the core of the solution to that problem (or steps to achieve the goal) in such a way that it can be reused in many different situations (Frysch, 2006). Thus, each pattern is usually based on either broadly accepted CL techniques, or on learning theories that have been repetitively used/tested/validated by theorists and practitioners when structuring collaboration to obtain better learning outcomes.

In this direction, the special group of CSCL from the European research network, referred to as “Kaleidoscope” ([http://www.noe-kaleidoscope.org](http://www.noe-kaleidoscope.org)), and the Intelligent and Cooperative Systems Research Group at the University of Valladolid in Spain have been leading the development of CL patterns based on CL best practices, including jigsaw, brainstorming and peer review (Hernandez-Leo, Asensio-Perez, & Dimitriadis, 2005). The development of patterns to support CL design is essential for creating models that describe effective CL sessions from a macro-level perspective.

However, to understand the impact of CL activities in learning development, and thus propose better ways to design CL scenarios, it is necessary to analyze the relationships between interactions and learners’ growth. Although research on this topic has been going on for many decades (Vygotsky 1930/1978; Anderson, 1982; Rumelhart & Norman, 1978), recently, notable achievements in analyzing the impact of interactions in collaborative learning settings with technological support have been presented by numerous researchers in the community (Dimitrakopoulou et al., 2006; Inaba et al., 2002; Suthers et al., 2007). These results are stimulating new research questions that need to be solved in order to have a better comprehension of the relationships between interactions and knowledge construction. Furthermore, the results achieved to date show promising potential to obtain a better understanding of how people learn through interactions, and how we can maximize learning by creating better collaborative learning scenarios (Miyake & Shirouzu, 2006; Stahl, 2006; Suthers, Vatraru, Medina, Joseph, & Dwyer, 2008).

Another rich source of information for understanding collaboration and the impact of interactions in the learning processes, are learning theories. Each theory contributes to support CL by providing the rationale for creating a CL scenario and the interactions that help learners to achieve learning goals. A theory defines the essential conditions in which learners are able to learn more effectively (Hayashi, Bourdeau, & Mizoguchi, 2006). By explaining the learning process (besides trying to explain what happens inside of a learner), a learning theory also gives, either explicitly or implicitly: the context in which learning activities have been taking place, the target knowledge/skill that has been tackled, and the roles played by learners. Thus, from an engineering perspective, through the analysis of theories it is possible to grasp the core concepts in order to propose frameworks and models of CL processes that can support the effective design of CL. Besides that, these models can provide theoretical justifications to explain why the interactions among learners should follow a certain order, and why the CL processes should have specific conditions.

There are many benefits of using the results of learning theories and interaction analysis, together with patterns and scripts, to support effective CL design. However, to use such a large amount of information is a very difficult and time-consuming task. There are several reasons that diminish the viability of using this kind of information during CL design. We would like to emphasize two of them:

(a) First, most of the information available to support CL (e.g. learning theories, CL techniques) is presented in natural language, without a common vocabulary. Thus, teachers have difficulties in choosing a theory or technique according to the characteristics of their learners and the constraints of the learning environment. To address this issue we need to create a new method for exposing teachers to theories and CL techniques in a way that teachers can use them effectively and systematically.

(b) Second, there is a lack of models/frameworks or a common conceptual infrastructure on which we can clarify, at least partially, what collaborative learning is and how information about learning theories, interactions, and patterns can facilitate the design of a well-thought-out group structure. Without such models it is difficult to create common knowledge bases that can be used by intelligent support systems to help teachers, especially novice teachers, to develop better CL scenarios.
To solve these problems some researchers have been using ontologies and learning theories to establish a system of concepts that models CL formally (Babic, Wagner, & Paralic, 2008; Villasclaras-Fernández, Isotani, Hayashi, & Mizoguchi, 2009). The application of ontologies has shown some interesting results in terms of formalizing instructional and learning theories to support the design of learning activities (Psyche, Bourdeau, Nkambou, & Mizoguchi, 2005). This formalization provides a common vocabulary to describe CL and to facilitate the development of intelligent authoring systems to design more effective CL sessions. Remarkable achievements in using ontologies to support CL have been presented by Inaba et al. (2002), Inaba et al. (2003a), Hoppe et al. (2005) and Kumar, Gress, Hadwin, and Winne (2008), in addition to others. The first version of an ontology that represented collaborative learning was presented by Ikeda et al. (1997) and it is referred to as CL Ontology. Since this initial work, many steps have been taken to improve this ontology. A review of the CL ontology presented by Devedzic (2006) shows that this kind of ontology can support intelligent systems in many different ways by offering: (a) a standard vocabulary to describe CL; (b) a conceptual framework to represent and describe CL scenarios in a computer-understandable manner, including theoretical justifications; (c) explicit representation of the roles and behavior expected from learners during collaboration; and (d) a formal description of the CL process that helps intelligent pedagogical agents to communicate and negotiate, in order to select pedagogical strategies.

Many important and interesting results have been achieved by the community in this field. However, there is still plenty of room for improvement in order to propose pedagogically sound CL scenarios and to develop more complete and formal models to support CL design.

In this direction, our work aims at proposing a more systematic method to design CL scenarios with theoretical justifications.

In the next section we will provide the theoretical background necessary to understand the development of our ontological framework based on learning theories.

3. Theoretical background about the CL ontology

3.1. Individual learning goal (I-goal): the definition of "Learning"

Our working hypothesis for building a comprehensive ontology and defining individual learning goals is that every theory rests somehow on a common basis to explain learning (and instruction). While the assumed mechanism of developing knowledge/skills is different from each paradigm or theory (e.g., behaviorism, cognitivism, and constructivism), the idea of states and stages in the learning process is common. According to Ertmer and Newby (1993), although instructional/learning theories have unique features and different points of view, they describe the same phenomena of "learning." Thus, it is possible to have an engineering approximation of the states/stages where we can conceptualize "learning" as changes in the learner’s state/stage of development (Hayashi et al., 2006). These changes can occur in an individual learning environment or in a more social environment (group learning).

Following such an observation, the authors adopted the theory of knowledge acquisition proposed by Rumelhart and Norman (1978) and the theory of skills development proposed by Anderson (1982) to describe individual learning goals that are domain independent. Both theories are used to give a common background to describe learning as changes in the learner’s stage, regardless of whether these changes occur in an individual or social environment. According to Rumelhart and Norman (1978), Anderson (1982), and Inaba et al. (2003), although there is a variety of learning goals, the process of a learner’s growth can be described in terms of the stages of knowledge acquisition and skill development as shown in Table 1. Thus, concerning individual goals, the CL ontology succinctly describes the learner’s knowledge acquisition process and skill development process by adopting the stages and vocabulary used by these theories.

The process of acquiring specific knowledge includes the following three stages of learning: accretion, tuning, and restructuring (Rumelhart & Norman, 1978). **Acretion** is adding and interpreting new information in terms of pre-existing knowledge. **Tuning** is understanding knowledge through its application in a specific situation. **Restructuring** is considering the relationships of acquired knowledge and rebuilding the existing knowledge structure.

Considering the development of skills, there are also three stages of development including the cognitive stage (rough and explanatory), the associative stage, and the autonomous stage (Anderson, 1982). The cognitive stage involves an initial encoding of a target skill that allows the learner to present the desired behavior or, at least, some crude approximation. The associative stage is the improvement of the desired skill through practice. In this stage, mistakes presented initially are gradually detected and eliminated. The autonomous stage is the gradual and continued improvement of the skill. In this stage, the learner can accurately and quickly perform the desired behavior.

To simplify the representation of the learner’s condition in terms of knowledge and skills, we adopt the following notation: \( s(x, y) \) represents the learning stage of a learner, where \( x \) represents the current stage of skill development and \( y \) represents the current stage of knowledge acquisition.

<table>
<thead>
<tr>
<th>Individual learning goals (I-goal)</th>
<th>Stages of development</th>
<th>Abbreviation</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition of content-specific knowledge</td>
<td>Nothing</td>
<td>( s(x, 0) ), ( x = 0 \ldots 4 )</td>
<td>(Rumelhart &amp; Norman, 1978)</td>
</tr>
<tr>
<td></td>
<td>Accretion</td>
<td>( s(x, 1) ), ( x = 1 \ldots 4 )</td>
<td>(Anderson, 1982)</td>
</tr>
<tr>
<td></td>
<td>Tuning</td>
<td>( s(x, 2) ), ( x = 1 \ldots 4 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Restructuring</td>
<td>( s(x, 3) ), ( x = 1 \ldots 4 )</td>
<td></td>
</tr>
</tbody>
</table>

### Development of skill

<table>
<thead>
<tr>
<th>Some types</th>
<th>Stages of development</th>
<th>Abbreviation</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cognitive skills</td>
<td>Nothing</td>
<td>( s(0, y) ), ( y = 0 \ldots 3 )</td>
<td>(Anderson, 1982)</td>
</tr>
<tr>
<td>Meta-cognitive skills</td>
<td>Rough-Cognitive</td>
<td>( s(1, y) ), ( y = 0 \ldots 3 )</td>
<td></td>
</tr>
<tr>
<td>Skill for self-expression</td>
<td>Explanatory-Cognitive</td>
<td>( s(2, y) ), ( y = 0 \ldots 3 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Associative</td>
<td>( s(3, y) ), ( y = 0 \ldots 3 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Autonomous</td>
<td>( s(4, y) ), ( y = 0 \ldots 3 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Associative</td>
<td>( s(3, y) ), ( y = 0 \ldots 3 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Autonomous</td>
<td>( s(4, y) ), ( y = 0 \ldots 3 )</td>
<td></td>
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</tbody>
</table>
knowledge acquisition. For instance, $s(0, 1)$ illustrates a situation where the learner’s stage of skill development is nothing and the stage of knowledge acquisition is accretion. This simplified representation will be used in the next chapters of this thesis when exemplifying the learner’s development in a CL session.

The adoption of the theories from Rumelhart and Norman (1978) and Anderson (1982) allows for the definition of the vocabulary to describe the concept of individual learning goal. In the CL ontology, an individual learning goal is referred to as I-goal.

3.2. Interaction (influential I_L event)

In Section 2 we highlight the importance of understanding and modeling interactions among learners in order to facilitate collaboration. According to Strijos, Martens, Jochems (2004a), the community has produced some intriguing evidence of a connection between learning outcomes and interactions. Some researchers claim that a successful collaboration implies that learners have completed effective interactions (Dillenbourg, 2002; Fiechtner & Davis, 1985; Rummel & Spada, 2005; Suthers et al., 2007).

Nevertheless, to equip computers with the necessary knowledge to facilitate interactions that positively affect learning, it is necessary to create models that represent interactions and interaction processes. By establishing a formal model of interactions, it is possible to show the relationships among learning actions and expected learning outcomes (when these actions are completed satisfactorily). Furthermore, by modeling interaction processes, it is also possible to show the sequence of interactions that leads learners to achieve desired benefits. Thus, either an intelligent system, or a human designer, can use these models to identify which interaction is more effective at achieving specific learning goals, and thereby utilize them more effectively in different occasions.

Nowadays, there are many types of collaborative learning scenarios that focus on knowledge and skill development. Each intended educational benefit that can be obtained through collaborative learning may have its own interaction processes. Therefore, a model of interactions needs to be flexible to appropriately represent the various kinds of collaborative learning processes and facilitate the distinction among them.

In the CL ontology, we try to explicitly represent the concept that describes an interaction in terms of its semantic connections with other essential concepts that support CL. In an ideal CL environment, a good interaction is composed of the following two events: a learning event and an instructional event. These events include the actors (the learners) and their actions. An actor can act as an instructor (learner doing an instructional action) or as a learner (learner doing a learning action), and through the interaction among actors and learning objects (collaborative tools) the attainment of educational benefits occurs.

Each actor plays a specific role in the group, and each action influences other learners in the group, as well as the actor himself. These influences are the key to elicit the changes in the learning state/stage and helping learners to achieve their individual learning goals. Therefore, an interaction activity can be represented by influential I_L event (abbreviation for influential instructional-learning event), which is the concept that links learning and instructional events in our ontology. The top left of Fig. 1 shows the image of the relationships among concepts that describe an influential I_L event, and the right side of the figure shows the representation in its ontological form. A similar structure for individual learning was presented by Hayashi et al. (2006).

This formalization in the CL ontology allows explicit representation of the interaction and its benefits from both points of view: for those who do the action and for those who receive the action. Furthermore, it also provides a macro-view of the CL process, in terms of flow of interactions and sequence of activities, and a micro-view of the CL process, in terms of actions and reactions among learners, which facilitates the educational benefits of each action.

The use of influential I_L events is the basis for representing interaction processes and constructing interaction patterns of learning theories as introduced by Isotani and Mizoguchi (2007).
3.3. Interaction pattern from learning theories

In theory-based structured collaboration, an interaction pattern shows how interactions are organized to facilitate learning. To create such a pattern and avoid possible misinterpretations, a common vocabulary and a basic model to represent interactions needs to be defined. Section 3.2 provided the concept of an influential I-L event that can be used to model an interaction. In this section we will provide the necessary common vocabulary to describe an interaction and a interaction pattern.

Previous achievements of Inaba et al. (2002), Inaba, Ohkubo, Ikeda, and Mizoguchi (2003b) prepared a set of utterance labels to represent the interaction process based on concrete CL activities; that is, labels which characterize the utterances of learners following theory-based CL scenarios. For example, in Peer Tutoring, the learner who plays the role of peer tutor should perform the activity “tutoring.” Thus, this learner gives some distinctive utterances to perform the tutoring activity, and the utterances are represented as utterance labels such as teaching his/her own knowledge, answering a question, etc.

A label is composed of the following three elements: action, source, and object. For example, in the label teaching his/her own knowledge, the term teaching refers to the learner’s action; his/her refers to the ownership of the information (source); and, own knowledge refers to what the learner is teaching (object). There are some labels where the source or the object can be suppressed such as in the label showing a solution where the action is showing, the object is solution, and the source is implicit. Another example is the label monitoring, where only the object is presented and the other information is suppressed. Through the use of these labels, it is possible to determine what learners are actually doing during a CL activity.

Utterance label is used as common vocabulary to describe interactions at a concrete and fine-grained level (i.e., actions). Although some actions are completely different and others are quite similar, a computer cannot obtain such information because utterance labels are just sentences to describe individuals’ actions. Thus, Inaba et al. (2003b) proposed a way to cluster the utterance-labels (similar actions that may lead to similar benefits) using a hierarchical cluster analysis method. Each cluster is named to represent the meaning of a set of utterance labels. The name of each cluster is referred to as utterance types.

As a result, they have produced a basic common vocabulary to represent interactions at the concrete level (utterance labels) and to describe interaction processes on a more abstract and coarse-grained level (utterance types). This type of common vocabulary is essential for representing structured collaborative learning as interaction patterns that characterize a CL session. Fig. 2 shows some examples of the utterance types and their relationship with some utterance labels. The CL ontology uses these achievements to provide common vocabulary to describe interactions at macro- and micro-perspectives.

To represent the interaction patterns suggested by learning theories, it is necessary to represent the flow of interactions, their intentions (expected goals), and their prerequisites. For instance, a specific interaction may require a specific learner’s behavior to be completed successfully; other interactions may require that a learner has already experienced some previous situation. Furthermore, depending on the desired learning goals, some interactions are necessary and others are complementary. It is also desirable to know when an interaction can (or should) be repeated many times, and when it can (or should) be done only once.

Through the use of the ontological formalization presented in Fig. 1 and the utterance labels and types proposed by Inaba et al. (2003b), we defined interaction patterns which are models of typical interaction processes frequently observed in theory-based CL sessions. Each interaction pattern shows desired interaction processes described by a learning theory. To construct interaction patterns, it is first necessary to understand the theories and organize the main concepts in terms of utterance labels through investigation and analysis. Then, represent the interaction processes as sequences of utterance labels and convert the utterance labels into more abstract utterance types.

Through this process we obtain a sequence of utterance types which characterize the interaction pattern in a theory-based model of collaborative learning. To date, the CL ontology has provided the representation of interaction patterns based on the following eight different learning theories: Cognitive Apprenticeship (Collins, 1991), anchored instruction (CTGV, 1992), Peer Tutoring (Endsley, 1980), Cognitive Flexibility (Spiro, Coulson, Feltovich, & Anderson, 1988), LFP (Lave, & Wenger, 1991), Socio-cultural Theory (Vygotsky, 1930/1978), Distributed Cognition (Salomon, 1993), and Observational Learning (Bandura, 1977).

Fig. 3 shows a graphical representation of the interaction pattern based on the Cognitive Apprenticeship theory. The top of the figure shows the flow of interactions represented in the ontology; and, the use of the structure of Influential I-L events to model two different

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interactions is shown at the bottom. In this example, master and apprentice are roles played by learners in a scenario proposed by the theory. The interactions are represented with double-line labelled boxes (in terms of utterance-types). The dotted-line boxes identify interactions that are complementary to achieve the goal, while the solid-line boxes are necessary to complete the CL session successfully. Each interaction includes events inside that are represented with single-line labelled boxes. The links represent possible transitions between interactions. Necessary transitions are represented using solid lines and desired transitions using dotted lines.

One of the benefits of formally represented interactions using ontologies is the possibility to compare any interaction process with the interaction patterns inspired by learning theories. For example, when a CL session is designed based on theoretical settings, it is possible to check, with a good accuracy rate, if this session was carried out successfully based on the data from learners’ interactions (Inaba et al., 2003b). Furthermore, it is also possible to estimate how much benefit learners received after the collaboration. This kind of understanding about interactions and their educational benefits is one of the most important issues for producing intelligent support systems that can help teachers create effective CL sessions.

Another benefit of our formalism is the possibility to identify the relationships among components in the CSCL scripts introduced in Section 2, such as roles and activities, and thus to support a better CL design. For example, a non-expert instructor usually does not know what roles can be combined to develop a better interaction process during a CL activity, how many learners can play a specific role, or which CL activity can help a learner achieve a desired learning goal. By using interaction patterns, an instructor can identify the relationships between the concepts of CSCL scripts to create pedagogically sound CL sessions. For instance, Fig. 3 illustrates a situation where an instructor can observe that the role of Master should be used together with the role of Apprentice. Furthermore, the role of Master can be played by one participant of the group, while the role of Apprentice can be played by a number of different participants. It is also possible to identify which interaction activity helps learners to achieve a desired learning goal, and how the flow of interactions should occur to facilitate learning development according to the given theory. Besides this information, many other correlations among components and mechanisms of CSCL scripts can be used to create better learning scenarios.

4. Overview of the CL ontology

To create the CL ontology as a set of conceptual building blocks to describe theory-based CL scenarios and avoid possible misunderstandings of using a conventional vocabulary, a specific terminology has been defined to better represent a scenario in the CL ontology (Inaba & Mizoguchi, 2004; Isotani et al., 2009). Let us introduce the basic terminology of the CL ontology as follows:

I: Person in focus
You or Y: Any participant of the group expected to interact with I
Using the above terminology, the CL ontology describes a CL scenario as shown in Fig. 4a. Fig. 4a represents a CL scenario with three main parts including the learning strategy and the CL process. As we discussed above a learning strategy \( W(A) \)-goal represents the strategy used by \( I \) (learner in focus) to interact with \( Y \) (another learner) in order to achieve the I-goal.

\( W(L) \)-goal: Common learning goal for members of the group (group goal).

\( W(A) \)-goal: Goal of the rational arrangement of the group’s activity used to achieve the \( W(L) \)-goals and I-goals. It characterizes the CL process according to a specific theory.

Using the above terminology, the CL ontology describes a CL scenario as shown in Fig. 4a. Fig. 4a represents a CL scenario with three learners: \( L_A \), \( L_B \), and \( L_C \). Each of these learners has an individual goal (I-goal) described as \( I\text{-goal}(L_A) \), \( I\text{-goal}(L_B) \), and \( I\text{-goal}(L_C) \), respectively. Concerning interactions among learners, from the point of view of \( L_A \), he/she will play a role to interact with \( L_B \) using the strategy \( Y \leq I\text{-goal}(L_A) \) in order to attain his/her I-goal. From the point of view of \( L_B \), he/she will play a role to interact with \( L_A \) using the strategy \( Y \leq I\text{-goal}(L_B) \) in order to attain his/her I-goal. There is also the point of view of \( L_C \) when he/she interacts with \( L_A \) or \( L_B \), and so on. Besides the representation of individual goals, there are the group goals. The goals of the whole group are represented by \( W(L)\text{-goal}(L_A, L_B, L_C) \) and \( W(A)\text{-goal}(L_A, L_B, L_C) \). Furthermore, it is useful to represent the goals of a specific cluster of learners who belong to a larger group (a small group inside a larger group).

In Fig. 4a, the group goals of a small group that consists of the learners \( L_A \) and \( L_B \) are represented by \( W(L)\text{-goal}(L_A, L_B) \) and \( W(A)\text{-goal}(L_A, L_B) \). Fig. 4b shows a simple example of the instantiation of the presented concepts to describe a group based on the following two different theories: Cognitive Apprenticeship by Collins (1991) and Observational Learning by Bandura (1971).

Fig. 4 tries to provide a succinct and comprehensive illustration of the CL scenario concept represented in the CL ontology. More formally, the concept of CL scenario represents the adequate connection of all the concepts presented previously providing the context where roles, strategies, goals, and interactions can be organized and effectively used to propose theory-based CL sessions.

Fig. 5 shows a representation of a CL scenario in the CL ontology. The ontological structure of the concept CL scenario consists of two main parts including the learning strategy and the CL process. As we discussed above a learning strategy (\( Y \leq I\text{-goal} \)) is the form used by a learner to interact with other learners (or a group) to obtain the desired benefit. In a CL scenario, this concept shows how learners may collaborate (role), what benefits they can get (I-goal), and with whom they will collaborate in the context of a specific theory. Then, the CL process shows the rational arrangements of elements for a theory (\( W(A)\text{-goal} \)), with particular interest on the common goal of the group and how learners can use the given strategies to attain their goals (individual and common goals) through a set of interactions supported by a theory.

5. Learner’s growth model (LGM)

Sections 3 and 4 provided the background of the CL ontology. This section will show how to use the concepts in the ontology to create models that can support a better visualization of the benefits that each theory, collaboration script or any other pedagogy provides for learners in CL scenarios. Thus, initially a brief recapitulation about some of the concepts of the CL ontology will be provided and then the model of learner’s growth will be presented.

As discussed in Sections 3 and 4, learning goal is a broad concept that generally defines the objectives of a learning/instructional method. It states what learners will ultimately achieve after the teaching-learning process. A learning goal (I-goal) can be defined as a change in the actual learning stage of a learner to a desired learning stage. Because of that, learning goal is one of the most important concepts used during the design of any instructional/learning activity. It not only helps the designer to adequately select the content, but also guides them to identify appropriate strategies to teach and to measure the benefits of the learning process. This concept can be described in concrete
terms (e.g., memorize a written sentence) or in more abstract terms (e.g., develop skills of self-expression). Furthermore, usually, there is a logical connection among them that shows the learner’s development. Therefore, an ontology that supports learning needs to explicitly represent the learning goals and the learning development processes in terms of these goals.

The CL ontology succinctly represents the learner’s knowledge acquisition process and skill development process following the remarkable achievements of Rumelhart and Norman (1978) and Anderson (1982). Based on these works, it is possible to describe a learner’s growth in a collaborative learning scenario, showing what each learner in a group is in fact learning. To facilitate the visualization of the information related to learning development in the CL ontology and to obtain a better understanding of the impact that a CL scenario may have on learning, Inaba et al. (2003) and Isotani and Mizoguchi (2006) proposed the learner’s growth model (LGM). This model shown in Fig. 6 represents in a simplified way the learner’s knowledge acquisition and skill development processes according to the definition presented in the CL ontology as shown in Table 1.

As shown in Fig. 6, LGM is a graph that represents the states of the learner’s development at a specific period in the learning process. To facilitate the graphical visualization, each state is represented by two triangles. The upper-right triangle represents the stage of knowledge acquisition (nothing, accretion, tuning, and restructuring); meanwhile, the lower-left triangle represents the stage of skill development (nothing, rough-cognitive, explanatory-cognitive, associative, and autonomous). Therefore, LGM has twenty states (multiply the number of stages related to knowledge by the stages related to skills). On the top of each state a simplified form of representing these states (x, y) are shown (Table 4.1). The arrows show possible transitions between stages. According to Rumelhart and Norman (1978), knowledge acquisition is a process which is completed step by step without skipping any of the stages. This means that you cannot move from accretion to restructuring, without completing the tuning stage in advance. However, Anderson’s (1982) model includes some flexibility that allows for developing skills without following all of the transitions between stages. Consequently, it is possible to go from nothing to the associative stage without moving through the cognitive stage.

One of the most interesting uses of this model is the possibility to graphically represent the educational benefits that different pedagogies (e.g., learning theories) offer from the group learning perspective. To do so, the concept of CL scenario (Fig. 5) is quite useful because it describes how and why a learner, in a given scenario proposed by theories, should interact with other learners to obtain certain benefits.

In a CL scenario, learners are always working towards educational benefits. Roughly speaking, the main reason (why) learners interact is to obtain these benefits (I-goal). Furthermore, to get these benefits a scenario provides roles and learning strategies that show how group members should behave and interact during the CL process. By showing formally and explicitly the connections among these elements, the CL scenario concept in the CL ontology facilitates the prediction of benefits that a learner will attain when following a specific learning strategy described by the learning theories. Table 2 presents some of the relationships between strategies, learner’s roles, and educational benefits that the CL ontology provides.

The explicit representation of concepts from theories, in terms of a standard vocabulary helps instructors to make some pedagogical decisions regarding CL activities and group structure. Thus, during the design of CL activities, an instructor can ask a learner to follow a
specific learning strategy to facilitate the acquisition of desired benefits with confidence. In other words, such explicit formalization is useful for designing goal-oriented CL activities. It can also help during the analysis of interactions, to check how effective a CL session was, and how much benefits learners have obtained after collaboration.

The utilization of concepts from the CL ontology enables to graphically represent the educational benefits of several learning strategies from theories through LGM. This kind of visualization is useful to gain a quick understanding of the differences between theories, and to support the selection of appropriate strategies for learners during CL design. For example, based on the information available in the fourth column of Table 2, Fig. 7 shows four different strategies extracted from two theories: Cognitive Apprenticeship and Anchored Instruction. The expected educational benefits of each theory can be visualized graphically. The bold arrows represent the transition from one state to another one; and the states and arrows in faded-gray are either not reached or desired by the selected learning strategies.

When a designer/teacher understands the LGM, he/she can rapidly check which theory is more useful to fulfill the desired learning goals, or propose learning goals based on a theory. In the example of Fig. 7, a teacher can realize that Cognitive Apprenticeship is useful to design CL activities that help learners to develop skills at different levels. However, if he/she wants to design activities to help learners to acquire knowledge, then it would be more beneficial to adopt Anchored Instruction. Furthermore, it is also possible to verify that novice learners (e.g., learners in a state like S(0,0)) cannot follow strategies such as learning by guiding or learning by diagnosing because the path in the graph for these strategies starts from states such as S(3, 0) – skill in associative stage and S(2, 1) – skill in explanatory stage and knowledge in accretion stage. These initial states can be understood as basic requirements for a learner to follow such strategies satisfactorily and obtain some benefits from them.

Another interesting use of the LGM is to understand the impact of a learning strategy on learners with specific conditions. In Section 4, we have discussed the use of states to define a learner’s current situation, I-goal. Thus, imagine that a learner already has the target knowledge, then it would be more beneficial to adopt Anchored Instruction. Furthermore, it is also possible to verify that novice learners (e.g., learners in a state like S(0,0)) cannot follow strategies such as learning by guiding or learning by diagnosing because the path in the graph for these strategies starts from states such as S(3, 0) – skill in associative stage and S(2, 1) – skill in explanatory stage and knowledge in accretion stage. These initial states can be understood as basic requirements for a learner to follow such strategies satisfactorily and obtain some benefits from them.

Table 2

<table>
<thead>
<tr>
<th>Learning theory</th>
<th>Learning strategy (Y ≤ I-goal)</th>
<th>Learner’s role (behavioral role)</th>
<th>Expected benefits (I-goal) initial stage → following stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anchored instruction</td>
<td>Learning by being taught</td>
<td>Anchor holder (presenter)</td>
<td>s(x, 0) → s(x, 1) → s(x, 2); x = {0, 4}</td>
</tr>
<tr>
<td></td>
<td>Learning by diagnosing</td>
<td>Anchored instructor (adviser)</td>
<td>s(2, 1) → s(3, 1) → s(3, 2); s(2, 1) → s(2, 2) → s(3, 2);</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>s(2, 3) → s(3, 3)</td>
</tr>
<tr>
<td>Cognitive</td>
<td>Learning by apprenticeship</td>
<td>Apprenticeship (imitator)</td>
<td>s(0, y) → s(1, 1) → s(2, y) → s(3, y); y = {0, 3}</td>
</tr>
<tr>
<td>Apprenticeship</td>
<td>Learning by guiding</td>
<td>Master (guide)</td>
<td>s(3, y) → s(4, y); y = {0, 3}</td>
</tr>
<tr>
<td>Cognitive flexibility</td>
<td>Learning by reflection</td>
<td>Audience (reviewer/evaluator)</td>
<td>s(x, 2) → s(x, 3); x = {0, 4}</td>
</tr>
<tr>
<td></td>
<td>Learning by self-expression</td>
<td>Panelist (presenter)</td>
<td>s(2, y) → s(3, y); y = {1, 3}</td>
</tr>
<tr>
<td>Distributed cognition</td>
<td>Learning by discussion</td>
<td>Full participant (problem solver)</td>
<td>s(3, y) → s(4, y) and s(x, 2) → s(x, 3); x = {3, 4}, y = {2, 3}</td>
</tr>
<tr>
<td>LPP</td>
<td>Learning by practice</td>
<td>Peripheral participant (problem solver)</td>
<td>s(0, y) → s(1, 1) → s(3, y); y = {0, 3}</td>
</tr>
<tr>
<td></td>
<td>Learning by discussion</td>
<td>Full participant (problem solver)</td>
<td>s(3, y) → s(4, y) and s(x, 2) → s(x, 3); x = {3, 4}, y = {2, 3}</td>
</tr>
<tr>
<td>Peer tutoring</td>
<td>Learning by being taught</td>
<td>Peer tutee (passive learner)</td>
<td>s(x, 0) → s(x, 1); x = {0, 4}</td>
</tr>
<tr>
<td></td>
<td>Learning by teaching</td>
<td>Peer tutor (explainer)</td>
<td>s(x, 1) → s(x, 2); x = {0, 4}</td>
</tr>
</tbody>
</table>

edge and also possesses some knowledge about the target cognitive skills, \((2, 1)\). In this situation, LGM can help teachers to check beforehand what will be the benefits of a strategy for a specific learner and in which part of the CL process better support would be required.

Fig. 8 shows an example where the initial state of a learner is \((2, 1)\). Such state is shown on LGM in the center of the figure. There are many learning strategies that can help this learner to obtain some benefits as shown in Table 2. In the example of Fig. 8 the strategies learning by being taught (left of the figure) and learning by diagnosing (right of the figure) are represented using LGM. Each strategy leads to different benefits. The former helps the learner to reach the state \((2, 2)\), which means to acquire knowledge in the Tuning stage by receiving information (hints, advice, comments, lectures) from other individuals. The latter helps the learner to reach the state \((3, 2)\), which means to acquire knowledge in the Tuning stage and develop skills in the Associative stage by using the target knowledge and cognitive skills during the execution of collaborative activities. Through this visualization a teacher can decide more rapidly which strategy a learner should use to achieve desired benefits.

Note that when using the strategy learning by being taught (first row of Table 2) the initial interactions aim at helping a learner who has a state \((2, 0)\) to reach the state \((2, 1)\). In our example where the learner already has the state \((2, 1)\) these initial interactions do not bring much benefit for him/her. Therefore, in this case the second part of the interaction process is much more important and the teacher can take this information into consideration to give more attention to the learner during that time. However, using the strategy learning by diagnosing the learner needs to complete all the interactions successfully and the support of the teacher is fundamental during the whole process.

6. A model to describe learner’s growth through interactions

The previous section presented a model based on the CL ontology that shows learner’s growth according to specific strategies and theories. It can be quite useful to decide which strategy and theory should be selected to provide the adequate support for learners. Nevertheless, as the reader may notice in Fig. 8, by looking into the path on LGM a teacher can be aware that depending on the students’ conditions some interactions are more important than others. However, with LGM there is no mean to distinguish which set of interactions can provide more benefits for a specific situation. To enable that, there is a need to have a better understanding of the impact of collaboration at a fine-grained level.
6.1. Growth model improved by interaction patterns (GMIP)

To understand collaboration at a fine-grained level, the benefits of each interaction accomplished in a specific scenario should be identified. This task can be done by carefully analyzing the interactions described in each theory and using the ontologies and vocabulary presented in Sections 3 and 4. In particular, the CL scenario concept is key to identify the relationships between interaction patterns and a learner’s growth, because it connects some of the essential concepts that support the design of theory-based CL scenarios.

Thus, by using the CL scenario concept it is possible to establish a path in the LGM through a set of interactions. It clarifies the relationships between interaction patterns, learning strategies, and learning goals at a very fine-grained level. It also helps to make tacit characteristics of learning theories explicit by clarifying expected benefits, use restrictions, and guidelines for leading/performing activities, in addition to other important aspects of the CL processes.

The basic elements in the CL scenario concept used to create the LGM. To explicitly represent the relationship between a learner’s growth and a learner’s interactions we need to connect these elements with interactions that are represented using influential I_L events. Thus, we re-analyzed the theories and mapped the interactions described by different theories into the influential I_L events and explicitly connected the goals of each interaction in terms of l-goals and within a context of a $\chi < l$-goal.

Table 3 shows some influential I_L events used by the Cognitive Apprenticeship theory (CA) and the Anchored Instruction theory (AI); along with the expected benefits for learner-instructors (learners playing the role of instructor and following an instructional strategy) and learners (following a learning strategy).

It is also worth pointing out that, in spite of the fact that each influential I_L event has one main objective for each learning theory, the same influential I_L event may have different learning purposes according to theories; and, for this reason, may have different actions and/or different expected benefits. This happens because each theory is looking to help the learner regarding the different states of knowledge and the different states of skill development, by using different learning resources. For example, although the influential I_L event “Setting

<table>
<thead>
<tr>
<th>ID</th>
<th>Influential I_L events</th>
<th>Event (instructor/learner)</th>
<th>Theory</th>
<th>Expected benefits (l-goal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Affirmative reaction</td>
<td>Acceptance/understanding</td>
<td>CA</td>
<td>s(3, 2) → s(4, 2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AI</td>
<td>s(2, y) → s(3, y), y = 1, 2</td>
</tr>
<tr>
<td>3</td>
<td>Clarify the problem</td>
<td>Identifying learner’s problem/externalization of problem</td>
<td>CA</td>
<td>s(3, 2) → s(4, 2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AI</td>
<td>s(2, y) → s(3, y), y = 1, 2</td>
</tr>
<tr>
<td>2</td>
<td>Demonstration of how to solve a problem</td>
<td>Demonstration/observing demonstration</td>
<td>CA</td>
<td>s(3, 2) → s(4, 2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AI</td>
<td>s(2, y) → s(3, y), y = 1, 2</td>
</tr>
<tr>
<td>6</td>
<td>Instigating thinking</td>
<td>Argumentation/analyzing arguments</td>
<td>CA</td>
<td>s(3, 2) → s(4, 2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AI</td>
<td>s(2, y) → s(3, y), y = 1, 2</td>
</tr>
<tr>
<td>10</td>
<td>Instigating discussion</td>
<td>Requesting opinion/exposing opinion</td>
<td>CA</td>
<td>s(3, 2) → s(4, 2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AI</td>
<td>s(2, y) → s(3, y), y = 1, 2</td>
</tr>
<tr>
<td>4</td>
<td>Monitoring</td>
<td>Checking/carrying out a task</td>
<td>CA</td>
<td>s(3, 2) → s(4, 2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AI</td>
<td>s(2, y) → s(3, y), y = 1, 2</td>
</tr>
<tr>
<td>5</td>
<td>Notifying how the learner is</td>
<td>Giving information/processing information</td>
<td>CA</td>
<td>s(3, 2) → s(4, 2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AI</td>
<td>s(2, y) → s(3, y), y = 1, 2</td>
</tr>
<tr>
<td>7</td>
<td>Requesting problems’ details</td>
<td>Asking about problematic understanding/pointing out problematic understanding</td>
<td>CA</td>
<td>s(3, 2) → s(4, 2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AI</td>
<td>s(2, y) → s(3, y), y = 1, 2</td>
</tr>
<tr>
<td>1</td>
<td>Setting up learning context</td>
<td>Set information context/contextualization of information</td>
<td>CA</td>
<td>s(3, 2) → s(4, 2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AI</td>
<td>s(2, y) → s(3, y), y = 1, 2</td>
</tr>
<tr>
<td>8</td>
<td>Showing a solution</td>
<td>Explanation/understanding explanation</td>
<td>CA</td>
<td>s(3, 2) → s(4, 2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AI</td>
<td>s(2, y) → s(3, y), y = 1, 2</td>
</tr>
</tbody>
</table>

Table 4
Skill development template used to represent the skill to manipulate a drawing tool. The phrases in bold are the variables where domain-specific skills can fit; all the other phrases come from the definitions provided by Anderson (1982).

<table>
<thead>
<tr>
<th>Stage name</th>
<th>GMIP</th>
<th>Template definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nothing</td>
<td></td>
<td>Does not have the desired skills</td>
</tr>
<tr>
<td>Rough-cognitive stage</td>
<td></td>
<td>Involves an initial encoding of the skill to manipulate a drawing tool into a form that is not sufficient for us to generate the desired behavior, usually by observing a process in which another person manipulates a drawing tool</td>
</tr>
<tr>
<td>Explanatory-cognitive stage</td>
<td></td>
<td>Encodes the skill to manipulate a drawing tool into a form sufficient to permit a learner to somewhat manipulate the drawing tool</td>
</tr>
<tr>
<td>Associative stage</td>
<td></td>
<td>Tunes the skill to manipulate a drawing tool through practice. Errors in the initial understanding of the skill are gradually detected and eliminated</td>
</tr>
<tr>
<td>Autonomous stage</td>
<td></td>
<td>Demonstrates gradual continued improvements in the performance of the skill to manipulate a drawing tool</td>
</tr>
</tbody>
</table>

"up the learning context" is used to contextualize the learner to improve their understanding of the content, as we see in Table 3, in the context of Anchored Instruction we expect learners to acquire some content-specific knowledge; and in the context of Cognitive Apprenticeship we expect learners to develop certain skills. Thus, it is possible to separate the information about the goal of the interaction from the information about how to achieve the goal.

Using the CL scenario concept shown in Fig. 5 and the findings presented in Table 3, a connection between the interactions and their benefits in the context of different learning theories can be found. Thereby, we can achieve a fine-grained understanding of the impact of interactions in the learner’s growth. Furthermore, it is also possible to offer a better model to represent a learner’s growth in terms of interactions, and to support the CL design based on it. To create such a model, the concepts of each analyzed theory were represented using the structure in Fig. 5. Through this process, a common framework and vocabulary can be used to clarify which sequence of interactions help learners to develop their knowledge/skills, and consequently, changing their learning stage. Thus, a formal description of the learning process through a sequence of CL activities can be proposed.

Based on these results we augment the LGM by adding to each edge of the model the set of interactions that helps the transition between stages. To give an example, Fig. 9 shows the part of the ontology that represents the Cognitive Apprenticeship theory, where some of the interactions, their impact on learners’ development, and their connection with the LGM are shown.

In this example, Fig. 9a shows the strategy learning by apprenticeship, where the learners who play the role of apprentice are the main focus, and the learner who plays the role of master supports the learning development of his/her apprentices. Moreover, this portion of the ontology represents the expected benefits (I-goals) that this kind of strategy offers to learners who act as apprentices. The apprentices usually start from stage s(0, y), which means they can possess knowledge in different stages, but their skills are at the initial stage.

Through the execution of CL activities based on Cognitive Apprenticeship, apprentices can develop their skills up to the associative stage s(3, y). This development is represented as a path on the learner’s growth model which is shown in Fig. 9c. Each interaction activity is represented as influential I_L events, as shown in Fig. 9b. These events explicitly show instructional events, learning events, and the educational benefits of these events in the learners’ development. In Fig. 9b the interaction pattern starts with Setting up learning context, which helps an apprentice to acquire cognitive skills in the rough-cognitive stage. This benefit supports the transition from stage s(0, 0) to stage s(1, 0); which is shown by the dashed arrows connecting a transition in LGM with a specific interaction in the CL ontology.

Based on our ontology, the LGM, and the interaction patterns, we propose the Growth Model Improved by Interaction Patterns (G-MIP), which offers the following:

- An explicit representation of typical interactions based on learning theories;
- A simplified way to represent the learner’s growth (knowledge acquisition and skill development) based on interactions.

This model is an extension of the learner’s growth model, where each edge is associated with a specific set of influential I_L events (interactions inspired by learning theories) that facilitate the transitions between stages. Fig. 10 shows the G-MIP for the strategy learning by apprenticeship in the context of the theory of Cognitive Apprenticeship. The bold arrows represent transitions from one stage to another, which is facilitated through this learning strategy using the linked interactions. There are two kinds of interactions: (1) the necessary interactions, represented by black circles and (2) the desired interactions, represented by white circles. The interactions are linked by ellipses. The dashed ellipse represents a directed link between two interactions (I_L events); and the solid ellipse represents a non-directed link between two interactions (I_L events). The number (ID) in each circle refers to an interaction in the CL Ontology. The circles and the ellipses that surround them are a simplified way of representing the interaction pattern that appears in Fig. 3.
With the interactions linked with the path of learning development, it is easier to identify how much benefit a learner can gain by following the CL process. For example, in the context of the Cognitive Apprenticeship shown in Fig. 10, the influential IL events “1: Setting up the learning context,” “2: Demonstration how to solve a problem,” and “3: Clarify the problem” are events to facilitate learners who do not have any cognitive skill ($s(0, y)$), to attain some cognitive skills in the rough-cognitive stage ($s(1, y)$). The events “2: Demonstration how to solve a problem” and “3: Clarify the problem,” together with “4: Monitoring,” “5: Notifying how the learner is,” and “6: Instigating thinking” also facilitates learners with cognitive skills in the rough-cognitive stage ($s(1, y)$), to achieve the explanatory cognitive stage ($s(2, y)$), and so on for the other stages.

The main contributions of our proposed GMIP are to identify the relationships among interactions and a learner’s growth, to explain a path in the learner’s growth model through a set of events, and to offer a formal representation to unify interaction patterns and the learner’s growth model.

GMIP clarifies, more precisely, how interactions can affect a learner’s development, facilitating CL design/analysis and group formation based on goals and events. Thus, it becomes a powerful tool helping designers to select events (interactions) and roles for each learner, based on interaction patterns and learning strategies appropriate for desired learning goals (and vice versa). Furthermore, it is possible to offer new alternatives for designing, guiding, and analyzing CL sessions. For example: for each achieved sub-goal (a stage in the middle of the path in GMIP), a teacher can “intervene” in the CL session, guiding learners or analyzing the learning outcomes obtained thus far. This is in contrast to making adjustments after the session has ended, as usually happens in CL sessions which do not have strong technological and pedagogical support. It should be noted that we are not trying to say that it is possible to intervene in real time. What we are emphasizing is the possibility of splitting the collaborative process into several stages (sub-goals), facilitating the teacher’s intervention after each stage.

6.2. Merging strategies using GMIP

An intriguing feature of GMIP that deserves some mention is the possibility of blending learning strategies. Because each strategy is intrinsically represented as paths on the GMIP graph, we can find common points (stages) between strategies, and thus, provide guidelines to blend learning theories by “linking” two or more strategies from different theories to achieve a desired goal. The blend of strategies from theories during the design process enables designers to choose one strategy that leads learners to obtain certain benefits, and then later...
change to another strategy to obtain other benefits which the first strategy could not offer. The authors are not trying to say that it is possible to blend every strategy and every theory; the argument here is: if we deeply understand the theories and provide formal methods to represent them explicitly, it is possible to identify common points among theories and then propose techniques to blend them rationally.

To blend learning theories for CL is a challenging task. To give an example of how to use the GMIP to blend strategies let us propose the following problem: In a group, the desired goal of learner \( L_A \), who does not have any content-specific knowledge or skills, \( s(0, 0) \), is to attain skills in associative level and content-specific knowledge in accretion level, \( s(3, 1) \). Considering how can we design a collaborative learning session, supported by the theories, to help him?

To solve such a problem, first, it is necessary to choose a theory and a strategy that will lead the learner from \( s(0, 0) \) to \( s(3, 1) \) and after propose activities in agreement with it. To choose a theory/strategy, on Table 2 we show six learning theories, their strategies, roles, and their respective paths in the GMIP graph. By using only a single theory in Table 2 it is impossible to help the learner \( L_1 \) to achieve the desired goal \( s(3, 1) \).

Using the GMIP and the idea of blending strategies, to achieve \( s(3, 1) \) from \( s(0, 0) \) we can combine learning strategies to develop skills and acquire some knowledge. As shown on Table 2, there are four learning strategies that initiate from \( s(0, 0) \): learning by being taught (used by Anchored Instruction and by Peer Tutoring), learning by apprenticeship (used by Cognitive Apprenticeship) and learning by practice (used by LPP). Nevertheless, none of them have a direct path to the desired goal \( s(3, 1) \). In such a situation, one strategy can be initially chosen and then be combined with another strategy to cover its lack.

Fig. 11 shows one possible solution using initially the theory Anchored Instruction and the strategy learning by being taught and after moving to the theory Cognitive Apprenticeship and the strategy learning by apprenticeship. Thus, for this example we blended at the macro-level (learning path level) the strategies learning by apprenticeship (solid arrows in Fig. 11) and learning by being taught (dashed arrows in Fig. 11) to find a path from \( s(0, 0) \) to \( s(3, 1) \). This solution provides four possible paths labelled as A–D, to achieve the goal (bottom of Fig. 11).

As a result of blending these two strategies (Fig. 11), in compliance with the GMIP, the bottom of Fig. 12 shows at the micro-level (interaction level) the suggested sequence of interactions that intends to help the learner \( L_A \) to achieve \( s(3, 1) \) from \( s(0, 0) \) supported by Cognitive Apprenticeship and Anchored Instruction. The bold-dotted arrows labelled (A)–(D) in Fig. 12, have their correspondent in Fig. 11, and show where the set of interactions inside of the gray box \( AI \) (top of Fig. 12–1) should be placed in the sequence of interactions of Cognitive Apprenticeship.
Apprenticeship (center of Fig. 12-2) to solve the problem. The gray box labelled AI is the set of interactions provided by Anchored Instruction which eventually helps the learner who plays the role of anchored holder to acquire some content-specific knowledge in accretion stage, s(x, 1), using the strategy learning by being taught. This set of interactions supports the interactions provided by Cognitive Apprenticeship, which helps the learner who plays the role of apprenticeship to develop some skills in the associative stage, s(3, y), using the strategy learning by apprenticeship. The bottom of Fig. 12 also shows in more detail how the CL scenario can be designed in agreements to these theories having in focus a particular learner. Thus, the learner LA can eventually acquire the desired benefits s(3, 1) during a CL session by adopting the suggested sequence of interactions as shown in the bottom of Fig. 12.

It is worth to point out that to completely realize blended learning for CL it is necessary to consider the relationships among many assumptions described by theories (for instance, context, delivery methods, learning preferences, etc.), besides the synergy among learners in a group. However, this thesis does not tackle this problem. It is our intention for future research to include a deeper study demonstrating some examples and possibilities to blend learning strategies semi-automatically. Other works such as Hernandez-Leo et al. (2006) have also shown some possibilities to blend CL techniques during the design of CL scenarios.

The main contributions of GMIP for CL design are summarized as follows:

- To make some tacit characteristics of learning theories explicit.
- To identify the relationships among interactions, strategies, and goals.
- To offer an explicit visualization of learning strategies and their characteristics; consequently, users can quickly understand their benefits and propose a sequence of activities which is in compliance with them which preserves the consistency of the learning process and guarantees a suitable path for learners to achieve desired benefits.
- To enable new ways of dealing with many pedagogies and their strategies which facilitates the designing of CL activities using blended strategies.
- Finally, to be strongly connected with the CL ontology allowing for systems to conduct reasoning on concepts from theories (actions, roles, strategies). Thus, it is possible to propose new alternatives interfaces for intelligent guidance where an authoring system can offer pedagogically-sound and well-thought-out suggestions for users during the CL designing processes.

7. Towards an theory-aware authoring tool for CSCL

As we mentioned throughout this paper, to design an effective and pedagogically sound CL scenario, a teacher can rely on learning theories such as Anchored Instruction or Peer Tutoring to assist with the assignment of roles, selection of learning activities, definition of learning strategies, formation of groups, and so on. Besides that, to select an appropriate learning theory it is necessary to consider learners’ conditions (e.g., previous knowledge/skills and behavior), the learning goals, and other variables that may influence and promote good interactions among group members.
This flexibility in the choice of different learning theories, and in the consideration of different variables, can therefore provide us with a wide range of options for designing and conducting CL processes. However, it also suggests the difficulty of selecting an appropriate set of learning theories during the instructional design process, to ensure learners’ benefits and the consistency of the learning processes.

Thus, to help users design CL scenarios based on learning theories, we need an elaborate authoring system. While the number of technologies that support collaboration have increased considerably over the past decades (Soller, Martínez-Monés, Jermann, & Muehlenbrock, 2005), only a few educational authoring systems have been developed to deal with multiple theories (Mizoguchi et al., 2007). As wisely pointed out by Laurillard (2009), the technology itself does not support good CL environments. Creating or using mechanisms for collaboration without pedagogical considerations does not necessarily improve learning outcomes and may possibly harm learners’ development.

One of the reasons for the limited number of tools that are “aware” of pedagogies (e.g., learning theories) is due to the difficulty of representing pedagogical knowledge and principles in a computer-understandable way. Because of this, none of the available authoring systems for CL has the desired functionality to retrieve appropriate learning theories for selecting collaborative methodologies that “match” a specific situation, or to provide pedagogical principles, based on multiple theories, for structuring collaborative learning environments. In this direction, the results presented in the previous sections enable us to create models that will serve as the pedagogical knowledge that are formally represented as ontologies to build the so-called “theory-aware” systems which can help teachers/designers to structure learning materials compliant with instructional and learning theories and guide learners to perform collaborative learning more effectively.

To exemplify the benefits of our approach, we have been developing a theory-aware authoring tool for CL called CHOCOLATO – a Concrete and Helpful Ontology-aware Collaborative Learning Authoring Tool. To allow for the application of multiple theories during the authoring process, CHOCOLATO uses the CL ontology, GMIP to:

- Prevents unexpected interpretations of the theories while designing CL scenarios.
- Provides common vocabulary to describe these scenarios.
- Offers enough information for computational semantics to allow for “intelligent” guidance with theoretical justifications during the authoring process.

CHOCOLATO aims at assisting both novice and expert users. For example, during the design process for novice users, the tool provides structured guidance in relation to the different learning theories. Through an authoring interface it allows users to set initial conditions and goals for a learner (or a group). Then the system automatically recommends the theories, strategies, roles, and activities to be performed by learners in order to achieve the desired goals. Furthermore, users can customize the recommendations in order to satisfy specific requirements related to particular situations.

For expert users, CHOCOLATO offers a common language and guidelines to formally express CL scenarios, the interaction flows, learners’ roles and strategies, and the benefits for learners. Thus, it is possible to describe new strategies and roles for learners, to reuse and share them, and instantiate sequence of interactions to suit different situations.

The basic architecture of CHOCOLATO is represented in Fig. 13. It is composed of different sub-systems that aim to support different levels of guidance during (a) group formation, (b) the design of CL activities, (c) the recommendation of learning materials, (d) the analysis of individual and group outcomes, and (e) the identification of a learner’s stage of development. The aim is to support the design of CL sessions based on learners’ conditions, desires, and requirements. All of the sub-systems of CHOCOLATO are empowered with ontologies to support their reasoning.

It is worth pointing out that, if the initial scenario of a CL session is established before the real interactions take place, it is easier to analyze (quantitatively and qualitatively) how much benefit was attained by the learners. By comparing the initial scenario with real interaction data, we can assess whether the learners interacted as expected and whether the CL session was successful or not. Finally, with the results of this comparison, it is possible to support users to create better CL scenarios afterwards. Therefore, although CHOCOLATO is an authoring tool, it has some potential to analyze interactions in its architecture.

In the next section, a prototype that uses CHOCOLATO architecture will be presented. The main idea behind their development has been to show the possibilities of using the CL ontology and GMIP to create computational programs that can help users design theory-based CL scenarios. The description of the prototype will concentrate on the CL design support system through the use of GMIP and the result of an experiment with teachers during the creating of a geometry drawing course.

**Fig. 13. Architecture of CHOCOLATO.**
7.1. MARI: a prototype of a theory-aware authoring tool

The first prototype developed to follow the CHOCOLATO architecture was **MARI – Main Adaptive Representation Interface**. It focuses on the design process in order to help teachers to produce effective CL scenarios. MARI is an ontology-aware system that uses ontologies developed in the HOZO ontology editor (http://www.hozo.jp) to provide its theoretical knowledge and to represent them on the screen using the GMIP. Through the use of ontologies, MARI allows a high degree of expression and interoperability between theories and their features. Currently, MARI works with the eight learning theories represented in the CL ontology (see Section 3.3). MARI has been developed in Java (http://java.sun.com) and to treat ontologies it uses the HOZO API.

Initially, MARI starts with a neutral network that can show any theory represented in the CL ontology as a path on GMIP (bottom left of Fig. 14). A useful function that helps during the CL design process is that given the learner’s conditions, the program automatically searches for theories that facilitate his/her development. Thus, in MARI a user can select the initial stage of a learner using GMIP graphical representation. This selection will be transformed into a constraint and MARI will start the reasoning process by searching for concepts in the ontology to identify whether there are theories and strategies that match such a constraint.

In the particular case where the user selects the initial stage of a learner, such a selection will be mapped into the learner’s initial conditions that are represented as knowledge/cognitive states in the CL ontology. As introduced in Section 4, the I-role concept shows the minimum conditions for a learner to play a role in a given scenario (Fig. 14a). Thus, I-role expresses the initial conditions of a learner in the beginning of the CL process. Then, MARI will check in the CL scenario concept to verify if there is an I-role where the necessary and desired conditions match with the constraints given by the user (Fig. 14b). In GMIP such a search is equivalent to find a path on the graph where the selected node is the starting point of the path. In addition to the search by initial stage, a user can search by selecting a goal stage (a node at the end of a path in GMIP) or sub-goal stages (node within a path in GMIP). In such cases, MARI will transform these selections into I-goals that the CL scenario must satisfy (Fig. 14c).

The initial stage and the goal stage presented in Fig. 14 can be any stage in the graph allowing users to select specific learners’ pre-conditions and design activities to achieve intended learning outcomes. Thus, MARI can recommend theories and strategies that help a learner in a specific condition to acquire the desired educational benefits. Furthermore, when MARI finds more than one theory and strategy that can support a learner, it shows on the bottom of the window a table where users can visualize and choose a theory/strategy; and thus, it enables users to decide which theories are more appropriate to help them.

Fig. 15 shows a search for a theory-based CL scenario where the initial stage of a learner is \((0, 0)\) – no knowledge or skills; and, the goal stage is \((3, 0)\) – develop skills in associate stage. This search returns two solutions. The first solution is to use a CL scenario based on Cognitive Apprenticeship where the learner will play the role of apprentice and follow the strategy learning by apprenticeship (left of Fig. 15).

![Fig. 14. Example of the interface of MARI and its connection with concepts of the CL ontology.](image-url)
The second solution is to use a CL scenario based on LPP where the learner will play the peripheral participant role and follow the strategy learning by practice (right of Fig. 15).

In this interesting situation the user (teacher) can realize that Cognitive Apprenticeship has two sub-goals while LPP has only one. This means that the cognitive load in LPP is higher than in Cognitive Apprenticeship; and therefore, LPP is more suitable for learners with strong cognitive capabilities (or if the teacher needs to speed up the CL process) while Cognitive Apprenticeship is better to provide support for novice learners during the CL process as a whole, especially when the restriction of time is not an issue.

Another interesting function of MARI is the presentation of interaction patterns. When the user selects a strategy from a theory (Fig. 16), the system automatically shows the path in GMIP at the top of the window; and at the bottom, it shows the sequence of interactions prescribed by the selected theory to help learners move from the beginning of the path (initial conditions) to the end of it (learning goals). The GMIP at the top and the interaction patterns at the bottom are connected through the ontologies. Thus, by clicking on one of the edges of the path in GMIP, MARI automatically identifies the specific interactions related to it, emphasizing these interactions (changing the color) at the bottom of the window.

The process of creating the path on the graph and linking each edge to interactions is completely supported by the CL ontology. Fig. 16 shows part of the ontology and a screenshot of MARI when a user selects the Cognitive Apprenticeship theory and the strategy learning by apprenticeship. The top of the MARI’s interface shows the path in GMIP, and the bottom shows the necessary and complementary interactions as solid boxes and dashed boxes, respectively.

When the user selects one of the edges in GMIP, MARI transforms this action into constraints that the interactions in the CL scenario must satisfy. Fig. 16a gives an example where the user clicked in the first edge of a path. This action is transformed into a constraint that can be satisfied only by the interactions that help the apprentice to move from s(0, 1) to s(1, 1). Thus, MARI will check in the ontology to verify if within the interaction pattern of the selected theory there are interactions that satisfy the constraint. In the example, three interactions satisfy the constraint and have their color changed (Fig. 16b): “setting up learning context,” “demonstration how to solve a problem,” and “clarify the problem.” Such functionality is very helpful when teachers need to focus in particular deficiencies of learners and choose appropriate interactions to overcome them. Furthermore, each box of the interaction pattern provides other information that can be obtained from the ontology. Fig. 16c shows additional information that could be presented to users to facilitate the design of theory-based CL scenarios. The interaction pattern shown in Fig. 16b is a simplified version of the Fig. 3.

The suggestions given by our system are guidelines for users to propose theory-based CL scenarios which (a) preserve the consistency of the learning process and (b) guarantee a suitable path for learners to achieve desired benefits. However, expert designers do not need to follow the suggestions. They can propose their own path on GMIP and their own sequence of activities. In these cases the ontology can assist expert users providing a framework to describe their knowledge. The ontology can also provide different kinds of information about theories, activities, strategies, learner’s roles, and other related information that can be useful for defining new CL scenarios.

Finally, as we discussed in Section 6.2, through the use of GMIP, ontologies, and a systematic approach to the designing of CL scenarios, MARI has the potential to blend learning strategies from different theories. MARI can reason on GMIP and ontologies to find common points (stages) between the strategies; and thus, provide guidelines to blend them by “linking” two or more strategies from different theories to achieve a desired goal. Thus, when a teacher needs to help students achieve a goal that is not “achievable” using a single theory/strategy, the system could semi-automatically suggest a new sequence of CL activities based on more than one theory. To complete such functionality MARI needs to check the viability of blending strategies, the consistency of the learning processes, and the difficulty of changing from one strategy to another, besides many other factors. The current version of MARI cannot do all necessary verifications; however, it offers some support for teachers to blend strategies.

8. Experimental use of MARI

The objective of the experiment with MARI was to check its usefulness to design CL scenarios. Thus, the description presented in this section will focus on the designing process using MARI rather than on the students’ evaluation. We tested MARI with four teachers and their assistants during the designing of CL scenarios for a geometry drawing course with about 50 students. In a geometry drawing course...
supported by technology students learn geometric concepts and their utilization for drawing geometric figures through the use of interactive (dynamic) geometry systems.

An interactive geometry system is an alternative to the traditional geometry, which makes use of a ruler and compass and produces static constructions. In the traditional way of teaching geometry, if the student, after having accomplished a construction, wants to analyze the same construction using some of the objects in another disposition, he needs to repeat (rebuild) the entire construction. However, using an interactive geometry system, objects can be freely moved over the screen, maintaining all the constraints and properties established initially in the construction. Interactive geometry systems have proved to be an excellent resource for teachers and students (Moura et al., 2007; Ruthven et al., 2008). Fig. 17 shows the construction of a median line between the points A and B. Note that the arrangement of the points in the screen does not affect the properties of the construction (distance between the point A and line r is the same as the distance between point B and line r).

Usually, the philosophy of a geometry drawing course that utilizes an interactive geometry system is to “learn by doing”, which means that teachers avoid as much as possible writing the concepts on a blackboard. Instead, they stimulate students with interesting, interactive exercises that help them to learn the desired content or skills including drawing objects, making conjectures, applying geometric definitions, and so on.

8.1. An interactive geometry system: iGeom

To create exercises (learning objects) for this experiment we used an interactive geometry system referred to as iGeom (Isotani & Brando, 2008). This program is a complete multi-platform interactive geometry system that has been in development at the Institute of Math-
demonstrate his/her statement to prove its validity with several examples (or counterexamples). Constructions of squares and rectangles, he/she can generalize and state: ‘most important skills are related to making conjectures and inferences to generalize particular concepts. For example, a learner can specialize names, for example triangles where all sides have the same size are classified as equilateral triangles. and same plan), and the angle of the intersection between each other. Another possible definition can be stated as follows: given two lines can be defined (in the Euclidean geometry) as lines that are in the same plan being equidistant everywhere and will never intersecting skills to manipulate these definitions the easier is to create geometric objects with the expected properties. For example, parallel lines can be defined (in the Euclidean geometry) as lines that are in the same plan being equidistant everywhere and will never intersecting each other. Another possible definition can be stated as follows: given two lines \( s \) and \( r \), if both lines are intersected by a third line \( t \) (in the same plan), and the angle of the intersection between \( s \) and \( t \) have the same value of the angle of the intersection between \( r \) and \( t \), then \( s \) and \( r \) are parallels.

Propose conjectures, generalize concepts and make inferences (e.g., this object is equal to another one because \( \ldots \)). In geometry, some of the most important skills are related to making conjectures and inferences to generalize particular concepts. For example, a learner can observe a construction of square to make the following conjecture: “any square is a rectangle.” Then, after observing/manipulating many constructions of squares and rectangles, he/she can generalize and state: “any square is a rectangle, but not vice versa.” Finally, he/she can demonstrate his/her statement to prove its validity with several examples (or counterexamples).

The flexibility of the learning resources and activities in a geometry drawing course is very high, especially because of the utilization of interactive geometry systems and other technologies. Thus, although the main learning goals remain the same, teachers can decide to include or remove new exercises from the curriculum while students are taking the course. One of the goals of the course we have designed is to provide learners with the basic knowledge and skills to accomplish the following:

- **Construct objects** (e.g., an angle, a triangle, and a circle). To create a geometric construction the learner needs knowledge/skill to manipulate the available drawing tools and also about the definition of the construction. For example to construct one of the fractals presented in Fig. 18, a learner needs to know how to produce recursive functions. He/she also needs knowledge about the fundamental construction that generates the fractal and skills to use it to create the fractal.
- **Define objects** (e.g., what is a point, an angle, and a triangle). There are many ways to define a geometric object. The more knowledge and skills to manipulate these definitions the easier is to create geometric objects with the expected properties. For example, parallel lines can be defined (in the Euclidean geometry) as lines that are in the same plan being equidistant everywhere and will never intersecting each other. Another possible definition can be stated as follows: given two lines \( s \) and \( r \), if both lines are intersected by a third line \( t \) (in the same plan), and the angle of the intersection between \( s \) and \( t \) have the same value of the angle of the intersection between \( r \) and \( t \), then \( s \) and \( r \) are parallels.
- **Classify objects according to certain properties** (e.g., whether a triangle is equilateral or isosceles). A geometric object has many properties related to different aspects of the construction. Thus, it is possible to classify objects using different properties. Some classifications have special names, for example triangles where all sides have the same size are classified as equilateral triangles.
- **Check properties** (distances, angles, sides). To classify, define and construct objects correctly, an individual needs to have knowledge and skills to check geometry properties. In the case of triangles, if a learner wants to classify a triangle as equilateral he/she needs to know that what should be measure are the sides of the triangle. Furthermore, he/she should have skills to measure sides of triangles.
- **Propose conjectures, generalize concepts and make inferences** (e.g., this object is equal to another one because \( \ldots \)). In geometry, some of the most important skills are related to making conjectures and inferences to generalize particular concepts. For example, a learner can observe a construction of square to make the following conjecture: “any square is a rectangle.” Then, after observing/manipulating many constructions of squares and rectangles, he/she can generalize and state: “any square is a rectangle, but not vice versa.” Finally, he/she can demonstrate his/her statement to prove its validity with several examples (or counterexamples).

![Fig. 18. Interface of iGeom with examples of fractal constructions.](http://www.matematica.br/igeom)
In our experiment, we utilized MARI during a semester to create activities that uses collaborative learning to support the development of the knowledge/skills related to the topics presented above.

Because MARI is based on ontologies that are completely domain-independent, it is necessary to link the domain-specific content related to the course into the CL ontology and GMIP. To accomplish that, the knowledge and the skills involved in each general learning goal presented above (e.g., construct objects) needs to be separated from each other. Furthermore, the knowledge to achieve the learning goal should be decomposed into smaller “pieces” of knowledge (sub-goals) that need to be acquired. Similarly, the skills should be decomposed into skills of more fine-grain size (sub-skills). The resulting structure will be a decomposition tree. A simplified example of a tree that identifies the knowledge and skills necessary to construct a geometric object is shown in Fig. 19.

The granularity of the decomposition tree depends on the learning goals and the expertise of the person who performs the decomposition. After the tree is created, it is necessary to explicitly identify the relationship of the knowledge and the skills in the tree, as shown by the dotted line in Fig. 19. Each skill can be related to one or more pieces of knowledge, and vice versa. Thus, for each relationship between knowledge and skill identified, an instantiated GMIP will be created. Such a domain-dependent GMIP can support the development of knowledge and skills in the specific domain.

It is worth noting that our decomposition tree is different from those proposed by Gagne, Briggs, and Wager (1992) and Hayashi et al. (2006). While those studies provide decomposition trees that represent instructional design plans, our trees represent the knowledge and skills to be developed, without any reference to how this development will occur.

By using this approach (GMIP instantiated using a decomposition tree), we can separate information about the content from the information about how to learn the content. Such differentiation is important when we think about developing learner-centered (or group-centered) environments which can provide different ways to teach/learn the same content (Isotani & Mizoguchi, 2008b).

Finally, for each linked knowledge/skill in the decomposition tree, it is necessary to identify how the development process occurs according to the stages in GMIP. To facilitate such a task, we provide templates that use a summarized definition of the stages of knowledge and skills. These templates help users to adequately understand the knowledge and skill development process. Furthermore, they help us to create a support system that semi-automatically maps specific skills/knowledge into our model GMIP. An example of the template for skill development instantiated for the example in Fig. 19 (to manipulate drawing tools) is shown in Table 4. The template uses the definition of stages of skills development proposed by Anderson (1982). $\ddagger_1$ and $\ddagger_2$ are variable that can be changed by phrases related to the domain-specific skills.

Through this process, decomposition trees that explicitly identify the knowledge and skills which need to be acquired during the geometry drawing course were created. Then, using the templates we provided, it was possible to map the desired knowledge and skills into our GMIP model and, consequently, to our ontologies.

Finally, users can link appropriate learning resources (exercises, texts, activities, animations, and others) with the instantiated concepts in the GMIP. In our example, about 70 learning objects were created and linked with the respective knowledge and skills as shown in Fig. 20. Thus, on one hand, we have a very powerful and sharable knowledge-base that can be applied in many different situations to support the authoring of CL scenarios, with the corresponding theoretical justifications. On the other hand, we have learning objects related to the domain connected with the proper theoretical foundations to support well-designed CL sessions through the use of technology. Thus, teachers could rely on our structure to design and conduct CL activities more easily.

The experiment consisted of asking teachers to form pairs of students to work together during the resolution of geometric exercises. The current stages of learners’ development (knowledge/skills) were evaluated by teachers. Thus, the objective of the experiment was to verify if teachers could use this information adequately to conduct CL activities and if MARI could help them to propose CL scenarios with pedagogical justifications. The duration of the experiment was about one semester long. According to teachers, the proposed framework helps them in many situations during the design of CL scenarios. Following is an introduction of two of these situations where our system facil-

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**Fig. 19.** Example of a decomposition tree which separates knowledge and skills to construct a geometric object.

Itated the selection of important pedagogical strategies that positively influenced the way the groups were formed and the implementation of the CL activities in the classroom.

In our experiments, one of the most common mistakes that occurred during the introduction of peer tutoring activities in the classroom was related to group formation. When novice teachers started to form groups without any support from our system, the heuristic approach that they commonly used was as follows: “peer tutoring requires a tutor and at least one tutee per group; therefore, the formation of the groups will occur by joining the best student (or highest-achieving student) with the worst student (or lowest-achieving student) in the class, followed by the second best student with the second worst student, and so on.”

The overall explanation for this heuristic approach was that the best student would have more knowledge/skills and thus be better equipped to help the weaker student. Although this argument sounds reasonable, the work of Isotani et al. (2009) shows that such an approach often fails to create good learning results. One of the reasons is that advanced learners frequently understand the content very quickly and cannot comprehend why their peers cannot follow their pace after some guidance.

In this situation, both learners (i.e., the tutor and tutee) feel stressed and unmotivated to work collaboratively. Endlsey (1980) suggested in his book that if peer tutoring is not adequately structured, the desired learning gains will likely decrease. According to him, group formation and explicit determination of learning goals are the first two steps to be considered when establishing a peer tutorial system. Indeed, neither can be neglected.

To support the preparation of peer tutoring scenarios, novice teachers relied on MARI to select the initial stages and the goal stages for their learners. Based on this, MARI uses the available information about the domain and concepts in the ontology to recommend group formation and interaction patterns that support group learning with the corresponding theoretical justifications. Thus, teachers successfully learned how to adequately use peer tutoring and form better groups. They also understood the reason why their heuristic approach (i.e., group the best student with the worst student) should not be used in peer tutoring groups.

The reason why their heuristic approach has given poor learning results is because the tutor also should learn something when interacting with his/her peer. Thus, although the tutor always needs to have more knowledge than the tutee, in reality, the best situation occurs when the tutor has sufficient knowledge to complete the activity but still encounters some difficulties in completing it while the tutee does not have enough knowledge to complete the activity. Thus, during the process of solving the activity, both tutor and tutee are able to understand each other, work better as a group, and attain some educational benefits.

Another interesting situation occurred during the tasks of structuring learning resources (also known as learning objects – LO), identifying learners’ misunderstandings, and conducting CL activities. During a CL session, teachers usually give the same materials and run the same activities for all groups. This means that any material or CL activity that is proposed by teachers must support the learning of all learners without considering that “advanced” learners (i.e., students with satisfactorily skills/knowledge about the content) and also “poor” learners (i.e., students with a lack of skills/knowledge about the content or with some misunderstanding that must be carefully considered) can occupy the same classroom.
In fact, in our experiments, we experienced many cases in which some groups could finish all tasks quickly while other groups could not solve a single task. In the latter case (i.e., learners could not finish the task in the given amount of time), the teacher had to complete it for them in order to proceed with the other learning activities. According to Webb, Nemer, and Ing (2006), this teaching practice neither helps learners to learn nor supports learners to change their behavior in order to work better in groups. On one hand, the learners who finished their tasks rapidly felt that the CL activities were a waste of time. Conversely, the learners who could not complete the tasks felt that the teacher did not give them enough support.

To cope with the problem of conducting similar activities independently of the individuals in the group, MARI does not allow teachers to propose the same activities for all formed groups. Due to the fact that teachers must input information about learners in the system such as learners’ stages of development, MARI can identify good group formations and suggest learning materials and activities that can help a specific group to achieve its desired learning goals. Thus, depending on the learners’ conditions the activities will differ from group to group.

Using the example of groups formed for peer tutoring, when the tutor and tutee are both advanced learners, then the system would recommend highly interactive activities that compel learners to explore the content to achieve a better understanding of it. For example, in geometric drawing, the activities in which learners need to manipulate objects and explore solutions in an interactive way have been very effective in helping advanced learners to obtain a better degree of understanding about geometric concepts (Isotani & Brandao, 2008). However, for groups in which the tutor or the tutee is not an advanced learner, the system would recommend guided tasks that help them to identify and overcome their misunderstandings about the content.

Teachers who used our framework and our system commented that:

- They were able to interchange their created CL scenarios more easily.
- The interaction patterns offered good recommendations during the design of CL activities.
- The recommendation given by the CL ontology, including the theoretical justifications, helped them to identify some essential characteristics that compose a well-thought-out CL scenario.
- The information provided was successfully used to propose real activities.

In summary, the development of MARI and its use to design CL scenarios in a domain-dependent situation help us to demonstrate how our ontological framework allows for the development of theory-aware systems that support users (teachers/instructors) to propose CL scenarios with strong theoretical justifications. Through MARI’s recommendations, users can more precisely understand how a sequence of activities can affect learners’ development; and how to use other information from different theories to form groups and to design CL scenarios based on learners’ pre-conditions and desired learning goals. Thus, our ontological framework plays a central role in the decision making process about how, when, and why we should use learning theories to form groups that take account of personal and social (group) goals.

9. Conclusions

There is no single recipe to create a watertight (perfect) CL scenarios. However, a designer (e.g., a teacher) has the opportunity to change the settings of the learning environments to create CL activities that are more suitable for his/her purposes and which support more effective learning. The main results of this work rely on the necessity of a more systematic and sophisticated design of CL activities before a learning session starts. To propose pedagogically sound CL scenarios which preserve the consistency of the learning process, and increase the chances that desired benefits are going to be achieved by learners, it is important to have a better understanding of the different theories, their features, and the requirement to apply them. Our approach uses ontologies to clarify the fundamental characteristics of theories and the essential conditions for using them to propose a framework that can facilitate the design of CL scenarios, with corresponding theoretical justifications.

Thus, the main contributions of our work can be divided in three parts. The first and most important contribution has been the development of an ontological structure and a model, referred to as GMIP, that work as a skeleton on which we can represent learning theories and other CL techniques explicitly and formally. This implies that part of the information available to support CL (e.g., learning theories, CL techniques) which are presented in natural language can be partially transformed into a structure that makes tacit characteristics explicit, uses a common vocabulary to describe the same concepts and, finally, can be fully used by computers to open new opportunities for creating innovative systems that offer pedagogical support for teachers and learners.

The second contribution has been an attempt to provide substantial support for designing CL activities. Currently, although a few systems have the capability to support the authoring of CL activities using scripts (e.g., Collage (Hernandez-Leo et al., 2006)), we have not seen authoring tools that support intelligent guidance during the authoring process such as checking the consistency of designed CL processes or verifying if a set of CL activities really achieved the desired learning goals. In this context, our ontological structure offers a high level of expression that minimizes the problem of representing collaborative activities in a formal language, and provides the semantically rich structure required to create computer-understandable CSCL scripts. Thus, it is possible to create intelligent programs that can reason using information that is semantically interconnected (such us interactions, roles, and learning development) and provide intelligent support for users to create well-thought-out CL scenarios.

The third contribution is in the context of intelligent educational systems (IES). The use of our ontological structure and GMIP model allow for a declarative and explicit representation of learning theories; facilitating the development of theory-aware systems that offer intelligent guidance for designing CL activities supported by theoretical knowledge. To verify the usability of our framework we have developed MARI, a prototype of an IES to support CL design. MARI is part of a bigger system called CHOCOLATO – a Concrete and Helpful Ontology-aware Collaborative Learning Authoring Tool. With a principled CL design process, MARI creates favorable conditions for learners to perform collaboration, while helping instructors to more easily create/select sequence of activities that support the achievement of learning goals. Through an authoring interface using the GMIP, MARI allows users to set initial conditions and goals for learners. Then, the system can semi-automatically recommend group formation, learning strategies, roles, and sequence of activities (interaction patterns).
to be performed by learners to achieve the desired goals. Furthermore, users can customize the recommendations in order to satisfy requirements related to a particular domain. Through the use of an instantiated GMIP to a particular domain, a user can represent specific domain-dependent problems, connect them with supporting learning objects, and propose CL activities based on well-grounded theoretical knowledge.

We would also like to emphasize the intriguing possibility of blending strategies from different theories by using our model as a feasible and novel solution to deal with the problem of unreachable goals (stages in GMIP where none of the analyzed theories has a path through by itself). Because each strategy is intrinsically represented in the ontology, and as a path on GMIP, we can find common points (stages) between strategies; and thus provide guidelines to blend learning theories by “linking” two or more strategies from different theories to achieve a desired goal. In these cases, during the CL design the system can dynamically suggest for users a set of activities supported by blended theories in order to find a suitable way to lead learners to achieve desired benefits/goals. Our future research will include a more exhaustive study, demonstrating the possibility of blending learning strategies semi-automatically, based on GMIP and ontologies. Furthermore, it is also our intention to map more collaborative learning techniques (best practices) into our framework, providing more options for users to choose the best approach to design CL sessions.

Developing an IES for collaborative learning is especially challenging in view of knowledge representation, because it is based on various learning theories. It is also difficult given the context of group learning where the synergy among the learners’ interactions affect the learning processes; and hence, the learning outcome. Our ultimate goal is to complete the development of CHOCOLATO by bridging the gap between the theoretical understanding of collaborative learning and the practical foundations that support the learning processes.

10. United references

Alfonseca et al. (2006), Barkley et al. (2005), IMS GLC (2003), Romiszowski (1981), Vega-Gorgojo et al. (2005), and Weinberger et al. (2005).

Acknowledgement

We would like to thank Dr. Yusuke Hayashi from Osaka University, Japan, and Mr. Eloy D. Villasclaras-Fernandez from University of Valladolid, Spain, for their helpful comments and suggestions. We also would like to thank the Nippon Foundation, the Association of Nikkei & Japanese Abroad, JICA (Japan International Cooperation Agency), IBM Research and the Department of Knowledge System (MizLab) for their technical and financial support.

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