A multi-agent and emergent approach to learner modelling

Carine Webber[1,2] and **Sylvie Pesty**[1] and **Nicolas Balacheff**[1]

Abstract. User modelling has been a central issue in the development of user-adaptive systems, which behaviour is usually based on the user's preferences, goals, interests and knowledge. This is particularly the case when the user is a student and the system is a computer-based learning environment. The aim of this paper is to present a mechanism for diagnosing and modelling learner's conceptions based on a theoretical model of conceptions. Our approach takes the diagnosis of learner's conceptions as the emergent result of the collective actions of agents sharing an environment, transforming it and as a consequence influencing new actions. We apply techniques from voting theory for group-decision-making. This approach is at the core of the design of a distance learning platform for the learning of geometry.

1 INTRODUCTION

A system can be considered user-adaptive when it is possible to observe changes in its functionality, structure or interface in order to accommodate the different needs of users and their changing needs over time. Adaptability has been an important parameter for characterising and for comparing different systems' behaviours. Usually adaptive systems base their behaviours on user models. The user model may be related to one user or a group of users presenting similar profiles and it represents user's preferences, goals, interests and knowledge. User modelling techniques have been exploited by many applications in different domains [1], namely e-learning, recommendation systems, retrieval assistance, adaptive hypermedia and e-commerce applications.

So far two problems have been associated to user modelling: the identification of the relevant information to be modelled and the decision about which methods to apply in order to acquire the relevant information about the user. This paper is concerned by both problems since our research focuses on modelling conceptions of students in interaction with Baghera, a computer-based learning environment for the learning of elementary geometry, focussing in particular on geometry proofs.

Baghera student's interface for problem solving is shown on figure 1, where the element (a) corresponds to the learner's solution given to the problem described by the statement on (b). The student's solution is a free text. The interface offers some tools to help students when writing proofs like buttons and menus to express propositions and organise them in the text. Besides these tools, students can request the automatic verification of proofs, what is done by a theorem prover agent [2]. Teachers also work with Baghera, where they can propose new problems to students and supervise students' work. More details about Baghera are found at [3].

The model we propose is a computational framework of a theoretical model of representation of learners' conceptions developed in mathematics education. At the moment, this model allows Baghera to have a "picture" of a student when solving a problem. This "picture" can be sent to the teacher, who uses the diagnosis made by the system as a resource to guide her/his teaching strategies. The learner model itself is a collection of these pictures, which describe the behaviour of the student in different learning situations.

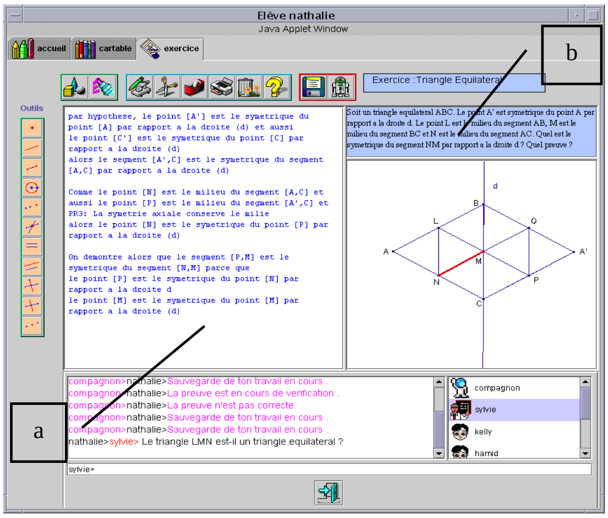

Figure 1. Baghera student's interface.

This paper is organised as follows: the next section presents a brief state of the art of learner modelling. Third and forth sections introduce the educational foundations of this work. The fifth section presents the computational framework we propose. Finally, some conclusions and perspectives are discussed.

2 LEARNER MODELLING

In educational technology, the user model has deserved intensive research effort in the last three decades but, so far, the best method has not been found. The most frequent method initially employed was the method of *overlay* [4]. This method assumes that learner's knowledge is a subset of the expert's knowledge in the domain. Easy to implement, the *overlay* method was unable to give account of the learner's misconceptions in the domain. The first solution to overcome this limitation was to construct *bug libraries*, or databases of misconceptions. Though, such static libraries have very quickly proved to be difficult to construct and to maintain. First machine learning algorithms have overcome limitations of

[1] Laboratoire Leibniz, IMAG, 46 avenue Félix Viallet, 38000 Grenoble, France. http://www-baghera.imag.fr
[2] Scholar of Capes/Cofecub, Brazil.

bug libraries construction and maintenance by inducting bugs from examples of learner's behaviours. Since then, improvements on machine learning techniques have shown some results learning about learners [5,6,7,8].

One origin of the problem of diagnosing student's conception is in the large variety of students' possible conceptions, either correct or not. Indeed anyone in the field can acknowledge the extraordinary capacity of human beings to develop ways of knowings well adapted to certain specific circumstances or environments, but contradicting the current knowledge of reference (ethnosciences are rich of such observations). Up to now, the ways to deal with this issue for the development of learning environments have proved rather limited in their capacity to cope with this problem; at a point where John Self [9] suggested it to be an intractable problem. In fact, one may suggest that even if we had a learner model well adapted to what we know and observe of students current conceptions, any environment based on this model may show severe limits. In fact, in the context of such a learning environment, students are likely to develop significantly new ways of knowings based on the strategies they develop to face the challenge of adapting to the new context. In the early 90's Van Lehn recognised, at the very end of his book on the origin of procedural misconceptions, that "the situation does much more of the work than had previously been thought" [10, p.216]. This is in support of our claim that a way of knowing is not a given, but an emergent property of the interactive system constituted by the learner and his or her environment [11]. The consequence of such a position is that we may not (have better not to) search for an *a priori* learner model, but to look for the model of a process which may allow to build the learner model on the spot depending on the specific circumstances which contextualise the learner. For this purpose, we offer a second claim which is that multi-agent modelling and the emergent approach will be better adapted to such a modelling; better than the dominant approach, essentially that of classical symbolic AI, which is driven by an hypothetico-deductive conception of modelling.

The learner model we propose is a computational framework of a theoretical model of representation of learners' conceptions developed in research in mathematics education. In this paper we present the result of a common effort of computer scientists and researchers in mathematics education to find a possibly new solution to the old problem of learner modelling. For this purpose, researchers from education have contributed with the theoretical model of representation of learners' conceptions, whereas computer scientists have brought the multi-agents methodology. Together we have been trying to answer the following question: is it possible to construct a computational framework of a well-established theoretical model of representation of learners' conceptions? The answer to this question is discussed in this paper: in the next section we introduce the educational foundations of our approach and then we introduce the computational framework to diagnose learner conceptions.

3 EDUCATIONAL FOUNDATIONS

During problem solving activities at school, teachers propose problems to the students, they observe their work and they answer questions when students have doubts. Teachers also ask questions to the students aiming at better understanding their reasoning and difficulties, and then they are able to propose new problems to the class. This process of creating problem situations and interactions is very important for successful learning. Mathematics education is a research field interested in creating such learning situations. Aware that it is not possible to develop a general learning strategy, researchers from this field are particularly interested in creating local solutions for the teaching of specific mathematical content. We give an example of a local solution for the teaching of reflection in geometry.

When teaching reflection, usually teachers start by the metaphor of a mirror. Next, they propose to the students to fold a piece of paper in two parts and to observe each part. Then, after some discussion, they give a problem where students should make use of their mathematical skills. For instance, a teacher could start proposing to students to construct on paper the reflection of a segment with respect to a line of symmetry, and soon increase the complexity of problems. As long as problems are being solved by the students, it is possible to observe "classes" of solutions constructed. Previous works have shown such results [12]. For example, similar solutions are given by students "believing" that if two segments are symmetrical then they are parallels. This "belief" is called a conception about reflection; more precisely conception of parallelism. The formal definition of a conception is given later in this paper. Typical constructions from this group are shown on figure 2, where line segment AB is the object and A'B' is its image through a reflection with respect to d. The reason why students hold such wrong conception is the fact that it is enough to solve some problems correctly, as shown on figure 2-a and 2-c.

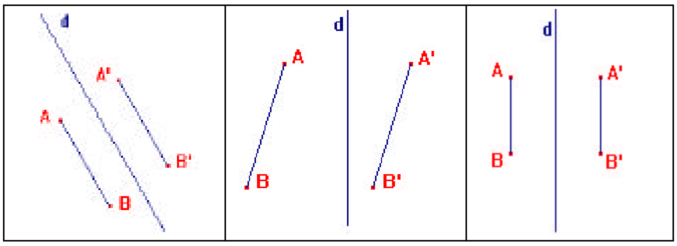

Figure 2 -(a,b,c). Constructions made by students holding the misconception of parallelism.

Other conceptions about reflection, besides the correct one, were recognised in students' constructions [13]. Some students hold the conception of *central symmetry*. Typical constructions are shown on figure 3.

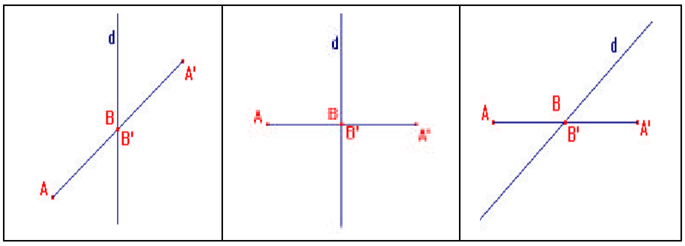

Figure 3-(a,b,c). Constructions made by students holding the misconception of central symmetry.

For this group of students, the intersection point between the line segment AB and the line of symmetry d becomes a centre of symmetry. Typical constructions are shown on figure 3. Observe again that students holding this wrong conception may make correct constructions in some situations, as illustrated on figure 3-b. Moreover, from the examples given (figure 2 and 3) it is possible to note that some problems are more favourable to one or another conception.

In the end, by observing students' constructions it was possible to identify some notions that may witness learning. It means that if the student is able to express these notions correctly through the operators available, it could be considered that the student has a correct conception about reflection. The notions are the following:

1. Equidistance: point A and its reflection A' are at the same distance of the line of symmetry.
2. Orthogonal: the lines segment AA' and BB' linking the extremities of the original line segment and its reflection are orthogonal to the line of symmetry.
3. Size: the original line segment and its reflection have the same size.

These notions, called controls, are useful to understand how conceptions work in different problems of reflection. The table 1 compares the value of each control for the two misconceptions, parallelism and the so-called "central symmetry".

Table 1. Comparing conceptions of parallelism and central symmetry

	Equidistance	Orthogonal	Size
Parallelism	Not respected	Not respected	Respected
Central Symmetry	Respected	Not respected	Respected

Thinking about conceptions has helped researchers on mathematics education to formalise students' knowledge and guide the decision of what aspect the next problem to be proposed must privilege. Since we have presented examples of conceptions about reflection, we can proceed introducing the theoretical formalisation of conceptions.

4 THEORETICAL MODEL OF CONCEPTIONS

Describing precisely conceptions is a difficult problem, for this purpose we use a model developed in mathematics education with a cognitive and didactical foundation [14,15]. In this model a conception is characterised by a quadruplet *C (P, R, L, S)* where:

- P represents a set of problems, which describe the conception's domain of validity, it is the seminal context where the conception may appear;
- R represents a set of operators, which are involved in the solutions of problems from P;
- L is a representation system; it allows the representation of problems and operators;
- Σ is a set of control structures.

The four sets of elements characterise a conception. Indeed, an element can contribute to the characterisation of several different conceptions; for example two conceptions may share problems in their domain of validity or may have in common operators, or controls, or even may rely on the same representation system. This can be observed in the description of the two conceptions of parallelism and central symmetry showed on table 2.

Table 2. Describing conceptions of parallelism and central symmetry

Parallelism P: problems demanding the construction by reflection of a line segment that does not intersect neither cuts the line of symmetry and possibly is parallel to the line of symmetry. R: parallel, horizontal, oblique and vertical line segments; points; circles to report distance; orthogonal relationship; parallel relationship; intersection relationship; L: drawings representing points, line segments, lines, circles, orthogonal relation, intersection operator, middle points; Σ: only the invariance of shape and size is controlled.
Central Symmetry P: problems demanding the construction by reflection of a line segment that intersects or cuts the line of symmetry. R: circles to report distance; intersection relationship; parallel, horizontal, oblique and vertical line segments; points; L: drawings representing points, line segments, lines, circles, orthogonal relation, intersection operator, middle points; Σ: the notion of equidistance is respected for both extremities; the orthogonal notion is not respected; the size notion is observed.

5 MULTI-AGENT MODEL OF CONCEPTIONS

From a theoretical perspective, the model of conceptions allows the formalization of students' conceptions. However, the difficulty is to develop a practical model founded on theoretical aspects, considering that only the problem solved and the solution given by the student are known. Besides, a conception is not an observable element; observable elements are operators used by student, the problem solved, the language used to express them, and theoretical control structures.

We recognise in this theoretical model a micro-level (the elements characterising conceptions) and a macro-level (the conceptions). For this reason, we have adopted an emergent approach for diagnosing conceptions since the behaviour observed in the micro-level can be interpreted at the macro-level by an observer using a different ontology from the ontology useful to describe the micro-level. Moreover, we cannot, and we might not, predefine all the possible conceptions that can arise.

5.1 Emergent models

Emergent systems are characterised by having a behaviour that cannot be predicted from a centralised and complete description of the component units of the system [16]. In emergent systems, the overall behaviour is the result of a great number of interactions of agents obeying very simple laws. The overall behaviour cannot be anticipated by simple reduction to individual behaviours following a logico-deductive model, which are conditioned by the immediate surroundings, like other agents and objects in the environment.

Very often the definition of emergence is attached to the notion of levels and detection [16]. Diagnosis can be effectively seen as an emergent property of certain complex systems, since in a diagnosis process lower-level symptoms or symbols are recognised by higher-level entities [17]. Note that emergent objects have a representation distributed over many different elements. Each of these elements may take part of many different objects simultaneously. This may be observed in the classifier systems proposed by Forrest [18], in the system for diagnosis of communication networks [17], and it is observed in the emergence of conceptions discussed in this paper.

5.2 Categories of agents

In the computational model conceptions are seen as sets of agents. The society of agents is composed of four categories: problem agents, operator agents, language agents and control agents. Each element from the quadruplet *C (P, R, L, S)* is in the core of one agent. For our experiments in the domain of reflection we have specified a set of around 100 elements. Observe that any possible subset may characterise a known conception about reflection, or an unknown conception or even a non-valid conception.

The general role of any agent is to check whether the element it represents is present in the student's solution. In the presence of the element the agent becomes "satisfied" and can vote for a set of conceptions believed to represent the conception hold by the student. In the absence of the element represented, the agent cannot vote. Each agent knows *a priori* to which conceptions it can start voting. A description of the role of each category of agents is given.

Problem Agents: a problem agent becomes satisfied when the category of problems it represents is present in the environment. In the case we consider, a category of problems is described by four didactical variables named: line of symmetry orientation, segment orientation, angle formed between line of symmetry and line segment and intersection formed between the line of symmetry and line segment. The combination of the different values these didactical variables could take, leads to more or less complex problems, allowing to focus on different aspects of the learning of reflection and most important, allowing the expression of different conceptions.

Operator Agents: an operator agent becomes satisfied when the element r of R it represents, is present in the solution constructed by the student. An operator transforms a problem in a new problem. A sequence of operators leads to the problem solution. An example of an operator in the domain of reflection is:

If the triangle ABC has three lines of symmetry
Then ABC is an equilateral triangle

Language Agents: a language agent becomes satisfied when the element l of L it represents, is present in the solution constructed by the student. It can be a grammar, a graphical representation, or an alternative way of expression allowing the description of the problem and the solution.

Control Agents: a control agent becomes satisfied when the element s of *S* it represents, is present in the solution constructed by the student. In problem solving, learners choose operators, validate actions and the final result. Each of these three decisions is guided by control structures. In the case considered, control elements are perceptive when attached to the fact that the learner makes assertions based on something "seen" on the screen and uses this information to take and validate decisions. On the other hand, control structures are theoretical when a learner bases decisions and validations on knowledge previously acquired. Reflection involves many visual elements of control; for instance, a learner holding the conception of parallelism may accept that a problem is correctly solved when the image line segment "looks" parallel to the original line segment.

5.3 Agent architecture

Before introducing the general description of an agent, some definitions are given. Consider K as the set of all known conceptions. For a set of agents $A = \{A_1, A_2, \ldots A_r\}$, let E_i be an element from *(P, R, L, S)* characterising an agent A_i. Let Q_i be a set of acquaintances $\{Q_{i1}, Q_{i2}, \ldots, Q_{iq}\}$ of the agent A_i. Assume K_i as the set of conceptions $\{K_{i1}, K_{i2}, \ldots, K_{ik}\}$ in which the agent A_i may take part in the characterisation. K_i is a subset of K. Finally, consider V_i as the set of votes $\{V_{i1}, V_{i2}, \ldots, V_{ik}\}$ given by an agent A_i to the k conceptions belonging to K_i.

Now we are able to describe an agent A_i as having:

1. an internal state $S_i \in$ {satisfied, unsatisfied}.
2. a set of acquaintances Q_i ,corresponding to those agents having an influence over A_i's voting behaviour.
3. a set of conceptions K_i in whose characterisation the agent may take part.
4. a sensor to the element E_i.
5. sensors to votes V_{Qij} , which were given by all the agents belonging to Q_i .
6. a satisfaction function $F_i(E_i) = S_i$, which operates over the element E_i and calculates its internal state S_i .
7. a voting function $G_i(S_i,Q_i,E_i,V_{Qi}) = V_i$, which decides about agent's voting behaviour.
8. effectors to output in the environment votes V_i given by the agent to the conceptions belonging to K_i.

In the next section, more details are given to the agents' voting behaviour.

5.4 Voting behaviour

In the domain of multi-agent systems, voting theory has been used as a technique for reaching consensus in a negotiation process and group-decision making [19]. In this work, voting has been used as a way for group-decision making. The voting mechanism tries to match the diagnosed conception to one or more known conceptions, which will be treated as candidates to be the conception(s) hold by the student.

Agents have simple strategies to vote: each agent can vote for one or more candidate conceptions. The voting function considers that there exist a space of votes R^I (the Euclidian space) having I dimensions; the number of conceptions to be diagnosed determines the number of space dimensions. Voters are represented by vectors in the space corresponding to their 'opinions' about candidate conceptions. Agents form dynamically coalitions with other agents that are spatially close. Our approach of coalition formation follows traditional approaches [20] and it considers that a coalition is a subset of agents having similar voting behaviour.

Let's consider the voting protocol of an agent A_i. Let V_i^m be the set of votes $\{V_{i1}, V_{i2}, \ldots, V_{in}\}$ given by the agent A_i to the n conceptions at the instant t_m. The voting process for an agent A_i occurs as follows:

1. At an instant t_0 the agent A_i is placed in the Euclidian space R^I according to its opinion about each conception as a good candidate (V_i).
2. For any other instant t_m, A_i applies its voting function:
   2.1. Find agents spatially close (V_{Qi});
   2.2. Propose coalitions;
   2.3. Accept/Refuse coalitions;
   2.4. Abandon weak coalitions;
3. $V_i^{m+1} \subset V_i^m$, meaning that voting tends to converge to a small set of elements or even to a unique element.
4. A_i stops voting when $V_i^m = V_i^{m+1}$, meaning that no more coalitional moves (from 2.1 to 2.4) are possible.

At the end of the voting process, possibly one of the candidate conceptions receives most of votes. It means that the conception that has emerged may be an instance of this candidate conception. If no convergent result is reached by the voting process, the system interprets that the emergent conception is not one of the candidate conceptions.

Since voting process has finished, two results may be observed: the emergence of a conception and the matching of this emergent conception as one of the known conceptions. Concerning the "emergent conception", an interesting point of discussion has appeared. How can one decide that a new set of agents, representing elements of *(P, R, L, S)*, characterise a valid conception? For the moment, this "emergent conception" can be sent to the teacher and she/he may decide the pertinence of it. However, is it possible to formalise this process of decision? Maybe through the observation of how teachers behave and take decisions based on emergent conceptions will bring some new variables to construct better learner models.

With this computational framework our goal is to obtain an emergent "picture" of a student in a solving problem activity. The learner model itself is a collection of these pictures. The model we propose differs from classical approaches since it does not try to match the student behaviour with some predefined student profile. The voting mechanism has been used to try to locate the emergent conception in a space of known conceptions.

6 CONCLUSIONS

In this paper we have presented a computational framework to diagnose learner's conceptions. The learner model is part of Baghera, a learning environment in the domain of geometry proof. The mechanism of diagnosis presented is based on multi-agents modelling and emergent theory. We have followed this approach since we recognise that we may not search for an a priori learner model.

The computational framework developed is the first result of a joint effort of two groups of researchers working on the same research domain (learner modelling) but in different perspectives. Researchers in mathematics education have been developing formalisms to represent students' knowledge and sequences of well-succeeded activities that may witness learning. Nevertheless, such formalisms are very complex and to find its computational counterpart representation is very complex as well.

Researchers in mathematics education have evaluated this computational framework. The next step may consist in obtaining an evaluation from the teachers using Baghera. The domain of reflection, used for the construction of this framework, will be extended and other domains will be modelled.

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