Layered Learner Modelling in ill-defined domains: conceptual model and architecture in MiGen

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Abstract. The design of learner modelling components for Exploratory Learning Environments (ELEs) presents a significant challenge, particularly when pertaining to ill-defined tasks and knowledge domain. We argue that representing a learner's knowledge just in relation to concepts is not adequate in such cases. We focus particularly on microworlds and present the conceptual model and architecture of the learner model of MiGen system that aims to support 11–14-year-old students develop the complex cognitive skill of mathematical generalisation.

1 Introduction

The work presented in this paper focuses on modelling learners as they are undertaking ill-defined tasks within exploratory learning environments (ELEs), and microworlds (MWs) in particular. A recent review of ill-defined domains [1] refers to such environments as 'model building' systems and identifies them as belonging to a particular genre of discovery learning whereby learners are provided with model-building tools and are encouraged to 'test their own intuitions about a domain' [1]. Although most ELEs provide non-adaptive feedback designed to scaffold students' learning, as with other constructivist approaches learning can be hampered in the absence of explicit support (c.f. [2]).

Our overarching objective is to enable the provision of adaptive feedback to students and information to teachers that will assist them in their efforts to integrate MWs into the classroom. However, the nature of the interaction in MWs, and their underlying pedagogical orientation, introduce difficulties in modelling the epistemological development of the learner, thus placing an additional hurdle for the provision of support in any form, e.g. explicit feedback, assistance for self-regulation through open learner modelling, assistance for teachers, etc.

The onus thus falls on the learner modelling component of an intelligent system, which is required to provide a substrate that describes, stores and manages short-term and long-term information about learners. However, following the usual approach in the field, whereby a learner's knowledge is represented only in relation to domain concepts, is not straightforward in this context. Similar to other intelligent learning environments that support learning in ill-defined

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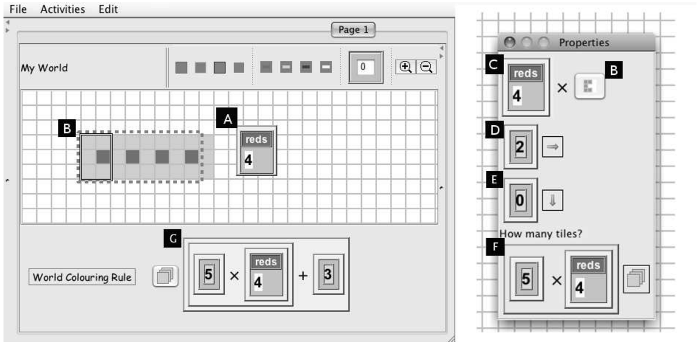

Fig. 1: Constructing a pattern in the eXpresser and describing it with a rule. Letters highlight the main features: (A) An 'unlocked' number that acts like a variable is given the name 'reds' and signifies the number of red (dark grey) tiles in the pattern. (B) Building block to be repeated to make a pattern. (C) Number of repetitions (in this case, the value of the variable 'reds'). (D,E) Number of grid squares to translate B to the right and down after each repetition. (F) Units of colour required to paint the pattern. (G) General expression that gives the total number of units of colour required to paint the whole pattern.

domains, MWs are designed to provide an empirical basis and opportunities for learners to develop complex cognitive skills rather than just to learn declarative knowledge of particular concepts. Moreover, even in cases where the knowledge domain underlying a MW is well-defined, the tasks that students are usually asked to undertake are open-ended in nature, have multiple approaches to a valid solution, and encourage students to explore the environment and follow a variety of strategies, not all of which can be sequenced or pre-defined (c.f. [3] for a detailed discussion on the need to distinguish between domain and task when discussing ill-definedness).

The MiGen project is creating a system to help 11–14 year olds to develop an appreciation of mathematical generalisation, which is considered one of the major routes to algebra in the UK curriculum. The system comprises a MW and several intelligent components that analyse the actions of students and provide support on different tasks. Fig. 1(A) shows the MiGen MW, called eXpresser. The MW encourages students to construct patterns and to find general expressions (i.e. rules) underpinning such patterns. Students use building blocks that they construct from unit tiles in order to make their patterns. To represent the generalities that they perceive, they can use numbers which they can 'unlock' to become variables. Locked and unlocked numbers can be used in expressions. The eXpresser gives a lot of freedom to students, who may construct their patterns in a multitude of different ways. For a detailed description of the eXpresser, see [4].

It is important to emphasise that interaction with a MW, such as eXpresser, does not necessarily provide direct evidence for assessing students' understanding of concepts. Behind the surface activities that students undertake, lies a different objective. The learning challenge addressed in eXpresser is not the creation of the patterns nor the building of the algebraic expression (both of which are well-defined), but rather the development of generalisation skills (e.g. finding common structures, identification of general unknowns) by means of those tasks, and the development of mathematical 'ways of thinking' (WOTs) [5], including abstracting a general rule from a set of specific examples, finding a common structure from several samples of a series or set, using variables to represent universal unknowns, and developing heuristics for verification of hypotheses and falsification of false conjectures, among others.

In this respect, it is necessary to make a distinction between the overall subject domain for which the MW is designed, and what is referred to as the 'epistemological domain of validity' of the microworld [6] i.e. the knowledge domain as it has been transformed by the affordances and interface of the environment. For example, the notion of a variable in the case of eXpresser is linked with the view of a variable as a 'generalised number' in the eXpresser's affordances and is operationalised as an 'unlocked number' (see Fig 1(A)). If the objective behind the modelling process were just to develop a model of the 'user', then this distinction between the subject domain and the MW domain would not be so important. However, our goal is to model learners and their learning progress, outside of the boundaries of the MW. Moreover, teachers need a correspondence between learners' interactions with the MW and the subject domain, as they are often required to identify and work towards specific learning objectives. Taking both requirements into account, it is imperative to represent explicitly the relationships between the subject domain and the MW domain.

In the next section, we present the conceptual model and the architecture of the learner model we use in MiGen, that satisfy these requirements. Section 3 presents our conclusions and future work.

2 Learner Modelling in MiGen

2.1 Conceptual Model

We address the requirements mentioned in the Introduction first by advocating that apart from the usual approach of modelling valid and invalid concepts in particular contexts, the learner model should also include epistemic and 'unproductive' ways of thinking. This approach is in line with [7] which argues for extending the scope of learner models with aspects outside the subject domain [1].

Second, in order to take into account the transformation of the domain, we consider a 'layer' of knowledge that involves microworld-specific concepts and that operationalises both the concepts of the subject domain and the ways of thinking (WOTs). Subject domain concepts are operationalised in the MW through the actions available using the objects and tools of the MW, i.e. its affordances. Because of their direct relationship to knowledge, we refer to these as

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[1] We recognise that the learner model should include affective factors and learner beliefs about the domain. Currently, such information is encapsulated under 'ways of thinking', as a fully-fledged affect modelling is beyond the scope of this research.

'epistemic' affordances. In order to distinguish those actions in the MW that are independent of any epistemic basis (e.g. 'knowledge of creating a building block' see Fig. 1(B)), we refer to these as 'pragmatic' affordances. In addition, this layer includes what we refer to as 'operationalised' ways of thinking. The two top layers of Fig. 2 present schematically the relationship between subject domain and the MW domain. This conceptualisation has the additional advantage of enabling us to take into account that learners' previous knowledge about the subject domain (or their intuitions) play an important role and can influence the way they perceive and interact with the MW. By representing both the subject domain and its operationalisation through the MW, it is possible to use such information (if available) to guide the adaptation process.

Finally, we recognise the critical role of specific tasks that are designed to contextualise students', otherwise unbounded, interaction with the MW. This provides specific goals that the learner is required to achieve during a task.

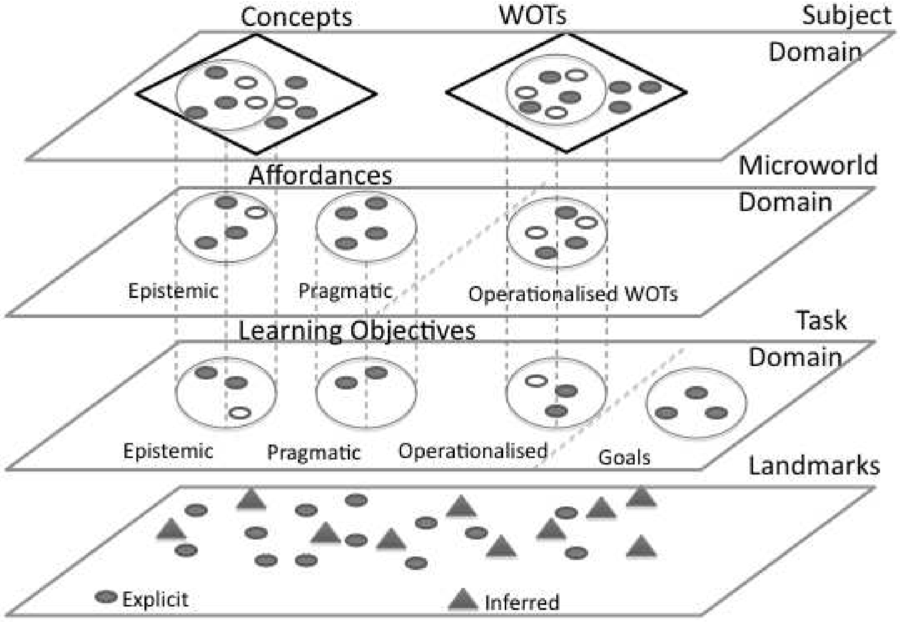

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Fig. 2: Conceptual model for learner modelling in microworlds. Concepts in the top layer (including 'invalid' conceptions for a particular context — blank ovals) are operationalised to epistemic affordances in the microworld layer. The same applies to productive and unproductive ways of thinking (WOTs). The microworld layer also includes pragmatic affordances corresponding to actions independent of any epistemic basis. It is projected to the task layer comprising concrete goals and learning objectives. Lastly, landmarks indicate the completion of goals and attainment of learning objectives.

Such goals include tangible objectives such as ‘find a general expression to colour a [certain] pattern’ — see Fig 1(G). Learning objectives are assigned to each task, e.g. an introductory task could have the simple objective to ‘explore how a [certain] tool behaves’ while a more complex task could have the objective to ‘appreciate the power of unlocked numbers’. As the task domain layer in Fig. 2 shows, there are three types of learning objectives: pragmatic learning objectives correspond to pragmatic affordances of the MW and are independent of the subject domain e.g. ‘knows how to drag numbers on the canvas’; epistemic affordances (e.g. ‘unlocking a number’) are mapped to epistemic learning objectives; and WOTs to operationalised WOTs (e.g. ‘validates the generality of construction by animation’). In MiGen, learning objectives, tasks and goals are co-designed by the research team with teachers (see also [8]); though we intend that in the future it will be possible for teachers (or trained learning designers) to define their own.

Ensuring that tasks have tangible goals and are associated with learning objectives, enables a much more tractable diagnostic aim: measuring beliefs in relation to learning objectives and not abstractly in relation to a student’s state of mind. This is achieved through the automatic inference of *landmarks* as students interact with the MW (bottom layer of Fig. 2). In particular, Explicit landmarks occur when specific actions are undertaken by the student, e.g. ‘clicking the animate button to validate their construction’, while Inferred landmarks are derived from occurrences of combinations of actions, e.g. ‘the student has started to construct generally’, or ‘the student is exploring in a systematic way’.

2.2 Learner Modelling Architecture

We now formalise the main entities of the learner model architecture and the relationships between them. An earlier paper [9] described the conceptual and architectural design of the overall MiGen system. Here we extend that work by focusing on details of the learner modelling aspects.

Figure 3 shows the major entities comprising the MiGen Learner Model, as well as some associated entities. For each eXpresser task undertaken by a Student, information on their ongoing progress through the task is maintained within a TaskShortTermModel. This information is derived from the occurrence of Landmarks as the student undertakes the task. The TaskShortTermModel is used to derive a longer-term model of the student’s strategies and outcomes in relation to a task — the TaskLongTermModel. This in turn is used to derive a model of the students’ attainment in relation to learning objectives pertaining to the whole MW — the MicroworldLongTermModel. Finally, this is used to derive a model of attainment of learning objectives related to the domain of mathematical generalisation — the DomainLongTermModel. Thus, overall, a student’s learner model consists of their TaskShortTermModels, TaskLongTermModels, MicroworldLongTermModel and DomainLongTermModel. For implementing these derivation processes, we are employing a hybrid of rule-based and case-based reasoning (see [10]) in order to infer the occurrence of Inferred landmarks and to update the learner’s TaskShortTermModel. Once a student

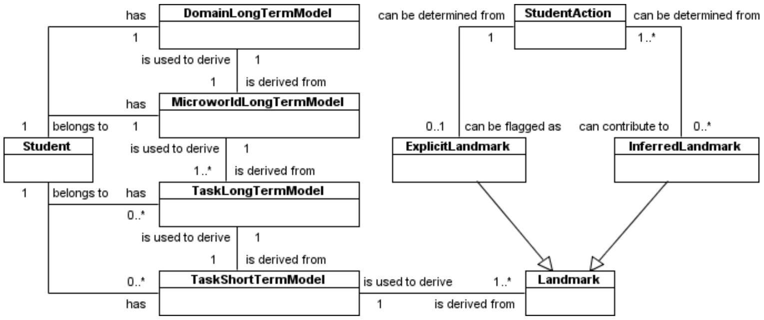

Fig. 3: MiGen learner model. At each end of an edge linking two entities is an indication of the cardinality of that end of the relationship and a verb phrase, e.g. a StudentAction can contribute to zero or more InferredLandmarks. A single-headed arrow indicates a sub-class relationship between two entities.

completes a task, the higher layers of the learner model are updated by additional rule-based components which successively infer updates to each higher layer based on its current values and the values of the layer below it.

The student's DomainLongTermModel is consistent with the subject domain model of MiGen, which includes concepts such as 'constants', 'variables', 'constructions' and 'expressions' and the corresponding learning objectives mapped from the U.K. National Maths Curriculum. e.g. 'visualise and draw on grids of different types where a shape will be after a translation', 'understand and use the rules of arithmetic in the context of positive integers', 'explore number relationships and propose a general statement involving numbers'. Similarly, the MicroworldLongTermModel is consistent with the second layer of Figure 2, and the TaskShortTermModels and TaskLongTermModels with the third layer. In practice, a teacher may initialise some attributes in a student's DomainLongTermModel, or may make explicit modifications to them over time.

Figure 4 shows the major types of Learning Objectives in MiGen and the relationships between them, as well as some associated entities. In brief, DomainLearningObjectives are separated into epistemic objectives (shown as ConceptualLearningObjective in the diagram) and objectives related to mathematical ways of thinking, e.g. 'appreciation of the use of variables'. Each TaskLearningObjective may be associated with a number of TaskShortTermModels and TaskLongTermModels. Likewise, each DomainLearningObjective may be associated with a number of students' DomainLongTermModels. Landmarks provide evidence for TaskLearningObjectives, as well as for LearnerInconsistencies — these are context-specific stumbling blocks, e.g. 'using more variables than needed'. Each TaskLearningObjective corresponds to a MicroworldLearningObjective; though there may be additional instances of the latter that have no counterpart TaskLearningObjective. There is a looser many-to-many correspondence between sets of MicroworldLearningObjectives and DomainLearningObjectives.

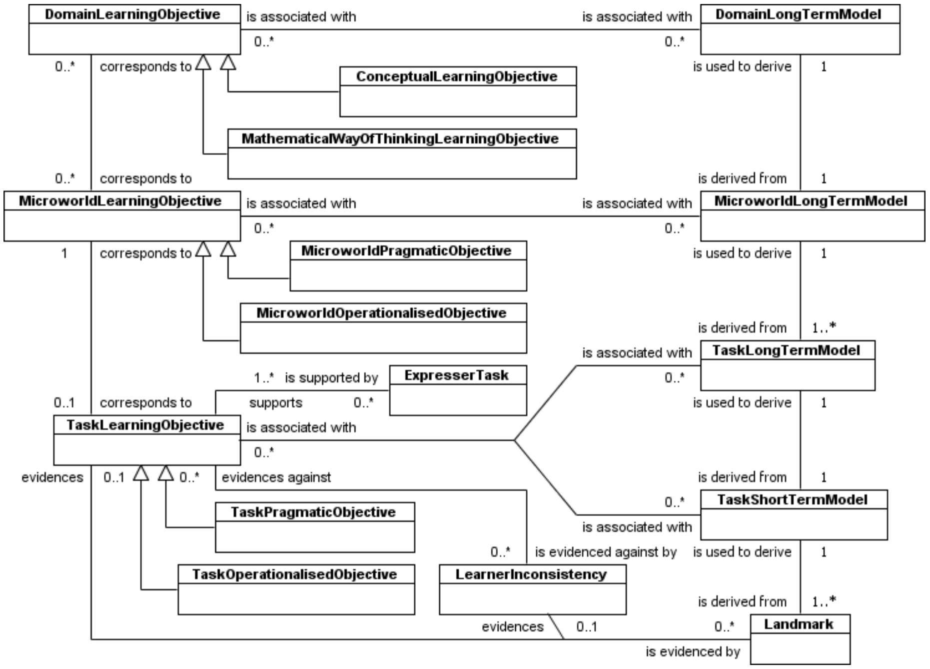

Fig. 4: Learning Objectives

3 Conclusions

This paper has argued that learner modelling in MWs introduces the need to extend the standard approach of representing the knowledge domain as concepts, with additional information representing learners' epistemic ways of thinking. The conceptual model we have presented here takes into account the transformative nature that MWs (and other ELEs) have on the nature of knowledge and on the domain they represent. Our layered approach simplifies the learner modelling problem by contextualising the domain first to its operationalisation in the MW, and subsequently to tasks with goals and particular learning objectives.

Several MWs have been reported in the educational technology literature. However, in most cases integration into the clasroom has been hindered because of the extensive requirement on teachers for helping students both with pragmatic and epistemic aspects. The ill-defined nature of the tasks that students undertake in MWs invites learner modelling methods such as the ones used in ill-defined tasks and domains (see [1, 3]). Independently of the precise techniques used to infer information and update the learner model, representing and maintaining the required knowledge is an important prerequisite, particularly when we need to expose such knowledge to stakeholders (e.g. teachers or students).

Our approach relies on explicit definition of the goals and the learning objectives underlying students' interactions, as well as their mapping to the MW and Domain layer. As a proof of concept, in MiGen, these mappings are captured as rules elicited from domain experts and teachers experienced with the MW. However, the conceptualisation is independent of the updating and inference techniques employed (for a review of related techniques see [11]).

This paper has also presented the learner model architecture of the MiGen system. For more details on the process by which the learner model is updated as students undertake tasks in the eXpresser see [11], where we also provide a preliminary investigation of how this approach can be applied to other ELEs with ill-defined tasks and domains. For the future, as more learners interact with the eXpresser, and teachers are exposed to our conceptual model in operation, we plan to investigate different inference techniques and design tools that enable the iterative refinement of the entities represented in the learner model.

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