Competence Based Adaptive E–Learning in Dynamic Domains

Cord Hockemeyer
University of Graz, Austria

Abstract: *This paper describes a competence–based approach to adaptive e–learning based on knowledge space theory and its competence–performance extension. Assigning to each learning object sets of required and taught competencies, one can easily build a course adapting in each step to the learner's current knowledge state. The competence assignments implicitly define a prerequisite structure on the set of competencies. At the same time, a decentralised storage of these assignments allows (i) for easy changes of learning objects and courses in dynamically changing domains and (ii) for reuse of adaptive material in different courses by implementing the competence assignments through slightly extended metadata standards. An example implementation will be briefly presented.*

Introduction

In this paper the concept of competence learning structures based on knowledge space theory is briefly introduced, and its application to adaptive e–learning is discussed. A major advantage of this approach is the distinction between observable performances and underlying competencies (from a psychological point of view) which corresponds one–to–one to a distinction between concrete learning objects and abstract concepts from a technological point of view. A central aim of this paper is to serve as a link between other publications which describe rather isolated aspects of this work, i.e. they focus either on the psychological or on the technological point of view.

According to this linkage aim, the main core of the paper is divided into two parts, whereas one part concerns psychological models for prerequisite structures and concerns adaptive e–learning systems based on prerequisite structures. Finally some conclusions will be drawn and open issues will be specified.

Psychological Models for Prerequisite Structures

While also other psychological models (e.g. the Rasch model) offer suitable means for representing prerequisite relationships, I will restrict to the non–linear approach of knowledge space.

Theoretical background

Doignon and Falmagne (1985, 1999) have developed the theory of knowledge spaces for an efficient, adaptive assessment of knowledge. Basically, they model prerequisite relationships through quasi orders, so–called surmise relations (if a learner solves item *a*, we can surmise that this learner is also capable of solving item *b*). Modelling learners, on the other side, through their knowledge states, i.e. the subset of items the respective learner is capable to solve, they define a knowledge space as the set of all possible knowledge states in accordance to a given surmise relation.

Another concept in knowledge space theory that is important especially with respect to e–learning, is the fringe of a knowledge state, i.e. the set any item by which the knowledge state differs from some upper or lower direct neighbour in the knowledge space. Items in this fringe can either be acquired soon because all prerequisites are known or they are likely to have been learned rather recently.

In order to model different solution paths for an item, Doignon and Falmagne (1985, 1999) have also introduced a more general means for describing prerequisite relationships: the surmise mapping. Different solution paths may involve different sets of prerequisites. Thus, a surmise mapping assigns to each item a family of subsets of items called clauses for the original item. Each clause contains the items which are prerequisites with respect to a certain solution path. Similarly to the mathematical concepts of quasi orders, Doignon and Falmagne have introduced, among others, the properties of extended reflexivity, i.e. from each mastered item we can surmise that this very item is mastered, and of extended transitivity, i.e. prerequisites of prerequisites of an item are also prerequisites for the item itself, for surmise mappings

The original theory of knowledge spaces as described above is behaviour oriented, i.e. it describes relations between items and item solving behaviour. Especially the group around Albert focused on the cognitive structures underlying this observable behaviour resulting in various approaches within and beyond that group (see, e.g., Albert & Lukas, 1999; Düntsch & Gediga, 1995). The work described in the following is based on Korossy's (1997, 1999) competence–performance approach. He distinguishes between observable performances, i.e. test item solving behaviour, and their underlying competencies. This is done by mapping each item to the subset of competencies required for solving this item and, vice versa, by mapping each subset of competencies to the subset of items which can be solved by a person who has all (and only) the competencies of the given subset. From these mappings, prerequisite structures on the sets of competencies and of performances (i.e. items) can be derived through the set inclusion principle: an item *a* is a prerequisite of item *b* (in the sense of the aforementioned surmise relation) if the set of competencies assigned to *a* is a subset of the set assigned to *b*.

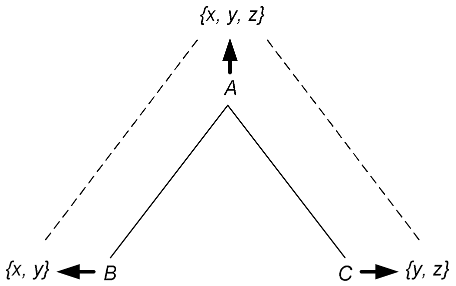

Figure 1: Competence assignment and induced prerequisite relationships

Figure 1 shows an example of three items *A*, *B*, and *C* to which subsets of competencies *x, y,* and *z* are assigned (denoted by the arrows). The set inclusion relation on the competence subsets (denoted by dashed lines) induces a surmise relation between the items (denoted by straight lines).

Competence Learning Structures

A major problem in knowledge space theory lies in the development of the prerequisite structures. Original approaches on querying experts on prerequisite relationships between items (see Doignon & Falmagne, 1999, for an overview) show quite some weaknesses (Held, Schrepp, & Fries, 1995). Improving this situation was one aim of the investigation of the underlying cognitive structures but specifying *all* competencies needed for solving still remains an error–prone task.

Based on this background, Korossy's (1997, 1999) competence–performance approach was extended to the concept of competence learning structures (Hockemeyer, 2002) was developed which is summarised below. The basic idea is to specify, for each learning object, separate subsets of required and taught competencies. Given two mappings *r* and *t* which assign to each learning object these subsets of competencies one can derive a surmise mapping s_L on the set of competencies. For each competence *c*, its set s_L *(c)* of clauses contains the sets *r(l) È t(l)* of all learning objects *l* teaching competence *c*, i.e. all learning objects *l* for which *c e t(l)* holds. This surmise mapping s_L can then easily be closed under transitivity etc. using well-documented efficient procedures (Dowling & Hockemeyer, 1998). Through this surmise mapping s_L (and its closure) on the set of competencies, a competence space, i.e. the set of all possible competence states, is well–defined.

The main difference between competence learning structures and Korossy's (1997, 1999) competence–performance approach lies first of all in the separation of taught and required competencies (in the case of test items, competencies which are actually to be tested by the item and other required competencies would be separated, instead). The advantage of this separation is that authors (or metadata creators) do not have to specify those prerequisites which can be derived through transitivity. This is especially important if the objects are to be used in different contexts where different sets of (especially low–level) competencies might be used.

It is important to mention that, although this approach defines a prerequisite structure for competencies through a surmise mapping, it does not yet cover multiple solution paths for test items (as a special type of learning objects). In order to achieve also that, we would have to replace the mappings *r* and *t* by one mapping *I* which assigns to each test item *l* a set of pairs *(R,T)* where R and T are subsets of competencies required or actually tested, respectively, by this item within some solution path.

Realising an adaptive e–learning system based on prerequisite structures

E–learning systems based on traditional knowledge space theory

While knowledge space theory was originally developed having the adaptive assessment of knowledge in mind (Doignon & Falmagne, 1985), this changed soon, and until now all practical applications of it are oriented towards e–learning.

The first systems were (and are) very item–centred, i.e. they view a domain of knowledge as a set of items. After an initial assessment of the learner's knowledge, teaching is primarily done by training, i.e. the learner is given some items for which s/he can request explanations as help in solving the items. The AdAsTra system (Dowling, Hockemeyer, & Ludwig, 1996) selects items from the fringe of the learner's current knowledge state, i.e. items which the learner either has acquired rather recently and, therefore, should still train in order to deepen that knowledge, or which s/he has not yet learned but for which s/he fulfils all prerequisites. The ALEKS system developed by Falmagne and his group (http://www.aleks.com/; see also Doignon & Falmagne, 1999) offers the learner a topic–sorted selection of item classes for which s/he fulfils all prerequisites. Selecting some of these new topics, i.e. item class, the learner can then decide whether s/he wants to see an explained example first or whether s/he wants to go directly into trying to solve such an item.

The RATH system (http://wundt.uni-graz.at/rath/; see also Hockemeyer, Held, & Albert, 1998) is the first knowledge space based system that focuses on teaching lessons. Based on an analysis of cognitive demands posed by test items in the field of knowledge (Held, 1993), lessons teaching the skills corresponding to the cognitive demands were developed, and a common prerequisite structure of lessons and test items was developed (Albert & Hockemeyer, 2002). On the technical side, RATH connects the relationally formalised theory of knowledge spaces with an also relationally formalised model of hypertext link structures and with relational database technology. Adaptivity in RATH is realised through navigation guidance, more concretely through link hiding. While a learner is browsing through the learning hypertext, any hyperlinks pointing to documents within the course for which some prerequisites are missing are disabled and presented as normal text. For any document presented to a learner, it is preliminarily assumed that s/he has understood the text and acquired the respective knowledge. However, the structure of lessons is intermixed with test items (see above), and a test item is regarded as known only if it has been solved correctly by the learner. Thus, it is ensured that learners cannot simply click through the course but also have to learn the contents taught in the lessons. Since RATH was implemented as a prototypical system, an initial assessment was not included; instead, the system starts with the assumption that any new learner is a complete novice in the field.

However, all these systems share a weakness with respect to dynamic domains, i.e. domains (in the sense of collections of items and other learning objects) that change due to changing knowledge in the field or simply due to ongoing course developments (see Albert & Kaluscha, 1997). AdAsTra and ALEKS both work on an explicit representation of the complete knowledge structure which has to be updated whenever new items are added to or existing items are deleted from the item pool. RATH does not have this explicit representation of the complete structure. However, the structure is represented implicitly through prerequisite links between the concrete objects which also need to be updated whenever new learning objects (lessons or test items) are created or existing ones are deleted.

APeLS — A metadata–driven approach to competence–based e–learning

This section describes the Advanced Personalised e–Learning Service (APeLS) system developed at Trinity College, Dublin, in co–operation with the University of Graz within the EASEL project (Educator Access to Services in the Electronic Landscape; http://www.fdgroup.com/easel). APeLS realises adaptivity to the learner's knowledge through the competency learning structures introduced above. We call it a metadata–driven approach because, in an APeLS course, metadata are used not only for describing the adaptivity but also for realising it.

Applying metadata for competence assignments

Standards for metadata describing learning objects have been a major issue in research and development on e–learning. Standardised metadata are a necessary prerequisite for retrieval and reuse of existing learning objects for new courses. However, current metadata standards do not support description of adaptivity. One central aim of the EASEL project within which APeLS was developed was to investigate the applicability of metadata standards to adaptive e-learning resources. A first major result in this issue was the suggestion of a generic adaptivity element extending the educational section of current metadata standards like IMS Metadata or IEEE LOM (Albert, Hockemeyer, Conlan, & Wade, 2001; Conlan, Hockemeyer, Lefrere, Wade, & Albert, 2001).

The generic adaptivity element basically consists of an arbitrary number of adaptivitytype entries each describing a different aspect of adaptivity (e.g. with respect to special needs, learning styles, or involved competencies). Two concrete examples for adaptivitytype were competencies.required and competencies.taught which resemble exactly the mappings *r* and *t*, respectively, of the basic competence learning structure definition above. While these metadata were originally developed aiming merely at the description of adaptive learning objects in order to allow respective searches in a repository, it became clear very soon that they could also be used as an instrument by the adaptive service for realising the described adaptivity as shown in the next section.

The APeLS system

The idea of an e–learning system based on competence learning structures and their specification through metadata was implemented at Trinity College, Dublin, as an extension of their existing personalised e–learning system (Conlan, Hockemeyer, Wade, & Albert, in press). Learners in APeLS find themselves with set of two frames, a table of contents on the left and a content frame on the right (see screenshots in Fig. 2). A novice gets a rather small list of contents (see left screenshots) but after some time the list of available contents gets increasingly larger (see right screenshot). During this process, the table of contents is rebuilt on demand, i.e. whenever the learner presses the "Rebuild TOC" link. Thus, a certain stability of the table of contents is guaranteed. APeLS could also prove its usability in dynamic domains: A course on

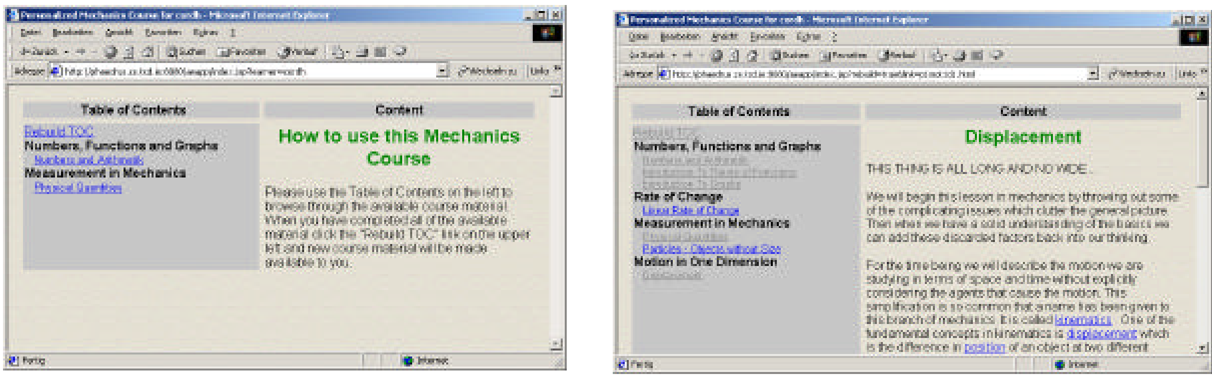

Figure 2: APeLS screenshots

Newtonian mechanics structured (i.e. enriched with adaptive metadata) at University of Graz could easily be enriched by additional chapters originating from Open University, UK, simply by adding the respective metadata information to the database and adding the learning objects to the repository.

Conclusions

The current paper shows that the psychological distinction between observable behaviour and underlying cognitive skills strongly coincides with the technical distinction of concrete learning objects and abstract concepts (or candidates in the terminology of Conlan et al., in press). This technological side of the medal also ensures an easy maintainability in the case of changing domains (or courses).

However, there remain still numerous issues open for further research of which three shall be mentioned here. An important topic are investigations on the structural properties of competence learning structures, especially with respect to the more elaborated version allowing for several solution paths for test items.

Furthermore, there remains the difficult issue of correctly differentiating the two types of assigned competencies for a test item. While it is rather easy to distinguish between taught and required competencies for lessons, examples, etc., it is clearly more difficult to distinguish for a test item which competencies are actually to be tested with this item and which competencies are prerequisites.

Finally, the various procedures for an adaptive assessment of knowledge which were developed within knowledge space theory (see, e.g., Doignon & Falmagne, 1999) and which are important for an initial assessment of new learner’s knowledge all have in common that they require an explicit knowledge structure as a basis for selecting new items to be posed to the learner.

Acknowledgements

The research described in this paper was financially supported by the European Commission through the EASEL project (Grant IST–1999–10051).

The author feels especially indebted to Owen Conlan who implemented the ideas described herein in his APeLS system, and to Michael Silly and Diane D. Evans who structured courses on Newtonian mechanics according to the model of competence learning structures.

References

Albert, D. & Hockemeyer, C. (2002). Applying demand analysis of a set of test problems for developing an adaptive course. In *Proceedings of the international conference on computers in education (ICCE) 2002.*

Albert, D., Hockemeyer, C., Conlan, O., & Wade, V. (2001) Reusing adaptive learning resources. In G. Cumming, T. Okamoto, & L. Gomez (Eds.), *Advanced research in computers and communications in education* (Vol. 2, pp. 325–328). Amsterdam: IOS Press

Albert, D. & Kaluscha, R. (1997). Adapting knowledge structures in dynamic domains. In C. Herzog, (Ed.), *Beiträge zum Achten Arbeitstreffen der GI–Fachgruppe 1.1.5/7.0.1 ``Intelligente Lehr–/Lernsysteme''* (pp. 89–100). Munich, Germany: Technische Universität München.

Albert, D. & Lukas, J. (Eds.). (1999). *Knowledge Spaces: Theories, empirical research, applications.* Mahwah, NJ: Lawrence–Erlbaum Associates.

Conlan, O., Hockemeyer, C., Lefrere, P., Wade, V., & Albert, D. (2001). Extending educational metadata schemas to describe adaptive learning resources. In H. Davies, Y. Douglas, & D. G. Durand (Eds.), *Hypertext ’01: Proceedings of the twelfth ACM conference on hypertext and hypermedia* (pp. 161–162). New York: ACM.

Conlan, O., Hockemeyer, C., Wade, V., & Albert, D. (in press). Metadata driven approaches to facilitate adaptivity in personalized eLearning systems. *International Journal of Information Systems in Education.*

Dowling, C. E. & Hockemeyer, C. (1998). Computing the intersection of knowledge spaces using only their bases. In C. E. Dowling, F. S. Robert, & P. Theuns (Eds.), *Recent Progress in Mathematical Psychology* (pp. 133–141). Mahwah, NJ: Lawrence Erlbaum Associates.

Dowling, C. E., Hockemeyer, C., & Ludwig, A. H. (1996). Adaptive assessment and training using the neighbourhood of knowledge states. In C. Frasson, G. Gauthier, & A. Lesgold (Eds.), *Intelligent Tutoring Systems* (pp. 578–586). Berlin: Springer.

Doignon, J.–P. & Falmagne, J.–Cl. (1986). Spaces for the assessment of knowledge. *International Journal of Man–Machine Studies,23,* 175–196 .

Doignon, J.–P. & Falmagne, J.–Cl. (1999). *Knowledge Spaces.* Berlin: Springer.

Düntsch, I. & Gediga, G. (1995). Skills and knowledge structures. *British Journal of Mathematical and Statistical Psychology, 48,* 9–27.

Held, T. (1993). *Establishment and empirical validation of problem structures based on domain specific skills and textual properties.* Doctoral Dissertation, Universität Heidelberg, Germany.

Held, T., Schrepp, M., & Fries, S. (1995). Methoden zur Bestimmung von Wissensstrukturen – Eine Vergleichsstudie [Methods for determining knowledge structures – a comparative study]. *Zeitschrift für Experimentelle Psychologie, XLII(2),* 205-236.

Hockemeyer, C. (2002). Extending the competence–performance–approach for building dynamic and adaptive tutoring systems. Talk given at the 33rd European Mathematical Group (EMPG) Meeting, September 2002, Bremen, Germany.

Hockemeyer, C., Held, T., & Albert, D. (1998). RATH — A relational adaptive tutoring hypertext WWW–environment based on knowledge space theory. In C. Alvegård (Ed.), *CALISCE’98: Proceedings of the fourth international conference on computer aided learning in science and engineering* (pp. 417–423). Göteborg, Sweden: Chalmers University of Technology.

Korossy, K. (1997) Extending the theory of knowledge spaces. *Zeitschrift für Psychologie, 205,* 53–82.

Korossy, K. (1999). Modeling Knowledge as Competence and Performance. In D. Albert & J. Lukas (Eds.), *Knowledge Spaces: Theories, Empirical Research, Applications* (pp. 103–132). Mahwah, NJ: Lawrence Erlbaum Associates.