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Are Web-based Adaptive Educational Systems suitable for constructivist instruction in Ill-Structured Knowledge Domains?

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Abstract

Intelligent Tutoring Systems and the evolution of Adaptive Hypermedia have opened the way for the emergence of Web-based Adaptive Educational Systems (AES). However, AES have not yet been sufficiently tested for ill-structured knowledge domains. In this paper we examine the question of applicability of AES for constructivist- oriented instruction for such domains. More specifically, we identify the basic problems related to this question, we analyze them and, for each case, we identify and propose conditions that are instrumental for the implementation of AES for ill-structured domains

Keywords: Web-based Adaptive Educational Systems, Ill-structured Knowledge Domains, Adaptive Hypermedia, Cognitive Flexibility Theory, Constructivism, Hypermedia in Education

Περίληψη

Τα έξυπνα συστήματα διδασκαλίας (Intelligent Tutoring Systems) και τα Προσαρμόσιμα Συστήματα Υπερμέσων (Adaptive Hypermedia Systems) άνοιξαν το δρόμο για την εμφάνιση των Προσαρμόσιμων Εκπαιδευτικών Συστημάτων στον Παγκόσμιο Ιστό (AES). Στην παρούσα εργασία, εξετάζουμε το κατά πόσο τέτοια συστήματα είναι εφαρμόσιμα για διδασκαλία σε μη καλώς δομημένα γνωστικά πεδία (ill structured domains). Πιο συγκεκριμένα, αναγνωρίζουμε τα βασικά προβλήματα που σχετίζονται με το ερώτημα αυτό, τα αναλύουμε και για κάθε περίπτωση προτείνουμε προϋποθέσεις οι οποίες είναι ουσιαστικές για την υλοποίηση AES για μη καλώς δομημένα γνωστικά πεδία.

1. Introduction

This paper deals with the question of suitability of Web-based Adaptive Educational Systems (AES) for constructivist-oriented instruction when the knowledge domain is ill-structured. The importance of this question is due to the following: (a) The foundation of web-based educational systems is hypertext. However and despite all the hype, effectiveness of hypertext-based instruction has been strongly contested (e.g. [Kotze98]). (b) In addition, a number of reasons for instruction failures in ill-structured domains have been identified (cf. [Spiro96]). Thus, although several AES exist, one can argue that certain problems should be first resolved for efficient application of AES in ill-structured domains. We further analyze this question into three basic sub-problems presented in Sections 2, 3 and 4 respectively. For each problem we identify some key issues and produce some initial conclusions that are instrumental for the implementation of AES for ill-structured domains. Thus, this paper proposes that such systems can be suitable, provided that some basic conditions, identified here, are met.

2. AES, Constructivism and Ill-Structured Domains

Sub-problem A: Are there any characteristics of AES that make them suitable for constructivist instruction in ill-structured domains? What types of AES are more suitable?

We first need to introduce a definition of AES. We define them as learning environments (typically hypermedia based) on the web, capable of adapting instruction (e.g. content delivery, user assistance, etc) to the learner's skills, needs and goals. According to [Brusilovsky98a], Web-based Adaptive Educational systems inherit from traditional Intelligent Tutoring Systems (ITSs) and Adaptive Hypermedia Systems (AHSs). ITSs typically partition the information space in knowledge about the domain, knowledge about the

user and teaching strategies to support individualized learning. Adaptive Hypermedia Systems usually enable content and navigation adaptation, by altering the link structure and the node contents of the hypertext that contains the educational material. The following classification of AES based on their goal, is due to [Brusilovsky98a]: *Curriculum Sequencing (or instructional planning)*: Provide the learner with the most suitable individually planned sequence of knowledge units and learning tasks. *Intelligent analysis of student solutions*: Identify in the student's solution of a problem what exactly is wrong or incomplete and which missing or incorrect knowledge may be responsible for the error. *Interactive problem solving support*: Provide the student with intelligent help on each step of the problem solving process - from giving a hint to executing the next step for the student. *Example-based problem solving*: Help students by suggesting the most relevant cases (examples previously explained or problems already solved by the students). *Adaptive presentation technology*: Adapt the content of a hypermedia page to the user's goals, knowledge and other information stored in the user model. *Adaptive collaboration support*: Use the system's knowledge about different users (stored in user models) to form matching collaboration groups. *Adaptive navigation support technology* is to support the student navigation and orientation in hyperspace by changing the appearance of visible links. In particular, the system can adaptively sort, annotate, or partly hide the links in the current page to make easier the choice of the next link to proceed. In the next two subsections, based on the hypermedia nature of the web and features of ill-structured domains, we attempt to select appropriate types of AES.

2.1 Constructivism and Hypertext – the need for adaptivity

The question of what constitutes effective constructivist computer mediated instruction is one of the broadest and most controversial issues in instructional technology. It appears that constructivist approaches dominate today's research, especially for systems operating on the World Wide Web; such approaches range from simple use of the Web in didactically original manners to complex cognitive tools such as concept maps. We believe that at least two of the Web's features make it appealing for constructivist learning. The first is its nature as a communication medium that may facilitate activities like peer learning even over large distances and in asynchronous fashions. The second, is the fact that the key Web technology is hypertext: Constructivism, in contrast to behavioristic pedagogy, stresses the importance of generating understanding versus training for performance ([Henze99a]). Generating understanding requires partition of the knowledge domain in declarative, procedural and structural knowledge. The use of learning, or cognitive models within the learner to structure efficient hypertext promotes the understanding of structural knowledge, which is the important link between declarative and procedural knowledge [Eklund95]. In principle, the non-linear nature of hypertext can help students assimilate such structural knowledge; the use of hyperlinks allows explicit (through indexes) and implicit (through hyperlinks embedded in the text) representations of structural information in more effective manners than printed material or temporally continuous media. For instance, selection by the learner of different hyperlinks in a hypertext page can place the same piece of information within different contexts and display different structural relationships between fragments of information.

Even though in theory the above reasoning appears sound, in practice, the use of hypertext for learning has been strongly contested. Important studies emphasize user disorientation problems in hypertext (e.g. [Nielsen90] - perhaps the most cited paper in this field). Compared to more traditional CBI models, two drawbacks of hypermedia can be identified [Kotze98]: (1) the deterministic nature of linking (links are unconditional) and (2) the fact that hypertext traversal is referential (elicited by the user) and not contextual (decided by performance information on the student). It appears that the question of whether the non-linearity of hypermedia is effective for instruction should be replaced by several more specific questions, such as who, what and how does non-linearity help. Individuals vary on their skills, preferences, and degree of familiarity toward information technology. These differences make

individuals more or less likely to take advantage of systems based on choice and self-organization ([Rouet92]). It is such questions that curriculum sequencing and adaptive presentation / navigation AES attempt to solve, through the production of individualized instruction with the correct ratio of learner control and user guidance.

2.2 Ill-structured domains and AES

An ill-structured knowledge domain is one in which the following two properties hold ([Spiro96]). (1) Each case or example of knowledge application typically involves the simultaneous interactive involvement of multiple, wide-application conceptual structures (multiple schemas, perspectives, organizational principles, and so on), each of which is individually complex (i.e., the domain involves concept- and case-complexity). (2) The pattern of conceptual incidence and interaction varies substantially across cases nominally of the same type (i.e., the domain involves across-case irregularity). For instance, in well-structured domains like math or physics, application of the same principles in similar problems provides equally similar results. The same does not necessarily hold for an ill-structured knowledge domain such as History.

When the knowledge domain for which the system is built is well structured, AES techniques like building bug libraries and modifying correct examples to match user errors and perceive user misconceptions can be used to support problem solving [Beck99]. But when the domain is ill structured, problem solving support, in the spirit of many ITS, is very difficult and costly to implement. This case is more evident if the knowledge domain lacks well-established formalisms (as with math or physics) and tutor-learner interaction is typically carried out in natural language. The problem solving process is difficult to model and perhaps impossible (with today's technologies) to simulate with a machine. It seems very difficult to see in the near future a system like ANDES ([Conati99]) used to coach problem solving in a complex domain like History. For such reasons, we see curriculum sequencing and its variations (adaptive presentation and adaptive navigation) as the most promising and realistic candidates for implementing successful AES in ill-structured domains.

Conclusions: Hypertext is a promising means for constructivist learning, but its use poses problems that require curriculum sequencing, adaptive presentation and adaptive navigation AES. Such hypertext-based systems allow moderation of user-control vs. user guidance in navigation and provide for better user orientation. Furthermore, ill-structured domains pose several important problems that are hard to solve for systems that provide problem-solving support and analysis of student solutions.

3. The effect of ill-structured domains on the design of AES

Sub-problem B: How are the basic features of AES affected by an ill-structured domain?

3.1 Basic architectural components of an AES

In order to identify the major architectural components of AES we examined one reference model and three state-of-the-art AES: the Adaptive Hypermedia Application Model [deBra99] (a reference model extending the Dexter Reference Model, detailed in [Halasz94]); AHA [DeBra98]; Interbook [Brusilovsky98b]; and Hyperbook [Henze99a] & [Henze99b]. All four systems can be classified as systems for curriculum sequencing, adaptive presentation and navigation and comprise three fundamental architectural components:

The domain model includes all content presented to the student along with any constructs representing structural information on the content. Content is typically organized in units, resembling book chapters or sections. Structural information may be incorporated in the content (AHAM, AHA) or organized in external structures ("glossary" in Interbook or "Knowledge Items" in Hyperbook). These structures partition the knowledge domain in concepts and represent concept relationships (such as "prerequisite", "outcome" and "inhibitor"). Concept relationships result in the creation of simple structural constructs, such

as directed acyclic graphs in AHAM, hierarchies combined with partial order in Interbook and taxonomies in Hyperbook. In addition, in Hyperbook the Knowledge Items are used to index not only content but also learning goals and student projects. The user model is usually an overlay of the domain model with user specific values annotated for each concept. The way these values are represented and maintained varies between systems. In Interbook and AHA discrete values include “unknown”, “learnt”, “ready to learn” etc. In Hyperbook a Bayesian Network is used. The teaching model implements adaptation strategies. In AHA for instance these strategies are explicitly detailed within the content in the form of “if condition then action” clauses (like preprocessor directives). “Condition” is formed from observations on the student model or outcomes of other rules and “action” results in content or link adaptation (e.g. fragment variants – link annotation, hiding, removal). Additional adaptation strategies supported in Hyperbook include guided tour generation, project and learning goal selection.

3.2 Modeling the Knowledge Domain.

Domain modeling primarily answers the question of «What do we want the learners to learn». The way knowledge can be modeled and represented has been a very important issue, in Computer Aided Instruction. ACT theory for instance discriminates between declarative and procedural knowledge and models the domain in appropriate ways [ACTTutorial]. Quoting from [Jonassen94]: declarative knowledge is not a sufficient prerequisite for procedural knowledge; in order to acquire procedural knowledge, it is necessary to understand the prepositional relationships between the entities involved in both the procedural and declarative knowledge; structural knowledge provides that link between procedural and declarative knowledge; and, the underlying assumption of all descriptions of structural knowledge is that meaning for any concept is implicit in the pattern of relationships to other concepts or constructs. From the discussion so far, three apparent reasons lead to the need for conceptual modeling of the domain in AES: (1) Assessing user knowledge and goals with respect to the domain, so that instruction may be tailored to the needs and skills of the user. (2) Applying rules on the ways learners shall access the information modeled. (3) Converting concept relationships into meaningful and semantically rich navigational links, allowing for effective reuse of content in different navigation scenarios.

As seen previously, domain-modeling techniques vary from loosely structured concept repositories (AHA) to well structured conceptual constructs. In the latter case, concepts are defined in parallel or independently of the actual content and organized through taxonomical relationships (Hyperbook). This model could be extended to include full-fledge ontologies with taxonomical as well as non-taxonomical relations. In the remainder of this subsection we present introductory definitions and examples of these conceptual modeling constructs.

From the discussion presented so far, it seems that the simplest way for organizing content is in loose constructs with dependency relations dominant. More explicit cognitive models include semantic networks. Perhaps the simplest form of a semantic network is a hierarchically organized taxonomy. In previous work, (cf. [Papaterpos99a], [Papaterpos99b]), we have used taxonomies to organize content in a non-adaptive hypermedia educational system. Three main taxonomical criteria (time, place and subject) were used to organize content and navigational tools were built to accommodate exposure of content structure to learners. The approach followed was rather «author oriented», since an important goal of this organization was to allow a group of authors to collectively decide on and maintain the content of the application. A similar approach is followed in Hyperbook, where, in the example given (course on Java programming), a generally accepted taxonomy (ACM Computing Classification System v.1998) is adopted. However, this taxonomy is enhanced with partial order relationships between concepts.

Taxonomies can be seen as simple modeling constructs, compared to explicit, complex ontologies. There are several definitions of ontologies in the literature ranging from philosophical: «An ontology refers to a particular theory about the nature of being or the

kinds of existence» (in [vanHeijst96]) to AI-related definitions: «An AI ontology is a theory of what entities can exist in the mind of a knowledgeable agent» [Wielinga93]. According to a classification of ontologies, based on amount and type of structure, ontologies can be classified into: (a) Terminological ontologies like lexika, taxonomies; (b) Information ontologies, specifying record structure of databases; (c) Knowledge modeling ontologies, specifying conceptualizations of knowledge with a richer internal structure and often tuned to a particular use of the knowledge they describe. [vanHeijst96]. This classification is not unanimously accepted ([Guarino97]), however, even so, a distinction based on the «detail of conceptualization» is still considered acceptable.

The question that logically follows this reasoning is: are there any reasons for moving from simple structures (lexika and taxonomies) to more detailed ontologies that imply increased development costs? According to [Chandrasek98], there are two reasons to use ontologies: (a) ontological analysis clarifies the structure of knowledge; and (b) ontologies enable knowledge sharing. Explicit and detailed Ontologies lead to better understanding of knowledge structure and more efficient knowledge sharing. Additional arguments may be introduced if ill-structured domains are taken in mind.

In our opinion, simple ontological constructs represent static knowledge representations. It appears that in ill-structured domains, concept complexity and across-case irregularities imply the need for flexible domain modeling constructs. Drawing from experience gained in previous work ([Papaterpos99a] & [Papaterpos99b]), we have seen that taxonomies can enable knowledge sharing and collaborative content authoring. However, simple taxonomical relationships (like part-of, is-a and Generalization / Specialization) are not enough to capture conceptualization details that could lead to representations of the difference of concept meaning according to the context that concepts are examined in. By using hierarchical taxonomies, we have found out that it is difficult to establish relationships between content fragments classified in distantly related positions in the hierarchy. The basic hindrance in building and using knowledge modeling ontologies is the cost inherent in determining how many and what type of non-taxonomical conceptual relationships should be modeled in a particular ontology. Sophisticated techniques, e.g. mining such relationships from text, are currently being developed (cf. [Maedche00]). To the best of our knowledge, such techniques are in early experimental stages.

3.3 Modeling learners

User modeling primarily answers the question «What are the learner's goals, background and preferences and what does the learner know so far». The user modeling component is perhaps the heart of an Adaptive Educational System. If one cannot represent the status of the learner, it is very difficult to tailor instruction to the learner's skills, goals and knowledge, to offer guidance and collaboration. In a typical adaptive hypermedia system, the properties to monitor for each user may include: *Goals, Background & Experience, Knowledge and Preferences* (cf. [Brusilovsky96a] & [Brusilovsky00]).

There are however some complexity and cost problems related to user modeling. Given the importance of user models in AES, the next question is what sort of models should be used and how they could be implemented. Implementation difficulties and costs in building explicit, "high fidelity" user models have generated critique on the need for such user models. Such difficulties and costs seem to be much higher when the knowledge domain is ill structured. The complexity of capturing and recording user characteristics, such as competence with regard to the knowledge domain, can increase when the domain concepts are complex by nature. In addition, differences across-case irregularities can make static user models not only difficult to construct but also ineffective. For instance, using multiple representations of knowledge to capture different meanings of the same concept in different contexts can increase the level of complexity of the user model, since each representation should be taken into account.

In the oft-cited paper [Self90], Self attempts to answer this line of reasoning – which literally disregards user modeling as too expensive – by pointing out four guidelines (slogans in Self's wording) for the “affordable” development of realistic user models. Examples include asking the student to provide definite information and refraining from using the user model for remediation. From such guidelines, as well as from the standard practice presented in the previous sections, it appears that in curriculum sequencing and adaptive presentation / navigation AES, user modeling should concentrate on capturing learners' competencies on the given knowledge domain, in ways that can be exploited by the “teaching component”. This direction can be broadened if one models learner goals by indexing them through concepts present in the user model [Henze99a]. Implementation complexity and costs may be reduced if standard and non-heuristic algorithms, such as the ones mentioned in the end of this paragraph, are used.

If limited information on the user is necessary for implementing a teaching strategy, two basic approaches may be employed: Definition of (hierarchically structured) user stereotypes and plan generation. Stereotype based systems identify subgroups in an expected user population, enumerate key user characteristics and structure hierarchical user stereotypes. Plan recognition systems observe the user's input actions and try to determine all possible user plans to which the observed actions can be complemented - a plan is a sequence of user actions that achieve a certain goal ([Kobsa93]).

These methods have a general application in a variety of fields. However, user modeling in AES presents the following ideas that are not evident in most other fields: (a) The basic motivation for creating a user model is to capture user competence with regard to certain knowledge. (b) Knowledge is partitioned in concepts and modeled accordingly (cf. previous paragraph). (c) Concepts are related not only at conceptual level but also, at presentation level, with navigational links that may carry little or no semantic information. Such characteristics, and especially the existence of a knowledge model, which is independent of the particular state of the learner, suggest different techniques, all based on numerical management of uncertainty. Uncertainty is an important factor in representing views about learner. For instance, a system can seldom be certain that a student is 100% competent on a certain concept or concept structure. Jameson in [Jameson95] examines three basic technologies for implementing user models:

Bayesian Networks of Belief (cf. [Pearl95], [Henze99c]): Bayesian nets are used to reason in a principled manner about multiple pieces of evidence [Beck99]. If the domain model of the AES is represented as a network (Directed Acyclic Graph), a Bayesian Net may be used to allow propagation of information on the student's knowledge. Bayesian Nets are often used to describe causal relationships, but they can also be used to represent other relations, such as concept dependence, which is common in knowledge domain models.

Dempster-Schaffer Theory of Evidence: It can be seen as a generalization of Bayesian Networks. Typical case for applying DST is the case of the unreliable witness where the goal is to model assumptions on learner's competence, which cannot easily be conceived as events caused by the learner's actual competence level.

Fuzzy Logic (FL): The term fuzzy logic has been used in various senses, some broader than others. Jameson uses it to include any system that makes use of one or more typical concepts such as those of a linguistic variable, a fuzzy set, or a fuzzy if-then rule. FL's appeal seems to be based on the following two reasons: (1) People often reason in terms of vague concepts when dealing with situations in which they experience uncertainty. (2) When users supply explicit information about themselves to a system, they may express this information vaguely.

Of course, when the system's main goal is not curriculum sequencing (or adaptive navigation / presentation), other techniques may be employed. For instance, machine learning algorithms can be used for modeling user misconceptions in an interactive problem solving support system [Beck99]. However the case presented in that paper deals with a narrow and well-structured domain (multi-column subtraction).

3.4 Modeling Teaching Strategies

The teaching component of an AES answers the question: «Given the knowledge domain and the learner's goals and competence with regard to that domain, in what ways can the system assist the learner to achieve his goals». Across-case irregularities and differences of concept meaning in ill-structured domains imply the need for case-based teaching strategies that provide clear navigational contexts. We believe that standard adaptation technologies and techniques can be applied to this end. A summary of such techniques, taken from is outlined below - see [Brusilovsky96a] and [Brusilovsky00] for explanation and details: Adaptive Presentation: modifying the content of «pages» presented to the learner (includes StretchText – Conditional Text – Frame based techniques); Adaptive Navigation: modifying the link structure of the hypertext (includes Direct Guidance, Sorting, Hiding, Annotation);

Conclusions: Domain modeling should be based on flexible knowledge structures and incorporate concept dependencies. However, the issue of effectively establishing non-taxonomical concept relationships is hard to resolve. Detailed information on the user is required, therefore stereotyping and plan generation are not suitable techniques. Using standard techniques (e.g. Bayesian Networks), provides means to combine modeling of student knowledge and goals and, especially if software modules are available, may decrease development complexity and costs.

4. A sound pedagogical approach to guide the design of AES for ill-structured domains.

Sub-problem C: Is there a constructivist theory that can exploit generic AES features and guide the design of an AES for an ill-structured domain?

So far, we have examined examples and core components of AES and highlighted some implications from their application in ill-structured knowledge domains. It has been indicated that the ill structure of the knowledge domain may affect design decisions such as choice of AES class, domain and user modelling technologies. In this concluding paragraph, we present an initial attempt to couple AES design with the Theory of Cognitive Flexibility (CFT), a constructivist theory that specifically targets instruction in such domains and is closely related to the educational use of hypertext.

A number of “flaws” in instructional systems that lead to poor knowledge transfer are enumerated in [Spiro96]. Among them, oversimplification, knowledge compartmentalisation, additive and reductive bias are identified as the most important. Spiro proposes a new theory for learning in ill-structured domains, the theory of cognitive flexibility. Basic CFT features are epitomised in [Jacobson96] and among others include: (a) use of multiple knowledge representations, (b) linking of abstract concepts in cases to depict knowledge-in-use, (c) demonstration of the conceptual interconnectedness or web-like nature of complex knowledge. These features have been used prescriptively to specify design elements for complex, multidimensional, and non-linear environments such as hypertext and hypermedia. Based on these features and combining the CFT approach with the more “conventional” approach of Situated Cognition (SC), Jacobson proposes three guidelines for hypertext design: (1) Case-based hypertext materials – based on both the recommendations of CFT to use case-based materials and of SC theory to involve students in authentic activities. (2) Conceptual indexing and variable hypertext links – conceptual indexing involves coding the case-based materials with important abstract conceptual or structural knowledge (e.g., cognitive or mental models, schemas, themes) based upon understandings and representations held by domain experts. (3) Case-theme commentaries – short explanation of how a structural dimension of knowledge (e.g., a theme or concept) applies in different case-specific or situated contexts

The characteristics of AES described in the previous sections and the discussion in the above paragraph suggest strong ties between AES and the application of CFT in hypermedia system design: (1) The features of conceptual indexing and the variability of hypertext links provide the most obvious connection for the applicability of AES for CFT based instruction. Building

the domain model through a “conceptualisation of knowledge” (ontologies) and providing for link variability are capacities inherent in most AES appropriate for implementing requirements from CFT. (2) Conceptual indexing of “knowledge-in-use” and link variability can lead to complex schemata and, in effect, cause user disorientation in the hypertext. Guiding the user in the hyper-space according to user competencies may provide ways for reducing cognitive overload and implement learner-tailored instruction. (3) The main goal of CFT is advanced knowledge acquisition in ill-structured domains. Even though findings suggest suitability of CFT for learners in lower and intermediate levels (cf. [Simonson97]), Spiro and Jacobson suggest that for introductory level, different approaches may be more suitable. The ability of the system to determine when the user is in need of an introductory approach and to alter its behavior accordingly is an important challenge for an AES (cf. [Beck99]).

Naturally, using an AES to implement a CFT-driven hypermedia application poses certain issues, pertaining to most hypermedia systems. Concluding this paper, we point-out one such issue, perhaps the most important one: hypertext coherency and comprehension. In linear text, hierarchical structures (e.g. table of contents) and prepositions within the text increase the text’s coherency and help the reader comprehend the text’s macrostructure. In hypertext documents, this is not always the case [Folz96], [Thuring95]. The problem can be augmented when applying certain features of CFT. Examine for instance the requirement to guide the learner to revisit concepts in a number of different navigational contexts. This approach is very likely to reduce coherency in the hyper-document, especially if the person defining the cases and the navigational contexts is not the same as the author of the hypertext, or if the hyper-documents are built on top of a hyper-base (cf. [Stotts91] for the hyper-document / hyper-base distinction). The number of links in the hypertext graph may increase (in contrast to using static fixed hyperlinks) and techniques outside the field of AES may need to be applied. Using an AES to implement a CFT based approach should be complemented with techniques that increase hypertext coherency and comprehension.

***Conclusions:** Cognitive Flexibility Theory appears a good candidate for guiding the design of AES for ill-structured domains: CFT is designed particularly with ill structured domains in mind, requires conceptual indexing and variable links and may lead to user disorientation. However, issues like increasing hypertext coherency remain unresolved.*

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