Adaptive Hypermedia for Education and Training

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SUMMARY
Adaptive hypermedia is a relatively new direction in research at the crossroads of hypermedia and user modeling. Adaptive hypermedia systems build a model of the goals, preferences and knowledge of each individual user and use this model throughout the interaction with the user, in order to adapt to the needs of that user. Educational hypermedia was one of the first application areas for adaptive hypermedia and is currently one of the most popular and well-investigated. The goal of this presentation is to explain the nature and the mechanism of adaptation in educational adaptive hypermedia and to provide several examples of using adaptive hypermedia in educational and training applications of different natures and complexity.

KEYWORDS: *Adaptive Hypermedia, Web-based Education, Intelligent Tutoring System, E-learning, Training, Student Model, Personalization*

INTRODUCTION

Adaptive hypermedia (AH) is an alternative to the traditional "one-size-fits-all" approach in the development of hypermedia systems. Adaptive hypermedia (AH) systems build a model of the goals, preferences and knowledge of each individual user; this model is used throughout the interaction with the user in order to adapt to the needs of that particular user (Brusilovsky, 1996b). For example, a student in an adaptive educational hypermedia system will be given a presentation that is adapted specifically to his or her knowledge of the subject (De Bra & Calvi, 1998; Hothi, Hall & Sly, 2000) as well as a suggested set of the most relevant links to proceed further (Brusilovsky, Eklund & Schwarz, 1998; Kavcic, 2004). An adaptive electronic encyclopedia will personalize the content of an article to augment the user's existing knowledge and interests (Bontcheva & Wilks, 2005;

Milosavljevic, 1997). A museum guide will adapt the presentation about every visited object to the user's individual path through the museum (Oberlander et al., 1998; Stock et al., 2007).

Adaptive hypermedia belongs to the class of *user-adaptive* systems (Schneider-Hufschmidt, Kühme & Malinowski, 1993). A distinctive feature of an adaptive system is an explicit user model that represents user knowledge, goals, interests, as well as other features that enable the system to adapt to different users with their own specific set of goals. An adaptive system collects data for the user model from various sources that can include implicitly observing user interaction and explicitly requesting direct input from the user. The user model is applied to provide an adaptation effect, i.e., tailor interaction to different users in the same context. In different kinds of adaptive systems, adaptation effects could vary greatly. In AH systems, it is limited to three major adaptation technologies — adaptive content selection, adaptive navigation support, and adaptive presentation. The first of these three technologies comes from the fields of adaptive information retrieval (IR) and intelligent tutoring systems (ITS). When the user searches for information, the system adaptively selects and prioritizes the most relevant items (Brajnik, Guida & Tasso, 1987; Brusilovsky, 1992b). Adaptive navigation support was introduced in early adaptive hypermedia systems (de La Passardiere & Dufresne, 1992; Kaplan, Fenwick & Chen, 1993) and is specifically associated with browsing-based access to information. When the user navigates from one item to another, the system can manipulate the links (e.g., hide, sort, annotate) to guide the user adaptively to the most relevant information items. Adaptive presentation stems from research on adaptive explanation and adaptive presentation in intelligent systems (Boyle & Encarnacion, 1994; Paris, 1988). When the user gets to a particular page, the system can present its content adaptively.

The goal of this paper is to provide an overview of adaptive educational hypermedia (AEH). The paper, however, neither provides a historically-centered overview of the field nor offers a detailed classification of AH technologies, since these reviews can be found elsewhere (Brusilovsky, 2001; Brusilovsky, 2004; Brusilovsky, 2007; Bunt, Carenini & Conati, 2007; Knutov, De Bra & Pechenizkiy, 2009). Instead, the paper attempts to give a developer-oriented insight into the internal structure of AEH systems. The remaining part of the paper focuses on three educational hypermedia design approaches of increasing complexity, illustrating the presentation with examples from the past research projects of the author. We conclude with a brief discussion of challenges in the field of adaptive educational hypermedia.

Adaptive Educational Hypermedia: from Classic Hypertext to the Adaptive Web

From the very early days of AH, educational hypermedia was one of its major application areas. In an educational context, users with alternative learning goals and knowledge of the subjects require essentially different treatment. In educational hypermedia, the problem of "being lost in hyperspace" is especially critical. A number of pioneer adaptive educational hypermedia systems were developed between 1990 and 1996. These systems can be roughly divided into two research streams. The systems of one of these streams were created by researchers in the area of intelligent tutoring systems (ITS), who were trying to extend traditional student modeling and adaptation approaches developed in this field to ITS with hypermedia components (Beaumont, 1994; Brusilovsky, 1993; Gonschorek & Herzog, 1995; Pérez, Gutiérrez & Lopistéguy, 1995). The systems of another stream were developed by researchers working on educational hypermedia in an attempt to make their systems adapt to individual students

(De Bra, 1996; de La Passardiere & Dufresne, 1992; Hohl, Böcker & Gunzenhäuser, 1996).

ADAPTIVE EDUCATIONAL HYPERMEDIA: THE SECOND GENERATION

Despite the number of creative ideas explored and evaluated in the early educational AH systems, it was not until 1996 that this research area attracted attention from a larger community of researchers. This process was stimulated by the accumulation and consolidation of research experience in the field. The research in adaptive hypermedia performed and reported on up to 1996 provided a good foundation for the new generation of research. While early researchers were generally not aware of each other's work, many papers published since 1996 were clearly based on earlier research. These papers cite earlier work, and usually propose an elaboration or an extension of techniques suggested earlier. In addition, the Web, with its clear demand for personalization served to boost adaptive hypermedia research, providing both a challenge and an attractive platform. Almost all the papers published before 1996 describe classic pre-Web hypertext and hypermedia. In contrast, the majority of papers published since 1996 are devoted to Web-based adaptive hypermedia systems.

In the field of educational adaptive hypermedia, the major driving factor behind second-generation adaptive educational hypermedia was Web-based education. The imperative to address the needs of the heterogeneous audience for Web-based courses individually was clear to many researchers and practitioners. A few early adaptive hypermedia systems developed for Web-based education context by 1996, such as ELM-ART (Brusilovsky, Schwarz & Weber, 1996b), InterBook (Brusilovsky, Schwarz & Weber, 1996a), and 2L670 (De Bra, 1996), provided "proof of existence" and influenced a number of more recent systems. The majority of adaptive educational hypermedia systems developed since 1996 are Web-based systems which were developed for Web-based education context. Some earlier examples are: ADI (Schöch, Specht & Weber, 1998), RATH (Hockemeyer, Held & Albert, 1998), ACE (Specht & Oppermann, 1998), TANGOW (Carro, Pulido & Rodríguez, 1999), Arthur (Gilbert & Han, 1999), CAMELEON (Laroussi & Benahmed, 1998), KBS-Hyperbook (Henze et al., 1999), AHA! (De Bra & Calvi, 1998), and Multibook (Steinacker et al., 1999).

The choice of the Web as a development platform turned out to be a wise one for educational hypermedia systems. It extended the life of a number of pioneer systems. In particular, the first Web-based adaptive educational hypermedia systems developed before 1996 such as ELM-ART, InterBook, and 2L670 are still in use and have been significantly updated and extended to incorporate a number of new techniques were used for several experimental studies (Brusilovsky & Eklund, 1998; De Bra & Calvi, 1998; Weber & Brusilovsky, 2001) that further guided development of the field.

The work on second-generation adaptive educational hypermedia was performed mainly between 1996 and 2002. It can be roughly split into three different streams which lack clear-cut borders. The largest group of work (produced mainly by researchers coming from the Web-based education side) focused on creating adaptive Web-based educational systems with elements of adaptive hypermedia. The main motivation was to produce systems to be used in teaching, not in developing new technologies. As a result, the works of this stream broadly re-used already existing technologies and explored various subject areas and approaches. A smaller stream of work (produced mainly by researchers who were very familiar with ITS or the adaptive hypermedia area) focused on producing new techniques for adaptive hypermedia. For example the early AHA! project (De Bra & Calvi, 1998) explored several approaches to link removal.

MetaLinks (Murray et al., 2000) explored advanced approaches to hyperspace structuring. INSPIRE explored the use of learning styles (Papanikolaou et al., 2003) and MANIC (Stern & Woolf, 2000) explored innovative approaches for user modeling and adaptive presentation. Finally, another stream of work (which was small, but rapidly expanded) focused on developing frameworks and authoring tools for producing adaptive hypermedia systems. The majority of this work produce hat we can call *frameworks* for adaptive Web-based education: KBS-Hyperbook (Henze et al., 1999), Multibook (Steinacker et al., 1999), ACE (Specht & Oppermann, 1998), CAMELEON (Laroussi & Benahmed, 1998), MediBook (Steinacker et al., 2001), and ECSAIWeb (Sanrach & Grandbastien, 2000). While not resulting in end-user authoring tools, a framework typically introduces a generic re-usable architecture and approach that could be used to produce a range of adaptive systems with low overhead. A few of the most experienced teams, those working on adaptive hypermedia projects for several years, introduced practical authoring systems that could be utilized by end-users to develop adaptive hypermedia systems and courses. Examples are InterBook (Brusilovsky et al., 1998), ART-Web/NetCoach (Weber, Kuhl & Weibelzahl, 2001), AHA! (De Bra & Calvi, 1998) and MetaLinks (Murray et al., 2000).

ADAPTIVE EDUCATIONAL HYPERMEDIA: THE THIRD GENERATION

Altogether, the systems of the second-generation adaptive educational hypermedia demonstrated a variety of ways to integrate adaptation technologies into Web-based education systems as well as the value of these technologies. Yet, they failed to influence practical Web-based education. Almost 10 years after the appearance of the first adaptive Web-based educational systems, just a handful are used for teaching real courses, typically for a class led by one of the authors of the adaptive system.

Instead, the absolute majority of Web-enhanced courses rely on so-called learning management systems (LMS). LMS are powerful integrated systems that support a number of needs of both teachers and students. Teachers can use a LMS to develop Web-based course notes and quizzes, to communicate with students and to monitor their progress. Students can use it for communication and collaboration. The complete dominance of LMS over adaptive systems may look surprising. Actually, for every function that a typical LMS performs, we can find an adaptive Web-based Educational System (AWBES) that can significantly outperform the LMS. Adaptive textbooks created with systems like AHA!, InterBook or NetCoach mentioned above can help students learn faster and better. Adaptive quizzes delivered by such systems as SIETTE (Conejo, Guzman & Millán, 2004) and QuizGuide (Hsiao, Sosnovsky & Brusilovsky, 2010) evaluate student knowledge more precisely with fewer questions. Adaptive class monitoring systems (Oda, Satoh & Watanabe, 1998) give the teachers more opportunities to notice students that are lagging behind. Adaptive collaboration support systems (Soller, 2007) can reinforce the power of collaborative learning. It seems obvious that the drawback to modern adaptive systems is not the quality of their performance, but their inability to meet the needs of practical Web-enhanced education. The challenge of integrating adaptive hypermedia technologies into the regular educational process has defined the current third generation of adaptive educational hypermedia research.

Various research groups stress different reasons for the domination of LMS and thus, pursue different research directions. One research stream focused on the versatility of LMS, attempting to provide in one system as many teacher and learner support features (from content authoring to quizzes to discussion forums) as provided by a modern LMS -– plus, the ability to adapt to the user (Morimoto et al., 2007; Specht et al., 2002; Ueno, 2005). A different stream addressed another superior feature of an LMS -- the ability to integrate open corpus Web content. The systems in this stream explored several approaches to integrating open corpus content in an adaptive hypermedia system while providing adaptive guidance for this content (Brusilovsky, Chavan & Farzan, 2004; Brusilovsky & Henze, 2007; Henze & Nejdl, 2001). Most recent projects, however, choose not to compete with present-day LMS, but instead to focus on adaptive features of the coming generation of Web-based educational systems. This new generation, which will replace modern LMS, will be based on system interoperability and reusability of content and supported by a number of emerging E-Learning interoperability. A number of research teams are trying now to integrate existing adaptive hypermedia technologies with the ideas of standard-based reusability (Conlan, Dagger & Wade, 2002; Dolog et al., 2003; Morimoto et al., 2007). However, other teams argue that the current generation of standards is not able to support the needs of adaptive learning (Mödritscher, García Barrios & Gütl, 2004; Rey-López et al., 2008). Yet another direction of work attempts to explore the ideas of the Semantic Web for content representation and resource discovery, capitalizing on standards such as Resource Description Framework (RDF) and Topic Maps (Denaux, Dimitrova & Aroyo, 2005; Dichev, Dicheva & Aroyo, 2004; Dolog et al., 2003; Henze, 2005; Jacquiot, Bourda & Popineau, 2004)(Dolog & Nejdl, 2007).

Adaptive Educational Hypermedia: A Designer's View

2.1 KNOWLEDGE BEHIND PAGES

Despite an amazing diversity of existing AEH systems, almost all of them are based on the same set of design principles. It is important for those who are interested in applying or developing AEH systems to understand these principles. The key to intelligence and adaptivity in these systems is the presence of a *knowledge space* (formed by topics, concepts, rules or other kinds of *knowledge elements*) beyond the traditional hyperspace formed by interconnected pages (Fig. 1).

The knowledge space (also known as the *domain model*) serves as the backbone for AEH systems. It is used to structure the information about individual user knowledge and goals (known as the *user model* or *student model* in AEH systems). It is also used to describe the content of information pages in these systems. In this capacity, the knowledge space empowers a range of specific AH technologies (such as adaptive sequencing or adaptive link annotation) to bridge the gap between user knowledge and goals on one side and the information content on the other side. Such technologies help the user to receive the most appropriate educational or training content. While the general principles of knowledge structuring and user modeling are shared by the majority of AES systems, practical system may differ a great deal in their complexity and the range of supported adaptation techniques. More specifically, larger and more diverse information spaces typically require more sophisticated approaches to information indexing (i.e., connecting information pages with knowledge elements) and user modeling. For example, systems with a small information space (such as those developed in the early days of adaptive hypermedia) frequently use just one concept to describe an information fragment. Larger information spaces – with many pages related to the same concept – demand more precise multi-concept indexing to make pages more distinct from the system's point of view. In turn, these more sophisticated approaches enable a wider range of adaptation techniques. Following earlier reviews (Brusilovsky, 1996a; Brusilovsky, 2003) three groups of information indexing approaches of increasing complexity are identified.

The analysis of these three groups is the focus of the second part of this paper. After a brief introduction to the principles of domain modeling and student modeling in AEH systems, the remaining part of the paper analyzes these major information indexing approaches one by one, illustrating each with an detailed practical example.

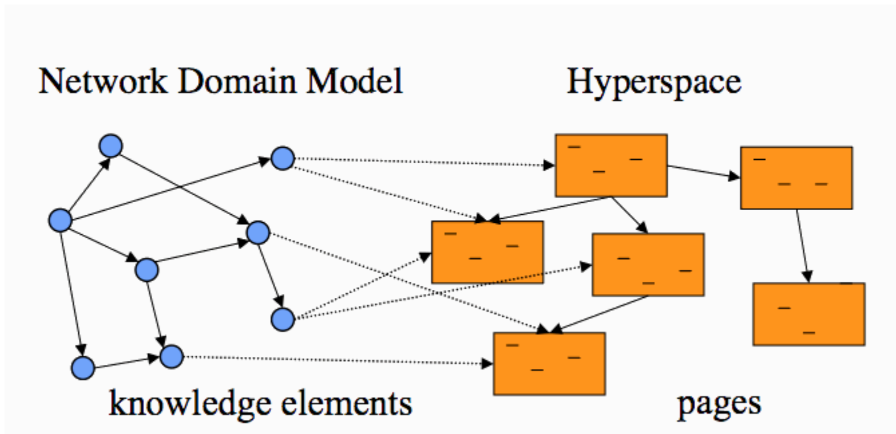

Figure 1. The key to adaptivity in AEH systems is the knowledge layer behind the traditional hyperspace

2.2 THE DOMAIN MODEL

The heart of the knowledge-based approach to developing adaptive hypermedia systems is a structured *domain model* that is composed of a set of small domain knowledge elements (KE). Each KE represents an elementary fragment of knowledge for the given domain. KE can be named differently in different systems—concepts, knowledge items, topics, knowledge elements, learning objectives, learning outcomes; however, in all cases, they denote elementary fragments of domain knowledge. Depending on the domain, the application area, and the choice of the designer, KE can represent bigger or smaller pieces of domain knowledge. A set of KE forms *a domain model.* More exactly, a set of independent KE is the simplest form of domain model. It is typically called a *set model* or a *vector model*

(Brusilovsky, 2003) since the set of KE has no internal structure. In a more advanced form of domain model, KE are related to each other thus forming a semantic network. This network represents the structure of the domain covered by a hypermedia system. This kind of model is known as a *network model* (shown on the left part of Fig. 1).

The structured domain model was inherited by adaptive educational hypermedia systems from the field of ITS, where it was used mainly by systems with task sequencing, curriculum sequencing, and instructional planning functionality (Brecht, McCalla & Greer, 1989; Brusilovsky, 1992a). This model proved to be relatively simple and powerful and was later accepted as the de-facto standard by almost all educational and many non-educational adaptive hypermedia systems.

Domain models in AEH systems seriously differ in complexity. Some systems developed for teaching practical university courses employed only the simplest vector domain model (Brusilovsky & Anderson, 1998; De Bra, 1996). At the same time, a number of modern AEH systems use sophisticated ontology-based networked models with several kinds of links that represent different kinds of relationships between the KE. The most popular kind of links in AEH are *prerequisite links* between the KE. A prerequisite link represents the fact that one of the related KE has to be learned before another. Prerequisite links are relatively easy to understand by authors of educational systems and can support several adaptation and user modeling techniques. In many AEH systems, prerequisite links are the only kind of links between KE (Davidovic, Warren & Trichina, 2003; Farrell et al., 2003; Henze & Nejdl, 2001; Papanikolaou et al., 2003). Other types of links which are popular in many systems are the classic semantic links, "is-a" and "part-of" (De Bra, Aerts & Rousseau, 2002a; Hoog et al., 2002; Steinacker et al., 2001; Trella, Conejo & Bueno, 2002; Vassileva, 1998). The popularity of these links is currently increasing following the expanded use of more formal ontologies in place of domain models (Dagger, Wade & Conlan, 2004; Mitrovic & Devedzic, 2004; Trausan-Matu, Maraschi & Cerri, 2002).

Another difference in complexity is related to the internal structure of concepts. For the majority of AEH systems, the domain concepts are nothing more than names that denote fragments of domain knowledge. At the same time, some AH systems use a more advanced frame-like knowledge representation; i.e., represent the internal structure of each concept as a set of attributes or aspects (Beaumont, 1994; Brusilovsky & Cooper, 2002; Hohl et al., 1996; Weber & Brusilovsky, 2001).

2.3 THE STUDENT MODEL

One of the most important functions of the domain model is to provide a framework for representation of the user's domain knowledge. The majority of AEH systems use an *overlay model* of user knowledge (also known as an overlay student model). The overlay model was also inherited from the field of ITS. The key principle of the overlay model is that for each domain KE, the individual user knowledge model stores some data that is an estimation of the user's knowledge level for this KE. In the simplest (and oldest) form, it is a binary value (known – not known) that enables the model to represent the user's knowledge as an overlay of domain knowledge. While some successful AEH systems (De Bra, 1996) use this classic form of an overlay model, the majority of systems use a weighted overlay model that can distinguish several levels of the user's knowledge of a KE through a qualitative value (Brusilovsky & Anderson, 1998; Papanikolaou et al., 2003) (for example, good-average-poor), an integer numeric value (for example, from 0 to 100) (Brusilovsky et al., 1998; De Bra & Ruiter, 2001), or a probability that the user knows the concept (Henze & Nejdl, 1999; Specht &

Klemke, 2001). A few AEH systems use an even more sophisticated *layered overlay model* (Brusilovsky & Millán, 2007) to store multiple evidences about the user's level of knowledge separately (Brusilovsky & Cooper, 2002; Brusilovsky, Sosnovsky & Yudelson, 2005; Weber & Brusilovsky, 2001). The level of sophistication in student modeling has been constantly increasing to support increasingly sophisticated personalization needs and we expect this process will continue in the context of lifelong modeling (Kay & Kummerfeld, 2010).

All kinds of weighted overlay models are known to be powerful personalization tools due to their ability to independently assess and store the evidences of the user's knowledge about different KE. This power can be further extended by taking into account connections between KE represented in the domain model and using them for weight propagation between KE. Weight propagation increases the impact of a single observation (such as answering a single question) on the student model and decreases student modeling *sparsity*. Good examples of student models incorporating weight propagation are Bayesian student models (Brusilovsky & Millán, 2007; Conati, 2010; Conati, Gertner & Vanlehn, 2002; Zapata-Rivera & Greer, 2003).

2.4. CONNECTING KNOWLEDGE WITH EDUCATIONAL MATERIAL

The complexity of an AEH system depends to a large extent on the complexity of the *knowledge indexing* approach it uses. In the AEH literature, *indexing* denotes the process of connecting domain knowledge with educational content, i.e, specifying a set of underlying KE for every page or fragment of educational content. This process is very similar to traditional indexing of a page using a set of keywords. The literature distinguishes four aspects of indexing approaches: cardinality, granularity, navigation, and expressive power (Brusilovsky, 2003). The first two are most important in the context of this paper.

From the *cardinality* aspect, there are essentially two different cases: single KE indexing where each fragment of educational material is related to one and only one domain model concept, and multi-concept indexing where each fragment can be related to many concepts. Single KE indexing is simpler and more intuitive for the authors. Multi concept indexing is more powerful, but it makes the system more complex and requires more skilled authoring teams.

Expressive power concerns the amount of information that the authors can associate with every link between a concept and a page. Of course, the most important information is the very presence of the link. This case is called *flat indexing* and it is used in the majority of existing systems. Still, some systems with a large hyperspace and advanced adaptation techniques want to associate more information with every link by using roles and/or weights. Assigning a role to a link helps to distinguish several kinds of connections between concepts and pages. For example, some systems want to distinguish between a case where a page provides an introduction, a core explanation or a summary of a KE and a case where it provides only a core explanation of the KE (Brusilovsky, 2000) or even some domain-specific aspects of a KE (Brusilovsky & Cooper, 2002). Other systems use the *prerequisite* role to mark the case where the KE is not presented on a page, but it is required to understand it (Brusilovsky et al., 1998; Holden, 2003).

Existing AH systems suggest various ways of indexing that differ in all aspects listed above. However, all this variety can be described in terms of three basic approaches that are explored in the remaining part of this paper. Systems using the same indexing approach have similar hyperspace structure and share specific adaptation techniques that are based on this structure. Thus, the indexing approach selected by developers to a large extent defines the functionality of an AEH system.

3. Concept-Based Hyperspace: The Case of QuizGuide

The simplest approach to organizing connections between knowledge space and hyperspace is known as *concept-based hyperspace*. This is the organization approach used in an AEH system that uses single-KE indexing. In systems with *simple concept-based hyperspace*, the hyperspace is built as an exact replica of the domain model. Each KE (concept) of the domain model is represented by exactly one node of the hyperspace, while the links between the KE constitute main paths between hyperspace nodes. This approach was quite popular among early AEH systems (Brusilovsky, Pesin & Zyryanov, 1993; Hohl et al., 1996). Its current use is limited to developing encyclopedically structured learning material such as encyclopedias (Bontcheva & Wilks, 2005; Milosavljevic, 1997) and glossaries (Brusilovsky et al., 1998; Weibelzahl & Weber, 2003). For other kinds of practical AEH systems, multiple pages of educational material can be created to teach the same domain model concept.

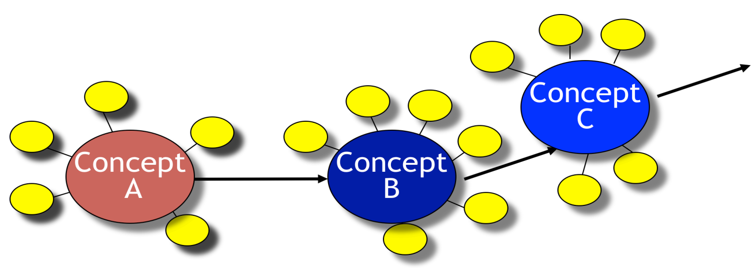

Figure 2. An enhanced concept-based hyperspace

A typical AEH system with rich content and single-concept indexing uses an *enhanced concept-based hyperspace* design approach. With this design approach, multiple pages describing the same concept are connected to this concept in both the information space and hyperspace. Each concept has a corresponding “hub” page in the hyperspace. The concept hub page is connected by links to all educational hypertext pages related to this concept. The links can be typed and weighted (Papanikolaou et al., 2003), although it is not necessary for using the approach. The student can navigate between hub concept pages along conceptual links and from hub pages to the pages with educational material. An even faster approach to navigate to specific KE and associated educational content can be provided by a visual representation of the domain model (also known as a domain map), which is used in AEH systems such as AES-CS (Triantafillou, Pomportis & Demetriadis, 2003). The enhanced concept-based hyperspace approach was used to create relatively large AEH systems with quite straightforward structure, and allows for a number of adaptation techniques (Kavcic, 2004; Papanikolaou et al., 2003; Steinacker et al., 2001).

Either form of concept-based hyperspace design approach provides excellent opportunities for adaptive navigation support technologies such as link annotation. For example, ISIS-Tutor (Brusilovsky & Pesin, 1998), InterBook (Brusilovsky et al., 1998), and INSPIRE (Papanikolaou et al., 2003) used annotated links to the concept hub page featuring special font colors and icons to express the current educational state of the concept (not known, known, well known). ISIS-Tutor (Brusilovsky & Pesin, 1998), AES-CS (Triantafillou et al., 2003), ELM-ART (Weber & Brusilovsky, 2001), and a number of other systems use annotation to show that a concept page is not ready to be learned (i.e., its prerequisite concepts are not yet learned). Hiding technology can be used to hide links to pages representing KEs, which have prerequisites not yet learned (Brusilovsky & Pesin, 1998; Kavcic, 2004) or which do not belong to the current educational goal (Brusilovsky et al., 1998; Papanikolaou et al., 2003).

A good example of a practical system with enhanced concept-based hyperspace is QuizGuide (Brusilovsky, Yudelson & Sosnovsky, 2004), an adaptive front-end to a collection of interactive self-assessment questions in the domain of C programming. The domain model in QuizGuide was formed by 22 *topics* such as *variables, constants* or *character processing*. In contrast to more traditionally used *concepts*, topics are coarse-grain knowledge elements: each topic covers a relatively large fraction of domain knowledge. QuizGuide topics were connected by prerequisite relationships forming a network domain model. The educational content in the system was formed by a set of more than 40 programming quizzes (each comprised of several questions). Each quiz was classified under one of the domain topics. Most of the topics have several quizzes associated with them, thus forming a clean example of enhanced concept-based hyperspace, as shown in Fig. 2.

The topic-level domain model was made visible in the QuizGuide interface (Fig. 3) in the form of a linear topic map. Each topic name works as a link. When a student clicks on the link, the topic opens and expands the links to quizzes available for this topic. A click on a quiz link loads the first question in the quiz presentation area. A click on an opened topic collapses the list of topic questions.

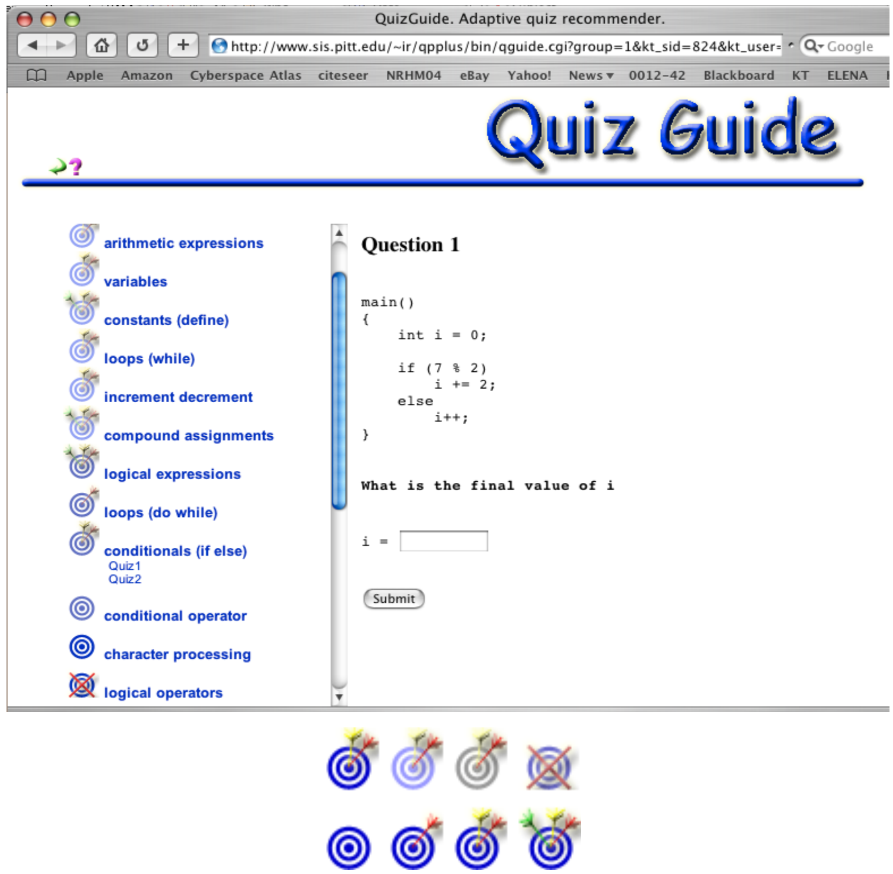

Figure 3. (a) Links to topics in QuizGuide Interface were annotated with adaptive target-arrows icons displaying educational states of the topics.
(b) goal adaptation is shown by the color of the target and knowledge adaptation is indicated by the number of errors.

Adaptive navigation support is provided in the quiz navigation area thorugh adaptive icons shown to the left of each topic. QuizGuide adapts to the most critical characteristics of the user: the knowledge level and the learning goal. To reflect both the goal and knowledge relevance of each topic in one icon, QuizGuide uses the "target-arrow" abstraction (Fig. 3). The number of arrows in the target reflects the level of knowledge the student has acquired on the topic: the more arrows the target has, the higher the level of knowledge. The intensity of the target's color shows the relevance of the topic to the current learning goal: the more intense the color is, the more relevant the topic. Current topics are indicated by the bright blue targets and their direct prerequisites are indicated by dimmer blue targets and so on. Topics that are not ready to be studied are annotated with the crossed target. In total, there are four levels of knowledge (from zero to three arrows) and four levels of goal relevance (not-ready, important, less-important and non-important). Since the student goals and knowledge are constantly changing, different icons will be shown practically each time the student accesses QuizGuide. To reflect changes in the user model that happened during the same session, the student can click on the refresh icon.

Despite a relatively simple hyperspace structure and adaptation approach, the navigation support provided by QuizGuide resulted in a remarkable impact on student performance and motivation to work with the system. In comparison with QuizPACK (Brusilovsky & Sosnovsky, 2005b), an earlier version of the system which provided access to the same quizzes with no navigation support, the average knowledge gain (a difference between post-test and pre-test results on a 10-point test) for the students using QuizGuide increased from 5.1 to 6.5. By guiding students to the right topics at the right time, the system caused a significant increase in the percentage of correctly answered questions from 35.6% to 44.3% (Brusilovsky & Sosnovsky, 2005a). Most remarkable, however, was an increase in the students' interest in working with the system. The number of attempts, the percentage of students using the system actively, and the percentage of attempted topics increased significantly (Brusilovsky & Sosnovsky, 2005a). The remarkable effects of QuizGuide on student performance and motivation were discovered first in 1994 and confirmed in several other studies (Brusilovsky, Sosnovsky & Yudelson, 2009). Moreover, a re-implementation of QuizGuide's adaptive navigation support approach for SQL (Sosnovsky et al., 2008) and Java programming (Hsiao, Sosnovsky & Brusilovsky, 2009) confirmed this impact in two other domains.

4. Page Indexing: The Case of InterBook

The *page indexing* approach is typically used in cases when the volume of educational content is relatively large and when it is desirable to increase the precision of user modeling using finer-grained KE (which are most frequently referred to as *concepts*). In these cases, page indexing (the most straightforward implementation of multi-concept indexing) becomes very attractive. With this approach, the whole hypermedia page (node) is indexed with domain model concepts. In other words, links are created between a page and each concept that is related to the content of the page (as shown in Fig. 1). The simplest indexing approach is flat content-based indexing, where a concept is included in a page index if some part of this page presents the piece of knowledge corresponding to the concept (Brusilovsky & Pesin, 1998; Henze & Nejdl, 2001). A more general – but less often used – way to index the pages is to add the role for each concept in the page index (role-based indexing). The most popular role is "prerequisite": a concept is included in a page index if a student has to know this concept to understand the content of the page (Brusilovsky et al., 1998; De Bra, 1996; Holden, 2003). Other roles can be used to specify the kind of contribution that the page is providing to learning this concept (introduction, main presentation, example, etc). Weights also can be used in multi-concept page indexing to show how much the page contributes to learning the concept (De Bra et al., 2002b).

A good example of the page indexing approach is provided by InterBook (Brusilovsky et al., 1998), one of the first authoring systems for developing AEH. ACT-R allowed the authors to create a domain-based *bookshelf* containing a set of *electronic textbooks* on the same subject. All books on the same bookshelf were indexed by concepts from the domain model associated with this bookshelf using the page indexing approach. For example, each section (page) of each textbook was connected to all concepts related to that section. The original version of InterBook supported role-based indexing with two roles: a concept can be either a prerequisite or an outcome of a page. The domain model also defined the structure for an overlay *student model*. As an authoring system, InterBook allowed flexibility in defining thresholds for the different states of domain knowledge; however, almost all AEH systems produced with InterBook distinguished four states of student knowledge of a concept: "unknown", "known" (learning started), "learned" and "well-learned".

The hyperspace of each bookshelf was formed by a set of *electronic textbooks* and a bookshelf *glossary.* Textbooks were hierarchically structured into units of different levels: chapters, sections, and subsections. As explained above, each of these units was indexed with prerequisite and outcome concepts. Unless hidden by settings, this indexing was clearly visible on the border of the textbook page of InterBook (Fig. 4).

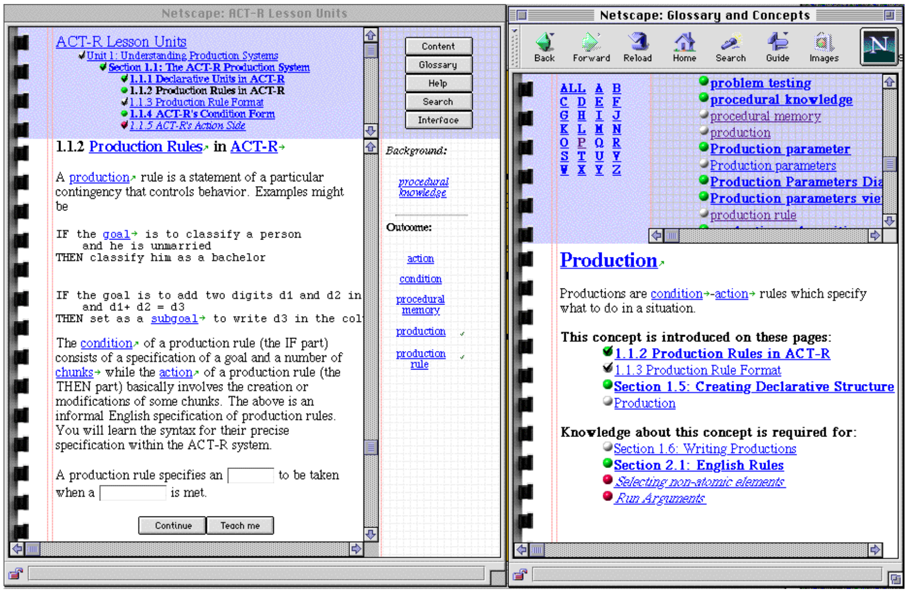

Figure 4. A textbook page and a glossary page in InterBook. Links to textbook sections are annotated with colored bullets indicating educational states of the pages. Links to glossary pages (which represent one concept each) are annotated with checkmarks of different sizes indicating the current knowledge level of the explained concept.

The glossary was simply the visualized domain network. Each node of the domain network was represented by a glossary page with links between domain model concepts serving as navigation paths between corresponding glossary pages. Thus, the structure of the glossary resembled the pedagogic structure of the domain knowledge. In addition to providing a description of a concept, each glossary page provided links to all of the book sections which introduced or required the concept (Fig. 4). This means that the glossary integrated traditional features of an index and a glossary. Vice versa, concept names mentioned in the text or on the border of textbook pages served as links to glossary pages.

The hypertext structuring approach supported by InterBook produced a rich interlinking space with many links both within the textbook and glossary components and between these components. To help guide users to the most appropriate information in this multitude of links, InterBook used two types of link annotation. Links to glossary pages were annotated with checkmark icons of several sizes: the more knowledge of this concept registered in the student model, the larger the size of the annotating checkmark. Links to book sections were annotated with bullet icons of three different colors. The bullet color (and the link font) indicated the current educational state of the section, which was determined through tracking of user reading. White bullets indicated pages with already learned outcome concepts. Green bullets indicated, “ready to be learned” pages (some new outcome concepts, but all prerequisite concepts learned already). Red bullets marked those pages which the system considered “not ready to be learned” (some prerequisite concepts were not yet learned). The icon and the font of each link presented to the student were computed dynamically from the individual student model. The goal of the latter approach was to guide the users to interesting “ready to be learned” pages, while discouraging them from spending too much time on “already learned” or “not ready to be learned” pages. To provide additional guidance, the educational state of the current page was shown by a bar of the corresponding color at the top of the page. Needless to say, these link and text annotations were generated dynamically taking into account the current state of individual student knowledge.

While the adaptive navigation support provided in InterBook was relatively simple, it had a significant impact on student navigation and learning (Brusilovsky & Eklund, 1998). It increased student non-sequential navigation (i.e., use of links beyond “back” and “continue”) and helped students who followed the system’s guidance to gain better knowledge of the subject. The prerequisite-based “traffic light” annotation approach introduced originally in ELM-ART (Weber & Brusilovsky, 2001) and popularized by InterBook, was later successfully applied in a number of other systems (Carmona et al., 2002; Henze & Nejdl, 2001; Kavcic, 2004).

5. Fragment Indexing: The Case of ADAPTS

Fragment indexing is still a relatively rare indexing approach, but it is the most precise one. The idea of the approach is to divide the content of each hypermedia page into a set of fragments and to index some (or even all) of these fragments with domain model concepts, which are related to the content of these fragments. Similar to the page indexing approach, it can be used even with unstructured vector domain models. The difference is that indexing is done on a more fine-grained level. Generally, multi-concept indexing is used. With smaller fragments, it is often possible to use exactly one concept to index a fragment. In both cases, the fragment indexing approach gives the system more precise knowledge about the content of the page: the system knows what is presented in each indexed fragment. This knowledge can be effectively used for advanced adaptive presentations. Depending on the level of user knowledge about the concepts presented in a particular fragment, the system can hide the fragment from the user (De Bra & Calvi, 1998; Stern & Woolf, 2000), shade it (Hothi et al., 2000), or choose one of several alternative ways to present it (Beaumont, 1994). One of the problems in fragment-based content adaptation, especially in its versions which hide some part of the page from users, is the lack of control from the user side. In case of user modeling or adaptation errors, a user may miss some valuable information without knowing of its existence. Several approaches were suggested to return ultimate control over the process to the user. For example, Kay (2006) argues for *scrutable* content adaptation where a user can opt to see all content along with an explanation of which parts were hidden and why. Tsandilas and schraefel (2004) suggest sliders as a way for the user to control fragment adaptation. Höök (1996) explored *adaptive stretchtext* – a specific kind of hypertext where both the user and the system can decide which fragments are hidden or visible.

A good example of a system with fragment indexing and adaptive stretchtest is ADAPTS (Brusilovsky & Cooper, 2002), a system for workplace training and performance support developed for avionics technicians. ADAPTS is able to guide the user through the troubleshooting process building a plan of action adapted to the users' knowledge. At each step of the plan, the system uses adaptive content selection and adaptive stretchtext to bring up the most relevant information (i.e., the information which matches user goals and knowledge) from gigabytes of information stored in an interactive electronic technical manual (IETM). The goal of this information is to help the user in performing this step and to expand his knowledge (Fig. 5).

As in other AEH systems, the key to the intelligent performance of ADAPTS is the domain model. ADAPTS uses a standard concept network approach to domain modeling; however, due to the complexity of the domain, its domain network is very large. The network is formed by two main types of domain concepts: a component and a task, which form two separate hierarchies. One hierarchy is a tree of components: from the whole aircraft at the top, to subsystems, to sub-subsystems, down to elementary components called addressable units. Another hierarchy is a tree of tasks: from big diagnostic tasks that are handled by the diagnostic engine, to subtasks, and then to elementary steps. The two hierarchies are tightly interconnected because each task is connected with all components involved in performing the task.

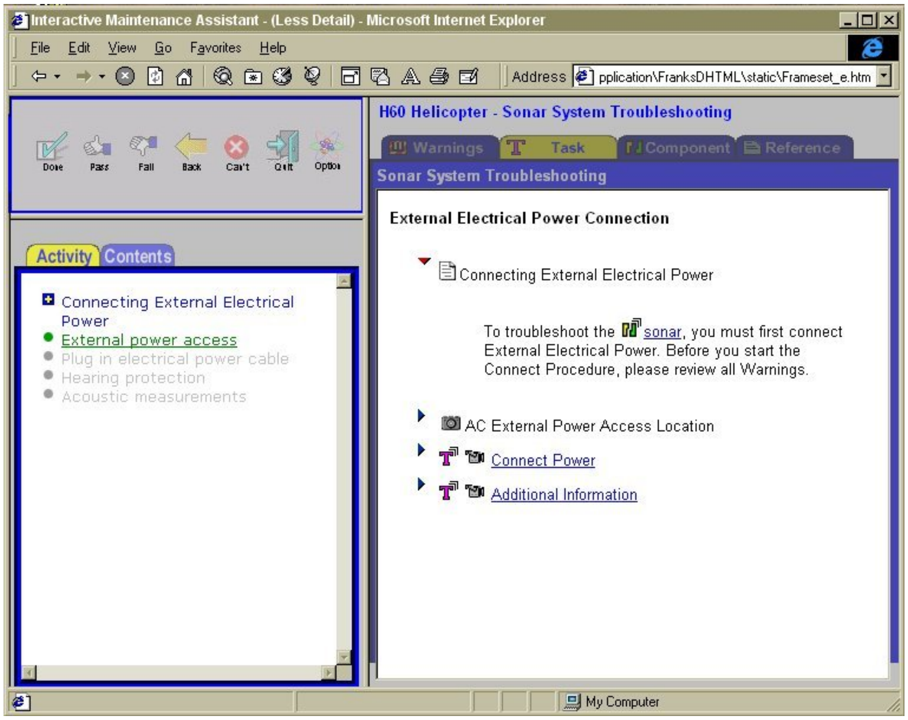

Figure 5. When presenting supporting information for a troubleshooting step, ADAPTS uses the strerchtext approach (right): depending on user goal and knowledge, fragments can be shown or hidden; however, the user can override system's selection.

To support the user in performing a diagnostic task, ADAPTS uses *rich content* stored in the IETM database. In addition to textual documents and diagrams, the rich content includes various pieces of multimedia: color photos, training videos, animations, and simulations. Moreover, the rich content includes variations of the same information fragments oriented to users with different levels of experience. One of the functions of ADAPTS is to find pieces of the rich content that are relevant to the selected subtask, and to adaptively present it to the user. To deal with large volumes of rich content, ADAPTS uses a very elaborate indexing approach, which is explained in detail in (Brusilovsky & Cooper, 2002). In addition to other types of indexing, ADAPTS uses role-based indexing with components.

Conceptually, this means that each fragment of the rich content is linked by *typed* (categorized) links with all components *involved in* this fragment. The type of link indicates the kind of involvement (i.e., its role). For example, a piece of video that shows how to remove a component is indexed with a component-role pair *(component ID, role=removal).* Similarly, a figure that shows the location of a component is indexed with a component-role pair *(component ID, role=location).*

To match the complexity of the domain model and content indexing, ADAPTS uses a layered multi-aspect overlay user model. A technician's experience with a concept can be judged on many aspects, each weighted to indicate its relative influence on the decision. The user model independently accumulates several aspects (roles) of the experience as well as the knowledge of each technician about each concept as defined in the domain model. From this record, ADAPTS uses a weighted polynomial to estimate the proficiency of a user in locating, operating, and repairing equipment or performing each step of a recommended procedure. The weighting of aspects can be adjusted for different individuals. Factors measured in the ADAPTS prototype include whether and how often a technician has reviewed, observed, simulated, expressed understanding (self- evaluation), previously worked on, or received certification on specific equipment or procedures.

6. Adaptive Educational Hypermedia in a Broader Context

The paper provided a brief overview of adaptive educational hypermedia. As shown by multiple examples cited in the paper, AEH technology is rich and flexible. It supports a range of personalization scenarios and offers multiple ways to guide a student to the most relevant learning context – presentation, examples, problems, etc. While working well in multiple contexts, AEH is not a silver bullet and it has to be applied with an understanding of its limitations. To start with, AEH needs to work with a hyperspace. Hyperspace provides the best fit for educational applications, which already use hypertext to present various education-oriented information (i.e., educational encyclopedia) or to provide access to rich learning content (i.e., a typical Web-based education system). It is also a good choice for any educational system that needs to operate with a large number of information items, examples, or tasks. Even if this information is not yet hyperlinked, it is typically not hard to structure it as a hyperspace and AEH technologies can provide additional help by offering semantic links. At the same time, AEH is just one of many kinds of adaptive educational systems (Shute & Zapata-Rivera, 2010). AEH provides neither a step-by-step problem solving support as many ITS do, nor tools for groupwork or collaboration as collaborative learning systems. It means that a really versatile educational and training system should not be limited to AEH technology alone, but should wisely use a combination of technologies to support multiple needs of students and trainees. We hope that this book as a whole provides a well-balanced overview of many technologies and will enable the designers of educational and training systems to create rich and balanced systems in which AEH serves as one of the primary components.

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