Adaptive Hypermedia Technology for Multi-Intelligent Online Learning

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Introduction

Coupled with a theoretical foundation in cognition and learning, and an educational methodology based on cognitive constructivism (Chen, 2002) and the Theory of Multiple Intelligences (Gardner, 1983/1993), the research in Multi-Intelligent Online Learning builds on a technology foundation from adaptive hypermedia and online learning technology. The shaded rectangles on the right side of Figure 1 depict the technology foundation and the underlying schemata of the research. This paper provides a review of relevant literature and prior work in the fields of adaptive systems, intelligent tutoring systems, and adaptive hypermedia. Along with Web technologies for online learning (Dara-Abrams, 2002i), these areas of Computer Science provide the technological underpinnings for the research conducted for the Ph.D. in Computer Science and Educational Psychology, described in the dissertation entitled *Applying Multi-Intelligent Adaptive Hypermedia to Online Learning* (Dara-Abrams, 2002a).

To understand the research undertaken in Multi-Intelligent Online Learning, the reader is referred to a companion paper entitled *Overview of Research Study in Multi-Intelligent Online Learning* (Dara-Abrams, 2002g). The methodology of the research study is described in the companion paper entitled *Methodology of Research Study in Multi-Intelligent Online Learning* (Dara-Abrams, 2002f).

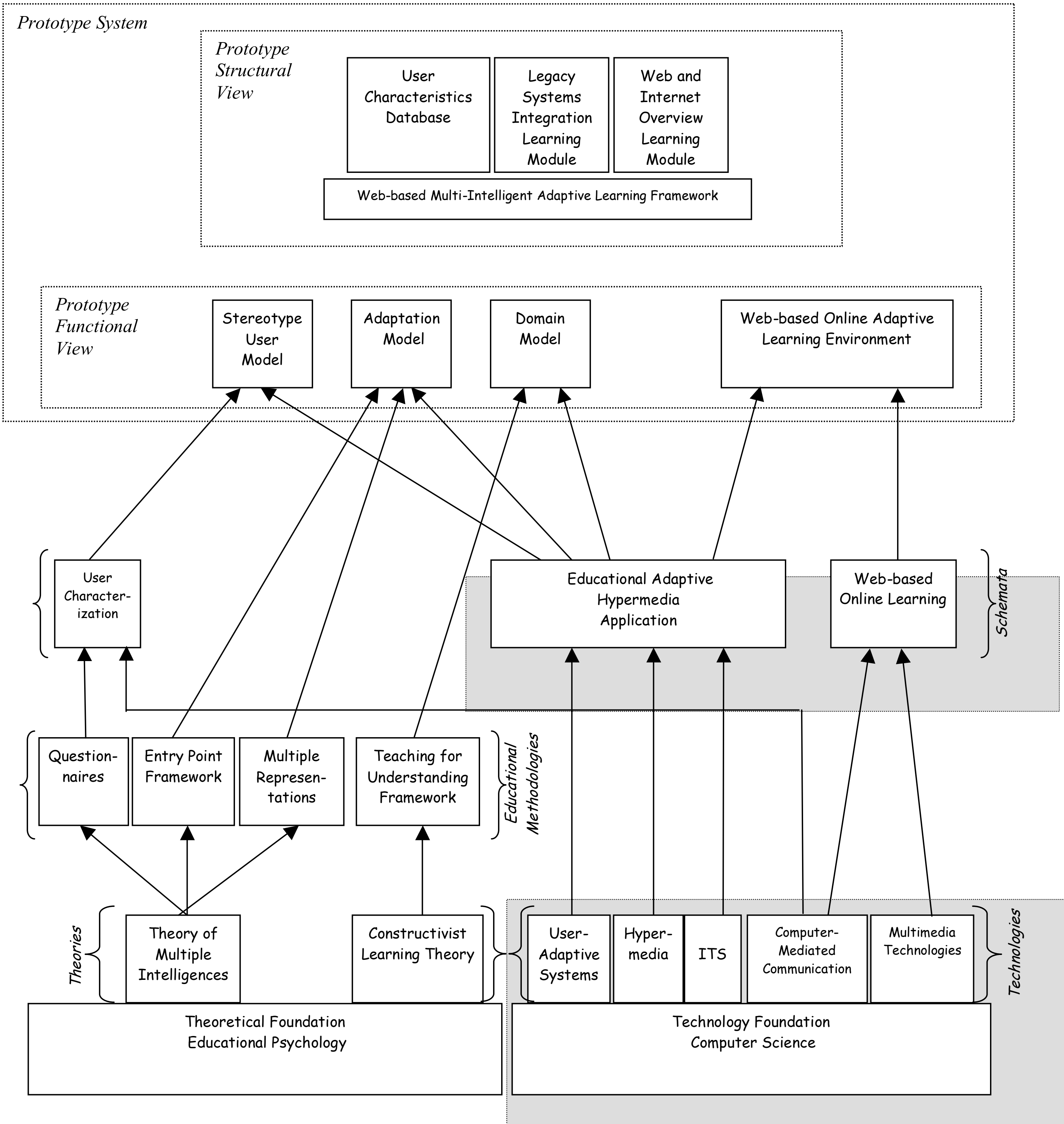
For information on the theoretical underpinnings of the study, the reader should consult the companion paper entitled *Theoretical Foundation in Educational Psychology for Multi-Intelligent Online Learning* (Dara-Abrams, 2002h). The educational methodologies that are employed in the Multi-Intelligent Online Learning prototype are described in the paper entitled *Educational Methodologies for Multi-Intelligent Online Learning* (Dara-Abrams, 2002d). The adaptive hypermedia technology described in this paper is used to instantiate the theory and educational methodologies discussed in these two companion papers.

In addition, Web-based online learning technologies are used to design and implement the prototype Multi-Intelligent Online Learning framework and modules. The Web-based technologies that are employed are described in the companion paper entitled *Web Technologies for Multi-Intelligent Online Learning* (Dara-Abrams, 2002i). The adaptive hypermedia technology and Web-based online learning technology described in this paper and the companion paper on Web technologies contribute to the development of the prototype, which is described in the companion paper entitled *Design and Implementation of a Multi-Intelligent Online Learning Prototype* (Dara-Abrams, 2002c). The companion papers entitled *Formative Evaluation of a Multi-Intelligent Online Learning Prototype* (Dara-Abrams, 2002e) and *Conclusions of Research Study in Multi-Intelligent Online Learning* (Dara-Abrams, 2002b) describe the results of using the Multi-Intelligent Online Learning prototype and interpret the formative evaluation data in terms of the conclusions and implications that can be drawn from the research study.

Let us focus now on the technology that underlies the development of Multi-Intelligent Online Learning. In order to understand the technology used in an online adaptive learning system, it is important to have an understanding of what adaptive systems are. Therefore, this paper begins with an overview of the field of adaptive systems. Then, in order to understand how online learning systems have evolved to their present state, it is useful to have an understanding of intelligent tutoring systems. A critical piece to understand in intelligent tutoring systems and adaptive learning systems is the use of student, learner, or user modeling. The components of adaptive learning systems under development are presented to complete the overview of intelligent tutoring and adaptive learning system technology, constituting prior work that provides a technology foundation for the dissertation research.

Next we move on to building an understanding of adaptive hypermedia, a combination of the technologies of hypermedia and user-adaptive systems. Adaptive hypermedia methods and techniques are employed in the design of the prototype adaptive hypermedia learning modules, and an understanding of these technologies is fundamental to understanding the prototype online adaptive learning environment. Therefore, we delve into a technical overview of adaptive hypermedia systems, discussing applications of adaptive hypermedia, a reference model for adaptive hypermedia applications, user modeling in adaptive hypermedia, and a classification of adaptive hypermedia systems. The final section is critical to the development of the prototype adaptive learning modules, providing an overview of adaptation methods and techniques that are used in adaptive hypermedia applications, such as the prototype learning environment.

Figure 1 Technology Foundation of Multi-Intelligent Online Learning in Computer Science



Adaptive Systems

The Oxford English Dictionary defines the verb *adapt* as "to fit (a person or thing *to* another, *to* or *for* a purpose), to suit, or make suitable" (Simpson & Weiner, 1989, p. 139). The word *adaptation* is defined as "the action or process of adapting, fitting, or suiting one thing *to* another" (Simpson & Weiner, p. 139). A specific definition applied to biology defines *adaptation* in the following way: "organic modification by which an organism or species becomes adapted to its environment" (Simpson & Weiner, p. 139). The adjective *adaptive* is defined as "characterized by, or given to adaptation" (Simpson & Weiner, p. 139).

Adaptive systems are studied in different scientific domains:

- Biological systems
- Physical systems
- Artificial systems

A number of researchers have observed similarities in adaptation across these domains and have attempted to develop theories to explain the similarities in form among biological, physical, and man-made adaptive mechanisms. One of these approaches is an area of applied mathematics known as complex adaptive systems (*cas*) theory. John Holland, a leading researcher in *cas* theory, defines adaptation as "changes in structure (strategy) based on system experience" (Holland, 1995, p.9). Holland expands on his definition of adaptation based on its usage in biological systems, viewing adaptation as "the process whereby an organism fits itself to its environment. Roughly, experience guides changes in the organism's structure so that as time passes the organism makes better use of its environment for its own ends. Here we expand the term's range to include learning and related processes. With this extension, adaptation applies to all *cas* agents, despite the different timescales of different *cas* processes" (Holland, 1995, p. 9, italics added).

In his book *Hidden Order*, Holland considers the source of the complexity in *cas*: "Overall, then, we will view cas as systems composed of interacting agents described in terms of rules. These agents adapt by changing their rules as experience accumulates. In *cas*, a major part of the environment of any given adaptive agent consists of other adaptive agents, so that a portion of any agent's efforts at adaptation is spent adapting to other adaptive agents. This one feature is a major source of the complex temporal patterns that *cas* generate. To understand *cas* we must understand these ever-changing patterns" (Holland, 1995, p. 10, italics added).

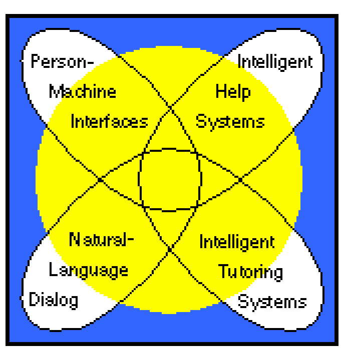
Research in complex adaptive systems theory offers models for growth and change in various types of biological, physical, and artificial systems. Adaptive mechanisms observed in physical systems, such as those found in the fields of geology, astronomy, physics, and chemistry, are often surprisingly similar to those found in biological systems. However, the complexity of the adaptation is greater in biological systems than in physical systems. Both physical and biological adaptive mechanisms provide models for artificial or man-made systems.

Proceeding in two different directions, artificial or man-made adaptive systems vary based on who or what is doing the learning. Studying adaptation in artificial systems, research centers on two areas:

- Systems that modify their behavior based on what the systems themselves learn.
- Systems that fit their behavior to models of users in order to help human users learn.

A relatively new journal (published quarterly since 1991), *User Modeling and User-Adapted Interaction (UMUAI)* offers a useful perspective on adaptive systems. The journal "provides an interdisciplinary forum for the dissemination of new research results on interactive computer systems that can be adapted or adapt themselves to their current users, and on the usage of user models for adaptation purposes" (http://umuai.informatik.uni-essen.de/). Figure 2 shows the UMUAI logo, illustrating the interdisciplinary fields addressed by the journal (http://umuai.informatik.uni-essen.de/).

Figure 2 UMUAI logo



Intelligent Tutoring Systems

In the introduction to their book entitled *Intelligent Tutoring Systems*, Sleeman and Brown state that, "one of the original goals for ITS was to extend the domain of applicability, the power, and the accuracy of adaptive systems" (Sleeman & Brown, 1982, p. 1). In order to understand advances in Intelligent Tutoring Systems (ITS), this section provides a brief overview of ITS, considering earlier developments underlying ITS and the differences between Computer Assisted (or Aided) Instruction (CAI) and ITS as well as the architecture of ITS, learner modeling in ITS, and adaptive learning systems.

History

According to Yazdani, (Lawler & Yazdani, 1987), the precursor to Computer Assisted (or Aided) Instruction (CAI) was the programmed learning machine of the 19th century. In the 1950s with the availability of computers, CAI programs offered simple learning sequences for students to follow. Based on the belief of Skinner and other behaviorists that reinforcement increases the strength of association between concepts, CAI programs presented pieces of text that led students step-by-step toward the desired outcome. The student then performed exercises based on the knowledge he/she had acquired and the CAI program responded by informing the student of the correctness of his/her response. A sequence of such programmed steps constituted a "linear program." Progressing through the material step-by-step allowed each student to proceed at his/her own pace, receiving immediate feedback on the correctness of his/her responses.

In the 1960s, CAI programs were enhanced by using the student's response to determine the next piece of information to be presented (Lawler & Yazdani, 1987). Programs could then follow different branches, allowing students to skip steps and move more quickly through the material while others could move at a slower pace and receive assistance. Not only did these "branching programs" offer immediate corrective feedback, but also they adapted their response to the responses of the student. Since designing instructional materials to follow every possible branch is extremely labor-intensive, "author languages" were developed to support CAI.

Early generative CAI systems were developed in the mid to late 1960s by Uhr and his colleagues (Uhr, 1969), who developed CAI systems that generated arithmetic problems and vocabulary-recall exercises (Sleeman & Brown, 1982). Researchers such as Suppes (1967) and Woods and Hartley (1971) developed CAI systems that drilled students in arithmetic and matched the level of difficulty of problems to the student's performance level (Sleeman & Brown, 1982).

While CAI systems improved dramatically during the 1970s, they could not compare with human teachers who possess a far greater knowledge base (Lawler & Yazdani, 1987). In generative CAI systems, the program's internal processes were represented by Boolean arithmetic while students' cognitive processes were presented by rules and tables. In addition, generative CAI systems could only inform students when their answers were incorrect but could not explain "why" or "how."

In the 1980s, intelligent CAI sought to deal with the problems of generative CAI, resulting in the development of Intelligent Tutoring Systems (ITS) (Lawler & Yazdani, 1987). Benefiting from work in artificial intelligence (AI) and expert systems, "production systems" were used to represent knowledge and were found to be quite well suited to the domain of tutoring (Anderson, 1985). Production systems have been used to organize knowledge into facts (declarative knowledge about a specific case), rules (procedural knowledge about how to reason in a particular domain), and inference (control knowledge of how to devise a conclusion based on certain facts and rules) (Lawler & Yazdani, 1987).

Self discusses two major threads in ITS (Self, 1998):

- An individualized approach to learners rather than leading students step-by-step through programmed learning - the defining feature of ITS.
- Opportunity to systematically investigate teaching and learning processes.

To accurately represent knowledge, ITS models must also show connections between individual facts and procedures, not just individual pieces of knowledge (Psotka, Massey, & Mutter, 1988).

Types of ITS

Beck, Stern, and Haugsjaa (1996) classify ITS in various ways:

- Method used for abstraction of the learning environment - Some ITS use a simulated environment as an abstraction of the learning environment while others provide problem sets in an artificially constructed learning environment.
- Type of knowledge addressed in the instruction – Instruction is often categorized by subject matter, via approaches derived from Bloom's Taxonomy (Beck et al., 1996).
- Procedural skills vs. concepts and frameworks - Training students in developing procedural skills, systems employ a cognitive task analysis of expert behavior. Teaching concepts and frameworks, systems employ general teaching strategies and a larger knowledge base, focusing on effective communication (Beck et al., 1996).

Systems teaching procedural skills and concepts combine cognitive and knowledge based instructional approaches. These categories are points along a continuum.

<u>CAI and ITS</u>

Larkin and Chabay (1992) compare and contrast CAI and ITS as indicated in Table 1.

Table 1 Comparison between CAI and ITS

	CAI	ITS
Proponents	Experienced teachers. Educational researchers. Subject matter experts.	Researchers in cognitive psychology, computer science. Interest in developing principles of learning, applying principles to instructional programs.
Goals	Address existing needs of particular groups of students. Tailor programs to domain, topic, and targeted students.	Design and develop software embodying instructional principles to address range of teaching tasks.
Instructional modes	Based on subject matter experience. Activities designed to build and apply domain knowledge in varied contexts. Not necessarily traditional instructional practices.	Contains explicit model of instruction. Employs model of domain knowledge considered necessary to demonstrate mastery of particular subject.
Program structure	Interaction centered. Interaction via computer screen as way to learn material.	Knowledge centered. Interaction to support student performance of learning.
Implementation	Responsive interaction and interesting graphics on low-end machines in schools.	AI techniques and large knowledge bases. Rule-based knowledge acquisition.
Implications	Designed to support teaching of particular subjects. Based on developers' knowledge, experience in teaching material to students.	Based on learning theories. Systematic approach to master subject matter to match performance of domain experts.

Larkin and Chabay (1992) also discuss principles shared by CAI and ITS:

- Engage students in active work on central tasks – “Ask, don’t tell” constructivist approach, supporting active learning rather than passive viewing of text or graphics.
- User interface design – help with reasoning tasks through interaction with the screen.
- Center work on appropriate reasoning – supporting students’ active thinking and reasoning through problems, not just getting the right answer.
- Prompt feedback focusing attention on erroneous thinking – inform students of their errors right away so that they can build on correct fundamental knowledge.
- Adapt instruction to individual student knowledge – instruction at different levels depending on the needs and level of understanding of individuals.

ITS Architecture

In his seminal paper entitled *The design and evaluation of an adaptive teaching system*, Hartley (1973) established the basic model for intelligent tutoring systems (ITS). Hartley’s model for an ITS is composed of the following elements:

- Knowledge of the domain
- A learner model
- Knowledge about teaching.

Reflecting progress in ITS research, we see the addition of a fourth component in conferences and publications in the 1980s. In 1985, an international group of cognitive scientists convened in Tubingen, Germany. During their meetings, the group discussed the cognitive processes of learning and how these processes can be enhanced by intelligent instructional systems. The book entitled *Learning Issues for Intelligent Tutoring Systems* reflects the discussions during these meetings (Mandl & Lesgold, 1988). In his chapter entitled *Mental Models and Metaphors: Implications for the Design of Adaptive User-System Interfaces*, Streitz presents the knowledge such systems possess as including the same three elements as Hartley’s original model, with the addition of “the interaction process (modeling human-computer interaction)” (Streitz, 1988, p. 165).

In the proceedings from the Intelligent Tutoring Systems conference held in Vermont in October, 1986, Psotka, Massey, and Mutter (1988) define the architecture of an ITS as "a systematic approach to structuring the many components that comprise an effective, working ITS. Usually these consist of a student model, an organized domain of knowledge, instructional principles, and a tutorial interface" (Psotka et al., 1988, p. 533). Again, we see Hartley's original three components with the addition of the tutorial interface, the component Streitz refers to as the interaction process.

In his chapter *Research on Teaching and the Design of Intelligent Tutoring Systems*, Goodyear (1991) explains the types of knowledge formalized in ITS as follows:

- Domain knowledge - "most systems teach about some subject, about the content of some domain. In so far as they need to be able to solve problems in that domain, they need explicit representations of *domain knowledge*" (Goodyear, 1991, p. 8).
- Student or learner model – "most systems adapt their teaching to the needs of the particular learner with whom they are interacting, by building and dynamically updating some explicit representation of attributes of the learner (especially his or her presumed knowledge or misconceptions about the domain). Such representation is called a *student model* or *a learner model*, and the process involved in its construction and maintenance is sometimes referred to as cognitive diagnosis" (Goodyear, 1991, p. 8).
- Teaching knowledge - "Most systems have teaching knowledge, often explicitly represented as rules comprising one or more teaching strategies" (Goodyear, 1991, p. 8).
- Rules for dialogue or interface – "Many systems have some explicit representation of rules for dialogue, for conducting some form of conversation across the computer-learner interface. In earlier systems, this knowledge may often have been intimately bound up with the teaching knowledge. More recently, attempts are made to separate higher-level pedagogical reasoning from reasoning about the details of how to display a particular piece of information, for example" (Goodyear, 1991, p. 8).

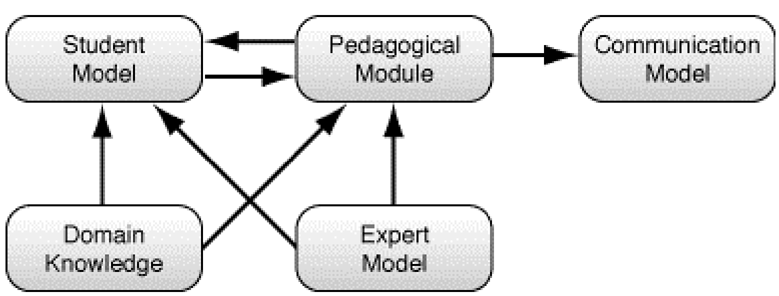
Burns and Capps (1988) extend the types of expertise required for an ITS to include the skills needed to implement and evaluate an ITS:

- Subject matter expertise
- Diagnostic expertise to determine what students know
- Instructional and curriculum expertise
- Expertise in designing instructional environments
- Expertise in human-computer interface (HCI)
- Implementation expertise
- Evaluation expertise

In more recent work, Beck et al. (1996) present a model of ITS containing five components. The pedagogical module encapsulates what Hartley refers to as knowledge about teaching; the communication model encapsulates what Goodyear refers to as rules for dialogue or user interface. Beck et al. expand the model to include an expert model.

The expert model provides a representation of the knowledge in a way that a person who is skilled in the subject matter represents such knowledge. In recent intelligent tutoring systems, the expert model is a runnable program with the facility to solve problems in the subject matter domain. The expert model is used to compare the learner's solution to the expert's solution; in this way, the intelligent tutor identifies specific points that the learner does not yet understand or topics the learner has not yet mastered. Figure 3 illustrates interactions among ITS components proposed by Beck et al. (listed as Figure 1 in Beck et al., 1996, p. 2).

Figure 3 ITS Components and Interactions



Learner Modeling

Psotka et al. define a student model as “the component of an ITS that is used to make inferences about a trainee’s state of knowledge. Various student modelling (sic) systems have been proposed: bug catalogs, overlay models, issue oriented models, coaching systems, and psychometric systems” (Psotka et al, 1988, p. 534). Issues arise concerning the amount and type of information that should be included in a student model. Some researchers recommend that student models only include information that can actually be used to tailor instruction (Beck et al., 1996). While the student model is designed to record the student's understanding of the domain, it is not clear what “grain size” of understanding should be represented. A model on one end of the spectrum might simply indicate whether the student knows the domain whereas a model on the other end might include a record of every student action. Most ITS represent domains in terms of topics and student models at the same granularity. Student models may include other pedagogical information, such as a student’s general learning preferences, for example, that the student prefers to see examples before answering questions (Beck et al., 1996).

Self (1988) identifies twenty different functions of student models categorized in six different ways. Corrective functions address misunderstandings, or “fix bugs” in procedural and conceptual knowledge. Corrective functions include the following:

- Bug identification – recognizing an error and letting the student know what is wrong.
- Direct remediation – presenting correct knowledge rather than errors.
- Indirect remediation – hint to help students figure out correct knowledge.
- Counterexample – examples that lead students to understand their errors.
- Solution tracing – breaking down steps of problem-solving process.
- Retrospection – walking through steps to show where student had a problem.
- Try again – offering remedial examples for students to work through.
- Tactical withdrawal – addressing knowledge that should have been gained.

Elaborative functions are useful when the student’s knowledge is incomplete and include:

- Curriculum-driven choice – topic and interaction based on overall approach.
- Expert-student comparison – topic based on expert and student knowledge.

- Internal analysis – contents of student model determine next topic.
- Learner control – allowing student to choose next topic.

Strategic functions allow the student model to change plans. Such functions include:

- Change of plan – modification of direction to explain related concepts.
- Modus operandi – changes in interaction style with student, based on traits.

Diagnostic functions are used when the model is not clear on what action to follow next:

- Diagnose student model – asking student for help to clear up confusion.
- Diagnose student – providing student examples of varying hypotheses.

Predictive functions in the student model include the following:

- Performance prediction – focusing on items that require interpretation.
- Learning prediction – modeling learning to predict effect of instruction.

Evaluative functions use the student model to evaluate the student and the system itself.

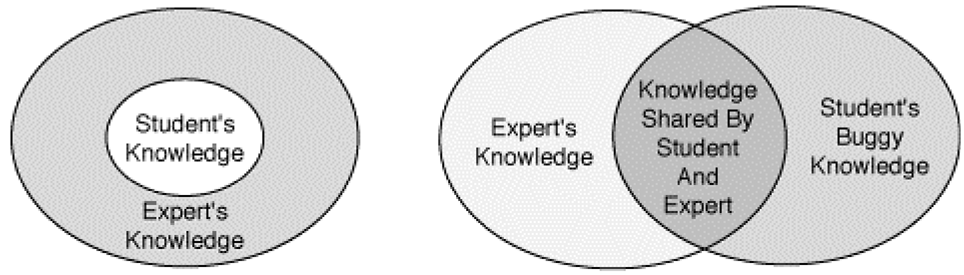
- Student evaluation – appraising state of student's knowledge.
- System evaluation – simulating student to predict outcome of teaching.

<u>Overlay models.</u>

The standard student model is an overlay model in which a student's knowledge is considered to be a subset of that of a subject matter expert (Beck et al., 1996). An overlay model is defined as a "student modelling (sic) technique in which a trainee performance is measured against the standard of an expert's model" (Psotka et al., 1988, p. 534).

An extension of the overlay model includes the student's misconceptions or "buggy" knowledge (Beck et al., 1996). In Figure 4 (b), we see the student's knowledge including misconceptions or "buggy" knowledge. The student model keeps track of errors made by the student and records them in a bug catalog, "a set of well-analyzed and carefully collected patterns of typical errors" (Psotka et al., 1988, p. 531).

Figure 4 Overlay Model



(a) Overlay student model (b) Overlay model with "buggy" extensions

(Figure 2 in Beck et al., 1996, p. 7)

Bayesian models.

Another mechanism for recording a student's knowledge is Bayesian networks (Beck et al., 1996). These networks probabilistically reason about a student's knowledge state based on his interactions with the tutor. Each node in the network has a probability indicating the likelihood of the student "knowing" that piece of knowledge.

In his paper delivered at the 4th International Conference on Intelligent Tutoring Systems, Murray (1998) describes what he refers to as a rigorous formal approach to student modeling as *A Practical Approach to Bayesian Student Modeling*. Murray reduces the computational complexity and difficulties in knowledge acquisition that normally plague Bayesian modeling techniques by categorizing performance data according to skill levels and limiting the number of parameters used in the belief network model. The student model uses only an expected probability distribution for the skill categories and the expected conditional probabilities for slips and lucky guesses so that the model can be updated in linear time.

Collaborative models.

Another approach to learner modeling is that suggested by Cumming and Self (1991) in their chapter entitled *Learning Modeling in Collaborative Intelligent Educational Systems*. Cumming and Self recommend the development of collaborative intelligent educational systems, in which there is active collaboration between the learner and the system. Learner models in such systems require multiple representations to allow alternate paths for learners to pursue.

However, Cumming and Self recommend limiting the scope of the learner model to cover only what the mentoring component can actually use. Therefore, the learner model has a much more limited scope than a full cognitive simulation of the domain. Since Cumming and Self view the learner as an active, responsible agent who exercises initiative in the learning process, it is important that the learner model be open to inspection and change by the learner. The learner can then provide information to the learner model, engaging in a joint process with the system in an analogous manner to that of a relationship with a human tutor.

Two-level learner modeling.

Huang and Bonzon (1995) present two-level learner modeling for teaching declarative knowledge based problem solving.

- Shallow modeling - In the learning process, learners internalize aspects of a problem. These aspects are abstracted into shallow chunks, that is, models that do not require deep cognitive process for retrieval. The task of shallow modeling in ITS is to identify both the incorrect use of the correct shallow model and the correct use of the incorrect shallow model. With experience, learners develop problem solving patterns, which allow them to bypass other concrete aspects of the problem; these patterns constitute shallow models as well (Huang & Bonzon, 1995).
- Deep modeling determines the learner's representation of aspects of problem solving through explanatory questioning. Explanatory questioning helps learners focus on important aspects of problems. Deep modeling helps learners identify aspects of the problem solving process of which they are unaware though they are using them implicitly (Huang & Bonzon, 1995).

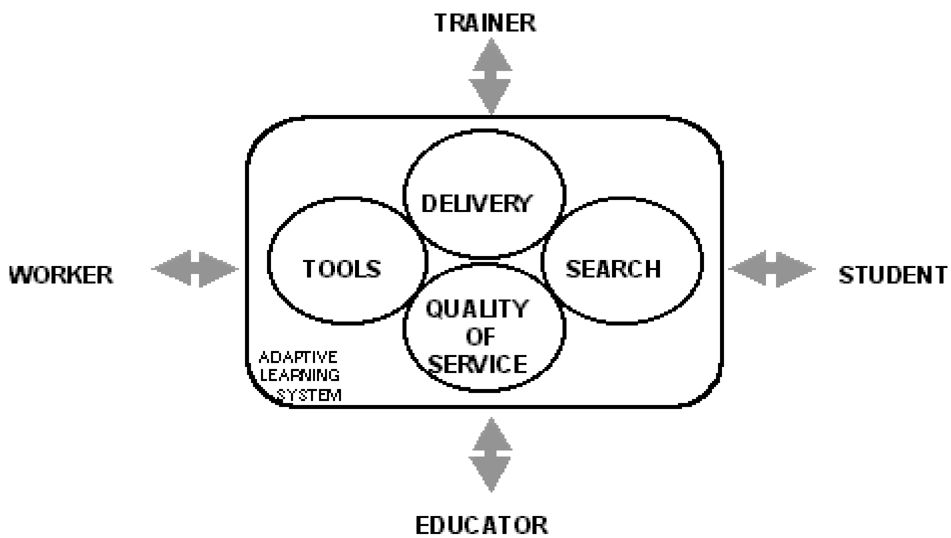
Adaptive Learning Systems

In order to spur the development of high-risk programs, the National Institute of Standards and Technology (NIST) sponsors the Advanced Technology Program (ATP) in specific areas. In 1998, ATP competition targeted the development of "adaptive learning systems," covering the fields of CAI, ICAI, ITS, and knowledge based systems. According to ATP (1998c), adaptive learning systems tailor knowledge to the requirements of the learners to help them learn.

Figure 5 illustrates the components of adaptive learning systems with the following features (ATP, 1998c):

- Content is adapted according to requirements of learners.
- Instructional materials are delivered via multiple channels when and where needed.
- High bandwidth network infrastructure disseminates complex multimedia data.
- Infrastructure tools support learning activities of various types.

Figure 5 Components of Adaptive Learning System



(ATP, 1998c, p. 4)

RAILS and the Courseware Conversion Factory are examples of adaptive learning systems under development. Such systems are designed to deliver content that adapts to users' needs, can be reused, reorganized, and interchanged with other content components.

Real Adaptive Intelligent Learning Systems (RAILS).

eCollege.com (formerly Real Education) received an ATP grant to integrate latent semantic analysis (LSA), an automated method of deriving meaning from text, with radial basis function (RBF), a neural network to improve software performance through machine-learning algorithms (ATP, 1998a). Designed to improve document retrieval for online courses by sorting documents into possible course paths, the system reduces the time required to organize courses.

Courseware Conversion Factory.

Teknowledge received an ATP grant to develop a "Courseware Conversion Factory," an open framework integrating authoring tools and reusable educational software components with a knowledge-based coach to guide the restructuring of traditional course content (ATP, 1998b).

Adaptive Hypermedia

The area of adaptive hypermedia (AH) combines the technologies of hypermedia and of user-adaptive systems. Adaptive hypermedia systems (AHS) provide adaptive navigation support and adaptive content to personalize hypermedia systems, thereby increasing their functionality and usability. AHS build a model representing the goals, preferences, and knowledge of the user; a model employed to adapt interactions to the needs of the user (Brusilovsky, 1998). The system collects information about the user through observing the user's behavior when browsing and using the application (Wu, Houben, & De Bra, 2000).

Adaptive vs. Adaptable

In describing adaptive hypermedia systems, it is useful to distinguish between adaptive and adaptable system facilities. Totterdell and Rautenbach (1990) define an adaptable system as one that provides users with the capability to make an explicit change to the system, while an adaptive system is one that monitors the user's interactions with the system, selecting the information presented based on the learner's progress and understanding.

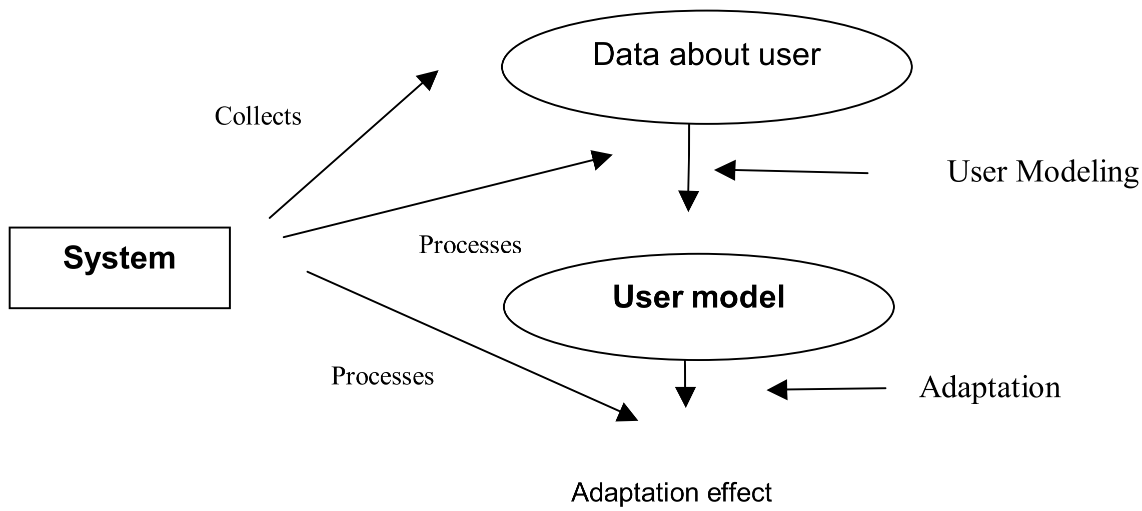
De Bra (1998) indicates that the term adaptive hypermedia has different meanings in the hypermedia literature. De Bra defines adaptable hypermedia systems as those that "allow the user to explicitly set preferences, or provide a profile through filling out a form. This information is stored in the user model. The presentation of the information is then adapted to that model, which is only updated upon explicit request by the user" (De Bra, 1998, p. 2).

In distinguishing between adaptable and adaptive hypermedia systems, De Bra defines adaptive hypermedia systems (AHS) as those that "build a user model by observing the user's navigation through the information space, and in educational systems also by means of (mostly multiple-choice) tests. The presentation is adapted to the user model, and the user model is constantly updated as the user reads the information" (De Bra, 1998, p.2). According to De Bra, most AHS are both adaptive and adaptable in nature, due, in part, to the need to initialize the user model, or to allow users to modify the model as needed.

Adaptation Process

To address the problem of large hyperspaces, AHS use their knowledge of user characteristics to limit the browsing space, recommend particular links, or offer adaptive comments on links (Brusilovsky, 1998). Figure 6 illustrates the process of adaptation based on information from the user model.

Figure 6 Classic loop "user modeling – adaptation" in adaptive systems



(Brusilovsky, 1998, figure 1, p. 2)

Applications of Adaptive Hypermedia

AHS are used in traditional hypermedia areas, such as online information systems, online help systems, educational hypermedia, and newer application areas such as information retrieval (IR) hypermedia, institutional hypermedia, and personalized information spaces. AHS are useful when users have varying goals and knowledge and when the relevant hyperspace is quite large (Brusilovsky, 1998). Variation in goals and knowledge results in users exhibiting interest in different pieces of information presented on a hypermedia page and users selecting different links for navigation. AHS address this variation by employing knowledge represented in the user model to adapt the information and links seen by an individual user.

Adaptive Hypermedia Reference Model.

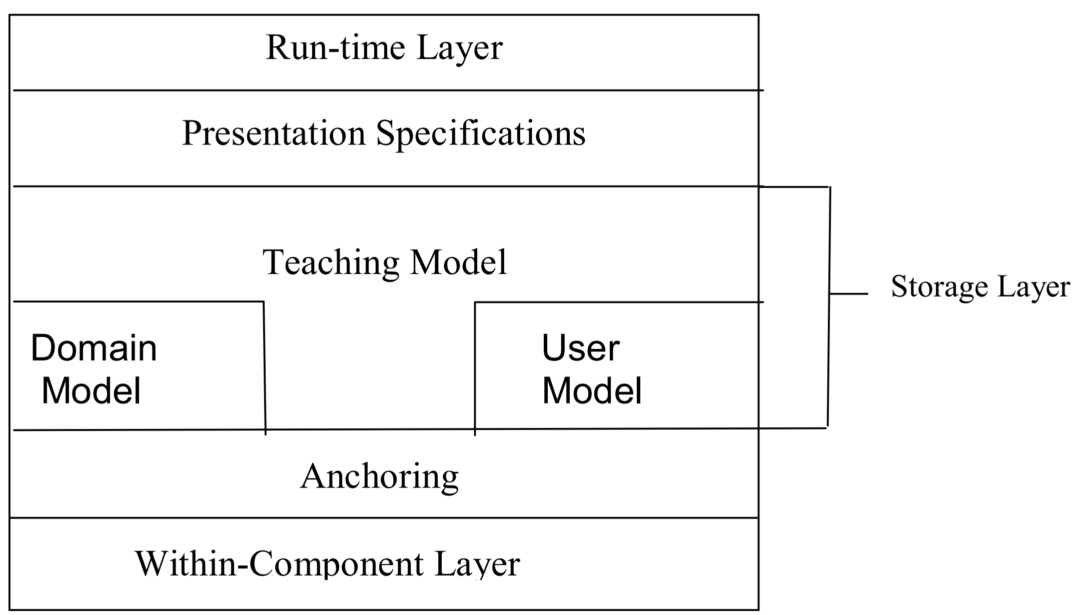
AHAM, the Adaptive Hypermedia Application Model (Wu, Houben, & De Bra, 2000) is an extension of the Dexter hypermedia reference model (Halasz & Schwartz, 1994). According to the AHAM reference model, an adaptive hypermedia application requires the following:

- A domain model underlying the application. The domain model describes the structure of the information content of the application. The model specifies the relationship between the concepts handled by the application and the connection between the concepts and the information fragments and pages (Wu et al., 2000).
- A user model representing such individual characteristics as the user's preferences, knowledge, goals, and navigation history. The user model may also include observations of the user's behavior while using the system. The user's knowledge is characterized in terms of domain model concepts (Wu et al., 2000).
- An adaptation model to allow the system to modify information presentation so that reading and navigation style conform to user preferences and knowledge level. Information presentation should be adaptive on both a content and link structure level, with the adaptation rules that comprise the adaptation model specifying relations between concepts that guide the selection and order of pages presented to the user (Wu et al., 2000).

Figure 7 illustrates the structure of adaptive hypermedia applications according to the AHAM model. Hypermedia applications focus on information nodes and the connections between nodes, represented by the storage layer of the AHAM reference model. The domain model in the AHAM reference model specifies the concepts contained in the domain, with the author determining which concepts to include.

The user model represents the relationship between the user and the domain model and plays a central role in determining the adaptation. The task of the user model is to observe and monitor user interactions with the system in order to determine the user's knowledge of the concepts in the application domain. The adaptation model (Teaching Model in the diagram) specifies the way in which the user's knowledge modifies the presentation of information. The adaptive engine uses adaptation rules to manipulate link anchors (Anchoring in the diagram) and to generate presentation specifications. The Storage Layer, anchoring, and presentation specifications are the focus of the AHAM model as well as that of the Dexter hypermedia model.

Figure 7 Global Structure of Adaptive Hypermedia Applications



(Wu, Houben, & De Bra, 2000, Figure 1, p. 3)

User Modeling in Adaptive Hypermedia

Adaptive hypermedia systems include a user model that represents the characteristics of an individual user on an abstract conceptual level. The user model also represents the state of each characteristic of the user as the system moves from page to page (Wu et al., 2000).

User Features.

Brusilovsky (1998) describes five user features to which current AHS can adapt. These features vary among different users and across time for the same user.

- Knowledge – most adaptive presentation techniques use the state of the user's knowledge as the main source of adaptation. User knowledge varies among different users and for an individual user over time. AHS must recognize changes in the state of the user's knowledge and update the user model accordingly.
- User Goals – what the user is attempting to achieve through his/her use of the adaptive hypermedia system. The user goal may take the form of the work goal in an application system, the search goal in an information retrieval system, or the problem-solving or learning goal in an educational hypermedia system. The user goal uses a modeling approach similar to that used by an overlay knowledge model. Many adaptation techniques, particularly link-level adaptation approaches, consider user goals to adapt the path that the user follows through the system.
- Background – relevant data about the user, such as his/her profession, work experience in related areas, and point of view on the subject. Some AHS use the user's background as the basis for content or link-level adaptation.
- Hyperspace experience – an indication of the user's familiarity with the structure of this particular hyperspace and the ease with which the user is expected to navigate around in the hyperspace. In some cases, a user may be familiar with the subject matter but not with the hyperspace structure.
- Preferences – the user may want to use certain nodes or links or view particular segments of a page, information that the user must provide to the system since the system cannot deduce such predilections. In most adaptive information retrieval (IR)

hypermedia systems, preferences constitute the only information stored in the user model. Preferences are usually expressed as numbers whereas other aspects of the user model are expressed in symbolic form.

Overlay and Stereotype Models.

Most adaptive hypermedia systems use domain models that include several types of concepts representing different kinds of knowledge, and multiple types of links representing different kinds of relationships between concepts. Overlay models are used to compare the state of the user's (or student's) knowledge to the domain model. An earlier section of this paper describes overlay models used in intelligent tutoring systems.

A simpler stereotype user model is sometimes used to represent the user's knowledge though many adaptation techniques require the detailed information from an overlay model for efficient performance. Kobsa (1993) describes the stereotype approach to user modeling originally developed by Rich (1979, 1989). The stereotype approach offers a quick assessment of the user's background knowledge. Though this assessment may not be completely accurate, it provides sufficient differentiation of background knowledge level for some systems. Stereotype modeling can be used to classify a new user and initialize the state, then an overlay model can be used for a more fine-grained representation of the user's level of knowledge.

The developer of the stereotype user modeling component must perform three tasks:

- Identify the user subgroups – it is necessary to define subgroups within the overall population whose members have similar attributes relevant to the application.
- Identify key characteristics – for the user model, it is necessary to identify a small number of important features that differentiate subgroups from each other.
- Develop representation of hierarchically ordered stereotypes – the characteristics of the user subgroups that are relevant to the application must be appropriately described in an abstract representation system.

Knowledge Representation.

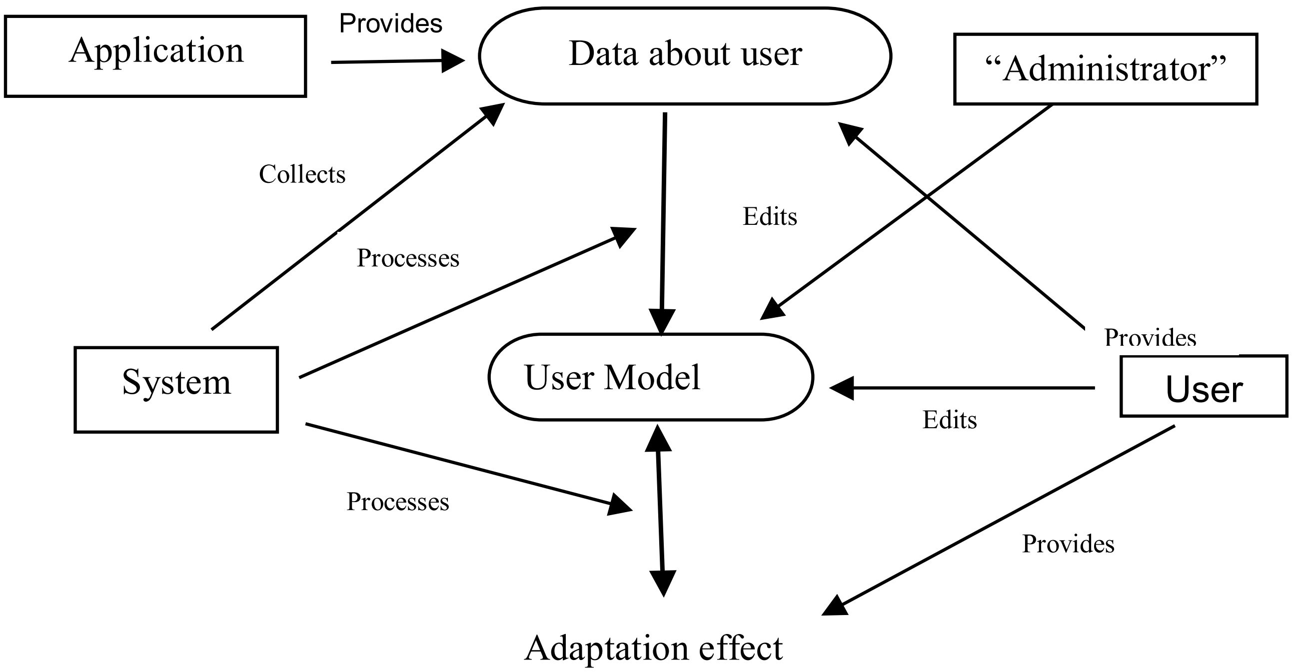
De Bra (1998) describes three types of knowledge representation for the user model.

- Boolean model – each concept has two possible values: true or false, known or not known, or two extremes along a continuum, such as verbose or terse to indicate whether the user desires the long or short version of a page.
- Discrete model – each concept has a small number of values. Thus, the Boolean model is the simplest form of the discrete model. A discrete model might have four values, such as not known, learned, well learned, and known to indicate the state of the user's knowledge of a particular concept.
- Continuous model – each concept has a range of values. The value indicates how much a user knows about a particular concept or the probability that a user knows this concept.

Collaborative user modeling.

Adaptive hypermedia systems require information about the user for adaptation. In many cases, the best way to obtain needed information is to include the user in the user modeling process, thereby engaging the user in collaborative or cooperative user modeling. Brusilovsky (1998) distinguishes three approaches to involving the users in the process of user modeling as depicted in Figure 8. The first approach is for the system to request input from the user. The second approach is for the system to be adaptable, allowing the user to demonstrate exactly what he/she would like displayed in a particular situation. The third approach is for the user model to be viewable and modifiable so that the user has the ability to inspect the contents of the user model and to update its characteristics directly.

Figure 8 Collaborative user modeling in adaptive hypermedia



(Brusilovsky, 1998, Figure 5, p. 33)

<u>Problems with automatic user modeling in hypermedia systems.</u>

Brusilovsky (1998) discusses two major problems arising from automatic user modeling.

- Reliability problems due to errors made while deducing the user model as well as errors made while performing the adaptation even when the user model is correct.
- Insufficient information to update the user model from observation of the user navigating through an adaptive hypermedia system. User background and preferences cannot be deduced from the user's actions and must be provided by the user him/herself.

In general, online help systems and educational hypermedia in intelligent tutoring systems have more reliable user modeling than other types of adaptive hypermedia systems. As part of an interactive system, online help systems can use regular methods of user modeling to recognize the goal and level of user experience. Educational hypermedia in intelligent tutoring systems can access the student model, which is updated through analysis of the student's answers to problems, questions, and tests. The student model provides information about the student that is generally more reliable than information obtained through observation of the student's navigation through the system.

Classification of Adaptive Hypermedia Systems

Brusilovsky (1998) classifies adaptive hypermedia systems along four major dimensions based on earlier work in adaptive user interfaces by Dieterich, Malinowski, Kuhme, and Schneider-Hufschmidt (1993).

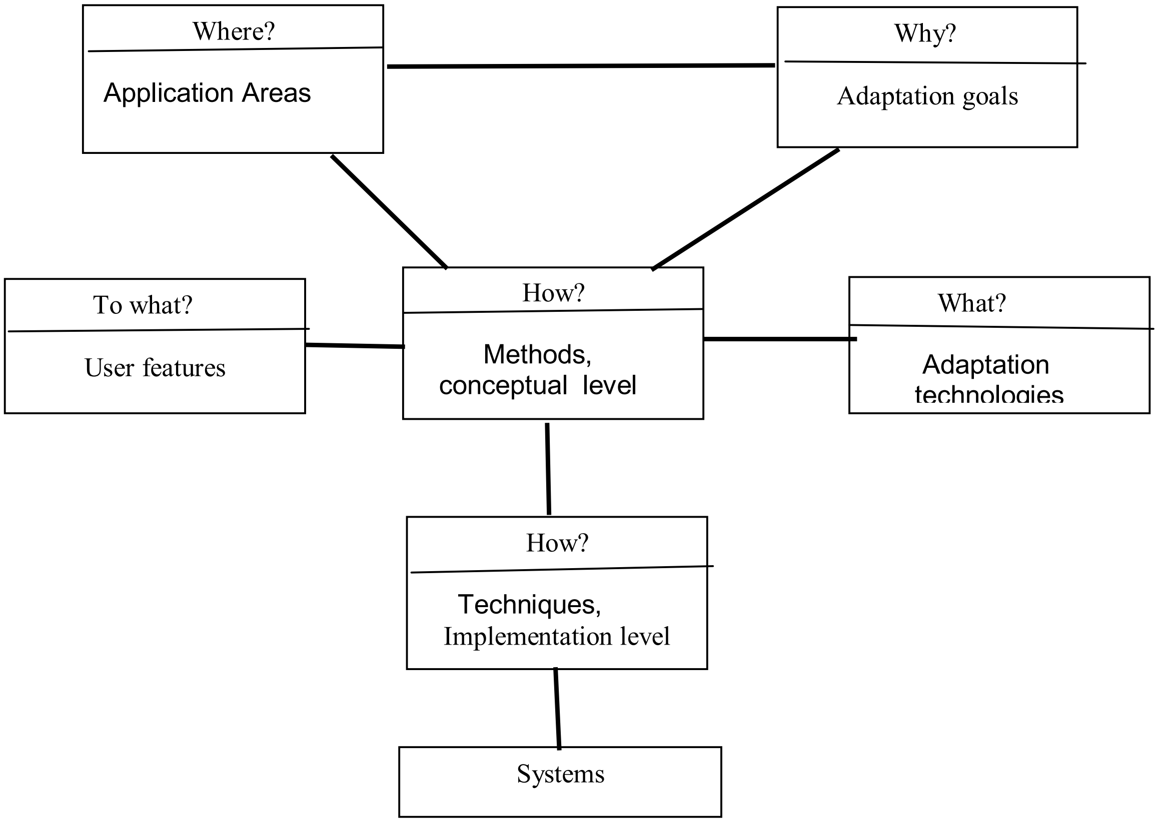
Dimensions.

Figure 9 illustrates the dimensions used to categorize adaptive hypermedia systems.

- Where? One dimension along which to classify AHS is where adaptive hypermedia approaches are useful. In answering the "where" question, we categorize each AHS in terms of its application domain.
- Why? It is also useful to categorize AHS in terms of the goals of the adaptation. Various adaptation methods and techniques can be used to solve specific user problems in particular application domains.
- To what? Another way to classify AHS is to consider the user features to which adaptive hypermedia systems can adapt their behavior. User modeling approaches discussed in the previous section provide a method of categorizing various AHS.
- What and how? It is also important to consider what features of an adaptive hypermedia system may vary according to the needs of different users. Brusilovsky (1998) divides the ways in which AHS can adapt into two major categories:
  - Content adaptation
  - Link adaptation

Brusilovsky (1998) subdivides these categories into different adaptation technologies, which we discuss further in the section on Adaptation Technologies. These adaptation technologies are described in terms of their underlying conceptual methods and implementation techniques, in other words, how they are used in AHS.

Figure 9 Possible Classifications for Adaptive Hypermedia Methods and Techniques



(Brusilovsky, 1998, figure 2, p. 4)

Application Areas.

Reviewing existing adaptive hypermedia systems, we find six major application domains:

- Educational hypermedia
- Online information systems
- Online help systems
- Information retrieval (IR) hypermedia systems
- Institutional information systems
- Systems for managing personalized views (Brusilovsky, 1998).

Educational hypermedia constitutes one of the earliest application areas and is still the most widely encountered application domain for adaptive hypermedia systems (Brusilovsky, 1998). Most educational hypermedia systems limit the size of the hyperspace by focusing on a specific course or topic for learning. User modeling based adaptive hypermedia techniques are useful in educational hypermedia systems since knowledge level varies widely among users, the knowledge of an individual user can expand very quickly, and novice users need navigational assistance even in a limited hyperspace.

Online information systems employing adaptive hypermedia techniques include online documentation systems, electronic encyclopedias, and other systems designed to provide reference access to information for users with varying degrees of knowledge in the subject matter. Both online information systems and educational hypermedia systems face the challenge of satisfying the needs of a wide range of users. Online information systems must understand the user's goal, which is difficult to determine except in circumstances when the user provides this information directly (Hook et al., 1998).

Online help systems are similar to online information systems. However, online help systems are part of their application systems, not standalone systems like online information systems. While both online help systems and online information systems must selectively provide information that is geared to the needs of different users, online help systems need only handle a limited hyperspace for adaptation purposes (Brusilovsky, 1998).

Combining the techniques of information retrieval (IR) with hypertext access to documents using index terms, IR hypermedia systems define a new class of information retrieval systems (Mathe & Chen, 1998). Unlike online information systems in which designers provide links, IR hypermedia systems must calculate links in the hyperspace through similarity measurements or other techniques. Adaptive IR hypermedia systems help users locate needed information by recommending links and limiting choice in navigation (Mathe & Chen, 1998).

A relatively new application domain for adaptive hypermedia systems is that of institutional information systems. These systems provide online information needed by an institution to support day-to-day operational tasks. An example of an institutional information system is a hospital information system (Vassileva, 1998). Employing database management system technology in earlier versions, newer systems provide an umbrella hyperspace encompassing the databases. Most workers in the institution require access to a limited subset of this relatively large hyperspace. In addition, new employees need navigational assistance in a similar way to that of novices using educational hypermedia systems.

Systems for managing personalized views constitute another fairly new application area for adaptive hypermedia systems (Brusilovsky, 1998). The World Wide Web offers an extremely large hyperspace, offering an extensive repository of many types of information. Systems for managing personalized views use adaptive hypermedia techniques to hide some of the complexity of the overall hyperspace and allow users access to subsets of the hyperspace for their own use. Particular subsets of information are selected based on the user's specific goals, interests, and background.

Adaptive Hypermedia System Continuum.

In classifying adaptive hypermedia systems in terms of application areas, we find that these categories are not mutually exclusive (Brusilovsky, 1998). There are cases in which one domain is similar to another, with overlap between the domains in terms of features, approaches, and problems that need to be addressed. In some cases, adaptive hypermedia systems can be classified as belonging to two of these domains.

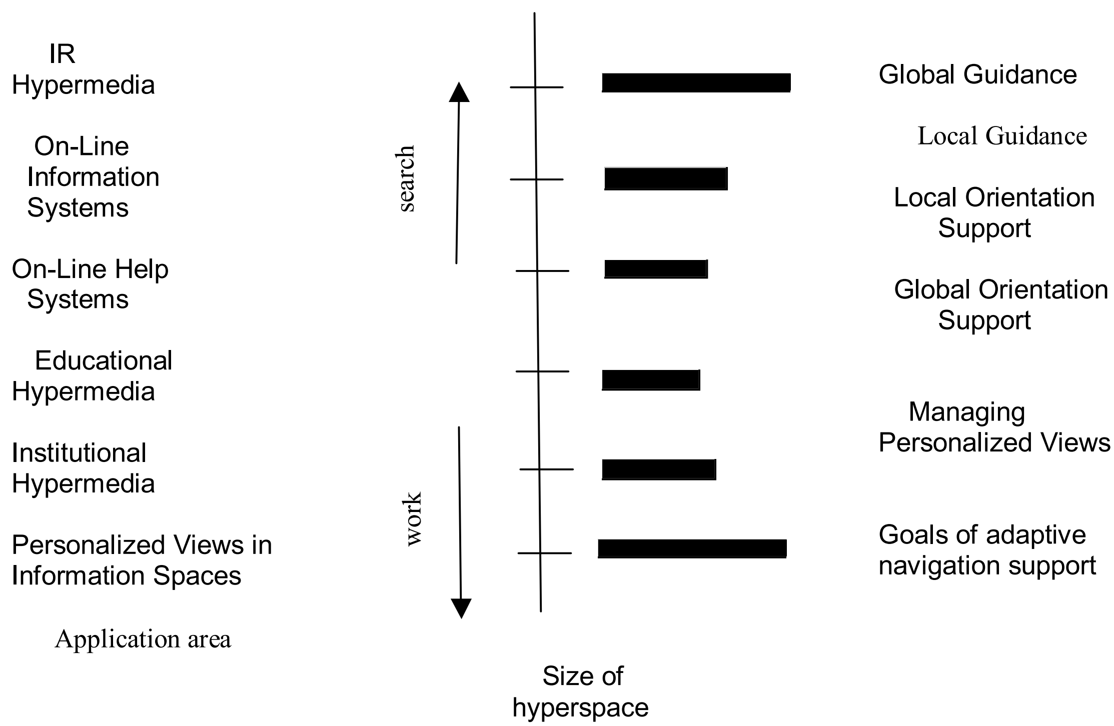
Pairs of application domains that share these similarities are:

- IR hypermedia and Online information systems
- Online information/help systems and Educational hypermedia
- Educational hypermedia and Institutional hypermedia
- Institutional hypermedia and Information space management systems.

To address pairwise similarities as well as subtle differences between application areas, Brusilovsky (1998) orders application areas along a continuum as in Figure 10.

In Figure 10, we see educational hypermedia and online help in the middle of the continuum (Brusilovsky, 1998). Educational hypermedia and online help are traditional domains for adaptive hypermedia approaches, using classic adaptive hypermedia features such as contextual links, indexes, maps (both local and global), and guided tours. On either end of the continuum, we find AHS that use a subset of traditional hypermedia features. We also find that the size of the hyperspace increases at both ends of the continuum, with AHS in the application domains of IR hypermedia or Personalized views in information spaces, forced to contend with the problems of dealing with extremely large hyperspaces of information. At the top of the continuum, the systems are search-oriented since their major task involves search and retrieval of information whereas at the bottom of the continuum, the systems are work-oriented, focusing on the task of the application. The right side of the diagram depicts the major goals of adaptive navigation support at various points along the continuum of adaptive hypermedia systems.

Figure 10 Continuum of Adaptive Hypermedia Systems



(Brusilovsky, 1998, Figure 3, p. 9)

Adaptation Technologies

Brusilovsky (1998) classifies adaptive hypermedia systems in terms of what can be adapted and which features can vary according to the needs of different users. Figure 11 illustrates Brusilovsky's categorization of the two major classes of hypermedia adaptation: content and link adaptation, with further subdivision into specific technologies to implement such adaptation. De Bra (1998) follows and refines Brusilovsky's classification, describing two additional link adaptation techniques: adaptive link removal and adaptive link disabling. These additional techniques are also included in Figure 11.

Content Adaptation - Adaptive Presentation.

Content adaptation is also referred to as adaptive presentation and includes techniques that adapt the content of a page based on the user model (Brusilovsky, 1998). Online information systems, online help systems, and educational hypermedia constitute the application domains that use content adaptation methods (Brusilovsky, 1998).

There are two types of adaptive presentation:

- Adaptive text presentation: user model determines page's textual content. While there are various techniques for adaptive text presentation, they look similar from the perspective of "what can be adapted," that is, those with varying user models see different textual content as the content for the same page (Brusilovsky, 1998). Thus, the same information can be presented to various levels of users, offering additional explanations for novices and further details for advanced users (De Bra, 1998).
- Adaptive multimedia presentation: adaptive multimedia presentation currently allows for selection of the presentation medium based on the needs of the user but does not yet allow for adaptation of individual elements of multimedia content (De Bra, 1998).

Content adaptation methods include (Brusilovsky, 1998):

- Additional explanations: the most widely used method of content adaptation offers special information designed for particular categories of users and not displayed for other users. This method involves hiding specific parts of the information from individual users. The hidden pieces may be details that novice users are not yet prepared to understand or explanations that are unnecessary for advanced users.

- Prerequisite explanations: a method that modifies material presenting a new concept based on the user's level of prior knowledge. If the user does not have a thorough understanding of material on which to base his/her learning of a new concept, the system offers needed background information prior to introducing the new concept.
- Comparative explanations: using similarity links to present new concepts, based on a discussion of similarities and differences between the new concept and related ones.
- Explanation variants: storing variations of sections of information and presenting each individual with the particular variation that best fits the individual's user model.
- Sorting: a method that considers both the background and knowledge level of the user in order to categorize pieces of information about a particular concept, placing the most relevant information toward the front.

Techniques to implement these methods (Brusilovsky, 1998; De Bra, 1998):

- Fragment variants: creating multiple versions of pieces of pages, with variables in the user model determining which pieces to use. Users receive structurally different explanations of concepts based on knowledge level.
- Page variants: fragment variants in which a fragment is an entire page. Multiple versions of particular pages exist and are selected based on user model. Easy to implement, this technique offers a variant for each user stereotype.
- Frame based techniques: assembling pages from individual information items, such as words and parts of sentences. The most powerful content adaptation technique represents the information about a particular concept in the form of a frame with slots containing explanation variants of the concept, links to other frames, and examples. Presentation rules determine the selection and order of the slots presented to each individual user.

Brusilovsky (1998) describes additional techniques for adaptive text presentation:

- Conditional text: dividing pieces of information about a particular concept into chunks of text, associating each chunk with a condition on the level of user knowledge, and presenting chunks for which the condition is true for that user. This technique can be used to implement content adaptation methods of additional explanations, prerequisite explanations, comparative explanations, and explanation variants.
- Stretchtext: a special type of hypertext that offers a way to turn on and off various segments of the content based on the user knowledge level. Activating a hot word extends the text of the current page rather than moving to another page as in regular hypertext. With stretchtext, both the user and the system can adapt the content of a particular page, considering the preferences as well as the knowledge level of the user. Users can collapse or uncollapse explanations and details as they so choose.

Link Adaptation - Adaptive Navigation.

Link adaptation is also referred to as adaptive navigation and includes adaptive hypermedia techniques that modify the links accessible to the user at a particular time.

Brusilovsky (1998) describes several methods for adaptive navigation support:

- Global guidance: helping users follow shortest and most direct path to reach information goals. Whether telling the user which link to follow next or sorting links from a given node according to their relevance to the overall goal, global guidance methods use the information goal to determine the path to follow.
- Local guidance: offering suggestions for the most relevant link to follow for the next step, based on the user's preferences, knowledge, and background. Sorting links based on user preferences is a local guidance method used in IR hypermedia and online information systems. Educational hypermedia systems use local guidance methods to sort links based on user knowledge level or to help the user select the most relevant problem to solve next.
- Local orientation: helping users understand their location in hyperspace and nearby information, offering information about nodes available from the current location or limiting navigation possibilities, focusing on the most relevant links.

- Global orientation: offering annotation landmarks and hiding non-relevant information so that users understand the structure and position in hyperspace.
- Managing personalized views in information spaces: reducing the size of hyperspace to what the individual needs. An adaptable feature traditionally performed by users, methods of collection and maintenance of links relevant to user goals are performed by intelligent agents in some new systems.

Brusilovsky (1998) describes five adaptive navigation techniques:

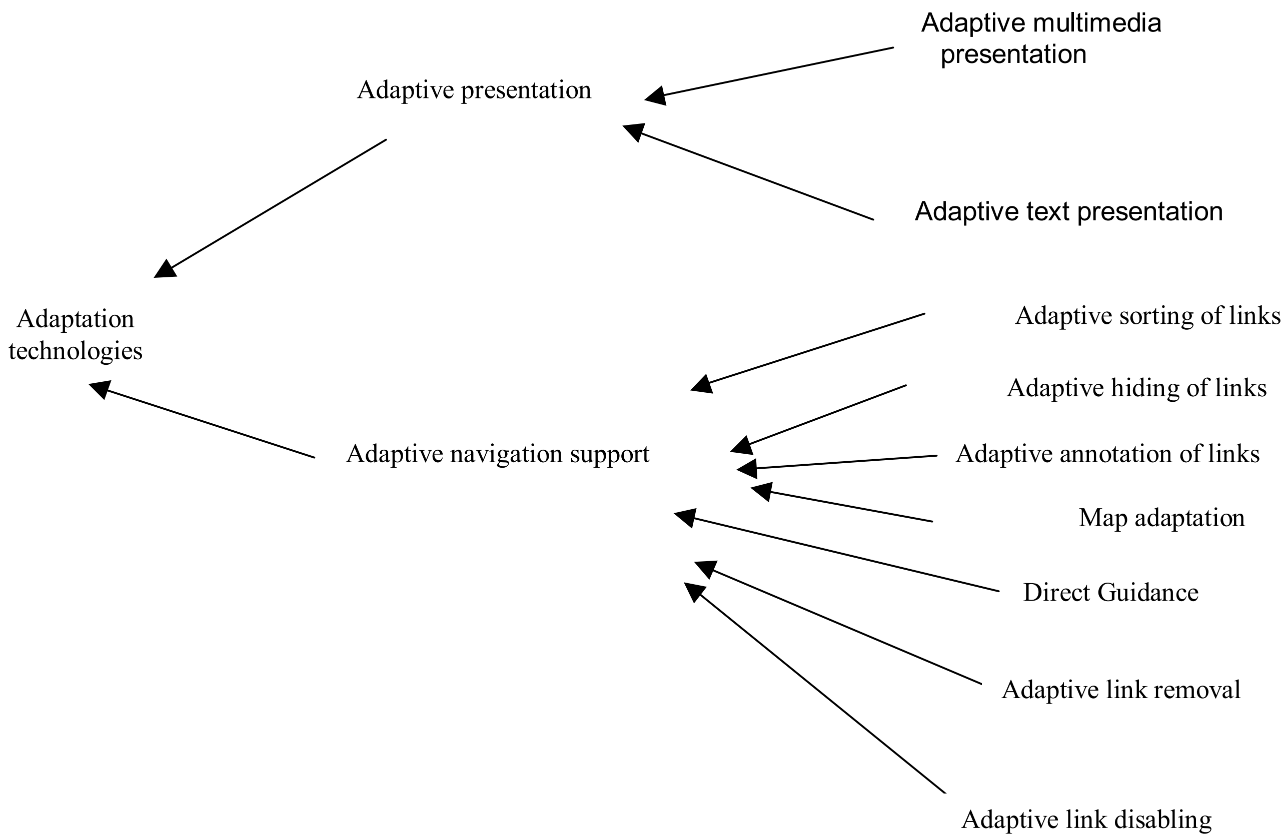
- Direct guidance: providing a link to the page that the system determines to be the most suitable next stop along the path to the user's information goal. Usually provided via the "next" button, direct guidance offers a guided tour based on user needs.
- Adaptive sorting of links: presenting ordered list of links, from most to least relevant as determined by the information goal. Typically used in IR hypermedia systems to present search results, this technique is used in educational hypermedia to guide users to certain pages to learn about a specific concept.
- Adaptive link hiding: making link anchors to non-relevant information look like normal text, restricting visible links to those that are relevant at that time.
- Adaptive link annotation: indicating the relevance of a link by modifying anchor appearance or displaying a colored symbol. Eklund and Brusilovsky (1998) found this technique helpful in increasing understanding and in reducing the number of steps to reaching a goal.
- Map adaptation: presenting a graphical view of hyperdocument organization and adaptively filtering the view to focus on the most relevant components.

De Bra (1998) describes two additional adaptive navigation techniques:

- Adaptive link removal: removing the link anchor for links determined to be non-relevant, making sure that the surrounding text still makes sense.
- Adaptive link disabling: while text for a link is still available, the link does not function. Used in conjunction with link hiding to avoid confusion from a non-working link, this

technique is preferred by users over adaptive link removal. However, Calvi & De Bra (1997) found that users dislike both techniques.

Figure 11 Adaptation Technologies in Adaptive Hypermedia



(Brusilovsky, 1998, Figure 4, p. 14, with additions from De Bra, 1998)

The adaptive hypermedia technology discussed in this paper along with the Web technologies for online learning discussed in the companion paper entitled *Web Technologies for Multi-Intelligent Online Learning* (Dara-Abrams, 2002i) together form the technology foundation for research in and development of Multi-Intelligent Online Learning. The technology of user-adaptive systems (Kobsa, 1993) and stereotype user models (Rich, 1979, 1989) provide the underpinnings for adaptation based on individual variations in the development of different intelligences based on the Theory of Multiple Intelligences (Gardner, 1983/1993). Adaptive hypermedia technology offers methods and techniques with which the educational methodologies of multiple representations (Gardner, 1999) and the Entry Point Framework (Gardner, 1999) can be instantiated in Multi-Intelligent Online Learning modules. The methods and techniques represented in Figure 11 are useful in implementing the adaptation model, domain model, and user model of the educational adaptive hypermedia application that forms the basis of the Multi-Intelligent Online Learning prototype framework. To understand how adaptive hypermedia technology is used in the development of the Multi-Intelligent Online Learning prototype, the reader is referred to the companion paper entitled *Design and Implementation of a Multi-Intelligent Online Learning Prototype* (Dara-Abrams, 2002c).

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