Cognitive Media Types for Multimedia Information Access

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Abstract

Multimedia repositories, libraries, and databases offer the potential for providing students with access to a wide variety of interconnected information resources. However, in order to realize this potential, multimedia systems should provide access to information and activities that support effective knowledge construction and learning by students. This article proposes a theoretical framework for organizing information and activities in educational hypermedia systems. We show that such systems should not be characterized primarily in terms of the kinds of physical media types that can be accessed; instead, the important aspect is the content that can be represented within a physical media, rather than the physical media itself. We propose a theory of "cognitive media types" based on the inferential and learning processes of human users. The theory highlights specific media characteristics that facilitate specific problem solving actions, which in turn are enabled by specific kinds of physical media. We present an implemented computer system, called AlgoNet, that supports hypermedia information access and constructive learning activities for self-paced learning in computer and engineering disciplines. Extensive empirical evaluations with undergraduate students suggest that self-paced interactive learning environments, coupled with multimedia information access and constructive activities organized into cognitive media types, can support and help students develop deep intuitions about important concepts in a given domain.

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Introduction

Multimedia repositories, libraries, and databases offer the potential for providing students with access to a wide variety of interconnected information resources and activities. Moreover, network-accessibility allows these resources to be distributed over wide distances. However, simply providing access to information is not, by itself, sufficient. Multimedia systems instead should facilitate access to information and activities that support effective knowledge construction and learning by students. Designing such a system requires research into how students will actually use such systems, what kinds of usage actually improves learning, and what types of educational materials these systems should provide.

To address these issues, we have been developing a theory for designing educational multimedia systems based upon the cognitive and learning needs of students. This theory argues that rather than base the design of multimedia systems on the physical properties of the information (e.g., pictures, audio, video, etc.), the structure and content of the system should be based on cognitive aspects of the users of that information. By this, we mean that the access methods in a multimedia system should be "cognitively relevant" to the learning and information-seeking goals of the student.

These *cognitive media types* form the basic building blocks of the system. They are based on an understanding of the learning and constructive processes of students, and encapsulate different methods or strategies for problem solving and learning. These strategies rely on specific media characteristics that facilitate specific learning activities, which in turn are enabled by specific kinds of physical media.

In this paper, we present our theory of cognitive media types. We then describe an implementation of a multimedia learning environment, whose design is based on the theory. The system, called AlgoNet, supports hypermedia information access and constructive activities, and is targeted at self-paced learning in computer and engineering disciplines. Specifically, the system contains instruction on graph theory and graph algorithms, which are fundamental concepts widely used in computer and engineering fields. Information access in AlgoNet is structured in terms of cognitive media types such as descriptions, examples, case studies, and constructive visualizations. The system uses a client-server architecture, thus making the courseware accessible via the Internet to students in wide geographical locations. Similarly, the system can employ resources that are distributed over a computer network.

To evaluate the effectiveness of our theory in guiding design, we have performed several empirical evaluations of the system. The evaluations were motivated by our view of student learning as mediated by several interacting factors. These factors include (1) the structure of the underlying system, (2) the means of information access, and (3) the knowledge, goals, and strategies of students in the learning context. As such, our evaluations employed several methods. The structure of the system was analyzed via techniques for revealing its underlying navigational and hypermedia topology. The effects of information access via cognitive media types and student learning goals were investigated in an empirical study with over 100 students from two undergraduate introductory computer science classes.

The results from both the structural and empirical studies are considered in tandem in terms of their implications for our theory of cognitive media types and the design of multimedia learning environments. The results suggest ways in which self-paced interactive learning environments, coupled with multimedia information access and constructive activities organized into cognitive media types, can support students and help students develop deep intuitions about important concepts in engineering domains.

The remainder of the paper is organized as follows. In the next section, the theory of cognitive media types in presented, after which the computer system is described in detail. This is followed by a description of the empirical studies and discussion of the results. We conclude with a discussion of the implications of our research for the design of educational systems.

Cognitive Media: Design Considerations for Multimedia Systems

When building systems targeted for educational settings, designers must address important issues in how novices can gain access into a potentially large database of interconnected media types. In particular, designers need to address the kinds of indices that support access and learning in media-rich environments. There has been little research into how people actually use such systems, what kinds of usage improves learning and under what conditions, and what types of educational materials such systems should provide. The research that has been done reveals a cloudy, complex picture (Jonassen and Mandl, 1990). A cursory review of the research literature reveals several approaches to the problem in which access and structure of a hypermedia system is determined by various "physical" properties of the information contained in the system. In one common approach, indices provide access into various physical media types. This means that the learner can choose to view text, video, sound, etc. However, research that compares learning from different media types are inconclusive in showing advantages of one physical medium over another. Research on what kinds of media types and materials facilitate learning is confusing and contradictory (Kozma, 1991).

The lack of conclusive evidence demonstrating the superiority of one physical media over another reflects the fact that many factors, above and beyond simple media, affect a student's learning process. These factors include, for example, students' background knowledge, their motivation and interests, their learning strategies and goals, and the overall learning context (Chi et al., 1989; Ng and Bereiter, 1991; Ram and Leake, 1995; Recker and Pirolli, 1995; Schank et al., 1994). Therefore, rather than base the design of a hypermedia system on the physical properties of the information contained in the system, we propose that the indices and structure of the system should be based on cognitive aspects of the *users* of that information. By this, we mean that the access methods in a hypermedia systems should be "cognitively relevant" to the learning and information seeking goals of the user.

There have been some previous attempts to utilize "cognitively meaningful" information of this kind. For example, TextNet (Trigg and Weiser, 1986) uses "link types" to link nodes in structured texts. TextNet is a text-based document composition environment that support two types of nodes: chunks and tocs. Chunks are the basic data objects that contain text; these include data entries such as author, date, and text, as well as links to other chunks. Tocs, similar to chunks but lacking the text field, are hierarchically organized as a table of contents connecting multiple chunks. Links between these nodes are explictly specified by "link types," such as summary, example, continuation, and criticism. Link types are "cognitively relevant" to the information-processing goals of the users; for example, a link might correspond to expanding an idea or criticizing that idea. One difference between this approach and ours is that link types in TextNet are used mainly to organize thoughts, not as primary means to navigate through the multimedia system. In manual navigation mode, users must rely on the table of contents or keywords to jump to a specific text entry.

In our work, we have been developing a theoretical framework for designing indices for educational hypermedia systems. In this framework, we argue that their design and indices are best thought of terms of what we call "cognitive media types." Specifically, we argue that systems should not be characterized primarily in terms of the kinds of physical media types that can be accessed. Instead, the important aspect is the content that can be represented within a physical media, rather than the physical media itself. Moreover, the content and means of access to the content should structured so as to be cognitively relevant to the user's goals.

Text is an example of a physical media type. It can be used to represent several cognitive media types. For example, text can be used to present abstract, general instructions; it can also be used to display instantiations of these concepts within examples, to define concepts, or to provide explanations and annotations. Instructions, worked examples, definitions, and explanations encapsulate fundamentally different types of knowledge, and support different types of reasoning and learning processes. We argue that these kinds of knowledge, although physically represented in text, constitute different types of media when viewed from a cognitive perspective. Similarly, animations and pictures are also examples of physical media types. Animations can be used to exemplify general or specific instantiations of dynamic displays of processes. Pictures can be used to display graphical relations among concepts. In general, cognitive media are characterized in terms of the inferential processes of the human user rather than physical properties of the computer representation. Cognitive media encapsulate different kinds of problem solving information which might, in turn, be composed of many different physical media.

We believe that it is essential to focus on cognitive media in order to understand how best to design multimedia systems that can support novices in learning or training situations as well as aiding experts in on-the-job situations. We are developing a theory and taxonomy of cognitive media types that we believe are useful in learning situations. In addition, we are attempting to specify at which point during learning they may prove to be more advantageous. For example, is a general principle more useful at the beginning of a learning session, or after the student has gained some experience in a domain? Finally, we are interested in determining the physical media types that can best represent the different cognitive media types.

Types of Cognitive Media

We view multimedia information as composed of three layers: (1) physical media, (2) media characteristics, and (3) cognitive media.

At the lowest level are physical media, for example, text, video, animation, etc. They are defined by characteristics of the physical (on-screen) media used to represent different kinds of information. Although often distinguished based on perceptual modalities (for example, visual vs. auditory), they may be also characterized by the types of inferences that they facilitate. For example, figures (or diagrammatic representations) can facilitate spatial inferences (Larkin and Simon, 1987; Larkin, 1988) Thus, media types can be classified based on "cognitive" distinctions that depend not on physical characteristics of media but on the reasoning processes of users.

To illustrate this distinction, consider the following example from Boden (Boden, 1991).

A 20-foot rope is tied to and hanging between two buildings that are some distance apart. Given that the lowest point of the rope is 10 feet below the tethered ends, how far apart are the buildings? In this example, most people tend to draw a diagrammatic representation of the problem showing the two buildings and a rope hanging in some sort of arc between them—this representation enables all kinds of fancy mathematical (geometric) reasoning which in this case is absolutely the wrong way to solve the problem. Boden points out that mathematically-inclined people tend to take a long time to solve this problem because they usually start by drawing a picture of the hanging rope, whereas less math-sophisticated people find it easier to solve because they do not rely on diagram-based geometric reasoning. The point is that a type of physical media—here, a diagram—can affect the course of problem solving by facilitating certain kinds of inferences and making others harder.

At the next level are the media characteristics (Kozma, 1991). These are a characterization of the kinds of problem-solving actions that people might perform during a task. For example, *zooming* is a problem-solving action that focuses attention on and highlights the details of a problem situation; such an action is easier in a diagrammatic representation than in a symbolic one.

Finally, at the level above media characteristics, are cognitive media types. For example, *zooming* is a particular problem solving action—more precisely, a particular schema for a problem solving action which results in certain inferences—whereas at the higher level one might have schemas for problem solving strategies as a whole. So, for example, one may resort to case-based reasoning (Kolodner, 1993), go back to first principles using basic definitions and equations, or reason using constructive simulations (Soloway et al., 1992).

A case is a type of medium (characterized at the cognitive level) that facilitates the former problem solving strategy (case-based reasoning). Using a case requires (among other things) zooming into the differences between the case and the problem situation so that the differences can be characterized and the case suitably adapted. Zooming in and adaptation are specific problem solving actions that are facilitated by different media characteristics; these characteristics, in turn, are enabled by specific physical media.

To take another example, consider EMILE, a multimedia environment in which subjects learn physics by constructing physics simulations (Guzdial, 1995). While the physical media characteristics—animations—are similar to those of many other animation-based learning environments, the crucial difference lies in the reasoning processes used by the student—here, constructive experimentation rather than passive observation.

To organize information and knowledge construction activities in a multimedia learning environment, it is necessary to develop a taxonomy of the types of cognitive media used in learning, how these are best represented within physical media types, and the kinds of learning inferences they facilitate. Table 1 shows a partial taxonomy and examples of types of physical media used in ALGONET, and the types of cognitive media that are best suited for representation within each physical media. Note that while most physical media types can be used to represent many of the cognitive media types, some of the correspondences are more "natural" than others. Typically, a cognitive media type will require one primary physical media type along with annotations that use other physical media types, but in general there may be a many-to-many mapping between the two.

As described in more detail later, ALGONET uses cognitive media types to communicate important concepts in computer science algorithms. In addition to using examples and definitions, we use constructive visualizations to help students develop a mental model of the process of particular algorithms. A constructive visualization is a kind of dynamic interactive representation that was specifically designed to help students understand computing algorithms. In a constructive visualization, students define the inputs and their relations for a particular algorithm. A software visualization program then shows an animation of the algorithm process operating on the input specified by the student.

It is important to note that physical media types and media characteristics can be defined without a strong appeal to a cognitive theory of reasoning and learning. This is not true of cognitive media types—the structure, content, and use of cognitive media types is a function of the researcher's theory of cognition. This has two implications. First, the design of effective hypermedia environments must take into account a cognitive theory of how the user interacts

Table 1: Partial taxonomy of physical media and cognitive media. The left column presents the set of commonly used media within educational multimedia. The left column shows some possible uses of these types of media in implementing educationally useful materials.

Examples of Physical Media	Examples of Cognitive Media Types
Text	Abstract principles
	Specific instructions
	Annotated cases or examples
	Explanations
	Annotations
Animations	Dynamic interactive representations
	Constructive visualizations
Pictures	Graphical display of relation among processes
	Examples
	Diagrams
Sound	Voice-over of text
	Warnings
	Summaries

with the environment. In particular, the design must be based on considerations of how the user will think, use, interact with, and learn from the environment. The second implication is that such cognitively-based hypermedia environments are not just likely to be more effective, but in addition might be used to test the validity of the cognitive principles on which they are based. In the research presented here, different configurations of the computer environment were used to evaluate the effectiveness of cognitive media in organizing information for learning under different conditions.

AlgoNet: A Multimedia Learning Environment

The theory presented above was used as the basis for the implementation of a computer-based self-paced educational environment. For the implementation, we used the "MultiMedia Education Delivery System" (MMEDS) as our multimedia authoring tool. MMEDS runs on Unix workstations under X-Windows and Motif and provides a set of tools for authoring and presenting multimedia-based courseware. These tools enable the author to create, organize, and synchronize educational information within an open and extensible architecture. Authored course modules utilize a hypermedia, networked organizational model and support the presentation of text, audio, still graphics, visualizations, and other arbitrary programs (Li et al., 1994).

Using the MMEDS authoring environment, we designed an educational module targeted for introductory computer science and engineering classes. The module allows students with minimal background to learn about basic algorithmic concepts, such as graphs and sorting. The subject material for the module comes from introductory computer science courses in Georgia Tech's College of Computing that are taken by computer science and engineering majors in their first or second year. AlgoNet consists of a collection of information nodes, which are linked together to create one large, educational document. These nodes are analogous to sections of a book in that they each cover one specific subsection of the entire module. However, unlike a book, the nodes do not have to be viewed in any particular sequence. Moreover, the nodes within the module can contain a variety of different information types such as text, pictures, visualizations, buttons, and sound. Each node can be activated (or played) many times. In addition, the AlgoNet module is an active document. Many nodes are interactive, requiring active student input, construction, and involvement.

Content and Organization of the Module

The AlgoNet module is comprised of 57 nodes or screens of information. These nodes are hierarchically organized into three submodules: (1) a glossary, (2) applications, and (3) case studies. The *glossary* module explains the basic concepts and terms used in graph theory and graph algorithms. These topics include cycles, degrees, edge weights, paths, trees, and so on. Each topic is explained with a definition and an example (two kinds of cognitive media). The definition nodes are all text-based, while the example nodes present the topics using both graphics and text. Some nodes, such as "Edge Weight", include an interactive exercise, in which students construct a graph in a specified structure. With these exercises, students are actively involved in learning the topics.

The *applications* module describes two widely-used procedures in engineering and computing fields, the shortest path and minimum spanning tree algorithms. Each algorithm is explained with a definition, example, pseudo-code, visualization, and exercise (the cognitive media), so that students understand and learn how to implement these algorithms. The minimum spanning tree sub-module contains two specific algorithms, namely Kruskal's and Prim's algorithms. Both algorithms are explained with cognitive media such as definitions, visualizations of their algorithm process, pseudo-code, and interactive exercises; each type of cognitive media is implemented in terms of one or more physical media.

The final sub-module in AlgoNet contains two large *case studies* that illustrate the use of graphs and graph algorithms in real-world problems. The first case study demonstrates minimizing the cost of traveling from one city to another as an application of the shortest path algorithm. Figure 1 shows an example screen shot of the first case study. This case study uses both text and graphics to illustrate the material. The second case study illustrates

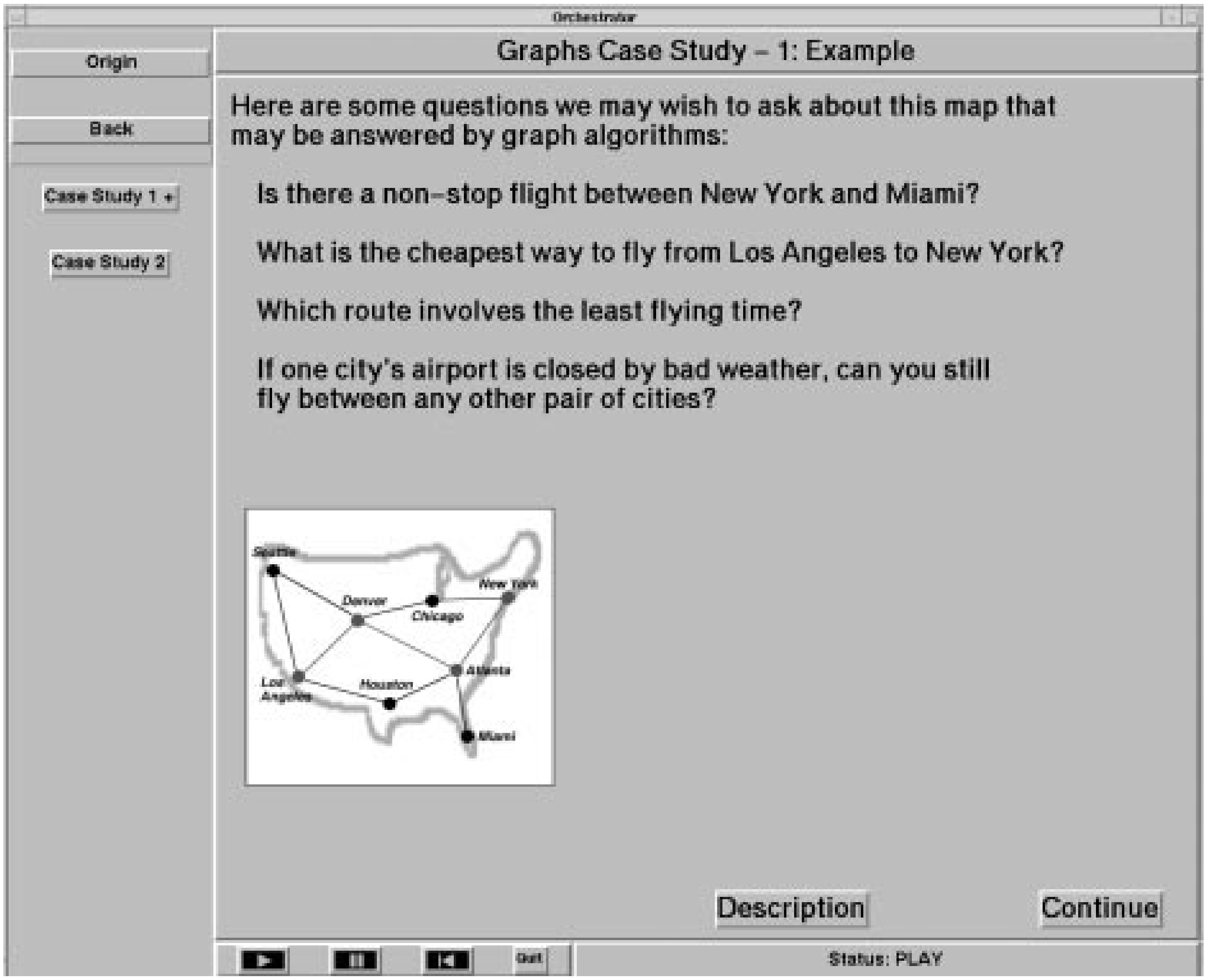

Figure 1: An example screen showing a case study on the shortest path algorithm.

various graph topologies as they are instantiated in computer networks.

The constructive visualizations and exercises are implemented in POLKA (Stasko and Kraemer, 1993), a software environment for developing dynamic interactive visualizations of programs that provides support for various graphical objects such as shapes and text. It also includes an interactive component so that users may directly control the visualization. MMEDS directly supports POLKA visualizations, so they can be included in nodes just like other presentation media such as text, graphics, and audio.

Figure 2 shows an ALGONET node that includes a POLKA animation of Prim's algorithm. The animation depicts the operations of Prim's algorithm on an example graph by highlighting, flashing and coloring edges and vertices. POLKA provides a control panel that

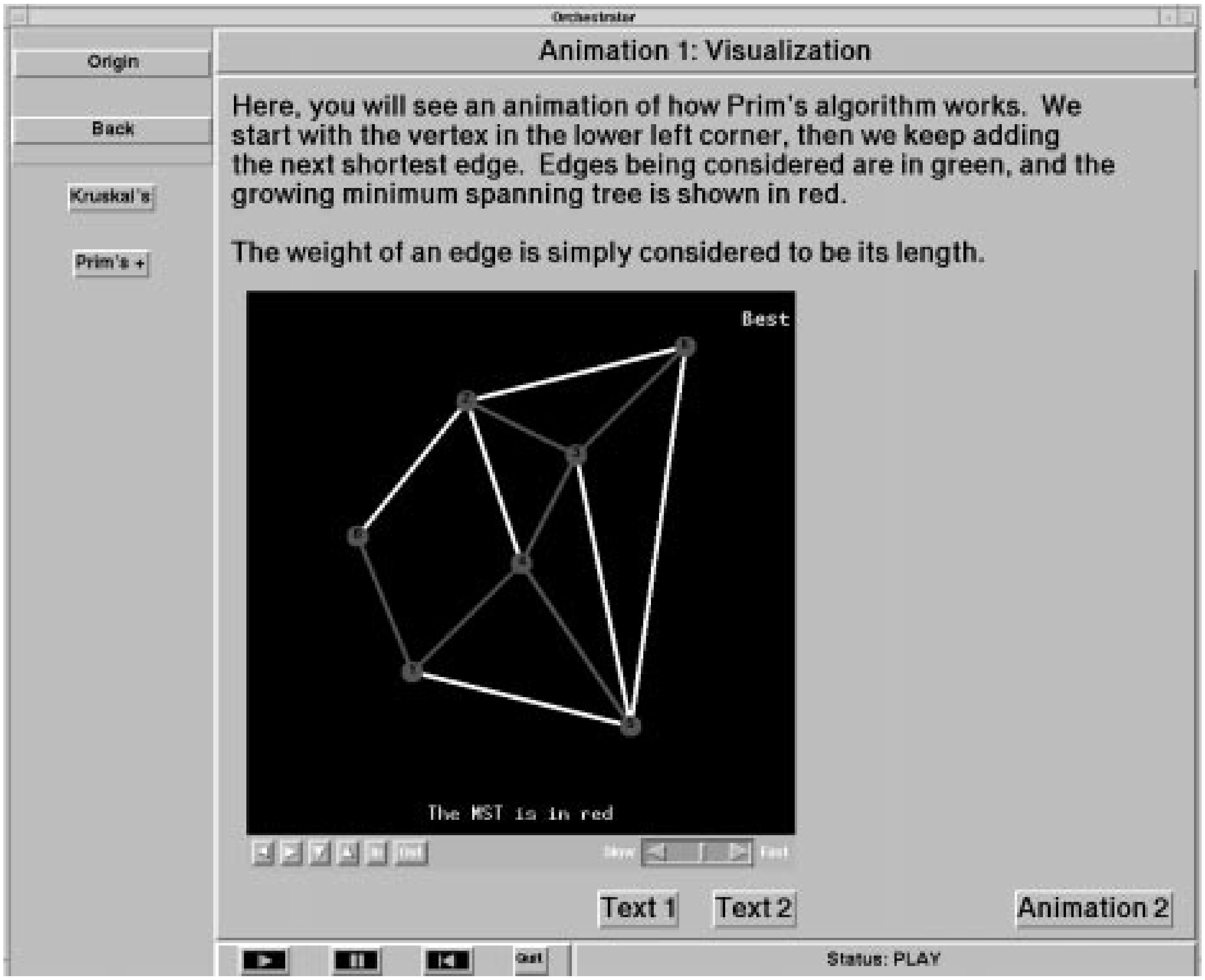

Figure 2: A POLKA animation of Prim's algorithm.

permits viewers to adjust the speed of the animation, to zoom in for detailed examination of a particular part, and to zoom out for observing the entire process. In addition, the animation in this node is accompanied by textual explanations.

Navigational Methods

Navigation is, without doubt, a design issue of fundamental importance in hypermedia systems (Halasz, 1988; Jonassen and Mandl, 1990; Nielsen, 1990; Rivlin et al., 1994). Methods must be designed to provide users with means for efficiently and effectively navigating through the system without getting lost. AlgoNet employs several navigation methods and

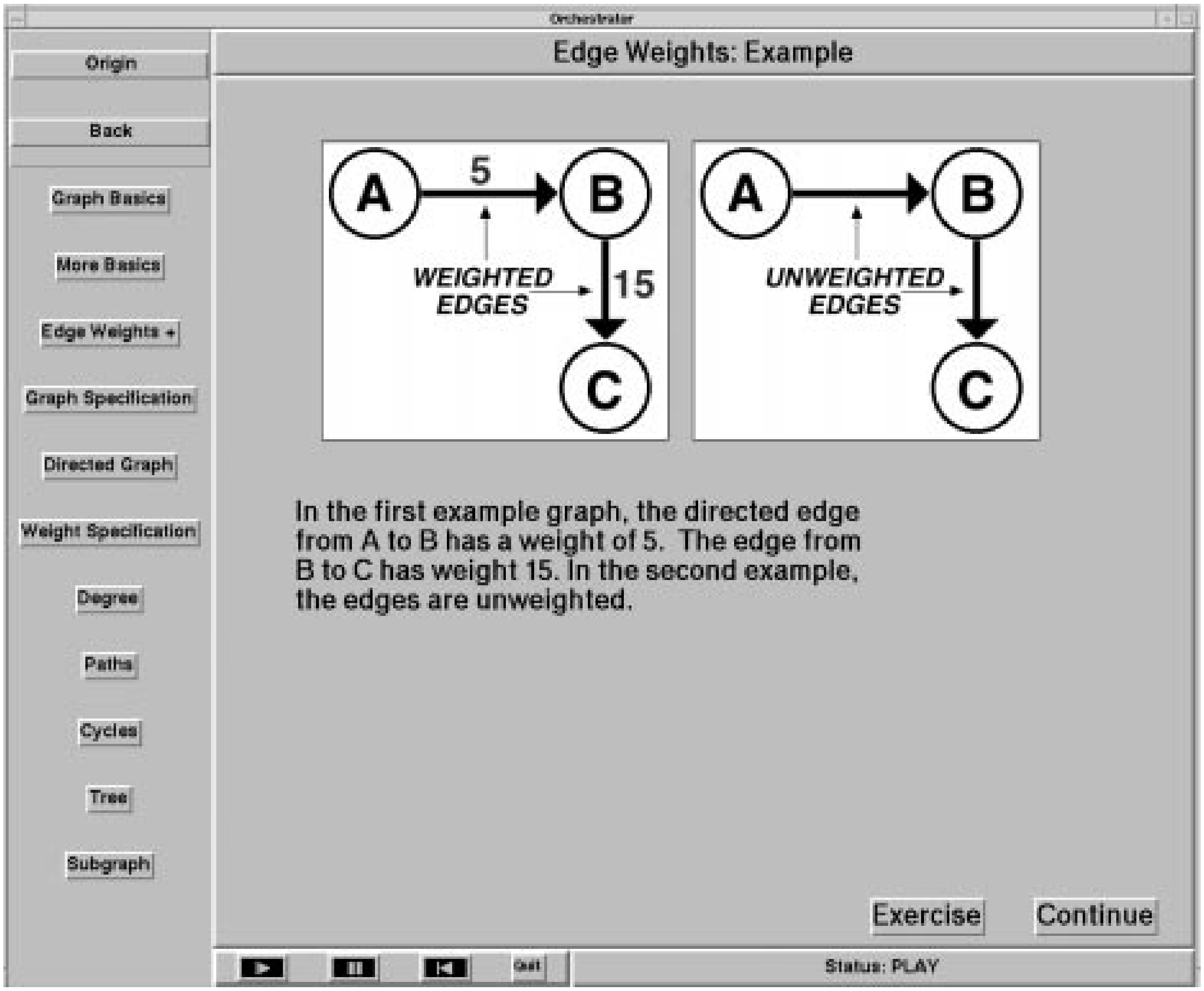

Figure 3: A screen from the Glossary in `Algonet`.

metaphors. These fall into four categories: (1) system navigation, (2) topic-based navigation, (3) cognitive media (local) navigation, and (4) node interactors. AlgoNet navigation is controlled by either the left mouse button or/and the middle mouse button. The former lets users to jump to a specified node, while the latter one both jumps to the node and automatically starts playing its presentation.

System Navigation. As shown in Figure 3, the left side of the main window contains a row of buttons, called the *Navigation Panel*. These buttons can be clicked on in order to select a node to be viewed.

The top two buttons in the left-hand corner are always available to the user. They are examples of system navigation buttons. Clicking on the *Origin* button returns the user to the starting node in the lesson. Clicking on the *Back* button returns to the node previously viewed.

Topic-based navigation. The remaining buttons that are displayed in the left Navigation Panel are dynamic: the buttons that appear depend on the node that is currently being viewed. These buttons are examples of topic-based buttons, in that they provide access to topics in the module. Figure 3 shows the "Edge Weights: Example" node. The topic that the student is currently viewing is indicated by a '+' sign following the topic name. Thus, in Figure 3, the plus sign is visible after the topic name "Edge Weights."

Cognitive media buttons (local navigation). The bottom of the window may also contain a row of buttons. By selecting one of these buttons, more information can be viewed on a particular topic. Figure 4 shows the cognitive media types accompanying Kruskal's algorithm. Access to each available cognitive media type—here, *Definition*, *Pseudo-Code*, and *Exercise*—is provided through a button. Unlike the topic buttons, once a user enters a cognitive medium, that button disappears, leaving the other available buttons. Note that in Figure 4, the *Visualization* button has been removed because that is the currently active node. In addition, the *Continue* button may appear when there exists a natural order for visiting a series of nodes.

Node Interactors. The *Flow Control Panel* resides on the bottom of the main window on the left side. When a student wishes to see the same node repeatedly, these buttons are used to interact with node presentation. The Flow Control Panel consists of a set of buttons based on the VCR metaphor. From left to right, the buttons are *Play*, *Pause*, *Rewind*, and *Quit* (see Figure 4). Clicking on one of these buttons with the left mouse button causes the appropriate action in the currently loaded node. The *Play* button is used to play or replay the current node. The *Pause* button is used to pause nodes, such as nodes containing visualizations. Students can stop visualizations any time they wish. In a similar way, the *Rewind* button is used to rewind the current node. Lastly, the *Quit* button is a command to exit the AlgoNet system.

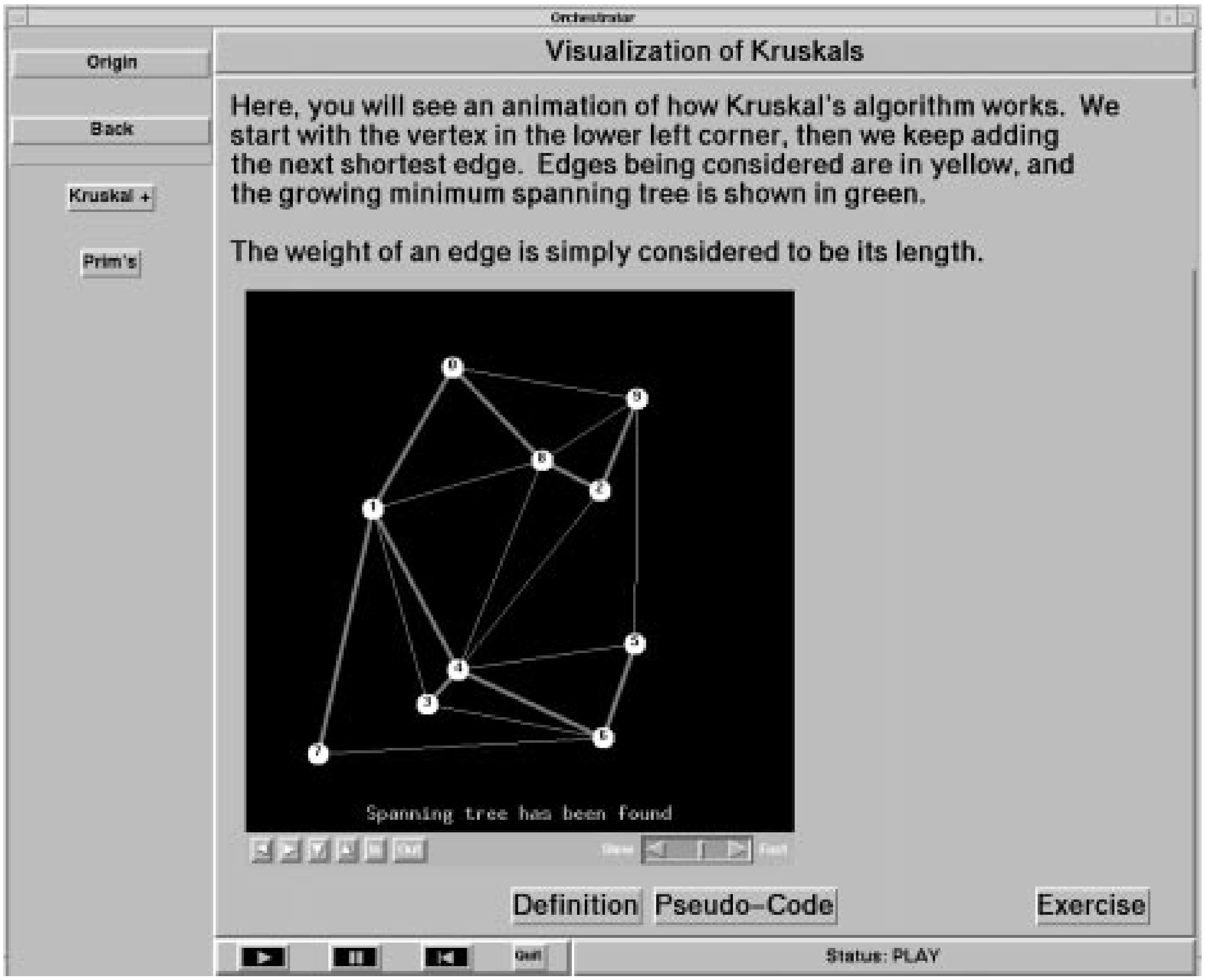

Figure 4: A screen showing Kruskal's algorithm, with accompanying cognitive media.

Structural Evaluation of AlgoNet

To evaluate the effectiveness of our theory in guiding design, we performed several empirical evaluations of the system. The evaluations were motivated by our view of student learning as mediated by several interacting factors. These factors include (1) the structure of the underlying system, (2) the means of information access, and (3) the knowledge, goals, and strategies of students in the learning context. This section describes analyses of the underlying structure of the system. These results are important in determining the navigational and hypermedia topology.

Node Links

The AlgoNet system can be represented as a directed graph, with information nodes connected via link traversal. Link traversal is performed by clicking on buttons. Recall that the system has four types of navigational buttons: (1) system navigation (e.g., *Root*, *Back*), (2) topic-based navigation, (3) local navigation (cognitive media buttons), and (4) node interactors. In the remaining analyses, system navigation and node interactor buttons are ignored since they are present on every screen.

In order to determine number of choices available per node, we computed the number of links available per node in the system. Table 2 shows the mean number of links per node. As can be seen, nodes possessed an average of 10 buttons and ranged from 1 to 15 buttons. The node that had only one button was the overview node, which displayed the overall structure of the module. Glossary nodes with an exercise component had the largest number of available links.

Node Connectivity

While the node link analysis indicates that, on average, information nodes possessed many links, it does not reveal the underlying topology and interconnectivity of nodes in the system. Since the structure of the system can affect student navigation and browsing, it is important

Table 2: The number of links per node.

	Topic-based	Local	Total
Mean	5.89	4.02	9.91
S.D.	4.56	1.20	4.72
Min	0.00	0.00	1
Max	11.00	6.00	15.00

Table 3: A subset of the distance matrix.

Node Name	Title Page	Overview	Applications	Intro to Case Studies	Graph Basics
Title Page	0	1	1	1	1
Overview	1	0	2	2	2
Applications	1	2	0	2	2
Intro to Case Studies	1	2	2	0	2
Graph Basics	1	2	2	2	0

to determine how easy it is to navigate from one node to another. Similarly, within the system, we wished to determine the most central nodes, and those that are more difficult to reach. These node attributes may affect student browsing patterns.

In order to address these questions, we employed metrics that were developed for analyzing and revealing the structure of hypermedia systems (Rivlin et al., 1994). These metrics depend of the construction of a matrix that has as its entries the shortest distance (the number of links) between every node in the system. This is called the *distance matrix.* Table 3 shows a subset of this matrix for the AlgoNet system. The entries represent the shortest path between the nodes listed in each row and nodes in the corresponding columns.

Using this matrix, we performed several operations. First, we computed the *converted out distance* (COD) vector, which is a vector containing the sum of all entries for each row in the matrix. Similarly, we computed the *converted in distance* (CID) vector, which is a vector containing the sum of all entries for every column in the matrix. Third, we computed

Table 4: Relative in and out centrality values for sample nodes, and overall means.

Node Name	ROC	RIC
Case Study Example	38.68	46.24
Min. Span Tree Example	62.52	43.61
Kruskal's Definition	57.47	37.52
Title Page	51.72	177.54
Overall Mean	56.11	62.84
S.D.	5.04	22.94

the *converted distance* (CD), which is a scalar with the sum of all entries in the distance matrix (Rivlin et al., 1994).

The COD and CID values are normalized for the size of the matrix by computing the *relative out centrality* (ROC) and *relative in centrality* (RIC), as follows (for each ith element):

$$\mathrm{ROC}_i = \mathrm{CD}/\mathrm{COD}_i$$
$$\mathrm{RIC}_i = \mathrm{CD}/\mathrm{CID}_i$$

The ROC values indicate how easily a node can access other nodes. The higher the ROC value, the easier the node can access other nodes and, thus, the more central it is. Table 4 shows sample nodes in AlgoNet with high and low ROC values, and the overall mean. As can be seen, the "Case Study Example" node has a low ROC value, indicating that, once there, it is difficult to access other nodes.

The RIC values indicate how easily a node is accessed by other nodes. The higher the RIC value, the more easily the node is accessed. Table 4 shows sample nodes in AlgoNet with high and low RIC values, and the overall mean. The "Title Page" node had the highest RIC value, indicating that it was the most easily accessed node. This result follows design intuition, as this node represents the point of departure for accessing the main sub-topics in AlgoNet.

Empirical Evaluation of AlgoNet

The previous section presented results from analyzing the underlying navigational and hypermedia topology of the system. We have argued that this structure may impact students' resulting interactions. In addition to system structure, student learning is also affected by the means of information access, and the knowledge, goals, and strategies of students in the learning context. In this section, we report results from a study that involved over 100 beginning undergraduate computer science students who used the AlgoNet courseware to learn about basic computer and engineering concepts and algorithms.

To evaluate our theory of cognitive media types, we implemented two versions of the AlgoNet courseware. In the first system, access into the courseware is via indices that specify particular types of *cognitive media*. For example, students can choose to view definitions of concepts, examples of concepts, or case studies that use the concepts, etc. In the second contrasting system, access is provided via types of *physical media*. For example, students can click on buttons to view animations, pictures, text, etc. In other words, the "local navigation" buttons were labeled by cognitive media types in the first system and by physical media types in the second system. The only difference between these two systems was the labeling of the media buttons; topics and contents of the two systems were identical.

In addition to manipulating index types, we investigated how these indexing schemes may interact with student learning goals. To examine this aspect of multimedia use, subsets of students using each version of the AlgoNet system were provided with focused "study questions" that they answered as they interacted with the course module. These study questions served to provide students with explicit learning goals, and thereby to focus their browsing.

Participants

Students were 111 volunteers from 2 introductory-level computer science courses (01 and 02) held during the summer of 1994. These courses are taken by students in various schools at

Georgia Tech. One course (01) was much larger than the other, and serves as the prerequisite course for the other computer science course (02). Eighty-one students were drawn from the first class, and 30 from the second. Students received class credit for their participation. The data from 16 students in 01 and 3 students in 02 were discarded either because of system crashes or because the students failed to complete the post-test.

Procedure

Students began the study by completing a background survey and reading a brief manual that described the use of the ALGONET system. Students were then randomly assigned to one of the two versions of the ALGONET system, for up to one hour. In addition, half of the students in each condition received study questions. Students completed the study by answering a questionnaire and a post-test.

Design

The design was a 2 X 2 factorial design, where learning system (cognitive vs. physical media) was crossed with learning goals (no study question vs. study questions). Students were randomly assigned to one of four resulting conditions, with an attempt to balance students drawn from the two classes across conditions.

Materials

Students received a booklet describing how to use the ALGONET system. Upon completion, students completed a post-test and a questionnaire. The post-test contained 21 questions varying from basic terminology in graph theory to applications such as minimum spanning tree and shortest path algorithms. The mean score on the post-test was 13.28, with a possible maximum of 16. The questionnaire asked students to rate their enjoyment and understanding of the materials.

Results

The MMEDS software records in a log file all mouse actions performed by the students, the nodes visited, and the time spent viewing each node. We developed log file analysis software in order to analyze student interaction patterns. For the purposes of our analysis, we separated students into groups based on the class in which they were enrolled, since the students in the second class (02) possessed more relevant background knowledge.

Usage

On average, students in 01 spent about 38 minutes interacting with the system, visited 87 (non-unique) nodes, and made approximately 164 mouse actions. On average, students in 02 spent about 39 minutes interacting with the system, visited a total of 79 nodes, and made approximately 149 mouse actions.

Figure 5 shows the mean number of mouse actions per navigation method. As can be seen, the largest proportion of actions (82 clicks or 50% of the total number of clicks) occurred in the node interactor category, *Flow Control* buttons. 90% of those actions were *Play* requests (74 out of 82 clicks, as shown in the second bar of the figure). The second largest proportion (51 clicks or 31%) were local button mouse actions. Recall that these provided access to the cognitive or physical media. Hyperlink buttons, which provided access to different topics, were seldom used (16 clicks or 10%); so were system navigation buttons (15 clicks or 9%).

Since mouse clicks to access cognitive or physical media types accounted for a large proportion of student actions, we analyzed these to determine the most frequently accessed type of media.

The first column of Table 5 shows the mean number visits to each type of cognitive media, normalized by the total number of types available in each type of media. As can be seen, the concrete interactive representations accounted for a majority of student accesses. The least frequently used cognitive medium was "Definitions." Students' preference for concrete examples within instructional materials is a robust finding in the literature (Chi et al., 1989;

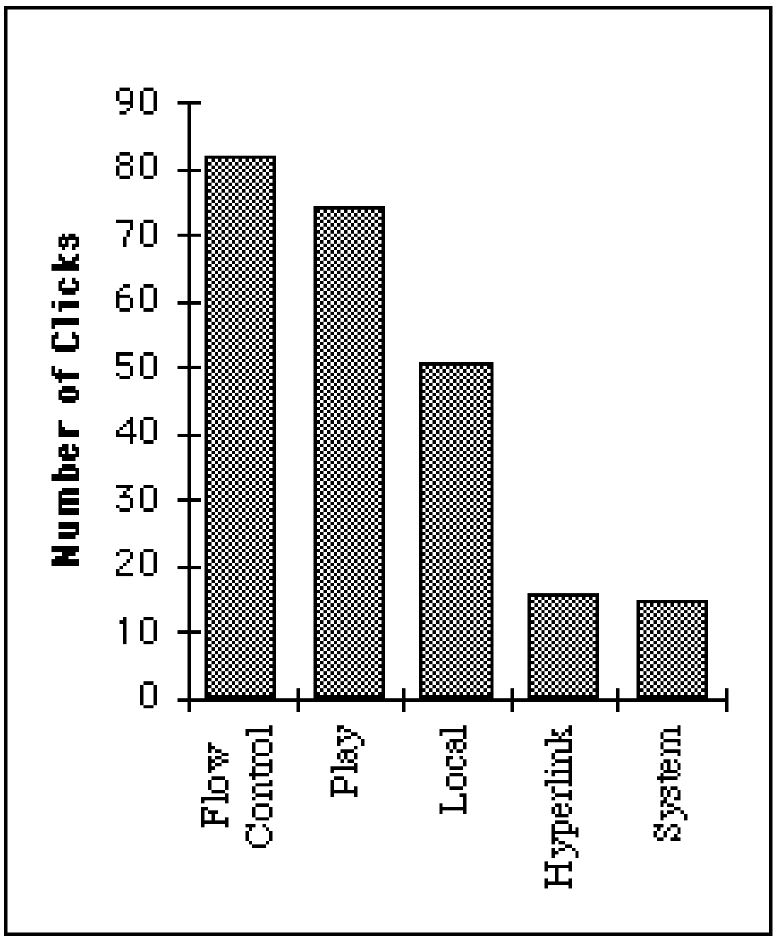

Figure 5: The mean number of mouse actions per navigation category.

Table 5: The number of visits normalized by total number available in each category of media, and time spent viewing different cognitive media.

Cognitive Media	Media Visits (%)	Time (secs)
Visualization	28	272.6
Exercise	21	123.4
Example	19	28.4
Pseudo-Code	17	44.8
Definition	15	35.5

Table 6: The number of visits normalized by total number available in each category of media, and time spent viewing different physical media.

Physical Media	Number of Visits (%)	Time (secs)
Animation	28	132.1
Figure	25	35.8
Text	24	37.3
Diagram	23	27.6

Sweller and Cooper, 1985). In contrast, in the physical media condition, accesses were much more balanced across all of the physical media available (see Table 6).

Similarly, we analyzed the time spent viewing the different nodes of information. Students tended to spend more time viewing the "Exercise" and "Animation" nodes, while spending less time viewing the "Example" and "Diagram" nodes. However, these results are subject to two confounds. First, the difference may be partly due to the fact that animations took longer to load and view, compared to reading text materials. Second, students with study questions may have used their viewing time to write down their answers, which possibly made their viewing times longer than those without study questions.

Usage and node connectivity

We hypothesized that the underlying structure of the system affects students' browsing patterns. To examine this possibility, we analyzed the effects of node connectivity on student browsing patterns, using the distance matrix described above. A stepwise regression analysis found that in the cognitive AlgoNet condition, the *relative in centrality* (RIC) accounted for 56% of variance in predicting users' navigational strategies, $F(1{,}55) = 71.65$; $p < .001$. In the physical AlgoNet condition, it accounted for 55%, $F(1{,}55) = 69.142$; $p < .001$. In contrast, for both modules, the ROC did not appear to significantly affect students' navigational patterns. These results suggest that nodes with more incoming links play a more important role in determining browsing than do nodes with many outgoing links, perhaps because their accessibility tends to channel users towards those nodes. Furthermore, unlike a typical hypermedia environment in which nodes spread out from a central node that serves as a table of contents, nodes in AlgoNet are organized around topics in mutually accessible clusters which increases the RIC and, in turn, influences browsing patterns.

In addition, we performed hierarchical cluster analyses using type of media, RIC, and ROC to reveal document clusters. The analysis of the cognitive media version of AlgoNet, RIC, and ROC yielded clusters of case studies, definitions, examples, minimum spanning trees, and shortest paths. Case studies and definitions were further clustered together. Likewise, examples and minimum spanning trees were clustered together. Figure 6 shows the result of the cluster analysis for the cognitive media version of AlgoNet.

In contrast, a cluster analysis on the physical media version of AlgoNet, RIC, and ROC generated many small clusters. These findings suggest that when students used cognitive media, their navigation strategies were strongly influenced by the way the modules were organized. This did not appear to be true in the physical media condition.

Figure 6: Hierarchical cluster analysis of nodes in the cognitive media version of AlgoNet.

Table 7: Performance on post-test for students in 01.

		AlgoNet	
Study Questions		Cognitive	Physical
No	N	19	22
	Mean	12.58	13.64
	SD	3.42	4.51
Yes	N	20	18
	Mean	12.90	12.68
	SD	4.14	4.04

Learning Outcomes

We analyzed post-test results to measure learning outcomes for the students in the different learning conditions. We conducted ANOVA with type of media (cognitive and physical) and study-questions (yes and no) as the independent variables. Students' performance on the post-test was the dependent variable.

For students in 01, we did not find any significant differences in performance on the post-test. Results are shown in Table 7. However, for students in 02, we did find a significant media by study-question interaction, $F(1, 26) = 4.83$; $p < .05$ (see Table 8). Students using cognitive media with study questions performed significantly better on the post-test (17.00), while students using physical media with study questions showed the worst performance (11.80). It is possible that students with more background knowledge were more strongly affected by the different browsing modes available.

Use of AlgoNet

We first analyzed the amount of time students spent viewing the material. For both 01 and 02 students, we found that students with study questions spent significantly longer amounts of time viewing the material (see Table 9). This suggests that concrete learning goals induced a better and more thorough viewing of the materials. However, we note that the increase in

Table 8: Performance on post-test for students in 02.

Study Questions		AlgoNet Cognitive	AlgoNet Physical
No	N	10	8
	Mean	13.20	14.12
	SD	3.79	4.67
Yes	N	7	5
	Mean	17.00	11.80
	SD	2.23	3.27

Table 9: Time spent viewing materials per condition.

Class	Study Questions no	Study Questions yes
01	2129	2468
02	2176	2547

time may be due to the extra time that students spent writing down answers to the questions.

For students in 01, there was also an interaction of type of media with study-question on time spent viewing the materials $F(1, 61) = 3.99$; $p = .05$. The students using cognitive media without study-questions spent the least amount of time (mean = 1868.06), while students with cognitive media and study questions spent the most time (mean = 2461.47). No such interaction was found for students in 02.

Finally, we looked at the total number of information nodes viewed by students. For students in 02, we found a significant main effect of type of media $F(1, 23) = 4.53$; $p < .05$. The students using cognitive media viewed significantly more nodes (mean = 251) than students using physical media (mean = 192). This suggests that these indices promote information exploration. For students in 01, we did not find significant effects of interaction, types of media, or instruction, $F(1,75) = 0.57$; $p < 0.45$, $F(1,75) = 1.42$; $p < 0.24$, and $F(1,75) = 1.20$; $p < 0.28$, respectively.

Summary

Overall, the results from our studies showed that the navigation strategies of students using the cognitive media version of AlgoNet were strongly influenced by the way the modules were organized. This was not true in the physical media condition. Thus, design based on cognitive media types appears to act as a stronger guide for student learning than does design based on the physical characteristics of multimedia.

In addition, students with some background knowledge appeared to benefit from cognitively organized modules more than students without relevant knowledge. This effect was further enhanced by the use of study questions. This suggests that students with more background knowledge are better able to set learning goals, form information-seeking strategies, and take advantage of the cognitively-based access methods than students with less knowledge.

Discussion

In this article, we have presented a theory for the design of hypermedia learning environments. This theory argues that the design of such systems is best thought of in terms of what we call "cognitive media." Cognitive media are based on a cognitive theory of the inferential and learning processes of human users, and encapsulate different methods or strategies for problem solving and learning. Specifically, we argue that systems should not be characterized primarily in terms of the kinds of physical media types that can be accessed. Instead, the important aspect is the content that can be represented within a physical media, rather than the physical media itself. Moreover, the content and means of access to the content should be structured so as to be cognitively relevant to the learner's goals.

The design of educational software is a multi-faceted problem, and its successes, failures, and impacts are dependent on many complex, inter-related aspects. Effective educational software must be based upon an understanding of student learning and cognition, the target classroom context, the subject-matter domain, and the capabilities of the underlying technology. In this article, we have examined only a few facets of this large problem.

We hope that our theoretical approach contributes both general and practical guidelines. In particular, we expect that they can be used by at least two key groups involved in the various phases of designing and developing hypermedia learning environments. First, designers of hypermedia systems, we argue, should take into consideration a functional theory of human cognition that specifies learning and reasoning strategies in sufficient detail to allow the system designer to understand how precisely they might be facilitated. These problem solving and learning strategies rely on specific functional media characteristics that facilitate specific problem solving actions. These, in turn, are enabled by specific kinds of physical media as realized in computing technology. For example, in designing AlgoNet, we wished to take advantage of a particular type of physical medium, animation, which is increasingly available on all platforms. Using animations, we designed a cognitive medium called constructive visualizations which cognitive theory predicts ought to facilitate learning. As described, this interactive dynamic representation was particularly useful for communicating the processes of various computing algorithms. In sum, designers should focus on devising new representations, which are negotiated between the physical media capabilities and cognitive and domain considerations.

Second, we anticipate that our theoretical approach is relevant to activity designers (for example, classroom teachers) within and around multimedia learning environments. It is a practical reality that the cost of developing multimedia systems from scratch, from both computing and human capital points of view, is prohibitive. At the same time, new standards and common formats for multimedia elements are emerging and becoming widespread. Moreover, the growing presence of computer networks enables the easy dissemination of these elements. Therefore, activity designers will increasingly rely on small, inter-operable units. These will then be integrated to create larger learning modules for students. Naturally, the units selected are subject to hardware and software constraints. However, given this trend, we argue that the selection, access, and use of these units should be based on cognitive media types, and the kinds of learning activities they foster.

In future work, we plan to focus more on the learning and metacognitive strategies of students. In particular, we wish to better understand the learning and metacognitive strategies of effective learners. This knowledge will then be incorporated into the design of our software systems. Specifically, tools will be designed to support the kinds of reflective and metacognitive reasoning processes that have been found to facilitate learning in the cognitive psychology, metacognition, and machine learning literature. This literature covers a broad range of processes—comprehension monitoring, self-explanation, goal-driven learning, strategic deliberation—many of which have been shown to facilitate certain kinds of learning in certain kinds of situations in humans and/or in artificial intelligence systems. In this way, our guidelines will be enhanced to promote design that supports effective learning processes. This will result in the design of multimedia system that encourage and scaffold less-effective learners into using more effective learning processes.

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References

Boden, M. (1991). *The Creative Mind: Myths and Mechanisms.* Abacus, London.

Chi, M., Bassok, M., Lewis, M., Reimann, P., and Glaser, R. (1989). Self-explanations: How students study and use examples in learning to solve problems. *Cognitive Science*, 13:145–182.

Guzdial, M. (1995). Software-realized scaffolding to facilitate programming for science learning. *Interactive Learning Environments*, 4(1):1–44.

Halasz, F. (1988). Reflections on notecards: Seven issues for the next generation of hypermedia systems. *Communications of the ACM*, 31(7).

Jonassen, D. and Mandl, H., editors (1990). *Designing Hypermedia for Learning*. Springer Verlag, Berlin.

Kolodner, J. L. (1993). *Case-Based Reasoning*. Morgan Kaufman Publishers, San Mateo, CA.

Kozma, R. (1991). Learning with media. *Review of Educational Research*, 61(2):179–211.

Larkin, J. H. (1988). Display-based problem solving. In Klahr, D. and Kotovsky, K., editors, *Complex Information Processing: Essays in honor of Herbert A. Simon*. Lawrence Erlbaum, Hillsdale, NJ.

Larkin, J. H. and Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science*, 11:64–100.

Li, G., Gallant, E., and Stasko, J. (1994). MMEDS: An environment for multimedia-based education delivery. *GVU Technical Report 94-20*.

Ng, E. and Bereiter, C. (1991). Three levels of goal orientation in learning. *The Journal of the Learning Sciences*, 1(3&4):243–271.

Nielsen, J. (1990). *Hypertext & Hypermedia*. Academic Press, San Diego, CA.

Ram, A. and Leake, D. B. (1995). Learning, goals, and learning goals. In Ram, A. and Leake, D. B., editors, *Goal-Driven Learning*, chapter 1. MIT Press/Bradford Books, Cambridge, MA.

Recker, M. and Pirolli, P. (1995). Modelling individual differences in students' learning strategies. *Journal of the Learning Sciences*, 4(1):1–38.

Rivlin, E., Botafogo, R., and Shneiderman, B. (1994). Navigating in hyperspace: Designing a structure-based toolbox. *Communications of the ACM*, 37(2):87–96.

Schank, R. C., Fano, A., Jona, K., and Bell, B. (1994). The design of goal-based scenarios. *The Journal of the Learning Sciences*, 3(4).

Soloway, E., Guzdial, M., Brade, K., Hohmann, L., Tabak, I., Weingrad, P., and P., B. (1992). Technological support for the learning and doing of design. In Jones, M. and Winne, P., editors, *Adaptive Learning Environments*. NATO ASI Series, Springer Verlag, Berlin.

Stasko, J. T. and Kraemer, E. (1993). A methodology for building application-specific visualizations of parallel programs. *Journal of Parallel and Distributed Computing*, 18(2):258–264.

Sweller, J. and Cooper, G. (1985). The use of worked examples as a substitute for problem solving in learning algebra. *Cognition and Instruction*, 7:1–39.

Trigg, R. H. and Weiser, M. (1986). Textnet: A network-based approach to text handling. *ACM Transactions on Office Information Systems*, 4(1):1–23.