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A Tool for Examining the Development
of Students' Conceptual Understandings

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KNOWLEDGE MAPPING IN THE CLASSROOM: A TOOL FOR EXAMINING THE DEVELOPMENT OF STUDENTS' CONCEPTUAL UNDERSTANDINGS[1]

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Abstract

The objective of this study was to investigate how computer-based knowledge mapping could be used simultaneously as an instructional tool and an assessment tool in a classroom setting. Data are presented that demonstrate how knowledge mapping served as a tool to support, facilitate, promote, and evaluate students' development of understandings in science. In this study, knowledge mapping was (a) integrated into instruction, (b) employed as a repeated measure to capture the ongoing development of ideas, (c) used individually as well as collaboratively, (d) scored according to algorithms that emphasized the recursive and incremental nature of both learning and the development of scientific ideas, and (e) accessed online through the computer. A non-equivalent control group design was utilized. Fifty-two fourth- and fifth-grade students from two intact classrooms participated in this study. Both groups generated pretest and posttest knowledge maps of their understandings of the digestive, respiratory, and circulatory systems. Students in the experimental group created three additional (collaborative) maps during the course of instruction. Students in the control condition worked in small groups on three occasions to research the human body by using the Internet and related instructional materials. Results suggest that for students in the experimental group, repeated use of the mapping software supported and facilitated the development of scientific and principled understandings. Further, collaborative work with the mapper also afforded students the opportunity to establish connections between the systems in the human body to more fully develop their understandings of the domain—both integral components of learning and the development of scientific understandings.

Overview of the Study

The search continues for new and better ways to understand how children learn. We acknowledge the complexity of human development, yet measures that capture the complex and interactive nature of the growth of ideas and conceptual

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understandings remain elusive. Computer-based knowledge mapping, a graphical representation of the relationship between ideas in a given content domain, is one promising approach to both foster and analyze the development of children's understandings in science.

The objective of this study was to investigate how computer-based knowledge mapping could be used simultaneously as an instructional tool and an assessment tool in a classroom setting. Data will be presented that demonstrate how knowledge mapping served as a tool to support, facilitate, promote, and evaluate students' development of understandings in science. In this study, knowledge mapping was (a) integrated into instruction, (b) employed as a repeated measure to capture the ongoing development of ideas, (c) used individually as well as collaboratively, (d) scored according to algorithms that emphasized the recursive and incremental nature of both learning and the development of scientific ideas, and (e) accessed online through the computer. In this manner, students constructed knowledge maps to develop their scientific understandings while the classroom teacher made use of the mapping software to analyze and assess students' developing understandings. This approach to examining learning—which embedded assessments in authentic, meaningful instructional tasks—was the focus of this study.

Rationale for the Study

This study combines a number of theoretical frameworks and approaches to assessment, learning, and development. We build on prior knowledge mapping literature in instructional settings (Heinze-Fry & Novak, 1990; Holley & Dansereau, 1984; Horton et al., 1993; Jonassen, Beissner, & Yacci, 1993; Novak & Gowin, 1984; Novak, Gowin, & Johansen, 1983; Okebukola & Jegede, 1988; Stice & Alvarez, 1987), work at CRESST using knowledge mapping for assessment purposes (Baker, Niemi, Novak, & Herl, 1992; Herl, 1995; Herl, Baker, & Niemi, 1996) and related assessment studies (Jonassen et al., 1993; Markham, Mintzes, & Jones, 1994; Novak & Musonda, 1991; Ruiz-Primo, Schultz & Shavelson, 1997; Ruiz-Primo & Shavelson, 1995; Trowbridge & Wandersee, 1994). Research has shown knowledge mapping to be both (a) a useful instructional tool to facilitate integration, organization, comprehension, retention, and recall of new material and (b) a powerful and psychometrically sound method of assessing conceptual development. Our study also builds on cognitive development research (e.g., diSessa, 1988; Smith, diSessa & Roschelle, 1993), in which learning is characterized as being constructed piece by piece and new ideas are combined and re-combined with old understandings to create progressively more complex systems of understanding. The data collection and scoring schemes used in the study were designed to reflect our view of learning as a gradual refinement of ideas, which lead to progressively more complex understandings of science concepts.

Knowledge maps were employed in this study as a way to capture the continual, ongoing development of students' understandings in science. We define knowledge maps as diagrammatic representations of the major semantic relationships among a set of conceptual terms. Nodes represent concepts and lines between the concepts show the relationships between concepts. The basic unit of meaning on the maps consists of a concept-link-concept set, called a proposition. Carey (1986) suggested that "by comparing successive knowledge maps produced as the student gains mastery of the domain, the researcher can see how knowledge is structured and restructured in the course of acquisition" (p. 1126). We believed that computerized knowledge mapping would allow us to easily make those comparisons, by examining students' knowledge maps over time to understand how students learned about the human body and its interconnected systems.

Previous research has found that knowledge mapping accesses aspects of students' understanding distinct from more conventional measures of understanding. Recently, CRESST has extended knowledge mapping research from paper-and-pencil tasks to include computer-based knowledge mapping (Herl, O'Neil, et al., 1996). The incorporation of technology into the knowledge mapping tasks has provided new instructional and assessment opportunities, by providing the capacity for real-time and database-driven storage, retrieval, scoring, feedback, reporting, Internet/Web access, and increased interactivity. These capabilities enable new and novel uses of knowledge maps for instruction (e.g., as a tool to focus student discussion over the Internet) as well as for assessment (e.g., immediate scoring and reporting, analyses of students' map over time).

Our previous knowledge mapping research has employed knowledge mapping primarily as a stand-alone assessment tool, where maps were used as posttest measures of students' understanding. In this study, we extended our knowledge mapping application to include an instructional component. Knowledge maps were employed to foster and promote the development of conceptual understandings in science. The online knowledge mapping software, with its automated scoring and retrieval system, served as a learning tool around which students organized, refined, and connected their understandings in science. Data generated from the student maps also served as pretest and posttest measures of scientific understandings.

In addition to adding a new purpose for the knowledge mapping software (i.e., assessment tool embedded in an instructional context), we extended our previous scoring system to better capture the incremental and dynamic nature of the development of ideas and understandings in science. Knowledge maps are traditionally scored against one or more "expert" maps in a given domain (Herl, 1995; Roth & Roychoudhury, 1993). The original scoring scheme offers a number of advantages because it is based on an expert's understandings of a content area. The expert map score provides general information about increases in understandings, but it is somewhat limited in its capability to capture the nature and quality of *change* in students' ideas. For example, by using a expert match approach, how do we make sense of change in a map score from 4 to 7? Did the second map have more connections, better connections, connections that revealed deeper, more scientific understandings? In response to these limitations, a new scoring scheme was devised to address the issues of development of understandings (Osmundson, 1998). Our new scoring scheme addresses the issue of the change in understandings by allowing us to understand quality and nature of the changes in students' ideas over time.

In sum, our research questions in this study focused on using the knowledge map as an instructional tool, embedded with assessment capabilities: (a) Did students' map scores improve as they studied the human body?—i.e., is knowledge mapping as an assessment tool sensitive to instruction? (b) Did knowledge mapping support and/or promote learning? (c) Did use of the mapping tool foster development of understandings that were interconnected? (d) How was the knowledge mapper used during instruction? In addition, from a technical standpoint, we were interested in exploring the feasibility of multiple, simultaneous, online users of the mapping software, as well as of providing an online automated scoring system for the student knowledge maps.

Method

Participants and Setting

Students. This study took place in a large urban elementary school. Fifty-four 10- and 11-year-old students participated in this study. Of this original number of participants, two were dropped from the study because of missing data, resulting in a final sample of 22 boys and 30 girls.

Ethnicity and socioeconomic status were mixed. Students were White (26), Latino (6), Asian American (5), and African American (4). Eleven students belonged to other ethnic groups. Forty-eight (of the 52) students spoke English as their first language. Median family income was less than $50,000; the range was less than $20,000 per year to greater than $250,000 per year.

Students were drawn from two intact classrooms. The classes were roughly equivalent in terms of achievement and other academic indicators, according to the classroom teacher's informal assessment. The mean SAT-9[2] total reading stanine was 5.92 (SD = 1.80, range = 0 to 9, N = 52) and the mean SAT-9 total math stanine was 6.23 (SD = 1.79, range = 2 to 9; N = 52). Students were familiar with computers and their use. The knowledge mapping software had been used by students in a previous study (see Klein, Chung, Osmundson, Herl, & O'Neil, 1999, for more details). Thus, students were familiar with the task of knowledge mapping and its technical requirements.

Classroom setting. The teacher was a veteran instructor, with over 20 years of teaching experience, who volunteered her classroom as a site for the study. Science instructional practices were characterized as innovative: lectures, investigations, discussions, and dissections characterized instruction. The teacher's experience with computers was minimal prior to this study; as a result, technology was not a regular feature of students' science learning. Students were divided into two groups (morning and afternoon classes); science instruction occurred daily for approximately 45 minutes. The same classroom teacher taught both groups. This research was conducted near the conclusion of the school year; thus, prior to the onset of the study, students had learned about a number of systems in the human body, including vision and hearing.

The curriculum and instructional materials used included published materials and materials developed specifically by the classroom teacher. She had taught the unit for a number of years prior to this research. The general teaching approach was to consider each of the systems individually; that is, each subsystem in the body was researched and studied individually. During this study, emphasis was placed on

[2] *Stanford Achievement Test*, 9th edition. New York: Harcourt Brace.

understanding the interconnections that exist between the related systems of digestion, circulation, and respiration.

Instrumentation

Knowledge mapping system architecture. The online knowledge mapping system was designed to provide anytime-anywhere access capability for students and teachers. Thus, we created a Web site and integrated the use of a relational database into the knowledge mapper. The requirements for this site were (a) to support the creation and maintenance of knowledge maps by students, teachers, and experts, and (b) to provide scoring and reporting of knowledge maps in real-time. We used a relational database to collect student maps over time. By maintaining a running record of student maps over time, we scored the maps in real-time and generated reports of student performance over all mapping occasions. The reports were returned in standard HTML format readable by a Web browser, making them readily available and accessible to the classroom teacher and to researchers.

Knowledge mapping user interface. Figure 1 shows the main user interface of the system. The knowledge mapper was written in Java and was accessible from Netscape browsers running on either a Macintosh or a Windows platform. The mapper was adopted from earlier work for use in the current study (Herl, O'Neil, et al., 1996).

The user interface required only the use of a mouse. Concepts were added to the map via menu selections. Links were created by connecting two concepts and then selecting the desired link from a pop-up menu to form a proposition. The set of concepts and links was defined a priori. Students were allowed to use a concept only once, but they could create as many links between concepts as they wished. Our pilot studies and in-house usability testing from previous research showed that participants of various ages (fifth graders to graduate students) could be trained to use the knowledge mapper in approximately 10 minutes.

Development of knowledge mapping terms and links. To create a high-quality mapping task that covered the intended topic area (the human body and the three systems), the classroom teacher and five content area experts (three biologists, one medical student, and one physician) were asked to list important concepts relating to the circulatory, respiratory, and digestive systems. Researchers also reviewed the instructional materials used by the teacher and generated concept lists.

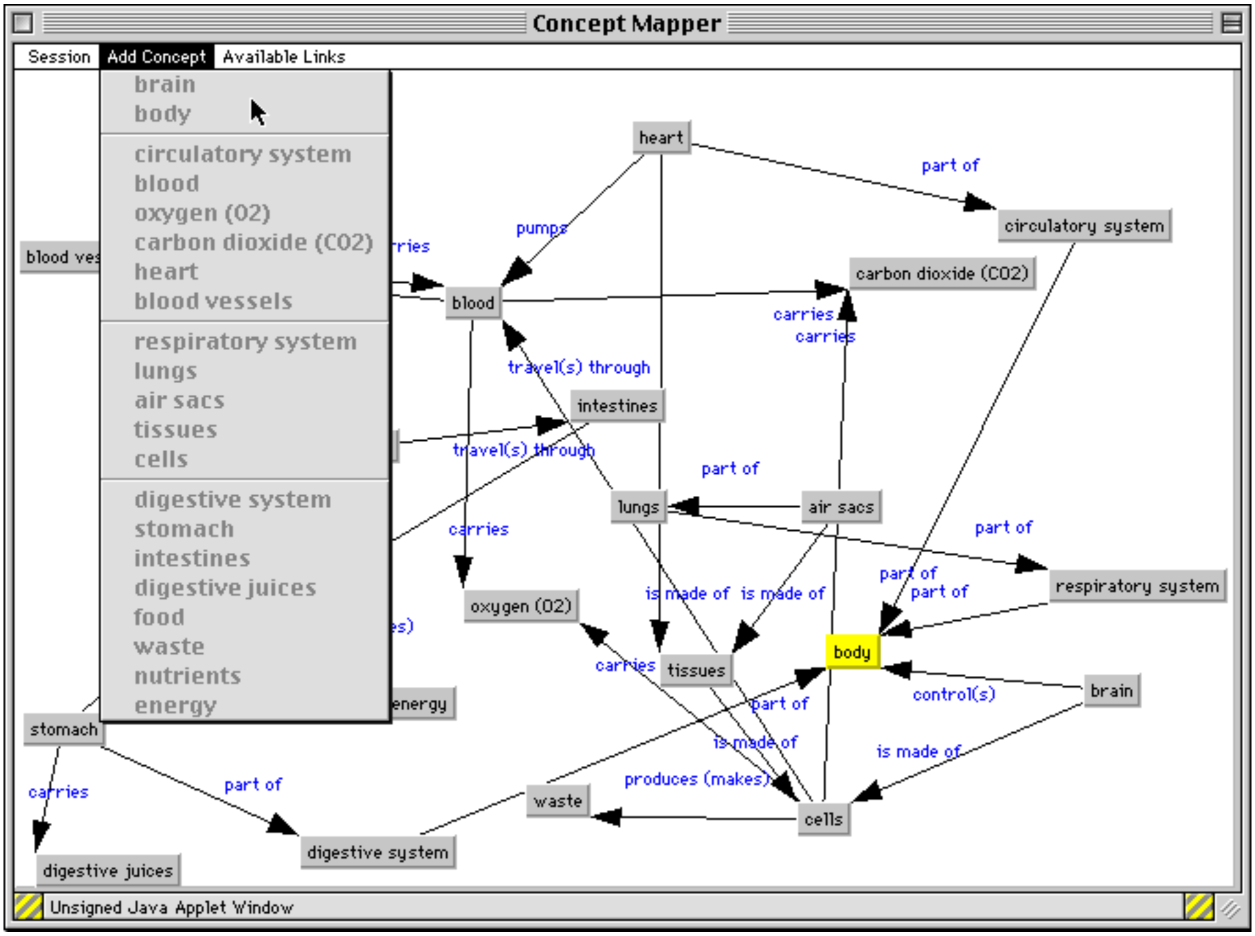

Figure 1. Primary user interface: Initial knowledge map of digestive, respiratory and circulatory systems.

Emphasis was placed on including concepts that were general (and comprehensible) to 10- and 11-year-old students.

Using a compiled concept list, experts and researchers were then asked to refine their list of concepts and linking words. A basic list of connections from existing literature on knowledge mapping and work at CRESST (Herl, 1995; Herl, Baker, & Niemi, 1996) was suggested. In addition, refinement of the links by the teacher, experts, and researchers ensured the formation of reasonable propositions (term-link-term sets)—propositions that made sense in the context of the study of the human body. This process involved modifying existing links to fit both the instructional units covered by the teacher and the reading level of fourth- and fifth-grade students. Further, it was important to include link terms that would allow the three systems (circulatory, respiratory, and digestive) to be interconnected on the maps.

Once concept and link lists were compiled from all sources, the teacher, researchers, and experts reviewed these lists again. Final modifications were made; the final knowledge mapping list contained 21 terms and 14 links. Each expert then generated a knowledge map using the final list of terms and links. Table 1 summarizes the process of creating the lists of concepts and links. Table 2 presents the list of terms and links used in this study.

Tasks

Knowledge mapping tasks. Two types of mapping tasks were administered to students. An individual mapping task was administered to all students prior to the start of the instructional sequence (as a pretest measure), and at the end of the instructional sequence (as a posttest measure). The mapping task prompt is shown in Appendix A. Students were given 25 minutes to complete their maps.

Students in the experimental condition (i.e., group mapping) received the same mapping task instructions, used the same set of concepts and links, and used the same mapping software as the individual mapping task. The amount of time groups received to create, review, and revise their collaborative maps was increased to 45 minutes, the approximate length of science instruction each day.

Essay task. A second task was designed as a posttest measure of students' understandings of the respiratory, digestive, and circulatory systems. The assessment was based on prior work at CRESST using explanation tasks to assess deeper conceptual understanding in a domain (e.g., Baker, Aschbacher, Niemi & Sato, 1992; Klein et al., 1999). The essay task in this study was administered as a paper-and-pencil post-assessment of students' understandings of the three related systems of respiration, digestion, and circulation. Instructions for the essay

Table 1

Procedure Used to Generate Final Concepts and Links for Knowledge Mapping Task

Step	Procedure
1	Reviewed relevant instructional materials.
2	Experts generated a list of all possible terms relevant to circulatory, respiratory, and digestive systems.
3	Preliminary set of terms and links reviewed by experts and classroom teacher.
4	Final list of terms and links created.
5	Classroom teacher and experts created knowledge maps using final list of concepts and links.

Table 2

Physiology Knowledge Map Terms and Links

Terms	Links
Body	Absorb(s)
Brain	Carries
Digestive system	Control(s)
Stomach	Digests (breaks down)
Intestines	Excrete(s)
Digestive juices	Goes to
Food	Is made of
Waste	Maintains
Nutrients	Part of
Energy	Produces (makes)
Circulatory system	Pumps
Blood	Reduces
Oxygen (O2)	Removes
Carbon dioxide (CO2)	Travel(s) through
Heart	
Blood vessels	
Respiratory system	
Lungs	
Air sacs	
Tissues	
Cells	

emphasized that students should write about the most important ideas they learned about physiology and explain the purpose of each subsystem (circulatory, respiratory, and digestive systems) and how the subsystems functioned together in the body. See Appendix B for the essay task prompt.

Design

A non-equivalent control group design was utilized in this study. Data were collected from intact classrooms that were taught by the same classroom teacher. It was the teacher's belief that both classrooms were comprised of students with roughly the same achievement level for academic performance and for interest and performance in science. Selection of the experimental classroom was random.

Data were collected over a period of six weeks. All students in both classrooms completed three tasks: an introductory, Week-1 knowledge mapping task; a final, Week-6 knowledge mapping task; and a final, Week-6 essay task. During three (of the four intervening) weeks, students worked in small collaborative groups of three or four students each. These small groups remained constant during the three weeks of group work. The difference in treatment between experimental and control groups lay in the classroom activities during Weeks 2 through 4: Small groups in the experimental classroom worked together one day each week to generate collaborative online knowledge maps on the human body. In the control classroom, small groups used the computers and other instructional resources to research the human body. Week 5 of the study involved science instruction but no study-related group work due to a previously scheduled classroom field trip. Table 3 displays the design for the study.

Procedure

Student work. At the beginning of the first week, all students created an individual knowledge map using the mapping software. During Week 2, all group members were given paper copies of their individual, Week-1 knowledge maps to review prior to working as a team. These maps served as a starting point for group discussions. Experimental groups then used their collaborative time to create group maps each week—each group revising, elaborating, and improving their

Table 3

Design of Knowledge Mapping Study

	Occasion and tasks			
Condition	Week 1	Weeks 2-4	Week 5	Week 6
Non-mapping	Individual knowledge map	Small group work: Research, review, and discuss concepts and systems	Regular science instruction and field trip	Individual knowledge map Essay
Mapping	Individual knowledge map	Group knowledge maps: Create, review, and revise collaborative maps	No mapping Regular science instruction and field trip	Individual knowledge map Essay

collaborative map from week to week. During Weeks 3 and 4 of the study, each group was given paper copies of their most recent group map. In addition, groups were given a general map score each week. Control groups used the collaborative time to find information on the World Wide Web regarding the human body, to utilize off-line instructional resources (such as text, manipulatives, and assorted games), and to review and debate their group findings. The classroom facilitated instruction for both groups by providing ongoing comments and feedback to students as they conducted their collaborative work and research on the human body.

Teacher role. Copies of students' individual knowledge maps, with quality ratings for each proposition, were provided to the teacher after the first mapping session. Subsequent copies of the group maps were available to the teacher online to help her guide discussions, provide accurate information, and facilitate instruction for both groups. During collaborative work time for both the experimental and control groups, the teacher circulated throughout the classroom, facilitating discussion between group members and answering questions about the circulatory, respiratory, and digestive systems. Throughout the study, the researchers met with the classroom teacher to discuss the knowledge maps and their scores to gain further insight about students' ideas and understandings of the concepts addressed in the investigation of the human body.

Results

Coding Systems

Knowledge maps. All student knowledge maps received three ratings, based on three distinct scoring systems: (a) an expert content score, (b) a proposition quality rating score, and (c) a system interconnection score. The expert content system yielded one overall score, based on matching each student's map to maps from five content experts. The proposition quality rating system involved scoring each proposition on a student's map; experts rated the quality of every possible proposition (term-link-term sets) for accuracy and level of complexity. The interconnection score used the expert-scored propositions and yielded one holistic score to capture the level of interconnectedness of the digestive, respiratory, and circulatory systems in each student's map. Scoring student maps against expert maps provided a general idea of how students understood the concepts overall, and the interconnection score revealed how well students understood the relationships between systems in the human body. The proposition quality ratings provided information about which *particular* conceptual relationships were changing and developing. In combination, these three scores provided information about the nature and development of students' understandings of the human body's circulatory, respiratory, and digestive systems.

1. Expert content score. Five expert maps (four science experts' maps plus the classroom teacher's map) were used as criterion maps to obtain an overall score. Student maps were scored via a computer-based matching algorithm, proposition by proposition, with each proposition subscore dependent upon the proportion of experts (from none to all) who included the particular proposition in their maps. These subscores (each ranging from 0 to 1) were then summed for a final map score. A copy of the classroom teacher's map is provided in Appendix C; a map from one content expert can be found in Appendix D.

2. Proposition quality rating score. The quality rating system used for each proposition in the quality rating approach is displayed in Table 4. Proposition scores ranged from illogical or impossible connection (score = 0) to most highly principled, most scientifically correct connection (score = 3). The two midpoints represent pragmatic understandings (score = 1) and scientific understandings (score = 2). Once each map proposition is scored on this scale, the number of illogical, pragmatic, scientific, and highly principled propositions are each calculated for each student's map. In this way, it is possible to examine the nature and quality of each proposition type by comparing successive maps. This scoring approach is in line with our thinking about how learning occurs: Bits and pieces of knowledge are combined

Table 4

Description and Examples of Propositions Used in the Quality Rating Approach

Quality of proposition	Description of proposition	Example
0	Proposition does not make sense in any circumstance. Illogical/inappropriate.	Cells CARRY the brain.
1	Proposition appropriate and correct in an everyday, pragmatic sense. Explanatory power is limited to an everyday event.	Cells ARE PART OF the body.
2	Proposition appropriate. Reflects scientific understanding, but has limited explanatory power.	Cells ABSORB nutrients.
3	Proposition is abstract and explanatory. Reflects most highly principled, scientific understanding.	Cells PRODUCE carbon dioxide.

and recombined to form progressively more complex ideas, often evolving from illogical or nonsensical to pragmatic or everyday conceptions, to scientific constructions, to highly principled understandings. The scoring scheme also acknowledges the importance of commonsense, everyday understandings as a valid and important part of scientific learning.

Development of the ratings to score the propositions occurred in stages. The first stage consisted of the computer identifying all propositions from student maps. During the second stage, an expert rater scored each unique proposition based on the quality of the proposition and entered the ratings into a database. The third stage of the scoring process involved the automated counting of all individual propositions to arrive at four final proposition quality counts, one for each type of proposition. While this scoring approach appears daunting initially, the number of new propositions to score decreased rapidly over time. The first mapping session resulted in 364 unique propositions. For the subsequent group mapping sessions (mapping sessions 2–4), the number of unique propositions students created was 69, 67, and 46, respectively. For the final individual map, the number of new, unique propositions was 174. Thus, the total number of unique propositions across all occasions for all students was 720 out of a total of 5880 possible combinations (21 total concepts × 14 links × 20 concepts). Using the computer identification process, it was possible to save a great deal of time by scoring less than 15% of all possible propositions while simultaneously employing a scoring approach that allowed us to examine refinements in student understandings.

3. System interconnection score. The interconnection score was computed by examining the quantity and quality of links that described how the three systems (circulation, respiration, and digestion) related to one another. This scoring process involved an algorithm that took into account both the *number* of propositions that related two different systems (e.g., term about circulatory system linked to term about digestive system, such as "blood—carries—nutrients") and the *quality* of those interconnected propositions (i.e., were there any highly principled propositions?). Table 5 shows this scoring algorithm. In addition, Table 6 details the system categorization for each concept. Because all data were logged directly into the computer, interconnection scores were computed automatically from students' knowledge maps. Appendix E contains a sample student knowledge map with an interconnection score of 5, and Appendix F contains a map with an interconnection score of 1.

Table 5

Computing System Interconnection Score From Number and Quality of Interconnected Propositions

Interconnection score	Number of interconnected propositions	Number of highly principled interconnected propositions
1	0	—
2	1	0
3	1	1
4	2 or more	0
5	2 or more	1 or more

Table 6

System Categorization for Mapping Concepts

System	Concepts
Circulatory system	Blood vessels, blood, circulatory system, heart
Digestive system	Energy, intestines, digestive juices, digestive system, food, nutrients, stomach, waste
Respiratory system	Carbon dioxide (CO2), oxygen (O2), air sacs, cells, lungs, respiratory system, tissues
Other	Brain, body

Essays. All student essays were scored on a 5-point holistic scale by six independent raters for overall quality of the essay. Interrater reliability was computed using Cronbach's alpha across all essays (excluding the anchor papers, which were used as training papers). Each rater was considered an item in the scale. The resulting alpha coefficient was .94, a score deemed high enough to warrant using the average score of all raters to represent the essay score. Table 7 shows the holistic rubric used to score students' essays. Appendixes G–K contain the anchor papers used for each score point of the student essays.

In addition to the overall quality rating of student essays, we were interested in how working with the knowledge mapping software might influence students' thinking about the relationships that exist *between* systems (i.e., the interconnections). Therefore, student essays were also scored for their level of system interconnection. Interrater reliability for essay interconnection was calculated using Cronbach's alpha across all essays (excluding the anchor

Table 7

Quality Rating Rubric for Student Essays

Essay score	Description of essay quality
1	No indication that student understood any of the three systems.
2	Basic, pragmatic understanding of processes (e.g., heart pumps blood). Little or no elaboration in essay.
3	At least one system description includes concepts and functions. Processes partially correct. Minimal elaboration of ideas and concepts.
4	Two systems discussed thoroughly or one system in detail. Essay shows some principled understanding. Processes somewhat elaborated in essay.
5	Complete response, with all three systems discussed and elaborated. High level of detail present in essay.

papers, which were used as training papers). Each rater was considered an item in the scale. The resulting alpha coefficient was .96, a score high enough to warrant using the average score of all raters to represent the system connection score.

As shown in Table 8, we used an analogous definition of interconnection for knowledge maps and essays; the same categorization of interconnections for the knowledge maps was used for the essay scoring. This related scoring system subsequently allowed us to compare students' understandings of the relationships between systems in the human body in two separate, but related, assessments. Appendix L contains a sample student essay with an interconnection score of 5, and Appendix M contains an essay with an interconnection score of 1.

Table 8

System Interconnection Rating Rubric for Student Essays

Interconnection score	Description of system interconnections
1	No connection between systems.
2	Two systems described, with one connection established. Connection not elaborated.
3	Two systems described, with one connection established. Connection elaborated.
4	Three systems described, with two connections established. Connections not elaborated.
5	Three systems described, with two connections established. Both connections elaborated.

Initial Analyses of Student Performance

Group equivalency checks. To ensure that the two classroom groups were equivalent prior to instruction, we compared students on a variety of demographic variables, a standardized achievement measure, and pretest map performance.

There were no significant differences between the control and experimental groups on demographic variables (gender, ethnicity, and income), or on scores from the SAT-9 standardized test or any of its subscales. We also tested for existing differences between the control and experimental groups using the pretest map performance. No significant differences were found between the control and experimental groups on the pretest map performance based on the expert match scoring scheme, or on the total numbers of scientific and principled links in students' maps using the proposition quality rating approach. Finally, there were no significant differences between the control and experimental groups on the interconnection score on the pretest knowledge maps. These results indicated comparable groups at the beginning of the study.

Overview of results. We conducted three types of analyses to answer our research questions. In the following discussion, we present our research questions and results of the analyses in answer to those questions. Note that the sample sizes used for the analyses are smaller than the total *N* given for the final sample because students were absent from either the pretest or the posttest.

Table 9 shows the means and standard deviations on the different knowledge mapping measures for the control and experimental groups by occasion (pretests and posttests). Table 10 shows the performance on the essay measures (administered posttest only), and Table 11 and Table 12 show the interrcorrelations between the outcome measures for the control and experimental groups, respectively. In general, students' performance on the knowledge map measures were consistent with expectations about instruction—similar performance across groups on pretest measures, and improved performance on posttest measures. Overall, the experimental group showed higher mean performance on the outcome variables than the control group. The interrcorrelations shown in Table 11 and Table 12 with respect to the expert match scoring method are consistent with our previous work. These results indicate that the relationship between the knowledge map content score and essay holistic score was significant and of moderate magnitude.

Table 9

Student Knowledge Map Score Means and Standard Deviations for All Scoring Approaches

Occasion	Condition		Expert content score	Proposition quality rating score: Number of illogical propositions	Number of pragmatic propositions	Number of scientific propositions	Number of highly principled propositions	Inter-connection
Pretest								
	Control[a]	*M*	2.24	5.68	5.36	1.64	0.09	3.09
		SD	2.26	5.26	4.46	1.40	0.29	1.27
	Experimental[b]	*M*	2.43	3.85	5.35	2.35	0.05	2.85
		SD	1.88	4.27	4.15	1.95	0.22	1.23
Posttest								
	Control[a]	*M*	5.06	5.18	11.23	4.77	0.27	3.86
		SD	3.27	4.31	4.47	3.28	0.46	0.64
	Experimental[b]	*M*	7.23	3.80	11.45	7.10	1.15	4.40
		SD	4.04	3.22	4.73	4.17	1.35	0.50

[a] $n = 22$. [b] $n = 20$.

Table 10

Student Holistic and Interconnection Essay Score Means and Standard Deviations (Posttest Only)

		Holistic score	Interconnection score
Control[a]	*M*	2.89	1.83
	SD	0.89	1.13
Experimental[b]	*M*	3.12	2.48
	SD	0.84	1.24

[a] $n = 22$. [b] $n = 20$.

Table 11

Intercorrelations: Posttest Control Group ($n = 22$)

	Content score	Number of illogical propositions	Number of pragmatic propositions	Number of scientific propositions	Number of highly principled propositions	Knowledge map inter-connection score	Essay holistic score
Number of illogical propositions	-0.31						
Number of pragmatic propositions	0.59**	-0.06					
Number of scientific propositions	0.83***	-0.22	0.27				
Number of highly principled propositions	0.47*	-0.20	0.46*	0.46*			
Knowledge map inter-connection score	0.10	0.03	0.24	0.19	0.30		
Essay holistic score	0.64**	0.00	0.57**	0.60**	0.47*	0.21	
Essay interconnection score	0.42*	0.19	0.26	0.47*	0.23	0.26	0.77***

*$p < .05$. **$p < .01$. ***$p < .001$.

Pretest and Posttest Map Scores: Instructional Sensitivity

To analyze knowledge mapping performance differences across occasions (i.e., from pretest to posttest) and between conditions on the posttest measures, a repeated measures analysis of variance (ANOVA) was conducted for each knowledge map measure in Table 9. The within-subjects factor was the pretest and posttest concept measures, and the between-subjects factor was the control or experimental group.

Significant differences were found between pretest and posttest performance for the control and experimental groups on the following knowledge mapping measures: content score, $F(1, 40) = 82.14$, $MSE = 3.54$, $p < .01$; knowledge map interconnection score, $F(1, 40) = 32.85$, $MSE = 0.86$, $p < .01$; number of pragmatic

Table 12

Intercorrelations: Posttest Experimental Group ($n = 20$)

	Content score	Number of illogical propositions	Number of pragmatic propositions	Number of scientific propositions	Number of highly principled propositions	Knowledge map inter-connection score	Essay holistic score
Number of illogical propositions	0.02						
Number of pragmatic propositions	0.79***	0.21					
Number of scientific propositions	0.80***	0.15	0.72***				
Number of highly principled propositions	0.50*	-0.10	0.20	0.25			
Knowledge map inter-connection score	0.26	-0.11	-0.01	0.16	0.68***		
Essay holistic score	0.46*	0.17	0.23	0.39	0.17	0.13	
Essay interconnection score	0.70***	-0.02	0.43	0.54*	0.29	0.35	0.78***

*$p < .05$. **$p < .01$. ***$p < .001$.

propositions (Type 1), $F(1, 40) = 69.63$, $MSE = 9.87$, $p < 01$; number of scientific propositions (Type 2), $F(1, 40) = 67.52$, $MSE = 4.77$, $p < .01$; and number of highly principled propositions (Type 3), $F(1, 40) = 15.86$, $MSE = 0.51$, $p < .01$. No significant difference was found between groups in the number of nonsense propositions (Type 0).

Thus, these results indicate that both groups performed higher on the outcome measures at the end of the study compared to their scores before instruction. While unsurprising, these results are interesting because they support the idea that our concept assessment measures were sensitive to the intervening instruction.

Knowledge Mapping as a Learning Tool

To determine whether the group knowledge mapping task had an effect on learning, performance on the knowledge mapping and essay posttest measures was compared between the control and experimental groups. The *p* values reported are one-tailed, reflecting our expectation that the experimental group (repeated mapping) would generate higher scores on the posttest knowledge mapping and essay measures.

Significant differences were found between the control and experimental groups on the following knowledge mapping measures: content score, $F(1, 40) = 6.88$, $MSE = 3.54$, $p < .01$; knowledge map interconnection score, $F(1, 40) = 3.68$, $MSE = 0.86$, $p = .03$; number of scientific propositions (Type 2), $F(1, 40) = 3.02$, $MSE = 4.77$, $p = .05$; and number of highly principled propositions (Type 3), $F(1, 40) = 9.63$, $MSE = 0.51$, $p < .01$. In each case, students in the experimental group performed higher on the posttest knowledge mapping measure. No significant differences were found between groups in the number of nonsense propositions (Type 0) or the number of pragmatic propositions (Type 1).

These results indicate that students in the experimental group using the knowledge mapper on multiple occasions learned more scientific and principled information about the systems of digestion, respiration, and circulation than did control group students. Repeated use of the mapper had no significant impact on the development of understandings that were impossible or pragmatic in nature.

To analyze essay performance differences between the experimental and control groups, *t*-tests were conducted on the essay holistic and essay interconnection scores. No significant difference was found for the essay holistic score. However, a significant difference was found for the essay interconnection score, $t(40) = 1.76$, $p = .04$. On average, students in the experimental group had significantly higher system interconnection scores. This finding suggests that students in the experimental group, compared to students in the control group, wrote essays that stated a connection between two or more systems (i.e., circulatory, digestive, and respiratory), and that these connections were elaborated.

Thus, it appears that for the experimental group, repeated use of the mapping software supported and facilitated the development of students' scientific and principled understandings. Further, collaborative work with the mapper also afforded students the opportunity to establish connections between the systems in the human body to more fully develop their understandings of the domain—both integral components of learning and the development of scientific understandings.

In-Depth Analyses

Microanalyses of the propositions generated by one group were conducted to further investigate the dynamics underlying the development of students' understandings when using the knowledge mapping software. At issue was how students' propositions changed over time. We thus examined in detail one group's development from their first collaborative map during Week 2 through their third collaborative map during Week 4 of the study. Results from this collaborative group, Group D, are displayed in Table 13. Again (see below), all numbers of proposition types increased as students studied the three subsystems (digestion, respiration, and circulation). The total number of propositions created increased as students learned about the body, as did the number of nonsense, pragmatic, scientific, and highly principled propositions. For Group D then, the process of learning about the human body appeared to involve adding bits and pieces of knowledge to their systems of understanding (with varying levels of accuracy and scientific complexity) as students worked to make sense of the complicated processes involved with digestion, respiration, and circulation. Appendix N contains a list of propositions for each proposition type.

Finally, analysis of videotapes of small-group work suggested that the knowledge mapping software supported the development of understandings by allowing students to draw on the resources offered by others in the group. The visual display of the monitor and its interactive nature provided a tangible organizer around which students could negotiate meaning. Discussion and heated debate characterized these exchanges around the group maps. Further, the mapping

Table 13

Group D: Summary of Knowledge Map Expert Matching and Proposition Quality Rating Scores

Mapping session	Overall content score	Total number of propositions	Number of nonsense propositions	Number of pragmatic propositions	Number of scientific propositions	Number of highly principled propositions
Week 2	9.2	20	1	11	7	1
Week 3	10.4	27	3	12	11	1
Week 4	14.0	41	6	18	14	3

software allowed students to make connections within a system and interconnections between systems *graphically* as they learned about the digestive, respiratory, and circulatory systems in the human body. Graphical representations of concepts and interconnections appeared to focus students' attention on the importance of these connections.

Discussion

The purpose of this research was to examine how computer-based knowledge mapping was used in an instructional setting as both a learning and an assessment tool. Our data suggest that students who used the knowledge mapping software over a period of weeks gained a deeper understanding of the relationships between the scientific concepts, both within each system of the human body and between these systems. Students in the experimental group made more scientific and also more highly principled links in their knowledge maps. In addition, knowledge map scores suggest (and essay results support) the possibility that knowledge mapping helped students construct more interconnected understandings of the human body. This construction allowed students to link the digestive, respiratory, and circulatory functions together to see the human body as one large, interconnected system.

How did students who used the knowledge mapping software as an instructional intervention build their understandings of the three systems? Examination of the changes in understandings is based on an analysis of the individual propositions students used to create their maps. Our analysis suggests that students developed their ideas in four fundamental ways: (a) New ideas (nonsense, pragmatic, scientific, and highly principled) were added to students' repertoire of understandings; (b) some nonsense or impossible ideas were transformed into more scientific understandings, or they disappeared from the maps; (c) some pragmatic ideas became more principled in nature; and (d) more connections between systems were developed.

Beyond the knowledge mapping software's ability as a classroom instructional tool to improve students' conceptual understandings, the mapping software clearly functioned well as an assessment device. Changes in mapping scores for all students from pretest to posttest demonstrate knowledge maps' sensitivity to instruction: All students learned during the six-week period and all students' map scores increased from pretest to posttest. The knowledge mapping software, employed as *both* an instructional tool and an assessment tool, combined to make it such a useful—and powerful—device. By using the mapping tool in the classroom, a teacher can facilitate children's learning and also gain a better understanding of that learning by seeing how well students are grasping new material and where instructional emphasis could / should be placed.

From a technical standpoint in this study, we were able to easily support multiple simultaneous online users of the mapping software. We created a system that supported universal access by relying on a Web-based system. A relational database was used successfully to maintain student assessment data (individual and group map scores) over time. The database allowed us the capability to score knowledge maps and generate reports of student performance in real time. The reports were returned in a format readable by any Web browser and thus were readily available to the classroom teacher and researchers. Scoring information provided the classroom teacher with help in identifying where to target instruction, based on students' developing understandings of the human body.

Conclusion

Integrating an assessment tool such as the knowledge mapping software into a classroom setting and infusing it with a strong theoretical framework for learning was a productive component of this research. Tools that allow us to understand more about the development of children's ideas are critical to supporting and facilitating good instruction and good learning. Further, these tools may allow teachers to pinpoint specific constructs or ideas that will help students gain a better, more conceptual understanding of a domain.

We plan to continue our work with the computer-based knowledge mapping software in a variety of different instructional settings; further work will help to clarify the complex and dynamic nature of learning. Tools such as the knowledge mapper, with their automated scoring and ability to deliver immediate feedback to users, have the potential to serve both as instructional supports for students and teachers *and* as information providers for teachers about the ways in which students gradually come to refine their understandings in science. A second line of continued research will examine the nature and types of information provided by the different scoring schemes, as well as the reliability and feasibility of providing online scoring data to teachers. As we state in our introduction, we believe that one way to use technology well in the classroom is to embed assessment opportunities in authentic, meaningful instructional tasks. In this manner, students learn important and conceptual information while teachers both support and evaluate that learning.

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Appendix A
Knowledge Mapping Task Prompt

Name:___________________________________

Class Time:_____________

Circulatory, Digestive and Respiratory Systems
Knowledge Mapping Task

Your friend has missed the last two months of school and asks you to explain the circulatory, respiratory and digestive systems. Using this mapper, create a knowledge map to organize all of the important ideas about circulation, respiration and digestion. Show how the different systems work and how they go together in your body. Make sure you include how the systems are connected to one another. Your knowledge map should include all of the information you learned about respiration, digestion and circulation.

Appendix B
Essay Task Prompt

Name:_________________________________

Class Time:____________

Circulatory, Digestive and Respiratory Systems Essay

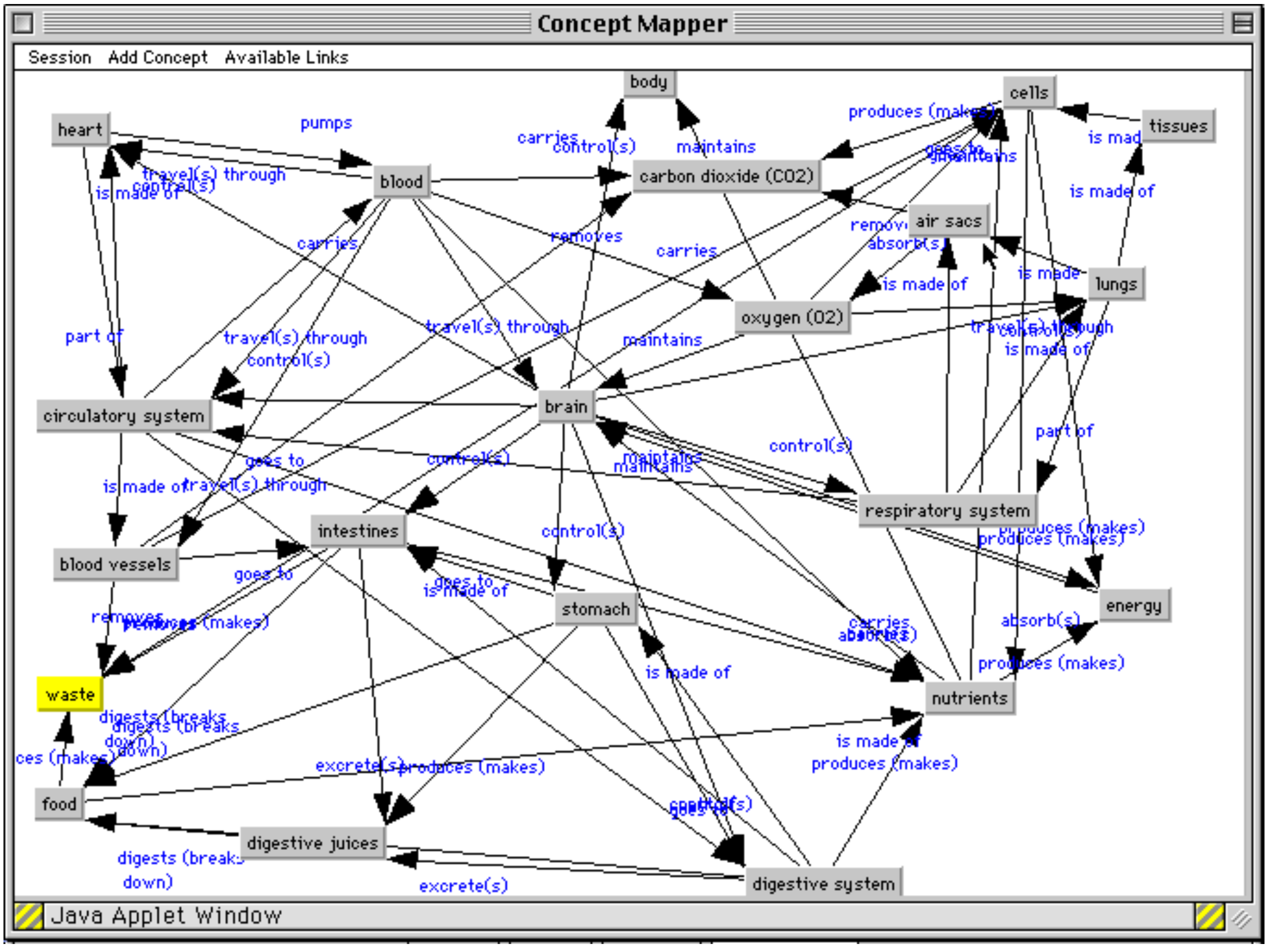
Your friend missed the last two months of school and asks you to explain the circulatory system, respiratory system and digestive systems. Write an essay for your friend to organize all of the important ideas you learned about circulation, respiration and digestion. Write about how the different systems work and how they go together with one another. Your essay should include all of the information you learned about respiration, digestion and circulation.

- Write an essay explaining the most important ideas you want your friend to understand.
- Include what you've learned in class about the most important elements of the respiratory, circulatory and digestive systems.
- Include both general concepts and specific facts that you know about each system. Make sure you explain the purpose of the different parts of each system and how they work together in the body so your friend will understand how respiration, circulation and digestion work.

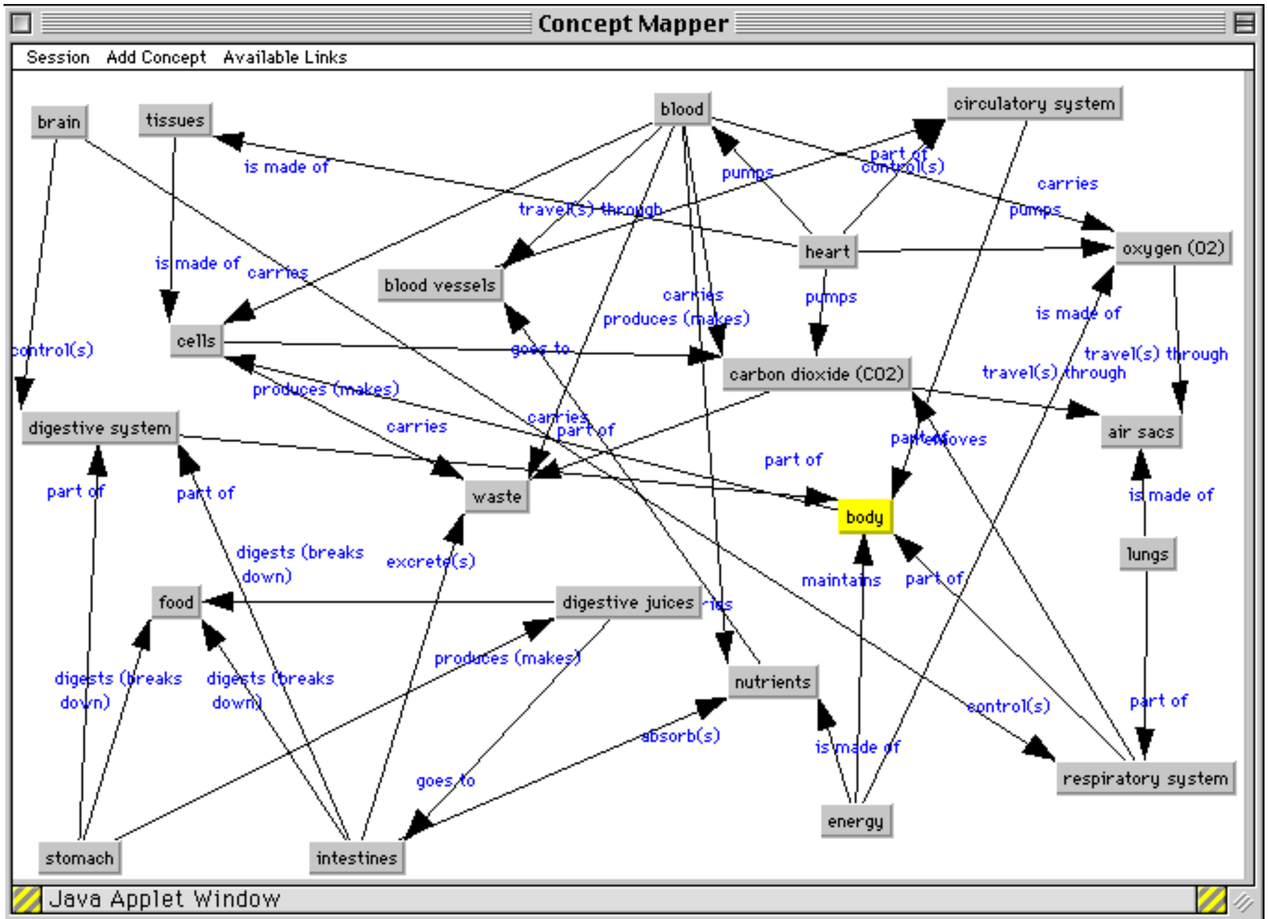
After you have finished writing, you may want to reread your answer and make corrections.

Begin your essay on the next page.

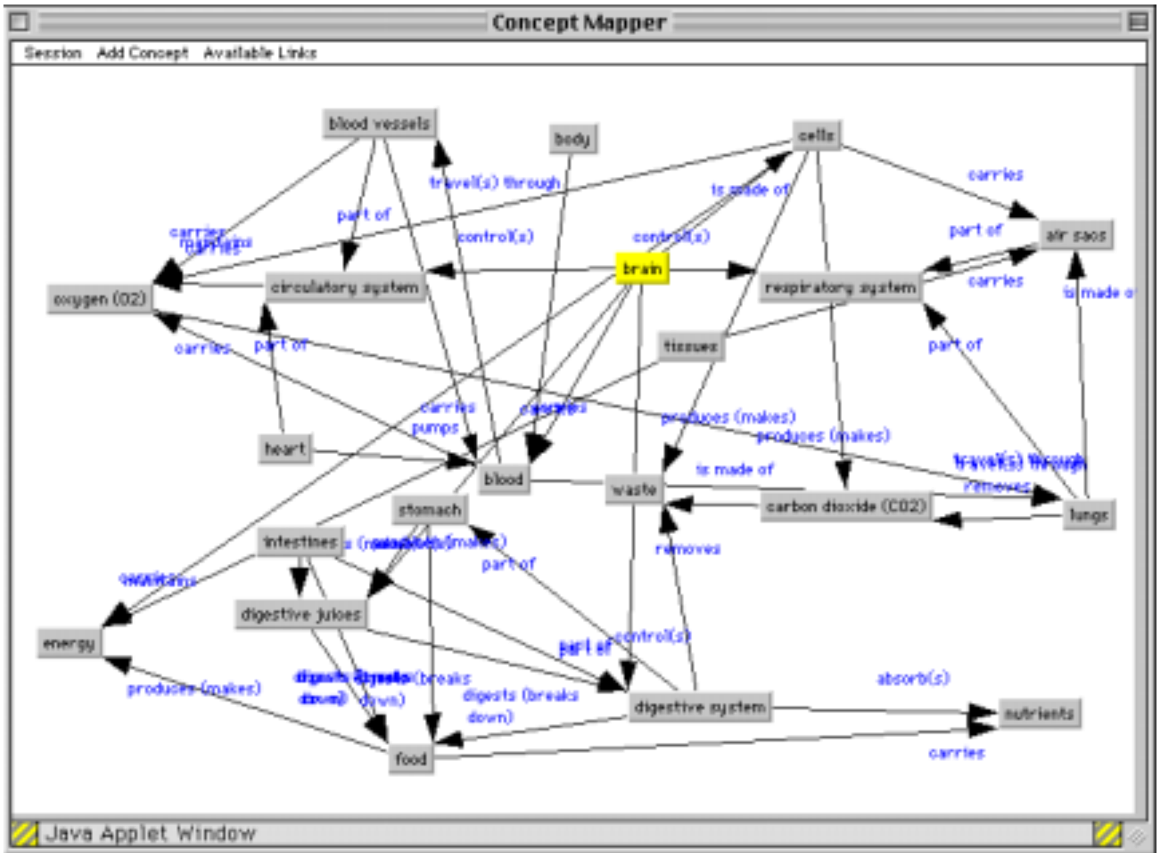
Appendix C
Teacher Map



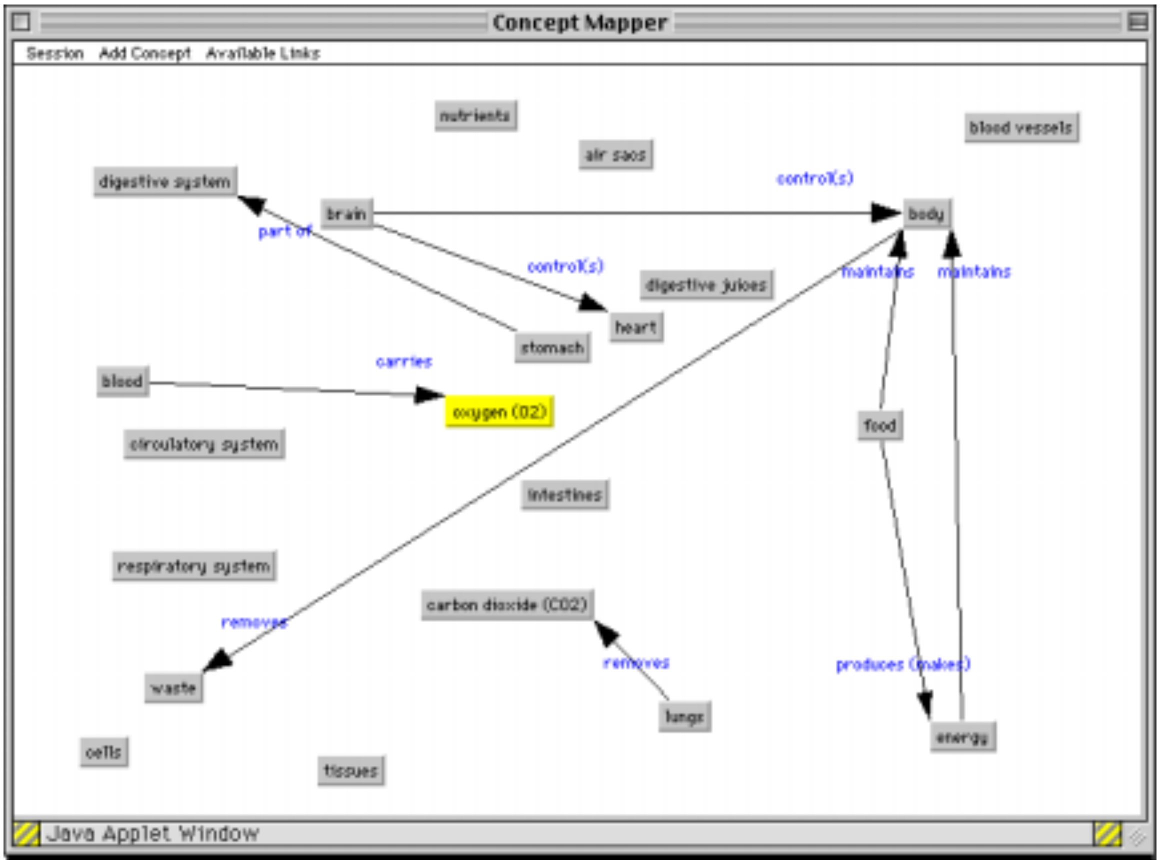
Appendix D
Expert Map



Appendix E
Sample Knowledge Map
System Interconnection Score of 5



Appendix F
Sample Knowledge Map
System Interconnection Score of 1



Appendix G
Essay Anchor Paper: Score of 1

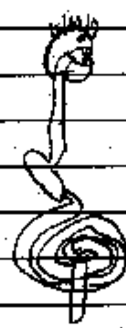
24

Essay
PL 2

The Resaration system is a tube that starts at the mouth and goes to the stomack and to the intestins and most of your body

The Diegestiv system
This system made to mosh up the food, wate you drank or ate So you can diejest it.

Resaration



Diegestiv squzit

1

Appendix H
Essay Anchor Paper: Score of 2

(32)

Essay
Pt. 2

Food → mouth → teath chew food → swalow → stomach digests food → intestinns digest food more → nutrience goes into blood → to the whole body. O_2 goes into nose and/or mouth → to lungs

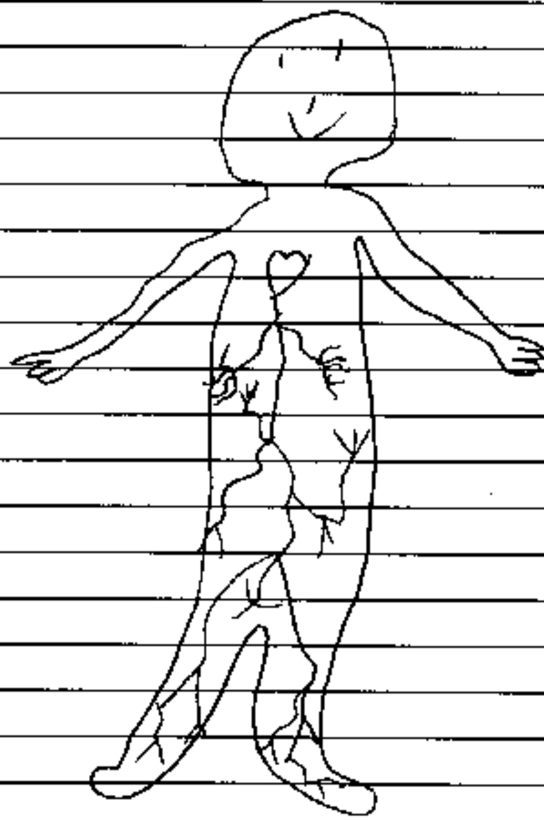
1

Appendix I
Essay Anchor Paper: Score of 3

(46)

Essay
Pt. 2

So, blud gets pumped to the body by the heart so you can live. it gets pumped thrue the Vains. Like so



When you eat food your teeth make it smaller so you can sowl it then it meets 2 tubs 1 going to your lungs the other

1

Essay Anchor Paper: Score of 3, continued

Essay
Pt. 2

To your stuick. It goes to your stuick. there the food gets seperated from the good stuff and the bad. the bad gets made into wast. the good goes to your intestns. The wats left goes to your hart. Witch goes in your blub and gets pumed to your body.

When you beath it goes in your noes. goes down your throt. then it goes to the lunds thats were it goes into small are. sak's were it gets to your bodys needs. Wats left is (co2) when you x-hail it comes out.

2

Appendix J
Essay Anchor Paper: Score of 4

Essay
Pt. 2

The digestive system starts out with your saliva glands. When you take a bite of some thing your 3 saliva glands pour out saliva on the food and your teeth grind it to make it softerand smaller. Then it goes down your esophagus to your stomach where muscles make it even smaller. Then the villi absorb the nutrients that are then transford to the blood stream the extra part of the food travels through the intestine and leaves the body.

The Circulatory system is about breathing. Your lungs take in oxygen and the millions of send it into the bloodstream the cells take in what they need and and exhale Carbon dioxide.

The respiratory system is how

1

Appendix K
Essay Anchor Paper: Score of 5

37

Essay
Pt. 2

in the digestive system to digest
food you put the food in your
mouth and chew it and it
goes down you esofogus into
your stomach your stomach turns
and mixes the food then acid
comes out of the stomach
walls to help digest the
food sylivan coats the inside of
the stomach so the acid
dose not give you alsors then
a mucel opens a little door
in the stomach and lets the
food out into the small intestens
in the small intestens there
are little fingers things
called villi that digest
the food even more in the
villi there are little capalaries
the capalares takes the nutreints
out of the food and brings it
to the blood cells and the blood cells
take it to other cells the
extra food goes to the
large intestens and you go to
the bathroom the nutreints
goes to the heart and the

1

Essay Anchor Paper: Score of 5, continued

Essay
Pt. 2

hart pumps it all over the body in the blood strem the blood cells give food to the cells and pick up waste from the cells and brings the waste to the lungs and you breth it out the cells also need o2 (oxegen) So when you breath air in it gose into your lungs and in the lungs are millions of tiny air sacks So the o2 gose there then the blood cells pick the o2 up from the air sacks and bring them to the cells and the blood cells pick up co2 (carbon dioxide) co2 is used o2

2

Appendix L
Sample Essay
System Interconnection Score of 5

Cirvlatory system

The heart pumps the blood through the body. The blood gose to the lungs so the the carbondioxid (CO_2) can be gotten rid of. The the blood back up to the heart is you skeletal muscles. The skeletal muscles squeze the blood back up. Do you now why arteries are so big? They are big because the pressure of the pumping is strong.

Respiratory System

There are to ways oxygen can get into your body. They are the nose and the mouth. The lungs clean the oxygen by getting rid of the (CO_2) The air gose to air sacs where there a capillaries. The oxygen goes into the capillars

Digestive System

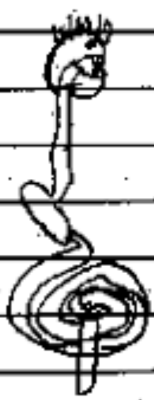
food goes into your mouth and you chew it up and the slevry glands makes the food soft and liquedy. It goes down you throat and into your stomach. The stomach mixes it with digestive juices. It goes to your intestin. The Intestine mix it with more digestive juice On the wall there are capillars that take in the nutrients. The waste goes out of your body.

Appendix M
Sample Essay
System Interconnection Score of 1

The Resaration system is a tube that starts at the mouth and goes to the stomock and to the intestins and out of your body

The Diegestiv system
Its a system made to mosh up the food, wate you drank or ate So you can diejest it.

Resaration



Diegestiv

squzit

Appendix N
List of Propositions by Type for Group D Final Map

Source concept	Relation	Destination concept
Type 0 (Illogical) Propositions		
air sacs	carries	oxygen (O2)
brain	carries	nutrients
brain	carries	oxygen (O2)
brain	control(s)	heart
cells	carries	oxygen (O2)
intestines	part of	stomach
Type 1 (Pragmatic) Propositions		
air sacs	is made of	tissues
blood	part of	circulatory system
blood	travel(s) through	body
brain	control(s)	body
brain	control(s)	respiratory system
brain	is made of	cells
brain	is made of	tissues
circulatory system	part of	body
digestive system	part of	body
food	carries	nutrients
food	produces (makes)	energy
food	travel(s) through	intestines
heart	part of	circulatory system
intestines	part of	digestive system
lungs	part of	respiratory system
respiratory system	part of	body
stomach	carries	digestive juices
stomach	part of	digestive system
Type 2 (Scientific) Propositions		
air sacs	part of	lungs
blood	carries	carbon dioxide (CO2)
blood	carries	oxygen (O2)
blood	travel(s) through	blood vessels
blood vessels	carries	blood
blood vessels	carries	carbon dioxide (CO2)
cells	absorb(s)	nutrients
cells	travel(s) through	blood
digestive juices	digests (breaks down)	food
heart	is made of	tissues
heart	pumps	blood
lungs	removes	carbon dioxide (CO2)
stomach	digests (breaks down)	food
tissues	is made of	cells
Type 3 (Principled) Propositions		
cells	produces (makes)	carbon dioxide (CO2)
cells	produces (makes)	waste
intestines	digests (breaks down)	food