

A Knowledge Map-Centric Feedback-Based Approach to Information Modeling and Academic
Assessment

Ricky Thomas Castles

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Dr. Pushkin Kachroo, Co-Chairman
Dr. Vinod K. Lohani, Co-Chairman
Dr. Thomas L. Martin
Dr. A. Lynn Abbott
Dr. O. Hayden Griffin

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ABSTRACT

The structure of education has changed dramatically in the last few decades. Despite major changes in how students are learning, there has not been as dramatic of a shift in how student learning is assessed. Standard letter grades are still the paradigm for evaluating a student's mastery of course content and the grade point average is still one of the largest determining factors in judging a graduate's academic aptitude.

This research presents a modern approach to modeling knowledge and evaluating students. Based upon the model of a closed-loop feedback controller it considers education as a system with an instructor determining the set of knowledge he or she wishes to impart to students, the instruction method as a transfer function, and evaluation methods serving as sensors to provide feedback determining the subset of the information students have learned. This method uses comprehensive concept maps to depict all of the concepts and relationships an educator intends to cover and student maps to depict the subset of knowledge that students have mastered. Concept inventories are used as an assessment tool to determine, at the conceptual level, what students have learned. Each question in the concept inventory is coupled with one or more components of a comprehensive concept map and based upon the answers students give to concept inventory questions those components may or may not appear in a student's knowledge map. The level of knowledge a student demonstrates of each concept and relationship is presented in his or her student map using a color scheme tied to the levels of learning in Bloom's taxonomy.

Topological principles are used to establish metrics to quantify the distance between two students' knowledge maps and the distance between a student's knowledge map and the corresponding comprehensive concept map. A method is also developed for forming aggregate maps representative of the knowledge of a group of students. Aggregate maps can be formed for entire classes of students or based upon various demographics including race and gender.

XML schemas have been used throughout this research to encapsulate the information in both comprehensive maps and student maps and to store correlations between concept inventory questions and corresponding comprehensive map components. Three software packages have been developed to store concept inventories into an XML Schema, to process student responses to concept inventory questions and generate student maps as a result, and to generate aggregate maps. The methods presented herein have been applied to two learning units that are part of two freshman engineering courses at Virginia Tech. Example student maps and aggregate maps are included for these course units.

Dedication

Dedicated to the memory of Brian Bluhm and Matt Gwaltney- two great friends taken from this world far too soon. Their memory and those of the 30 others lost on April 16, 2007 live on in the hearts and minds of those of us who carry on their legacy.



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Most of all, glory be to God. Any insights found within the pages of this document pale in comparison to the wisdom of the Lord.

For it is written: "I will destroy the wisdom of the wise; the intelligence of the intelligent I will frustrate." Where is the wise man? Where is the scholar? Where is the philosopher of this age? Has not God made foolish the wisdom of the world? For since in the wisdom of God the world through its wisdom did not know him, God was pleased through the foolishness of what was preached to save those who believe. Jews demand miraculous signs and Greeks look for wisdom, but we preach Christ crucified: a stumbling block to Jews and foolishness to Gentiles, but to those whom God has called, both Jews and Greeks, Christ the power of God and the wisdom of God. For the foolishness of God is wiser than man's wisdom, and the weakness of God is stronger than man's strength.

-1 Corinthians 1: 19-25

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1 Introduction

1.1 **Background**

A proper evaluation of feedback is vital to successful education. An academic course must have a certain set of objectives and there must be some method whereby students' gains in understanding may be measured to assess their attainment of the knowledge requisite to meet those objectives. In their famous work, *Classroom Assessment Techniques: A Handbook for College Teachers* [1], Angelo and Cross advocate classroom assessment as a method that should be used to evaluate what students are learning and how well they are learning it. They propose that classroom assessment should be "learner-centered, teacher-directed, mutually beneficial, formative, context specific, ongoing, and rooted in good teaching practice". One of the fundamental assumptions in [1] is that appropriate and focused feedback should be presented early and often in order to help students learn how to assess their own learning. With a learner-centered approach, education and assessment techniques are focused on each individual student's gains in understanding of information and helping students understand how they best learn. The assessment is teacher-directed as the instructor is the one primarily responsible for providing instruction to students and determining how to assess student learning of the information presented. Classroom assessment should be mutually beneficial as it showcases students' strengths and weaknesses and allows teachers to realize the strengths and deficiencies in their own teaching methods. To that end, evaluation should always be formative and ongoing more so than summative. Certainly a summative evaluation is useful to measure the success of teaching strategies, but there are always improvements that can be made based on formative assessment and proper classroom assessment allows instructors to learn what works and what does not. The evaluation should be context specific as the expectations for students in different courses are often quite different, particularly if those courses are in very different disciplines. For example, the expectations in a humanities course are typically very different than the expectations for students in an engineering course.

The National Academy of Engineering has proposed fourteen "Grand Challenges [2]." Similar to the UN millennium development goals [3], these challenges are fourteen areas of global significance the academy is calling for the engineering community to contribute to during the 21st century. Some of these challenges involve energy and environmental concerns, others

involve access to and management of resources, others involve health concerns and information management, and others involve the use of engineering methods to better understand how the mind works and to address how people learn. One of these fourteen challenges is to advance personalized learning. Given the ubiquity of Internet access and the pervasive use of technology in the classroom, education is a rapidly changing field. The use of modern telecommunication systems and mobile computers has enabled online education to become a reality so that people can learn from virtually anywhere in the world. There has been increasing demand for better use of technology for education both inside the classroom and out, particularly as such technology is becoming more affordable. Despite such advancement in technology, the presentation of material both inside a classroom and online is largely a one-size-fits-all approach when in reality learners come with an extreme variety of abilities and preferences. Some students' learning preferences are compatible with the presentation methods that their instructors use and some are not. Some students may learn very well in one environment while others would struggle under the same circumstances. Different students learn at different paces, but unfortunately in the context of the same course all students are prodded along at the same rate leaving some students bored due to a slow pace and some students behind in a course that moves too quickly for them. Personalized learning systems allow students to better understand information in a manner that is compatible with their strengths and preferences. These systems can better communicate to students what it is they are doing well and how they can increase their knowledge base.

Another of the fourteen grand challenges is to reverse engineer the brain. Over thousands of years of learning, much research has been done into how learning occurs and how the brain works. A great deal has been learned about how different actions are carried out using the brain and how information is processed, but largely many aspects of the brain remain a mystery. The research work presented herein, is one step toward improving personalized learning and presents a method for evaluation of student learning centered around feedback and universal modeling of knowledge allowing greater insight into the learning process and how the brain works.

ABET, Inc is the accreditation board primarily responsible for evaluating the quality of engineering programs in the United States. They currently provide accreditation to approximately 2,700 engineering programs at 550 colleges and universities [4]. In 1997, ABET, Inc, known at the time as the Accreditation Board for Engineering and Technology, made a significant change in their evaluation criteria for engineering programs when it adopted

Engineering Criteria 2000 (EC2000). This new set of criteria shifts the focus away from a focus on teaching methodology and instruction toward evaluating what is learned by the students. When a university undergoes the new accreditation process they must demonstrate that students gain abilities in eleven different broad categories such as the “ability to apply knowledge of mathematics, science, and engineering” and “the ability to communicate effectively.” Thus new means of assessment to determine student gains in each of these areas is necessary. The system developed during this research work provides output that can demonstrate at the conceptual level what knowledge students are gaining and has potential to refine the accreditation process.

1.2 The Paradigm of Traditional Student Education and Evaluation

The traditional structure of education begins by giving students some sort of instruction, typically through a lecture or a provided reading assignment. Upon receipt of the instruction, either through attendance at a lecture or after completing the assigned reading, the students formulate a mental model of the information presented. This mental model may be reinforced, expanded, or modified through application of the learned material by completion of homework assignments, participation in project work, or experiments in a laboratory. The student’s mental model and ability to apply the presented knowledge is then assessed through graded examinations and assignments, which can take on many different forms. Ideally some assessment would be done in real-time so that both the instructors and their students are aware instantaneously of what the students have understood in the lecture, however most of the time the assessment is done a significant time after the instruction. This time delay allows the information to transfer from short-term memory to long-term memory, but also allows time for information to be lost and never stored.

1.2.1 Student Feedback and Grading

Feedback to students is largely incorporated into academic courses in terms of grades on assignments, project work, and examinations. The student’s assignments and examinations are compared with an answer key or grading rubric and the result is a numeric score or a letter grade. While an instructor may provide additional written feedback on students’ work, typically the only written record the instructor has available of each student’s performance is a numerical or letter grade representing what is hopefully an objective (although it is often prone to significant subjectivity) assessment of the knowledge the student possesses compared with the knowledge

the instructor intended to impart. In [5] it is stated that “We don’t spend a lot of attention right now to giving students feedback on their progress as learners. Mostly, students get grades that tell them how they have done relative to their classmates. That information is not useful feedback on their progress as learners, nor does it do anything to help students develop skills for self-assessment.”

Figure 1.1 presents the way student grades are usually generated by instructors. Typically each assignment category is weighted and the overall weighted average is correlated to a letter grade. While a passing grade demonstrates a satisfactory level of understanding based on at least one instructor’s standards, a letter grade on a transcript does little to indicate what skills and knowledge the student has obtained from their enrollment in the course. These traditional evaluation methods in which the knowledge a person has of a particular subject is condensed into one of 5 letters with perhaps a plus or minus provide such a trivial representation of student knowledge and understanding that it becomes difficult, if not impossible, to ascertain what students know. Is one to assume when comparing two students’ academic records that if they have earned the same grade in a course or even the same grade point average that they have the same body of knowledge at their disposal? Of course not! Two students who earn the same final grade in a course may (and likely do) have very different levels of mastery of the concepts presented in the course. One student may be very strong in one subject area and weak in another while their colleague may have the opposite abilities and struggles. At the end of the course, however, each of the aforementioned students may end up with the same or very similar numeric averages or letter grades and their academic transcript indicates the same level of performance. There is significant variability and noise in academic assessment that can result from such confounding variables as who the instructor was, what textbook was used during the course, what questions were asked on the test, how much time was allotted for each assignment, the effort the student put forth on each assignment, etc.

Significant work has been done to allow students to showcase their accomplishments and their work through the use of electronic portfolios, or ePortfolios [6] in order to provide a more complete description of a student’s accomplishments. Through such online archives, students may gather together some of their writing and project work to provide a representative sample of their work to any interested parties. The unfortunate drawback of ePortfolios is that they only present the information students want to showcase. Students are allowed to pick and choose the

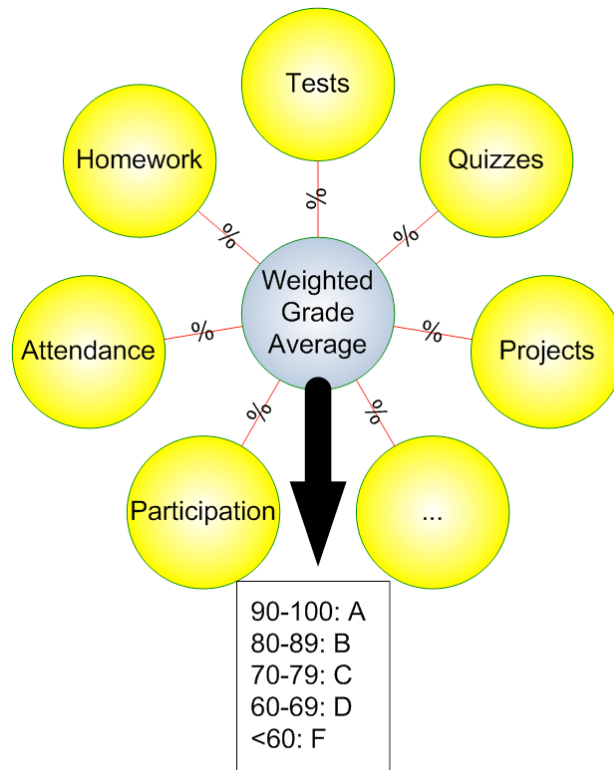


Figure 1.1 The paradigm for traditional grade assignment. Weighted averages of various assignment categories are condensed into an overall numeric score and that score is evaluated based on a lookup table to determine the final course grade.

content of their ePortfolio, so this is a very biased representation of their work and does not paint a clear and comprehensive picture of all of a student’s strengths and weaknesses.

Ultimately the current assessment strategies largely deployed throughout academia evaluate students based upon the scores attained on various assignments aimed at instilling certain concepts and relationships in student’s mental conceptual model. This universal one-size-fits-all model fails to adequately assess a large portion of students who may perform well on some assignments while not understanding the fundamental concepts behind the work they are doing. The converse is also true in that some students are penalized based on the work submitted toward certain assignments while they may have developed an adequate working knowledge of the concepts and relationships intended to be instilled by their instructor.

1.2.2 Faculty Assessment

The current way faculty members are evaluated is not objective. As an example, faculty members at Virginia Tech are evaluated by their students using the very subjective ratings of “Excellent,” “Good,” “Fair,” and “Poor” in a variety of categories. While Figure 1.2 is a slight

Please rate your instructor:



Figure 1.2 The traditional student evaluation of their instructor provides vague feedback much like this evaluation system

oversimplification of this process, the insight gained from such feedback is not much better. Students have opportunities to justify their ratings by making written comments, but there is really no objective way for students to say in concrete terms that the instructor did a good or a bad job in their teaching based on their personal knowledge outcomes gained from enrollment in the course. Most of the student evaluation of their instructor is done at the end of the course also and is summative rather than formative in nature so there is no way for faculty members to improve their instruction of those students. Further, a faculty member has their teaching evaluated by their colleagues. This too is subjective as it supposes that one faculty member can ultimately decide whether or not the way someone is teaching is effective by observing his or her classroom habits. Certainly there is valuable insight in feedback from one's peers, but a true assessment should have concrete data to showcase whether or not students are learning. The traditional model of faculty assessment is not outcomes-driven and thus not compatible with the ABET accreditation criteria previously discussed.

1.3 Modeling Education as a Control System

Based upon Angelo and Cross's model, education can be modeled by a closed-loop control system as depicted in Figure 1.3. The first step in developing such a model is selecting the desired knowledge to be imparted to the students, which can be thought of as the input to the control system. The instructor must then decide how to best present that information to their students. The students then are presented with the information and serve the role of the plant in the loop in that they take in the instructional information and develop their own representation of

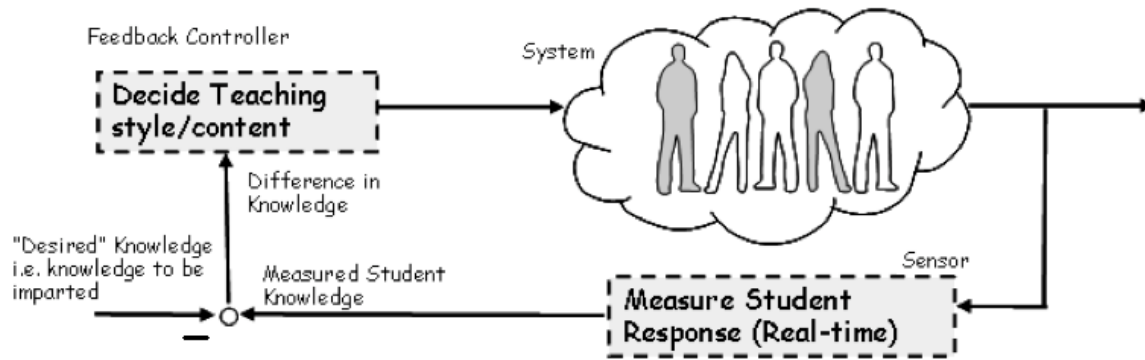


Figure 1.3 Modeling education as a closed-loop control structure

the knowledge. Their knowledge is then measured through various student responses to assignments, quizzes, tests, and other evaluative sensors and the knowledge the students have is compared to the desired knowledge the instructor intended to impart to determine if the instructor’s teaching was effective. The entire process is of course time dependent as the information is presented to students over time and the student’s mental model is expanded and modified over time within the context of a constructivist model of learning. The transformation of the input information into a mental model and eventually long-term memory can be thought of as the transfer function of the control system. The presentation of the returned assignment can be thought of as the closing of the feedback loop and should clearly show the differences between the desired knowledge the instructor intended to impart to students and the knowledge demonstrated by students. The weakness in many educational systems is that the difference between desired knowledge and measured knowledge is often not used effectively to improve the curriculum. The next section introduces the new system developed through this research that allows for detailed feedback to showcase at the conceptual level what students are learning and how that may be used to improve instruction and evaluate faculty effectiveness.

1.4 Establishing A New Feedback-Based Education Paradigm

This dissertation introduces a new framework for feedback-based education that expands the method used to assess each student in a course. Based upon the model depicted in Figure 1.3, the first part of the framework is determining the desired knowledge to be imparted to students. Under this new framework this begins by developing a visual mapping with all the concepts and relationships outlined. These maps, called “comprehensive maps,” take the form of a directed graph. Each concept and relationship within a particular discipline is embedded

within the comprehensive maps and links to representative multimedia data including videos, PowerPoint slides, images, and web pages can be included at each link and node in the graph. It is recommended that this mapping be done in collaboration with other instructors and experts in the field so that a complete model of the subject material can be agreed upon. A universal adoption of this paradigm will allow for the full body of knowledge of various disciplines to be clearly modeled. Similar collaborative development has been used to form the American Society of Civil Engineers (ASCE) Civil Engineering Body of Knowledge for the 21st Century [7], a comprehensive list of 24 outcomes practicing civil engineers believe are required in order to be successful in the field of civil engineering in the 21st century.

The instructors then decide how they are going to present such information to their students. This new paradigm does not dictate a particular presentation style or medium, as many instructors have been very successful in conveying knowledge to their students in a variety of ways. The proposed paradigm encourages the use of various presentation methodologies spanning a variety of modalities to engage all of their students. The evaluation scheme is compatible with any type of education setting.

Once the desired knowledge has been mapped out and the information has been presented to the students, the instructor must find a way to assess the students' working knowledge of the material presented. This dissertation work presents a method for developing a proper assessment which tests student understanding of each of the concepts and relationships presented within the discipline using concept inventories. Methods are described later in this document to develop a comprehensive assessment designed to quickly and thoroughly test a student's knowledge of a discipline while identifying common student misconceptions.

The third stage of development is the presentation of feedback to students. Based upon the assessment given to students, the software developed as part of this research work analyzes each student's responses to the concept inventory questions and generates a customized visual representation of the knowledge demonstrated by each student. This visual representation takes on the same form as the comprehensive knowledge map developed by the expert panel and is representative of the subset of the overall body of knowledge each student has mastered. This feedback will show students and instructors what concepts and relationships the student knows and will easily point out which concepts and relationships are not yet mastered when the student's knowledge map is compared with the comprehensive knowledge map. This is a much

more comprehensive and useful feedback method than simply assigning a numerical or letter grade to a student based on the completion of an assignment. This knowledge representation allows one to account for individual differences and paints a fuller picture of a student's gains from course enrollment. This new method of feedback directly addresses a call to the nation in a special report in the October 2006 issue of the Journal of Engineering Education [8]. This special report proposed five research areas for engineering education including engineering assessment. Since information about each of the concepts and relationships will be embedded into the mapping created by the instructor, this mapping can also be considered an engineering learning system, which addresses another of the five research areas.

This feedback-based assessment methodology has been exemplified through the modeling of a two-week unit in a first-semester freshman-level engineering course. This work has been followed up by a study of a similar unit in a subsequent course to examine concept retention and knowledge-base expansion over time as more advanced topics are introduced to students. A mapping of all the concepts and relationships contained within the first unit and the assimilation of information gained through the second unit into the cognitive structure developed by the first unit is presented herein. Data has been collected from approximately 1800 students throughout the development and deployment of the system and the data has been compiled into individual student maps and also aggregate maps representing various groups of students based upon self-reported demographics. This dissertation discusses the data collected in detail and the iterative process by which the assessment system was developed. The evaluation method and software presented herein are generally applicable to virtually any course and any discipline.

1.5 Definitions

This dissertation uses some very specific terminology from both the education and engineering community. This section serves to clarify the definition of each term being used within the work:

- ◆ Concept map- Throughout this document the definition used for concept maps will be the same one used by the inventor of concept maps, Joseph Novak,
“Concept maps are graphical tools for organizing and representing knowledge. They include concepts, usually enclosed in circles or boxes of some type, and relationships between concepts indicated by a connecting line linking two concepts. Words on the line, referred to as linking words or linking phrases, specify the relationship between the two concepts [9].”

- ◆ Knowledge Resources- Knowledge resources are references and illustrations that can be used to convey knowledge and illustrate information. These include, but are not limited to links to websites containing relevant information, charts, diagrams, movie clips, pictures, books, journal articles, and conference proceedings.
- ◆ Knowledge Map- A knowledge map is a concept map with knowledge resources embedded within it. Thus a knowledge map outlines the concepts and relationship within a discipline and contains multimedia files to further illustrate those concepts and relationships. These maps may be made for a course unit, an entire course, or even an entire degree program or field of study.
- ◆ Comprehensive Map- A comprehensive map is a concept map developed by one or more experts and is considered to be a complete representation of the knowledge being modeled. When appropriate knowledge resources are embedded within the maps these are referred to as comprehensive knowledge maps. For purposes herein an expert is considered anyone with considerable working knowledge of the subject including professors, teachers, researchers, and industry specialists.
- ◆ Concept inventory- A multiple-choice and/or multiple-answer assessment used to evaluate student understanding of the fundamental concepts and relationships within a discipline.
- ◆ Student Map- A student map is a subset of the comprehensive map representative of the concepts and relationships that each individual student has learned within the knowledge outlined in the comprehensive map. Student maps contain no embedded knowledge resources.
- ◆ Student Map Generation- A process for analyzing student knowledge that generates student maps based on a comprehensive map and student responses on a corresponding concept inventory.
- ◆ Aggregate Map- An aggregate map is a graphical representation of all of the student maps generated for a set of students and takes the form of an annotated comprehensive map with annotations indicating the portion of students who have learned each concept and relationships. Aggregate maps may be developed for all

students in a particular section of a course, or based on self-reported demographics such as gender, instructor, class time, etc.

- ◆ Map Element- A generic reference to any portion of a concept map, either a concept or a relationship.
- ◆ Extensible Markup Language (XML)- Developed by a committee of the World Wide Web Consortium in 1996, XML is a way to add tags and annotations to text. It provides a hierarchical structure, which is ideal for modeling relationships between concepts as is done in concept maps and knowledge maps. It is primarily used to represent information on the World Wide Web [10]. This will be used as the primary structure for developing knowledge maps and storing concept inventories.

1.6 The Organization of this Dissertation

The remaining chapters are structured as follows:

- ◆ **Chapter 2: Literature Review** -This chapter discusses the theory behind concept mapping and knowledge representation and discusses the current methodologies implemented in education to facilitate construction of knowledge maps and current evaluation strategies. Previous and current work done in the area of concept inventories is addressed and will illustrate their role in the construction of concept maps and ultimately knowledge maps. The categorization of different levels of learning through Bloom's taxonomy is introduced. The state of the art in the related fields is discussed including artificial intelligence. Some of the author's previous work on educational data collection is discussed.
- ◆ **Chapter 3: Goal, Objectives, and Outcomes**- Having discussed the current state of the art in the related fields and the limitations therein, this chapter discusses the goal, objectives, and outcomes of the dissertation work. The importance and the novelty of this research are discussed and an outline of the work done to address each of these outcomes is presented.
- ◆ **Chapter 4: Methods and Deliverables**- This chapter focuses on the underlying details of the implementation of this object-oriented approach to knowledge representation and knowledge mapping. The multiple stages of software development are discussed along with the data collection and analysis procedures

followed throughout the work. This chapter also showcases methods for topological analysis of the distance between knowledge encapsulated in knowledge maps including determining the distance between two students' knowledge and the distance between a student's knowledge and the comprehensive set of knowledge in a discipline. The outcomes from each stage of development are presented

- ◆ **Chapter 5: Conclusions-** This chapter summarizes the outcomes produced by this research and discusses the overall implications of this work.
- ◆ **Chapter 6: Future Work-** This chapter discusses work that can be done to increase the utility of the knowledge representation strategy presented herein.

2 Literature Review

2.1 Comprehensive Knowledge Models

It is becoming more important to the engineering community to define the skills an engineer should know in order to be a competent practicing engineer in their chosen field. The American Society of Civil Engineers (ASCE) has developed the Civil Engineering Body of Knowledge for the 21st Century [7], a list of the various background knowledge and coursework they believe should be required in the 21st century for someone to be a successful practicing civil engineer. Since 1998 this document has been crafted and revised several times in order to develop a comprehensive list of outcomes expected of a civil engineer. The list spans 24 outcomes, which are grouped into three broad categories: foundational, technical, and professional. The outcomes are organized using Bloom's Taxonomy [11] in order to clearly define actions which demonstrate the required skills.

In [12] an analysis of the mechanical engineering curriculum at nine academic institutions including both public and private universities, two historically black schools, and one all-women's college. The authors performed a rigorous analysis of all twenty of the required courses to earn a bachelor's degree in mechanical engineering from John's Hopkins University and compared the subject matter at Johns Hopkins to the other eight schools curriculum. It was discovered that the BS in Mechanical Engineering curriculum at Johns Hopkins is comprised of 281 distinct technical and professional topics. When this list of topics was compared with the other eight collaborating institutions and the Massachusetts Institute of Technology (MIT)'s OpenCourseWare project [13] a total of 2,151 topics were found and this list was reduced to 1,392 topics when duplications were eliminated. This list of topics included material typically taught by engineering programs specifically including thermodynamics, dynamics, and statics along with topics generally covered by engineering core curriculum including calculus and physics, which are required by engineering departments but typically taken through other departments in a university. Such surveys and analysis of what is being taught at multiple universities allow collaboration in order to determine how engineers should be educated. It is beneficial to compare curriculum when noting that accreditation of engineering departments and licensing of professional engineers is done using a common standard [14, 15] and engineering majors are being prepared to work in collaboration with others within a global workforce.

2.2 Concept Maps

Concept maps are a way of graphically representing the underlying components of a particular field or subfield or, more generally, knowledge [9]. The concepts are enclosed in circles or boxes and lines or arrows linking the boxes indicate the relationship that exists between the concepts. The lines are labeled to indicate the specific relationship that exists between the concepts using linking phrases such as “has a,” “is a,” “helps with,” etc. Knowledge itself can be considered hierarchical in nature in that certain concepts are developed on other concepts or correlated with other concepts. Concept maps can be used to illustrate how one concept or entity relates to another either directly or indirectly through other concepts. Cross-links also exist to show that relationships exist between certain concepts in one discipline and similar concepts in another discipline. Figure 2.1 is a concept map about concept maps; this figure illustrates much of the underlying structure and functionality of concept maps in a hierarchical manner. It first shows that concept maps represent organized knowledge, which is comprised of concepts and propositions. Organized knowledge is necessary for effective teaching and effective learning. Concepts are labeled with symbols and words. This concept map also illustrates that this process of conceptual understanding begins with infants as they begin to perceive patterns and develop creativity and continues over a lifetime of learning..

Joseph Novak developed concept maps in 1972 at Cornell [9]. The pioneering work on concept maps stemmed from a study on the evolution of children’s knowledge of science over the course of their development. Novak’s work was based on the cognitive psychology work of David Ausubel in the 1960s and 70s [16-18]. The fundamental principle of Ausubel’s model of learning was that new concepts are learned through assimilation. That is to say that in order for someone to understand a new idea they must be able to cradle it into the framework of other concepts they already know, known as their *cognitive structure*, and find relationships that exist between previously known concepts and the new concept. Jerome Bruner performed similar work noting that in order for learners to solve new problems, they must first categorize them as exemplars of old principles they had previously mastered [19]. Concept maps therefore are visual representations of the underlying structure and the assimilation of new concepts within the existing framework of other concepts.

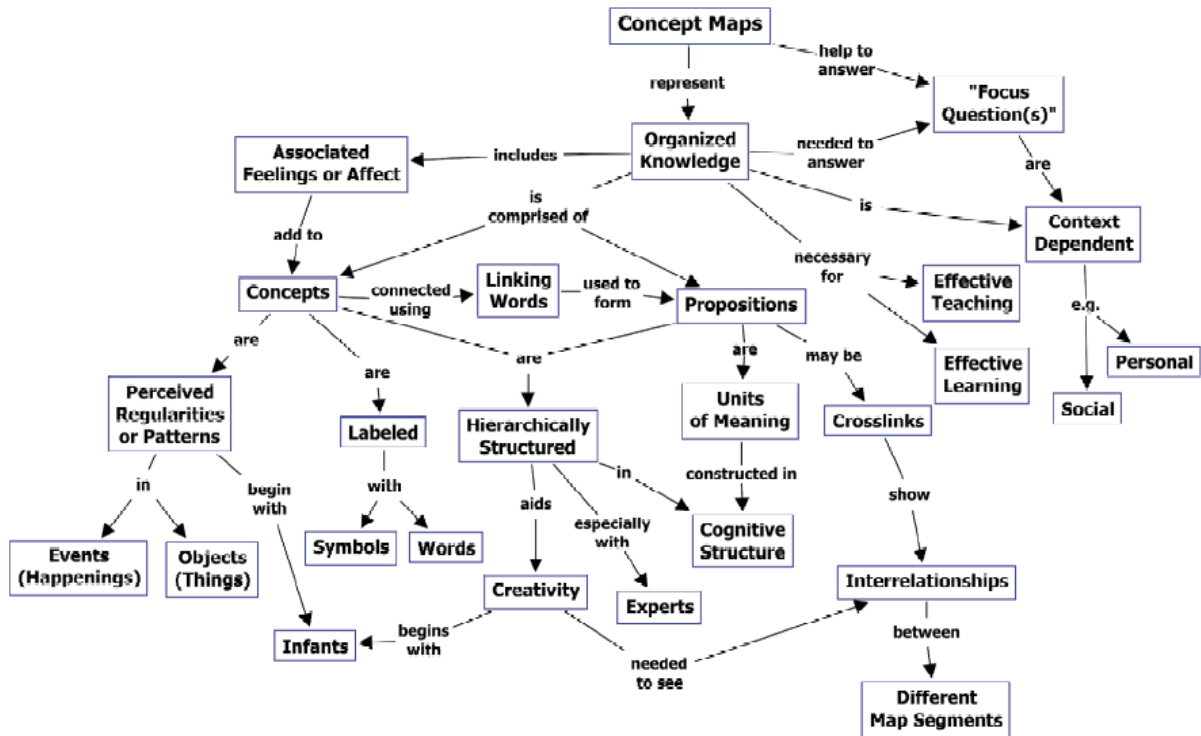


Figure 2.1 A Concept Map of Concept Mapping [9]

Image Copyright Institute for Human and Machine Cognition. Used with Permission of Dr. Joseph Novak and Dr. Alberto Cañas.

Concept maps can be used not only to illustrate concepts or show what students should learn, but also as an evaluation tool for learning. Concept maps can be used to evaluate valid and invalid ideas held by learners. Through the formation of each learner's concept map, one can see the links and underlying structure the learner has formed and discover any flaws in logic either with the newly learned concepts or the underlying structure to which it is assimilating. In the Virginia Tech entomology department, students use concept maps to graphically assemble the various concepts and relationships learned in several entomology courses and the maps are evaluated by comparing the student maps to a faculty generated criterion map [20]. A similar tool termed Robograder™ is in use at Michigan State University and involves autonomous grading of student generated concept maps with added flexibility added by searching through a set of synonyms in WordNet to determine if the student responses are semantically equivalent to the criterion map although variances in word choice are made [21].

Novak points out that learning can either be rote or meaningful. Through rote learning one understands many fundamental concepts and much of the information gained in early childhood education comes from rote learning including memorizing the multiplication tables,

counting, memorizing shapes, letters, and colors. Meaningful learning stems from the information learned through rote learning and synthesizes and expands upon such knowledge to formulate new conceptual understanding. Nowak identifies three levels of instruction, which include reception instruction, guided discovery instruction, and autonomous discovery instruction. Reception instruction is where a learner is simply receiving information from another source be that a book, a lecture, a website, etc. Guided discovery instruction involves some activity or investigation on the part of the learner in order to gain insight into some concept. This can be done in the form of a lab or the use of educational and training software. Autonomous discovery instruction is found when a learner devises his or her own methods of learning or experimenting to validate or discover a concept. This can include things like independent research or personal discovery without guidance. A complete concept map can synthesize information gathered through meaningful learning, rote learning, reception instruction, guided discovery instruction, and autonomous discovery instruction to map out the knowledge a person has and show the links which exist in their knowledge framework whereas traditional student evaluation methods typically are unable to encapsulate knowledge gained through autonomous discovery learning.

Currently the bulk of academic testing at nearly every level from kindergarten through higher education provides only an assessment of rote learning and does not facilitate a true evaluation of the students' abilities to link various concepts into a meaningful body of knowledge. A true assessment of one's academic gains comes when one can draw meaningful knowledge from a concept and clearly weave that new knowledge into their existing cognitive framework. The utility of concept maps to illustrate information organization is gradually becoming more pervasive as several science textbooks now include concept maps to summarize a unit or chapter. Novak and Canas believe that in the next decade or two the use of concept maps in school instruction will increase substantially [9].

Novak and Canas further suggest that entire courses can be designed using concept maps [9]. They suggest that each course should have several "macro maps" which outline the key topics to be covered. Each of these macro maps is constructed of one or more "micro maps" which outline the detailed knowledge encapsulated in the macro maps. This type of course design may be done either independently or collaboratively as instructors may choose to design an entire course or divide the design of various micro maps amongst a team of teachers while

agreeing on the assembly of these micro maps into the overall macro map of the course. Novak and Canas go on to discuss the possibility that this type of course design allows students who may otherwise struggle to make connections between topics to see the connections illustrated. Thus the focus of learning shifts from the memorization of topics in a rote manner to learning of key concepts and relationship development amongst knowledge.

2.3 Concept Inventories

2.3.1 Introduction to Concept Inventories

Concept inventories are a method of evaluating students' understanding of a discipline at the conceptual level. They are used to "bring to light the disparity between what we want our students to learn and what they really learn [22]." Many of the principles underlying concept inventories are found in the three-pronged model of assessment outlined in the book *Knowing What Students Know* [23]. In this model, assessment is depicted as a combination of a cognitive model, observations, and interpretation. The cognitive model includes the list of concepts and topics and the underlying student learning process to gain a working knowledge of these topics. Observation is done through the use of various assessments given to students who are learning or have previously learned various concepts. Interpretation is done by scrutinizing the collected data in a variety of ways including statistical analysis and interpretation of data trends and patterns to determine both correct and incorrect concept encapsulation by students.

In [23] the current state of education is discussed and the authors conclude that traditional tests are legacies of older theories of learning which do not fully evaluate the kinds of complex knowledge and standards emphasized in the modern day. More and more emphasis in the modern day is placed upon testing and test results as an analysis of student learning and understanding of concepts at both a high level and a detailed level. But according to [23],

"Traditional tests do not focus on many aspects of cognition that research indicates are important, and they are not structured to capture critical differences in students' levels of understanding. For example, important aspects of learning not adequately tapped by current assessments include students' organization of knowledge, problem representations, use of strategies, self-monitoring skills, and individual contributions to group problem solving."

The development of concept inventories and concept maps is a way to evaluate students' organization of knowledge and problem representations. Well-designed concept inventories can also determine strategies and self-monitoring skills used to learn various concepts.

It is also argued in [23] that most assessment strategies simply provide a “snapshot” of the knowledge a person possesses at any given time. Tests typically fail to show the progress of knowledge over time. The heart of learning is the progress of conceptual understanding over time and this is not represented in traditional evaluation models. A concept inventory-based assessment can be given to students both before and after a unit in a course and the difference in assessment results can be viewed as the gains in knowledge from studying the presented material.

2.3.2 History of Concept Inventories

The first concept inventory, the well-known “Force Concept Inventory (FCI),” was developed by Hestenes, Wells, and Swackhamer in 1992 [24]. The FCI asked students very basic questions about concepts covered by an introductory high school or college physics class. The results of the inventory showed the disparity between understanding of the theory of Newtonian physics and the conceptual understanding of physics students have developed based on their previous life experience and through common sense and intuition. The inventory was purposefully designed to evaluate concepts alone, rather than mathematical ability with questions on the inventory designed to be conceptual in nature rather than computational. Although, this work was the first concept inventory, it was not the first effort to determine students’ basic understanding of physics concepts. In 1985 a study was conducted using pre and post course assessment of students’ understanding of basic physics concepts and it determined that the knowledge students have going into a physics course is highly correlated with their gains from the course and ultimately their performance and understanding of the concepts presented within the course [25]. The first concept inventory was in fact a continuation of this work as one of the authors of [25] was the primary author of [24].

The force concept inventory has spawned a variety of educational research interest from several academic communities. Since the release of the force concept inventory in 1992, concept inventories have been developed for a variety of subjects. The Foundation Coalition [26], one of eight NSF coalitions, has tracked the development of several concept inventories since the mid 1990s. Some inventories are more tested and mature than others, but a significant number of experts from a variety of fields have been working on the development of concept inventories since the mid 1990s. The Wave Concept Inventory (WCI) consists of 20 multiple choice questions with eight of those questions having multiple correct answers and evaluates student

understanding of electromagnetic waves at various levels of understanding. The work on this inventory began in 1995 at Arizona State University by Ron Roedel and Samir El-Ghazaly [27]. In October 2000, work began on concept inventories in the areas of thermodynamics [28], strength of materials [29], signals and systems [30], and electromagnetics [31]. At this time, researchers from multiple universities began collaborating to develop these inventories. In October 2001, research continued in this arena and the development of concept inventories in circuits, fluid mechanics [32], and materials [33] began. At the 2003 ASEE/IEEE Frontiers in Education conference a panel session was held to review the progress toward development of concept inventories in eleven different fields including several of the aforementioned areas along with new inventories in thermal and transport processes, dynamics, chemistry, and statistics [34].

In 2004, work on the Chemistry Concept Inventory was presented at the ASEE/IEEE Frontiers in Education conference [35]. This two-part concept inventory included a variety of subjects from a two-semester general chemistry sequence. A total of 30 questions were assigned to the first part of the inventory drawing from concepts covered in the first semester and 31 questions were assigned to the second part of the inventory drawing from concepts covered in the subsequent semester.

As of 2005, the signals and systems concept inventory (SSCI) had been developed and implemented [30]. It is a 25 question multiple-choice assessment and has been given to a pool of over 900 students at 7 different institutions. The SSCI has found that students enrolled in a signals and systems course tend to master approximately 20% of the material they did not know prior to enrolling in such a course. A workshop on the SSCI was offered at the 2008 ASEE/IEEE Frontiers in Education conference and it was reported that at that time the SSCI had been deployed to 1800 students by more than 30 instructors [36].

2.3.3 The Steps in Developing a Concept Inventory

Richardson [22] outlines a five step iterative process for constructing concept inventories. These five steps are very generic and applicable to any set of concepts or body of knowledge for which one wishes to develop an inventory. The five steps are as follows:

1. Determine the concepts to be included in the inventory
2. Study and articulate the student learning process regarding those concepts.
3. Construct several multiple-choice questions for each concept.

4. Administer the beta version of the inventory to as many students as possible. Perform statistical analyses on the results to establish validity, reliability, and fairness.
5. Revise the inventory to improve readability, validity, reliability, and fairness.

Ideally the developer of the inventory should perform the first step in consultation with experts in the particular field being inventoried. This step should identify the main topics and key relationships between the topics within the field. Broader fields will likely rely on information from a variety of disciplines in order to develop a complete inventory. It is important to select the proper level of depth for the concept inventory so that enough of the concepts are tested without making the inventory so long that it cannot be given to students in a reasonable time period.

The second step is particularly difficult and requires the developer of the inventory to be able to determine how students go about learning the concepts in both formal and informal ways. This step goes beyond simply observing a lecture where the concepts are disseminated to students, but potentially includes observation of students while they are studying concepts or surveying students to ask them about how they gained the knowledge that they now possess about a concept. This may uncover that some concepts are best learned through reading while other concepts may best be learned through experimentation and the most effective method of learning may in fact differ from one person to another.

The third step provides a foundation for the evaluation of students' understanding of the concepts in the inventory. The development of a good question pool will make the inventory more robust and better able to discern varying levels of understanding among students of the concepts in question. The development of multiple-choice questions rather than free response questions allows for faster scoring of tests without the need to sort through varying equivalent semantics of varying verbiage. The development of the choices for multiple-choice questions is just as important, if not more so, than the development of the questions themselves. Obviously one of the choices must be the correct answer, but the other choices should not simply be random. The possible choices should include answers that would identify misconceptions about the particular concepts in the inventory.

A concept inventory is useless without application. The fourth step is the first evaluation of both the students taking the inventory and the inventory itself. If a question is consistently answered incorrectly it could indicate that the question is not phrased well or there is a common

misconception of the concept being tested. In this beta evaluation period it is important to get feedback from those taking the inventory about the quality of the questions. Statistical analysis will show if there is some bias based upon gender, ethnic background, the instructor teaching the concepts in question, etc. The concept inventory should be specific enough to test the details of student understanding of the many components of a topic area, but should be broad enough that it is applicable to a general audience. That is to say, a concept inventory presented to students enrolled in an introductory physics course at one university should be applicable to students enrolled in an introductory physics course at another university because the key introductory physics concepts should be nearly the same at both schools (although the emphasis placed on each topic will vary from school-to-school and instructor-to-instructor). The reliability of a concept inventory can also be evaluated by comparing the results given on the inventory to the results on a traditional examination.

The process of developing a concept inventory is an iterative one and requires evaluation and reevaluation of the questions in the inventory. As new discoveries are made in the discipline they will also need to be included over time into the inventory for it to resist obsolescence. Careful consideration of language should be included in the development of the original inventory and the various revisions for purposes of both clarity and elimination of bias.

2.4 Bloom's taxonomy

In 1956 Benjamin Bloom developed a hierarchical structure of learning that categorizes learning into six different levels, knowledge, understanding (or comprehension), application, analysis, synthesis, and evaluation [11]. At the lowest level, knowledge, students can regurgitate something they have memorized such as the definition of a term or a mathematical formula. At the second level, understanding, the students can explain things in their own words and provide meaning to information they have memorized. At the third level, application, students can take the information they have learned and put it to use to solve a problem or develop something. In traditional engineering education the progression from knowledge to application is best illustrated by the application of theoretical principles learned in the classroom into a practical application in a laboratory or course project. At the fourth level, analysis, students can break down complex problems into components and determine the appropriate way to solve each part. At this level students can make inferences and discover fallacies in logic. At the fifth level,

synthesis, students can put together knowledge from various domains to develop something meaningful. At the highest level, evaluation, students can use decision structures to judge the best possible solution to a problem although several approaches may work [37]. The six levels of Bloom's taxonomy are depicted in Figure 2.2.

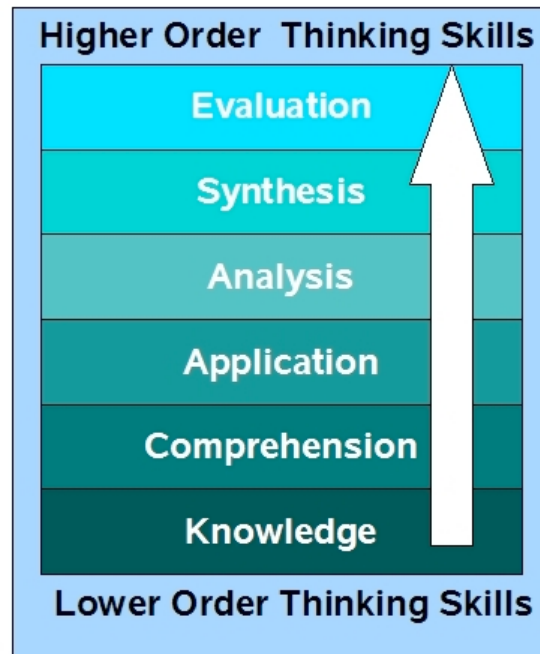


Figure 2.2 The levels of Bloom's Taxonomy

Image available at <http://edorigami.wikispaces.com/Bloom's+Digital+Taxonomy>, last accessed February 15, 2010.

2.5 Knowledge-Based Systems and Artificial Intelligence

All living beings possess the ability to gain and apply knowledge. In the last half of the 20th century, computer scientists and engineers began to tap computational resources in an effort to mimic human knowledge with a logical and computational approach. The aim of such innovation was to reduce the burden on human resources and allow computers to gain insight like humans in order to solve complex problems in a manner similar to the way humans approach such problems and to automate the problem-solving process. Over this time the field of artificial intelligence emerged as a very exciting discipline whose potential has yet to be fully realized. The focus of this research work is in developing systems to encapsulate and process human knowledge while developing methods for encapsulating domain knowledge. There are many implications of this knowledge representation strategy to the intelligent systems community.

This section discusses the benefits of expert systems and gives a brief survey of their applications to a variety of fields including education. Two simple classic artificial intelligence problems are explained in detail to showcase how proper data encapsulation methods can be used to solve problems.

From a computational standpoint, knowledge is defined as “the information about a specific domain needed by a computer program to enable it to exhibit intelligent behavior with regard to a specific problem.” and it “includes information about both real-world entities and the relationships between them [38]” A knowledge-based (expert) system is defined as “a computer program that performs a task normally done by an expert or consultant and which, in so doing, uses captured heuristic knowledge [39]” Thus a knowledge-based system goes beyond the traditional approach of most computer programs which execute statements in a sequential order following predefined rules and rather incorporates various rules of thumb (heuristics) and inferences that an expert trained in the field with years of experience would be able to provide in a problem solving application. There are six basic types of knowledge-based systems as defined by [40]. The first type of knowledge-based systems is generic systems, which are designed in such a way that the framework is general enough to be customized to the individual needs of various applications. The second type of system is general-purpose which include systems designed to operate in a “domain common to many potential customers’ requirements”. The third type of system is the bespoke system, which are designed very specifically for each client with a customized problem solving strategy designed for the specific needs of the client. The fourth type of system is the embedded system, which combines knowledge-based systems into an existing software or hardware infrastructure. In embedded systems the knowledge-based system is a component of the solution rather than the entire solution to the problem. The fifth type of system is an adaptable system, which allows the system to adapt to solve different problems or serve different types of clients on an issue-by-issue basis. The final type of system is the hybrid system, which is ultimately either a combination of the other knowledge-based system types or a combination of knowledge-based systems and other artificial intelligence techniques such as neural networks or fuzzy logic.

2.5.1 A Brief History of Knowledge-Based Systems

Although the term “artificial intelligence” was not coined until 1956, Alan Turing’s article “Computing Machinery and Intelligence” which appeared in *Mind* in October of 1950 [41] is heralded as the seminal effort in artificial intelligence. This article asked the question, “Can machines think?” In this work, Turing describes an imitation game where a computer attempts to mimic the behavior of a human while behind a closed door in an effort to convince a human subject that the machine is actually human. The idea being that if a machine can convince a human that the results it produces were actually produced by a human rather than a machine, then artificial intelligence has been achieved. This agrees with the definition of an expert system provided by Giarratano and Riley that “an expert system is a computer system which emulates the decision-making ability of a human expert [42]”.

In the late 1950s, the primary efforts in artificial intelligence were very ambitious and attempted to create very generic intelligence systems. In 1957 Newall, Shaw, and Simon began work on the General Problem Solver (GPS), which was intended to apply rules to the solving of any type of problem. Newall and Simon developed a 920-page book titled “Human Problem Solving” from their research efforts in 1972 [43]. Upon Simon’s death in 2001, *Science* magazine heralded this book as “perhaps the most important book on the scientific study of human thinking in the 20th century [44].” This research attempted to correlate the way humans solve problems to how such problem solving techniques may be implemented in computer programs. Their theory, which is still present in human factors research and human information processing literature, was that humans group their knowledge into smaller, more manageable units called chunks. They further believed that most all reasoning could be enumerated in IF and THEN statements. IF _____ happens THEN the response should be _____. IF _____ condition exists THEN _____ must be true/false. They further recognized that one condition does not necessarily imply that another condition exists, but rather allows for a secondary condition or response to be plausible. For example IF a car alarm goes off THEN someone may be trying to steal the car. It is certainly plausible that the alarm indicates that the car is being stolen, however the sounding of a car alarm often is a false alarm and it is also possible that a car may be stolen without a car alarm sounding. The human brain stores thousands of such IF THEN conditions. When a stimulus arrives the brain must decide which rules are appropriate to apply to the given situation. In the human mind this is the job of the cognitive processor. The

cognitive processor is used to determine what the stimulus is and to sort out which rules are applicable when such a stimulus is received. There is also the possibility that a certain stimulus may activate multiple rules. Thus, each of the rules must be given some level of priority of activation and the rule with the highest priority that is applicable to the stimulus will be evaluated first and, if appropriate, lower priority rules will be evaluated later. In a knowledge-based system, the evaluation of priorities and the application of appropriate rules based upon input stimulus are done by the inference engine.

In 1965, Edward Feigenbaum and Joshua Lederberg began work on DENDRALL, which is considered the first expert system. The premise of the system was to construct hypotheses in the domain of organic chemistry. The goal was to be able to identify the molecular structure of a chemical sample based upon data taken from numerous laboratory tests. Such analysis required very specific knowledge of organic chemistry and expertise in analyzing large amounts of data.

In the 1970s, more advanced research into problem solving led to the belief that domain knowledge was more critical to solving a problem than reasoning skills. Researchers determined that the critical reasoning skills of an expert in a domain were very similar to that of a novice, and what actually separated experts from novices was their experience and ability to apply various heuristics to the problem. The early intelligent systems which relied solely on reasoning and logic without implementation of heuristic knowledge were plagued with always needing to learn each of the rules about each domain from first principles which created machines that embodied the skill level of a novice at best. The adoption of knowledge-based, rather than reasoning-based, systems allowed successful prototypes to be developed to perform a variety of tasks.

In 1973 development began on a knowledge-based medical diagnosis program called Mycin. In medicine, doctors often rely on many heuristics and their experience with various patients to determine what illnesses are occurring in their patient and to prescribe the proper course of treatment. An exhaustive search of all rules of medicine is not plausible in the medical field because that would require hours of examination of every patient any many unnecessary tests would be performed. Heuristic knowledge is thus required in order to efficiently diagnose a patient. Thus, the medical field also was an ideal field to implement computer programs based on domain knowledge and generalized medical heuristics. To that end, Mycin made use of “metarules”, which are rules about the priority of invoking other rules. These metarules acted as

heuristics to speed processing by invoking rules which would be most applicable given currently entered medical knowledge [39]. In knowledge-based systems, the rules to be invoked are typically given a priority order in which they shall be invoked, however these metarules allow for the bypass of the standard priority or the establishment of a new priority order. The Mycin system consisted of a knowledge base and an inference engine. The knowledge base contains the fundamental rules of medicine and various associations. The developers of Mycin continued to use If and Then statements in the representation of such rules. The system also has a data gathering system to find out information about a patient, which is then fed into the inference engine to determine the applicable rule. A similar medical diagnostic expert system named DIALOG (for DIAgnostic LOGic) was developed at the University of Pittsburgh in 1977 [45]. This system took in preliminary patient data and then prompted for further data to gain a deeper understanding of the medical conditions that existed. The DIALOG system also established that some medical conditions are mutually exclusive and thus cannot occur simultaneously while accounting for the fact that some patients may suffer from multiple related or unrelated medical conditions concurrently. The DIALOG system did not invoke the metarules of Mycin and thus the system was not as sophisticated or as popular as the competing Mycin system. The further development of Mycin led to a more advanced medical diagnosis system, EMYCIN or Essential Mycin, which provided a shell for knowledge to be inserted into the system from various domain experts such as doctors, technicians, and engineers. This was the first such shell and allowed the architecture used in EMYCIN to be transferred to other domains without the complete recoding of a new system. SACON was the first such transport of the EMYCIN shell, which was a knowledge-based system used by structural engineers for finite element analysis. Shells became quite popular in the early 1980s [39].

MYCIN was a pioneer in medical diagnosis through a knowledge-based system and prompted interest in more specialized medical diagnosis software. PUFF was a production rule-based system developed in 1978 at Stanford University to interpret pulmonary function test results [46]. A more advanced system for pulmonary diagnosis called CENTAUR was developed at Stanford under a grant by NIH in 1979 [47]. This system works by formulating hypotheses about the ailments facing the patients and then reformulating them once the hypotheses coincide or are conflicted by data taken from the patient through test results and demographic information collection. In this system, all possible pulmonary ailments are

modeled via a prototype and each of these prototypes is prioritized in a cue based upon the likelihood of each of them being the actual ailment facing the patient. As more data is entered, the cue is reordered appropriately and the most likely diagnosis is generated by the system. CENTAUR thus included both the rule-based system of PUFF and incorporated on top of it prototypes of each of the pulmonary diseases it was designed to diagnose.

A similar system based on the idea of intelligent hypothesis formation was CRYNALIS. This system was also a Stanford University innovation and was being developed about the same time as the CENTAUR system. The CRYNALIS system, however, was utilized in a very different domain than the medical field. CRYNALIS was an intelligent system used in protein crystallography that took in x-ray crystallographic data and from that inferred the three-dimensional structure of the molecule in question. Experts perform this sort of construction by hand in a matter of weeks or months using a very detailed analysis of known data. The CRYNALIS system thus represented very complicated heuristic knowledge and rules. A very primitive system was being worked on in 1979 [48] and it was refined as part of Allan Terry's Ph.D. work at Stanford which was completed in 1983 [49]. In a similar domain as the identification of crystalline structure identification, the Prospector system, developed at the Stanford Research Institute, was designed to emulate an expert in the selection of mineral drilling sites. This system was shown to perform comparably to an expert in the selection of appropriate drilling sites by comparing the output from the system to a range of acceptable output values generated by a mineral expert. The range of values were from -5 to 5 with -5 indicating with certainty that a particular feature of interest did not exist, 5 indicating with certainty that that feature did exist, and 0 indicating no ability to discern the existence of a particular feature. For all the samples tested in [50], the system performed acceptably in its identification.

The field of expert systems began to evolve in the late 1970s and early 1980s as more and more industries began to realize the potential application of expert systems. A complete survey of all expert systems would be difficult and beyond the scope of this paper. The previous history of expert systems was intended to show the breadth of expert system applications and give a brief introduction to the historical development of this technology. The remainder of this section will focus on advances in expert systems in the education domain, as that is the field of primary relevance to this work.

2.5.2 Expert Systems in Education

2.5.2.1 Intelligent Tutoring Systems

In 1985, researchers at Carnegie Mellon University developed an expert system to tutor high school geometry students [51]. In the preliminary education research of the tutoring system developers, they compared the performance of students learning when only exposed to traditional classroom instruction to the learning of those who also utilized the services of a private tutor. They found that 98 percent of students who had a private tutor performed better than the average student exposed only to classroom instruction. The strongest benefit was found to be for the lowest performing students as the highest achieving students in both categories did not exhibit significantly different performance. They suggested that there are a variety of reasons for the improvement in performance when a private tutor is introduced, including the individual real-time feedback on student work that a private tutor affords which is often not logistically possible within a traditional classroom environment. In this way a private tutor can identify deficiencies and strengths of their students as they are solving the problem and point out any information or concepts that a student may be struggling with to get a student back on track toward solving a problem. This is in contrast to a student trying to solve a problem in a traditional classroom who might give up on solving a problem once they run into difficulty. The developers of the tutoring system decided to develop two models to have the system perform like a human tutor. The first model is the “ideal model” which is the “correct” way to solve a particular problem. The second model is the “buggy model” which tries to encapsulate common errors that students may be prone to making. This two-phase problem-solving model was drawn out of work done by Brown and Burton in the late 1970s that attempted to identify “bugs” in problem solving [52]. Burton also extended his work in the early 1980s by developing a debugging method to determine what led to particular mistakes [53]. The tutoring system presents a problem to the student and presents a user interface that allows him or her to go about solving the problem on his or her own. The software then traces through the “ideal model” solution and compares it to the student’s work. If the student’s work differs from the ideal solution, the tutor will present information to the student to try to get them back on track while it will remain silent if the student’s approach matches the ideal solution.

In the same year as the development of the high school geometry tutor, a similar tutoring system was being developed at Carnegie Mellon University to guide students in an introductory

circuit analysis class [54]. Introductory circuit analysis typically involves a circuit diagram with various known quantities and a problem statement asking for one or more of the unknown quantities, such as current, voltage, or resistance. Typically various laws and mathematical properties are invoked in the solving of such problems including Ohm's law and Kirchoff's current and voltage laws. These laws and mathematical properties allow for nodal or loop analysis of the circuit and allow the student to develop simultaneous equations governing the behavior of the circuit with n equations being required to solve for n unknown quantities. As of 1985, the system being developed by CMU researchers had knowledge of the current and voltage laws and various mathematical properties such as the transitive and commutative properties. The expert system could evaluate the currents and voltages in a given circuit and then compare its analysis to the equations developed by the students in their solving of the problem at hand. Should an equation developed by a student not be correct, the expert system could identify the particular error and ascertain the correct equation.

In 1993, researchers at Carnegie-Mellon published their initial findings from project LISTEN (Language Instruction that Speech Technology Enables), an attempt to use the advances in speed detection that were made in the early 1990s to aid students learning to read. The first prototype software developed for this project, named Evelyn, presents text on a computer screen and has children read the text into a microphone. Advanced speech detection software is used to determine if the words that are read are correct or if the student has made any mistakes. Evelyn accounts for "substitutions"- when a word or passage is replaced by an incorrect word or passage by the reader, "deletions"- when the reader fails to read a word or passage without making any substitution, and "insertions"- when the reader adds in words that are not part of the text. The feedback given to the reader varies depending upon which of the three types of errors are made. In the case of a substitution, the software will read the passage correctly and play back the recorded mistake read by the reader so he or she can hear the difference. In the case of a deletion there is no passage to play back from what the reader read, but the software does read the omitted passage. Insertions are purposefully ignored because they are typically pauses or attempts at sounding out the word. The system uses Bellcore's ORATOR speech synthesizer [55] to generate spoken words from the written text for feedback to the user and uses the Sphinx-II [56] previously developed at CMU to analyze the speech input by the user. As of 1993 the Evelyn system was still rather primitive as only 63.6% of the words the reader missed in the

passage on average were actually detected by the software. Researchers, however, have continued to improve the software since it was originally developed and now the Reading Tutor (as it is now called) they have developed has made its way out of the lab in into the classroom and is being used in various public school settings to aid students who are having difficulty reading [57]. Their modern system now accounts for even more than just omitted words and takes into consideration the latency in reading time between words and collects data for post-session analysis. The modern system also evaluates not only the ability of the student to read the words, but also tests for reading comprehension using multiple-choice questions. Students are also given an option in the software to ask for help if they do not know a particular word. The Reading Tutor keeps track of the usage of the software for each student so that teachers can monitor progress and it adapts the level of the material to be read automatically based upon latency, the number of help requests, and reading comprehension so that students are continuously challenged to read at their current ability level. The Reading Tutor was used in a pilot study from 1996-97, improved to a point where it was tested in classrooms in 1998, and as of 2003 the Reading Tutor was being used in 9 schools on 200 different computers to provide reading exercises and assessments for 600 students in kindergarten through the fourth grade.

2.5.2.2 Intelligent Grading Systems

Grading student assignments is one of the most tedious tasks of an educator. As computing utilities have become more pervasive, educators have found a variety of ways to get computational resources to perform evaluations of student work that once had to be done manually. Computer programming classes have been an ideal platform to utilize autonomous grading systems. Grading student-submitted computer programs by hand involves organizing each student's work, compiling the code, running the corresponding executable, inputting test data, and examining the output. The earliest automated graders were implemented in 1960 to compare the results of student-submitted punch cards to the results of an instructor-generated solution. Several script-based utilities were developed in the late 1980s through the early 2000s to grade programming work. Most autonomous grading utilities check for the accuracy of the output generated by student solutions and also for the efficiency of the code submitted by students. Later solutions even allowed students to enter code into a web browser and have it automatically evaluated [58]. Typically each program is tested against multiple sets of data to

validate the capability of the program. In the late 1990s and early 2000s, with computer science departments increasing in enrollment and system capabilities increasing, many universities began implementing autonomous grading systems to compile and run student submissions. One such system, The Online Judge[59], was implemented in July 1999 at the National University of Singapore for an advanced undergraduate course involving competitive programming in preparation for the ACM Intercollegiate Programming Contest. In 2000 the system was modified to accept work submitted by a first-year programming course and also included methods for detecting plagiarism.

As was mentioned in a previous section, the Virginia Tech entomology department uses a computer-based system to evaluate student understanding of course material encapsulated in student concept maps. This system relies on an examination of the propositions expressed in student generated maps using predicate logic to compare them to the propositions expressed in a criterion, teacher-generated map. In this system a preposition is considered an ordered triple of a first concept node, a relationship, and a second concept node. The matching system also accounts for inexact, but semantically equivalent, propositions based upon the ordering of concepts and equivalence or inverse relationships between relationships. The system also compares the set of nodes contained in both the student map and the criterion map to determine any differences and also examines the paths and hierarchy represented in the maps. Although students are allowed to form the maps using whatever structure they deem appropriate, maps are limited to a set of concepts and relationships in a word bank [20]. A similar concept map grading system, Robograder, allows for a large thesaurus to be searched when evaluating student maps in order to recognize synonyms for the words students have used in maps without the need to use a word bank [21].

Early automated grading systems were applied to fields where there are concrete solutions that are either correct or incorrect. It is more difficult to automatically assess students' written work in essay assignments. Several research efforts are underway to develop systems that autonomously analyze student writing. Early essay grading systems, such as Project Essay Grade [60], did not take the semantics of the writing into account, but rather relied on either heuristics such as the number of words used and the number of propositions to predict the grades a human grader would assign to written assignments. Surprisingly, although the metrics were quite simple a fairly high correlation between the predicted score and the assigned score was

found in some studies (correlations above 0.8 in some comparisons with human graders). Later systems, such as the Intelligent Essay Assessor, incorporated semantics and used Latent Semantic Analysis to represent essay content in two-dimensional matrices. Several more advanced techniques have used natural language processing to evaluate student writing based on the content of the essay and also grammatical rules [61].

2.5.3 Advantages of Expert Systems

If expert systems emulate human knowledge, it certainly begs the question why one would implement such a system rather than hiring an expert to solve the problem. In [42] various advantages are outlined to using expert systems, they include:

Increased availability and rapid response time - The client no longer has to wait for an expert to crunch the numbers, nor must they contend with the expert's travel schedule or other availability issues. Once the appropriate expertise is encapsulated in the knowledge-based system, that information is available at a moments notice. A computer system is also perfectly willing to work nights, weekends, and holidays if asked to do so without any additional charge being added.

Reduced cost – Although there is a significant implementation cost in gathering the expert knowledge required to develop a knowledge-based system and there is a significant amount of time required to program a satisfactory system, once such a system is implemented it may be used at little to no cost for a long time. The cost of use of such a system is significantly less than paying an expert each time his or her expertise is needed to solve a problem.

Reduced Danger- An expert system may be used to analyze data in situations where it may be dangerous to use human personnel.

Permanence- The knowledge encapsulated in an expert system is permanently available in contrast to human experts who may retire, change jobs, move out of the area, forget, die, etc

Explanation of logic available- Unlike some analyses provided by human experts, the thought process involved may be enumerated to determine exactly how the system arrived at the solution. A human expert may use the same thought process as an expert system, but a large portion of the process may be done intuitively or instinctively leaving those without the same expertise in the dark as to how the solution was determined.

No emotional encumbrances- Human judgment may be clouded by emotions and other external factors that are difficult to account for. This is particularly problematic in the analysis of data in emergency situations, which require a fast and well-formed response, even in the midst of difficult circumstances.

Figure 2.3 shows the generic construct of a knowledge-based system. Since a knowledge-based system must possess the knowledge of an expert in the field, it follows that an expert in the domain must be involved in providing the information necessary for the logic of such a system to be incorporated. A knowledge acquisition facility is provided which allows for knowledge to be input to the system either directly or indirectly from experts. Direct input would include information gained from interviews with experts or via some interface whereby experts could provide their knowledge about the discipline or their approach to solving various problems. Indirect input would include the extraction and parsing of information from compiled records of knowledge such as online databases and inventories. Once the knowledge is input to the system from the expert then it must be incorporated into the system's knowledge base so each knowledge-based system must have some sort of syntax and representation of knowledge such that real world information can be digitally represented and easily accessed when appropriate. The knowledge base is a way that various facts and rules can be incorporated so that inferences can be drawn from the domain knowledge. The inference engine provides the link between the domain knowledge and the input data and query in order to solve the problem at hand or answer the question posed by the system user. The user of a knowledge-based system

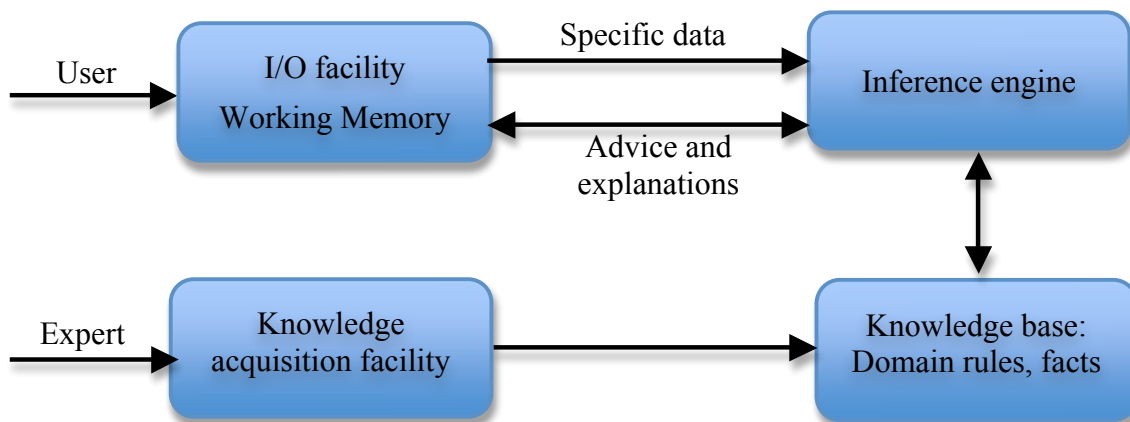


Figure 2.3 The components of a basic knowledge-based (expert) system [39]
 Image from Dym, Clive, et al. *Knowledge-Based Systems in Engineering*, 1991. Copyright The McGraw-Hill Companies, Inc. Used with permission.

must have an interface (I/O facility) for inputting queries and must have a way for the information contained in the system to be presented. The information put into the system by the user goes into the working memory of the system and the inference engine uses this information to establish the appropriate links to the requisite information in the knowledge base. Depending upon the domain and the types of problems to be solved in the domain, the actual structure and configuration of each of the components of the system will vary significantly.

2.5.4 State Assignment, Operations, and Preconditions

A knowledge-based machine is often represented with a state transition diagram. Such a diagram outlines each of the possible states of the system beginning with the initial condition of the system or problem and all of the possible transitions that exist from one state to the next. Certain transitions yield states that are not allowed or are illegal based upon some of the premises outlined in the problem statement. Once an illegal state is reached, that branch of the transition diagram should be terminated because it is illogical to illustrate transitions out of states that should not ever be reached. Some operations are also only allowed if certain preconditions are met. For example, in a knowledge-based system used to play the game of chess, the movement of the queen is only allowed if the player's opponent has not previously captured the queen and the queen does not have other pieces in its path that prohibit further movement. Similarly in chess the movement of a rook is governed by different rules than the movement of pawns, knights, and other pieces. The definition of states and possible transitions will vary widely and will be represented differently depending upon the problem statement and the possible states that exist. The following subsection showcases some examples of how a knowledge-based system may be used to solve and represent problems. The context of these examples is not important to the proposed research, but these examples are included to showcase the data structures and methods that are utilized in solving problems using an expert system. The heart of using artificial intelligence techniques for problem solving is being able to properly encapsulate the system state and the domain rules.

2.5.4.1 The Missionaries and Cannibals Problem

The artificial intelligence community has used knowledge representation for years in solving various problems. One such famous problem is the missionaries and cannibals problem. This problem is posed as follows:

Three missionaries and three cannibals seek to cross a river. A boat is available which will hold two people and which can be navigated by any combination of missionaries and cannibals involving one or two people. If the missionaries on either bank of the river, or en route in the river, are outnumbered at any time by cannibals, the cannibals will indulge in their anthropophagic tendencies and do away with the missionaries. Find a schedule of crossings that will permit all the missionaries and cannibals to cross the river safely.

In order for a knowledge-based system to be successful, it must use a logical representation of the data and find an organized way to represent and apply the rules of the problem [62]. A knowledge-based system can be used to incorporate the various rules mentioned above and can represent each of the possible states of the system using an ordered triple. The state (i,j,k) represents there being i missionaries and j cannibals on the nearest bank of the river and k is either '+' or '-' which is a token used to indicate the presence or absence, respectively, of the boat on the near bank. The rules in the problem are stored in the knowledge base to prohibit any unsafe or impossible conditions from occurring. There are 32 (i,j,k) triples because i and j can both take on the value of any integer 0 through 3 inclusive and k has two possible values. Some states present situations that violate the problem condition and others are simply impossible to achieve, for instance it is also impossible for the boat to traverse the river without at least one occupant, so the states $(0, 0, +)$ and $(3, 3, -)$ are impossible to achieve. Since it is illegal by the rules of the problem to have more cannibals than missionaries on either bank when at least one missionary is present, the following six triples are illegal states with more cannibals than missionaries on the near bank.

$(2, 3, +)$ $(2, 3, -)$ $(1, 3, +)$ $(1, 3, -)$ $(1, 2, +)$ $(1, 2, -)$

The complement of the state on one side of the river represents the players on the other side of the river; that is to say that for any state (i,j,k) the other side of the river contains $3-i$ missionaries and $3-j$ cannibals. Thus the following states where $3-j > 3-i > 0$ are also illegal.

$(2, 1, +)$ $(2, 1, -)$ $(2, 0, +)$ $(2, 0, -)$ $(1, 0, +)$ $(1, 0, -)$

Once all the possible states have been enumerated and legal and illegal states have been properly identified, this problem can be solved using a directed graph or tree as is depicted in Figure 2.4. The tree begins with the initial condition of the problem, $(3, 3, +)$. This initial condition becomes a parent node and child nodes can be added for states that can be reached in one move across the river. That is to say, any state that can be reached by sending one or two missionaries alone, one or two cannibals alone, or one cannibal and one missionary across the

river in the boat from the current state is a child of the current state. Thus, the children of the first node in the tree are:

(2, 3, -) (1, 3, -) (2,2,-) (3, 2, -) (3,1,-)

With the creation of each child node, the system must check to see if the state represented by the child is legal or illegal and if the state is duplicated from a state already represented in the tree. When an illegal state is reached in the tree that particular branch is terminated because there is no need to add children to states that should never be reached. It is also important to check for reoccurring states because the enumeration of children from previously listed states is redundant and shows a circular progression through the states rather than the optimal number of moves from initial condition to the goal condition. The solution to the problem requiring the least number or moves may be determined using a breadth first search of a properly formulated tree which begins at the initial condition (3, 3, +) and terminates at the goal condition (0, 0, -).

In Figure 2.4 red is used to identify illegal states that are invalid moves. The one yellow node is a legal state, but it can only transition back to the initial condition and thus represents a cycle or dead end in the tree. As can be seen the solution to the problem requires 11 moves across the river and there are four possible solution paths from the initial condition to the goal state.

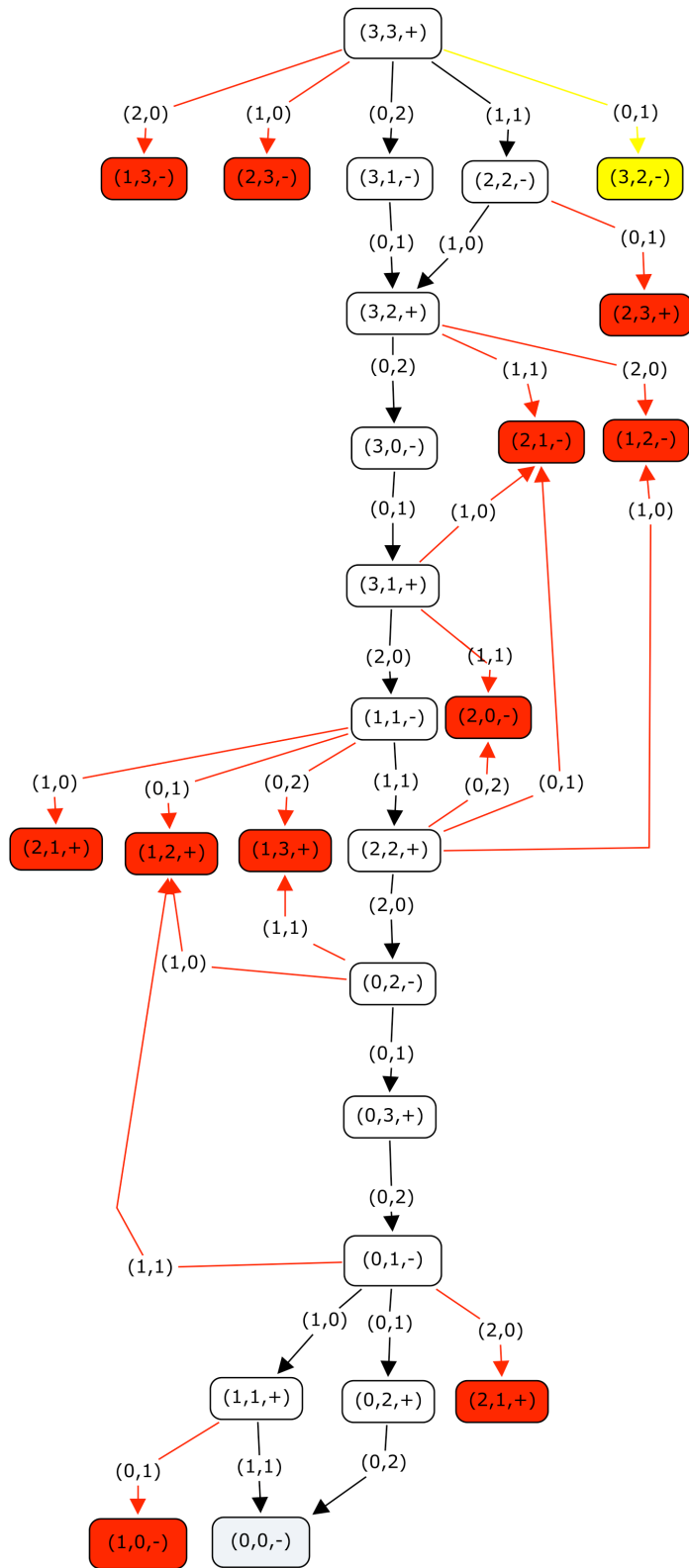


Figure 2.4 A tree showcasing the transition of states from the initial condition to a solution of the missionaries and cannibals problem. Red nodes indicate transitions to illegal states and yellow nodes indicate legal states that result in a cycle.

2.5.4.2 The 8-puzzle

A popular children's activity is to solve small puzzles with 8 movable tiles and one blank space like the one depicted in Figure 2.5. These puzzles allow the pieces to slide left and right and up and down, provided the blank space is adjacent to the moving tile with the goal of positioning all of the tiles back in the proper position to either put the tiles in order or recreate a picture. For example, in Figure 2.5 tile F may move down, tile D may move to the right, tile C may move to the left, and tile G may move up in the current state and the goal would be to have all the letter in the proper order from A through H with the blank space in the bottom right corner. Tiles A, B, H, and E are currently unable to move in their current state. In a knowledge-based system, each state may be represented as a 3x3 matrix. For example the state shown in Figure 2.5 may be represented as the following matrix with S indicating the space.

$$\begin{bmatrix} A & F & B \\ D & S & C \\ H & G & E \end{bmatrix}$$

A	F	B
D		C
H	G	E

Figure 2.5 A typical 8 puzzle

As is the case in the missionaries and cannibals problem, the problem may be represented as a tree with the initial condition established as the parent node of the tree structure and each possible transition represented as children nodes. Again, to prohibit circular transitions through states a child node should not be generated for any repeated state. Based on physical constraints, if the blank space is currently in the middle of the square (as it is in Figure 2.5) then there are four possible states that may be reached, if the blank space is in one of the four corners then there are two reachable states, and in all other positions there are three reachable states. From the state depicted above the 8-puzzle may reach the following 4 states:

$$\begin{bmatrix} A & S & B \\ D & F & C \\ H & G & E \end{bmatrix} \quad \begin{bmatrix} A & F & B \\ S & D & C \\ H & G & E \end{bmatrix} \quad \begin{bmatrix} A & F & B \\ D & C & S \\ H & G & E \end{bmatrix} \quad \begin{bmatrix} A & F & B \\ D & G & C \\ H & S & E \end{bmatrix}$$

For sake of brevity the entire tree is not depicted for this problem as this particular problem is much more complex to completely enumerate via a tree diagram than the missionaries and cannibals problem because there are $9!$ (362, 880) possible states, all of which are legal.

2.6 Contributions of the Author's MS Thesis Research

One of the most important factors in improving student learning is engagement. If students are not engaged in the learning process than it is highly unlikely that even the best educators will be able to teach them something. The author's MS thesis [63] incorporated ideas from many disciplines spanning ergonomics, signal processing, human-computer interaction, psychology, and education to study engagement during computer task performance based upon physiological data measurement. The goal of this thesis was to gain an insight into which types of tasks are more taxing on learners and if this varies depending on user preferences and preferred learning modality. Several learning tasks were developed that required study participants to memorize sets of data, some visual and some aural, and to recall what they had seen or heard. While study participants were engaged in the various learning tasks, the affect of such tasks was monitored based upon physiological data collection.

There are various physiological indicators of engagement and arousal. The author developed low-cost sensors to monitor heart rate, skin conductivity, and skin temperature. Physiological data was collected while study participants engaged in visual and auditory memorization and recall tasks. The difficulty of user tasks for the individual was evaluated through an analysis of physiological data collected throughout the experiment. Such information could be utilized to adapt the information presentation strategy in a customized manner on a user-by-user basis so that each computer user will be presented information in a manner that is most appropriate for their individual strengths, weaknesses, and expectations. The author mounted the sensors on soft, wearable materials and interfaced all of the sensors with the Measurement Computing's PMD-1208FS USB data acquisition module [64] to collect the physiological data.

2.6.1 Monitoring Heart Rate

Heart rate was measured using a Polar brand chest strap and a wireless receiver depicted in Figure 2.6. This adjustable chest strap, as shown in (a), is worn in direct contact with the chest under participant's clothing, as shown in (b), and provided wireless transmission of each heartbeat to a simple circuit, shown in (c), that is designed to receive the wireless transmission.

2.6.2 Measuring Skin Temperature

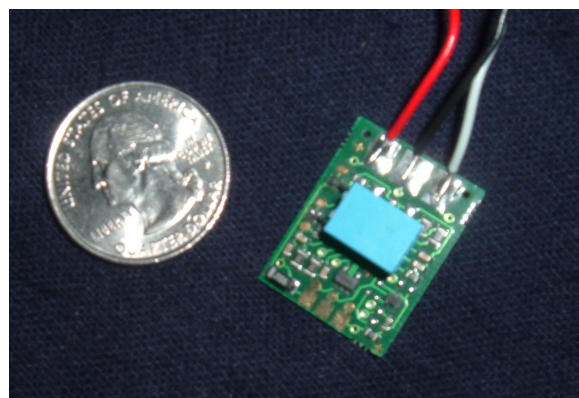
Skin temperature was measured using a thermistor. For this application the 334-NTC404, a 400k Ω (nominal at 25°C) thermistor was used to provide a large range of resistance



(a)



(b)



(c)

Figure 2.6 Heart rate monitoring hardware: a) Chest strap transmitter, b) Proper placement of the chest strap around the abdomen, c) The receiver circuit with a quarter to show scale

Figure 2.6(b) available at

http://www.maximfitness.net/Portals/0/Skins/maxim/images/scifit/access_cheststrap.jpg.

Last accessed February 15, 2010.

values so that subtle changes in temperature could be detected. The thermistor was placed in series with a known voltage source and a known resistance to form a voltage divider as shown in Figure 2.7. The circuit was designed with a large known resistance such that in the unlikely event of the thermistor being shorted across the subject's skin that only minimal current would flow. The voltage across the thermistor was measured over time in order to mathematically determine the resistance of the thermistor at any given time. Resistance is directly correlated to temperature and thus the resistance of the thermistor was indicative of the study participant's skin temperature at all times.

As shown in Figure 2.8, the thermistor was mounted on the inside of an inexpensive, one-size-fits-all athletic headband using soft foam and a hot glue gun such that the thermistor was centered on the front of the forehead during the experiment. The headband was used so that the thermistor could comfortably be worn by a variety of adult test subjects, each with a slightly different head size and shape. The elasticity of the headband held the thermistor firmly to the subject's forehead without the need for applying adhesive to the skin. The foam protected the thermistor leads and provided cushion to study participants. The front of the forehead was chosen as the point on the body to measure temperature as temperature measures there are reliable and many clinical and home health products measure patient temperature through the forehead. Although the forehead is not an optimal location to place wearable electronics [65], it is a relatively unobtrusive location on the body for this application because the user is fairly stationary throughout the experiment. The connecting wires were pulled away from the users face through a small strip of mounting Velcro on the back of the headband in order to try to

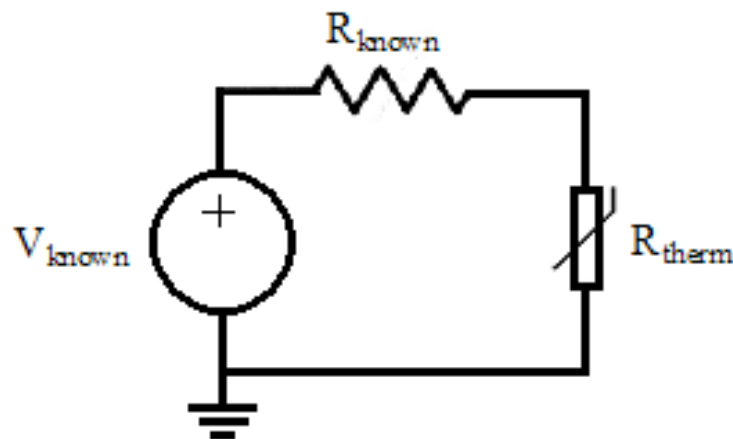


Figure 2.7 The circuit used to determine the skin temperature of test subjects

make the headband as comfortable as possible for the user. The thermistor was soldered to an Adaptaplug™ connector from Radio Shack and the signal was conditioned using an operational amplifier circuit and sent into the PMD-1208FS for data collection. Figure 2.9 shows the proper position of the headband on the forehead and how the signal wires were drawn away from the wearer's face using Velcro.

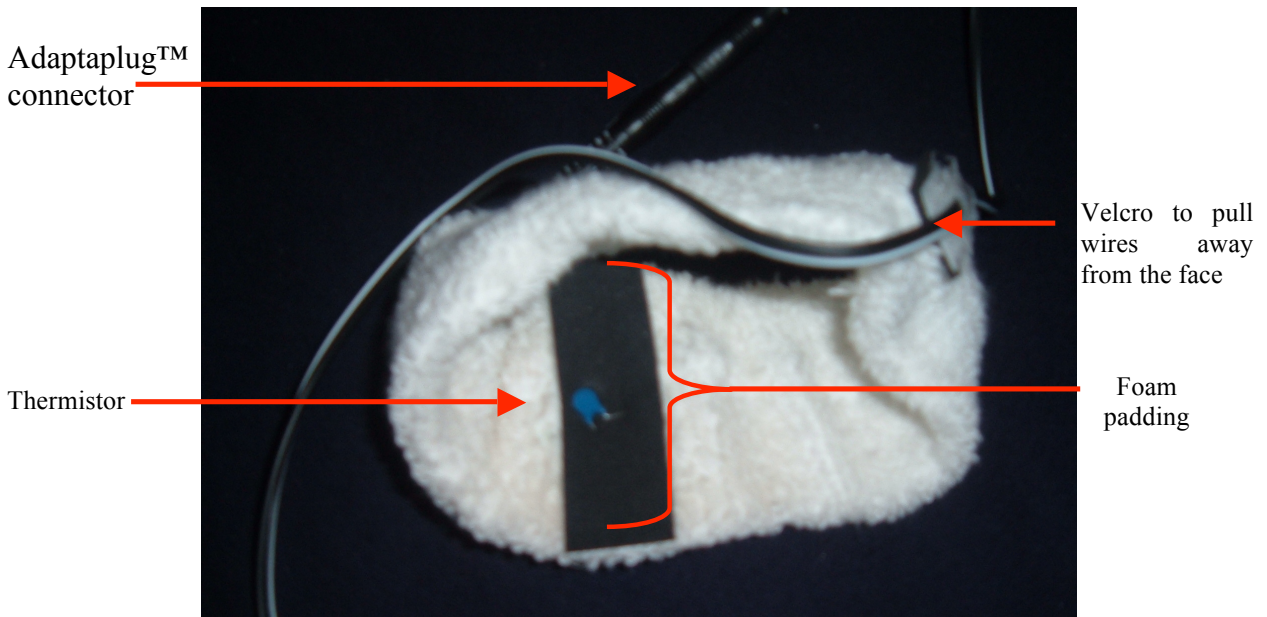


Figure 2.8 The skin temperature sensing headband design



(a)



(b)

Figure 2.9 a) Proper placement of the skin temperature sensing headband. b) The Velcro on the back of the headband draws the cable over the top of the head and way from the face.

2.6.3 Measuring Galvanic Skin Response (Skin Conductivity)

The hands and feet have the most dramatic change in resistance in response to arousal, known as the galvanic skin response (GSR). A circuit very similar to the circuit designed for determining skin temperature was developed to determine the resistance of the skin assuming the skin to be a variable resistance, R_{human} . This circuit, shown in Figure 2.10, connects the skin in series with a fixed resistance and a known DC voltage source. The selection of R_{known} was made to ensure human participant safety even in the worst-case scenario when R_{human} goes to 0Ω . Both this circuit and the temperature monitoring circuit were designed to expose a human subject to no more than $10\mu\text{A}$ of current based upon the guidelines the American Heart Association prescribes for electrocardiography (ECG) in [66]. Each study participant was connected to the circuit using homemade finger electrodes built out of brass washers and foam as depicted in Figure 2.11.

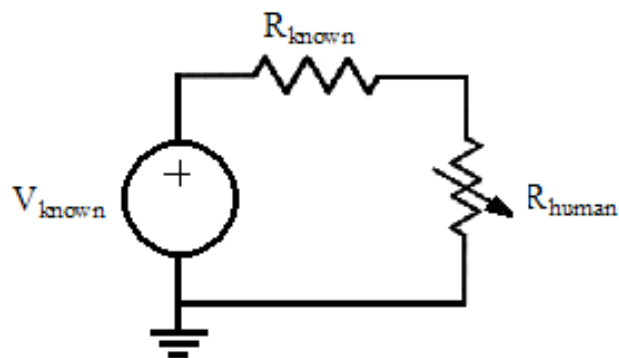


Figure 2.10 The circuit used to determine the galvanic skin response of test subjects

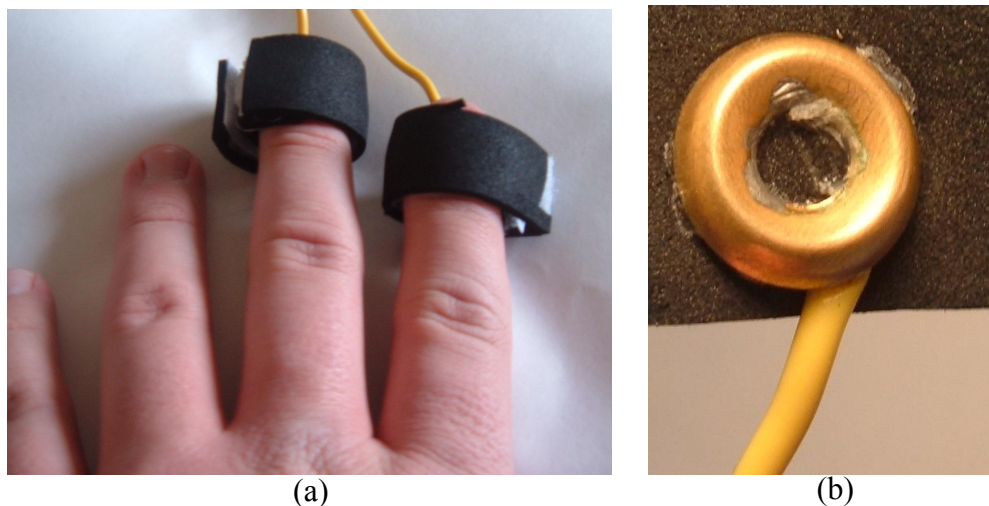


Figure 2.11 a) The proper wear of the finger electrodes b) a close-up view of one electrode

2.6.4 Signal-Buffering Circuit

In preliminary tests of the input devices described in the last three sections, it was discovered that the input impedance of the analog to digital channels of the PMD-1208FS was not large enough to maintain the integrity of the signal for GSR and skin temperature sensing before sampling. To compensate for the low input impedance, an operational amplifier circuit with large input impedance was used as a buffer to the signal. The TL082 Dual JFET Operational Amplifier (Op Amp) was selected for this application as it has an input impedance of $10^{12}\Omega$ [67]. A series pair of LM117 voltage regulators [68] were used to provide the voltage rails for the operational amplifier circuit. The entire signal conditioning circuit is shown in Figure 2.12. It was soldered to a circuit board and mounted in a project box as depicted in Figure 2.13 and Figure 2.14, respectively.

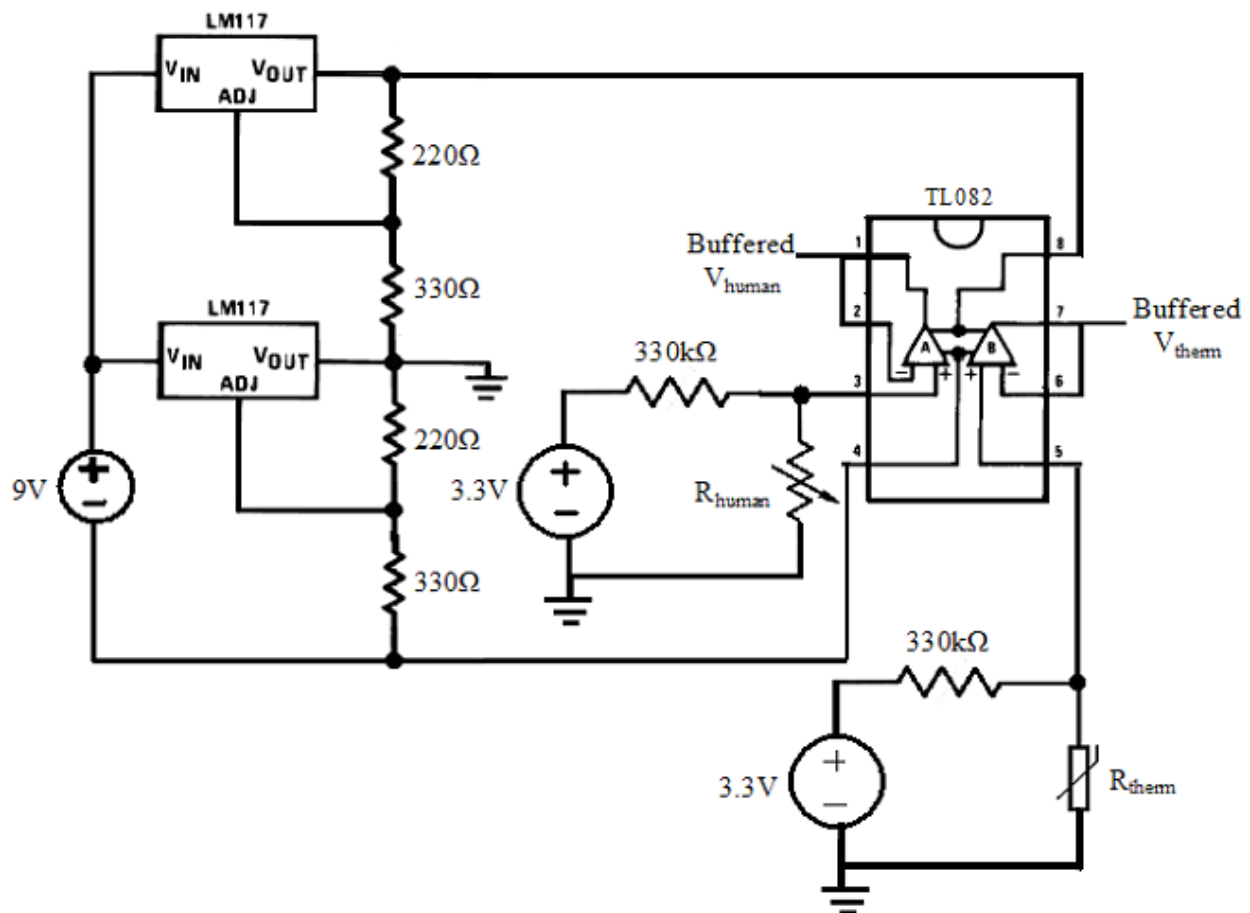


Figure 2.12 The signal-buffering circuit showing where the signals were sent into the Op Amp and where the buffered signal is output

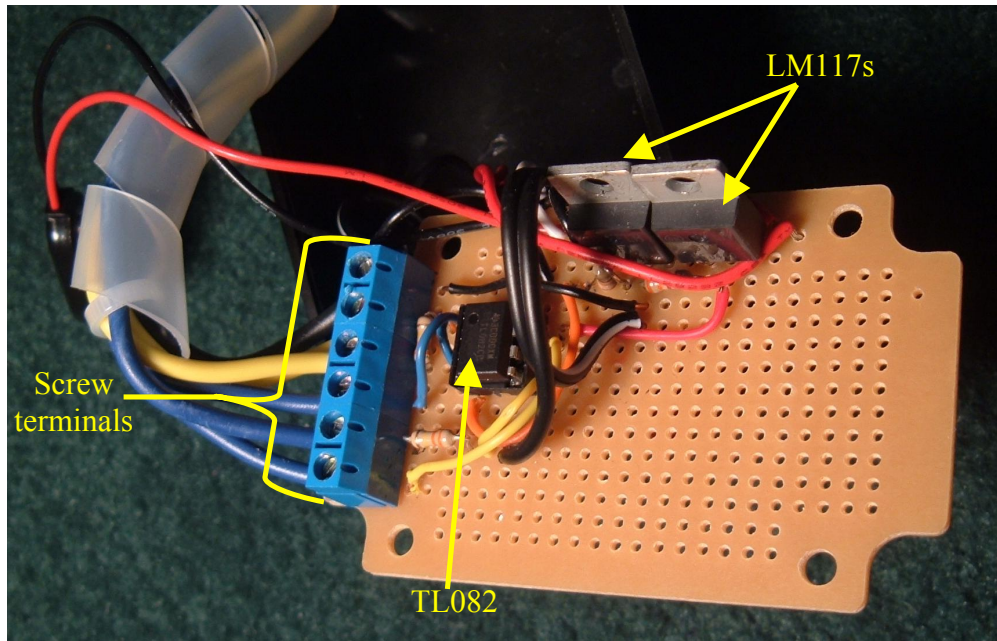


Figure 2.13 The signal-buffering circuit soldered to a circuit board

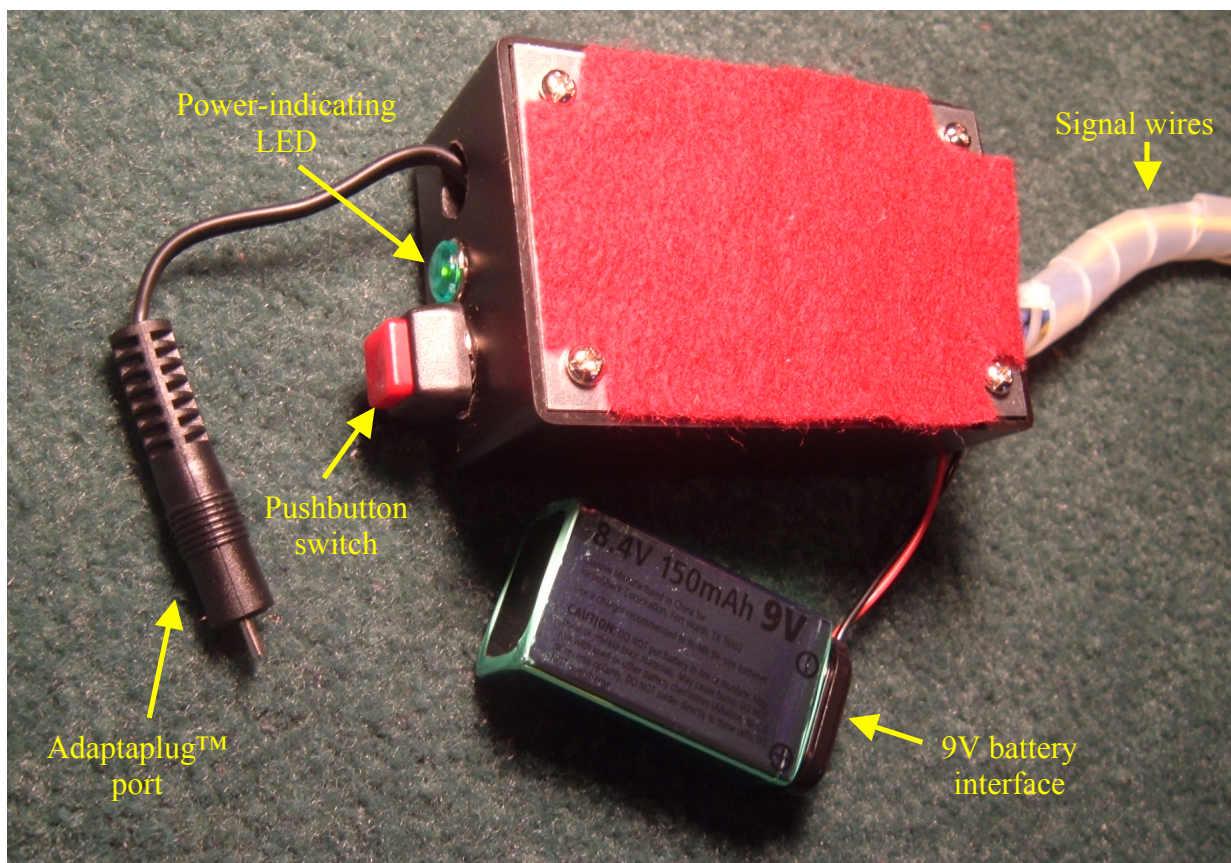


Figure 2.14 The completed signal-buffering project box

2.6.5 Learning Preference Assessment

The VARK learning preference assessment was used to determine each study participant's preferred learning modality. This 13-question assessment classifies those surveyed into one of four modality preference groups: visual (V), auditory and oral (A), reading and writing (R), and kinesthetic (K). Although this assessment did not provide a full learning style assessment it allowed for the determination of a user's learning preference in a short period of time. The questions in this learning style assessment and the scoring method for the assessment were taken directly from the VARK website (www.vark-learn.com).

2.6.6 Memorization and Recollection Tasks

The visual memorization task consisted of the presentation of sixteen two-dimensional simple shapes in a 4x4 array. The array of shapes was presented for a period of thirty seconds, during which time test subjects were prompted to memorize as many of the shapes as they could. At the end of the thirty-second period the shapes disappeared and test subjects were asked to recall which shapes they had just seen and to place the shapes back into the order presented. The auditory task was similar and asked participants to memorize a list of 16 words and to recall the words and place them back into the order presented. Data on task performance and physiological affect were analyzed to show how well people do performing tasks in different modalities.

2.6.7 Implications of MS Thesis Work

While the learning tasks analyzed in this study were trivial there are a variety of applications of physiological monitoring to education. By deploying small physiological sensors while students are learning it is possible to analyze the affect of the learning environment and to tailor the curriculum to each learner's needs. The physiological monitoring work done herein provides an additional axis of data to educational evaluation in order to not only monitor what students know and how well they know it, but to gain insight into how comfortable they feel with each subject.

3 Goal, Objectives, and Outcomes

The goal of this dissertation work is to develop a knowledge representation and assessment paradigm that will facilitate better student learning. This research work involves modeling knowledge, developing assessments to evaluate student understanding of that knowledge, and using feedback received from students to model student understanding of information. The knowledge representation and evaluation methods developed in this research serve as a paradigm for a modern and comprehensive approach to educational assessment and have potential to become the standard way of representing what students know within a variety of disciplines in order to comprehensively model a lifetime of learning.

Figure 3.1 depicts an outline of the proposed work broken down into three objectives, which are further broken down into six outcomes. The objectives are placed in a logical order in

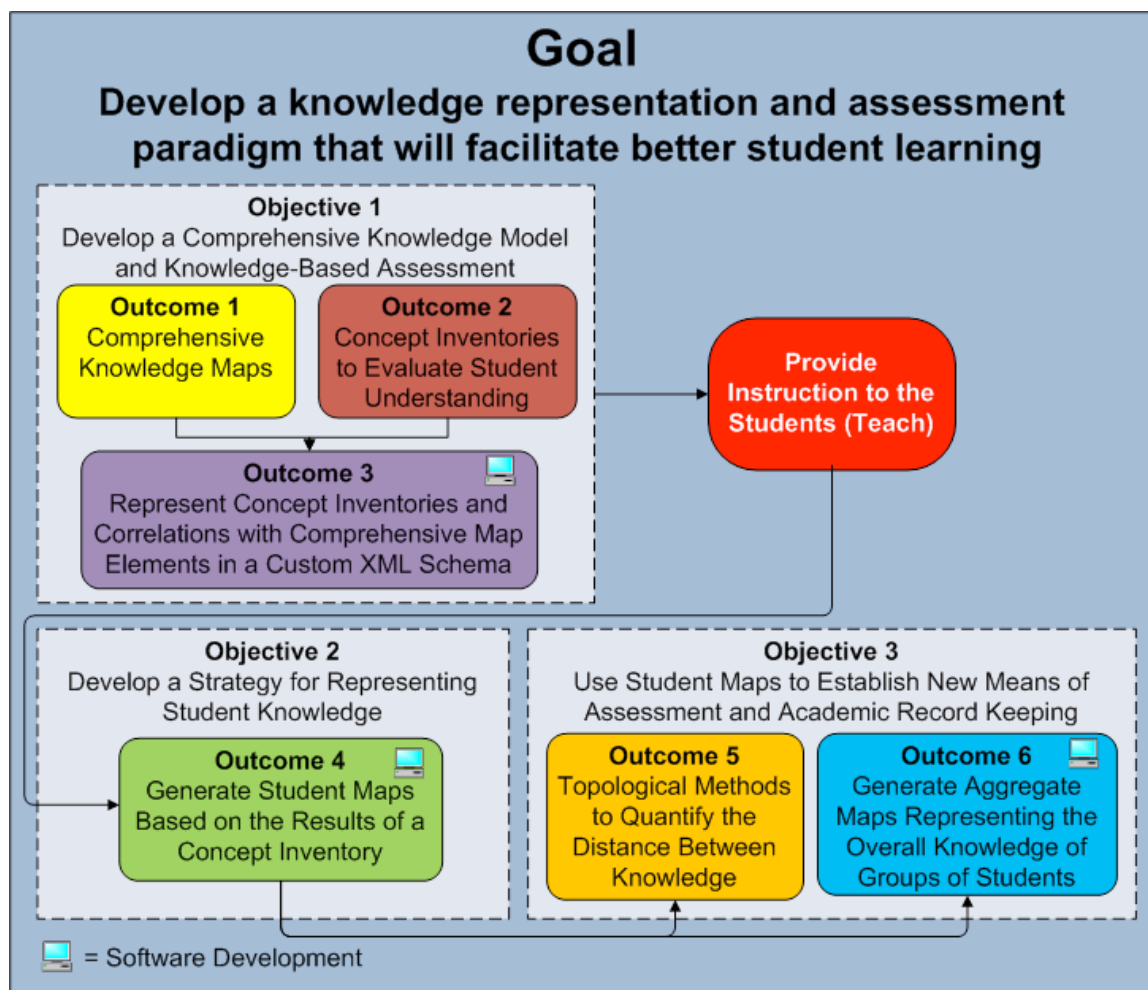


Figure 3.1 Overview of the system broken down by objectives and outcomes

Figure 3.1 as the outcomes from the completion of some objectives drive the development of outcomes to satisfy other objectives. For instance, the comprehensive knowledge map and concept inventory developed in outcomes 1 and 2, respectively, are embedded in an XML schema developed in outcome 3 and used as inputs for the student map generation software developed in outcome 4. Likewise, the student maps produced by the software in outcome 4 are evaluated using the assessment techniques developed in Objective 3. The computer icon in Figure 3.1 is used to indicate outcomes that produced software. The following sections introduce the objectives and proposed outcomes for this research work. The details of their implementation and example results showcasing how each of the objectives and outcomes has been met are included in chapter 5.

3.1 Objective 1: Develop A Comprehensive Knowledge Model and Knowledge-Based Assessment

The steps involved in achieving this objective are depicted in Figure 3.2 and are broken down into several different processes. The following subsections introduce the outcomes developed to meet this objective with the implementation details discussed in chapter 4 in sections 4.1, 4.2, and 4.3, respectively.

3.1.1 Outcome 1: Comprehensive Knowledge Maps

The assessment process begins with the development of a comprehensive knowledge map. Such a map allows researchers, instructors, or others with experience in a discipline to map out all of the concepts and relationships embedded in the information being studied. The maps may be very extensive spanning multiple fields of study and illustrating a multitude of concepts or very simple focusing only on the concepts embedded in a single day's lesson or activity. As depicted on the left hand side of Figure 3.2, the comprehensive knowledge map is developed collaboratively by a panel of experts who draw not only from their own expertise, but also the expertise contained in the appropriate literature to form a complete model.

Two comprehensive knowledge maps were developed for two learning modules that are part of two freshmen engineering courses. The knowledge maps are stored in an XML format, which allows significant flexibility to represent a variety of relationships in a very systematic way. The details of the development, including the courses and units studied and the XML schema used to store the knowledge maps are discussed in chapter 4 in section 4.1.

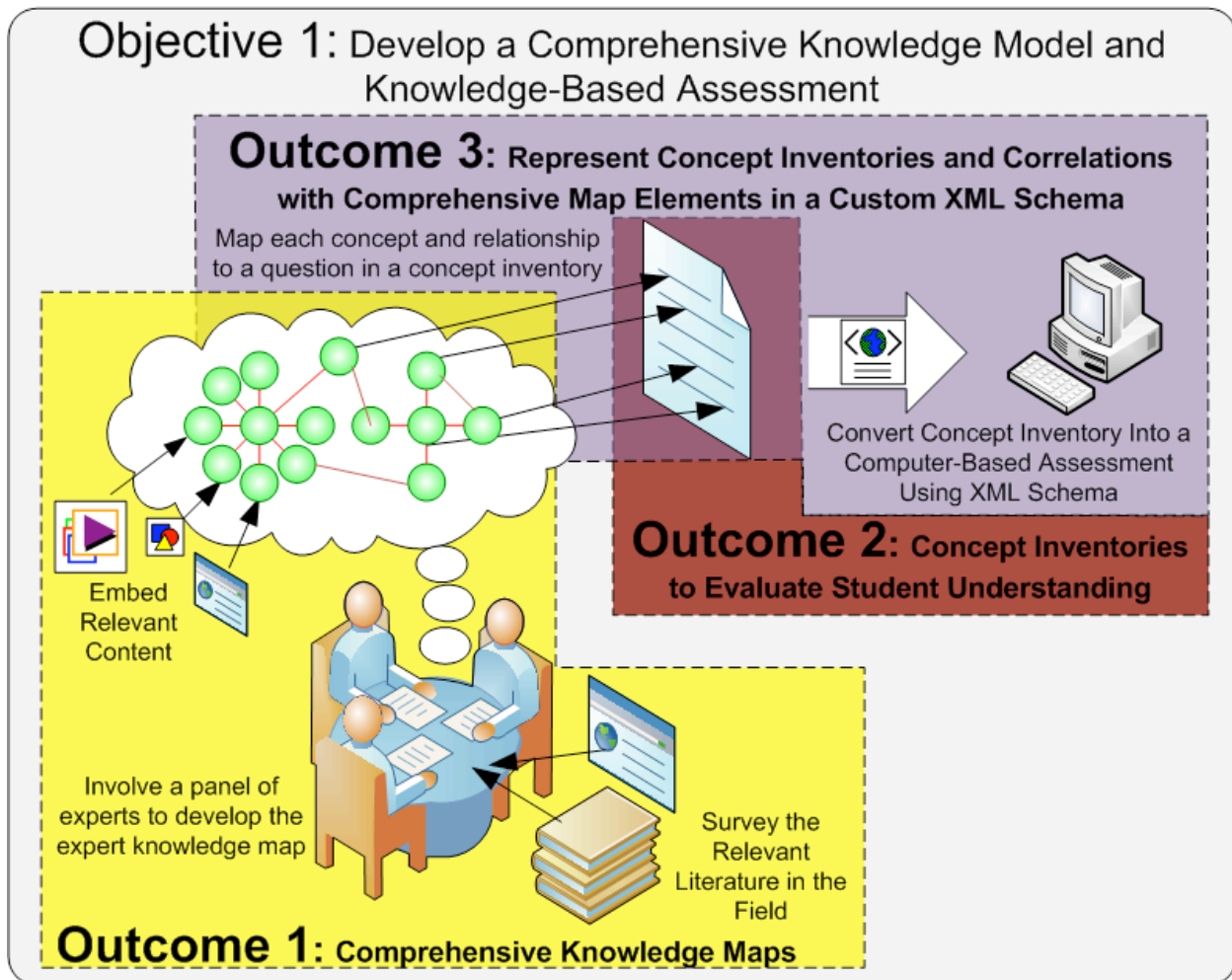


Figure 3.2 Outline for the development of a comprehensive knowledge map and a corresponding concept inventory

3.1.2 Outcome 2: Concept Inventories to Evaluate Student Understanding

A concept inventory provides an ideal knowledge assessment as the questions in concept inventories are typically very straightforward and allow one to assess an individual's working knowledge of concepts and relationships without undo complexity. Concept inventory questions are also usually multiple-choice or multiple-answer, which makes them easy to autonomously score and assess when compared to free response assessments. As depicted in the top right portion of Figure 3.2, each link and node in a comprehensive map is tied to a question or questions in the concept inventory. This research involved the development of two concept inventories that are tied directly to the concepts and relationships embedded within the comprehensive knowledge maps introduced in section 3.1.1. The concept inventories were developed iteratively though several revisions as described in chapter 4 in section 4.2.

3.1.3 Outcome 3: Represent Concept Inventories and Correlations with Comprehensive Map Elements in a Custom XML Schema

An XML schema was developed that logically encapsulates the text of the questions and all possible answer choices for each question in a concept inventory along with the correlations between the questions and the elements of the comprehensive map. Software was developed to enter the concept inventories, to draw associations between the comprehensive map and the questions, to and store them in the XML schema. The details of the design of the XML schema and concept inventory software are discussed in chapter 4 in section 4.3.

3.2 Objective 2: Develop a Strategy for Representing Student Knowledge

A key component in developing a paradigm for knowledge representation and assessment is to determine a way to model what students know. One of the most important contributions of this dissertation is a method for generating maps that represent each individual student's knowledge. As depicted in Figure 3.3, the student map generation procedure outputs a student map for each student based upon his or her responses to a concept inventory (such as the concept inventories introduced in section 3.1.2). The software development for student map generation is introduced in section 3.2.1. This software has been used to generate sets of student maps that can be analyzed using methods developed as part of Objective 3.

3.2.1 Outcome 4: Generate Student Maps Based on the Results of a Concept Inventory

Software was developed to process student responses to a concept inventory and output a student map representative of the knowledge a student has demonstrated. Since each question on the concept inventory is tied to one or more concepts or relationships in the comprehensive map, student maps are of the same structure as the comprehensive maps and contain the subset of map elements corresponding to the questions in the concept inventory that the student correctly answered. Student maps not only depict whether a student has knowledge of a concept, but Bloom's taxonomy [11] is used to graphically depict the level of mastery students have of each concept and relationship. The details of the implementation of the software and example results of execution are discussed in chapter 4 in section 4.4. This student map generation strategy has been implemented for two course units, but can be generalized for widespread use.

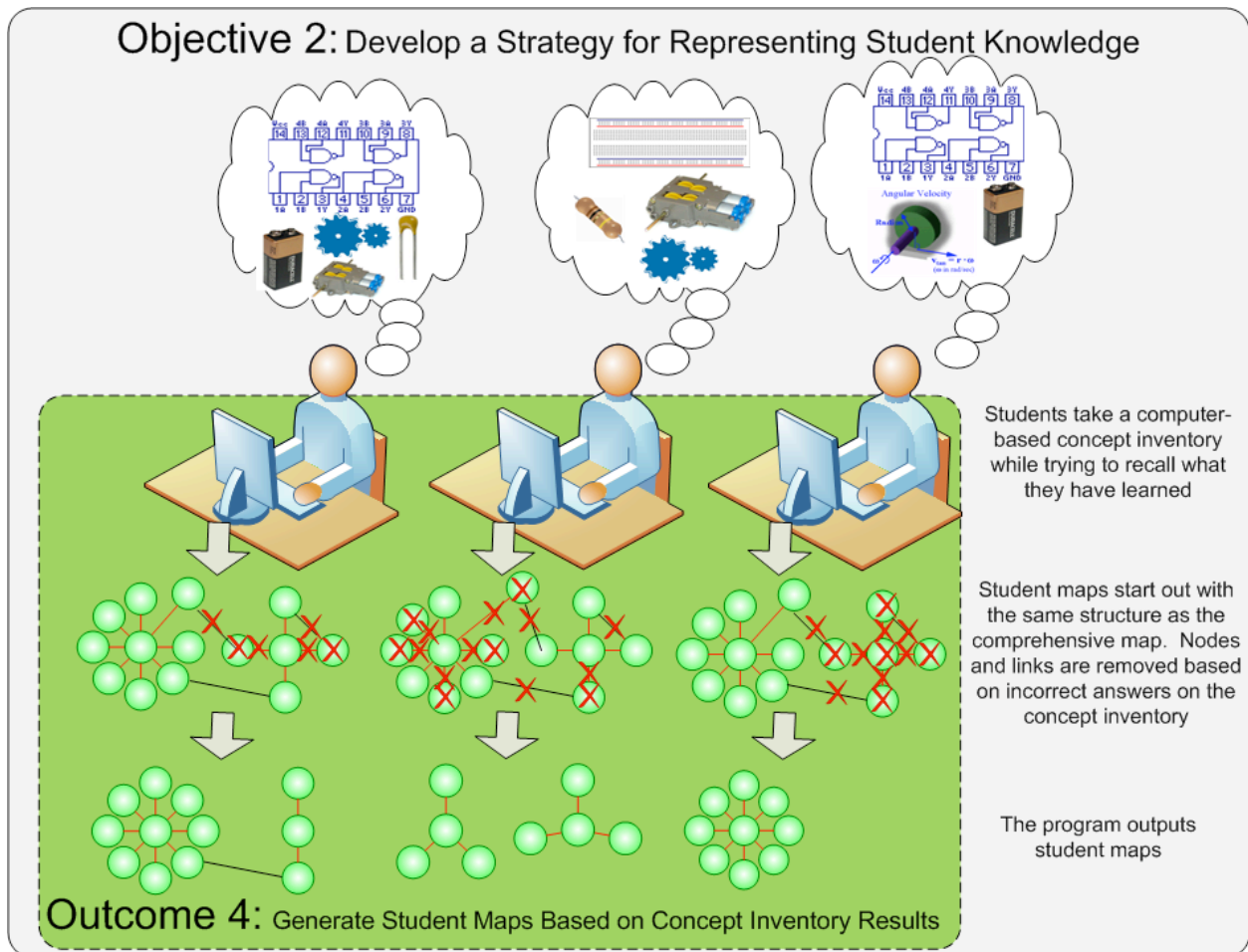


Figure 3.3 The strategy used to develop student maps based on the concept inventory

3.3 Objective 3: Use Student Maps to Establish New Means of Assessment and Academic Record Keeping

The student maps generated by the student map generating process provide educators and academic institutions with a new resource to represent what their students know. These student maps for each student have potential to eventually replace, or at a minimum augment, academic transcripts as a detailed record of student knowledge and achievement. The following two subsections showcase outcomes to show how evaluation of students and faculty members can be done using student maps.

3.3.1 Outcome 5: Topological Methods to Quantify the Distance Between Knowledge

The development of graphical models of student knowledge opens up doors for a variety of assessment techniques to be used to analyze that data. Methods to quantify the distance between knowledge maps can be developed using the principles of topology. As depicted in Figure 3.4, these methods allow one to quantify the distance between different students' knowledge, herein referred to as comparative knowledge, and also between the knowledge represented in a student map and the comprehensive set of knowledge encapsulated in the comprehensive map, herein referred to as the knowledge gap. The distance between a student map generated for a student at one particular time and a student map generated at a later time can be computed to determine the progress that student has made in mastering concepts. In section 4.5 of chapter 4 the development of a metric to quantify the distance between two maps is discussed along with relevant theory from topology.

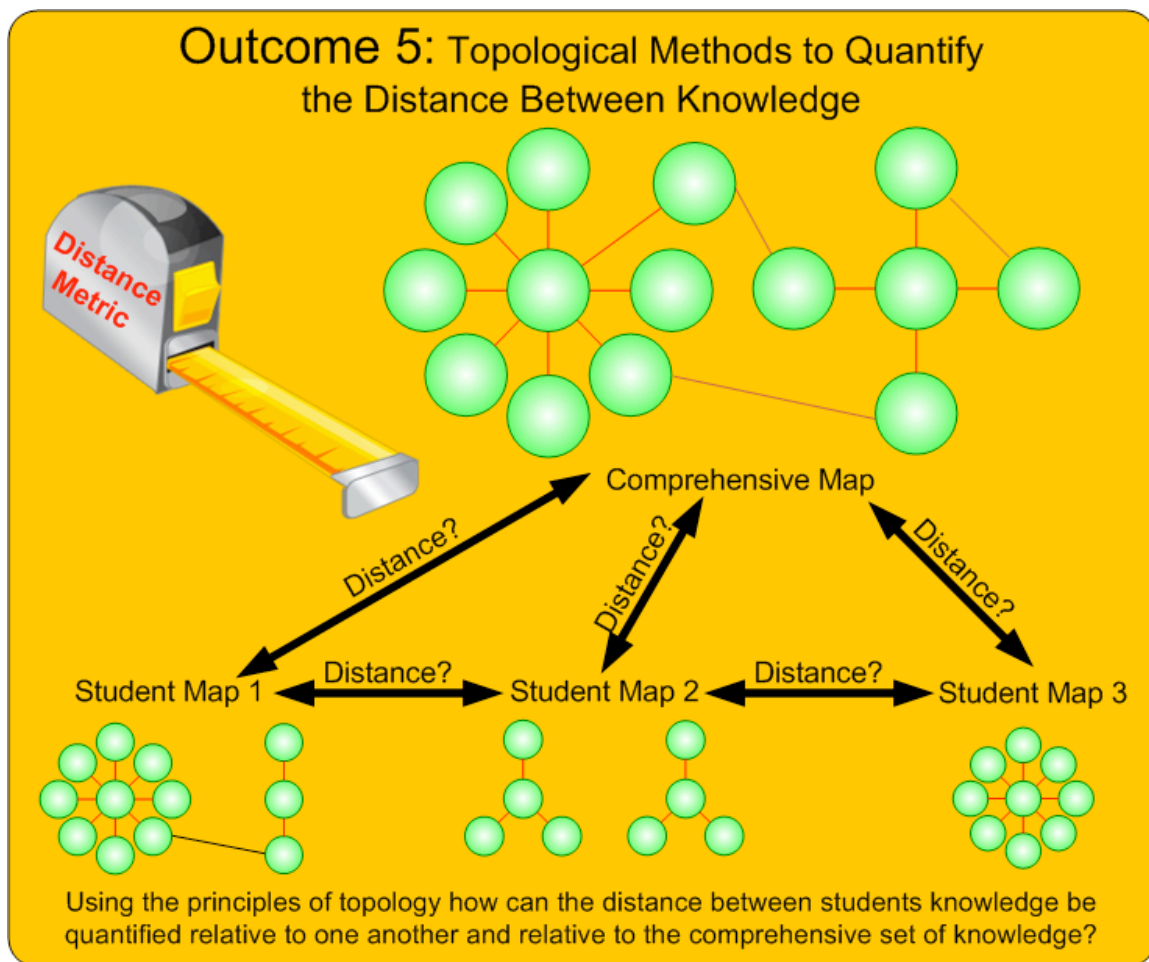


Figure 3.4 Using topology to quantify the distance between concept maps

3.3.2 Outcome 6: Generate Aggregate Maps Representing the Overall Knowledge of Groups of Students

As a second assessment method, software was developed to produce an aggregate map (as defined in chapter 1 in section 1.5) that encapsulates the knowledge represented in a group of students. As is depicted in Figure 3.5 the aggregate map has the exact same structure as the corresponding comprehensive map, but is annotated to indicate the portion of students who learned each concept or relationship. Even if a concept or relationship is not present in any of the student maps comprising the aggregate map, the corresponding node or link still appears, but

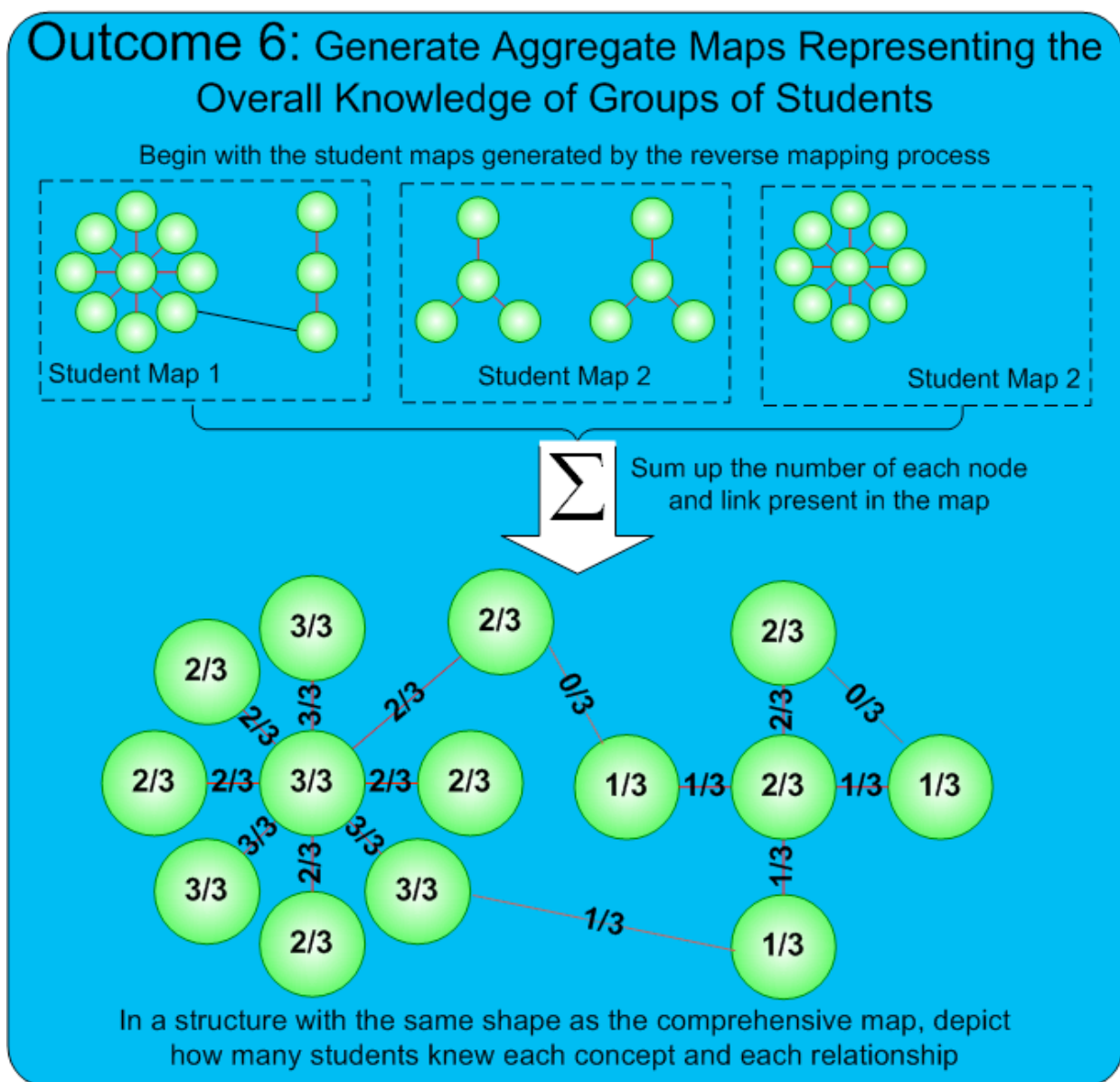


Figure 3.5 The method for developing an aggregate map from student maps

is labeled with 0/N indicating that none of the N maps forming the aggregate map contained that concept or relationship. An aggregate map can be formed for all students in the class or based upon any collected demographics such as gender, instructor, class time, ethnicity, etc. Aggregate maps allow instructors to assess the effectiveness of their teaching by examining the information that was imparted to their students at the conceptual level. The instructor can use the aggregate maps to identify adjustments that should be made in the curriculum in order to strengthen their teaching of concepts students are not learning well. Aggregate maps allow for objective, results-driven instructor evaluation and provide opportunities for faculty collaboration to determine the most effective teaching methods in order to optimize the learning experience for all students. The details of software implementation and sample aggregate maps are presented in chapter 4 in section 4.6.

3.4 Summary

This work includes the development of knowledge modeling and assessment techniques, but does not address how the knowledge should be presented to students. The assessment strategy developed herein is designed to be independent of the method of instruction and is applicable within a variety of educational settings including traditional lecture courses, online learning courses, and hands-on learning courses.

4 Methods and Deliverables

In this chapter the details of the work done and deliverables produced are discussed. This chapter is designed to be read in concert with chapter 3 as each of the sections and subsections within this chapter describe how each of the three objectives proposed in chapter 3 have been met and what work has been done to achieve the six proposed outcomes.

4.1 Comprehensive Knowledge Maps

As discussed in chapter 3 in section 3.1, this new paradigm for student knowledge evaluation begins with a comprehensive map. The comprehensive map is developed by carefully examining all of the concepts and relationships involved in the particular field of study being mapped. Ideally such maps are developed iteratively through consultations with other experts. It is beyond the scope of this research work to develop detailed comprehensive knowledge maps for all disciplines, but the work done towards this research showcases how this evaluation system may be used with a course unit and establishes a framework for implementation in any field. To that end, the focus of the work was one unit in a two-credit freshman general engineering course and a follow-up study was done with a related unit in a second-semester freshman course. Details regarding the courses and contents of the units are discussed in section 4.1.1. The methodology for data collection and evaluation were the same in both course units and exhibit how the proposed methods are generally applicable.

4.1.1 The Courses and Units Studied

4.1.1.1 EngE 1024 Engineering Exploration

The work involved an extensive study of an introductory unit in mechatronics taught to first semester freshman engineering students at Virginia Tech as part of the EngE 1024 Engineering Exploration course. This one-semester required course introduces students to a variety of concepts from various engineering disciplines and serves as a foundation course for all fourteen engineering majors offered at the university. The fall semester is the large offering of this course and typically has an enrollment of 1300+ students. During the spring semester approximately 150-180 students are enrolled in a smaller offering of the course. This course is also offered in a six-week summer session. During the fall and spring semesters students attend a 50-minute lecture taught by an engineering education faculty member once a week with

approximately 150-180 students and then they attend a 90-minute hands-on workshop taught by graduate teaching assistants (GTAs) once a week with 28-32 students. Up to five such workshop sections are taught concurrently with a total of almost fifty workshop sections being offered in the fall and six workshop sections in the spring. The author of this dissertation served as the coordinator of the two-week mechatronics unit in EngE 1024 from Fall 2006 through Fall 2008; he has also served several semesters as coordinator or co-coordinator of entire workshop.

4.1.1.2 EngE 1024 Mechatronics Unit

This unit introduces students to simple electrical components (resistors, diodes, capacitors, etc) and allows students to explore how the components may be joined together in a circuit to drive a simple mobile robot. Students also learn mechanical concepts and learn to assemble the mechanical portion of the robot. The unit typically has been done in weeks 8 and 9 of a 15-week semester, although during some semesters the two-week unit has been condensed into a one-week unit. Little mention is made of the mechatronics initiative within the weekly lecture. Instead, students are instructed to view an online lecture, which was prepared by Dr. Pushkin Kachroo, an expert in mechatronics, who serves as the author's co-advisor. This online lecture provides an introduction to the various concepts that the students then apply in a hands-on laboratory experience where students build the mobile robot depicted in Figure 4.1. The lecture begins by drawing on students' prior knowledge of other course material. By this point in the semester students have already completed a fluids experiment in which they measured the height of water and flow rate of water out of an orifice over time. Students were thus able to make a correlation between voltage (electrical potential) and water height (gravitational potential) along with electrical current (flow of electrons) and water flow. The lecture introduces basic mechanical concepts such as torque, friction, and the use of gears, electronics, Boolean logic, and problem solving techniques.

In the week 8 workshop students build the gearbox portion of the mobile robot. Pairs of students work together to assemble one gearbox. This assembly typically takes students about 20 minutes and involves the assembly of the 26 parts listed in Table 4.1, which are depicted in Figure 4.2. Students are supplied all the requisite parts and a Phillips head screwdriver to perform the assembly.

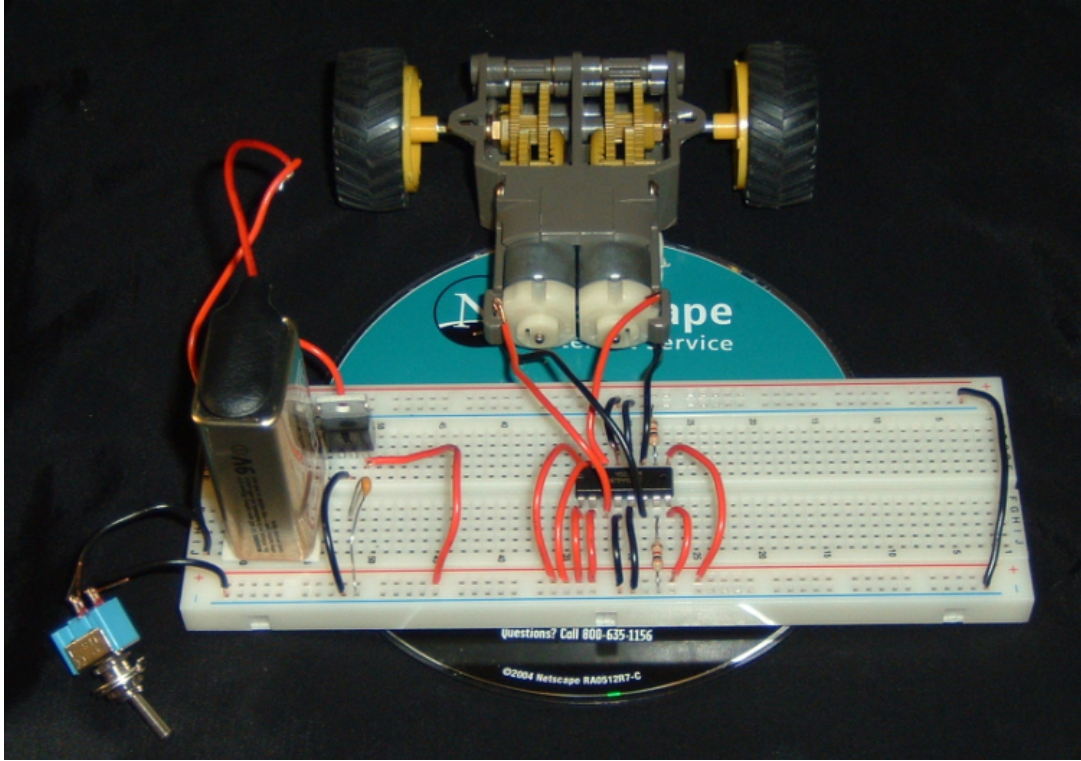


Figure 4.1 The mobile robot built by students during the mechatronics unit

8 spur gears	3 shafts	3 plastic housings	6 machine screws
2 DC servo motors	2 wheels	2 tires	

Table 4.1 Gearbox parts list

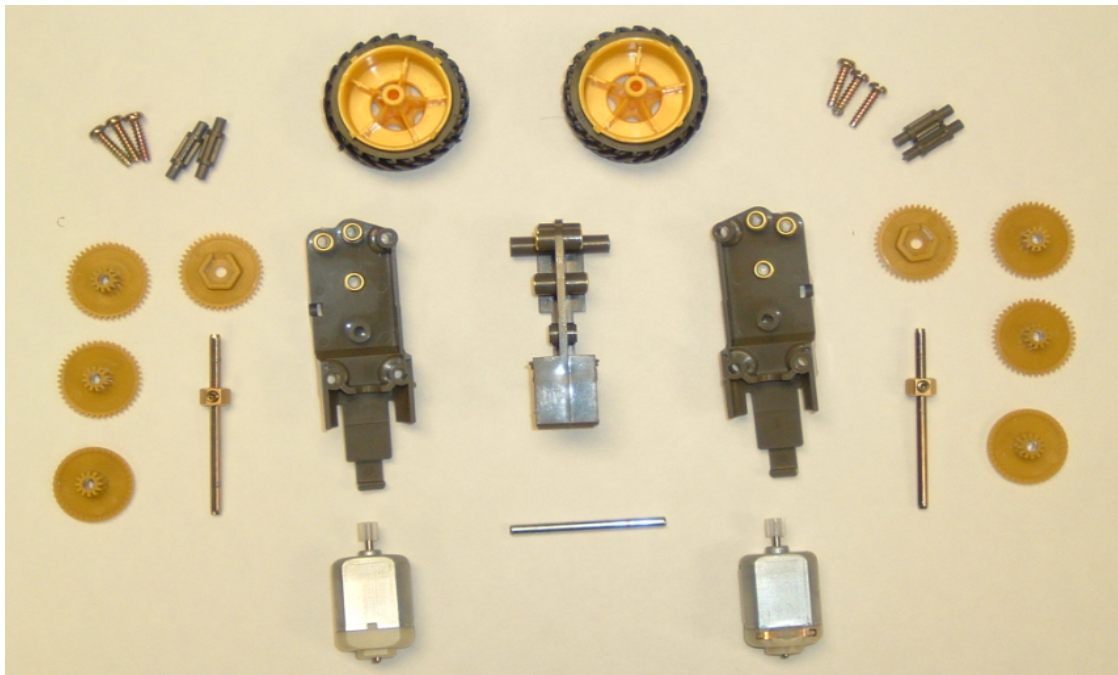


Figure 4.2 The parts provided for assembly of the gearbox

Photo courtesy of Tasha Zephirin. Used with permission.

In addition to the physical pieces required, detailed step-by-step assembly instructions are posted in an online PowerPoint presentation that students may download. Following some preliminary instruction from the GTA running the workshop, students may assemble the gearboxes at their own pace. The GTA then serves as a facilitator for any students having difficulty and checks to make sure all of the students in the workshop have completed the assembly properly. GTAs have an opportunity to practice assembly in a preliminary training session conducted by the unit coordinator so they are aware of any parts of the assembly which may be difficult to perform or any parts for which the students may need the most help. In several semesters undergraduate helpers have also been hired on an hourly basis to assist students having any difficulty with the assembly during the workshop. Figure 4.3 depicts a completely assembled gearbox.

During the week 9 workshop (or the second half of the week 8 workshop in some semesters) students build the electronic circuit that is used to control the gearbox. The final assembly of the circuit can be seen in the complete mobile robot pictured in Figure 4.1. This circuit is built on a prototyping breadboard, which allows for quick assembly and circuit troubleshooting. Students work once again in pairs to assemble all of the electrical components. Each pair of students is given a kit containing the items listed in Table 4.2.

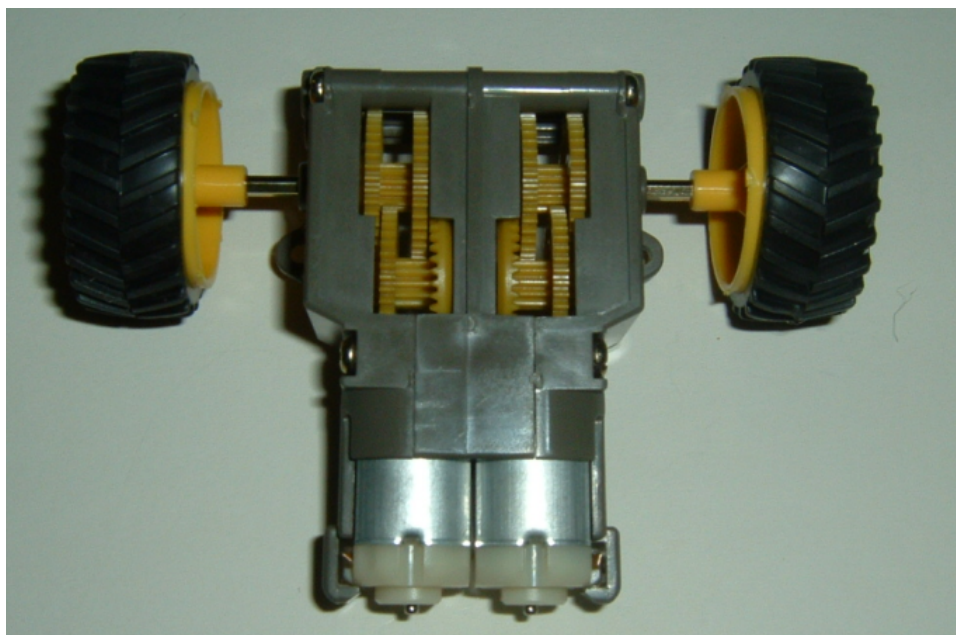


Figure 4.3 A completely assembled gearbox
Photo courtesy of Tasha Zephirin. Used with permission.

1 Breadboard	1 7805 Voltage Regulator
1 0.1 μ F capacitor	A few feet Black and Red Wire (22 AWG-solid core)
1 IN4148 diode	1 SN754410NE H-bridge (motor driver) dual inline package integrated circuit
2 2k Ω resistors	1 Single Post, Single Throw Switch
1 Pair of Wire Strippers	1 Free internet CD
1 Multimeter	1 9V Battery and battery snap
1 Complete Gearbox	

Table 4.2 Mechatronics kit contents for circuit assembly

Students are again given a set of instructions in a downloadable PowerPoint file with very detailed pictures illustrating each step of the assembly process. After some instruction regarding the purpose of each component, how to use a breadboard, and some safety guidelines, students are allowed to assemble the robot circuit at their own pace. The circuit assembly is divided into three stages as depicted in Figure 4.4. The first stage involves interfacing the battery with the breadboard. The second stage involves the use of the 7805 voltage regulator to convert the 9V input from the battery to the required 5V used to run the motor using the H-bridge motor driver which is connected in stage 3. The complete circuit representation as presented to the students is shown in Figure 4.5. As can be seen in this figure, the circuit is represented using a combination of schematic symbols and pictures in order to clearly convey what is being assembled without overwhelming students with a detailed schematic since most students enrolled in this course have limited to no circuit assembly experience and are not accustomed to reading schematics.

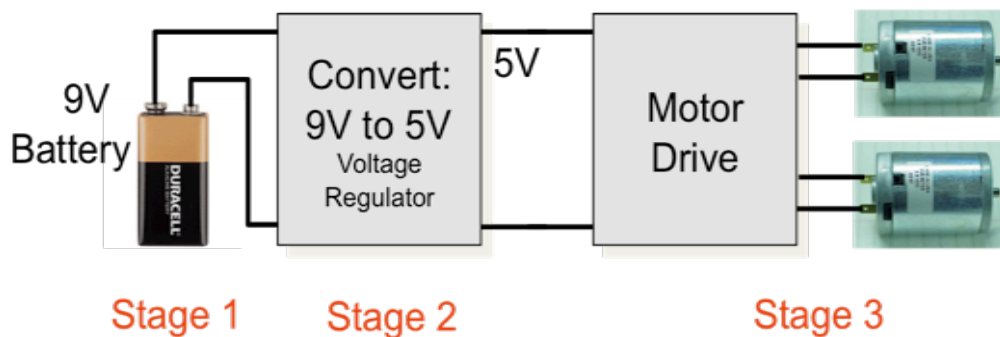


Figure 4.4 The three stages of the mobile robot circuit

Illustration courtesy of Tasha Zephirin. Used with permission.

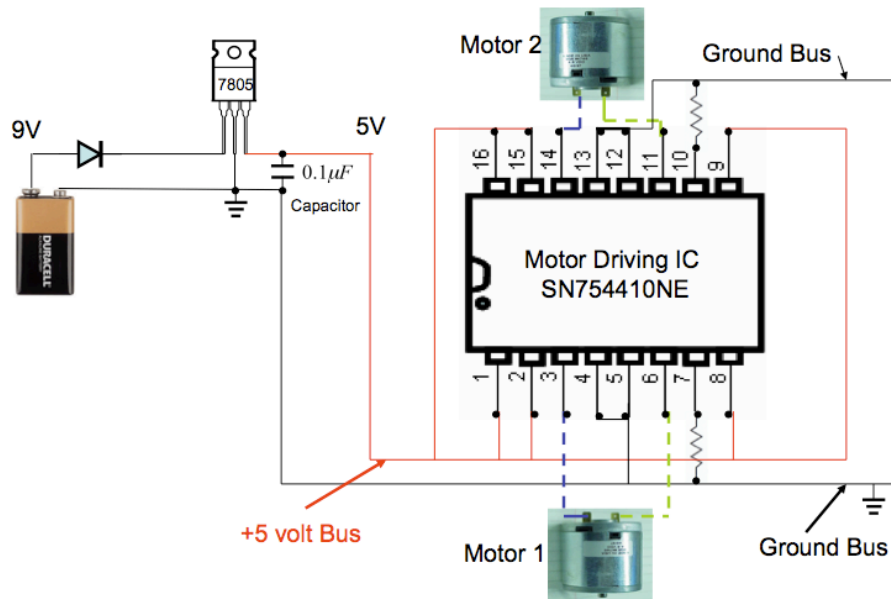


Figure 4.5 The representation of the complete circuit as presented to the students
 Illustration courtesy of Tasha Zephirin. Used with permission.

Students are given instructions about how to use the multimeter to troubleshoot their circuit and to check for the proper outputs at different stages of assembly. Some safety instructions are also included to keep the students from connecting components (such as the voltage regulator) incorrectly as erroneous wiring can cause component damage and injury to the students. After the circuit is completely built, students use double-sided tape to affix the breadboard and the gearbox to the CD, which provides a low-cost platform for the robot to run on. The assembly of the complete robot circuit takes approximately one hour. As was the case during the gearbox assembly portion, the GTAs and undergraduate helpers act as facilitators and help students troubleshoot any problems that may arise during circuit construction. Once several pairs of students have completed construction of their mobile robots they are allowed to participate in a race against their peers to see who has built the fastest robot.

The author and some colleagues have written a paper for the IEEE Transactions on Education journal (accepted for publication August 2010) on this unit its effectiveness in conveying electrical and mechanical knowledge to students. Student survey data was presented to indicate how challenging the activities were for students and what their overall perceptions were of the unit. In this paper an analysis was done based upon self-reported prior experience with electronics and mechanics and based on gender to determine what differences in perception existed based upon these factors. Interestingly although the electrical and computer engineering and mechanical engineering departments at the university continue to be comprised of a smaller

percentage of females than other engineering departments the perceptions of male and female students were not significantly different [69].

4.1.1.3 EngE 1104 Exploration of the Digital Future

In order to showcase the general applicability of this analysis method to multiple units or multiple courses, collaboration was also done with instructors of the second semester first year engineering course, EngE 1104 Exploring the Digital Future. This required course is taken by first-year engineering students intending to major in electrical engineering, computer engineering, or computer science. The course has a similar format to the EngE 1024 course with a weekly 50-minute lecture taught by a faculty member and weekly 110-minute hands-on lab sessions taught by graduate students. Course topics span a variety of areas of contemporary interest within the three represented major fields and include Matlab programming, signal processing, bio-system modeling, electrical power and power distribution, micro electro-mechanical systems (MEMS) and sensors, and autonomous vehicles.

4.1.1.4 EngE 1104 Autonomous Vehicles Unit

The EngE 1104 autonomous vehicles unit contains a pre-lab exercise, three programming tasks, two discovery activities, and a culminating task. The lab involves programming various settings for a mobile robot that has two downward-pointing infrared sensors (depicted in Figure 4.6) capable of distinguishing light and dark regions and two variable speed motors designed to control motion on the left and right side of the robot. The pre-lab assignment involves creating state tables indicating when the left and right motors should be on in the forward or reverse directions and whether they should be operating at full or half speed based on the detection of a black or white region under the left and right infrared sensors. The state tables should correspond to the logic for the first three in-lab programming tasks, which are:

1. Making the robot spin clockwise in place
2. Making the car drive forward until it detects a black line, at which point it should stop
3. Making the car follow a curvy loop defined by a black line on a white background.

After completion of the pre-lab assignment, the students come to the lab where they develop the control code for each of the three tasks above and test it with the robot. They are provided with six motor commands in a library that allow them to turn on either motor in the

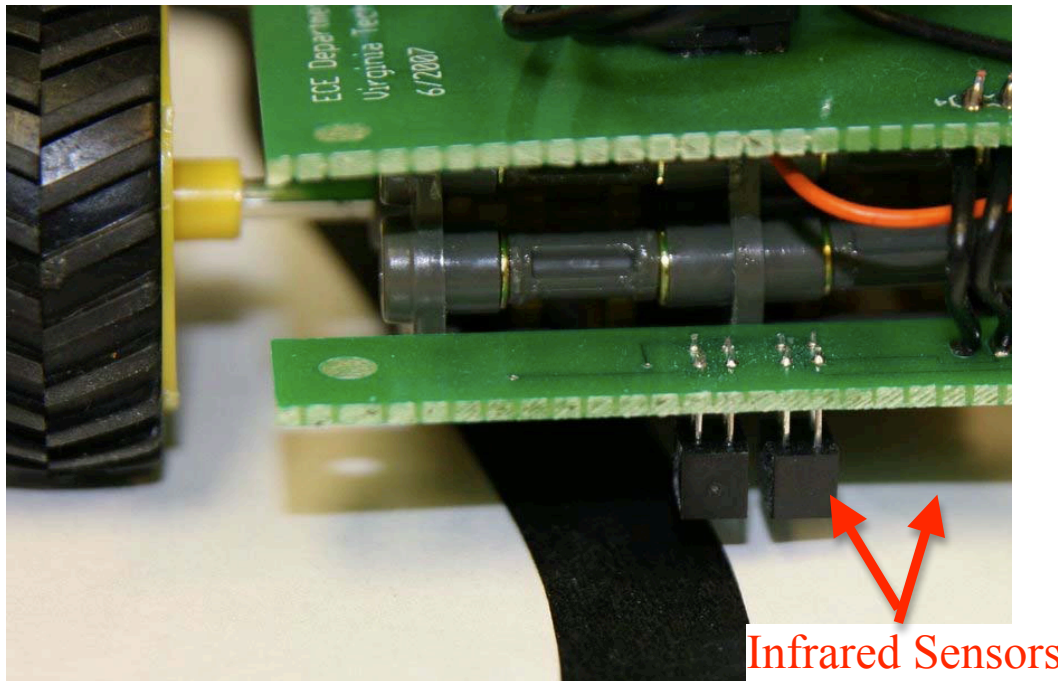


Figure 4.6 The mobile robot used in the autonomous vehicle lab with infrared sensors at the positions indicated by the arrows

Photo courtesy of Leyla Nazhandali. Used with permission.

forward or reverse direction or stop the motor. Other than the two stop commands, the commands take in a value from 1 to 10, which indicates a speed at which the motors should run. They are also provided with a programming framework that allows them to simply enter the appropriate motor commands into the four possible cases of input combinations on the two infrared sensors (left = black or white, right = black or white). The students are given instructions regarding how to download the code to the microcontroller onboard the robot, but have very minimal instruction regarding the robot hardware. The robot has a much more sophisticated controller than the one used in the EngE 1024 mechatronics lab, but the gearbox used is exactly the same.

After students perform the first three tasks they work on two discovery activities in which they learn more about how the underlying technology works. They are instructed in the notion of reflexivity and how the infrared sensor works by emitting an infrared signal and detecting the portion of that signal is reflected (with white surfaces reflecting more of the signal and black surfaces absorbing more of the signal). The students then use the same code that they developed to complete task 2 above and run it on a surface that has a gradient from white to black. Through this activity they learn about the notion of a threshold that the interpretation of sensor data uses

to distinguish white from black. They initially run this program at the slowest speed possible and then modify their code by increasing the speed to see if the point at which the robot stops is the same or if speed tends to increase or decrease the threshold. Through this experiment they are to realize that the reflexivity threshold remains the same, but the sampling rate causes slower-moving robots to detect that the threshold has been met earlier.

The second discovery exercise illustrates the importance of duty cycle and frequency in motor control. Students learn that the number entered into the motor control routines actually corresponds to the duty cycle of the square wave signal sent to the respective motors. The students vary the duty cycle and determine the time it takes to complete task 2 under different duty cycles. They then develop a chart containing these values and attempt to determine the correlation between duty cycle and completion time. The students learn to modify the frequency at which the square wave is output to the motors and set several different values for the frequency to determine if frequency has a similar correlation to the robot's motion as the duty cycle did. They plot the frequency vs. completion time and learn if there is any relationship between frequency and completion time. Students should observe that under a large range of frequencies there is no difference in speed based upon duty cycle and the dominant control of motor speed is duty cycle.

The culminating activity in this lab involves using the robot to navigate a maze. Students are told that theory dictates that if a person is trying to navigate a maze in real life and they can put their right hand on the wall and follow it through then they will eventually reach the exit from the maze. They use this logic to create a program that outputs proper control based upon input from the infrared sensors.

4.1.2 Modeling the EngE 1024 Mechatronics Unit in a Comprehensive Knowledge Map

The comprehensive knowledge map for the mechatronics unit in EngE 1024 is depicted in Figure 4.11. This map was developed by carefully observing the online mechatronics lecture, picking out each concept included in PowerPoint slides and the oral presentation and outlining all concepts that should have been learned through the hands-on gearbox and circuit building activity. The author watched the online lecture video numerous times in order to develop a complete list of every concept and relationship presented. The author has also drawn from his experience in teaching the unit several times in order to include concepts in the map that may

have been presented in the workshop but not explicitly mentioned in the PowerPoint slides. The map shows the various concepts involved in the mechatronics unit and how they are related to one another. As this is a knowledge map, the concepts and relationships are linked to additional information and files such as pictures of the various electrical components and the corresponding schematic symbols.

As was discussed in the previous chapter, comprehensive knowledge maps should ideally be developed iteratively with a panel of experts. This type of collaborative, iterative development is the recommended method to ensure the accuracy and completeness of the maps. Effort was made during the development of the knowledge map to use consist of vocabulary and visual concept illustration. Certainly many words can be used to represent the same relationship, but consistent vocabulary was used to ensure coherence and eliminate ambiguity. Section 4.1.4 discusses the benefits and appropriate use of ontologies and semantic representation of knowledge. The following subsection, 4.1.5, discusses the software that was used to aid the creation of this knowledge map.

4.1.3 Modeling the EngE 1104 Autonomous Vehicles Unit in a Comprehensive Knowledge Map

The comprehensive knowledge map for the mechatronics unit in EngE 1104 is depicted in Figure 4.12. This map was developed in a similar manner to the way the EngE 1024 mechatronics unit map was developed. The map in Figure 4.12 contains all of the concepts and relationships from the mechatronics unit map and new concepts and relationships have been assimilated into the structure to showcase how new knowledge is integrated into previous knowledge using assimilation theory. The map in Figure 4.12 uses yellow to depict new concepts and relationship not previously covered in the EngE 1024 mechatronics unit and orange to represent concepts and relationships that are covered in a new or more advanced way in the autonomous vehicles unit.

4.1.4 Use of Semantics in Knowledge Representation

The use of the World Wide Web and search engines has become ubiquitous since the mid 1990s. Over that time period, search engines have drastically improved in both their accuracy and their speed in locating information. Typically, web pages do not include much information in the html code that is used to design them other than the text and images that will be displayed and how all this information will be presented and linked to any other sites. A transition is being

made, however, to a semantic representation of information so that the content of the information being presented is defined in a universally accepted and standardized way. The language of such semantics is still being pioneered and standardized, but it is becoming more universally adopted. Such semantics help to refine web searches so that search engines can determine what it is their users are looking for and can apply better optimization algorithms to locate the information.

The National Center for Ontological Research defines ontology as shown below. Ontologies establish a common way within a domain to consistently describe various concepts and relationships. This consistency makes it possible for intelligent systems to parse the information and for collaboration with other researchers to provide clear descriptions of common information.

“Ontology is both a branch of philosophy and a fast-growing component of computer science concerned with the development of formal representations of the entities and relations existing in a variety of application domains. Ontology has been shown to have considerable potential on the level of both pure research and applications. It provides foundations for diverse technologies in areas such as information integration, natural language processing, data annotation, and the construction of intelligent computer systems. [70]”

Semantic webs are an ideal parallel to the knowledge map-based system discussed within this research work. Proper application of a universally accepted ontology will allow for a more consistent representation of knowledge that is not only readable by human viewers, but also easily parsed by web crawlers that search engines utilize to gather information. These ontologies contain the standardized vocabulary used within the appropriate discipline and allow relationships and concepts to be explained in a uniform manner. While some concepts are taught in different ways in different parts of the world and under somewhat different vocabulary, the use of ontologies allows all people to communicate the same information content without any ambiguity. The comprehensive knowledge map used within this work utilized consistent vocabulary in order to encapsulate the knowledge from both the mechanical engineering portion and the electrical engineering portion of mechatronics.

4.1.5 Knowledge Map Software

The author developed the comprehensive knowledge maps using the CmapTools software currently available at no charge from the Institute for Human and Machine Cognition (<http://www.cmaptools.com/>). This mapping software provides intuitive utilities to outline

concepts and relationships into concept maps, which the software refers to as cmap. Figure 4.7 depicts how a concept node is created, resized, and labeled appropriately in CmapTools. In CmapTools, double clicking on any portion of the map creates a new, generically sized concept node as depicted on the left of Figure 4.7. Dragging the bottom right corner of the concept node resizes it and double clicking on the concept node allows the user to type in the appropriate textual label. As is shown in Figure 4.8, links to establish relationships between concepts are represented using arrows and can be created easily by clicking and dragging the double arrow above the selected concept node in the desired direction. This process not only creates the relationship link, but also automatically creates a second concept node to complete the relationship structure. CmapTools allows the relationship links (which it refers to as propositions) to be labeled to indicate the appropriate relationship between any two concepts using linking phrases. Any set of words can be used as a linking phrase but some typical linking phrases are words like “is a,” “has,” “is not,” “contains,” etc. Figure 4.9 shows a simple concept map created using this process. All of the concepts and relationships within the mechatronics unit in the EngE 1024 course were mapped in Figure 4.11 using this mapping process and that process was extended to form the map for the EngE 1104 autonomous vehicles unit depicted in Figure 4.12.

CmapTools also allows users to embed knowledge resources within the maps. These embedded files may include appropriate PowerPoint slides from lessons about the topic, multimedia presentations including movies and audio clips, photos, diagrams, pdf documents, and links to relevant web content. Figure 4.10 shows a simple knowledge map created by embedding knowledge resources into a concept map previously similar to the one presented in Figure 4.9. This feature has been utilized to embed relevant knowledge resources within the nodes and links in the comprehensive mechatronics knowledge map depicted in Figure 4.11.

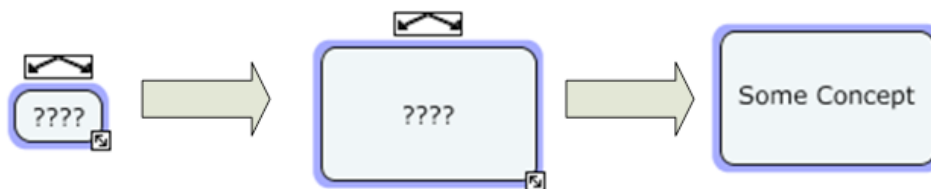


Figure 4.7 Node creation, resizing, and labeling in CmapTools

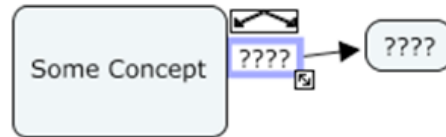


Figure 4.8 Creating linking relationships in CmapTools



Figure 4.9 A simple two-concept cmap created with CmapTools

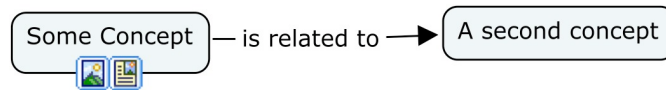


Figure 4.10 A generic knowledge map with an image file and a .pdf file linked to the concept node for “Some Concept”

4.1.6 Representing Concept Maps in an XML schema

The examples presented thus far in this section are of very simple concept maps. The foundation of this research work is the ability to represent large sets of student knowledge data in a graphical manner. The automated generation of maps for each student requires that the maps be represented in a standard and parsable format, particularly when modeling detailed conceptual relationships involving many concept nodes and relationship links. The Institute for Human and Machine Cognition (IHMC) has developed the .cxl XML schema for representing the data in concept maps in an XML format [71]. The use of XML simplifies data parsing and provides for the automatic generation of concept maps necessary for the completion of several objectives of this research work.

Table 4.3 contains the XML code used to represent the knowledge map in Figure 4.10. This is a very simple example of how the .cxl XML schema is used to represent all of the elements included in a very simple concept map. The .cxl schema was also used to represent the entire map for the EngE 1024 mechatronics unit and the EngE 1104 autonomous vehicles unit (albeit with several hundred more lines of XML). Line numbers have been added to Table 4.3 in order to aid the discussion of the file contents. Line 1 contains the standard XML header. Line 2 is the standard opening tag for concept maps and contains links to websites that support the XML schema. Lines 3-30 contain metadata regarding the map such as the title of the map (line 4), the name and contact e-mail address for the creator (lines 5-11). Similar metadata is included for anyone who has contributed to the map (lines 12-18) and the map’s rights holder(s) (lines 19-25).

Line 26 indicates that the map is in English. Line 27 indicates the MIME type of the data for web publishing purposes. Line 28 indicates the version of CmapTools used to create the map. Line 29 specifies the server id, folder id, and resource id used by CmapTools. The heart of the information in the .cxl file begins with the map tag (line 31), which indicates the start of the map data and defines the width and height of the map area. Each of the concept nodes is listed in the concept list (lines 32-35) and each of the linking phrases is listed in the linking phrase list (lines 36-38). Each of the concepts and linking phrases is assigned a unique id so that it can be identified and have properties set appropriately. This map is a very simple map so it only contains 2 concepts (“Some Concept” and “A second concept”) and 1 linking phrase (“is related to”); larger maps would have a much more extensive concept list and linking phrase list. The connection list (lines 39-42) indicates how the concepts and relationships are connected to one another. In the case of this map the first connection (line 40) indicates that the concept “Some Concept” is connected to the linking phrase “is related to” and the second connection (line 41) indicates that the linking phrase “is related to” is connected to the concept “A second concept.” The resource group list (lines 43-50) is used to track the attached knowledge resources. A resource group is associated with a concept or a linking phrase and has a group-type attribute to indicate the type of knowledge resource attached to the map (images, websites, audio, video, other cmaps, etc). In this case there are two different knowledge resources attached to the same concept node, but since the resources are of different types there are two different groups. The resource tag indicates the details of the embedded resource. The concept appearance list (lines 51-54) and the linking phrase appearance list (lines 55-57) define the position and size of each concept and linking phrase. The connection appearance list (lines 59-63) defines the location on each concept and linking phrase where the connection is made from and to as connections can be made to the center (default), top, bottom, left, right, top left, top right, etc. The style sheet list contains additional attributes regarding the appearance of the map, concepts, linking phrases, and connections. Style sheets can be used to specify the default appearance (as is done in lines 65-74) or to specify different styles used throughout the map. The style sheet is used to specify the fonts, colors, and shapes used for concepts and linking phrases, the thickness of lines, and the colors of the various map elements. The style sheet also indicates how arrows should appear for connections. The extra graphical properties list (lines 76-80) is used to specify additional appearance properties in the map and in this case is of no effect.

1	<?xml version="1.0" encoding="UTF-8"?>
2	<cmmap xmlns:dcterms="http://purl.org/dc/terms/" xmlns="http://cmmap.ihmc.us/xml/cmmap/" xmlns:dc="http://purl.org/dc/elements/1.1/" xmlns:vcard="http://www.w3.org/2001/vcard-rdf/3.0#">
3	<res-meta>
4	<dc:title>Generic Knowledge Map</dc:title>
5	<dc:creator>
6	<vcard:FN>Ricky Castles</vcard:FN>
7	<vcard:EMAIL>rcastles@vt.edu</vcard:EMAIL>
8	<vcard:ORG>
9	<vcard:Orgname>Virginia Tech</vcard:Orgname>
10	</vcard:ORG>
11	</dc:creator>
12	<dc:contributor>
13	<vcard:FN>Ricky Castles</vcard:FN>
14	<vcard:EMAIL>rcastles@vt.edu</vcard:EMAIL>
15	<vcard:ORG>
16	<vcard:Orgname>Virginia Tech</vcard:Orgname>
17	</vcard:ORG>
18	</dc:contributor>
19	<dcterms:rightsHolder>
20	<vcard:FN>Ricky Castles</vcard:FN>
21	<vcard:EMAIL>rcastles@vt.edu</vcard:EMAIL>
22	<vcard:ORG>
23	<vcard:Orgname>Virginia Tech</vcard:Orgname>
24	</vcard:ORG>
25	</dcterms:rightsHolder>
26	<dc:language>en</dc:language>
27	<dc:format>x-cmap/x-storable</dc:format>
28	<dc:publisher>FIHMC CmapTools 5.03 </dc:publisher>
29	<dc:source>cmmap:1205629459203_1949154945_0:1205629462030_552952403_28:1GTFTVS04-1DS3MHB-6D</dc:source>
30	</res-meta>
31	<map width="1002" height="1002">
32	<concept-list>
33	<concept id="1GTFTX8KC-19VH43T-7G" label="A second concept"/>
34	<concept id="1GTFTWV3X-1V61ZKK-6M" label="Some Concept"/>
35	</concept-list>
36	<linking-phrase-list>
37	<linking-phrase id="1GTFTX8L2-15H1SHW-7K" label="is related to"/>
38	</linking-phrase-list>
39	<connection-list>
40	<connection id="1GTFTX8L7-23L9C0K-7P" from-id="1GTFTWV3X-1V61ZKK-6M" to-id="1GTFTX8L2-15H1SHW-7K"/>
41	<connection id="1GTFTX8L8-DDCSTV-7W" from-id="1GTFTX8L2-15H1SHW-7K" to-id="1GTFTX8KC-19VH43T-7G"/>
42	</connection-list>
43	<resource-group-list>
44	<resource-group parent-id="1GTFTWV3X-1V61ZKK-6M" group-type="text-and-image">

45	<pre> <resource id="1GTFV0W50-26XDTG9-9C" label="An Adaptive User Interface Based on Personalized Learning" description="" resource-name="An Adaptive User Interface Based on Personalized Learning" resource-mimetype="application/pdf" resource-server-id="1205629459203_1949154945_0" resource-folder-id="1205629462030_552952403_28" resource-id="1223013683486_1667964112_1889" resource-url="UNKNOWN"/> </pre>
46	<pre></resource-group></pre>
47	<pre><resource-group parent-id="1GTFTWV3X-1V61ZKK-6M" group-type="image"></pre>
48	<pre> <resource id="1GTFV4F2R-784W1Z-C0" label="Picture 1" description="" resource-name="Picture 1" resource-mimetype="image/x-png" resource-server-id="1205629459203_1949154945_0" resource-folder-id="1205629462030_552952403_28" resource-id="1GTFV4C4M-1XC54JB-9G" resource-url="UNKNOWN"/> </pre>
49	<pre></resource-group></pre>
50	<pre></resource-group-list></pre>
51	<pre><concept-appearance-list></pre>
52	<pre><concept-appearance id="1GTFTX8KC-19VH43T-7G" x="368" y="133" width="121" height="28"/></pre>
53	<pre><concept-appearance id="1GTFTWV3X-1V61ZKK-6M" x="133" y="136" width="103" height="41"/></pre>
54	<pre></concept-appearance-list></pre>
55	<pre><linking-phrase-appearance-list></pre>
56	<pre><linking-phrase-appearance id="1GTFTX8L2-15H1SHW-7K" x="238" y="136" width="74" height="11"/></pre>
57	<pre></linking-phrase-appearance-list></pre>
59	<pre><connection-appearance-list></pre>
61	<pre><connection-appearance id="1GTFTX8L7-23L9C0K-7P" from-pos="center" to- pos="center"/></pre>
62	<pre><connection-appearance id="1GTFTX8L8-DDCSTV-7W" from-pos="center" to- pos="center"/></pre>
63	<pre></connection-appearance-list></pre>
64	<pre><style-sheet-list></pre>
65	<pre><style-sheet id=" Default "></pre>
66	<pre><map-style background-color="255,255,255,0" image-style="full" image-top- left="0,0"/></pre>
67	<pre><concept-style font-name="Verdana" font-size="12" font-style="plain" font- color="0,0,0,255" text-margin="4" background-color="237,244,246,255" background- image-style="full" border-color="0,0,0,255" border-style="solid" border-thickness="1" border-shape="rounded-rectangle" text-alignment="center" shadow-color="none"/></pre>
68	<pre><linking-phrase-style font-name="Verdana" font-size="12" font-style="plain" font- color="0,0,0,255" text-margin="1" background-color="0,0,255,0" background-image- style="full" border-color="0,0,0,0" border-style="solid" border-thickness="1" border- shape="rectangle" text-alignment="center" shadow-color="none"/></pre>
72	<pre><connection-style color="0,0,0,255" style="solid" thickness="1" type="straight" arrowhead="if-to-concept-and-slopes-up"/></pre>
73	<pre><resource-style font-name="SanSerif" font-size="12" font-style="plain" font- color="0,0,0,255" background-color="192,192,192,255"/></pre>
74	<pre></style-sheet></pre>
75	<pre></style-sheet-list></pre>

76	<extra-graphical-properties-list>
77	<properties-list id="1GTFTVS04-1DS3MHB-6D">
78	<property key="StyleSheetGroup_0" value="//*@!#\$%%^&*() No Grouped StyleSheets @"/>
79	</properties-list>
80	</extra-graphical-properties-list>
81	</map>
82	</cmap>

Table 4.3 The XML code in the .cxl file corresponding to the simple knowledge map depicted in Figure 4.10

4.1.7 Fully Developed Unit Comprehensive Concept Maps

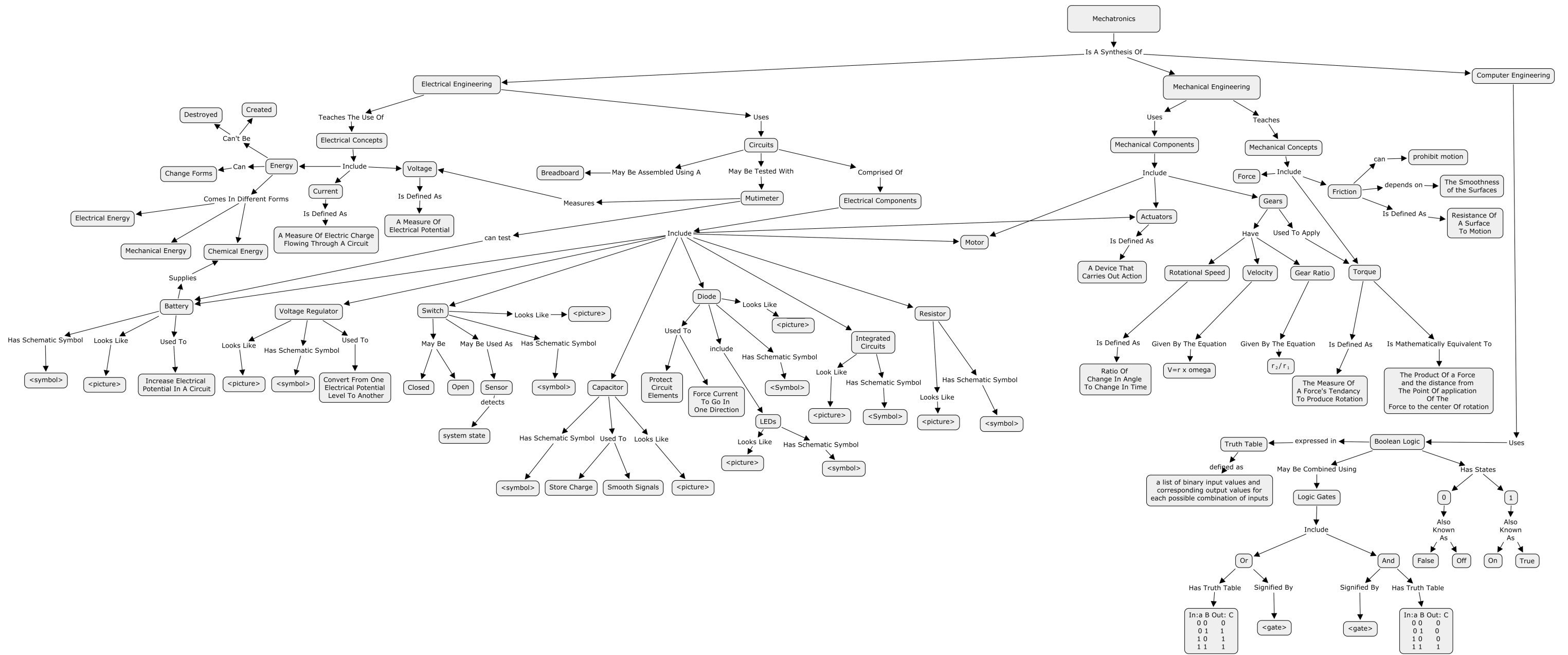


Figure 4.11 EngE 1024 Mechatronics Learning Module Knowledge Map

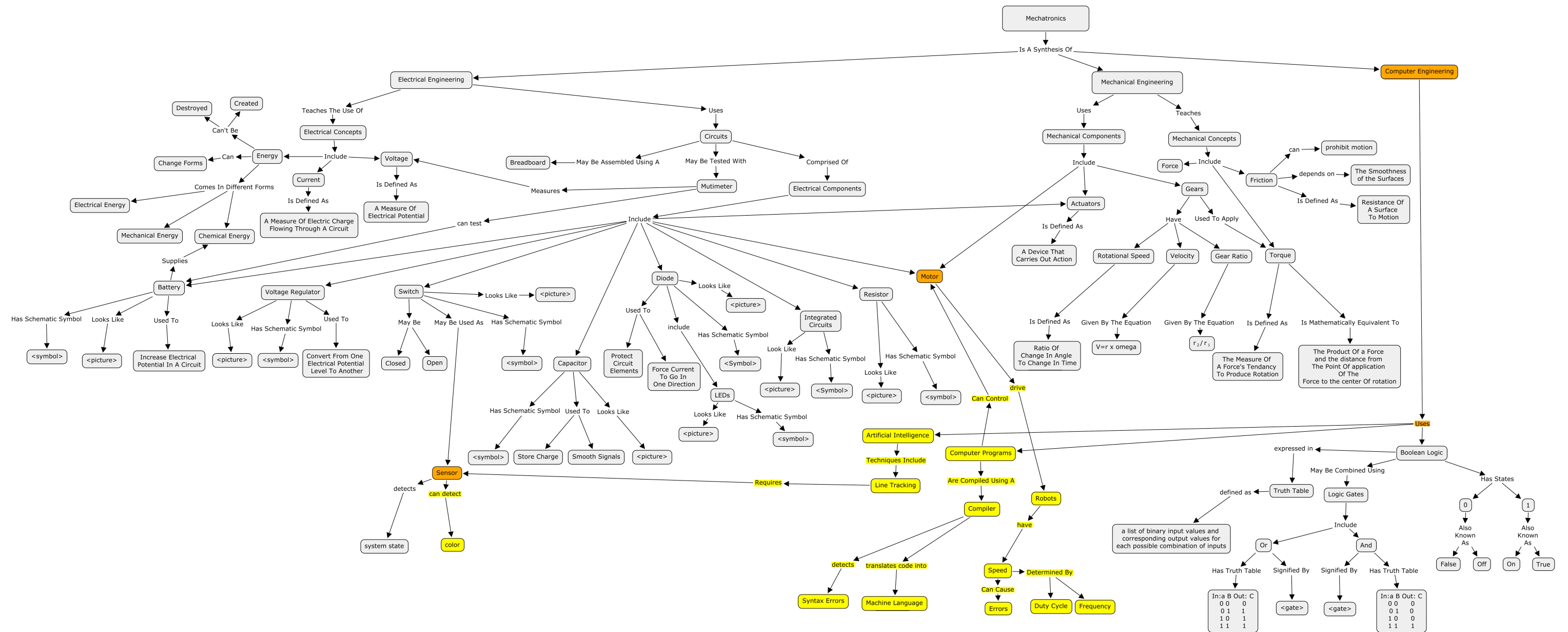


Figure 4.12 EngE 1104 Autonomous Vehicle Learning Module Knowledge Map. Yellow is used to indicate new concepts and relationships not present in the EngE 1024 mechatronics comprehensive knowledge map and orange is used to represent concepts in the EngE 1024 mechatronics comprehensive knowledge map addressed by Autonomous Vehicle Learning Module at a higher level of Bloom's taxonomy.

4.2 Developing a Concept Inventory for Mechatronics

As was discussed in chapter 2, many concept inventories have already been developed and many others are currently under development. The utilization of an applicable existing concept inventory, or the development of a new concept inventory, corresponding with the knowledge encapsulated in the comprehensive knowledge map is important within the proposed assessment strategy framework in order to determine what students have learned. While formalized concept inventories typically cover expansive sets of topics in a discipline, more focused concept inventories may also be developed in order to assess students' knowledge of each unit in a course.

It would be impossible for one person to develop a concept inventory for every subject. Formalized concept inventories are typically developed over several years and involve contributions from multiple researchers as well as formal and informal studies. Most instructors and researchers who will utilize the techniques presented in this dissertation work will have expertise in one or more fields. The work done as part of this dissertation outlines one method for the development of a concept inventory, which can serve as a foundation for the development of future concept inventories. This method, however, is not meant to be an exclusive method for such development as experts have been performing such work in a variety of ways for years. The following subsections discuss the development of the concept inventory used to assess students' knowledge of the contents of the EngE 1024 mechatronics unit and an additional concept inventory designed to assess the knowledge of students in the EngE 1104 autonomous vehicle unit. A strategy for representing concept inventories in an XML format is also discussed so that the results from the inventory can be autonomously processed.

4.2.1 EngE 1024 Mechatronics Unit Concept Inventory Development

As was previously mentioned, concept inventories are multiple-choice tests, which evaluate a person's understanding of the concepts underlying a discipline. The crafting of questions and answers to a concept inventory requires a very important attention to detail so that each important concept is included, but not overcomplicated with confounding details such as in-depth calculations. The author iteratively developed a mechatronics concept inventory based on the mechatronics unit in EngE 1024, discussed in section 4.1.1.2. This concept inventory was developed by carefully studying the information about mechatronics that is presented in lectures,

hands-on exercises, and homework assignments. This was done in very much the same manner as was done in the development of the concept map discussed in 4.1.2. Many concepts from electrical engineering, mechanical engineering, and computer engineering are covered in this unit including torque, gear ratio, voltage, current, voltage regulation, resistance, Boolean logic, and motor control which are taught using both the online lecture and hands-on activity discussed in section 4.1.1.2. The concept inventory developed as part of this research work is a set of questions that addresses at the conceptual level each of the topics in the unit. Similar work was done based upon the course unit presented in 4.1.1.4 in order to study some more advanced knowledge of mechatronics that students gain through their second semester of engineering study. The concept inventory deployed to students in EngE 1104 also included the same questions as the final inventory for the EngE 1024 mechatronics unit in order to determine how much information students retained from one semester to the next.

Clearly there are two important parts of the concept inventory: the questions and the answers. A diverse question set should be included so as to test all aspects of the discipline. One of the most difficult parts of the development of concept inventories is the development of the available answers to select from. Obviously the correct answer must be in the answer pool, but the incorrect answer choices should not be simply chosen at random, but rather reflexive of common student misconceptions. As such, the development of an appropriate concept inventory spanned several semesters in order to test various questions and to determine, based upon student input, the common misconceptions that students have about material in the unit.

The preliminary set of questions in Table 4.4 was developed as a rough first draft of the concept inventory for the EngE 1024 mechatronics unit and was deployed to students enrolled in EngE 1024 in the Spring 2008 semester prior to their participation in the mechatronics unit in order to assess their prior knowledge of mechatronics concepts. During the administration of this pilot assessment, the multiple-choice answers for most questions were not provided. The only questions that had multiple-choice answers provided were #6 and #7 because only a few options could be selected. These questions still provided an “other” option, which allowed students to fill in the details of what they believed should be the proper answer to the question if they didn’t believe the appropriate answer was given. By forcing students to give a free response answer rather than selecting from a list of choices, the responses from students are less biased toward the way the author of the inventory thought the problem should or may be answered and students are

free to answer the questions in a manner that reflects their own level of understanding. The most commonly observed incorrect responses observed during this pilot became the incorrect answer options in the finalized concept inventory and the wording used in correct responses was also used for the correct answers. This methodology of refinement should serve as a paradigm for similar development in multiple disciplines.

A total of 108 students answered the questions in this preliminary inventory. Their answers were compiled to develop a revised and improved concept inventory. One mistake was made in the wording of the inventory in Table 4.4 in that question 7 should describe the smaller gear as having “less teeth and a smaller radius” rather than “less teeth and a larger radius”. This mistake was realized after the survey was deployed so no editing was done until the data was collected. To illustrate how iterative the concept inventory development process is, the revised concept inventory in Table 4.5 was developed and delivered to students enrolled in EngE 1024 in

<ol style="list-style-type: none">1. What is potential energy?2. What is kinetic energy?3. What is a gear and what are gears used for?4. What is friction?5. What is torque?6. Suppose you need to remove a nut from a device using a wrench. Which of the following would allow you to use to be able to use less force while still removing the nut?<ol style="list-style-type: none">a. A shorter wrench handleb. A longer wrench handlec. The wrench handle length does not matterd. It can't be determined based on the information givene. Other7. If a big gear (gear with larger radius and more teeth) is used to drive a small gear (gear with less teeth and a larger radius), which gear will have the greater angular speed?<ol style="list-style-type: none">a. The big gearb. The smaller gearc. Both will have the same angular speedd. It cannot be determine with the information givene. Other8. What is an actuator?9. What is feedback?10. What is Boolean logic?11. What does it mean to connect components in series?12. What does it mean to connect components in parallel?13. What happens in a circuit if a complete path/closed loop does not exist?
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Table 4.4 The questions deployed in the pilot concept inventory in Spring 2008

Summer 2008. This revised concept inventory includes the above questions with the needed revision and asks students to describe the function and behavior of the various components used in the hands-on robot-building exercise. Questions 14 and 15 were also added to evaluate student understanding of two concepts that are part of the mechatronics unit, but were previously not included in the concept inventory. The summer deployment of the inventory also included a deployment of both a pre and post inventory so students were asked the questions in the survey before they saw any of the material in the mechatronics unit and then they were surveyed again after the mechatronics unit had ended. This method of pre and post surveying allows instructors to determine the baseline knowledge students came into the course unit with and allows them to see what knowledge gains have occurred through student participation in the course unit. The questions in Table 4.5 are the ones deployed in the post-unit assessment. The only difference between the pre and post-unit assessment was that question 18 was not included in the pre-unit assessment because the students needed exposure to the hands-on portion of the unit in order to answer that question.

1. What is potential energy?
2. What is kinetic energy?
3. What is a gear and what are gears used for?
4. What is friction?
5. What is torque?
6. Suppose you need to remove a nut from a device using a wrench. Which of the following would allow you to use to be able to use less force while still removing the nut?
 - a. A shorter wrench handle
 - b. A longer wrench handle
 - c. The wrench handle length does not matter
 - d. It can't be determined based on the information given
 - e. Other
7. If a big gear (gear with larger radius and more teeth) is used to drive a small gear (gear with less teeth and a **smaller** radius), which gear will have the greater angular speed?
 - a. The big gear
 - b. The smaller gear
 - c. Both will have the same angular speed
 - d. It cannot be determine with the information given
 - e. I don't know
 - f. Other
8. What is an actuator?
9. What is feedback?
10. What is Boolean logic?
11. What does it mean to connect components in series?
12. What does it mean to connect components in parallel?

13. What happens in a circuit if a complete path/closed loop does not exist?
- 14. What is current?**
- 15. What is voltage?**
- 16. On a scale of 0 to 5 rate your familiarity with and understanding of each of the following electrical components where 0 indicates that you have never heard of the component before and 5 indicates a very strong understanding of what the component is and how it works.**
 - a. Battery
 - b. Capacitor
 - c. Diode
 - d. Motor
 - e. Power supply
 - f. Sensor
 - g. Switch
 - h. Voltage regulator
- 17. Describe the function and behavior of each of the following electrical components**
 - a. Battery
 - b. Capacitor
 - c. Diode
 - d. Motor
 - e. Power supply
 - f. Sensor
 - g. Switch
 - h. Voltage regulator
 - i. Breadboard
- 18. What was the purpose of the gearbox in the robot you built?**

Table 4.5 The questions deployed in Revision 1 of the mechatronics concept inventory in Summer 2008. Bold face type indicates content added or modified from the inventory deployed in Spring 2008.

Table 4.6 lists some examples of the student responses to the free response questions in the draft concept inventory deployed in Spring 2008. Some of these answers were used to develop multiple-choice answers in the full concept inventory depicted in Table 4.7. It is important to note that these answers were given by students prior to participation in the mechatronics unit, so these responses are representative of some of the prior knowledge the students have and not based upon what they had learned through the course unit.

<p>1. What is potential energy?</p> <ul style="list-style-type: none"> • “Energy itself in any form which can convert to any other types of energy” • “The amount of energy that an object has potential to reach” • “Energy the object will have before performing an action” • “Stored energy” • “The energy stored in an object at rest” • “Not moving energy” • “PE=mgh” • “Stored energy”
<p>2. What is kinetic energy?</p> <ul style="list-style-type: none"> • “moving energy” • “energy of motion” • “expended energy” • “energy being used” • “movement” • “the energy possessed by a body because of its motion, equal to one half the mass of the body times the square of its speed”
<p>3. What is a gear and what are gears used for?</p> <ul style="list-style-type: none"> • “A gear is a flat, circular metal object that has teeth around the edges of it, used to turn objects within something in order to transfer energy” • “A toothed wheel that turns to engage another toothed wheel in order to change the speed/direction of motion.” • “gears are sprocket looking things that run a machine” • “A gear is a part of a machine, it's used to regulate rotational motion. Gears control the ratio between rotational velocity and torque, a big gear spinning a small gear will create more velocity and less torque, a small gear spinning a big gear will result in less velocity and more torque.” • “A mode of transmitting energy using a round object with grooves.”
<p>4. What is friction?</p> <ul style="list-style-type: none"> • “force opposing motion” • “resistance from surface tension” • “what slows down objects” • “Friction is a force of resistance between two surfaces against kinetic motion or a force acting to move these surfaces across each other; surfaces that are smoother typically have less friction, as this force acts on the molecular level.” • “resistant force” • “Friction is a force that opposes motion. It is what air resistance is, where it depends on multiple factors, such as speed and surface area present to the direction of motion, in addition to the general flow of the air, dependent on its shape, but on the ground, friction depends on the coefficient of static/kinetic friction between the surface and object and the normal force the surface is exerting on the object. Static friction is used when the object is not sliding across the surface, while kinetic friction is used when it is.”

5. What is torque?

- “the force and energy used to make something spin”
- “ $r \times f$ ”
- “the amount of circular energy that is applied to an object”
- “the force that is caused when something spins”
- “used in cars...pushes you back in your seat when you take off”
- “Torque is the rotational pull. It is composed of a "lever arm" and "line of action", with the lever arm being the closest distance from the center of mass along the "line of action", or the direction the force is being applied in, along with the position of the force's line. You multiply the lever arm by the force in the tangential direction, or perpendicular to the lever arm to get torque in a basic problem.”

8. What is an actuator?

- “like an arm that is powered by an energy source to move an object”
- “I know the actuator in my car door broke and I could no longer lock my doors effectively. I fixed it by replacing it, and I'm guessing it acts similar to a switch by allowing a button to transfer a current through all the door locks.”
- “An electrical device that moves an object.”
- “a device which transfers electrical energy into work.”
- “restricts the flow of current to one direction, as not to allow reverse current backwards”

9. What is feedback?

- “a ringing sound that is picked up through a speaker when something in the sound settings are not right”
- “when output becomes input, and then effects output”
- “information you get back from a device. Such as a robot programmed to move with a wireless control stick. The transmitter in the robot will send feedback to the control to allow the person moving the robot to see what's going on.”
- “The signal that results from two or more opposing signals interfering.”

10. What is Boolean logic?

- “using if then statements?”
- “if, and, or, not, equals, etc.”
- “I have heard of Boolean operators, like "if", "and", "or", and "not". They are used to narrow searches and receive more in-depth hits.”
- “boolean logic is when you use true/false in something like a program”
- “A chain of true false conditions represented by "0" for false, "1" for true”
- “and, or,not and,... it's used in logic gates and switches within binary systems”
- “two states: 1 0
- AND is 1 if both inputs are 1
- OR is 1 if either input is 1”

<p>11. What does it mean to connect components in series?</p> <ul style="list-style-type: none"> • “the components come one after another in a line” • “To link them together so that they work with one another” • “Current or fluid travels through one component, then the next, then the next, and so forth.” • “Electricity is sent to a component and then to the next component in the system.” • “to connect them such that the same pathway supplies current to all components” • “They are in a straight line. If one fails, they all do.”
<p>12. What does it mean to connect components in parallel?</p> <ul style="list-style-type: none"> • “it's sort of like looping a circuit. The circuit, when drawn, looks a bit like a ladder. The rungs of the ladder would be where the light or whatever component you're connecting would be” • “separate wires for each component” • “connecting components such that path of the current is split into multiple paths. The components are next to each other instead of being one after another.” • “components are connected but not in line. if one component fails, it doesn't affect the other components.”
<p>13. What happens in a circuit if a complete path/closed loop does not exist?</p> <ul style="list-style-type: none"> • “Electricity does not flow.” • “the energy and current cannot move and blocks up at the unconnected end” • “short circuit” • “Circuit is not complete and can't function correctly.” • “energy wont be conserved. it will be given off in some other form outside the circuit” • “lights up only until the break”

Table 4.6 Some student responses to the draft mechatronics concept inventory deployed in Spring 2008

The questions used in the draft concept inventories were very open-ended and were designed to elicit common student understanding and misconception regarding the concepts in the mechatronics unit. The final version of the concept inventory along with the available answer choices is shown in Table 4.7. In the finalized concept inventory, the comprehensive map was more carefully considered when developing appropriate questions and several questions in the draft inventory were either expanded into multiple questions or eliminated. Some topics in the draft concept inventory were not explicitly covered in the mechatronics unit and were eliminated from the inventory. The concept of feedback was not covered explicitly within the unit nor was the notion of connecting electrical components in parallel or series. In addition to the questions presented in the table, students were asked to provide the name of their workshop instructor and the time their workshop met, and their gender. For IRB purposes they were asked if they were at least 18 years of age as of the time they took the concept inventory and if they wanted their data to not be included in the data analysis done as part of this research work.

Question 1 was designed to make sure students understand the integration of theory and practice from a variety of fields. Several electrical concepts were introduced such as voltage, current, and energy. Questions 2 and 3 are designed to test student understanding of the definitions of current and voltage as some people mistake one for the other. The distracter answers here were based off of some responses to questions in the draft inventory; many students erroneously believe that voltage and power are synonymous. A significant portion of the online lecture focuses on the different forms of energy and how energy can be transformed from one form to another. Question 4 is designed to evaluate student understanding of energy and specifically the energy stored in the batteries they used in the lab exercise. The online lecture and corresponding homework assignment introduced several mechanical concepts including torque and friction and how gears can be used to overcome limitations imposed by friction. Questions 5 through 15 were designed to test students understanding of mechanical concepts and mathematical relationships related to the use of gears. Some of these concepts were introduced in the online lecture and others the students experienced in the lab. When beginning analysis of the data it was determined that questions 11 and 14 were redundant. Question 12 was designed to test students' understanding of Newton's third law and could have been worded a bit more specifically in order to reduce ambiguity. This question was slightly revised when the concept inventory was presented to EngE 1104 students in Spring 2009. A portion of the online lecture discussed how to control motors so that various types of motion could be achieved. Question 16 is designed to elicit students' understanding of the physical relationship between the motions of the onboard motors and how that applies to the motion of the overall robot. Questions 17 and 18 are designed to elicit fundamental student understanding of two basic elements of most robots, sensors and actuators and to see if students understood an example in the lecture of how a switch could be used as a sensor in a circuit. Questions 20-22 were designed to test understanding of some of the basic computer engineering concepts that were introduced in the lecture including Boolean logic. These questions make reference to some illustrations that were given to students in a supplemental .pdf file because the online survey tool used to collect data from the students did not support the use of embedded images with the questions. The four figures in the supplemental file are included in Appendix B: Supplemental File for Concept Inventory. Figure 1 on the supplemental file depicts a logical AND and a logical OR gate. Figure 2 on the supplemental file presents the truth tables for a logical AND gate and a logical OR gate. A

mistake was made when preparing questions 21 and 22 in that the last answer choice should have read “Has the truth table on the right hand side of figure 2,” and thus one of the correct answers for question 21 is missing and there are two redundant correct answers for question 22. Questions 23-28 were designed to evaluate student understanding of the functionality of various electrical tools and components used in the lab. Questions 29-36 can be thought of as a single question designed to evaluate students’ ability to identify electrical components. These questions refer to pictures presented in Figure 3 of the supplemental file. Questions 37-44 are designed to test students’ identification of the proper schematic symbols for each of the electrical components. The corresponding symbols are presented in Figure 4 of the supplemental file. In Table 4.7 diamonds (◆) are used to identify correct answers and dots (•) are used to identify distracters. Several questions have multiple correct answers that are designed to elicit multiple levels of understanding of various concepts. In addition to the possible answer choices listed, each question gave students the option to answer “I don’t know” so they could readily admit that they did not understand a concept and were not forced to guess.

<p>1. Mechatronics includes concepts from which of the following disciplines? (check all that apply)</p> <ul style="list-style-type: none"> • Aerospace Engineering • Biological Systems Engineering ◆ Computer Engineering ◆ Electrical Engineering • Materials Science Engineering ◆ Mechanical Engineering
<p>2. Electric current is defined as:</p> <ul style="list-style-type: none"> • A measure of electrical potential ◆ A measure of electrical charge moving through a circuit over time • The number of electrons stored in each component
<p>3. Electric voltage is defined as:</p> <ul style="list-style-type: none"> ◆ A measure of electrical potential • A measure of electrical charge moving through a circuit over time • Electrical Power
<p>4. Which of the following is true about energy (check all that apply):</p> <ul style="list-style-type: none"> • An alkaline battery like you used in workshop is a renewable source of energy ◆ Chemical energy is stored in a battery • Energy can be created ◆ Energy can be converted from one form to another • There is only one form of energy

<p>5. Which of the following is true about torque (check all that apply):</p> <ul style="list-style-type: none"> ◆ It is defined as the measure of a force's tendency to produce rotation ◆ It is given by the product of the magnitude of an applied force and the perpendicular distance between where that force is applied and the axis of rotation • Does not exist unless an object rotates ◆ Is equivalent to the output power in a revolving gear
<p>6. Which of the following is true about friction</p> <ul style="list-style-type: none"> ◆ It is a resistance to motion ◆ It exists when two surfaces rub against one another • Only exists on rough surfaces ◆ Depends on the smoothness (or roughness) of a surface ◆ Under some circumstances it can prohibit or limit motion
<p>7. If a gear takes one complete clockwise rotation around its axis of rotation, which of the following is true:</p> <ul style="list-style-type: none"> ◆ A tooth on that gear travels a distance equal to the circumference of the gear ◆ If the time for that rotation is T seconds, then the average angular speed of the gear is $2\pi/T$ radians/s • If the gear is used to turn another gear (in direct contact) then both gears will move clockwise ◆ If the gear is used to turn another gear (in direct contact) then the other gear will turn counter-clockwise
<p>8. If one gear is used to drive another gear and the two gears have a different radius, which gear will have the greater angular velocity if they turn without slipping:</p> <ul style="list-style-type: none"> • The bigger gear will have the greater angular speed ◆ The smaller gear will have the greater angular speed • Both gears will have the same angular speed
<p>9. Fill in the blank: Considering two gears with an input gear driving an output gear directly without slip, the angular speed of a gear is _____ proportional to the radius of that same gear.</p> <ul style="list-style-type: none"> • directly ◆ inversely • not
<p>10. True or false: The linear velocity of the teeth of two gears in contact with one another is the same at the point where the two gears meet.</p> <ul style="list-style-type: none"> ◆ True • False
<p>11. The linear speed of a tooth on a gear is given by:</p> <ul style="list-style-type: none"> • The product of the torque applied to the gear and the angular velocity • The ratio of the angular speed to the radius of the gear ◆ The product of the angular speed and the radius of the gear
<p>12. A big gear exerts _____ magnitude force on a smaller gear that it is turning.</p> <ul style="list-style-type: none"> • a greater • a lesser ◆ the same

<p>13. True or False: The two-wheeled robot you built in workshop could have successfully driven the wheels by connecting them directly to the motors without the gearbox.</p> <ul style="list-style-type: none"> • True ◆ False
<p>14. The linear velocity of any point on a gear is given by:</p> <ul style="list-style-type: none"> ◆ The product of the radius and the angular velocity • The quotient of the angular velocity and the radius • The product of the square of the radius and the angular velocity
<p>15. The input power of a gear is:</p> <ul style="list-style-type: none"> ◆ Given by the product of the torque on that gear and the angular velocity of that gear • Less than the output power of the gear it is driving ◆ The same as the output power of that gear • More than the output power of the gear it is driving
<p>16. If a two-wheeled robot has one wheel moving faster in a forward direction than the other wheel (which is also moving forward) then the robot will</p> <ul style="list-style-type: none"> • Turn towards the same side as the faster moving wheel ◆ Turn towards the side of the slower moving wheel
<p>17. Actuators: (check all that apply)</p> <ul style="list-style-type: none"> • Are purely mechanical devices • Are purely electrical devices ◆ Are electromechanical devices ◆ Receive electrical signals and perform a mechanical action as a result • Are control boxes used to drive other devices
<p>18. Sensors: (check all that apply)</p> <ul style="list-style-type: none"> ◆ Detect the current state of the system • Always directly control actuators ◆ Can be made out of switches • Let a user know if a circuit is on or not
<p>19. Boolean logic: (check all that apply)</p> <ul style="list-style-type: none"> • Has three states ◆ Has two states ◆ Allows one to represent true or false data ◆ Takes on the states of “on” or “off” ◆ Takes on the states “1” and “0”
<p>20. A truth table is: (check all that apply)</p> <ul style="list-style-type: none"> • A listing of axioms that show the true way to solve a problem ◆ A list of binary input values and the corresponding output for each possible combination of inputs • A list of all true facts known about how to solve a particular problem • A table showing all the people in the world who truly know how to build circuits.

<p>21. Which of the following is/are true about AND gates: (check all that apply)</p> <ul style="list-style-type: none"> • Takes in 1 binary or boolean input ◆ Takes in 2 binary or boolean inputs • Outputs 2 binary or boolean outputs ◆ Outputs 1 binary or boolean output ◆ Has the symbol on the left hand side of figure 1 • Has the symbol on the right hand side of figure 1 • Has the truth table on the left hand side of figure 2 • Has the truth table on the left hand side of figure 2*
<p>22. Which of the following is/are true about OR gates? (check all that apply)</p> <ul style="list-style-type: none"> • Takes in 1 binary or boolean input ◆ Takes in 2 binary or boolean inputs • Outputs 2 binary or boolean outputs ◆ Outputs 1 binary or boolean output • Has the symbol on the left hand side of figure 1 ◆ Has the symbol on the right hand side of figure 1 ◆ Has the truth table on the left hand side of figure 2 ◆ Has the truth table on the left hand side of figure 2*
<p>23. What is the purpose of a 7805 voltage regulator?</p> <ul style="list-style-type: none"> • Outputs a programmable voltage level ◆ Outputs a fixed 5 volt voltage given an input of any DC voltage greater than or equal to 5 volts in potential • Outputs a fixed 9V output to compensate for batteries that are running out of power • Divides the incoming voltage in half regardless of what the input voltage is
<p>24. Which of the following is true about diodes? (check all that apply)</p> <ul style="list-style-type: none"> ◆ It only allows current to travel in one direction through a circuit ◆ It can protect circuit components • It always lights up when it is activated • It changes the direction of current, so if current was going to go one way, it switches direction when it reaches a diode.
<p>25. What does a multimeter do?</p> <ul style="list-style-type: none"> ◆ It measures the electrical potential at different points in a circuit relative to some reference voltage. • Lights up when it discovers someone wired a circuit incorrectly ◆ Can be used to know when a battery is too far drained to be useful ◆ Helps electrical engineers check to make sure their circuit is operating correctly • Checks the speed of the motors to make sure it is fast enough
<p>26. What does a switch do?</p> <ul style="list-style-type: none"> • Slows down the speed of the motors in the gearbox ◆ Opens or closes a path in a circuit • Changes the direction current flows in • Stores charge
<p>27. What is a breadboard?</p> <ul style="list-style-type: none"> • a part of an integrated circuit where the transistors are stores • a special type of wood used to build electronic components ◆ a device that allows one to rapidly build circuits without needing to solder components

<p>28. What does a capacitor do? (check all that apply)</p> <ul style="list-style-type: none"> ◆ stores charge • forces current to travel in only one direction • establishes a maximum voltage ◆ smoothes the output from a voltage regulator to maintain reliability
<p>29. Referring to Figure 3, which of the following is the capacitor?</p> <p>◆ A • B • C • D • E • F • G • H</p>
<p>30. Referring to Figure 3, which of the following is the switch?</p> <p>• A • B • C • D • E ◆ F • G • H</p>
<p>31. Referring to Figure 3, which of the following is the resistor?</p> <p>• A • B • C • D ◆ E • F • G • H</p>
<p>32. Referring to Figure 3, which of the following is an integrated circuit?</p> <p>• A ◆ B • C • D • E • F • G • H</p>
<p>33. Referring to Figure 3, which of the following is an LED?</p> <p>• A • B • C • D • E • F • G ◆ H</p>
<p>34. Referring to Figure 3, which of the following is the battery?</p> <p>• A • B ◆ C • D • E • F • G • H</p>
<p>35. Referring to Figure 3, which of the following is the voltage regulator?</p> <p>• A • B • C ◆ D • E • F • G • H</p>
<p>36. Referring to Figure 3, which of the following is a diode (but not an LED)?</p> <p>• A • B • C • D • E • F ◆ G • H</p>
<p>37. Referring to Figure 4, which of the following symbols represents a diode (but not an LED)?</p> <p>• A • B • C ◆ D • E • F • G • H</p>
<p>38. Referring to Figure 4, which of the following symbols represents an integrated circuit?</p> <p>• A • B ◆ C • D • E • F • G • H</p>
<p>39. Referring to Figure 4, which of the following symbols represents a voltage regulator?</p> <p>• A • B • C • D • E ◆ F • G • H</p>
<p>40. Referring to Figure 4, which of the following symbols represents a battery?</p> <p>◆ A • B • C • D • E • F • G • H</p>
<p>41. Referring to Figure 4, which of the following symbols represents a resistor?</p> <p>• A • B • C • D • E • F • G ◆ H</p>
<p>42. Referring to Figure 4, which of the following symbols represents an LED?</p> <p>• A ◆ B • C • D • E • F • G • H</p>
<p>43. Referring to Figure 4, which of the following symbols represents a switch?</p> <p>• A • B • C • D • E • F ◆ G • H</p>
<p>44. Referring to Figure 4, which of the following symbols represents a capacitor?</p> <p>• A • B • C • D ◆ E • F • G • H</p>

Table 4.7 EngE 1024 Full Mechatronics Concept Inventory

4.2.2 EngE 1104 Autonomous Vehicle Unit Concept Inventory Development

A concept inventory was developed using a similar method in order to collect data from students in the EngE 1104 course. EngE 1024 is a prerequisite for EngE 1104 so all of the students enrolled in EngE 1104 have previously participated in the EngE 1024 mechatronics initiative. This concept inventory included questions designed to assess student learning of the concepts in the autonomous vehicle unit and also included all of the questions in the full mechatronics concept inventory listed in Table 4.7 in order to determine what mechatronics information the students retained several months after participating in the mechatronics unit. A few of the questions from the mechatronics inventory were slightly modified in order to address some of the concerns found in the wording of the mechatronics concept inventory, but it was largely unchanged. The concept inventory for this unit was not developed using the multiple iteration method with free response questions but was only given with multiple-choice answers provided. This inventory was given in a pretest and posttest manner with students taking the full inventory before participating in the autonomous vehicle unit in order to determine the information they retained from the EngE 1024 mechatronics unit and to determine their prior knowledge of the concepts introduced in the autonomous vehicle unit. After students participated in the autonomous vehicle unit they took the concept inventory again, but the posttest only included the questions relevant to the material covered in the autonomous vehicle unit. The ten questions and answers developed for the autonomous vehicle unit are listed in Table 4.8. As was done with the previous inventory, diamonds (◆) are used to identify correct answers and dots (•) are used to identify distracters.

1. Assume you have a robot designed to track a line on a track using sensors. These sensors let you know if they are above a line or not. If you are programming a robot to follow a line and your program has determined that the left sensor is on the line and the right sensor is not, you should:

- ◆ Make the robot turn to the left
- Make the robot turn to the right
- Make the robot go straight ahead

2. Which of the following happens when you compile and build a program?

- ◆ The compiler checks for any errors in the syntax of your code
- ◆ The compiler translates your code from a programming language to machine language
- The compiler determines if you have errors in your logic
- The compiler makes sure the program behaves the way you expect it to

3. Assume you have a two-wheeled robot with wheels on the left and right. How can you make a two-wheeled robot spin clockwise in place? (check all that apply)

- Stop both motors
- Stop the left motor and turn on the right motor in the forward direction
- Stop the left motor and turn on the right motor in the reverse direction
- Turn on the left motor in the reverse direction and turn on the right motor in the forward direction
- Turn on the left motor in the reverse direction and stop the right motor
- Turn on both motors in the reverse direction
- Turn on the left motor in the forward direction and stop the right motor
- ◆ Turn on the left motor in the forward direction and turn on the right motor in the reverse direction
- Turn on both motors in the forward direction

4. When working with a robot, to accomplish a task quickly it is always better to increase the speed of the robot

- True
- ◆ False

5. Suppose you were to design a line following robot with the capability of operating at different speeds. The way most such robots work is they determine if they are on the line and if not they take corrective action to put themselves back on the line. Which do you think would be the case if the speed the robot moved were adjusted?

- Slower moving robots would have more errors in tracking the line
- ◆ Faster moving robots would have more errors in tracking the line

6. Considering the line following robot previously described, which do you think would be the case if the speed the robot moved were adjusted?

- ◆ Faster moving robots would sometimes complete a lined course faster than slower moving robots
- Faster moving robots would always complete a lined course faster than slower moving robots
- Faster moving robots would never complete a lined course faster than slower moving robots

7. Suppose you have an infrared sensor that can determine the difference between a white paper and a black line. What would happen if you exposed the sensor to a gray line?

- The sensor will always assume anything non-white is a black line
- The sensor will always assume anything non-black is a white paper
- ◆ Depending upon how dark gray the line was it may register as either white or black.

8. What effect does the duty cycle of a square wave used to drive a motor have on the speed of the motor?

- ◆ A higher duty cycle produces a faster speed
- A lower duty cycle produces a faster speed
- Duty cycle is irrelevant to motor speed

<p>9. What effect does the frequency of a square wave used to drive a motor have on the speed of the motor?</p> <ul style="list-style-type: none"> ◆ A higher frequency produces a faster speed • A lower frequency produces a faster speed • Frequency is irrelevant to motor speed
<p>10. Which is most influential on motor speed relative to the signal used to drive the motor?</p> <ul style="list-style-type: none"> ◆ Duty Cycle • Frequency • Both have no influence ◆ Both have significant influence

Table 4.8 The concept inventory questions and answers designed to evaluate student understanding of the information presented in the EngE 1104 autonomous vehicles unit

4.3 Representing Concept Inventories and Correlations with Comprehensive Map Elements in a Custom XML Schema

4.3.1 An XML Schema for Representing Concept Inventories

In order to facilitate processing of student responses to the concept inventories, the author created an XML schema that is used to encapsulate the questions and all possible answers to the inventory. The XML schema also allows the concept inventory developer to indicate the correct answer(s) to each question and to select the appropriate level of understanding within Bloom’s taxonomy that a correct answer demonstrates. The complete knowledge representation system involves correlating student answers to concept inventories with concepts and relationships presented in a comprehensive knowledge map so the XML structure also includes correlations to the appropriate elements of a comprehensive knowledge map.

Table 4.9 is an example of the XML format used to represent the questions in the concept inventories. Line 1 is a standard XML header. The concept inventory is enclosed within the <Inventory> tag (line 2) and the list of questions is within the <Questions> tag (line 3). Each question begins with a <Question> tag and has the attribute BloomByAns, which takes on the value “true” or “false” to indicate whether the entire question is used to elicit the same level of understanding within Bloom’s taxonomy or if individual answers can be used to determine varying levels within Bloom’s taxonomy. In line 4 the BloomByAns attribute is set to false indicating that all of the answers to the question are at the same Bloom’s taxonomy level. The text of the question is embedded within the <qText> tag as shown in line 5. This particular question asks students to select which disciplines contain concepts relevant to mechatronics. The set of answer choices are enclosed within the <Answers> tag and each answer begins with an

<Answer> tag. As depicted in line 7, each answer has the attributes “correct” and “Bloom,” which are used to indicate whether that answer is the correct answer or not and what level of Bloom’s taxonomy that answer represents, respectively. In this particular case, the answer is at the lowest level in Bloom’s taxonomy, Knowledge. The text of the answer is embedded within the <AnsText> tag as shown in line 8. The correlations tag is then used to set correlations with appropriate portions of the comprehensive map. Most incorrect answers have no correlations with the map, so line 9 depicts an empty correlations tag. The third answer is a correct answer so line 17 is the opening tag for the set of correlations with the answer “Computer Engineering.” Each correlation has the attribute ConOrRel, which takes on the value “Concept” or “Relationship” to indicate whether it is a correlation with a concept or relationship. In the case of a concept, it has an id attribute that takes on the value of the concept’s id in the comprehensive map and the text label on that concept node is embedded within the tag. In the case of a relationship it is representing the connection between two concepts via a relationship. Correlated relationships have a connection id attribute for each the two connections (one from the first concept to the linking phrase and the other from the linking phrase to the second concept), ConID1 and ConID2, and attributes for the IDs of both the concepts involved in the relationship (FromID and ToID) and the linking phrase (RelID). Embedded within the correlation tag for a relationship is a concatenation of the first concept, the linking phrase, and the second concept involved in the relationship. Table 4.9 only depicts the XML for the first question in the EngE 1024 mechatronics unit concept inventory. The entire XML file contains similar tags for each question and is 1631 lines long.

1	<?xml version="1.0" encoding="utf-8" standalone="no"?>
2	<Inventory>
3	<Questions>
4	<Question BloomByAns="false">
5	<qText>Mechatronics includes concepts from which of the following disciplines? (check all that apply)</qText>
6	<Answers>
7	<Answer correct="false" Bloom="Knowledge">
8	<AnsText>Aerospace Engineering</AnsText>
9	<Correlations />
10	</Answer>
11	<Answer correct="false" Bloom="Knowledge">
12	<AnsText>Biological Systems Engineering</AnsText>
13	<Correlations />
14	</Answer>
15	<Answer correct="true" Bloom="Knowledge">
16	<AnsText>Computer Engineering</AnsText>

17	<Correlations>
18	<Correlation ConOrRel="Concept" id="1207630738883_517524975_639"> Computer Engineering</Correlation>
19	<Correlation ConOrRel="Concept" id="1224448487870_351193016_812"> Mechatronics</Correlation>
20	<Correlation ConOrRel="Relationship" ConID1="1224448573289_933409053_986" ConID2="1224448614495_563632645_1050" FromID="1224448487870_351193016_812" ToID="1207630738883_517524975_639" RelID="1224448573286_1634395768_983"> Mechatronics Is A Synthesis Of Computer Engineering</Correlation>
21	</Correlations>
22	</Answer>
23	<Answer correct="true" Bloom="Knowledge">
24	<AnsText>Electrical Engineering</AnsText>
25	<Correlations>
26	<Correlation ConOrRel="Concept" id="1207630724177_894092025_612"> Electrical Engineering</Correlation>
27	<Correlation ConOrRel="Concept" id="1224448487870_351193016_812"> Mechatronics</Correlation>
28	<Correlation ConOrRel="Relationship" ConID1="1224448573289_933409053_986" ConID2="1224448608431_112962706_1038" FromID="1224448487870_351193016_812" ToID="1207630724177_894092025_612" RelID="1224448573286_1634395768_983"> Mechatronics Is A Synthesis Of Electrical Engineering</Correlation>
29	</Correlations>
30	</Answer>
31	<Answer correct="false" Bloom="Knowledge">
32	<AnsText>Environmental Engineering</AnsText>
33	<Correlations />
34	</Answer>
35	<Answer correct="false" Bloom="Knowledge">
36	<AnsText>Materials Science Engineering</AnsText>
37	<Correlations />
38	</Answer>
39	<Answer correct="true" Bloom="Knowledge">
40	<AnsText>Mechanical Engineering</AnsText>
41	<Correlations>
42	<Correlation ConOrRel="Concept" id="1207630709310_2117233821_581"> Mechanical Engineering</Correlation>
43	<Correlation ConOrRel="Concept" id="1224448487870_351193016_812"> Mechatronics</Correlation>
44	<Correlation ConOrRel="Relationship" ConID1="1224448573289_933409053_986" ConID2="1224448573290_1457524147_992" FromID="1224448487870_351193016_812" ToID="1207630709310_2117233821_581" RelID="1224448573286_1634395768_983"> Mechatronics Is A Synthesis Of Mechanical Engineering</Correlation>
45	</Correlations>
46	</Answer>

47	</Answers>
48	</Question>
49	...
50	</Questions>
51	</Inventory>

Table 4.9 The XML format used to represent concept inventories

4.3.2 Development of Concept Inventory Software

The XML format described in the previous section provides a very logical framework for the storage of concept inventories and their associations with related portions of a comprehensive map. The files used to represent complete concept inventories can become quite large and the management of such files manually would be cumbersome. In order to facilitate the entry and editing of concept inventories, the author developed software that provides an intuitive graphical user interface to enter the questions and answers to the concept inventory. The software supports any combination of multiple-choice and multiple-answer questions. This software also enables the importation of a corresponding comprehensive map in order to establish the correlations between various concept inventory answers and the related portions of the comprehensive map.

The concept inventory software provides a variety of features to edit concept inventories previously created using the software as well as to create new inventories. A screen capture of the concept inventory software is depicted in Figure 4.13. The top left button labeled “Import CI from XML File” on the main dialog box allows the user to import a previously created XML file containing a concept inventory using a standard Microsoft Windows file open dialog. A button labeled “Save CI to XML File” allows the user to save the concept inventory to an XML file. Figure 4.13 is a capture of the software immediately after the XML file containing the EngE 1024 mechatronics unit concept inventory has been imported. After importation of a concept inventory file the first question in the inventory is displayed. As can be seen in Figure 4.13, each question is displayed one at a time and buttons are provided on the top right to navigate to the next question and the previous question. In this instance the previous question button is disabled because this is the first question in the inventory; the next question button is similarly disabled when viewing the last question in the inventory.

The question elements are set to be read-only until the user clicks on the “Edit Question” button. Figure 4.14 shows the software after the user has clicked on the “Edit Question” button. Note that the contents of the question textbox and the answer textboxes can now be modified and several of the buttons have been disabled to ensure that the user confirms or cancels any changes

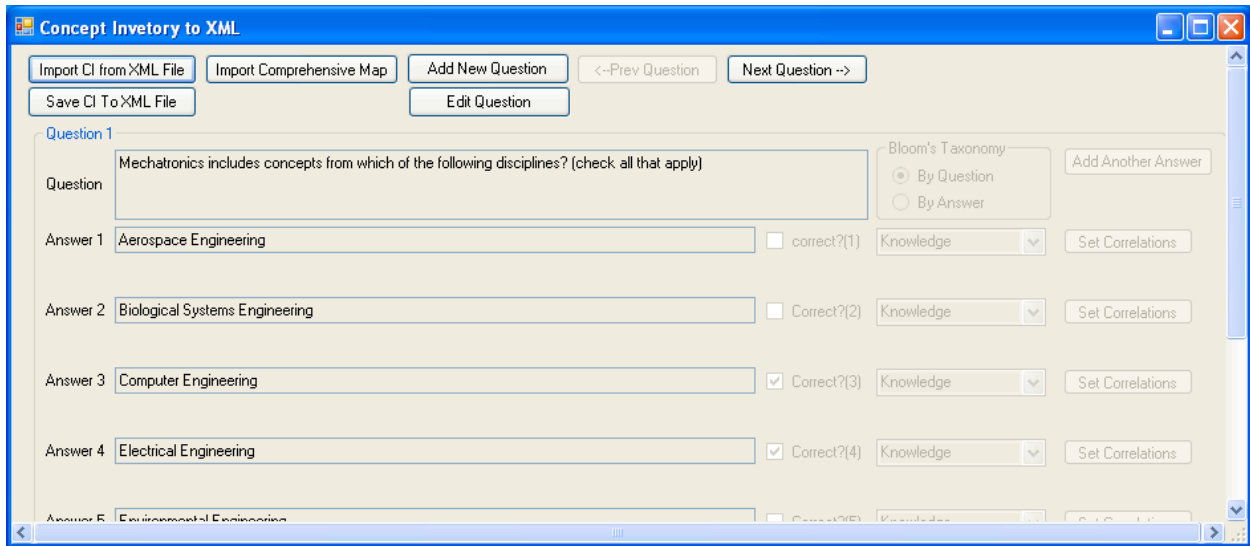


Figure 4.13 A screen capture of the concept inventory software

to the question before navigating to another question or saving the inventory to a question file. When the user is editing a question, two new buttons appear allowing the changes to be saved or canceled. As can be seen in Figure 4.14, each answer has a checkbox to indicate if the answer is correct or not. These checkboxes are enabled when the user is editing the current question or entering a new question and the corresponding answer box is not blank. To the right of the checkboxes indicating whether the answer is correct, each answer also has a dropdown box that is used to indicate the level of Bloom’s taxonomy that the answer measures. The level of Bloom’s taxonomy may be set for each individual answer or once for each question based upon the state of the radio button to the right of the question text. The interface supports the entry of up to 20 answers for each question and new answers may be added by clicking on the “Add Another Answer” button. The dialog box automatically adjusts a vertical scrollbar in order to allow the user to scroll to answers that are below those currently displayed.

A button is provided to add a new question to the inventory and to edit the currently displayed question. When a user adds a new question the dialog box depicted in Figure 4.15 pops up to allow them to decide where the new question should be placed within the list. For convenience, new questions may be added to the beginning of the list, the end of the list, or immediately before or after the currently displayed question.

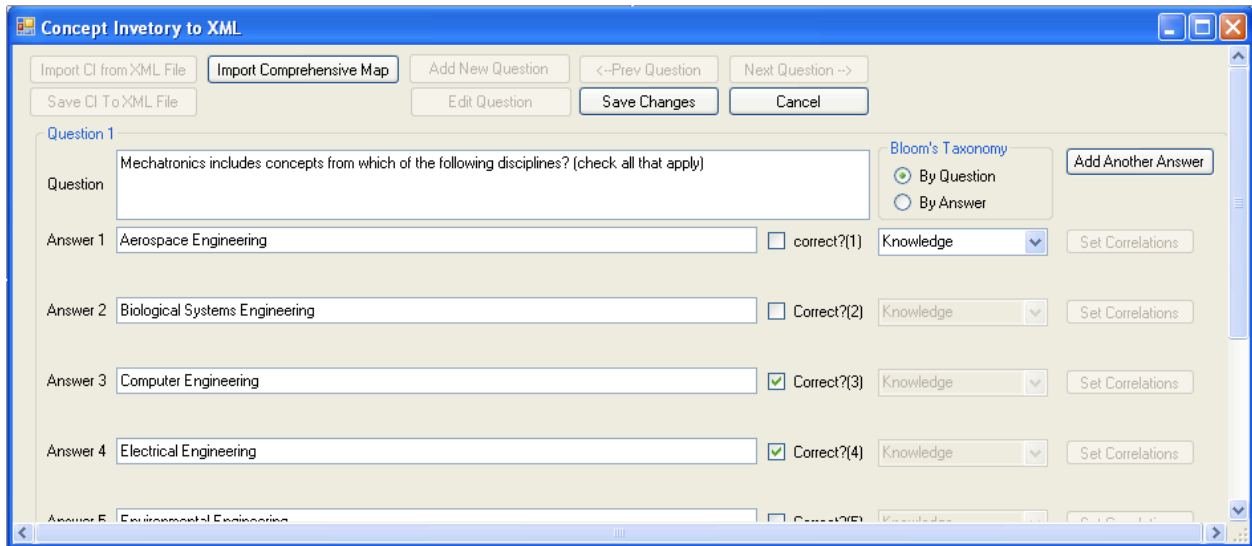


Figure 4.14 Screen capture of the concept inventory software while editing a question without importing a concept map.

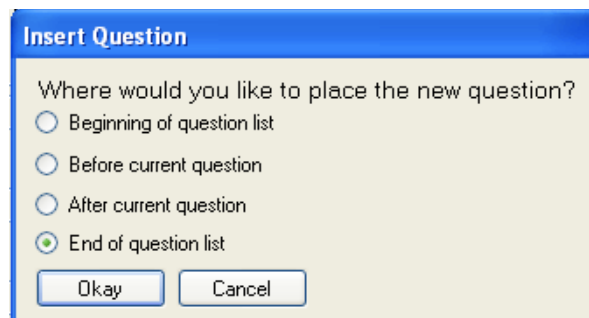


Figure 4.15 Dialog box prompting the user to select the location in the list to place a new question

The second button from the left is used to import the comprehensive map, which in turn enables each answer's "Set Correlation" button allowing the user to establish correlations between question answers and the appropriate map elements. When a user clicks on the button labeled "Set Correlations" for any answer, a dialog box similar to that depicted in Figure 4.16 pops up to allow selection of the appropriate concepts and relationships. In the concept listing each label on a concept node is listed and in the relationship listing the entire relationship is presented as a phrase including the two concepts involved connected by the linking phrase.

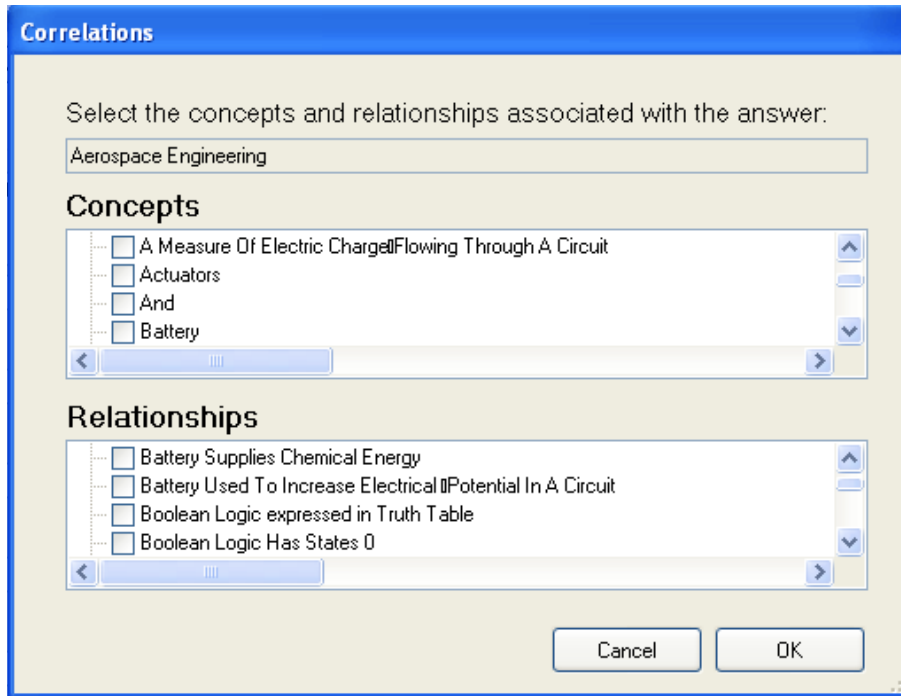


Figure 4.16 The dialog box that allows users to set correlations between answers and map elements.

4.4 Student Map Generation System

4.4.1 Correlating Student Answers with Concepts and Relationships in Student Maps

Under this assessment strategy, each question in the concept inventory is tied to at least one node or link in the corresponding comprehensive map. In several instances, specific questions are correlated with multiple links and nodes in the map. Based upon how each student answers the questions on the concept inventory a concept map is generated to showcase the subset of the comprehensive map corresponding to the topics the students have learned. If a student correctly answered a question on the inventory regarding a particular concept, then that concept appears in the student's knowledge map. Colors are incorporated in student maps to indicate the Bloom's taxonomy level representative of student's comprehension of each concept and relationship to indicate not only that the student understood the concept in question, but also how well they understood it. If a student answered a question correctly, the corresponding node(s) or link(s) appear in a student's knowledge map, but they do not appear in a student's map if the student answered all corresponding questions incorrectly.

As a simple example of how this works, consider the following simple generic comprehensive map shown in Figure 4.17 containing six concept nodes labeled 1 through 6 and six relationships between the concepts labeled A through F. This map is intentionally generic to show that this method will work for many concepts and relationships, not just those in the units being studied as part of this research. Under this system, each of these links and nodes is mapped to a question or questions in the concept inventory. Suppose a student incorrectly answered all of the questions corresponding to concept 4 and concept 5. This means that concept 4 and concept 5 would not appear in that student's map and any relationships involving those concepts would also not be present. Assuming the student answered all other questions correctly, the generated student map would look like the map depicted in Figure 4.18.

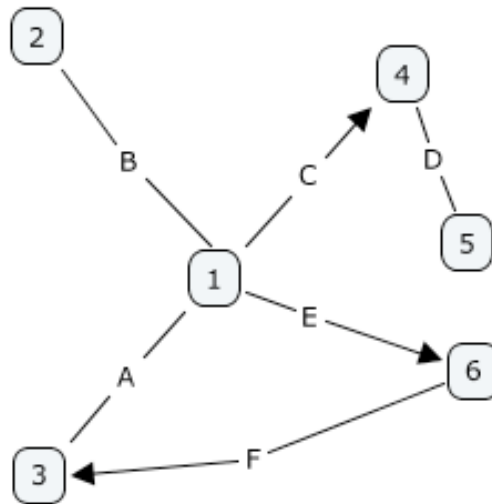


Figure 4.17 A simple comprehensive map

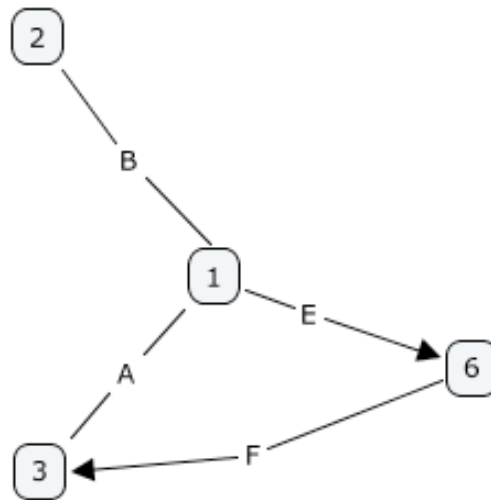


Figure 4.18 An example student map that would be generated for a student who missed all the questions corresponding to concepts 4 and 5, but got all other questions correct.

As an example of applying this strategy with the EngE 1024 mechatronics unit, question 25 in the EngE 1024 mechatronics unit concept inventory in Table 4.7 is:

What does a multimeter do?

- ◆ It measures the electrical potential at different points in a circuit relative to some reference voltage.
- Lights up when it discovers someone wired a circuit incorrectly
- ◆ Can be used to know when a battery is too far drained to be useful
- ◆ Helps electrical engineers check to make sure their circuit is operating correctly
- Checks the speed of the motors to make sure it is fast enough

As indicated by diamonds (◆), the first, third, and fourth answers are correct and correspond to various nodes and relationship links in the comprehensive map presented in Figure 4.11. The dots (•) indicate distracter (incorrect) answers and are not correlated with any portion of the comprehensive map. All three correct answers are associated with the concept node labeled “Multimeter.” The first correct answer is also correlated with the concept “Voltage” and the linking phrase “Measures” to express the relationship “Multimeter Measures Voltage.” The second correct answer is also correlated with the concept “Battery” and the linking phrase “can test” to express the relationship “Multimeter can test Battery.” The third correct answer is also correlated with the concepts “Electrical Engineering” and “Circuits” and the linking phrases “uses” and “may be tested with” to express the relationships “Electrical Engineering uses Circuits” and “Circuits may be tested with Multimeter.” For each correct answer selected by the students the corresponding concepts and relationships appear in the student map.

4.4.2 Using Color to Represent Bloom’s Taxonomy Within Student Maps

By correlating questions with map elements using the method described in the previous section it becomes possible to develop a student map representing the concepts and relationships each student has some knowledge of. In this section a methodology for using color to graphically and mathematically encapsulate not only the fact that a student has some knowledge of a concept or relationship, but the depth of that knowledge based on the number of correct answers to questions associated with the concept or relationship in question and the appropriate level of Bloom’s taxonomy [11] elicited by the associated questions.

To encapsulate the appropriate Bloom’s taxonomy level the colors of the visible spectrum are used to represent each of the six categories of Bloom’s taxonomy. Thus, as depicted in Table 4.10, the six color progression in the visible spectrum: red, orange, yellow, green, blue, and violet correlates with the six level progression in Bloom’s taxonomy: knowledge, understanding,

Bloom's Taxonomy Level	Knowledge	Understanding	Application	Analysis	Synthesis	Evaluation
Color						

Table 4.10 The colors associated with each level of Bloom's taxonomy in student maps.

application, analysis, synthesis, and evaluation, respectively. The color of each node in a student map is determined by the highest Bloom's taxonomy level question in the associated concept inventory that a student answered correctly. For example, if there are four different questions in the concept inventory that relate to a particular concept, two at the knowledge level, one at the understanding level, and one at the application level and the student answers only the two knowledge level questions correctly then the associated concept node would be red in the output student map indicating that the student has knowledge level mastery, but does not have understanding or application level mastery. If the student answered all four questions correctly then the corresponding concept node would appear yellow indicating application level mastery. The color of the node is based solely on the highest level question answered, so even if a student missed one of the knowledge level questions, they could still have a color indicating mastery beyond the knowledge level based upon correct answers to higher level questions.

Beyond merely using a color to represent the level of Bloom's taxonomy corresponding to the student's knowledge of a concept or a relationship, a gradient is used to represent the portion of the questions at or below the maximum level that a student answered correctly. Thus a very light red indicates a concept or relationship that a student has limited knowledge of and very dark violet indicates extremely strong mastery at the evaluation level. Table 4.11 shows how a color gradient can be used to represent both the Bloom's taxonomy level and the percentage of questions answered correctly at or below the maximum level answered correctly. The .cxl format uses RGB triples to represent colors and the associated RGB triples are included for reference in Table 4.11. Recall that concepts and relationships are eliminated from student maps if a student incorrectly answers all of the questions associated with them, so the lowest interval in the table is not inclusive of 0. Five different intervals are specified in Table 4.11, but ultimately any number of intervals could be supported by a continuous gradient as depicted in Table 4.12.

		Percentage of Questions at or Below the Top Level Answered Correctly				
		(0,20)	[20,40)	[40,60)	[60,80)	[80,100]
Level	Knowledge	(255,160,160)	(255,120,120)	(255,80,80)	(255,40,40)	(255,0,0)
	Understanding	(255,208,80)	(255,188,60)	(255,168,40)	(255,148,20)	(255,128,0)
	Application	(255,255,160)	(255,255,120)	(255,255,80)	(255,255,40)	(255,255,0)
	Analysis	(200,255,200)	(150,255,150)	(100,255,100)	(50,255,50)	(0,255,0)
	Synthesis	(200,200,255)	(150,150,255)	(100,100,255)	(50,50,255)	(0,0,255)
	Evaluation	(255,128,255)	(223,96,223)	(191,64,191)	(159,32,159)	(127,0,127)

Table 4.11 Using discrete elements of a color gradient to represent Bloom's taxonomy level and portion of questions answered correctly

		Percentage of Questions at or Below the Top Level Answered Correctly	
		>0	100
Level	Knowledge	(255,160,160)	(255,0,0)
	Understanding	(255,208,80)	(255,128,0)
	Application	(255,255,160)	(255,255,0)
	Analysis	(200,255,200)	(0,255,0)
	Synthesis	(200,200,255)	(0,0,255)
	Evaluation	(255,128,255)	(127,0,127)

Table 4.12 Using continuous color gradients to represent Bloom's taxonomy level and portion of questions answered correctly

Each color interval contains a pattern and clearly establishes a maximum and a minimum value for each component of the RGB triple. The color assigned to a map element, $Color_E$, in a student map is given by the following RGB triple

$$Color_E = \left(R_{\min_L} + \frac{C(R_{\max_L} - R_{\min_L})}{A_L}, G_{\min_L} + \frac{C(G_{\max_L} - G_{\min_L})}{A_L}, B_{\min_L} + \frac{C(B_{\max_L} - B_{\min_L})}{A_L} \right)$$

where L represents the highest Bloom's taxonomy level assigned to any question or answer the student answered correctly, C represents the total number of correct answers the student gave to any question in the concept inventory associated with the map element, A_L represents the total number of answers at or below level L associated with the map element in the concept inventory, and the RGB triples $(R_{\min_L}, G_{\min_L}, B_{\min_L})$ and $(R_{\max_L}, G_{\max_L}, B_{\max_L})$ are the ordered triples on the

low and high end, respectively, of the color gradient for Bloom's taxonomy level L.

The .cxl format supports entry of colors for concept nodes and linking phrases using the background-color attribute. This attribute takes on an ordered quadruple with the first three coordinates specifying the red, green, and blue values, respectively, and the final coordinate taking on the value 0 or 255 indicating whether the background is completely transparent or opaque, respectively. The .cxl format does not support translucent concept nodes or linking phrases and interprets any value other than 0 as opaque. Student maps are created using this color scheme via the software described in the next section.

4.4.3 Software to Process Student Data and Generate Student Maps

A visual C++ computer program was developed that parses the data collected from students through deployment of the concept inventory and generates a set of student maps representative of each student's conceptual knowledge. As can be seen in the screen capture of the program in Figure 4.19, this program takes in several inputs: the concept inventory XML file output by the program described in section 4.3.2, a .txt file containing the students' responses to the concept inventory, the comprehensive map file in .cxl format, the character used to delimit the data in the student response file, the numbers of identifiers and demographic questions in the data set prior to the responses to the concept inventory questions, and the directory to which the user desires to output the maps. The program then outputs a set of student maps in .cxl format representing the conceptual understanding of each student.

Upon clicking on the button labeled "Generate Maps" the program reads in the information in the concept inventory file including the text of the questions and answers, information about which answers are correct, the correlations between answers and elements in the comprehensive map, and the Bloom's taxonomy levels. The software then reads in information from the comprehensive concept map regarding the appearance of each node and linking phrase in the map so that the student map can take on the same form as the comprehensive map. Finally, the program reads in each student's response to each question one-by-one and develops a list of all the concepts and relationships the student has demonstrated knowledge of. The software then iterates through the lists of concepts and relationships that should appear in the student map and outputs them into a .cxl file. The output maps are structurally and conceptually subsets of the comprehensive map and maintain the same organizational arrangement of all concepts and relationships the students have learned.

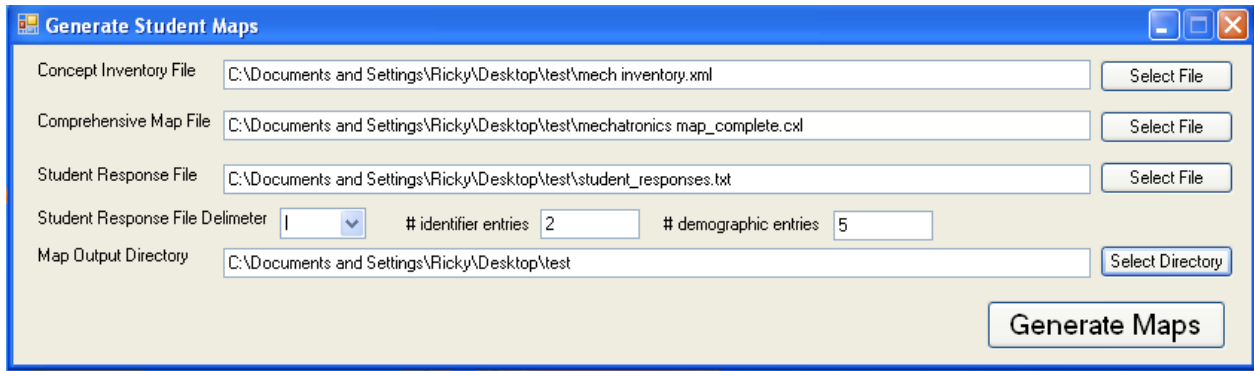


Figure 4.19 A screen capture of the student map generation software

The file structure created by the CmapTools software was extensively studied so the output student maps are readable by the CmapTools software described in 4.1.5. Several pieces of metadata in the .cxl file presented in Table 4.3 are not required for .cxl files to be read by CmapTools and have been eliminated in the output from the student map generating software. In order to reduce file size an unneeded data. Optional metadata includes information about language and information about the map creator, contributors, and rights holders which gives no additional insight into what a student knows. It is also unnecessary to output links to knowledge resources in the student maps so none of the embedded knowledge resources are present in the student maps. The demographic information collected when students responded to the concept inventory is also embedded into the output student maps in the metadata section. Table 4.13 contains an example of the XML used to represent the demographic information collected from a male student who was enrolled in the EngE 1024 workshop taught on Thursdays from 12:45-2:15 by workshop instructor John Doe. The demographics list is automatically inserted in each student map based upon the demographic information reported by the student when responding to the concept inventory.

As was discussed in section 4.4.2 the student map uses colors to represent the Bloom's taxonomy level of each concept and relationship. Additionally, each concept and relationship in the student maps is given six attributes in the .cxl file indicating the percent of answers correctly

1	<demographics>
2	<demographic category="workshopTime">Thursday 12:45-2:15</demographic>
3	<demographic category="instructor">John Doe</demographic>
4	<demographic category="gender">Male</demographic>
5	</demographics>

Table 4.13 XML used to represent demographics in student concept maps

given at each Bloom's taxonomy level. For instance the XML tag in Table 4.14 would represent the concept "Gears" in a student map and would indicate a student who correctly answered every question at the knowledge level, 83.3% of questions at the understanding level, and 100% of questions at the application level. The zeros for bloom4, bloom5, and bloom6 indicate that no questions relating to gears were asked in the concept inventory at those levels. There is a distinction in the student map file between 0.000 indicating that there were questions at that level, but the student incorrectly answered all of them, and 0 indicating that no questions at that level exist in the concept inventory. Using the short-comment attribute allows this information to be displayed when a user hovers over each concept or relationship with the mouse. The short-comment attribute in line 2 of Table 4.14 is standard to the .cxl format and supported by CmapTools. The six Bloom attributes are not standard to the .cxl format, but are simply ignored by CmapTools when the student maps is imported for viewing. This information is vital to the development of aggregate maps as is discussed in detail in section 4.6.

Once maps are generated for each student, the output file can then be sent to each corresponding student who can install the CmapTools software and open his or her student map file to see a graphical depiction of which concepts and relationships he or she has demonstrated mastery of and will be able to compare his or her student map to the comprehensive knowledge map to see which topics he or she may need to learn more about. The comprehensive map encapsulates both the knowledge the students possess and the knowledge they are missing and serves as a valuable resource for students to improve upon their mastery of the subject at hand as the embedded knowledge resources can be used to teach students the concepts they have yet to understand correctly.

1	<concept id="1207631453394 1638502451 1120" label="Gears"
2	short-comment=" K:1.000, U: 0.833, Ap: 1.000, An: 0, S: 0, E: 0"
3	bloom1="1.000"
4	bloom2="0.833"
5	bloom3="1.000"
6	bloom4="0"
7	bloom5="0"
	bloom6="0" />

Table 4.14 Annotating a concept with Bloom's taxonomy information

4.4.4 Beyond Multiple-Choice Assessment

Most any concept in engineering may be evaluated through a multiple-choice assessment. In fact, the Fundamentals of Engineering (FE) exam (formerly known as the Engineer in Training exam or EIT), the first in a two-exam series of professional engineering licensure exams, is composed entirely of multiple-choice questions designed to examine student's knowledge gained through enrollment in an accredited baccalaureate engineering program [14]. This 8-hour exam consists of 180 multiple-choice questions with a 120-question general section taken by all examinees in the morning and 60-question discipline specific or general section in the afternoon. The Principals and Practice Exam (PE), the second exam in the licensing process and is more discipline specific than the FE exam. This exam is also multiple-choice for most disciplines [15]. The PE is offered in seventeen engineering disciplines and of those, sixteen of the exams are entirely multiple-choice.

Despite the successful assessment of engineering knowledge using multiple-choice questions, some concepts may be more difficult than others to determine mastery through a multiple-choice examination such as a concept inventory. In these cases, instructors may need to develop alternate assessment techniques and may even incorporate the assessment techniques already being utilized in their courses. In these instances manual addition and subtraction of nodes may be necessary to provide a comprehensive assessment. With some knowledge of the .cxl file format, instructors could manually add appropriate concepts and relationships to the student maps. The instructors can of course open the student map in CmapTools and graphically edit the concepts and relationships present in the map. An extension of this work could provide a simple user interface allowing manual toggling of the student maps while maintaining the same framework within the student maps as is present in the comprehensive map.

4.4.5 Student Data Collection Protocol

One of the primary deliverables of this work is a set of student maps representing the concepts and relationships learned by each student in a course. This section discusses the student data collection protocol and how over 1,000 student maps have been developed as part of this research.

All versions of the concept inventory were deployed to EngE 1024 students using the online resources available at <http://www.survey.vt.edu>. This website allows Virginia Tech students and faculty members to create online surveys and to collect the data in a parsable

format. In Spring 2008 the first EngE 1024 mechatronics concept inventory (depicted in Table 4.4) was deployed to students as a survey of their prior knowledge before the mechatronics unit. The survey was posted as part of the weekly homework assignment for students, but it was not assigned a grade and students were told that taking the survey was voluntary. Students were instructed to not look over any of the material from the mechatronics unit prior to taking the survey and to not look up any answers online or in any other source. There was no time limit imposed. A total of 108 students completed the survey, which served as a basis for the complete mechatronics inventory. At this stage of development no student maps were created based upon student responses.

In Summer 2008 students were given a slightly revised concept inventory (Table 4.5). The survey was given twice, once as a survey before the mechatronics unit and the other was given after the mechatronics unit to determine the gains students had as a result of their participation in the mechatronics unit. The summer session offering of the course has many fewer students than the fall and spring semester offerings and only six students participated in the pre-unit survey and seven participated in the post-unit survey.

The full deployment of the survey, complete with answer choices (Table 4.7), was given in Fall 2008. This time the completion of the survey was a required homework assignment, but students were given credit for completion of the survey rather than the correctness of their responses. Once they had completed the mechatronics unit concept inventory a passphrase was provided for students to write on the top of their weekly homework assignment in order to get credit for survey completion. Completion of the survey counted as a portion of the weekly homework grade, but students were allowed to indicate that they did not want their data used as part of any research study. Students were also asked if they were at least 18 years of age as of the time they completed the survey to ensure that data was not collected from minors. Students were also asked to indicate the name of their workshop instructor, their gender, and the time that their workshop met in order to observe any data trends related to each of these factors. Gender is of particular interest as mechanical engineering, electrical engineering, and computer engineering tend to be fields in which females are very underrepresented relative to their male peers and it would be interesting to showcase any differences in conceptual understanding by males and females. A total of 1407 students responded to the survey with 205 students indicating they did not want their results included in the study and 47 students indicating that

they were not at least 18 years of age leaving a total of 1160 valid student responses (5 students were both under 18 and indicated they did not want their data included). Student responses were downloaded from the survey site via a delimited text file that can be entered into the software described in section 4.4.3. Student maps were created for all 1160 students who were of legal age and did not object to their data being used in this study.

In a similar manner students in EngE 1104 in Spring 2009 were assigned to take both a pre-workshop and post-workshop concept inventory. The pre-workshop concept inventory contained all of the questions in the EngE 1024 mechatronics unit concept inventory plus the ten new questions (Table 4.8) developed to test prior knowledge of the concepts introduced through the EngE 1104 autonomous vehicles unit. The post-workshop survey contained only the ten questions directly relevant to the EngE 1104 autonomous vehicles unit. The two surveys collected the same demographic information as was collected during deployment of the EngE 1024 mechatronics unit concept inventory and additionally student ID numbers were collected to associate the pre-workshop survey responses with the corresponding post-workshop responses for each student. A total of 209 student responses were collected to the pre-workshop concept inventory and 265 student responses were collected to the post-workshop concept inventory. Students were again given the option to opt their data out of the study and were asked if they were at least 18 years of age. Data was eliminated for students who opted out of the study or were under age 18. Data was additionally eliminated for students who did not complete both surveys or did not consistently report demographics regarding their instructor, gender, and class meeting time. It was discovered through analysis of some of the data that some students completed the same inventory twice with different answers. In these cases both sets of data were eliminated from consideration. A total of 112 student maps were created.

Since this study involved human subjects, the appropriate Institutional Review Board (IRB) paperwork was filed to ensure that the data collection procedures and instruments were acceptable. The study was approved as an IRB exempt study (approval letter included in Appendix A: IRB Approval).

4.4.6 Example Student Maps

4.4.6.1 Student Maps from Fall 2008 EngE 1024 Students

Figure 4.20 depicts one of the student maps output by the software based upon answers given to the EngE 1024 mechatronics unit concept inventory in Fall 2008. This student map is representative of one of the best students and includes nearly all concepts and relationships from the comprehensive map. As can be seen, many of the concepts and relationships are depicted in a yellow color indicative of correct answers to questions at the application level. Most of the concept nodes and relationship links in Figure 4.20 are bright indicating that the student answered nearly every question correctly.

Figure 4.21 depicts one of the worst student maps. This map contains relatively few concepts and relationships from the comprehensive map and many of those concepts that are present are in a light red color indicative of limited knowledge and several incorrect answers to questions on the concept inventory.

Figure 4.22 is representative of a typical student map with the majority of concepts and relationships present. Several concepts and relationships are missing and some of the present concepts and relationships are lighter in color indicating a few incorrectly answered questions on the concept inventory.

4.4.6.2 Student Maps from Spring 2009 EngE 1104 Students

The student maps in Figure 4.23-Figure 4.25 were generated based upon data collected in the pre-workshop survey for the questions relating to the EngE 1024 mechatronics unit and data collected from the post survey for questions relating to the EngE 1104 autonomous vehicles unit. Figure 4.23 is one of the best student maps generated based upon responses to the EngE 1104 autonomous vehicles unit concept inventory. While some concepts and relationships are missing, this map does contain most of the concepts and relationships in the comprehensive map. This student showed correct understanding of how compilers work, the role of duty cycle and frequency in motor control, and the potential for error when a robot is driven too quickly.

Figure 4.24 is one of the worst student maps generated based upon responses to the EngE 1104 autonomous vehicles concept inventory. While this student did demonstrate some understanding of many of the concepts and relationships presented in this course unit, they exhibited a fairly weak command of some of the most pertinent computer engineering concepts.

They had very limited knowledge of Boolean logic, they did not understand the role of frequency and duty cycle in motor control, and were unable to identify many electrical components and schematic symbols.

Figure 4.25 is a typical student map generated based upon responses to the EngE 1104 autonomous vehicles concept inventory. This student map was generated for a student who recalled most of the concepts and relationships in the EngE 1024 mechatronics unit and demonstrated a mastery of many of the concepts and relationships in the EngE 1104 autonomous vehicles unit. This student understood how duty cycle was related to motor speed, but, like many students, did not realize that motor speed is independent of frequency when motors are operated within a normal frequency range. This student identified many circuit components and their schematic symbols and recalled several other mechanical and electrical concepts presented in the EngE 1024 mechatronics unit.

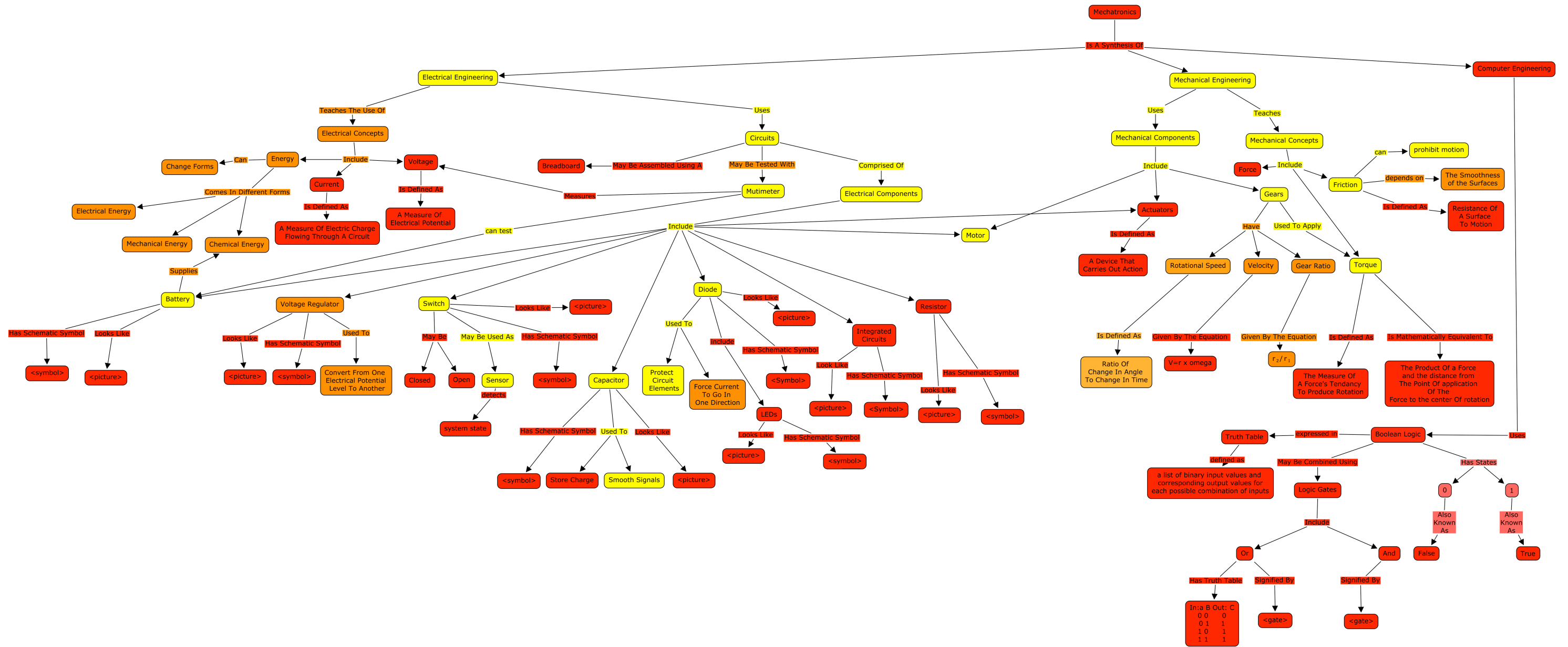


Figure 4.20 One of the best student maps based upon a student's responses to the EngE 1024 Mechatronics Unit Concept Inventory in Fall 2008

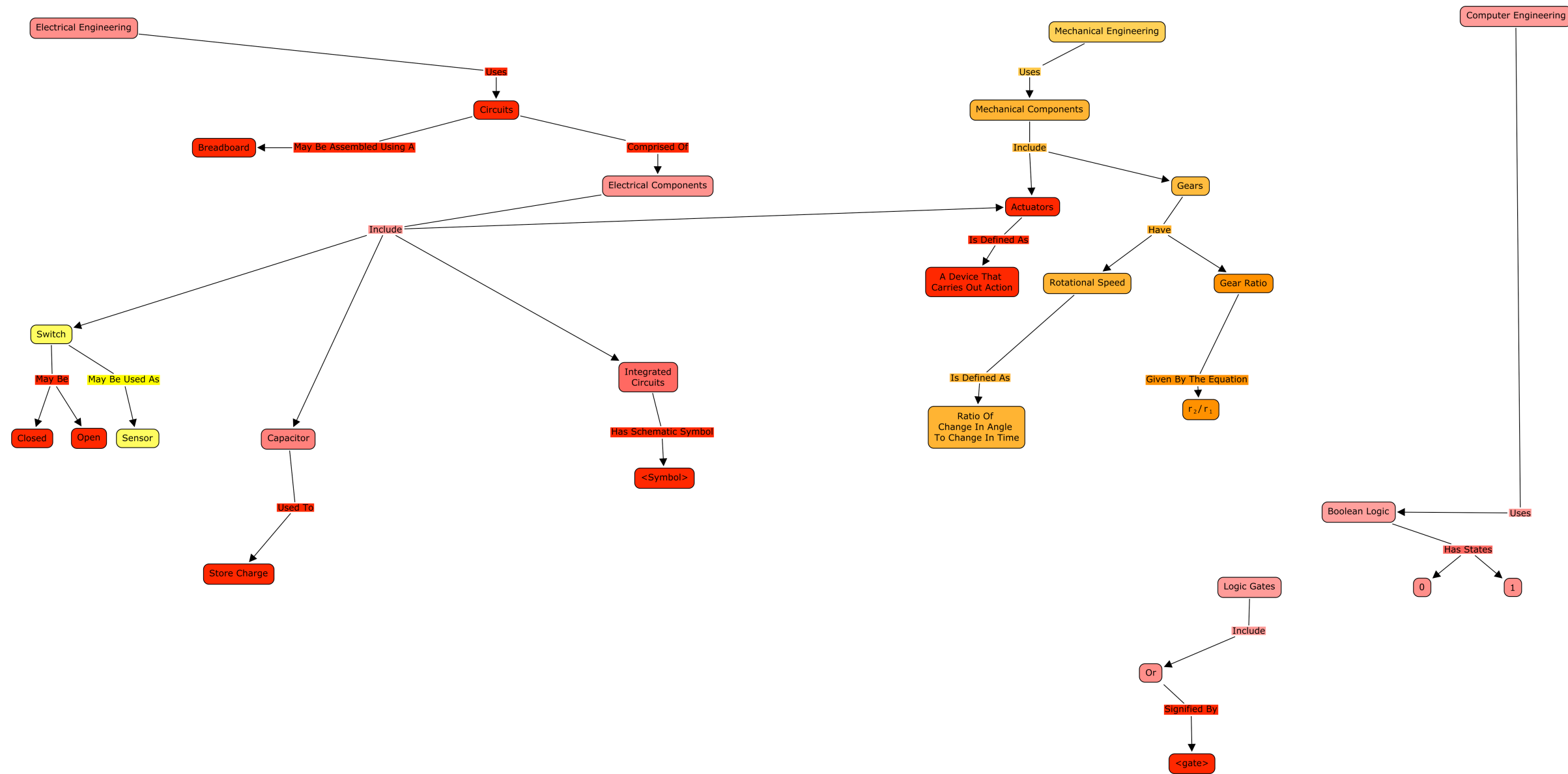


Figure 4.21 One of the worst student maps based upon a student's responses to the EngE 1024 Mechatronics Unit Concept Inventory in Fall 2008

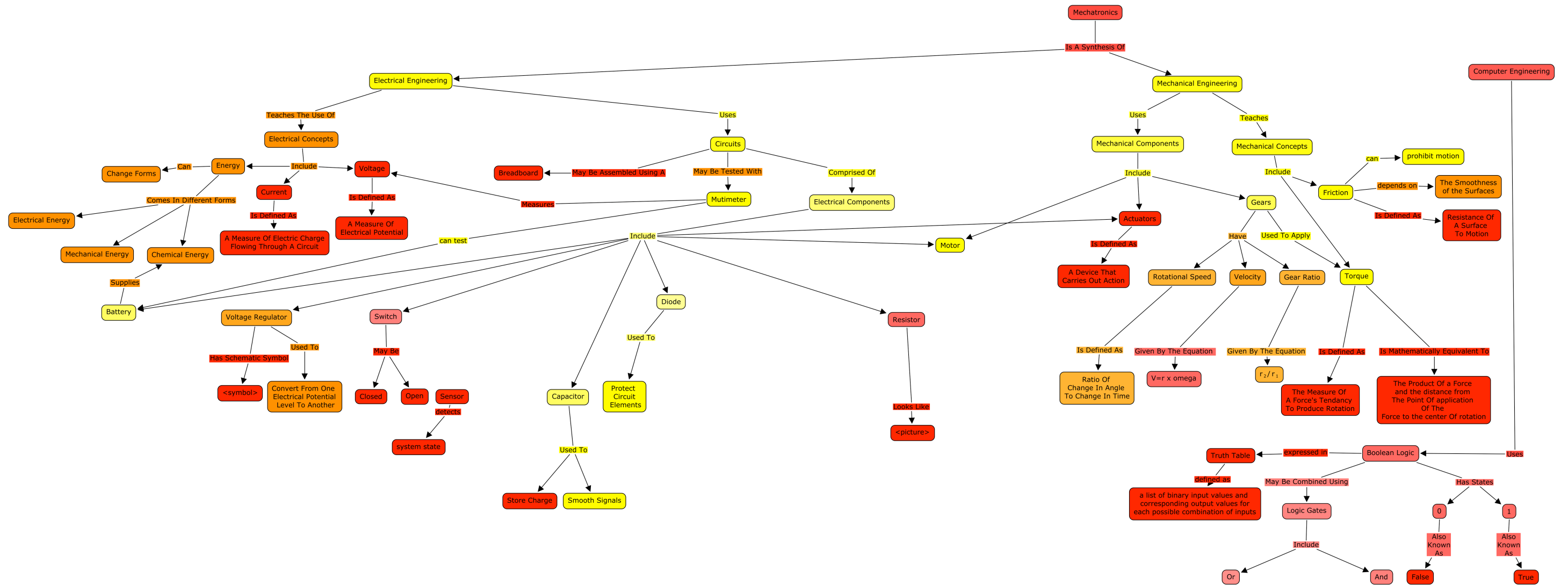


Figure 4.22 A typical (average) student map based upon a student's responses to the EngE 1024 Mechatronics Unit Concept Inventory in Fall 2008

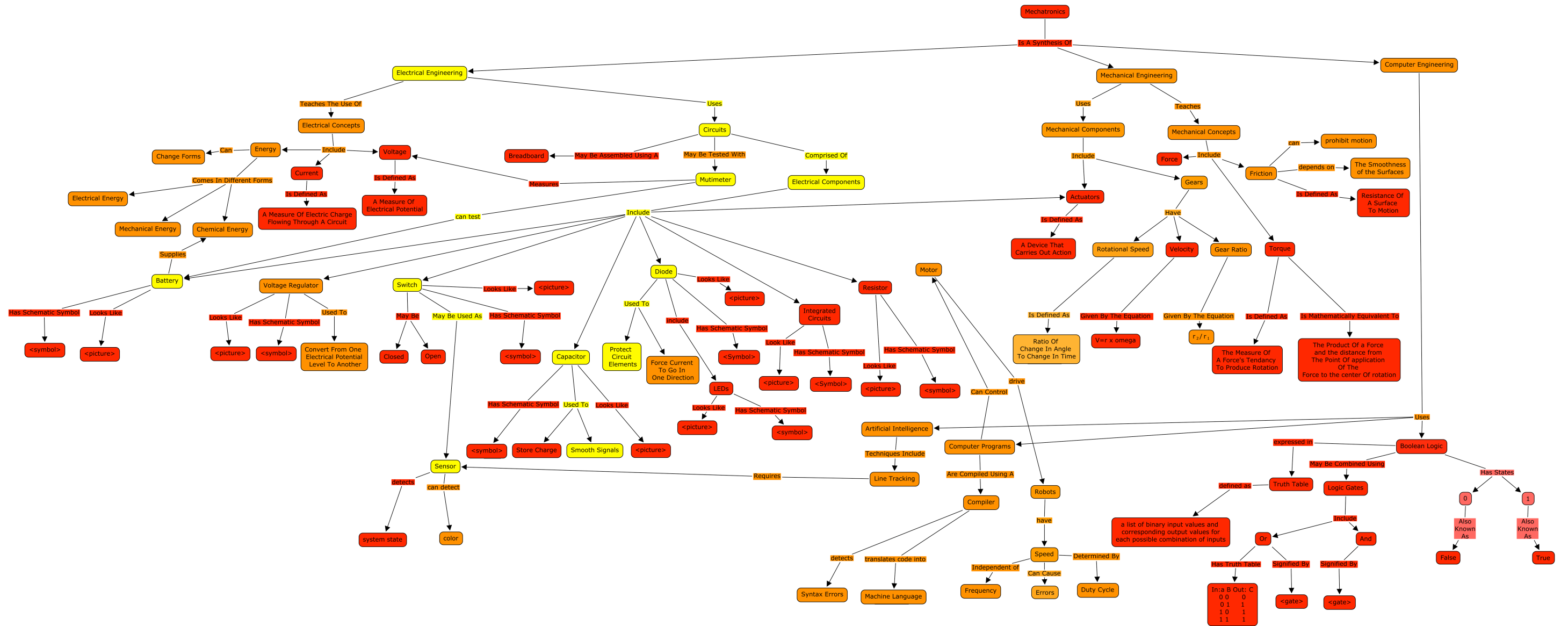


Figure 4.23 One of the best student maps based upon a student's responses to the EngE 1104 Autonomous Vehicles Unit Concept Inventory in Spring 2009

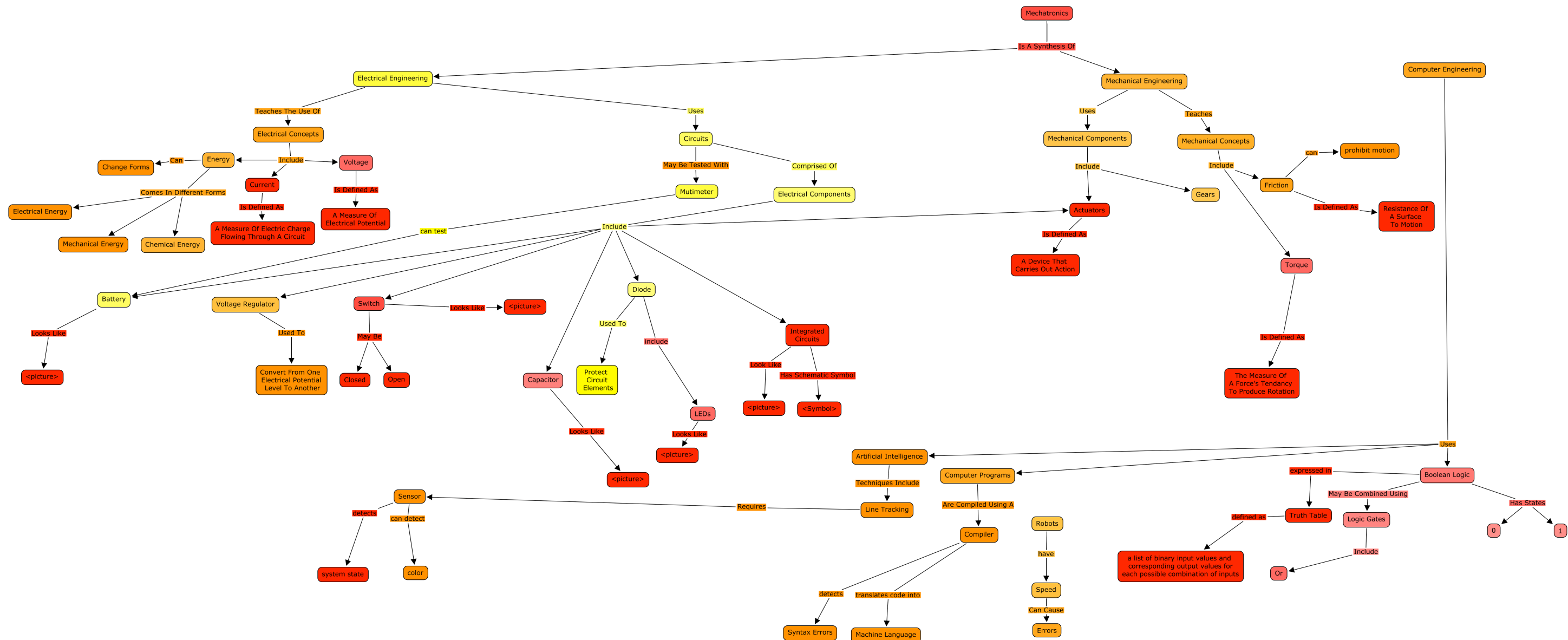


Figure 4.24 One of the worst student maps based upon a student's responses to the EngE 1104 Autonomous Vehicles Unit Concept Inventory in Spring 2009

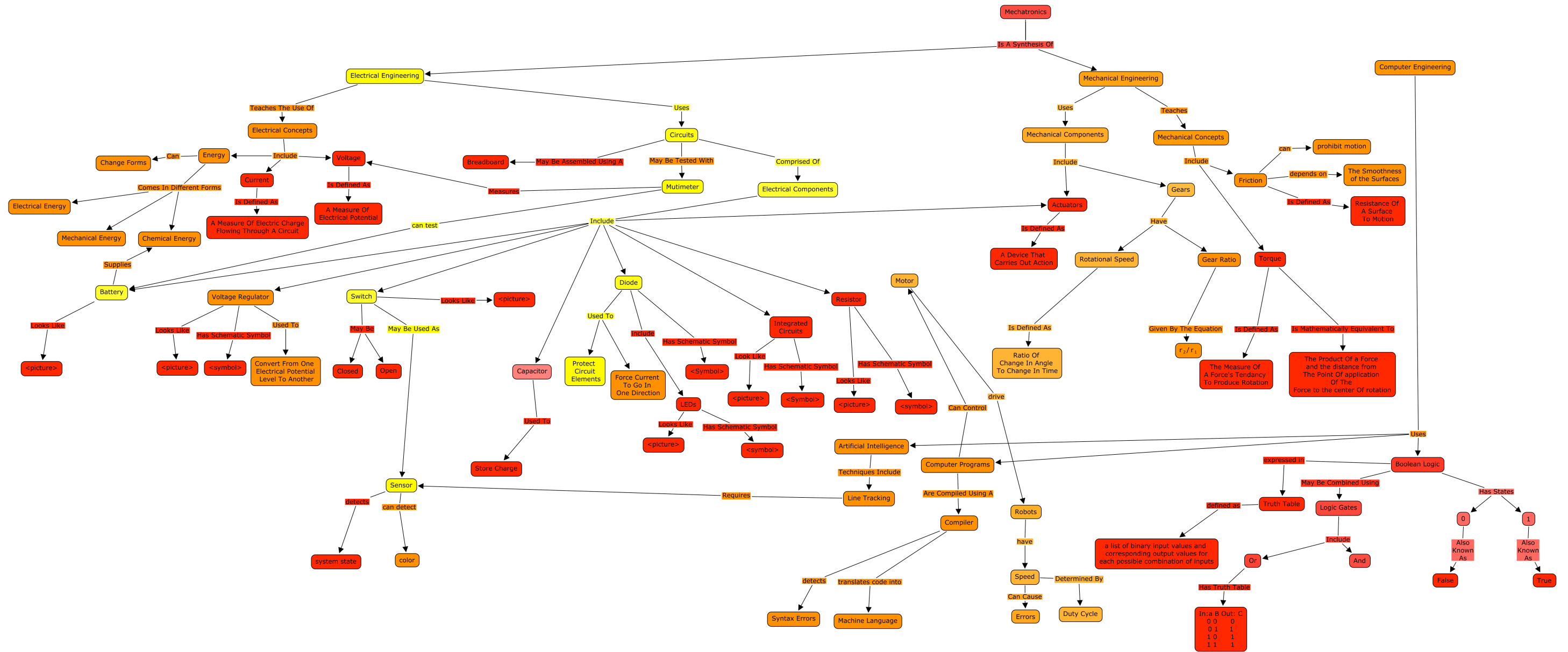


Figure 4.25 A typical (average) student map based upon a student's responses to the EngE 1104 Autonomous Vehicles Unit Concept Inventory in Spring 2009

4.5 Quantifying the Distance Between Knowledge Using Topology

In this section principles from topology are used to quantify the distance between two maps in order to determine how far a learner is from having a mastery of the entire body of knowledge based upon the knowledge they demonstrate possession of on a concept inventory. The work presents several approaches to quantifying the knowledge encapsulated within a concept map and incorporates logical mathematical factors relevant to such analysis. Four different methods for computing the distance between two concept maps are presented and the strengths and weaknesses of each method are discussed.

4.5.1 Introduction to knowledge quantification

Most academic programs have some method of scoring individual performance by assigning letter grades or percentage points to rate each student's mastery of course content. As was previously discussed in chapter 1 in section 1.2.1 and depicted in Figure 1.1, this typically is done by assigning grades or points for each individual assignment or test and then developing an aggregate grade based upon a weighted average of each of the grades in a particular category. The grading of each individual assignment or test is usually done by assigning a point value to each question or component of the assignment or test and then developing a rubric, which establishes either the errors that result in point deductions or the positive content and attributes that result in earned points. The work submitted by the student is compared with the standard established in the rubric and a general quantification of a student's mastery is established. The summation of all earned points or the reduction of all point penalties from the maximum number of points allotted to the assignment results in the quantification of a student's knowledge mastery.

The problem with such assessment systems is that students are evaluated based upon the means to the end rather than the end results themselves. Such measures are relative to the particular points assigned to examination questions or portions of assignments and are generally not able to be directly correlated with an absolute comprehensive standard of knowledge. Certainly all of the assignments given to students should be created with some academic purpose in mind to allow students to learn new concepts, but the grades earned on those assignments do not always directly quantify the knowledge a student has obtained. In some classes for instance homework problems are graded based on effort or the lowest grade on an assignment is dropped.

This essentially implies that it is irrelevant in the instructor's assessment of a student whether or not the corresponding material was mastered so long as the student did the work prescribed to convey that knowledge. This type of assessment system also reflects the individual bias of the instructor in that certain points may be over or underemphasized while some topics within a discipline may not be covered at all. The development and use of comprehensive knowledge maps and associated concept inventories is intended to provide an absolute standard that includes all topics within a discipline regardless of whether all of those topics are covered within a particular course.

Even with the use of comprehensive maps and corresponding inventories, it is a difficult problem to reliably quantify the distance between the knowledge exhibited by an individual and the ideal or target knowledge represented in the comprehensive map or to determine the distance between two students' knowledge. By quantifying the distance between the current state and the target state educators can quantify how much students have learned and use that information to grade students appropriately based upon their learning outcomes independent of how such learning occurred. Under such an evaluation system the focus becomes learning rather than assignment completion. Assessment of student knowledge independent of course assignments also accounts for the fact that learners in the 21st century often gain knowledge from many more sources outside the classroom than their predecessors once did.

Several questions arise when attempting to quantify knowledge and to establish a distance from current state to the ideal state. Is it sufficient to count the number of concept nodes in a map and compare that to the number of concept nodes in another map? Should all nodes and links in a map be weighted equally? Should the geometry of the comprehensive map structure be accounted for in the quantification? Can a universal quantification strategy be invoked for all such maps? In order to provide a more robust method of quantifying the difference between knowledge, principles from topology will be used to establish an appropriate metric.

4.5.2 Metric Spaces

In the field of topology, a metric space is defined as an ordered pair (M,d) containing a set, M , and a metric, d , where d defines the distance between the elements of the set M [72]. For purposes of applying a metric space to knowledge modeling, the set M contains all possible knowledge maps representing all possible combinations of nodes and links. Thus for a

comprehensive knowledge map containing N nodes and R relationships between nodes with each node and relationship having the ability to take on one of the six levels in Bloom's taxonomy or to not be present at all, there are theoretically 7^{N+R} possible knowledge maps in the set M . The set M may actually contain fewer than 7^{N+R} maps since some nodes or links may not be able to be elevated through all levels of Bloom's taxonomy and some relationships may be dependent on the presence of a related node in order to exist.

Topology prescribes that a metric, d , must satisfy four criteria: non-negativity, symmetry, the triangle inequality, and the identity of indiscernibles. In terms of knowledge modeling and quantification using knowledge maps the non-negativity requirement prescribes that the distance between two maps must be zero or greater. The symmetry requirement requires that the distance from one map to another must be consistent regardless of whether it is describing the distance from map x to map y or the distance from map y to map x . The triangle inequality requires that the distance from any map, x , to any other map, z , must be no greater than the sum of the distance from map x to another map, y , and the distance from map y to map z . The identity of indiscernibles requires that a metric may only evaluate the distance between two maps to be zero if those two maps are identical. In mathematical notation this is written as

$$\begin{aligned}
 d(x,y) &\geq 0 \\
 d(x,y) &= d(y,x) \\
 d(x,z) &\leq d(x,y) + d(y,z) \\
 d(x,y) &= 0 \quad \text{iff} \quad x = y \\
 \forall x,y,z &\in M
 \end{aligned}$$

4.5.3 Example Metrics

In a physical one, two, or three-dimensional Euclidean space it is trivial to quantify the distance between two points. In one-dimension, the distance between a point, x , and another point, y , is given simply by $|x-y|$, that is the absolute value of the difference between x and y . This relationship can be easily shown to satisfy all of the four above criteria. Such relationships can be expanded to two or more dimensions by using the Pythagorean theorem or some variation thereof to describe the distance between coordinates. For example in two dimensions, the distance between two points, (x_1, y_1) and (x_2, y_2) is given as

$d((x_1, y_1), (x_2, y_2)) = \sqrt{(y_2 - y_1)^2 + (x_2 - x_1)^2} \quad \forall (x, y) \in \mathfrak{R}^2$. In such spaces there is no constraint on motion so distance can be defined based upon the shortest distance linear path.

In other geometric spaces, however, there are constraints and the distance is not as easily defined. A classic example of this is driving distance. When one wishes to determine the driving distance between two points in a city then the geometry is constrained by conventional paths. Driving through buildings and other obstacles is not allowed and drivers are constrained to the roads that exist. In a simple example one could consider a city grid such that drivers can travel either East to West or North to South. The distance between any two points is given as the sum of the East to West difference between the points and the North to South distance between points. Developing an appropriate metric for driving distance becomes more complicated when the roads do not form perfect right angles and when other rules of the road need to be factored in such as one-way streets or road closures.

When examining human knowledge and attempting to determine the distance between the knowledge demonstrated by two people the distance between two people's knowledge is much more challenging to quantify because knowledge does not correlate easily with a distance in a physical space. The principles of topology can be used to formulate metric spaces representative of the set of knowledge maps and the distance between knowledge maps, but the choice of metric should be done in a way that not only satisfies the basic requirements for a metric, but also provides an intuitive quantification of the difference in knowledge exhibited by two maps. In the following section some approaches to quantifying the distance are discussed. Some of these approaches are not true metrics since they fail to pass one of the four required tests for a true metric and are thus referred to as pseudo-metrics.

4.5.4 Metrics and Psuedo-metrics Quantifying the Distance Between Knowledge

4.5.4.1 Counting Pseudo-Metric

As a first attempt at developing a metric, one needs to consider what constitutes similarity or "closeness" in knowledge, especially as it relates to knowledge encapsulated in a knowledge map. Those with similar knowledge of a topic likely have approximately the same number of nodes and links in their respective knowledge maps for that topic. A person with relatively few nodes and links in his or her knowledge map is likely much closer in knowledge to

another person with few nodes and links in their map than they are to a person with many nodes and links in their map, likewise a person with many nodes and links in their map is likely much closer to a person with many nodes and links in their map. To calculate the distance between two maps using this approach the notion of a “map score” is introduced with the map score defined as simply the total number of relationship links and concept nodes in the map, that is $map_i score = n_i + l_i$, where n_i indicates the total number of nodes present in map_i and l_i indicates the number of links in map_i . Under this pseudo metric the distance between two knowledge maps will be given by the absolute value of the difference between the map scores for the individual maps. Using this simple approach the representation of Bloom’s taxonomy embedded within the maps is ignored and the distance between map_1 and map_2 is defined as $d(map_1, map_2) = |map_1 score - map_2 score| = |(n_1 + l_1) - (n_2 + l_2)|$.

Strengths of this pseudo-metric

Non-negativity and Symmetry

The use of the absolute value of the difference between individual map scores ensures that this metric satisfies both the non-negativity and the symmetry requirements.

Triangle Inequality

In order to verify that the triangle inequality holds for this metric it must be established that $d(map_1, map_3) \leq d(map_1, map_2) + d(map_2, map_3) \quad \forall map_1, map_2, map_3 \in M$. For any three maps, map_1 , map_2 , and map_3 , in the set of maps, M , it can be proven that the distance between any two maps, $d(map_1, map_3)$, is no greater than the sum of the distance from the first map to an intermediate map and the distance from the intermediate map to the second map, $d(map_1, map_2) + d(map_2, map_3)$. Due to the use of the absolute value and the fact that all map scores are positive integers, if $map_1 score \geq map_2 score$ then $d(map_1, map_2) = map_1 score - map_2 score$, otherwise $d(map_1, map_2) = map_2 score - map_1 score$. It can also be noted that there are six possible orderings for three maps when they are ranked from highest to lowest by map score. If we denote the ordered triple (i, j, k) to indicate that $map_i score \geq map_j score \geq map_k score$ then six possible ordered triples may be used to notate all possible orderings of three randomly selected maps in set M : $(1, 2, 3)$, $(1, 3, 2)$, $(2, 1, 3)$, $(2, 3, 1)$, $(3, 1, 2)$, and $(3, 2, 1)$. To prove that the triangle inequality holds for all possible map scores the relationship has been demonstrated for each of

the six possible cases as follows. In each case the derivation begins by invoking the definition of the distance function and eventually yields a statement consistent with the stated ordering of the map scores. In each of these six cases the triangulation inequality requires that

$$d(\text{map}_1, \text{map}_3) \leq d(\text{map}_1, \text{map}_2) + d(\text{map}_2, \text{map}_3)$$

and therefore

$$|\text{map}_1\text{score} - \text{map}_3\text{score}| \leq |\text{map}_1\text{score} - \text{map}_2\text{score}| + |\text{map}_2\text{score} - \text{map}_3\text{score}|$$

For the (1,2,3) case:

$$\begin{aligned} |\text{map}_1\text{score} - \text{map}_3\text{score}| &\stackrel{?}{\leq} |\text{map}_1\text{score} - \text{map}_2\text{score}| + |\text{map}_2\text{score} - \text{map}_3\text{score}| \\ \text{map}_1\text{score} - \text{map}_3\text{score} &\stackrel{?}{\leq} \text{map}_1\text{score} - \text{map}_2\text{score} + \text{map}_2\text{score} - \text{map}_3\text{score} \\ \text{map}_1\text{score} - \text{map}_3\text{score} &\leq \text{map}_1\text{score} - \text{map}_3\text{score} \end{aligned}$$

For the (1,3,2) case:

$$\begin{aligned} |\text{map}_1\text{score} - \text{map}_3\text{score}| &\stackrel{?}{\leq} |\text{map}_1\text{score} - \text{map}_2\text{score}| + |\text{map}_2\text{score} - \text{map}_3\text{score}| \\ \text{map}_1\text{score} - \text{map}_3\text{score} &\stackrel{?}{\leq} \text{map}_1\text{score} - \text{map}_2\text{score} + \text{map}_3\text{score} - \text{map}_2\text{score} \\ -2\text{map}_3\text{score} &\stackrel{?}{\leq} -2\text{map}_2\text{score} \\ \text{map}_3\text{score} &\geq \text{map}_2\text{score} \end{aligned}$$

For the (2,1,3) case:

$$\begin{aligned} |\text{map}_1\text{score} - \text{map}_3\text{score}| &\stackrel{?}{\leq} |\text{map}_1\text{score} - \text{map}_2\text{score}| + |\text{map}_2\text{score} - \text{map}_3\text{score}| \\ \text{map}_1\text{score} - \text{map}_3\text{score} &\stackrel{?}{\leq} \text{map}_2\text{score} - \text{map}_1\text{score} + \text{map}_2\text{score} - \text{map}_3\text{score} \\ 2\text{map}_1\text{score} &\stackrel{?}{\leq} 2\text{map}_2\text{score} \\ \text{map}_1\text{score} &\leq \text{map}_2\text{score} \end{aligned}$$

For the (2,3,1) case:

$$\begin{aligned} |\text{map}_1\text{score} - \text{map}_3\text{score}| &\stackrel{?}{\leq} |\text{map}_1\text{score} - \text{map}_2\text{score}| + |\text{map}_2\text{score} - \text{map}_3\text{score}| \\ \text{map}_3\text{score} - \text{map}_1\text{score} &\stackrel{?}{\leq} \text{map}_2\text{score} - \text{map}_1\text{score} + \text{map}_2\text{score} - \text{map}_3\text{score} \\ 2\text{map}_3\text{score} &\stackrel{?}{\leq} 2\text{map}_2\text{score} \\ \text{map}_3\text{score} &\leq \text{map}_2\text{score} \end{aligned}$$

For the (3,1,2) case:

$$|map_1score - map_3score| \stackrel{?}{\leq} |map_1score - map_2score| + |map_2score - map_3score|$$

$$map_3score - map_1score \stackrel{?}{\leq} map_1score - map_2score + map_3score - map_2score$$

$$-2map_1score \stackrel{?}{\leq} -2map_2score$$

$$map_1score \geq map_2score$$

For the (3,2,1) case:

$$|map_1score - map_3score| \stackrel{?}{\leq} |map_1score - map_2score| + |map_2score - map_3score|$$

$$map_3score - map_1score \stackrel{?}{\leq} map_2score - map_1score + map_3score - map_2score$$

$$map_3score - map_1score \leq -map_1score + map_3score$$

Each of the six cases has been proven valid for any positive map score and thus the triangle inequality is satisfied with any metric that uses non-negative values to represent the score for each map and the distance as the absolute value of the difference between the map scores.

Weaknesses of this pseudo-metric

Identity of Indiscernibles

One of the primary drawbacks of this attempt at a metric is that the identity of indiscernibles is not fulfilled. That is to say, it is possible for two maps to have the same map score if they simply have the same number of nodes and links, regardless of which of those nodes and links are encapsulated in that map and what level of knowledge those nodes and links actually encapsulate. This results in a function, d , which evaluates the distance between such maps as being 0 when in fact the maps are not identical. Since this criteria is not fulfilled this cannot be considered a valid metric. Further, it is desirable to establish a metric that encapsulates the Bloom's taxonomy level exhibited within the maps.

4.5.4.2 Binary String-Based Pseudo Metric

In the previous section a metric was proposed that defines the distance between two maps as the absolute value of the difference between the total number of nodes and links present in the respective maps. The weakness of the metric described in section 4.5.4.1 was that it was impossible to distinguish between two maps that have the same number of links and nodes but represent very different topics within the overall set of knowledge. The pseudo-metric defined in

4.5.4.1 can be improved by establishing an improved method of scoring each map. By establishing a map score using a binary string with each bit representing the presence or absence of a particular concept node or relationship link within the map it becomes possible to determine exactly which nodes and links are present. The distance between two maps can still be defined as the absolute value of the difference between the two map scores as it was in 4.5.4.1 only this time the arithmetic for computing the map score will be done in unsigned binary rather than base 10.

Strengths of this pseudo-metric

Since the metric still utilizes non-negative integer map scores then all of the criteria for a metric that were met in the metric presented in section 4.5.4.1 are still met (non-negativity, symmetry, and the triangle inequality). The addition of a unique map score for each map configuration forces the distance to be non-zero between any maps that do not have exactly the same set of nodes and links representing the same concepts and relationships.

Weaknesses of this pseudo-metric

This metric improves upon the metric proposed in 4.5.4.1, but fails to account for the level of Bloom's taxonomy encapsulated within the map. The selection of which binary bits are used to represent which nodes and links should be done carefully so as to assign a proper weighting to each map and link. If one map contains a particular node or link and another map is missing that same node or link then the distance between the maps will increase proportionally to the place value assigned to that particular node or link. An appropriate weighting scheme must be developed so that nodes are given appropriate precedence so that the distances are not inappropriately enlarged due to a single missing node or link. The next section discusses how place value can be used to assign an appropriate weighting to a node or link and how different bases can be used to distinguish the various levels of Bloom's taxonomy.

4.5.4.3 Place Value Based Metric

The pseudo-metric introduced in 4.5.4.1 fulfilled three of the four requirements for a metric: non-negativity, symmetry, and the triangle inequality, but failed to satisfy the identity of indiscernibles. In 4.5.4.2 this pseudo-metric was expanded to establish a unique map score such that the identity of indiscernibles was partially fulfilled without accounting for the representation of Bloom's taxonomy within the maps. In order to continue using a similar distance function

that can be considered a true metric and is a more logical approach to knowledge quantization it is imperative to establish a more robust map scoring system. While the pseudo metric in 4.5.4.2 proposed the use of binary bits to represent the presence or absence of a corresponding node or link the method for assigning bits was not discussed. Higher-order bits should be used to represent nodes or links that are more important to a discipline and lower-order bits should be used to represent topics that have less relevance to the topic than other more key topics. This section introduces the notion of map centrality to establish node and link weighting and uses the principle of place value to establish a unique map score that accounts for the representation of Bloom's taxonomy within the maps.

In order to represent the various levels of Bloom's taxonomy within the maps we can simply replace a binary representation of the maps with a representation in base 7. By using base 7 the digits corresponding to each concept node and relationship link can take on a value corresponding to the appropriate Bloom's taxonomy level the student demonstrated when they answered the questions in the concept inventory with 1 representing knowledge, 2 representing understanding, 3 representing application, 4 representing analysis, 5 representing synthesis, and 6 representing evaluation. The digit 0 is used to represent any concept node or relationship link that a student has demonstrated no knowledge of based upon incorrect answers to all questions in the concept inventory associated with the particular concept or relationship. As a very simple example, consider a simple concept map with two concepts and one linking phrase (such as the one depicted in Figure 4.9). If this map were to be represented using base 7 and the most significant digit was assigned to one concept, the least significant digit were assigned to the relationship between the concepts, and the middle digit were assigned to the second concept then the value 523 would represent a person who has synthesis level knowledge of the first concept, understanding level knowledge of the second concept, and application level knowledge of the relationship between the concepts.

Assignment of place value

In order to establish the best possible numeric representation of a map it becomes important to appropriately assign the place within the representation scheme to each node or edge in the map. Concepts are the core of the concept maps so while relationships are important to link them together one could argue that understanding of the concepts should be regarded as more important than understanding the relationships between the concepts. A numbering

scheme is thus proposed to represent all concepts with higher order digits than the relationships between concepts. In order to set an ordering within the concepts it is important to determine which concepts are most central to the overall discipline. Those with the most relationships connected to them are most likely to be very important whereas those that are only connected by one relationship or a small number of relationships are likely of lesser importance. These heuristics are not necessarily prescriptive of the most appropriate numeric representation for each domain, but they provide a general approach that could be utilized for maps of every domain. Someone with more knowledge of the domain could apply more specific scoring criteria manually, but this approach provides a general starting point for evaluating the importance of each node and relationship in a knowledge map.

Consider once again the simple concept map in Figure 4.17 (presented again for reference in Figure 4.26). Since there are a total of six concepts and six relationships represented in the map, any map score corresponding to this map would be 12 digits long. By prioritizing concepts over relationships for scoring purposes the digits associated with nodes 1 through 6 will be given the six higher order digits and the six lower-order digits will be associated with relationships A through E. Concept 1 has 4 relationships linked to it and would thus be considered the most central and most important concept in the map and the best candidate for the most significant digit. Concepts 3, 4, and 6 all have two relationships connecting them in the map and concepts 2 and 5 both have one concept connecting them to the map. Without any more insight into the concepts and relationships represented in the maps one can assume that concepts 3, 4, and 6 are of roughly equal importance and concepts 2 and 5 are of roughly equal importance with the first

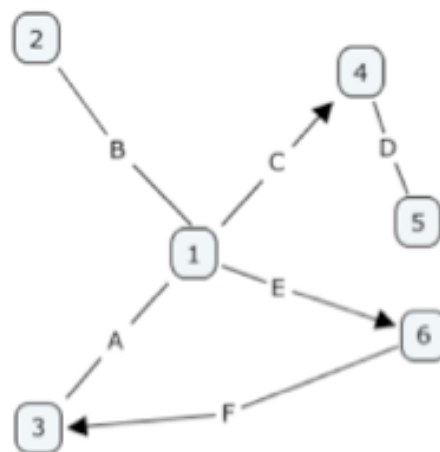


Figure 4.26 A simple concept map

group of concepts being more valuable than the second due to the greater number of relationships attached to them. The place value assignments for relationships can be made based upon which relationships are connected to the most important nodes. This prioritization can be done by summing the total number of relationships connected to the two concepts that the relationship joins.

Table 4.15 delineates which concepts are connected by each of the relationships represented in the map depicted in Figure 4.26. As can be seen in the table, relationship A connects concept 1 (four relationships) and concept 3 (two relationships) for a linkage of concepts with six total associated relationships. Relationships A, C, and E are all connected to concepts with a total of six relationships involved. These three relationships should receive the highest priority in terms of place value followed by relationship B, which connects concepts with five total relationships, relationship F, which connects concepts with four total relationships, and relationship D with three total relationships. In the case of ties, place values are assigned arbitrarily so one possible place value scheme that can be used to represent the map score for a knowledge map based on the comprehensive map depicted in Figure 4.26 would be $\langle 1 \rangle \langle 3 \rangle \langle 4 \rangle \langle 6 \rangle \langle 2 \rangle \langle 5 \rangle \langle A \rangle \langle C \rangle \langle E \rangle \langle B \rangle \langle F \rangle \langle D \rangle$ where each of the brackets would correspond to a digit 0 through 6 corresponding to the Bloom's taxonomy level of mastery demonstrated for each of the associated concepts or relationships. The distance between maps is then computed once again as the absolute value of the maps scores resulting in a sizeable base 7 value for each distance

Relationship	Concept ₁	# Rel Attached to Concept ₁	Concept ₂	# Rel. Attached to Concept ₁	Total relationships connected to related concepts
A	1	4	3	2	6
B	1	4	2	1	5
C	1	4	4	2	6
D	4	2	5	1	3
E	1	4	6	2	6
F	3	2	6	2	4

Table 4.15 The concepts associated by each relationship and the total number of concepts associated with the connected nodes.

Strengths of this metric

This metric satisfies all of the requirements for a metric, non-negativity, symmetry, the triangle inequality, and the identity of indiscernibles. Additionally, this metric accounts for the level of knowledge in Bloom's taxonomy encapsulated in the maps.

Weaknesses of this metric

The metric unfortunately assigns place value to concepts and relationships of equal importance in an arbitrary manner. If two concepts have the same number of relationships connected to them then in an arbitrary assignment of place value then these equally important concepts are given weights that differ in magnitude by a factor of 7. Given n concepts of equal value, in an arbitrarily assigned weighting the concept assigned to the highest-valued digit has a magnitude of 7^{n-1} times larger than the value of the concept assigned to the lowest-valued digit. This difference in arbitration can amount to significant differences in distance. Further, since this map scoring strategy requiring one digit for each concept and relationship the map scores can become very large for large maps and may risk overflow in some computer numeric representations.

4.5.4.4 Hamming Distance-Based Place Value Metric

In 1950 Robert Hamming introduced a method for detecting the number of errors in transmitted binary strings by comparing two binary strings of equal length and counting the number of differing bits between the two strings. This method has since been termed the Hamming distance [73]. The traditional Hamming distance simply compares a received binary string to the expected binary string adding one for every bit that is a 1 that should be a 0 or vice versa. As an example, the Hamming distance between the binary strings 00101010 and 00010100 is 5 because there are five bit positions that differ from the first to the second string, whereas the hamming distance between 0010 and 0011 is 1 because only one bit position differs.

A modified hamming distance can be used in order to eliminate the arbitrary assignment of differing values to concepts of equal importance and to reduce the magnitude of distance values for large maps. In so doing the maps can be represented using base 7 in a two-dimensional structure such that all of the concepts that are considered to be of equal importance (per the requirements delineated in 4.5.4.3) are clustered together as are all of the relationships of equal importance. A modified version of the hamming distance can be computed in base 7 on

each cluster by determining the ceiling of the mean of the absolute value of the difference between the enumerated Bloom’s taxonomy value (1 represents knowledge level, 2 represents understanding, 3 represents application, 4 represents analysis, 5 represents synthesis, 6 represents evaluation, and 0 represents no knowledge of the subject) for each corresponding concept or relationship within each cluster. The overall distance between the two maps is computed by simply concatenating the values for each cluster together in order of importance to form a base 7 value. Thus the average distance between concepts or relationships in each cluster produces a base 7 digit and the significance of each digit is based upon the importance of the elements within each cluster. Mathematically the cluster score, C_j , is given by

$$C_j = \left\lceil \frac{\sum_{i=1}^N |B_{i1} - B_{i2}|}{N} \right\rceil,$$

where N indicates the number of concepts or relationships in the cluster and B_{i1} and B_{i2} indicate the enumerated Bloom’s taxonomy level of the corresponding concepts or relationships in map_1 and map_2 . The ceiling function is used to force the cluster score to be an integer value between 0 and 6, inclusive, forming a valid base 7 digit. The ceiling function also prohibits any non-zero distances to evaluate to 0, which allows the identity of indiscernibles to be satisfied. The overall distance between two maps is simply computed as the base 7 concatenation of each cluster from most to least important.

Clustering the elements of the concept map in Figure 4.26 using this method would establish seven groups of equally important map elements as depicted in Table 4.16 left to right from greatest to least importance. As an example of computing the distance between maps using this metric, consider Table 4.17 and Table 4.18 representing the knowledge encapsulated in two different potential student maps at varying levels of Bloom’s taxonomy. These tables represent

Concepts			Relationships			
1	3	2	A	B	F	D
	4	5	C			
	6		E			

Table 4.16 Clustering map elements from most to least important

Concepts			Relationships			
1 Knowledge (1)	3 Understanding (2)	2 Analysis (4)	A Application (3)	B Analysis (4)	F None (0)	D None (0)
	4 Knowledge (1)	5 Knowledge (1)	C Knowledge (1)			
	6 None (0)		E None (0)			

Table 4.17 A potential tabulation of a student's understanding of the concepts and relationships in the map depicted in Figure 4.26

Concepts			Relationships			
1 Understanding (2)	3 Knowledge (1)	2 None (0)	A Application (3)	B None (0)	F Analysis (4)	D None (0)
	4 Knowledge (1)	5 Knowledge (1)	C None (0)			
	6 Application (3)		E Knowledge (1)			

Table 4.18 Another potential tabulation of a student's understanding of the concepts and relationships in the map depicted in Figure 4.26

students who have varying mastery of each of the concepts and relationships involved in the comprehensive map in Figure 4.26. Both of the students whose knowledge is represented in these tables have some concepts or relationships that have reached level 4 (analysis) and both of them also have some concepts and relationships that they have demonstrated no knowledge of. For a few of the concepts and relationships the students are at the same level of mastery, but the maps indicate quite a few differences in proficiency with the associated concepts and relationships.

In the leftmost (most significant) grouping the modified hamming distance value is given by:

$$\left\lceil \frac{|2-1|}{1} \right\rceil = 1$$

In the next group the modified hamming distance value is given by:

$$\left\lceil \frac{|2-1| + |1-1| + |0-3|}{3} \right\rceil = \left\lceil \frac{4}{3} \right\rceil = 2$$

In the third group the modified hamming distance value is given by:

$$\left\lceil \frac{|4-0| + |1-1|}{2} \right\rceil = \left\lceil \frac{4}{2} \right\rceil = 2.$$

This process continues for the remaining four groups of relationships with values 1, 4, 4, and 0, respectively. Of particular interest is the fourth cluster that contains three relationships. In both of the example student maps the students demonstrated application level mastery of relationship A. The students demonstrated similar abilities with the other two relationships with one student demonstrating knowledge level of relationship C and no knowledge of relationship E and the other student demonstrating the opposite, no knowledge of relationship C and knowledge level of relationship E. Despite having the same three levels of Bloom's taxonomy in the cluster of three relationships in both maps, the cluster score for this particular cluster is 1. The only way that a cluster score can evaluate to 0 is if all of the corresponding concepts or relationships are assigned the same Bloom's taxonomy level. In turn, the only way that the overall distance between the maps can evaluate to 0 is if each cluster score is 0 meaning that every single concept and relationship in the map is at the same level of Bloom's taxonomy. Thus the identity of indiscernibles requirement is fulfilled even in consideration of the Bloom's taxonomy levels encapsulated within the maps.

Continuing this example, the difference between the two student maps would be given by 1221440₇ or 156,632 decimal. This indicates that on average there was a difference of 1 level of Bloom's taxonomy in the most significant cluster when the proficiency of like concepts were compared, a distance of 2 levels in the second cluster, a distance of 2 levels in the third level, and so forth. The biggest disparity between the two maps was in the fifth and sixth clusters where one student demonstrated analysis level proficiency of a relationship and the other student had no knowledge of the relationship at all, resulting in a cluster distance of 4. The most extreme distance between maps would be 6 for each cluster indicating one student who had no knowledge

of any concepts or relationships in the cluster and another student who had evaluation level proficiency for every concept and relationship in the cluster.

Strengths of this metric

By using the arithmetic mean of the absolute value of element-wise differences non-negativity, symmetry, and the triangle inequality are satisfied. The use of the ceiling function on the averages forces each of the cluster scores to be an integer and a legal base 7 digit. Using the ceiling function (as opposed to the floor function or rounding) prohibited any differences in student maps from yielding a distance of 0 and thus the identity of indiscernibles is satisfied. This metric also ensures that all equally valuable concepts and relationships are given an equal weighting in consideration of the overall distance between maps. By clustering equally valuable nodes and links the distance between maps becomes a smaller value and avoids some problems of computational overflow that may exist for larger maps.

Weaknesses of this metric

Although not very difficult to compute, this metric requires more rigorous mathematical analysis when compared with the simple metrics and pseudo-metrics previously discussed. This metric also maximizes the distance between two maps. For instance in Table 4.17 and Table 4.18 the first student had knowledge of relationship C and the second student did not whereas the second student had knowledge of relationship E and the first student did not. Logically with these map elements being of equal value one might expect that the maps would be close to one another in distance, but these two differences do not cancel each other, but are rather additive. Some of the detail is lost with this metric when compared with the place value metric described in section 4.5.4.3 due to the computation of the average value in each cluster. This metric makes it more difficult to determine the exact concept or relationship contributing to the overall distance between the maps. This metric also assumes that the progression from one level of Bloom's taxonomy to another is linear, which may not be the case in reality. It is outside the scope of this work to determine a function representative of the transition from one Bloom's taxonomy level to another over time.

4.5.5 Example Applications of the metrics and pseudo-metrics

In this section the metric and pseudo-metrics will be applied to three simple knowledge maps. Consider the example student maps depicted in Figure 4.27, Figure 4.28, and Figure 4.29,

which represent three different students' knowledge of the concepts and relationships in the comprehensive knowledge map depicted in Figure 4.26. As can be seen, no student has a complete map indicating that they have a working knowledge of every concept and relationship in the comprehensive map. Some students appear to have a more complete understanding than others based upon the quantity of nodes and links that are present. The student whose knowledge is represented in Figure 4.27 does not have knowledge of concept 2 or relationship B. The student whose knowledge is represented in Figure 4.28 does not have knowledge of concepts 3 or 6 or relationships A, E, and F. The student whose knowledge is represented in Figure 4.29 does not have knowledge of concept 5 or relationship D. For simplicity's sake consider that in the comprehensive map all nodes and relationships are capable of being represented at every level within Bloom's taxonomy from "knowledge" to "evaluation." Also consider for this simple case that every node and relationship in the map for student 1 is at the "knowledge" (first) level, every node and relationship in the map for student 2 is at the "understanding" (second) level, and every node and relationship in the map for student 3 is at the "application" (third) level.

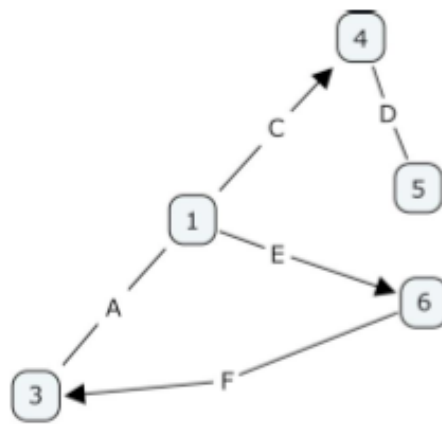


Figure 4.27 A knowledge map for student 1

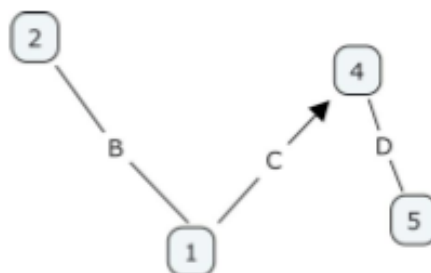


Figure 4.28 A knowledge map for student 2

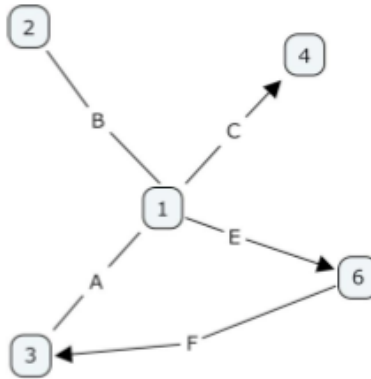


Figure 4.29 A knowledge map for student 3

Table 4.19 depicts the map scores for each of the student maps based upon the first three proposed map scoring strategies discussed in sections 4.5.4.1, 4.5.4.2, and 4.5.4.3. As can be seen in the table, despite the differences in the maps for student 1 and student 3 the map scores are the same under the counting pseudo-metric showcasing how this pseudo-metric fails to satisfy the identify of indiscernibles. The differences between the maps are illustrated in more detail using the binary string and place value methods.

The Hamming distance-based place value metric does not rely upon an individual map score in the same manner as the other three metrics. Tabulations of the clustering done in the Hamming distance-based metric are depicted in Table 4.20, Table 4.21, and Table 4.22 for the maps in Figure 4.27, Figure 4.28, and Figure 4.29, respectively.

Based upon the map scores in Table 4.19 and the clustering of map elements depicted in Table 4.20, Table 4.21, and Table 4.22 the distance between each of the student’s knowledge (comparative knowledge) as well as the distance between each student map and the comprehensive map (knowledge gap) can be computed using the four different approaches as shown in Table 4.23. Comparative knowledge differences between students are notated as $D(m,n)$ for positive integers m and n indicating the difference between the student map for

		Scoring Method		
		Counting	Binary String	Place Value
Map Scored	Student 1	10	1111 0111 1011 ₂	1111 0111 1011 ₇
	Student 2	7	1010 1101 0101 ₂	2020 2202 0202 ₇
	Student 3	10	1111 1011 1110 ₂	3333 3033 3330 ₇
	Comprehensive	12	1111 1111 1111 ₂	6666 6666 6666 ₇

Table 4.19 Map Scores for each student map (Figure 4.27-Figure 4.29) and the comprehensive map (Figure 4.26) based on each proposed metric or pseudo-metric

Concepts			Relationships			
1 Knowledge (1)	3 Knowledge (1)	2 None (0)	A Knowledge (1)	B None (0)	F Knowledge (1)	D Knowledge (1)
	4 Knowledge (1)	5 Knowledge (1)	C Knowledge (1)			
	6 Knowledge (1)		E Knowledge (1)			

Table 4.20 A tabulation of the clustering of concepts and relationships in the map depicted in Figure 4.27

Concepts			Relationships			
1 Understanding (2)	3 None (0)	2 Understanding (2)	A None (0)	B Understanding (2)	F None (0)	D Understanding (2)
	4 Understanding (2)	5 Understanding (2)	C Understanding (2)			
	6 None (0)		E None (0)			

Table 4.21 A tabulation of the clustering of concepts and relationships in the map depicted in Figure 4.28

Concepts			Relationships			
1 Application (3)	3 Application (3)	2 Application (3)	A Application (3)	B Application (3)	F Application (3)	D None (0)
	4 Application (3)	5 None (0)	C Application (3)			
	6 Application (3)		E Application (3)			

Table 4.22 A tabulation of the clustering of concepts and relationships in the map depicted in Figure 4.29

student m and the student map for student n. The knowledge gap is denoted by $D(m,C)$ indicating the distance between the student map for student m and the comprehensive map. It should be noted how the Hamming distance-based metric showcases very similar distance between the comprehensive map and each individual student map when compared to the distance expressed using the place value metric, but uses only 7 places instead of 12, reducing the overall value of the distance by a factor of 7^5 or 16801 decimal. Added concept nodes or relationship

	Counting	Binary String	Place Value	Hamming distance
Comparative Knowledge				
D(1,2)	3	0100 1010 0110 ₂	061620606161 ₇	1121211 ₇
D(1,3)	0	0000 0100 0011 ₂	222226222316 ₇	2222321 ₇
D(2,3)	3	0100 1110 1001 ₂	131305313121 ₇	1323132 ₇
Knowledge Gap				
D(1,C)	2	0000 1000 0100 ₂	5555 6555 5655 ₇	5565655 ₇
D(2,C)	5	0101 0010 1010 ₂	4646 4464 6464 ₇	4646464 ₇
D(3,C)	2	0000 0100 0001 ₂	333336333336 ₇	3353336 ₇

Table 4.23 The distance between student maps (comparative knowledge) and the difference from each student map to the comprehensive map (knowledge gap) based upon the proposed metrics and pseudo – metrics. D(1,2) is used to denote the difference between the student maps for student 1 and student 2 and D(1,C) indicates the distance between the student map for student 1 and the comprehensive map.

links would likely fit into some preexisting clusters and would not increase the size of the distance, whereas the use of the place value metric would most certainly require larger values to express the distance for each added concept and relationship.

4.6 Developing Aggregate Maps Representing the Knowledge of Groups of Students

4.6.1 Reasons for Aggregate Map Development

Just as individual student work can be evaluated to form a student map, the aggregate results from all students in a class may be evaluated to determine what portion of the students in the class learned each of the concepts and relationships. In this way it can be determined if all students learned a particular subject or if most students failed to learn it. The aggregate map of all students in a section of a course is created by summing up the number of students with each node and link present in their student map. Instructors are able to view an aggregate student map and determine that some percentage of students mastered one concept while a different percentage of students mastered another. Faculty can use aggregate maps to keep records of past semesters to compare how student understanding of the concepts involved in a course changes with time and any modifications made in the course from semester to semester. This will allow them to see if any implemented curriculum changes improved student learning or if such changes should be reversed or modified.

In addition to forming aggregates based upon the maps from the entire class, aggregates can be formed based upon reported demographics. In this way instructors can do a more thorough analysis to determine if there is any difference in understanding based upon factors

such as gender, age, ethnicity, grade point average, class time, etc. Analysis of demographic-based aggregate maps can determine if there are biases in the curriculum. This type of analysis can help instructors determine at the conceptual level if there are distinctions in understanding between A students and B students, between male students and female students, etc.

In [5], Mimi Steadman states “faculty need more opportunities to come together and talk about teaching.” This should be an ongoing process and these aggregate maps provide an open door to such discussions. Instructors can compare the aggregate maps generated for the courses they teach with the aggregate maps generated for other instructors to determine areas they can improve and can collaborate to form optimal teaching strategies.

4.6.2 Aggregate Map Generation Example

In software each node and link in a set of student maps may be counted to determine how many students had each node present or missing in their student map. Consider once again the comprehensive knowledge map depicted in Figure 4.17. It may be that all students had a mastery of the most centralized concept, 1, but students typically missed concept 3 and relationship F. This may indicate that the method of presentation of these lesser-learned concepts and relationships should be modified in the future to improve overall student understanding.

As an example of how faculty members can use aggregate maps to compare the results of their teaching, consider two different sections of the same course taught by different instructors, Instructor1 and Instructor2. Suppose the three student maps depicted in Figure 4.30, Figure 4.31, and Figure 4.32 were generated from student responses in Instructor1’s section of the course. Likewise, Figure 4.33, Figure 4.34, and Figure 4.35 depict three student maps for students of Instructor2. For simplicity, assume each instructor has only three students in their class and that the student maps are all based on the generic comprehensive map that has been presented in Figure 4.17 and used throughout this chapter.

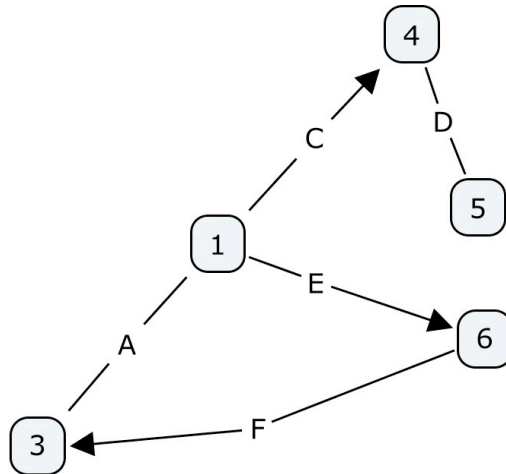


Figure 4.30 One student map from Instructor1's section of a course

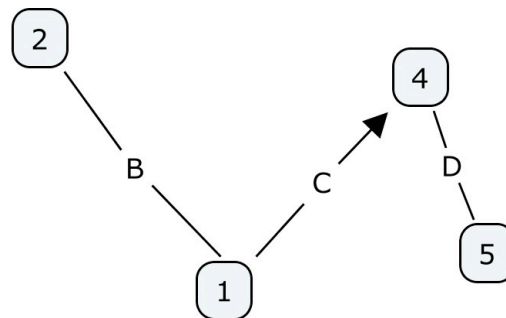


Figure 4.31 A second student map from Instructor1's section of a course

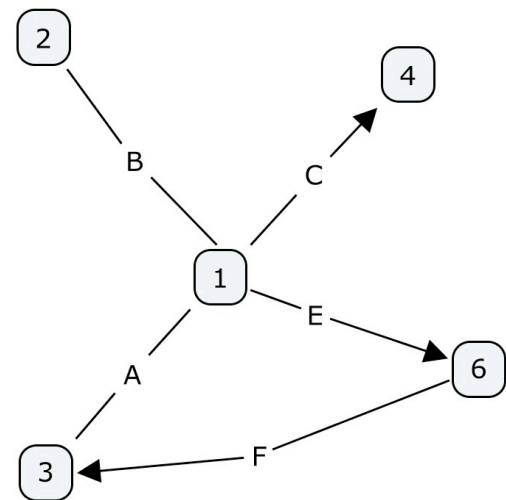


Figure 4.32 A third student map from Instructor1's section of a course

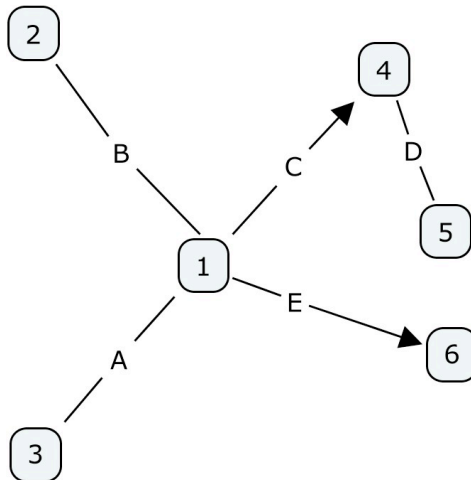


Figure 4.33 One student map from Instructor2's section of a course

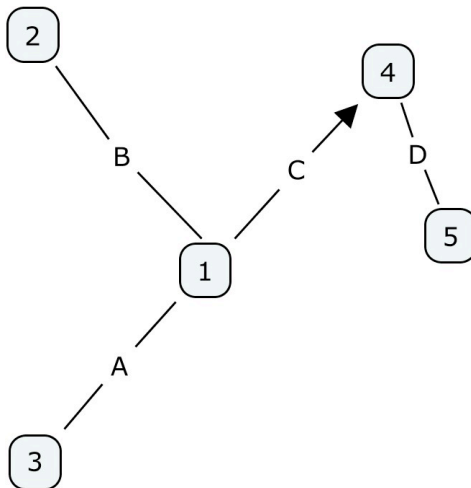


Figure 4.34 A second student map from instructor2's section of a course

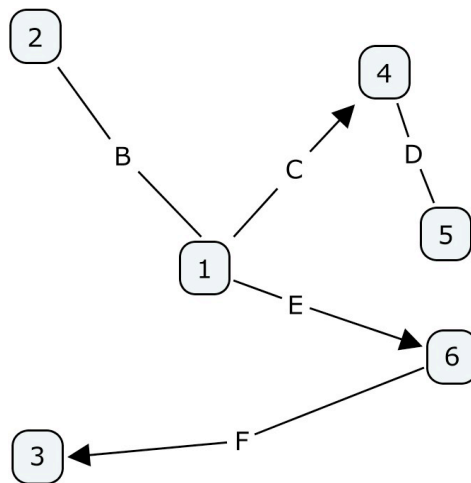


Figure 4.35 A third student map from instructor2's section of a course

Each of the six maps presented in Figure 4.30 - Figure 4.35 are different indicating that, although all students were in the same class, no two students had the exact same mastery of the course concepts. The aggregate maps for the two sections are depicted in Figure 4.36 and Figure 4.37 for Instructor1 and Instructor2, respectively. While statistical significance would be impossible to attain with such a small sample size (only three students in each class), one can notice that there are some concepts that appear to have been mastered differently based on the instructor teaching the class. For instance, 100% of instructor2's students demonstrated mastery of concept 3 while only 67% of Instructor1's students mastered this concept. With this method applied to a larger section of the course, the differences in the effectiveness of communicating each topic may be determined and statistical analysis may be performed.

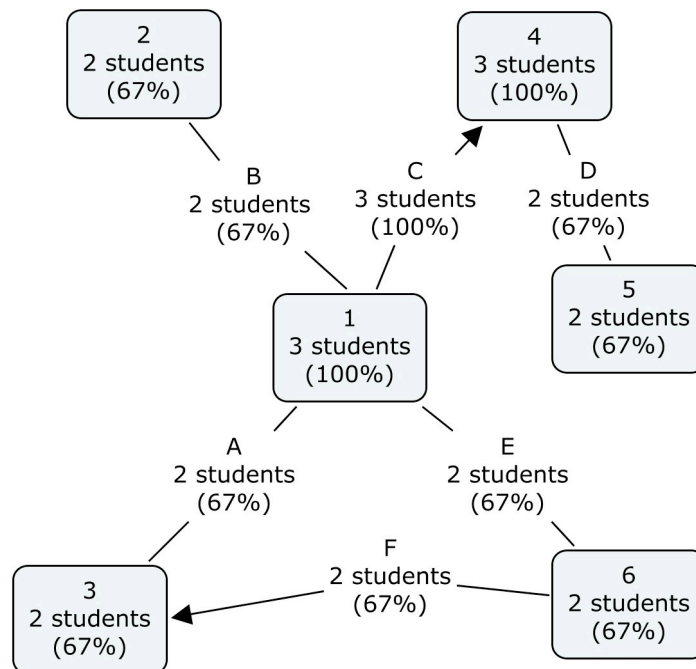


Figure 4.36 Aggregate knowledge map for all three students in Instructor1's class

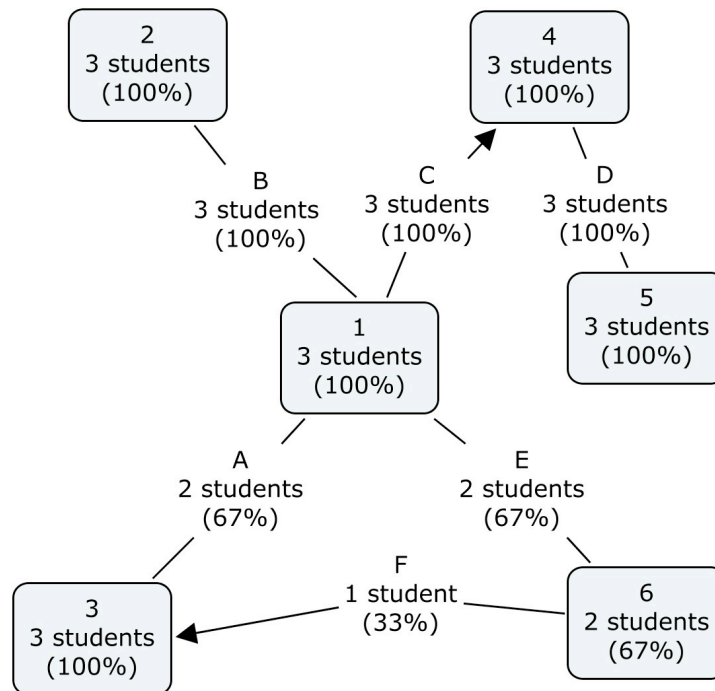


Figure 4.37 Aggregate knowledge map for all three students in Instructor2's class

4.6.3 Aggregate Map Generation Software

As depicted in Figure 4.38, the software designed to generate an aggregate knowledge map takes in the comprehensive map and the directory location for a class set of student maps based upon the information in that comprehensive map. The software gives the user the option to create maps based on all student maps in the directory or based on specific demographic criteria. If the user selects to generate maps based on demographic criteria then the “Import Demographics” button appears. When a user clicks on this button all of the student maps in the Student Map Directory are opened and scanned for the entries in the demographics section of the metadata (as described in Table 4.13). All of the demographic categories and entries represented in the set of student maps in the directory are then added to the tree view on the bottom right of the dialog box. The user then has the option to check which criteria they want to use as the basis for the aggregate map. The radio buttons to the left are used to indicate whether the aggregate maps should be based on maps for students meeting any of the selected demographics requirements or if the map should be based on students meeting all of the demographic requirements.

When the user clicks on the button labeled “Generate Maps(s)” the program searches through each map in the given directory that meets the selected criteria and tabulates how many maps contain each of the concepts and relationships present in the comprehensive map. The

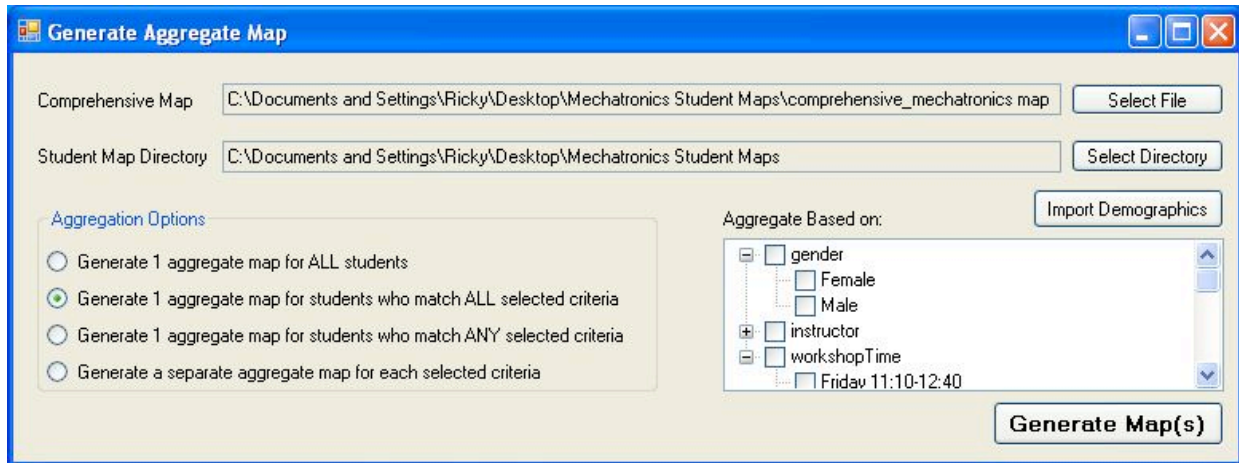


Figure 4.38 Aggregate Map Generation Software

software also examines the Bloom’s taxonomy data for each concept and determines the average portion of questions answered at each level for each concept and relationship. A color scheme similar to the one describe in section 4.4.2 is used to display each concept and relationship in an appropriate color representing the average level of understanding of students in the group forming the aggregate.

The comprehensive map may be stored in the same directory as the student maps and the search algorithm ensures that the comprehensive map and any previously generate aggregate maps are ignored when tabulating the concept and relationship counts. The program uses a naming convention to ensure that without opening the file the demographic group(s) encapsulated within the map are understood. The aggregate map for all student maps in the directory is named “aggregate_map_all.cxl.” The ‘|’ character is used to separate demographics represented in an aggregate map formed based upon any of several selected demographics with the naming convention “aggregate_map_<demographic category 1>_<demographic entry 1>|<demographic category 2>_<demographic entry 2>|...cxl,” for example the aggregate map representing the set of female students or students taught by any of the three female instructors would be named “aggregate_map_gender_Female|instructor_Jane Doe1|instructor_Jane Doe2|instructor_Jane Doe3.cxl.” Similarly the & is used to separate the demographics in aggregate maps formed based upon students meeting all of the selected criteria, for example the aggregate map based upon students in John Doe’s workshop that meets each week on Friday at 8AM would be named “aggregate_map_instructor_John Doe&workshop time_Friday 8:00-9:30.cxl.”

4.6.4 Example Aggregate Maps

4.6.4.1 Aggregate Maps from Fall 2008 EngE 1024 Class

Figure 4.39 is the aggregate map representative of all students participating in the EngE 1024 mechatronics unit in Fall 2008. The results presented in Figure 4.39 indicate that most students were able to identify electrical components and their schematic symbols. Students had a good understanding of electrical concepts such as voltage and current. Many students struggled with some of the Boolean logic concepts including the ability to identify logic gates and corresponding truth tables. There are a few concepts and relationships in the aggregate map that no student had in their student map. Some of these concepts and relationships relate to the notion that energy cannot be created or destroyed. In the corresponding concept inventory question students were asked to identify correct properties of energy with one of the options being that energy *can* be created. Since energy cannot be created, a student correctly understanding this concept would not select that answer. The problem with analyzing answers to such questions is determining whether a student did not check that answer because they indeed did know that energy cannot be created or destroyed or if they simply did not answer the question at all. The truth table for the AND gate is not present in any student map due to a typo in the concept inventory resulting in the proper answer not being present. The purpose of a battery was not tested in the inventory, and thus does not appear in any student maps, but was included in the comprehensive map for consistency with other components since the purpose all other components is included in the map.

Figure 4.40 and Figure 4.41 are the aggregate maps based upon the EngE 1024 mechatronics unit for male and female students, respectively. The maps for both genders are quite similar. A thorough gender-based analysis of the data is beyond the scope of this work, but upon examination of the data it does appear that male students on average answered slightly more questions correctly than female students. This is particularly noticeable in some of the computer engineering concepts and in the identification of electrical components and schematic symbols. Students of both genders were quite successful at learning electrical concepts such as energy, current, and voltage and had very similar performance on some of the mechanical concepts such as friction and force and the various questions related to gears. The differences in gender-based conceptual understanding are possibly due to prior experience with electronics. In a study taken of the students in EngE 1024 in Fall 2006 students were asked if they had any prior

experience working with breadboards and circuit components. Of those responding, 41.9% of males indicated prior experience while only 32.5% of females indicated prior experience [69]. Since a larger portion of male students had prior experience this exercise reinforced their prior knowledge while a larger portion of females were seeing these components for the first time.

Figure 4.42 is the aggregate map for the students in the author's workshops and Figure 4.43 is the aggregate map for another instructor. The concepts and relationships in the map represent information gained through the online lecture as well as the hands-on activity in the workshop. Since this is a team taught course with a common lecture and separate workshops, it is difficult to do an instructor-based analysis using simply these two maps without looking specifically and which information students learned from the lecture and which information students learned in the workshop. The hands-on activity illustrated the various electrical components and the students represented in the map in Figure 4.42 showed a much greater ability to identify such components, their schematic symbols, and their purpose.

4.6.4.2 Aggregate Maps from Spring 2009 EngE 1104 Class

Figure 4.44 is the aggregate map for all students participating in the EngE 1104 autonomous vehicles unit in Spring 2009. This map shows both the retention students have of the concepts learned one semester prior during their enrollment in EngE 1024 and their new insights based upon completion of the autonomous vehicles unit. It is important to note that most of these students intend to major in electrical engineering, computer engineering, or computer science so that may explain why these students had a very strong command of the various computer engineering and electrical engineering concepts and relationships. Their retention of mechanical concepts was also quite good and comparable to those taking the survey after just completing the unit. These results may have been influenced by the fact that most engineering majors at Virginia Tech take a Newtonian physics course during their second semester of enrollment (which is the same time these students were taking EngE 1104).

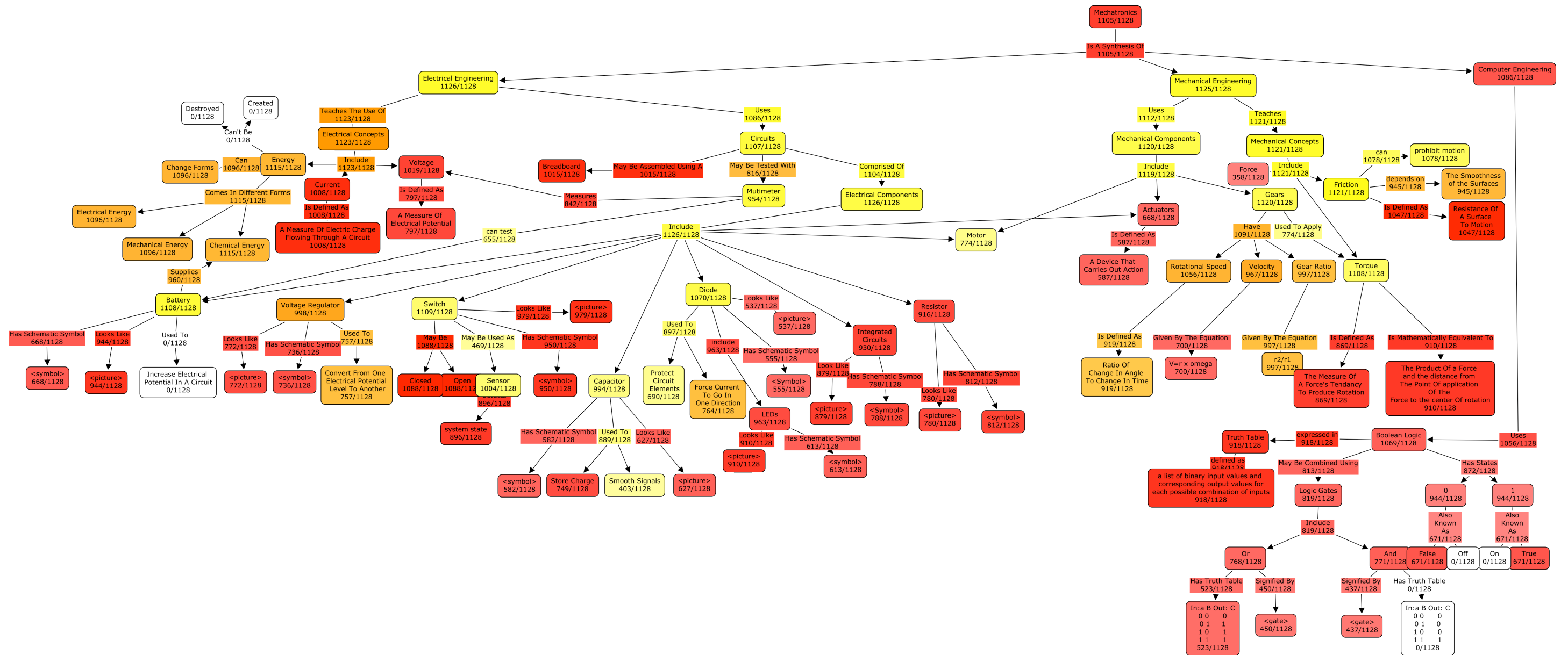


Figure 4.39 Aggregate map representing the overall understanding of all students participating in the EngE 1024 mechatronics unit during Fall 2008 (n=1128).

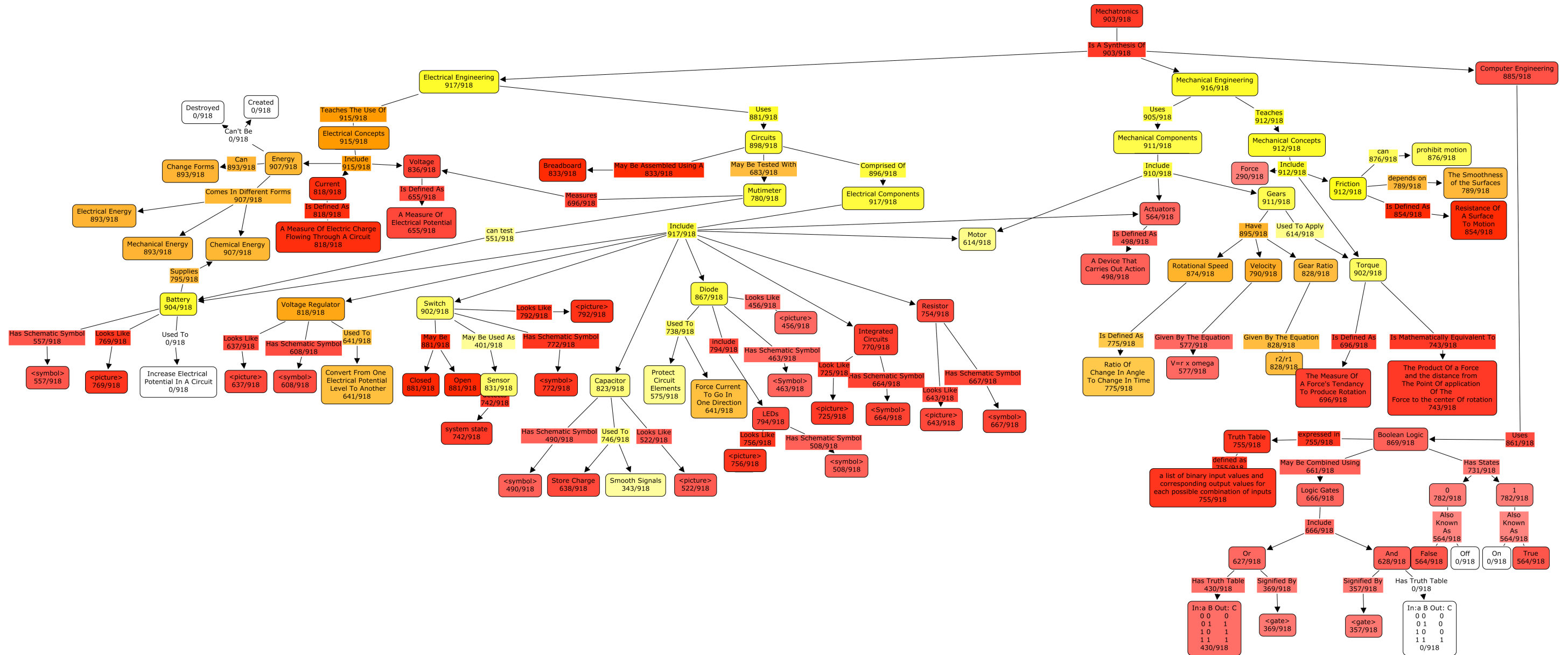


Figure 4.40 Aggregate map representing the overall understanding of male students participating in the EngE 1024 mechatronics unit during Fall 2008 (n=918).

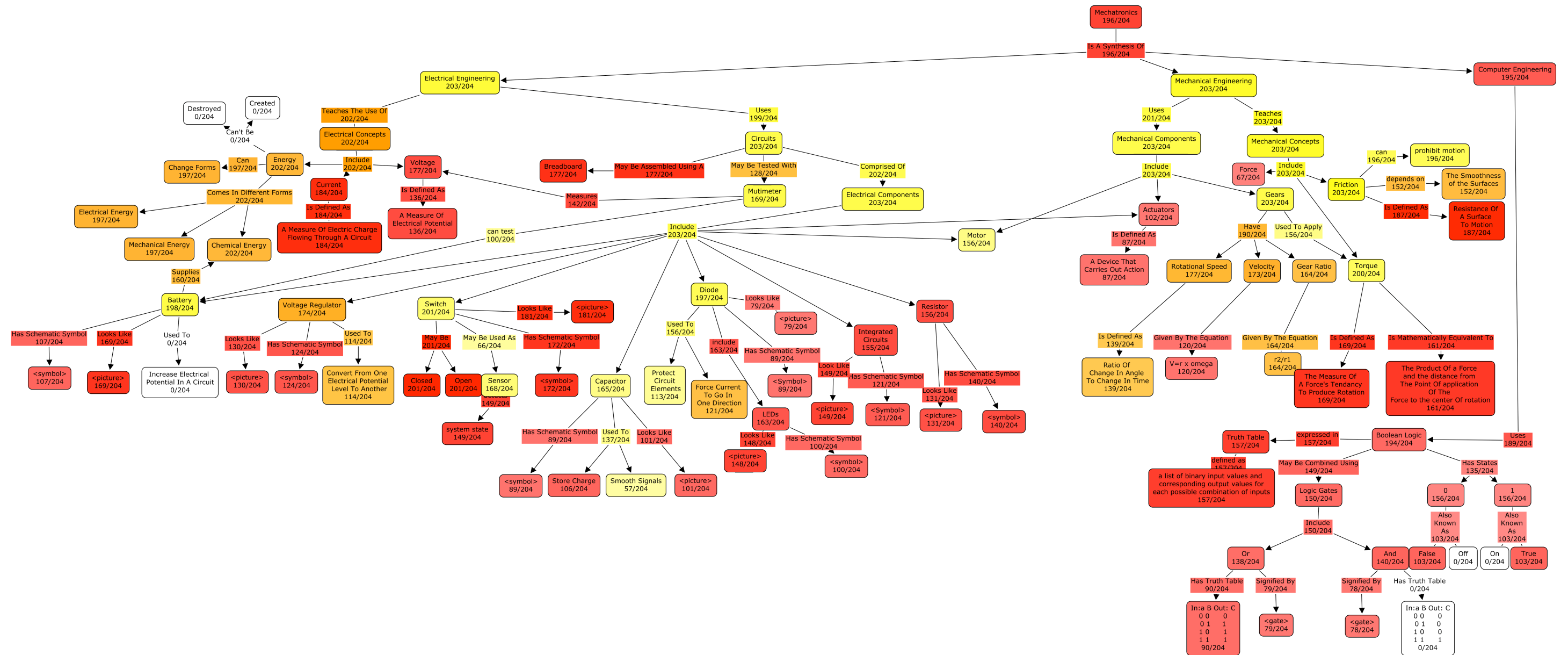


Figure 4.41 Aggregate map representing the overall understanding of female students participating in the EngE 1024 mechatronics unit during Fall 2008 (n=204).

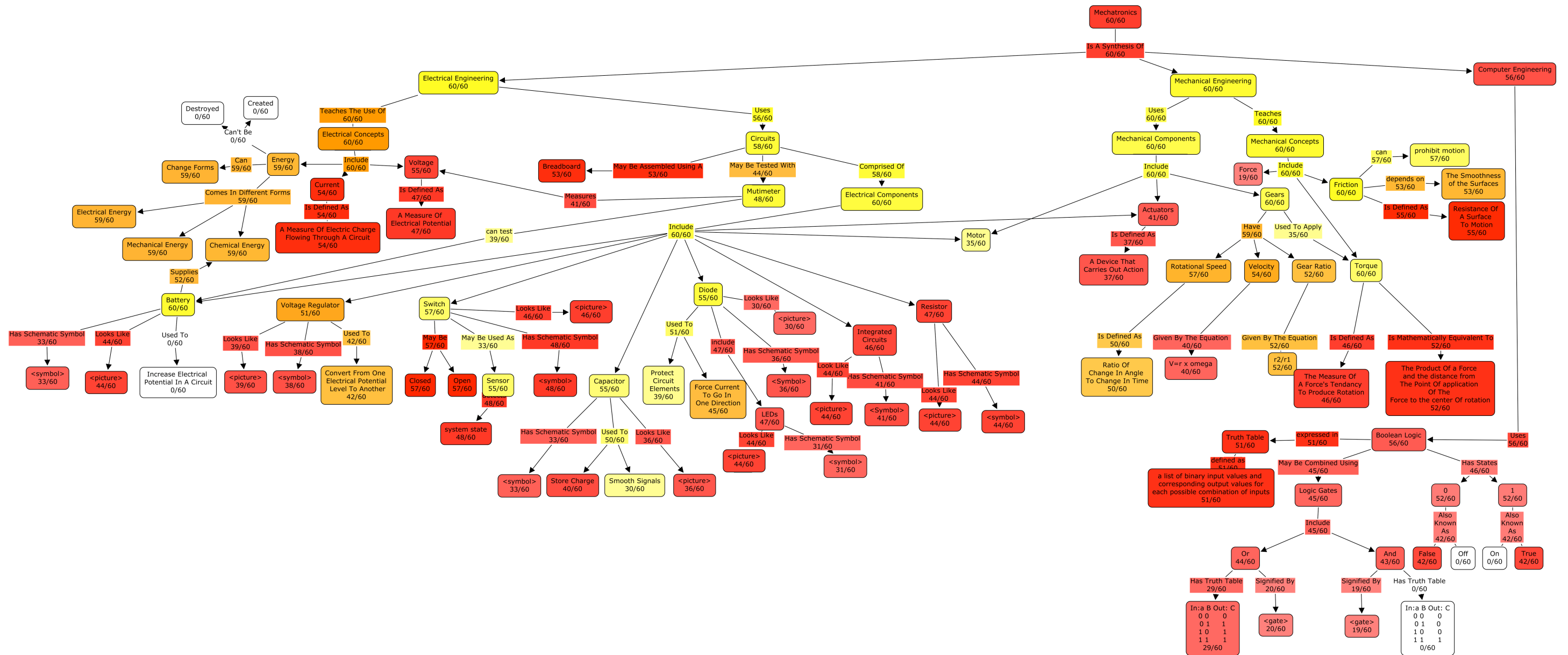


Figure 4.42 Aggregate map representing the overall understanding of the author's students participating in the EngE 1024 mechatronics unit during Fall 2008 (n=60).

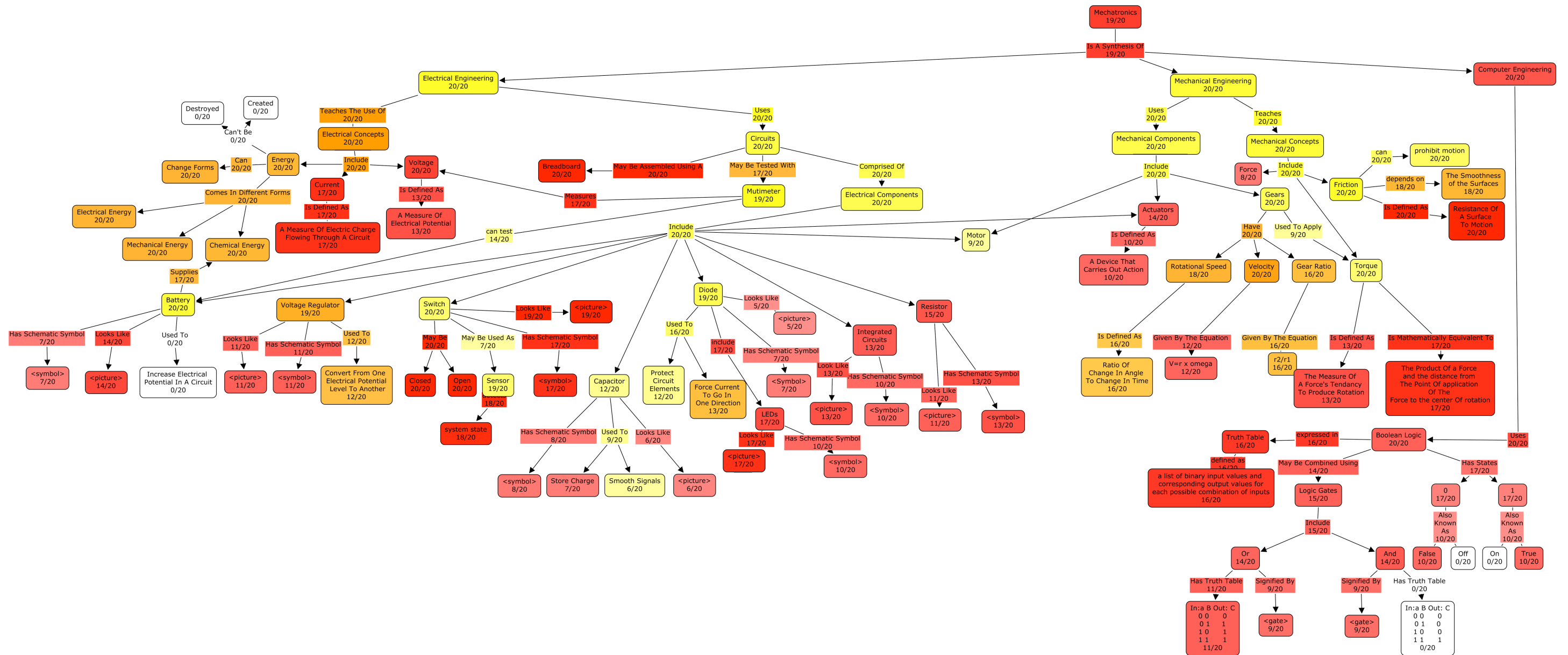


Figure 4.43 Aggregate map representing the overall understanding of another instructor's students participating in the EngE 1024 mechatronics unit during Fall 2008 (n=20).

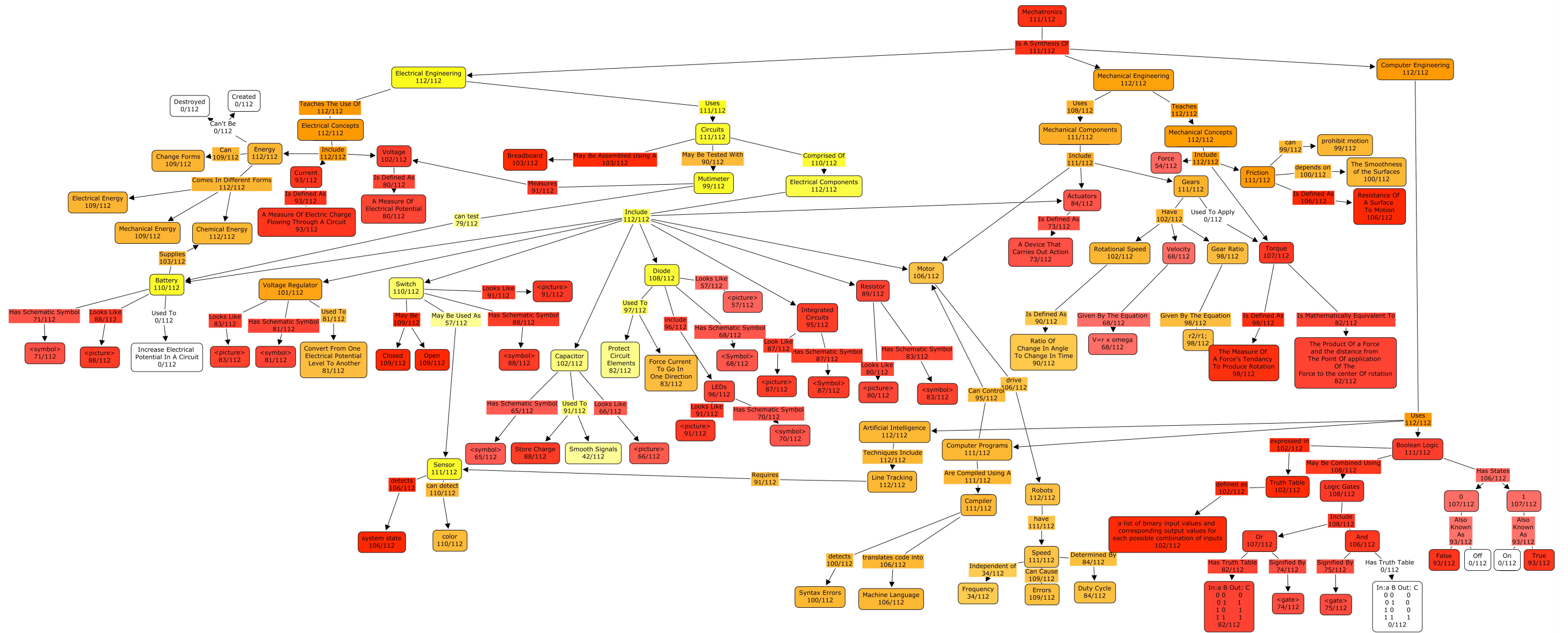


Figure 4.44 Aggregate map representing the overall understanding of all students participating in the EngE 1104 autonomous vehicles unit during Spring 2009 (n=112).

5 Conclusions

5.1 *Summary of Deliverables*

The following deliverables have been produced as part of this research work:

- ◆ Comprehensive maps depicting all of the concepts and relationships presented in two learning modules that are part of two freshman engineering courses (EngE 1024 and EngE 1104).
- ◆ Concept inventories to evaluate student understanding of each of concepts and relationships presented in those two learning modules
- ◆ An XML schema to represent concept inventories and the correlations between each answer on a concept inventory and the corresponding portion of a comprehensive map
- ◆ Software to generate an XML file based on the aforementioned XML-based concept inventory schema.
- ◆ Software to automatically evaluate student responses to a concept inventory and generate a set of student maps representing each individual students command of the knowledge encapsulated in a corresponding comprehensive map.
- ◆ A color scheme to represent varying levels of student learning of each concept and relationship in a comprehensive map based upon Bloom's taxonomy.
- ◆ Student maps representing the conceptual understanding of the two learning modules, discussed above, by 1240 students
- ◆ Four topological methods to quantify the distance between a student's knowledge and the comprehensive set of knowledge and the distance between two student's knowledge based upon the encapsulation of that knowledge in concept maps.
- ◆ Software that generates an aggregate map representing the knowledge demonstrated by an entire class or groups of students based upon various demographic categories.
- ◆ Several representative aggregate maps based on all students in EngE 1024 in Fall 2008 and all students in EngE 1104 in Spring 2009, based upon gender, and based upon instructor.

5.2 *Implications of Research*

This dissertation establishes a new framework for feedback-based education that has potential to expand modern educational assessment. By developing a comprehensive knowledge model, an assessment of the knowledge in that model, and a method to graphically represent the subset of the comprehensive set of knowledge students have learned, this research has established a novel paradigm for educational assessment that can be used in virtually any field. Typical student assessment is based upon evaluating student performance on various assignments. By developing models of student knowledge as subsets of the overall body of knowledge student learning can be evaluated based upon learning outcomes rather than

performance on assignments aimed at generating outcomes. This new model of assessment is independent of the method students use to learn the information and is compatible with the way modern students learn from sources both inside and outside the classroom.

Assimilation theory says that in order for learning to occur a student must incorporate new information into their current cognitive framework. This has been illustrated by assimilating the new knowledge students gain in a second semester engineering course into the map for the concepts and relationships learned in the previous semester. By developing knowledge maps for what students have learned over a lifetime of learning it becomes possible to model a student's cognitive framework and examine how it matures over time. Schools could maintain databases of each student's knowledge map and develop a record of student learning that is significantly more detailed than report cards or student transcripts by delineating at the conceptual level each student's strengths and weaknesses. This storage of knowledge maps into databases allows instructors to tailor their courses to the students and to identify deficiencies in preparation for a course that may exist so that an appropriate review of prerequisite material may be done. Should this knowledge mapping strategy be adopted on a large scale, this work has the potential to completely change the way education systems track students' progress. This method could begin in the primary grades and track knowledge gained in each course all the way through high school, college, and beyond. Colleges could look at the knowledge maps of their applicants to determine if their applicants have the requisite knowledge to be successful students. Professors could evaluate the preparedness of students who have taken prerequisite courses. Potential graduate students could be evaluated to determine if they have the knowledge a professor looks for in a research assistant. Employees could be evaluated to determine if they have the appropriate knowledge base to make a significant contribution to a particular project. Rather than simply submitting transcripts that indicate a single letter grade representation for each course or a resume which compacts an entire lifetime of learning into a single page, a continually updated knowledge map representative of what a person has learned allows significantly more insight into the working knowledge of people than any method currently available.

This comprehensive mapping of knowledge also has great relevance to some of the latest initiatives on the World Wide Web including the semantic web [74]. The semantic web is a method of organizing information so that computers may easily parse and "understand" the

information web developers store on websites so that they may more intelligently search through information to find what web users are looking for in more meaningful ways than simply locating keywords. Semantic representation of information is vital to the development of efficient search engines that better understand exactly what their users are looking for and comprehensive knowledge maps provide a good framework for semantic categorization. It is speculated by Wikipedia [75] and others [76-78] that semantic information storage will be a large part of the Web 3.0 [79] initiative which will further enhance the contributions made through Web 2.0.

The assessment strategy and knowledge representation methods presented herein have potential to become more relevant in the coming years as students are learning in many new ways through the use of online resources. No longer are the course instructor and a textbook the only sources students have for information. Students are learning new things through the use of the Internet and distance education classes are connecting students around the world. Modern college students perform information queries in a much different manner today than the college students of a generation ago and will usually search for information on the web using Google or Wikipedia before they will ask a question of their instructor or look up information in a textbook. Knowledge is no longer locally contained in individual classrooms and presented by isolated experts, but is rather becoming a global pool of information available to virtually anyone in any location. The proposed modeling of information is an effort toward universalizing knowledge representation and allows for a better encapsulation of knowledge, which will be very useful for everyone, but very specifically the millennials and generations thereafter.

The use of the principles of topology to develop metrics quantifying the distance between a student's knowledge and the comprehensive set of knowledge in a discipline establish novel techniques to assess student learning and to develop strategies to help novices develop expertise. Most instructors have techniques for evaluating student learning and providing a grade based upon student performance. This approach gives instructors a new set of tools to clearly show how close students are to mastering all of the concepts in a discipline and the use of pre and post tests allow instructors to quantify gains students make within the context of the overall body of knowledge.

The ability to develop aggregate maps representing entire classes of students allows for outcomes based assessment of instructors' teaching effectiveness. Instructors can use such maps

to clearly see which concepts their students are learning and can then take appropriate action to change the course curriculum in a meaningful way in order to improve student learning of each concept. These aggregate maps can also be used for accreditation purposes to showcase the student outcomes at a university from each course. Most engineering schools require undergraduate students to take several common courses like calculus, physics, chemistry, statics, dynamics, deforms, etc. and universally accepted comprehensive maps for these courses along with a well-designed concept inventory could greatly simplify how such courses are evaluated by accreditation boards.

6 Future Work

This chapter presents work that can be done to improve universal acceptance of the methods presented herein and several extensions of this work that could be developed in the future. This assessment method requires significant work to establish proper maps and concept inventories. Certainly it will be very difficult to gain global support for such a major shift in the assessment paradigm, but over time the author believes more instructors will see the value in such a detailed analysis and gains of support will be made. The following sections introduce some of the groundwork necessary for this system to increase in utility and some expansions that could be made to showcase the benefits of the system.

6.1 *Develop Comprehensive Maps For More Disciplines*

This assessment strategy relies heavily on a high quality comprehensive map to model the knowledge in a discipline. By recruiting panels of experts to develop comprehensive maps for a variety of disciplines this assessment strategy will be more widely applicable. The ASCE Body of Knowledge [7] is a good start in the civil engineering field and their work could be converted into several comprehensive maps. Similar work could be done by other professional societies such as IEEE, ASME, and NSPE. The best disciplines to start such mapping would be those that already have well-tested concept inventories. Further, this method is generally applicable to virtually any field so it is important to develop comprehensive maps for non-technical fields also to showcase the universality of this assessment technique.

6.2 *Develop More Concept Inventories*

The NSF Foundation Coalition [26] maintains repositories for a variety of concept inventories to evaluate conceptual understanding of technical disciplines. In order to showcase the universality of this method more concept inventories must be developed. As with comprehensive map development, concept inventories should not be limited to technical disciplines and concept inventories could be developed for the humanities, agriculture, business, and other fields.

6.3 Correlate Physiological Data with Concepts

As discussed in section 2.6, the author has done some work in the area of physiological monitoring. Attitude and perception are critical to learning and monitoring of data indicative of engagement helps to paint a clearer picture of how students are learning and the affect of learning modules on students. Correlating physiological data with raw academic performance allows educators to establish a dual-axis approach to educational modeling inclusive of both achievement and student effort.

6.4 Model the Transient Property of Knowledge

One of the major drawbacks to academic transcripts is that they present an evaluation of a students abilities some time in the past. As students matriculate through a curriculum they most certainly gain deeper insight into some of the material learned in prerequisite courses and also may forget things they once knew due to underuse. By modeling student knowledge over time it is possible to showcase how a student's cognitive structure evolves over a lifetime of learning.

6.5 Develop Faculty Evaluation Based on Aggregate Maps

Most methods for faculty evaluation are subjective and largely based upon opinion. Some highly effective teachers are given low marks on performance evaluations based on the opinion of their students or supervising faculty. By incorporating aggregate maps representative of the knowledge gains students make an objective metric for teaching performance can be established. It is not advocated that such a system completely replace current evaluation strategies, as student opinion is very important, but rather that a synthesis of objective and subjective feedback is necessary for a thorough evaluation of teacher performance.

6.6 Grade Students Based On Their Maps

The assessment given to students at the end of a course should be based upon the learning that has occurred, not merely a weighted average of grades on various assignments. Instead of assigning weights to individual assignment categories, an instructor could assign weights to each concept and relationship in a map based upon the importance of that concept to the overall discipline with the sum of all weights being 100%. Under this grading scheme, if a student has learned a concept, they get credit for it, regardless of whether they learned it by completion of

course assignments intended to teach the student about that concept or through independent study and exploration. A student is given a grade based upon the sum of the weights for all the concepts and relationships present in their student map. The sum of weights could then be converted to a score out of 100% and correlated with a standard grading scale by assigning an A to students with weights totaling over 90%, a B to students with weights totaling over 80%, etc.

6.7 Determine Methods for Encapsulating Professional Skills in Student Maps

In the modern workforce, it is equally important that graduates are proficient in not only technical skills and understanding, but also professional skills such as formal presentations and technical writing. It is difficult to encapsulate such abilities within the concept map-based framework described herein, but the ability to graphically represent such skills in concert with technical competency would provide a much more complete picture of a student's abilities.

6.8 Develop Software to Perform Topological Analysis

In section 4.5 several metrics and pseudo metrics were introduced to compute the distance between the knowledge encapsulated in student maps and comprehensive maps. This work could be extended by developing software that takes in two concept maps and computes the distance between them based upon the various proposed metrics.

6.9 Allow Manual Override of Concepts and Relationships in Student Maps

It may be found that errors exist in concept inventories or some knowledge is difficult to test through multiple-choice assessment. In these cases given an instructor the option to manually override certain concepts or relationships in a student's map may prove to be beneficial.

Appendix A: IRB Approval




VirginiaTech

Office of Research Compliance
Carmen T. Green, IRB Administrator
2000 Kraft Drive, Suite 2000 (0497)
Blacksburg, Virginia 24061
540/231-4358 Fax 540/231-0959
e-mail ctgreen@vt.edu
www.irb.vt.edu
FWA00000572(expires 1/20/2010)
IRB # is IRB00000667

DATE: October 14, 2008

MEMORANDUM

TO: Vinod K. Lohani
Ricky Castles

FROM: Carmen Green 

SUBJECT: **IRB Exempt Approval:** "Developing Graphical Representations of Student Understanding of Mechatronics", IRB # 08-605

I have reviewed your request to the IRB for exemption for the above referenced project. The research falls within the exempt status. Approval is granted effective as of October 14, 2008.

As an investigator of human subjects, your responsibilities include the following:

1. Report promptly proposed changes in the research protocol. The proposed changes must not be initiated without IRB review and approval, except where necessary to eliminate apparent immediate hazards to the subjects.
2. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

cc: File

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Appendix B: Supplemental File for Concept Inventory

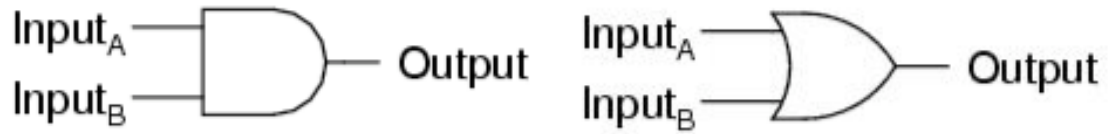


Figure 1. Logic gates

A	B	Output
0	0	0
0	1	1
1	0	1
1	1	1

A	B	Output
0	0	0
0	1	0
1	0	0
1	1	1

Figure 2

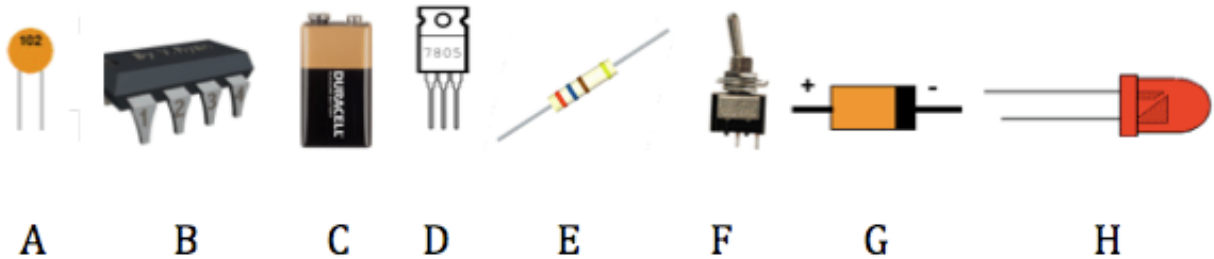


Figure 3. Electronic Components

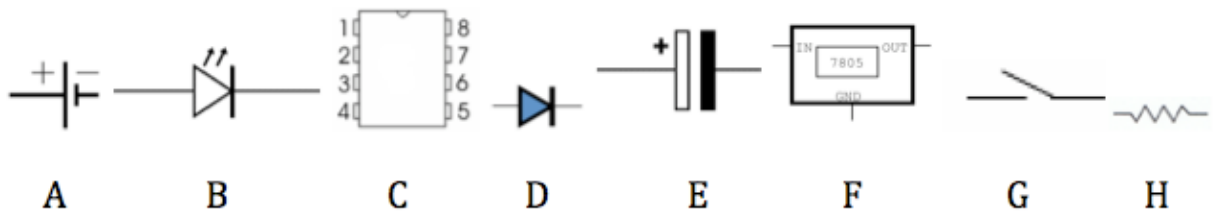


Figure 4. Schematic Symbols

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