

ATMAE WHITE PAPER  
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# Equipping Undergraduates *with* Effective Thinking Skills

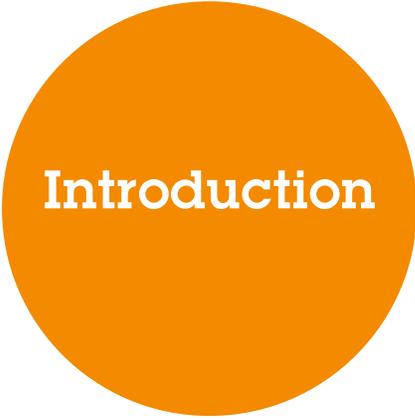
DEVELOPING THE 21ST  
CENTURY WORKFORCE

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The Association of  
Technology,  
Management, and  
Applied Engineering

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# Introduction

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Modern university technology, management, and applied engineering programs are known as rigorous “hands-on” learning environments that prepare graduates for successful careers in business and industry. For the most part, these are accredited programs with active industrial/business advisory committees to help ensure these programs meet the needs of both the students enrolled and the employers who will eventually hire them. In addition, the majority of these programs either require or strongly recommend that all students participate in internship or cooperative learning opportunities so that they graduate with as much “real world” experience as possible. Consequently, it is frustrating and puzzling to hear from employers that they are challenged to hire university graduates who can think.

From 2012 to 2015, the authors participated in a research and development project funded by the National Science Foundation (NSF) under the Transforming Undergraduate Education in Science program. NSF agreed that many issues remained and funded our effort to experiment with a specific method of improving undergraduate engineering and technology students’ ability to diagnose technical problems. In this white paper, we will provide a review of this project, but our purpose will be somewhat broader.

The purpose of this white paper is to explore an approach to teaching technical troubleshooting and problem solving that has demonstrated considerable effectiveness. First, it is necessary that we recognize some very important issues that impact our abilities to teach effective problem solving and thinking in general.

## Nature of Thinking, Technical Systems, and Problems

Kahneman (2011) divides cognitive activity into two systems. System 1 is automatic and quick. The kind of thinking when one is asked to spell “cat” for example. System 2 “allocates attention to the effortful mental activities that demand it, including complex computations” (p. 21). He points out that when we have to use System 2, it is often hard work, time-consuming, and even painful. He also notes that System 2 itself tends to be prone to taking shortcuts and requires a great deal of personal self-control. In other words, as we think about helping others improve their abilities to think, troubleshoot, and solve problems, we must remember that most of us find thinking deeply about anything quite difficult.

Second, it is central to this discussion to clearly understand what we mean when we call something a problem. Most of us face hundreds of issues every day that are technically problems (e.g., getting dirty, being hungry, and so forth). Most of us do not think of these things as problems, primarily because we have ready and routine solutions for each. Likewise, students are often presented with instructional activities typically called problems that actually cannot be accurately described as a problem for them. Even high school and university students find little personal relevance in the “real world” problems they are asked to address. In short, real problems are difficult to solve and are meaningful to the problem solver.

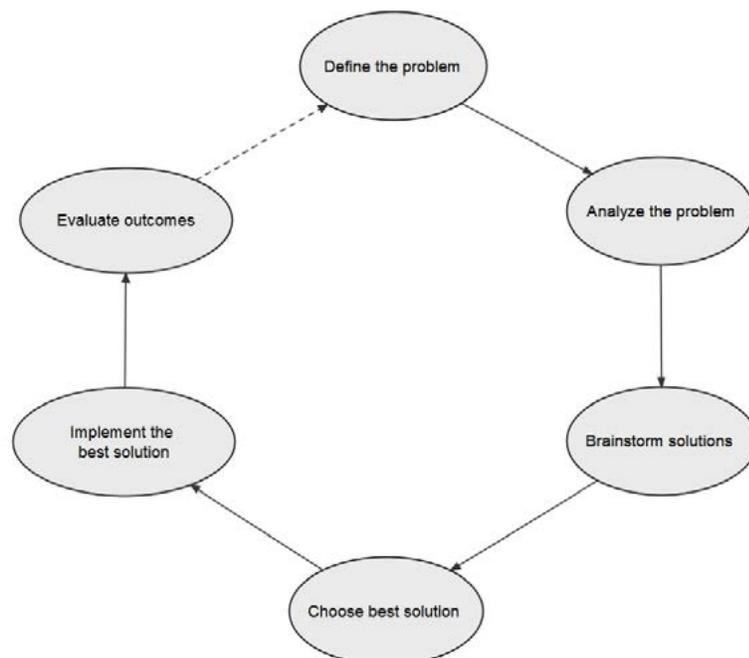
Finally, the nature of modern systems is such that they present industry with a significant challenge. For the most part, industrial systems are computer controlled and very complex. They are created according to a plan that is developed by multiple people and perspectives; it is also assembled by multiple people and companies. Today, many of those suppliers deny access to key elements of their hardware and software to ensure the customer must purchase maintenance services from them. Consequently, it is the case that

there is often no one in the company who has a comprehensive understanding of the system. Any effort to gain that understanding requires sifting through a mountain of documents including drawings, specifications, operating manuals and the like. Rarely do companies develop a comprehensive systemic representation of the system while designing and building. In addition, it seems that the majority of the people using and maintaining those systems recognize the value of their personal expertise (i.e., in terms of keeping one's job, and so forth) and are often hesitant to share that knowledge and skill with others.

### Changes in Our Thinking about Problem Solving

For more than 30 years, psychologists, educators, management experts and others have been promoting tools that are designed to help people improve their problem solving skills. In general, these techniques are called heuristics. Like a formula (i.e., algorithm), a heuristic is a device that increases the likelihood of success; unlike a formula, employing a heuristic does not guarantee success. Figure 1 is a simplistic representation of a heuristic often recommended for improving problem solving.

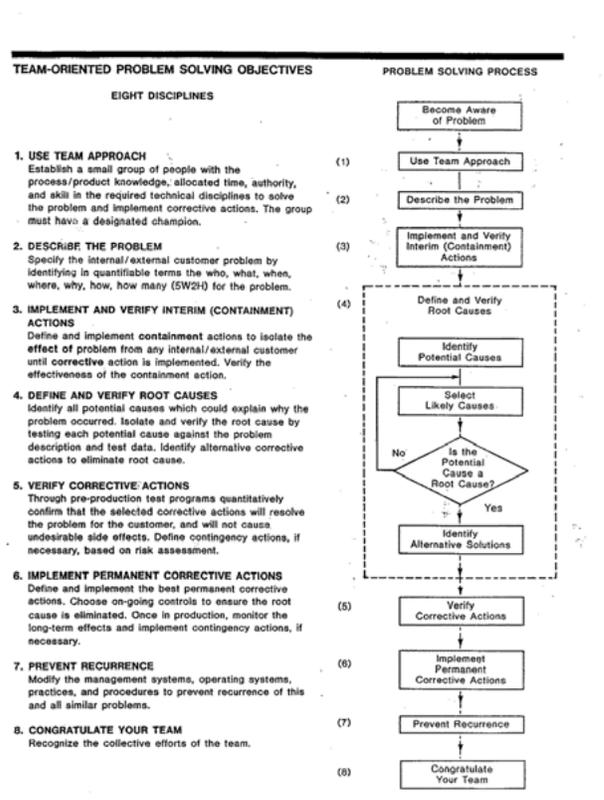
**Figure 1: Model of Generic Problem-Solving Model**



There is a great deal to be gained from this model. First, one cannot solve a problem that one does not understand and has not accurately defined. Second, there is a great deal to be gained from looking at possible solutions from multiple perspectives. Third, we are reminded that no solution is complete until implemented and evaluated (i.e., Did it work? Did it cause other problems?).

In the late 1980s, The Ford Motor Company popularized a version of this heuristic that they called the Team-Oriented Problem Solving (TOPS) or the Eight Disciplines method (See Figure 2). In addition, the guidance provided by a generic problem-solving model, they noted the importance of cross-functional teams to ensure adequate expertise from all relevant perspectives. They inserted a step to contain the problem while causes can be explored and a solution implemented. And they also noted the importance of celebrating success to reward the efforts of the team.

**Figure 2: Ford’s Team-Oriented Problem Solving Model**



Solving problems is difficult for many reasons. However, with practice and experience the majority of our students can master these skills to a high level of performance. A question remains whether general improvements are possible without detailed systemic knowledge. This was somewhat the focus of our recent NSF grant.

Undoubtedly, these heuristics, when employed, improve problem solving. However, Johnson (1987) argued that simply teaching a heuristic to students and having them practice it by solving well-defined and ill-defined problems is not enough. He recommended going much further (see Figure 3).

***Figure 3: Johnson's List of What Works***

**Problem Solving Instruction That Works (Johnson, 1987)**

- √ Identify both given and needed information.
- √ Obtain problem information via the senses.
- √ Obtain relevant information from technical manuals and other resources.
- √ Use technical devices to collect problem information.
- √ Create a simplified problem space.
- √ Create models to simplify the problem by using diagrams, tables, charts, and graphs.
- √ Develop a mental image of the problem.
- √ Use analogies/metaphors to look at the problem from different angles.
- √ Plan before taking action.
- √ Recognize patterns.
- √ Reason hypothetically.
- √ Estimate.
- √ Apply rules and formulas.
- √ Utilize various search methods such as trial and error, systematic, exhaustive, topographic, split-half.
- √ Solve a simpler problem.
- √ Work backwards.
- √ Utilize metacognitive skills such as planning, predicting, evaluating, reflecting." (p.27-28)

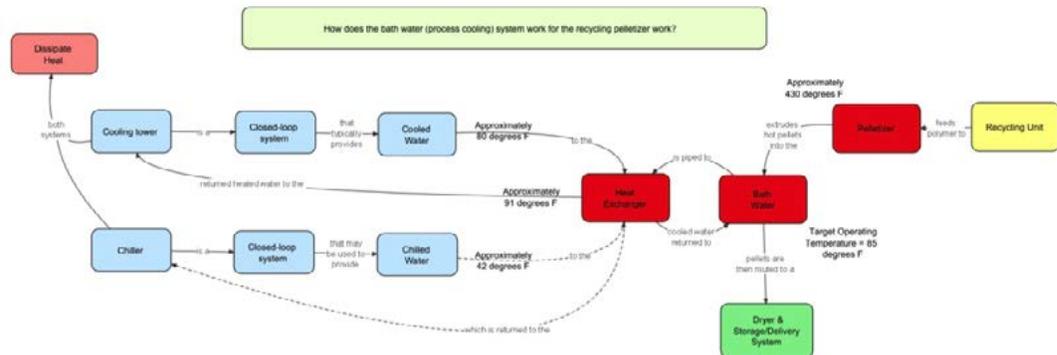
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## Summary of NSF Project

From 2012 to 2015, the NSF funded the Advancing Diagnostic Skills Training in the Undergraduate Technology and Engineering Curriculum at Indiana State University. The work was to experiment with using conceptual mapping to help undergraduates become more “flexible thinkers” relative to technical problem solving. For research purposes, we focused our attention on the diagnostic phase of technical troubleshooting.

Conceptual mapping was first introduced in the 1970s by Joseph Novak. The idea is to represent concepts in the form of interconnected “nodes”. The nodes are the basic elements of a concept. When two concepts are linked with a brief explanation it is called a “principle”. Concepts can then be defined as a set of inter-related principles. Novak’s work and subsequent research in multiple disciplines has demonstrated that mapping is an excellent tool for teaching/learning, planning, and evaluation tasks. Clearly, the benefits are such that there is little hesitation to recommend that university faculty become familiar with and proficient in the use of conceptual mapping techniques.

During this project, the research team designed and developed a self-contained, computer-based instructional program. During the first part of the training (approximately the first hour of the training), students/trainees were provided background information about systems, graphic tools, and troubleshooting techniques. This section ended with the presentation of two problems. The first was an example of a person mapping out a solution for a simple technical problem. The second problem provided an opportunity to practice developing a process map for a simple computer problem (a laptop that will not turn on) using the technique provided in the training that would be used for the main problem solving activities in section two of the program.

**Figure 4: Expert Map from Advancing Diagnostic Skills Program**

Using a process known as “similarity flooding” (Shahhosseini, Ye, Maughan & Foster, 2014), the research team developed a means of providing feedback to users by automatically comparing the student’s process map to that of an expert. In this way, we were able to provide users with immediate feedback based on how closely their work compared to an expert’s approach to the problem.

The second hour of the training consisted of two technical problems developed in cooperation with industrial partners. The first problem involved controlling the regional grid of a “typical” power company. The second was a problem in a heat exchanger system connected to a plastics “repelletizing” process. In each case, the research team worked with industry partners to describe the system and problem, present relevant data, and prepare a process map of how an expert would typically approach the problem.

The data we have collected to date is mixed. First, the mapping concept and the training program have been very well received. A large majority liked both and found them useful. Our experimental design, however, did not allow us to reject our null hypothesis. Our qualitative analysis of performance during data collection supported the notion that the majority of the subjects did not

take the training seriously. We believe mapping and direct troubleshooting training using mapping can help students and technologists perform better. Our current work is to expand the number and types of problems included in the training. We also plan to work with faculty who are willing to infuse these techniques as required activities in existing courses.

As a side note, the National Science Foundation invited the team to participate in an I-Corps for Learning experience during the Summer 2015 semester. The purpose of this initiative is to scale up a learning innovation into a sustainable enterprise. During our interviews with potential clients, we interviewed a significant number of manufacturing maintenance managers who expressed considerable interest in our ability to graphically represent their systems and capture “tribal knowledge” about their operation, maintenance, and repair.

## Conclusions

Those of us engaged in research and higher education have been schooled in the principles of disciplined inquiry. Basically, disciplined inquiry can be defined as a systematic approach to produce trustworthy information. The term is typically applied to the needs of research, evaluation, and assessment. Collins (2001) noted that one of the major elements that distinguished “great” companies was that they had disciplined people engaged in disciplined thought and disciplined inquiry. Kahneman (2010) notes that thinking, like the type needed for problem solving is difficult, time consuming, and requires a great deal of self-discipline, as well as skill. Thinking clearly and troubleshooting complex modern systems effectively calls for disciplined behavior; it is not easy and cannot be easily learned. Faculty tasked with helping students develop the knowledge and skills to think clearly, must themselves be excellent role models and provide a considerable amount of guided and independent practice. Ultimately, we are working together to lay a firm foundation of knowledge acquisition skills, self-discipline, and personal responsibility.

## Recommendations

1. There are multiple places where faculty can download high-quality, open-source software designed specifically for conceptual mapping. One program, Visual Understanding Environment (VUE), is available at [vue.tufts.edu](http://vue.tufts.edu). It is a forum site that brings together individuals interested in the development of this software and the uses of mapping. Programmers at Tufts have also developed Zotero, an open-source program that is promoted as “a free, easy-to-use tool to help you **collect, organize, cite, and share** your research sources”. Together they make a power resource to help faculty and students alike improve their performance in multiple directions.

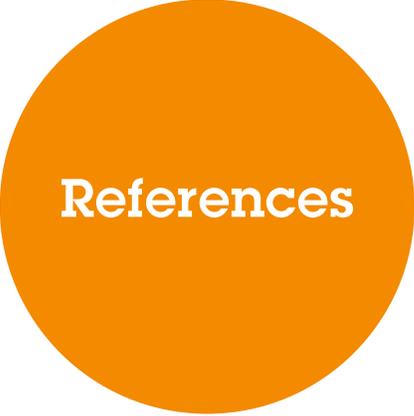
A second program, Cmap, is available at [cmap.ihmc.us](http://cmap.ihmc.us). In addition to a powerful software package, this site contains many resources that provide guidance in developing maps. It also contains downloadable articles for scholars who are interested in the research behind conceptual mapping.

2. Our research during the Advanced Diagnostic Skills grant demonstrated that course content that “would help them develop knowledge and skills desired by employers” was not adequate motivation for students to take these activities seriously. It was clear that the students took seriously those requirements set forth by the professor to receive credit for the course. Additionally, we know from learning theory that skill is developed with guided and independent practice supported by a “wise guide”. Students will develop these skills if they are consistently taught, observed (i.e., the professor uses them), and expected during future activities.

One example comes readily to mind. For years, this author has used a simple activity to get students (and trainees in team building training) to

think clearly and solve a simple problem. The problem has been called the House of Cards. The task is to create a "house" out of two 3"x5" cards using masking tape. With the house oriented so that the opening is parallel to the surface, the students are to add materials (they are given one sheet of paper, three additional 3"x5" cards, some string, and some masking tape) so that the house will support a ream of copy paper (about 5#). Experience has shown that in almost 100% of the cases, the individuals begin work immediately building something (i.e., trial and error). Given that the purpose of the exercise is to enhance thinking and teamwork, it became obvious that steps would have to be added to the process. Consequently, the participants must now present a detailed analysis of the problem and a detailed analysis of their solution ideas before they are given materials with which to make their "best" solution. In short, the extra steps force them to slow down, and think before taking action.

3. Our work has shown us that there are many companies interested in this work once they see what it can do for them. It has paid real dividends for our team to partner with industry in the region. We have found a ready supply of "real world" problems to catalog and present to students. Furthermore, our industrial colleagues are typically quite willing to provide assistance (given it does not take too much of their precious time, and does not reveal trade secrets).
4. Finally, as mentioned earlier, Kahneman's book on *Thinking Fast and Slow* is an excellent reference that provides detailed analysis on human thought processes along with practical ramifications. A second text entitled *Nudge* (Thayer and Sunstein, 2008) provides a practical treatise on what behavioral economists have learned about guiding human behavior. Both have been instrumental in informing this author.



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