A FRAMEWORK FOR TEACHING STEM DESIGN & PROBLEM SOLVING

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The engineering design and problem-solving approach is one that has many possibilities for creative teaching. This approach can clearly be used in many circumstances and is probably one of the most exciting teaching techniques that can be used in STEM classrooms. Problem solving is also one of the most often misused teaching techniques in the profession. Lewis, Petrina, & Hill suggest that classroom studies indicate that students find the prescribed design problem solving methods cumbersome to use, and if held accountable, merely retrofit methods to meet the results of their actual problem-solving experience. For this reason, the following section has been developed to help the STEM teacher gain a better understanding of the impacts of using the problem-solving method.

The term "problem solving" has become very popular in educational settings in recent years. One of the key skills that employers want their employees to possess is the ability to critically analyze situations and solve problems. The difficulty is that the term "problem-solving" (and the behavior and thinking associated with it) is complex and refers to different things in various contexts. STEM problems are distinct from other types of problems (e.g., social, environmental, interpersonal, economic, international, mathematical, puzzles, etc.). For example, a family with an alcoholic son or daughter has a problem, but it is not a STEM problem. There are distinct categories of problems that are appropriate in STEM settings. They are:

- *Design*: Design is one classification of technological, engineering, or STEM problem solving. Unlike some other types of problems that students in a STEM class might encounter, design problems are frequently less well defined and can often be solved in a number of different ways within a set of constraints. Design problems usually start with a phrase like, "design a device that will…" Solutions to design problems often reflect the unique knowledge and experience the designer brings to the situation, or information that they have gathered through research and questioning techniques.

- *Troubleshooting*: Troubleshooting is a classification of problem solving where problems tend to be well defined and activity is directed at finding a single solution to a problem (e.g., locating a fault in an electronic circuit, finding out why a flashlight won't work, etc.). Trouble-shooting problems typically require specific knowledge in order to solve. Before using a trouble-shooting problem in a STEM class, the teacher needs to provide the students with the background knowledge and experiences that can be drawn upon to solve the given troubleshooting problem.

- *Invention and Innovation*: Are among the most open-ended and creative approaches to problem solving. Unlike other forms of problem solving that deal with things already in existence, invention launches into the unknown and the untried. Invention is the process of coming up with new ideas, while design is concerned with applying those ideas. Invention tends to require considerable creativity, and an ability to visualize, model, and create. On the other hand, an innovation is an improvement of an existing product, system, or method of doing something. Invention problems used in a STEM class usually begin with a phrase like, "invent a new or more efficient device to affix a shoe to your foot" while an innovation problem might begin with a phrase like, "the shoelace has been used to affix shoes to human feet for thousands of years and they often break, create a new type of shoelace that will not break."

- *Research & Development*: After something has been conceived, it can take considerable time for teams of people to work the bugs out and prepare the product for the market. Research and development is a problem solving method that attempts to address a wide range of issues concurrently. The product must work. It must be reliable, safe, and have market appeal. Sometimes, questions about its value to society or potential harm to the environment must be addressed as well. Research and development problems often start with phrases like, "the Razor Scooter Company has created a new scooter for children ages 3-8 but discovered during product testing that too many children were being injured while operating the scooter. Conduct R&D to determine ways to make the scooter safer for children ages 3-8."
- *Experimentation*: Is the form of problem solving that resembles most closely the methods that scientists use. Using methods that are similar to the scientific approach, problem solvers apply iterative processes to experiment on technological products and systems. For example, performing hardness tests on various metals prior to selecting the steel from which to make a new tool.
- *Technical/Procedural*: Is a form of problem solving that requires a student to follow a set of technical directions to accomplish a task. For example, students might be required to build an electronic device following precise directions of a technical nature and then, when the device is complete, the students must complete a series of experiments.

A common error made in teaching problem solving is to attempt to reduce the process to a simple, generic set of steps (one size fits all). This usually takes the form of clarifying the problem, proposing solutions, selecting a solution, trying the solution, and evaluating the solution. Lewis et.al. implies that this model may have had political utility, but the method is constraining and does not fit all problem-solving scenarios. The framework that is used to guide activities in this document is more refined, considering that there are different kinds of problems and that different *classifications* of problems require different approaches, skills and knowledge to solve.

<u>Approaches to Problem Solving</u>

The methods used to solve STEM problem solving activities have changed because present technologies are more complex than previous technologies. Few problems can be approached and solved according to some neat step-by-step arrangement. Designers may move from the stated problem to a sketch of an imaginative solution. Or, such analysis may spark an idea leading to immediate experimentation. Many problem-solving steps may be used at the same time. For these reasons, several different formalized problem-solving methods (i.e., design loops) are used today.

One of the simplest problem-solving models (design loops) includes these steps.

1. Identify the problem
2. Select a solution
3. Apply the solution
4. Test and revise the solution

While this model contains the essential elements of a problem-solving sequence, it might be too general in nature. The problem-solving model which follows utilizes the same general sequence, however, it also includes features—which make it especially appropriate for use in STEM classes. In particular, the organization of the model is keyed closely to the organization of the systems approach. This model helps to clarify the problem to be solved, focuses attention on the criteria for deciding when the problem is solved, and provides an organized and detailed way of processing through the problem-solving process. The model is NOT intended to depict how the human brain functions; humans often think nonlinearly at many different levels and from several different perspectives within a short time period. The sequence of problem-solving steps in the model is designed to organize the approach, not to restrict it.

Problem-Solving Strategies

Another thing that instructors can do to help learners develop skills needed for STEM problem solving is to give them opportunities to practice solving problems. Problem-solving strategies are critical to any instruction aimed at improving all levels of STEM skills. To be effective problem solvers, students need to be able to do the following:

- Understand cause-effect relationships (e.g., What parts of systems affect and are affected by other parts?)
- Make comparisons (e.g., What commonalities and differences do systems have?)
- Recognize probable outcomes (e.g., How will the system react to a specific action?)
- Predict what should happen next (e.g., Based on what has been observed, what is known about a specific system, and what is known about related scientific principles, make a prediction about what will happen next.)
- Judge spatial relationships (e.g., Visualize how a system operates and mentally rotate system parts to solve problems within a given system.)
- Notice what appears out of place (e.g., Observe a malfunctioning system in operation to determine what is not working correctly.)

IDEAL General Problem-Solving Model (an introductory design loop)

One well-known problem-solving model is the IDEAL model. The IDEAL model was designed as an aid for teaching and improving problem-solving skills. The IDEAL process includes the following steps:

I = Identify the problem (e.g., determine what needs to be done).

D = Define and represent the problem (e.g., sharpen and clarify the boundaries).

E = Explore alternative approaches (e.g., analyze and evaluate alternatives).

A = Act on a plan (e.g., determine the logical steps to be used and how to progress through the steps).

L = Look at the result (e.g., determine whether or not the plan worked).

AIQEITS General Problem-Solving Model (an intermediate design loop)

Although it employs a similar approach to solving the problem, some instructors prefer to use the AIQEITS model to solve problems because it causes the student to ask/answer probing STEM questions as they pursue the solution to the problem.

1. **Analysis:** Carefully analyze the problem and break it into small parts
2. **Invent:** Invent as many possible solutions as possible before attempting to implement any of them

3. **Question:** Ask yourself (or your teammates) as many of the spur questions as apply:
   a. Is there another way to solve this problem or use these materials?
   b. Can I borrow or adapt previous solutions or technologies?
   c. Can I add a new element or twist that might lead to a solution?
   d. Can I add more to the problem in an effort to find a solution?
   e. Can I remove parts of the problem in an effort to solve it?
   f. Can I incorporate substitutes or use other materials/techniques?
   g. Can I rearrange the elements of the problem to find the solution?
   h. Can I do the opposite of what I am currently thinking?
   i. Can I combine elements or techniques to solve the problem?
4. **Envision:** Take careful notes and make sketches of potential solutions
5. **Implement:** Select the most logical solution (often the simplest) and implement it (build it)
6. **Test:** Test your solution
7. **Synthesize:** Evaluate your solution (does it solve the problem? If not, start the process over)

<u>*Advanced General Problem-Solving Model*</u> (for experienced students)

Clarify the Problem: Solving a problem is a process which results in a solution to a specific want or need. The beginning step for students must be to identify what is to be solved. They must formulate a clear, simple, direct statement of the problem. From this statement, they will know where to direct their efforts. Example: Build a fast self-propelled model vehicle.

Establish Parameters: The parameters (judgements, rules, or standards) within which the solution will be developed measure when the problem-solving process is finished. Example: The self-propelled vehicle must travel at least three feet per second and must not tip over.

Identify Values and Principles Involved: Students should clearly identify values relating to concerns such as environmental issues. They should also describe the scientific principles—which relate to the problem. Example: The self-propelled vehicle should not pollute the environment. Principles of force, motion, fiction, and inertia must be considered.

Identify Resources: Students should describe in detail each of the following resources: People, information, materials, tools, and machines, capital, energy, and time. Here is an example of a problem involving a self-propelled vehicle.

- People- Problem solving team, engineering experts
- Information- Instructor, library, Internet
- Materials- Raw materials (metal, plastic, composites), scrap bicycles, etc.
- Tools and Materials- what tools and materials are needed?
- Capital- Maximum expenditure: $?
- Energy- Solar electrical current
- Time- how much class time will this take?

Identify and Select Alternative Solutions: Many techniques can be used to identify alternative solutions, including trial and error, inspiration, and brainstorming. Students should start by making a list of many different solutions. One key is to identify characteristics—which can be varied. Example: For the self-propelled vehicle, different solutions could have a short or long wheel-base, light or heavy vehicle weight, three or more wheels, etc.

Refine One Solution: After the team has identified a number of potential solutions, these ideas should be condensed and combined into one central idea.

Develop and Test Solution: After discussion and perhaps some preliminary testing, students develop fully and test one solution. Example: Students build and test a long, lightweight, 4-wheel, self-propelled vehicle.

Test and Evaluate: Students record the results of the test. Example: the vehicle developed a speed of 3.2 feet per second and remained upright.

Monitor Solution for Additional Problems: Students discuss the results and examine any impact on values described earlier. Example: The vehicle did not pollute the environment, but the wheels damaged the layer of topsoil.

Is A Solution Possible? Students take both results and parameters into consideration to decide if the solution is the best one possible. If so, then the problem is considered solved. If not, then they refine the solution or select another solution for development.

Identifying Resources: Studying technology requires an understanding of each of these resource categories and the impact of each on the final product and the environment. These resources apply to the problem-solving model discussed previously and the section on systems in the following section.

- **People** are a resource for technology. The type of production and products manufactured depends on the skill level and education that manufacturers have. High technology jobs in areas such as robotics and space require advanced skills to apply technology. Assembling furniture and processing food require other levels of technical abilities. When a business considers a location for its industry, the characteristics of the work force are important factors.
- **Information** is needed for technology. The level of input and output needed is determined by the product a company wishes to market. Information processing accounts for many jobs. Information is recorded and exchanged by satellite, television, radio, computers, facsimile transfer (FAX), telephone, and numerous reproduction machines that produce an instant copy of both pictures and written words. New technology is developing at an explosive rate because information is readily available. Providing information is a business in itself.
- **Materials** including renewable plants and animals, and nonrenewable oils and metals, are usually considered first when the word resource is mentioned. Materials are an important resource for technology but no longer are the determining factor in the location of a company. Materials can be transported easily by air, land, or sea. Parts of many products today are manufactured in several countries and assembled in another country. The use of raw materials is becoming more closely examined. People are concerned that the consumption of raw materials exceeds their long-term availability. Even renewable resources such as wood, cotton, and livestock cannot be replaced at an ever expanding rate of consumption.
- **Tooling and Machines** are another resource for technology. People have been using tools such as hammers, vises and rolling pins for many centuries. Machines such as drills and chain saws have replaced many operations that people performed with simple tools. Electronics, computers, robots, and multifunctioning machines have replaced repetitive processes that were carried out by people using hand tools.
- **Capital** is one of the seven resources that keep a technological system in operation. Currency is a familiar form of capital. Other forms of capital are stocks, bonds, land, buildings, and equipment.

- **Energy** is a resource that is needed to keep technology applications functioning. The use of renewable energy such as that from solar, geothermal, and hydroelectric sources increases as nonrenewable energy sources such as coal, oil, and natural gas become more expensive. In many cases, the use of nonrenewable energy sources in not an environmentally sound practice.
- **Time** can be called the resource that has not changed. But has it? In the agricultural era, time was measured in months and seasons. In the industrial era, time was measured in days or weeks. In today's information age time is measured in seconds or fractions of a second. Retrieving data can take place almost instantly. Even the most complicated machines can be produced using high-speed production line techniques. We have even shortened the time required for food production by applying artificial light and chemicals to speed growth.

<u>Models for Solving STEM Problems </u>(by type of problem)

Because the nature and outcomes for each of the type of STEM problem solving (trouble shooting, design, technical/procedural, invention, etc.) is different, they each utilize a different strategy structure for solving the problem. The following paragraphs outline suggested steps in solving different types of STEM problems.

Strategies for Solving Troubleshooting Problems

Many STEM problem solving activities require the student to solve a technical problem that involves identifying the fault in a system. Finding a fault in a technological system is typically referred to as trouble shooting. Troubleshooting requires the student to have a background with the technology in question. Without a technical background in the given subject area, students will find it extremely difficult to solve problems that require trouble-shooting skills, much like the individual with a stalled automobile would not have the technical capability to fix the car without some automotive background. The following guidelines are useful tools for guiding students through trouble-shooting activities. These guidelines assume the student has a background in the appropriate technical areas:

1. *Problem Isolation:* Identify the specific problem that is causing a disturbance in the technical system (e.g. the bicycle will not move forward when pedaled);
2. *Systems Identification:* Identify the systems and subsystems involved in the device (e.g. the bicycle would include a support system, a mechanical power system, a guidance system, etc.);
3. *Desired Outcome:* After having identified the specific problem, the question is how to move from that starting point to a desired end situation (MacPherson). Essentially, this step involves identifying potential strategies, or maps, for reaching the appropriate end.
4. *Fault Identification and Implementation:* By using the strategies identified above, the technician would implement potential solutions that lead to the appropriate solution.
5. *Assessing the Results of the Implementation:* Trouble-shooting skills are enhanced through experience. These experiences are ultimately recalled through the personal assessment made following the trouble shooting experience.

Strategies for Solving Design-based Problems

Design problems always include the solution to the problem in the problem statement (e.g. design a vehicle that will travel the greatest distance using only the materials supplied). To solve STEM design problems, students should employ the following steps (or a similar design loop):

1. *Analyze and Clarify the Design Problem:* Carefully analyze the design problem and break it into its smallest systems and subsystems. Clarify the problem to determine exactly what you have been asked to create.
2. *Formulate:* Create as many possible solutions to the design problem as possible before attempting to implement any of them. Instructors should require students to produce several potential solutions prior to allowing the students to implement one of the solutions.
3. *Question the Solution:* Design teams should ask as many of the spur questions (below) as apply to the problem. By answering these questions, the team will add clarity to the proposed solution. The spur questions are as follows:
    a. Is there another way to solve this problem or use these materials?
    b. Can I borrow or adapt previous solutions or technologies?
    c. Can I add a new element or twist that might lead to a solution?
    d. Can I add more to the problem in an effort to find a solution?
    e. Can I remove parts of the problem in an effort to solve it?
    f. Can I incorporate substitutes or use other materials/technologies?
    g. Can I rearrange the elements of the problem to find the solution?
    h. Can I do the opposite of what I am currently thinking?
    i. Can I combine elements or technologies to solve the problem?
4. *Envision the Solution:* Teams should make sketches and drawings of the proposed solution. By crafting these drawings, teams will add clarity to the final solution prior to implementing the solution.
5. *Create:* Select the most logical solution (often the simplest) and implement it (build it).
6. *Evaluate the Solution:* Test the solution and determine whether it indeed solves the problem. If it does not solve the problem, find out why and make changes.

Strategies for Solving Technical/Procedural Problems

Technical/Procedural problem solving involves seeking relationships and working out new solutions. Sometimes problems are solved largely by trial and error, however, a number of STEM problems are best solved using a step-by-step chronology of procedures. This step-by-step chronology may be the result of following a set of technical directions, reading a schematic, or using a systems approach similar to one used to conduct technical troubleshooting. Conversely, technical/procedural problem solving may involve drawing the schematic or writing the technical directions that lead someone else to solving the problem (i.e. developing a set of plans for assembling a child's bicycle). Like troubleshooting, technical/procedural problem solving requires background experiences and knowledge of technical sequence. Technical sequence is knowledge related to the systematic order of technological devices. For example, when assembling a bicycle, the spokes must be installed prior to mounting the tire to the wheel because the tire will cover the spokes when installed. Although this author could locate no single definitive set of strategies for solving technical/procedural problem-solving activities, practice writing and following technical directions and procedures would seem to be the ideal preparation for solving technological problems of this type.

Strategies for Solving Invention or innovation-based Problems

Invention problems are similar to design problems in that they require the student to create a device that will solve a problem. They differ from design problems in that the solution is not given in advance. For example, a design problem might require a student to build a floatation device that will allow them to cross the river using only the materials available. However, an invention problem never states the solution to the problem in advance (a floatation device). Given this same example, an invention problem would simply present the student with the problem (e.g. you are unable to cross the river and you must find a way) and ask them to invent a device or technique that would allow them to solve the problem. To solve invention problems in STEM classes, students should employ the following steps:

1. *Analyze and Clarify the Technical Problem:* Carefully analyze and determine the nature of the problem. Clarify the problem by determining the root cause of the problem.
2. *Conduct Research:* Determine how others have solved similar problems in the past. Ask yourself if any of these solutions would be appropriate or could be adapted to solve this problem.
3. *Brainstorm:* On paper, create as many possible solutions to the problem as possible before attempting to implement any of them. For example, if the problem involved your inability to cross a body of water, the some possible solutions might include a pole vault system, a boat, a hot air balloon, a catapult, swimming, etc. Make certain that the proposed solutions are appropriate for the situation. Instructors should require students to produce several potential solutions prior to allowing the students to implement any one of the solutions.
4. *Analyze the Potentiality of Proposed Solutions:* By asking the spur questions in relation to the solutions identified above, students can bring focus to the appropriate answers to the problem. Researchers should ask as many of the spur questions (below) as apply to the problem. By answering these questions, the team will add clarity to the proposed solution. The spur questions are as follows:
   a. Is there another way to solve this problem or use these materials?
   b. Can I borrow or adapt previous solutions or technologies?
   c. Can I add a new element or twist that might lead to a solution?
   d. Can I add more to the problem in an effort to find a solution?
   e. Can I remove parts of the problem in an effort to solve it?
   f. Can I incorporate substitutes or use other materials/technologies?
   g. Can I rearrange the elements of the problem to find the solution?
   h. Can I do the opposite of what I am currently thinking?
   i. Can I combine elements or technologies to solve the problem?
5. *Sketch and Draw:* Teams should make sketches and drawings of the proposed solution. By crafting these drawings, teams will add clarity to the final solution prior to implementing the solution.
6. *Create:* Select the most logical solution (often the simplest) and implement it (build it).
7. *Evaluate the Solution:* Test the solution and determine whether it indeed solves the problem. If it does not solve the problem, find out why and make changes.

Creating the Appropriate Learning Atmosphere

The environment in which STEM is delivered has a significant impact on the learning that does or does not occur. STEM teachers can think of the classroom as a stage and the curriculum as the play—a good production requires both. Quality learning experiences depend upon classrooms with appropriate resources, materials, and tools as well as a sound curriculum. Some suggestions for creating an environment that is helpful for studies in STEM problem solving include:

1. Establish a resource center in the classroom or laboratory which includes technological, industrial, engineering, and design journals as well as government resources, resource texts, research and development materials, a list of references in the local library or local university library and Internet sites;
2. Obtain media materials free or almost free from industries such as General Motors, General Electric, John Deere, Caterpillar, NASA, EPA, United Technologies or institutions like the United Nations, the United States Peace Corps, Catholic Charities and other international organizations. These materials can be used to introduce the topic or to spur thought in the students;
3. Require students to develop activities, projects, or products which show the impacts of a particular technology (i.e. students develop a television commercial and after playing the commercial, study the impact it has on the viewer);
4. Conduct field trips to local businesses and industries;
5. Conduct field trips to non-traditional industries and sites like the local landfill, sewage treatment plant, a recycling center, or an EPA hazard site and then bring the students back to the classroom for a lively discussion;
6. Use reports and written or oral presentations to allow the student to conduct research on the effects of a particular technology and then take a position on the effects of that technology.