How to Re-Engineer Science Labs into Engineering Design Process (EDP) Projects

A Guide for Teachers

by

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PART 1. An Overview

There are many reasons to include some exposure to engineering in science classes. Years of research indicate that providing opportunities to apply concepts allows for more understanding, extension and incorporation into existing mental models. It makes sense to use the EDP to frame applications since, historically, engineering has been the vehicle for the application of science. The modern world is highly engineered and, as educators, we all have a responsibility to insure that our students have a basic understanding of the technology that surrounds them. Both developed and developing nations recognize the importance of increasing public understanding of engineering. On a more targeted level, countries around the world report difficulty in attracting innovative young thinkers to the science and engineering fields. Public perception of engineering is universally limited and often inaccurate, and often reverts to decades old images of socially awkward, technically competent but verbally challenged "geeks". Exposure to the creative side of science and to any aspects of engineering is minimal at the secondary and high school level. In the US, the Next Generation Science Standards highlight the need for exposure to engineering and engineering design across all three dimensions: core ideas, crosscutting concepts, and practices. In Singapore, initiatives such as TSLN, TLLM and C2015 encourage learning by doing, particularly in inter and multi-disciplinary ways. The 21st century skills of creativity, critical thinking, collaboration and communication create an imperative that requires students to work with information, rather than to just absorb it.

It is not difficult to find evidence to support the "why" of including exposure to engineering, but navigating through the issues related to the "how" is often quite problematic. There are perception issues that affect faculty and administrative commitments to engineering. In many cases, engineering is still viewed as part of vocational or technical education curriculum, and not considered to be part of the college preparatory sequence of science and math courses. At the other extreme, engineering is considering to be far too technically challenging to be understood by pre-college level students. Many science teachers face a continual challenge to stay current with advances in understanding and pedagogies in their specific subject specialization, and see engineering as a very challenging field they are not qualified to teach. High schools are frequently unable to include separate engineering courses in their programs due to resource and scheduling restrictions. And for many reasons, isolating engineering courses or curriculum may not be the best way to increase student exposure.

We cannot fully educate future engineers at the secondary level and no one with any understanding of the field would ever suggest that that is a reasonable goal. In reality, most of what we do in high school education involves building infrastructure for future learning, exciting some interest in different fields, and making sure our students have enough exposure to have viable options in their lives. Pre-college engineering can only serve to give students a taste of what engineering is all about. But in addition, it can help them to situate the ideas they learn in science, math and other subjects in real world contexts. It is so multi-faceted and so relevant to the world we live in that, as educators, we cannot afford to leave it out.

Replacing some conventional high school science lab experiences with engineering design based projects provides an opportunity to expose students to the nature of engineering. Using the engineering design process and foregrounding the project in terms of relevant scientific content enables teachers to employ an active approach that is "minds-on" as well as "hands-on". If done properly, the use of the EDP in projects can provide rich interdisciplinary, active learning in science classes. The impact of technology and the need to develop skills and mindsets for the 21st century affects every one of our students. Re-engineering science classes to provide those opportunities is the easiest and most impactful way to provide that learning opportunity.

Teachers today are continually confronted with new curriculum mandates, new pedagogies based on research and new findings about how students learn. Science teachers especially deal with changes from both research in science and research in science education. But classroom realities can make adjustments overwhelming. Science teachers deal with time and resource issues in planning and executing projects and the focus on "coverage" of enormous amounts of material in the face of curricular and testing mandates that are too broad. There is little time to plan and master an overall shift in approach and no "space" to incorporate new material. But if there is anywhere in the curricula to add engineering, it is in the application phase. After all, the purpose of engineering is to apply science to solve problems. And since time and space is already available in schedules for planning and executing lab activities, some constraints should be minimized by focusing on this phase.

The following guidelines should help teachers of various backgrounds from shift from a verification focused lab to EDP based activities. In addition, Part 2 contains pointers and ideas for incorporating the steps of the EDP along with sample forms. Resources for information on the EDP and project ideas can be found at the end of this guide.

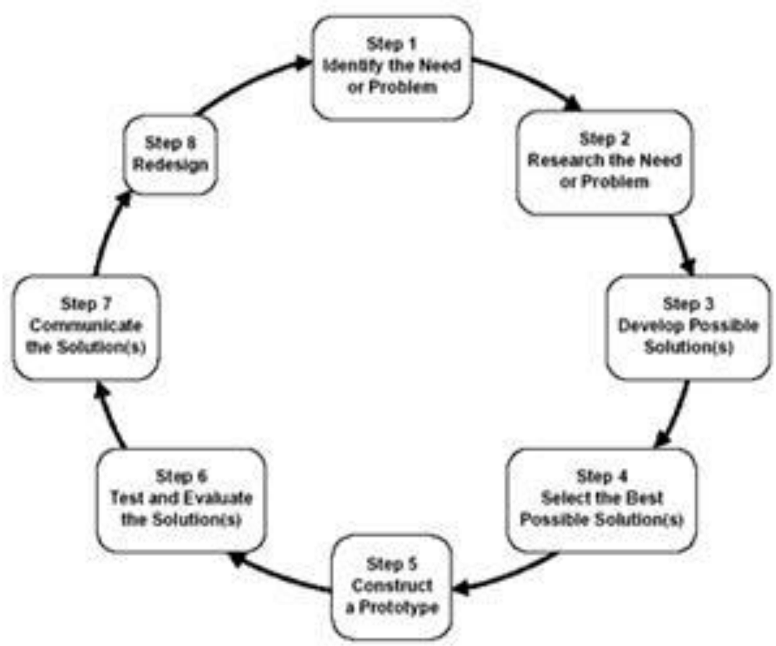

Figure 1 The Engineering Design Process

KEY IDEAS IN DESIGNING EDP PROJECTS

THROUGHOUT IMPLEMENTATION OF THE ANY OF THE TECHNIQUES AND IDEAS OF THE EDP IT IS KEY TO REMEMBER THAT YOUR PRIMARY GOAL IS TO PROVIDE AN APPLICATION TO FACILITATE SCIENTIFIC UNDERSTANDING!!

1. **DETERMINE THE KEY SCIENCE CONCEPTS TO FOCUS ON AND MAKE THOSE CONCEPTS CLEAR TO YOUR STUDENTS**

   In project based work, it is always important to start with a goal or end result. In the real world, no one undertakes a project without a purpose. In this case, start with a clear focus on the science that needs to be reinforced. Think of the Engineering Design Process as providing the road to get there. Most of us approach our own planning in daily life by figuring out what we need to do, how we are going to get there, and what we need along the way. In curriculum development, this is referred to as backwards design. An excellent resource for techniques and strategies for this type of planning can be found in *Understanding by Design* by Grant Wiggins and Jay McTighe. Your planning should start with the goal (scientific understanding), include assessments as milestones, and you should view any lessons or instructions as steps in the journey and key to reaching those milestones. In a way, you will be applying the engineering design process to curriculum design by identifying the goal, defining the criteria (assessments) and mapping out a plan to get there.

Knowing your destination helps you to plan your route and students need to know the point of the whole project if they are to plan for success. It is impossible to maintain student focus on the science involved if the connections to your chosen project are not clear. Clear connections provide a pathway for clear understanding. Most projects will involve just a few primary concepts, but there are often many extensions and opportunities for exposure to new topics along the way. Start with a clear primary focus, the rest will come as needed and by focusing on the endpoint and not the details, you will have the flexibility needed for student driven learning.

For example, in an introductory circuits unit, key concepts might be Ohm's Law and series vs. parallel circuits. A project might be designed involving lighting up a prototype house. Other issues such as wiring logistics, the use of potentiometers, switches, internal resistance, etc. can be introduced to or discovered by students as needed. As students need to navigate through the issues that they encounter, they often uncover or explore ideas you may not have even thought of. Everyone, both you and your students, learns!

2. **DETERMINE WHAT TYPE OF REAL WORLD PRODUCT OR PROCESS BEST ILLUSTRATES THE KEY IDEAS YOU WANT TO FOCUS ON.**

   When you choose or develop a project there are several things to keep in mind. First, as much as possible, it is important that systems and devices in the project are analogous to real world products and situations. Engineering puts science to use to create solutions for real world problems and needs. Seize this opportunity to make science real for your students. For instance, in using a mousetrap car project to focus on energy, it is easy to draw analogies between the engine and the mousetrap as initial energy inputs. Both a real car and the mousetrap car follow the same physics principles in terms of transferring energy via the drivetrain to the wheels. Obviously, a real car is more highly engineered, but every idea starts from the same physics principles your students will use!

   Second, it is very important that the concepts you are trying to highlight are clearly evident in the form and function of the product or process you choose. All teachers have limited time in which to maximize exposure to learning. Your overall goal in using the EDP to frame a project is to increase understanding of science through application. Student time is better spent putting the concepts to use rather than trying to figure out where they come into play in the project. You need to be sure that they are starting with some appropriate knowledge. It helps to maintain focus by giving students some guidance about where and how certain concepts are applied. They will gain a clearer understanding as they investigate causalities and dependencies. Think of the project as an opportunity for application and extension of concepts, not as an activity to discover those concepts. The initial discovery should precede the project. Discovery is an important individual learning process and assimilation of new knowledge is time consuming. Students need, by their own admission, selective guidance and basic information to keep a project from becoming overwhelming. Introducing ideas before the project and making time available in the form of the EDP project to further explore those ideas gives students the time needed to discover and assimilate concepts.

For example, if you are using a paper airplane design project to apply the principles of flight, make sure the link between wing (foil) morphology and Bernoulli's Principle is clear to your students; don't send them on a scavenger hunt to find it. It is better for students to understand the causality and to investigate it further. In the process, they may discover that this model is simplified and some will go on to investigate issues involved in in terms of camber, angle of attack, etc. That's great, but those are really more design and engineering fine-tuning issues. They are secondary to the velocity and pressure relationships of Bernoulli's Principle. Science is about discovering the link between cause and effect, independent and dependent variables. Engineering takes that discovery and puts it to use. Students should be clear about what idea or concept is being applied and should use the project to discover the "how" and "why" of its use. Keeping the concept in the forefront keeps the focus on science first and engineering second. Your goal is to facilitate knowledge integration through real world application; the project should aid student attempts to incorporate scientific concepts into their working model of the world. Different students will engineer beyond different concepts on different projects. And that is an enormous opportunity for knowledge and confidence building! But making those attempts a primary goal of any project shifts the focus to engineering not science, and you may lose those students who don't yet grasp the science and who are fledgling designers. When students don't have a good idea of what scientific ideas are important, they attempt to "throw everything" at a problem and they will over-engineer their solution. That will lead to difficulty troubleshooting and modifying their design since clear connections between variables will be buried.

3. **DO NOT LIMIT DESIGN PROJECTS TO PRODUCTS. CONSIDER HAVING STUDENTS DESIGN PROCESSES OR AN EXPERIMENT.**
   Having students design a product is the easiest way to track and assess student understanding of principles. It enables the creation of a tangible artifact with assessable milestones along the way. Students love to build and will be naturally enthusiastic about such a project. However, the reality of resource and space constraints often makes product- based projects challenging, if not impossible. Engineers often design other things and it is important for students to be exposed to a wide range of ideas about design and technology.
   How we do something is often as important as what we do or make. Engineers frequently deal with process design. How we solve a problem can be made into an interesting puzzle or game of choices, where students need to navigate to the end result while confronting constraints. They are, after all, experienced real world problem solvers; they have been doing it every day for years. Engineers basically solve problems for a living. Students are expert at using processes to reach an end result. The "how" or process is often as important as "what" or product. Think of aspects of traffic engineering. Suppose there are a lot of accidents at a certain intersection. Engineers decide to develop more visible signals for the intersection, but if the process of timing those lights is not well thought out and designed to meet the constraint of one car in each place at any one time, accidents can still occur. In this case, the process of controlling traffic is probably more important than the products used to provide some control.

In addition, engineers are often confronted by many situations that require decision-making that focuses on ethical choices and analyzing reasons for failure. And although we all hope to educate ethical young people, many argue that science is about pure discovery and it is not ours to decide what is or isn't.

It is, however, always our decision about how to apply that knowledge. It is also important to realize that science doesn't really go wrong or fail until you apply it. Science just exists. Engineers routinely deal with what can and does go wrong when they analyze failures or engineer to prevent them. All of these things can provide a backdrop for an EDP project and allow for different views and understandings of scientific concepts. Looking at an idea from myriad viewpoints and considering various outcomes of applications builds content understanding.

Perhaps the best way to introduce students to the idea of engineering a process is to use their own experience in science class. Many products are limited by process constraints and the inability to reliably monitor design choices. An analogous situation exists in designing experiments. The experiments and demonstrations you choose to do in class are often limited by resources, space and time and the need to have clear connections between dependent and independent variables. Similar situations exist in industry. In some cases, it is even necessary to engineer new technology to measure results. Experimental design is essentially done by the EDP. By asking students to design an experiment, you are asking them to engineer a process to observe or measure a scientific concept. It is actually an easy way to transition from traditional labs to design based projects and can serve as an introduction to process design. It also provides real world connections since the concept of "design of experiments" is an important one throughout many industries. The questions of "how will you measure what is important?" and "how will you determine success?" not only underlie scientific experimentation, but are an important part of assuring device and product compliance and quality. Applying the engineering design process to experimental design is a good lesson format for highlighting the similarities and differences between the engineering design process and the scientific method.

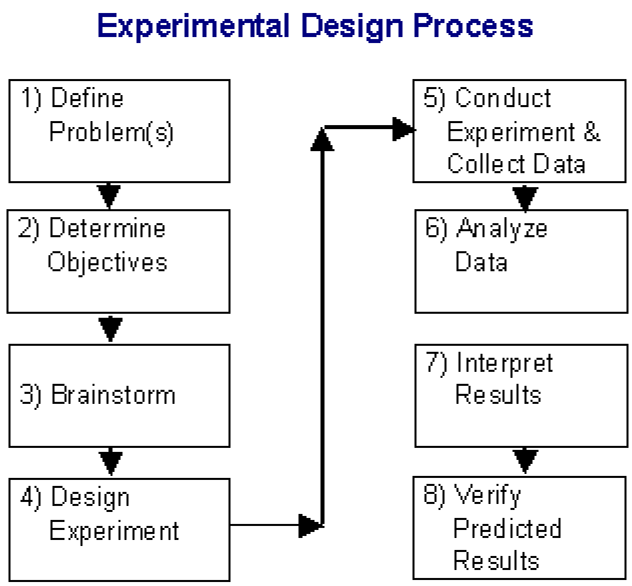

Figure 2 Experimental Design Process

https://www.moresteam.com/toolbox/design-of-experiments.cfm

Case studies and failure analysis are additional ways to incorporate an engineering approach. They can provide a low cost way to introduce engineering design ideas and decision-making into project work. They can also be used when class time is limited, since students can often work independently on these projects. However, it is always a good idea to provide some time for group discussion and debate. Skills such as scientific literacy, communication, reverse engineering and systems thinking can be highlighted. As much as possible, base your project on a real case or failure. Debates and discussion based on projects like this give students exposure to the need for informed citizens to be comfortable with the ideas of science and technology.

4. **REMEMBER THAT THE ENGINEERING DESIGN PROCESS (EDP) IS DESIGN BASED ON CONSTRAINTS AND CRITERIA.**

   The constraints are often instructor specified or situational limitations such as time, cost, size, etc. The distinction between the many things that can be made possible by science versus the choices we have to make in terms of what we can and should engineer provides opportunities for much discussion concerning practicality, impact and ethics.

   Criteria can be instructor or student determined depending on the project. Considerations such as designing for a specific end user, safety, sustainability and ease of manufacturing are often translated into criteria. It is useful to allow students to specify some or all of the criteria they will design to. Criteria determination can be facilitated by the use of decision matrices and Pugh charts. The discussion and determination of appropriate criteria is a good introduction to group decision making. In the real world, a designed product is always limited by constraints and it is only as good as its ability to serve the purpose delineated by the criteria. In other words, meeting design criteria is a way to judge success. Criteria should therefore, become a large component of assessment and, in that sense, students are designing part of their own rubric. Holding students accountable for meeting their criteria reinforces the goal of engineering something to provide a solution to a specific problem.

5. **ALWAYS REFER TO THE STEPS OF THE ENGINEERING DESIGN PROCESS.**

   The Engineering Design Process consists of the following key components:

   Problem Definition

Research

Design

Building

Testing

Analysis and Troubleshooting

Modification and Retesting

Communicate results

A more detailed description can be found in Part 2 of this guide along with ideas and considerations for each step of the cycle. In addition, ways to manage and implement different approaches to those steps are suggested.

Note that constraints and criteria are developed in the first two stages. Brainstorming, ideation and prototyping generally begin and end in the design and building phases. However, design is a fluid process and there is much overlap and iteration. The key things to emphasis are that in a well-designed product or process you need:

(1) **KNOW WHAT YOU ARE TRYING TO DO.** In other words, have a very clear definition of the problem and all factors influencing it (criteria and constraints).
(2) **KNOW WHAT YOUR OPTIONS ARE.** Thoroughly consider all alternatives and approaches.
(3) **KNOW IF AND HOW WELL IT WORKS.** You need a model (prototype) that allows for reliable, documented testing.
(4) **KNOW HOW TO MAKE IT BETTER.** It is important to have clear analysis and modification.
(5) **KNOW HOW TO SPREAD THE NEWS.** Communicate your results.