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# Art, Science, or Trade

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# ENGINEERING: ART, SCIENCE, OR TRADE

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**ABSTRACT**

Several definitions of the term "engineer" are presented, discussed, and contrasted with the term "scientist". These definitions demonstrate the fundamental differences between engineers and scientists and their professions. The engineering method is compared with the scientific method and the value of each is discussed.

Several aspects of engineering education are covered. The need for more liberally educated engineers is emphasized and the impact of computers on engineering education and the engineering profession is discussed. The value of a good science foundation in an undergraduate engineering program is also stressed.

An engineering education is only as good as the engineering educators and for this reason it is imperative that the best engineers be involved in education. This is especially true in engineering design courses. Practicing engineers with practical experience must be brought into the education arena to share their experiences.

Engineering and science are different professions. Each has a different set of goals and different methods of achieving these goals. This division or separation of science and engineering serves the best interest of each profession and also mankind as a whole.

## ENGINEER AND SCIENTIST DEFINED

What is an engineer? What is a scientist? The answers to these very basic questions can bring to light the fundamental differences between the two. Unfortunately there are few, if any, clear cut definitions of an engineer or a scientist. The few definitions that can be found do little to clarify the distinction and they do not recognize that there are certain areas in which the two overlap.

An engineer can typically be defined as a person who deals with artifacts rather than theory. An engineer designs artifacts such as bridges and machines, and he also analyzed artifacts and processes, such as the heat transfer in a boiler or the stress in a piston arm. A scientist, on the other hand, deals with facts and theories; his job is to expand the knowledge base through derivation and experimentation. A scientist only deals with things (artifacts) in the process of deriving or testing new facts or theories.

The dictionary, a standard reference for definitions, does little to give precise meaning to the terms. The *Oxford English Dictionary* defines an engineer as, "One who contrives, designs, or invents; an author or designer. Or, one whose profession is the designing and constructing of works of public utility, such as bridges, roads, canals, railways, harbors, drainage works, gas and water works, etc."

The masthead of *The Structural Engineer* states that structural engineering is the science and art of designing and making with economy and elegance, buildings, bridges, frameworks, and other similar structures so that they can safely resist the forces to which they may be subjected. This definition points out 3 important aspects of engineering: that engineering is both art and science; that engineering combines elegance and economy in artifacts; and that engineering is concerned with safety.

The National Research Council's Committee on the Education and Utilization of the Engineer defines an engineer as a person having at least one of the following qualifications: a. college/university B.S. or advanced degree in an accredited engineering program; b. membership in a recognized engineering society at a professional level; c. registration or license as an engineer from a governmental agency; or d. current or recent employment in a job classification requiring engineering work at a professional level (National Research Council, 1985).

The *Oxford English Dictionary* defines a scientist as, "A man of science." Science is defined as, "The state or fact of knowing; knowledge or cognizance of something specified or applied."

These definitions serve to illustrate that an engineer deals with artifacts whereas a scientist deals with facts. They point out that although an engineer uses science in his work, it is a tool. It is a mistake to consider engineering as applied science. Engineering is no more applied science than science is basic engineering — the two are distinct. If engineering is taken as the building of artifacts then the early engineers were primarily artists (Liebman, 1989). Early man did not analyze and hypothesize a slingshot, he engineered it. He learned from making slingshots how to make better slingshots. Science came along much later.

Engineering is a creative process. There is no book of designs that an engineer can go to and pull out a solution. True, parts of certain designs are well known and documented, but the use of these parts to create a whole usually involves creating new parts.

Engineers deal with artifacts; they may be physical objects or processes. The engineer first uses his imagination to create the artifact in his mind — he pictures it. Once the artifact has been imagined the analysis and refinement of the artifact can begin. Science is really thinking 'on second thought', and science is applied 'after the artifact', when the object has been pictured first in the mind of the engineer (Petroski, 1990). This is not to say that engineers only imagine artifacts and do nothing else, nor does it say that engineers are the only ones who have creative ideas. Engineers not only have ideas but they make them work to benefit mankind. This was summed up nicely in a recent theme of National Engineers Week — "Engineers: Turning Ideas Into Reality".

Engineering is the art that deals with materials and material forces and its purpose is to serve mankind. Pure science typically deals with fewer variables than does engineering. Science attempts to discover the fundamental facts about materials and phenomena (Cross, 1952).

The engineer, and more generally the designer, is concerned with how things ought to be — how they ought to be in order to attain goals, and to function (Simon, 1981). Science, on the other hand is concerned with explaining how things are and how they operate. Science is the study of what is; engineering is the creation of what is to be (Waldron, 1989).

Engineers tend to be makers — they make artifacts to accomplish certain goals. Engineering is the uniting of craft and science to develop artifacts (Petroski, 1990). They try to make the best artifact at the lowest cost. To the scientist, the final goal is the addition of new facts to the knowledge base. He is not concerned with the production of artifacts, just the attainment of knowledge. However, the scientist may, in his quest for answers, develop a new apparatus to aid him in his search. Likewise, the engineer, in his development of a new artifact, may discover a new fact. This indicates there is a certain overlap of science and engineering.

## METHOD

If science and engineering are truly different professions then this would be indicated in their respective methods. A close examination of both scientific and engineering methods does indeed reveal different premises, different expectations, and different attitudes. Often the engineer is thought of as an applied scientist — one who simply applies scientific laws to real world problems. But this reduces engineering to a mechanized process and ignores the creative aspects inherent in design.

The fundamental activity of science, and therefore of scientists, is to make observations. These observations are made carefully and without bias; they are then analyzed by the scientist to find similarities or differences. The ultimate goal of the scientist is to develop a theory or law which will not only explain the observations, but will predict future behavior. The theory, law, or hypothesis can never be proven correct. The theory may be used for centuries, accepted as true by everyone, but never proven. The theory can, however, be proven incorrect by just one example of some behavior which is contradictory to that predicted by theory.

The scientific method recognizes that theories can never be proven correct but can be proven incorrect. A scientist makes every attempt to disprove his own theory. If, after much effort, the scientist has not disproven his theory he will open it up for attack by his peers. His peers will attempt to disprove the theory, not because they are mean-spirited disbelievers, but because they recognize that a theory can only be disproven, never proven.

In contrast to the scientist who attempts to explain nature, the engineer attempts to use nature to effect change. The engineer does not attempt to explain how things work; he makes things work. While science explains the law of gravity, engineering allows man to overcome gravity and to walk on the moon. The engineer does not try to find the one correct solution but tries to find the best solution. The best solution is relative and depends on numerous factors: time, place, economics, and of course, problem definition.

The engineering method is defined as the strategy for causing the best change in a poorly understood or uncertain situation within the available resources (Koen, 1985). This is perhaps the best definition of the engineering method because it incorporates several aspects unique to engineering; it mentions the best change, not the only change or the correct change. The definition also points out that there are limited resources and that the problem is not always well defined or fully understood.

Unlike the scientist who must carefully lay out a path and follow it to demonstrate his theory, an engineer is not bound by this method. Engineers do not rely on pure, basic facts, they rely on analyses, tests, experience and common sense (Cross, 1952). This is not to say engineering is haphazard and undisciplined; it is not. Engineers must consider many aspects of a problem and its solution, many of which offer conflicting or contradictory evidence. The engineer must sort through this, justify his assumptions, and make sure if he errs, he errs on the side of added safety.

There is no single step-by-step method for engineers or scientists to use in solving problems or developing theories; each individual has his own method and frequently it varies from problem to problem. There are, however characteristics common to each method. These definitions indicate the fundamental difference between engineers and scientists, indeed between engineering and science. Whereas the scientist puts forth his theory to be proven incorrect, the engineer puts forth his solution on the basis that it will not be proven incorrect — that it will function as intended. Each method is well suited to its respective subscribers and serves them well; however, the use of the scientific method to solve an engineering problem would be impossible, and the use of the engineering method to develop a scientific theory would be disastrous.

## EDUCATION

Engineering is a profession that is practiced openly, with interaction from people and society. Engineering decisions and designs have an effect on individuals, if not on society as a whole. This is an aspect of engineering not shared with science. Science has had a profound effect on society and many ills have been produced by both good and bad science, but science is not concerned with social consequences (Harris, 1983). Although a scientist may develop a new plastic or discover a fundamental law of nature, this seldom affects society directly. It may have a profound effect on society when an engineer uses or misuses the new plastic or law in the design of a product, but this is due to engineering decisions and not due to scientific revelations.

Engineers are often placed in positions of deciding what 'best' is: what is best for society, what is best for a company, or what is best for the environment. Obviously their decisions affect the economy, environment, public policy, and people. Examples of how engineers and their decisions affect these areas can be found in ballistic missiles, automobiles, and the explosion of the Space Shuttle Challenger. These are but a few of the numerous ways in which engineering affects our lives. Some engineers are unaware of how they and their decisions will affect society as is evidenced by the recent catastrophic failures of the Hyatt Regency walkways, and the numerous EPA Superfund cleanup sites.

Engineering curricula need to be changed to allow engineering students to be exposed to more courses in liberal arts and social sciences. The result will not only be a better educated member of society, but a better engineer. Psychology and sociology will help the future engineer understand who he will be dealing with and how to deal with them. More courses in art will help the student appreciate aesthetic beauty and possibly design a nicer looking bridge. Engineering is, at one level, art. The creativity exhibited in the conception of an engineering design is similar to that exhibited by a painter or sculptor in the conception of their work. By requiring more true art courses in the engineer's undergraduate curriculum his creativity can only be improved.

In practice, engineers find themselves wrestling with many ethical decisions — something which most were not prepared for in school. There are no right or wrong answers in engineering ethics, only good or bad ones. Many times ethics cannot provide an answer, but can serve to clarify the issues involved, thereby influencing the final engineering decision (Gunn, 1990). Engineering students need to learn that all problems, especially ethical problems, do not necessarily have a solution. Undergraduate engineering students could learn this if they were exposed to real ethical decisions by those who make them — practicing engineers. Engineering professors with nothing but academic experience are only in a position to teach what they read. A practicing engineer, or a professor with practical experience, is in a position to share what he has lived and to discuss the difficult decisions he has made. At the very least, a student should not receive his degree unless he understands he is serving society first, his employer second.

Few, if any events have had a greater effect on engineering and engineering education than the development of the computer. By using a computer, an engineer can solve complex problems in minimal time. Drawings can be made, modified, and stored at speeds unheard of before the computer age. Productivity can be greatly increased by the proper use of a computer; unfortunately, improper computer usage can result in decreased productivity and dangerous designs.

Recognizing the value of the computer in engineering, engineering education has incorporated the computer into its curricula. Placing too much emphasis on computers can have disastrous results and, unfortunately, this seems to be the way engineering education is going. More and more, students are expected to solve problems on a computer by trying several iterations and giving a precise four-digit answer. Rather than solve an equation for $\chi$, they solve it by trial and error using a computer. There are several dangers in using this approach to computers — especially at an early stage in a student's education. First, it encourages the notion that any problem can be solved given enough computer time to execute enough iterations. Second, it encourages the student to expect one, precise, accurate answer. The student can forget that the data he uses are seldom accurate or precise — just close.

Computers, combined with the numerous software packages available, can give an engineer a false sense of security and allow him to tackle problems beyond his experience. Unless caution is exercised in all phases of design, disasters can result. The Hartford Civic Center is one such failure directly attributed to an engineer using a computer with software to design a structure far beyond his limits of understanding

(Petroski, 1985). Computers must be used in engineering; many of the problems engineers are required to solve today are too lengthy and complex to be done without a computer. But the answers given by computers, like the answers given by the slide rule and calculator, must be checked by basic, fundamental laws and equations of engineering; they must be tempered by engineering judgment and experience. By encouraging or requiring students to implement computers early in their educations, the students are given the message that everything done on a computer is better and more accurate than something done by hand. Students need to be taught that back-of-the-envelope and graphical solutions are quite valid and frequently more convenient than computer solutions. Teaching students rules-of-thumb will give them additional tools to verify computer solutions and give them the ability to solve problems in the field or get a "ball park" answer when pressed for time.

Although an engineer should receive a well rounded, liberal education, science courses should not be ignored. Science is one of the engineer's most important tools and a firm foundation in the fundamentals of science will prove invaluable. But the engineering student must learn that science is a tool and nothing more. Science is to be used with experience, tempered by an appreciation for art. Often an engineer's instinctive feeling is a better indicator than scientific data. The cause of the Challenger explosion was due, in part, to an engineer not having, in his opinion, conclusive data on O-ring erosion (Whitbeck, 1987). The available data, although not necessarily conclusive, did indicate a problem and that in itself should have been enough for the engineer to recommend against the launch. The contributing factor in the disaster was an engineer seemingly forgetting his ultimate responsibility to protect the safety of the public, and not looking at the available data with enough suspicion.

To achieve the goal of providing a well-rounded, liberal education to engineers and to provide them with the needed foundation to deal with ethical problems, 2 things need to be considered. First, thought should be given to extending undergraduate programs from 4 to 5 years (National Research Council, 1985). This additional time would allow for more humanities courses to be taught and would give the students a chance to explore areas which interest them while not detracting from the very important technical education. It would be a rigorous curriculum, and would involve hard work on the part of the student. It would also impress upon the students that engineering is hard work and the best engineers are the ones who work the hardest. A 5-year curriculum would also address the fact that it is rare for a person to go through an engineering curriculum in the prescribed 4 years.

Second, engineering educators should be given the opportunity to practice engineering before teaching it. Engineering started as an art then evolved into a trade. The first engineering education system consisted of an apprentice working for an experienced person. The apprentice learned engineering by doing and learned from the mistakes made by his employer. This system, however, was soon found to be inadequate and formal engineering schools were established in order to educate students in the humanities and sciences. A formal education gave the engineer the ability to solve new problems using new methods. The pendulum has now swung the other way; we are forgetting our roots as artists and craftsmen and are replacing experience with education. Inadequate funding is forcing a decline in both quality and quantity of engineering laboratory courses. Now some of our most respected engineers, those with doctorates, have never practiced engineering. They have gone from high school through graduate school, never taking the time to be an engineer. The current process of education tends to produce excellent researchers but does not necessarily produce excellent practicing engineers. Some people go so far as to say that engineering faculty who only teach are not considered to be practicing engineers (Hazelrigg, 1988).

The practice of engineering allows an engineer to learn theory by using it and recognizing its limits. Practical experience can be invaluable to an engineering educator, especially one who teaches design courses. No one would suggest allowing surgery to be taught by someone who has never held a scalpel outside of class, yet we routinely allow engineering design to be taught by those who have never designed anything outside of academia. Perhaps it is time to reconsider the necessity of a Ph.D. to teach design and consider the requirement of experience, A B.S. or an M.S. level engineer with years of design experience may be better qualified to teach design than the Ph.D. with experience limited to academia.

Another method of getting practical engineering experience in the classroom is to bring in practicing engineers for a short time. Engineers working in industry, government, or private practice have valuable knowledge and practical experience they can share with students. This sharing can be accomplished by allowing these engineers to come into the classroom and teach some engineering design courses for a semester or even for a few weeks. At the same time, the engineering professor could fill the role of the practicing engineer. The professor could gain some practical experience by working in the practice of engineering and not just in education or research.

## CONCLUSIONS

Engineering and science are fundamentally different endeavors. Where engineers design artifacts and find new uses for materials to benefit mankind, scientists seek truth, seek to explain nature. Each profession makes use of the other; the engineer uses science in his solution of a problem and the scientist often uses some engineering in his work. The danger comes when the engineer and the scientist confuse who they are and what they do. The engineering educator who has followed the path to a Ph.D. without gaining practical experience often confuses engineering with science.

To adequately solve problems that are presented, an engineer needs to consider all aspects of the problem including sociology, economics, and at times, even religion. To be prepared for this task, the engineer must have a more liberal education and it may require 5 years of schooling. The engineering student also needs to learn from experienced, practicing engineers in addition to the traditional research oriented Ph.D. engineering educators commonly found at universities.

Engineering is a unique blend of science, art, and trade. We all have engineering roots as evidenced by man's first use of tools, but today an engineer is determined by how he works, not what he produces. Many people have produced beautiful and useful artifacts, but these pepole are skilled craftsmen, not engineers. They lack the requisite ability and knowledge to analyze. They achieve their goals by the expensive and potentially dangerous process of trial and error. The engineer usually does his trial and error on paper and eliminates many designs before anything is constructed. The engineer still has failures — due in part to his mistakes, in part to the imprecision of engineering itself. The truly good engineer, one interested in bettering himself and his profession, analyzes the cause of the failure and learns from it.

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