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# Axiomatic Design and Design Thinking in Humanities and Social Sciences in the 21st Century

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**Abstract.** Since the Industrial Revolution (IR), science and technology have advanced at an ever-accelerating rate. In a mere 250 years since IR, advances in science and technology have changed nearly all aspects of humanity. Before IR, people and animals were used as the primary source of power and energy. After IR, steam engines and other power sources replaced human and animal power, which ultimately changed the economic and political structure of many nations and the world. Now, the world is undergoing socio-economic transformation due to information technology and will soon enter the age of biological revolution. These and other advances in science and technology are likely to accelerate, creating both opportunities and some unanticipated risks to humanity. To ascertain that the technological changes result in positive outcomes for humanity and society, more research in *humanities and social sciences* is needed so as to complement the advances being made in natural sciences and technology. The question raised in this paper is: "Can *Axiomatic Design and design thinking* be applied in the fields of humanities and social sciences so as to create imaginative societal solutions in the technology era?" Design examples are given that show how AD can be applied in non-technical fields.

## 1 Introduction

The life of people began to change because of the emergence of science and technology. The "new science" of the XVII century rejected the Aristotelian idea of seeking the essence of four causes. The new paradigm of science accepts that there are laws for physical phenomena, opening the doors for modern science and technology. The pivotal historical contributions that have initiated this transformation are Isaac Newton's pioneering contributions in physics in 1686, the discovery of electricity by Ben Franklin in 1767, the invention of the steam engine by James Watt in 1782, among other notable discoveries and inventions. Since then, various artifacts created by design have led to technology innovations, scientific advances, institutional development, and economic policies, all of which contributed to the creation of contemporary civilization. Notwithstanding some of the socio-political-economic experiments that led to unimaginable human tragedies, people have benefited from scientific advances and technological innovations. Many ingenious designs-in both technical and non-technical fields have established the foundation for modern socio-economic-political systems.

Notwithstanding tens of thousands of years of human existence, the current science and technology era began less than four hundred years ago. Table 1 lists some of the science and technological achievements that have led to modern civilization as well as those that may affect the future development of the world[1]. Although it seems that some of these advances were made a long time ago, they are relatively recent in terms of human lifecycle, i.e., about 12 generations. The pace of change has been accelerating with time. All indications are that this trend is likely to continue.

Before the invention of the steam engine by James Watt in 1782, people and animals supplied the primary energy needed in farming, transportation, manufacturing, and construction. Since the Industrial Revolution, machines began to replace humans and animals as the primary source of energy and force, which changed all aspects of motive power as well as the socio-economic political structure of many nations. England, the birthplace of the steam engine, became a leading industrial power and influenced the world with its industrial might for three centuries. England colonized many countries in Africa and Asia, in some cases, for a few centuries.

In the 20th century, the pace of advancement of science and technology has accelerated. It was helped by the war efforts and the conflicts among nations. Massive investments in research and development have been made during and following the Second World War. The current boom in high technology in the United States was partly initiated by the investment made in defense R&D by the U.S. government. Today, the market capitalization of rel-

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[1] Human history may go back a couple of million years when humans discovered fire. Since then, there were many important inventions, discoveries, and other advances that preceded and led to the Industrial Revolution. (For a historical list of major technological events preceding the Industrial Revolution, see Ref. Technology Timeline, Chris Woodford, Explainthatstuff!)

Table 1. Partial List of Important Events in Science and Technology (in Chronological Order)

- 1686: Newton's laws (331 years ago[2])
- 1767 Electricity by Ben Franklin and others ( 250 years ago)
- 1782: Watt Steam Engine by James Watt (235 years ago)
- 1854: Thermodynamics (Lord Kelvin) (163 years ago)
- 1861: Electromagnetism, Maxwell's Equations (156 years ago)
- 1876: Telephone, A. G. Bell (142 years ago)
- 1903: Airplane (Wilbur and Orville Wright) (114 years ago)
- 1905: Einstein's Special theory of relativity (102 years ago)
- 1911: IBM mainframe (94 years ago)
- 1917: Moving automobile assembly line by Henry Ford (100 years ago)
- 1928: Penicillin by Fleming (90 years ago)
- 1936: Turing machine by Alan Turing (81 years ago)
- 1946: Transistor (71 years ago)
- 1948: Information theory by C. Shannon (69 years ago)
- 1950: NC machine tools by John D. Parson and MIT (68 years ago)
- 1950: Jet airliner (67 years ago)
- 1953: DNA by Watson and Crick (64 years ago)
- 1960: FDA approval of the contraceptive pill (58 years ago)
- 1964: IBM Mainframe 360 (53 years ago)
- 1964: Medical IT software system by A. N. Pappalardo (53 years ago)
- 1973: First mobile telephone (44 years ago)
- 1975: Microsoft by Bill Gates (42 years ago)
- 1976: Apple by Steve Jobs (41 years ago)
- 1976: Axiomatic Design Theory (41 years ago)
- 1998: Google by Larry Page and Sergey Brin (19 years ago)
- 2004: Facebook by Marc Zuckerberg (12 years ago)
- 2011: On-Line Electric Vehicle (OLEV, 7 years ago)

atively young high technology companies such as Apple and Amazon is far greater than traditional industrial firms in automobiles (e.g., General Motors and Ford) and natural resources (e.g., ExxonMobile).

Three different approaches have been used to achieve major advances in science and technology since the Industrial Revolution: *axiomatic approaches, scientific discoveries, and technological inventions*. These three different kinds of contributions created the intellectual base of the current technology-based society. These advances also influenced the morphing of the socio-political-economic structure and system as well, ultimately leading to more transparent and democratic governance in many nations. It is most likely that this rapid progress in science and technology will continue in the future, a la even at a faster rate.

The motivation for writing this paper is based on the observation, as stated earlier, that the advances in and development of science and technology during the past three centuries have been unprecedented and that their pace of progress may accelerate faster in the future, and that there is no guarantee that some of these advances will not be misused or wrongly applied, resulting in irreparable damages to humanity and the global environment. To prevent such an event from happening, we need to accelerate further progress in humanities and social sciences. In this paper, we explore the applicability of Axiomatic Design (AD) in non-technical fields.

## 2 Application of Axiomatic Design in Social Science Fields

Table 2 lists of various ideologies, political structure, policies, and political actions that have been tried in the past. The results are mixed. Under some of these socio-economic political systems, millions of people lost their lives and led miserable lives. On the other hand, some systems brought enlightenment to human aspirations. The amazing historical fact is that the masses of people for centuries followed the dictates of few who have advocated some of these ideologies. As a result, many have suffered. The question is: "Had the fields of humanities and social sciences advanced to a higher level of understanding, could we have prevented some of these disasters?"

Table 2. A Random List of Significant Socio-Economic Political Experiments

1. Kingdom
2. Dictatorship
3. Liberalism — liberal democracy
4. Elitism
5. Progressivism
6. Ultra-liberalism
7. Capitalism
8. Fascism
9. Communism
10. Totalitarianism
11. Democracy

During the past 175 years[1], in countries that have adopted liberal democracy, much progress has been made. For example, the life expectancy of people has increased from 30 years to over 70 years, decreased people living below the poverty level from 80% to 8%, increased literacy rate to 80% from 16%, and granted freedom to more people than ever.

One of the current issues in the 21$^{st}$ century is the following question: When so much progress has been made under liberal democracy, why are there so many countries reverting to nationalism, racism, dictatorship, and oligarchy? To understand this dilemma, we need to acquire a basic understanding of various topics related to humanities and social sciences so as to provide a better roadmap for humanity. Ideally, as more advances are made in these fields, we may be able to *design appropriate socio-economic policies and organizations so as to create more enlightened and equitable societies and nations.*

One of the major differences between technological systems and non-technical systems is that many technological systems can be made to behave like a closed system, which is characterized by the fact that the number of design parameters (DPs) for a given set of functional requirements (FRs) can be fixed and vary only those DPs that the designer chooses to affect the FRs. On the other hand, many systems in humanities and social sciences behave like an open system where the number of DPs cannot be fixed, and many variables that act like DPs may be introduced into the system during its operation. Therefore, in these non-technical systems, special considerations must be given in order to make the number of design parameters (DPs) to be equal to the number of functional requirements (FRs) so as to satisfy a basic condition required for an *ideal design*[3] [2, 3]. The issues related to "open systems" versus "closed systems", including how to constrain an open system, is discussed in Appendix A.

## 3 Impact of Axiomatic Design and Design Thinking

"*Axiomatic design* and *Design Thinking*" refer to activities that create or synthesize systems to satisfy a set of functional requirements FRs within a given set of constraints. Thus, design and design thinking are fundamental in many fields, including both technical and non-technical fields. The first step in *design and design thinking* is the identification of the *problem(s)*.An example of the problem in social sciences may be stated as: "Develop economic policies that will increase the velocity of money circulation so as to increase the wealth of a nation, equalize the income distribution, and increase the overall wealth of a nation."

The modern science-technology era was born because of the bright people with exceptional minds (e.g., Isaac Newton, James Watt, Albert Einstein, Claude Shannon, Francis Crick, and James Watson), who changed the relationship between humanity and Nature through discoveries, inventions, and analysis. New power sources that were introduced for the first time with the invention of the Watt steam engine enabled people to replace human power with machine power; increase their productivity; and use their minds to conceive, discover, and invent many important artifacts that have improved the quality of life. Scientific theories explained the invisible as well as the observable causality of various critical natural phenomena. These advances amplified the efficiency and productivity of human efforts in diverse fields. Thus, in three short centuries since the Industrial Revolution, people have transformed the world, creating the enlightened modern era, with a promise of more rapid progress in the future. Modern democracy is a by-product of technological advances that raised the overall wealth of many nations. In this transformational process, "design and design thinking" has been at center stage in creating amazing technological miracles that have lifted the overall quality of life of people everywhere to a varying degree.

[3]Theorem 4 for ideal design [2]

## 4 Typical Paradigms in Science and Technology Development

People used three different paths for the development of scientific theories and technologies. First is the *technological invention* such as the steam engine by James Watt. The second path was through *scientific discoveries* (such as the DNA structure) that were based on observable experimental evidence. Many of these advances were readily accepted as soon as they were introduced or published.q The third is based on basic *scientific postulates/axioms*, e.g., geometry, thermodynamics, Newton's laws, and Einstein's theory of relativity, some of which have gone through years of checking for validity, debates, and discussions before they were finally accepted. Even today, the second law of thermodynamics, which is an axiom, is still being debated after more than a century since its advance. That has been the nature of *axioms* that make people incredulous because of the simplicity of many axioms that capture profound thoughts and principles. It is remarkable that even Newton's laws, which were axiomatic at the time they were advanced, were disputed by some of Newton's contemporaries.

Axiomatic Design (AD) was introduced to the engineering community about four decades ago [2–4]. AD consists of two design axioms:

- The Independence Axiom: Maintain the independence of functional requirements (FRs).
- The Information Axiom: Minimize the information content.

Following the introduction of AD theory and as its extension, the complexity theory was introduced which has a number of implications on the design of large systems [4]. Based on AD and complexity theory, many products and processes were created, many organizations were restructured, and government policies were formulated. However, AD is still in its early phase of replacing the old practice of making design decisions based on experience and empiricism that involve lengthy and costly recursive design/build/test cycles. Although Axiomatic Design was used in designing organizations and policies, in addition to engineering and other artifacts, it has not been formally introduced to deal with core issues in humanities and social sciences. Today, most organizations and subjects outside of engineering still dwell on social issues based on past experience and history, just as it was the case in science and engineering. The question raised in this paper is: "Can we make more progress in non-technological fields, i.e., humanities and social sciences, by adopting axiomatic approaches?" Scholarly and fundamental examinations of this issue may yield rich intellectual advances and scholarly dividends as well as progress in making rational societal decisions.

AD provides a logical framework and the scientific basis for the design of various systems in many fields, including engineering, materials, information, systems, and organizations. It has been demonstrated—through successful development of products and organizations—that Axiomatic Design can effectively replace prolonged trial-and-error processes often used in developing new systems and artifacts in engineering and technology development. AD enables the designer to organize one's thoughts quickly and correctly in dealing with large systems in making the right decisions. Creativity can also be enhanced through organized processes of AD for *design and design thinking*. People can improve their design practice and advance technologies by learning the basics of AD. The power of Axiomatic Design is illustrated in the following technical example of making thin- film semiconductors[4].

### 4.1 Example — Design of a Technological System: Manufacturing of Thin Film Semiconductor devices

A young professor at a leading university[5], who used to work for IBM, presented a seminar on how to manufacture thin film, single crystal III-V semiconductors without defects. The **problem** he identified is the following: We have known for a long time that if we deposit a new layer of a known crystalline material (e.g., III-V semiconductor compound) on the solid crystalline substrate of the same composition by vapor deposition, the newly deposited material assumes the crystal structure of the substrate. After deposition of several layers of the crystal material, if we could separate the newly deposited crystal from the substrate, it could be used to make semiconductor devices. The difficulty (i.e., the problem) in implementing this idea has been that it is difficult to peel off the newly deposited semiconductor layer from the substrate. AD teaches us that the functional requirements (FRs) of this process must be satisfied independently.

If we did not know the proposed process investigated at MIT, we would state the functional requirements (FRs), the design parameters (DP), and process variables (PV) for manufacturing the III-V thin film semiconductor as follows:

- FR = Make thin-film III-V compound semiconductors
- DP = Vapor deposited III-V compound
- PV = Vapor deposition of III-V material

The functional requirements (FRs) may be decomposed and stated as follows:

- $FR_1$ = Create the III-V compound structure by vapor deposition
- $FR_2$ = Control the thickness of the deposited film
- $FR_3$ = Separate the thin film from the substrate

The design parameters (DPs) may be stated as

- $DP_1$ = Vapor deposition apparatus
- $DP_2$ = Amount of deposition
- $DP_3$ = Separation layer

The Process Parameters (PVs) may be chosen to satisfy the Independence Axiom as follows:

- $PV_1$ = Control of vapor deposition of gallium and arsenide on a solid III-V semiconductor substrate
- $PV_2$ = Duration of vapor deposition of the III-V compound
- $PV_3$ = Pre-deposit an inert intermediate layer on the substrate, e.g., graphene

The role of the intermediate layer is to let the deposited layer to acquire the structure of the substrate without adhesion of the deposited layer to the substrate. It should be noted that the design matrix for the FR-DP relationship is diagonal, i.e., an uncoupled design, thus satisfying the Independence Axiom of AD. The DP-PV relation also satisfies the Independence Axiom.

The professor's idea was first to deposit an atomic layer of graphene (i.e., allotrope of carbon in the form of a two-dimensional, atomic-scale, honey-comb lattice in which one atom forms each vertex, shown in Fig. 1) on the solid semiconductor substrate first and then deposit a new layer of the semiconductor on top of the graphene by vapor deposition. Then, the newly deposited semiconductor material would assume the structure of the substrate crystal below the graphene sheet without being affected by the structure of the intervening graphene layer, because the extremely thin graphene sheet is a two-dimensional material and does not bond strongly to anything perpendicular to its surface. Thus, graphene will not affect the crystalline structure of the newly deposited semiconductor material on the top, letting the newly deposited material (on top of the graphene) assume the crystalline structure of the substrate below the graphene sheet. Thus, the newly deposited crystal on top of the graphene sheet can be peeled off to make a thin semiconductor device. If the design of this process can produce semi-conductors on a mass production basis, it should make a major impact on the field of III-V semiconductor

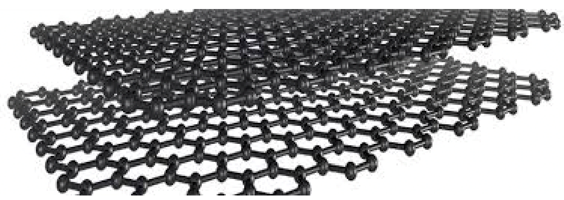

Fig. 1. Two layers of carbon atoms in the form of a two-dimensional, atomic-scale, honey-comb lattice in which one atom forms each vertex [5].

## 5 Application of AD in Humanities and Social Sciences

Humanities and social sciences include many diverse subjects, each at various stages of intellectual and theoretical advancement. For example, such fields as economics,

[4] There are a large number of products, processes, and systems developed for commercial use. See [2, 3].

[5] This example was made up after hearing a seminar given on the topic by Professor Jeewhan Kim of the Department of Mechanical Engineering at MIT.

literature, linguistics, history, psychology, political science, public policy, and others have a long history of outstanding scholarly achievements. Every year Nobel prizes are awarded in economics and literature[6]. Therefore, one should not lump all these fields together under one heading. Furthermore, the nature of some of these fields may not be amenable to generalization. Nevertheless, we should explore if we can develop a more predictive means of formalizing economic policies; make the field of political science a more predictive science; and condense the essence of historical lessons so as not to make similar mistakes in the future.

The basic questions pursued in this paper are: "can we establish rational policies in a socio-economic arena based on *Axiomatic Design?*" "Can we design socio-economic-political systems and policies based on the design axioms and avoid (or at least, minimize) many problems in the socio-economic political arena we seem to encounter for lack of reliable and absolute measures of correctness or satisfaction?" "Can we avoid many of the past mistakes that were often initiated because irrational arguments of a few were sold to the masses by identifying bad ideas prior to their implementation?" This paper explores possible applications of design axioms in non-technical areas: design and administration of universities, and designing a unit of a government agency, and in controlling the speed of money circulation. The first two, i.e., university administration and government agency, were actually implemented and proved that Axiomatic Design yielded desired results.

Key concepts and results of AD that are applicable to humanities and social sciences are the following:

1. Problem definition — the first step in design and design thinking (i.e., "What is the problem(s) we need to solve?")
2. Check the validity of the existing assumptions
3. Translation of the problem defined into functional requirements FRs
4. Designing the solution by developing means DPs of satisfying FRs
5. Designing uncoupled or decoupled system solutions to satisfy a set of FRs
6. Manage the system by making sure that the FRs are independent of each other by choosing a proper set of DPs, i.e., satisfy the Independence Axiom.
7. Assign a system architect who can lead the development of large systems projects by having a thorough understanding of the implications of AD.
8. Manage projects without incurring cost over-runs and missed schedules by creating uncoupled or decoupled systems.
9. Reduce the complexity of designs by introducing functional periodicity to the system, if possible.
10. Be able to lead and manage large organizations so as to achieve the intended goals of the organization without coupling FRs

[6]The Nobel committee does not give the same recognition to engineering and mathematics through the awards of the Nobel Prize. The Nobel Committee claims that these fields are not mentioned in the will of Alfred Nobel

Each one of the above-stated items needs much discussion among specialists in different fields. Unfortunately, specialists in different fields may come up with different problem definitions for the same problem, because they make different *assumptions* based on their professional background. For example, one of the issues discussed a great deal in the United States is the impact of free trade on the unemployment rate. There may be many equally acceptable solutions if we can satisfy each one of the FRs independently from each other. For example, we can come up with means of having free trade (i.e., a DP) and at the same time come up with another DP that can deal with unemployment rate without coupling the FRs, i.e., by developing an uncoupled or decoupled design.

When we apply Axiomatic Design to subjects in humanities and social sciences, the following execution steps should be common and equally applicable to all: first, *define the problem* to be solved, followed by design of an overall approach for solving the "problem" by defining *functional requirements FRs*. For instance, if one wants to write a book, the author must decide on the "problem" the author wishes to address. It may consist of "what to write", "how to develop the theme of the book", "the sequence of presentation", "how to capture and lead the interest of readers", "how to present the climatic part of the story", etc. A novelist should "design" how to deliver the story by satisfying functional requirements FRs of the book. For example, a novelist may wish to satisfy the following FRs: "capture the readers' attention from the very beginning of the book", "let the reader anticipate and be curious about the ultimate conclusions", "appeal to human common sense", and "ultimately reveal the main theme of the book". Sometimes, the author may design the story to convey a profound knowledge based on the extensive database, which was exemplified in the book, entitled "Capital in the Twenty-First Century" by Thomas Piketty[6]. Sometimes, the author may weave a story based on historical facts presented in a interesting and appealing way, with surprising twists, as was done in "Remains of the Day" by Kazuo Ishiguro[7], who was praised by the Swedish Academy as a writer "who, in novels of great emotional force, has uncovered the abyss beneath our illusory sense of connection with the world". However, in writing a monograph on a scientific topic, such as Axiomatic Design, the goal is to present a new theory with many examples to convey the essence of the theory in a concise and thorough prose to introduce a new perspective on an important scientific and technological topic.

The ten items listed above, once internalized by the designer, should give the designer the ability to deal with the design and operation of many different systems in the humanities and social science fields. They should complement the experience-based knowledge acquired through practice by managers, engineers, and leaders of organizations. Ultimately, their success in creating imaginative and rational systems solutions should enhance the probability of achieving the goals of the organization as well as satisfying of aspirations of the designer. The initial hurdle of overcoming skepticism may be one of the most difficult challenges of introducing *design and design thinking into these non-technical fields.*

The design and management of an organization also require the identification of the problem(s) that the organization must address, followed by specific goals (FRs) that the organization must satisfy to solve the identified problem.Then, specific means (DPs) of satisfying FRs must be selected, followed by securing of financial and human resources (i.e., PVs) to implement the DPs. The design of a government organization and two academic entities will be briefly reviewed in Section 6 in order to illustrate successful applications of AD to the design and operation of these organizations. As an example of how design might be applied in social sciences, the circulation of money will also be presented.

To illustrate how AD was used in designing non-technical systems, three examples will be given: (a) solution of the economic and industrial problem encountered by Korea in 1980, (b) how to increase the velocity of money circulation to promote economic growth, which is an issue in economics and finance, (c) how to design and implement a university structure so as to make it a leading institution of its kind in the world.

## 6 Example Korea's Economic and Industrial Crisis in 1980 and the Role of Design Thinking and AD in Solving the Crisis

In June 1980, the author unexpectedly became the key person who directed the Korean Government how to deal with their economic and industrial crisis. Axiomatic Design was applied to develop solutions to the crisis. The suggested policy changes were immediately implemented because of the seriousness of the crisis. To understand the urgency of the help Korea needed at the time, the following background story needs to be told. Until 1961, Korea was a very poor country with hardly any industry and industrial know-how, still recovering from the Korea war that devastated the country between 1950 and 1954. After the military coup led by Major General Park Chunghi in 1961, Korea successfully developed the labor-intensive industries such as shoemaking, apparel, and textiles. Ten years later n 1970, based on the success of labor-intensive light industries, Korea decided to shift its industries to heavy industries such as steelmaking, automobile, and shipbuilding. To build factories, they leveled mountains, created new harbors, and built new highways. It was an ambitious undertaking that no other nations had attempted until then.

In June 1980, the author was invited by KIST (Korea Institute of Science and Technology), a research institute, to look over their World Bank funding. When the author visited the World Bank in Washington on his way to Korea, the economists at the bank to expanded my mission, asking that I assess the results of their investment in Korean heavy industries. In 1980, Korea was in turmoil. After the assassination of President Park Chunghi in 1979, a young general was in charge, who was the head of the newly established "National Emergency Military Command". Korea was engulfed in a major economic crisis as well as political turmoil. The enormous investment made in the early 1970s in "heavy industries" to transform the Korean industry from light manufacturing to heavy industries encountered problems because unlike light manufacturing industries, the investment in heavy industries was not producing products even after many years of hard work. Many major industrial firms that had borrowed millions of dollars from foreign and domestic banks under government guarantees were not producing products. In some cases, the factories were only half built when their funding was exhausted. Overall, they under-estimated the enormous tasks involved in building heavy industries from scratch. Many companies were trying to borrow more money to finish their project and sustain their enterprises.

The author used Axiomatic Design as the basis for solving this problem without mentioning Axiomatic Design to anyone, since not too many people were aware of AD at the time. Often people could not believe that two simple concepts, i.e., the Independence Axiom and the Information Axiom, could provide the framework for solving difficult and complicated problems.

The basics of mapping in AD is shown in Fig. 2.

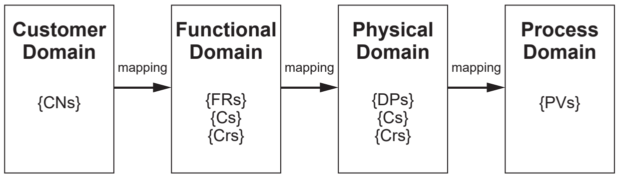


Fig. 2. Four Domains of the Axiomatic Design World [8]

### 6.1 Problem Identified

The author visited government officials in the Republic of Korea who were in charge of automotive industries, shipbuilding industries, machine tool industries, and power industries. He also visited many factories and corporate offices. He also talked with industrial leaders and field engineers as well as officers of the Armed Forces of Korea, who were with the "Military Emergency Council" that was running the country at the time. Through these interactions, two problems were identified:

1. *Unlike the light manufacturing industries (e.g., apparel, shoes, etc.), it took a long time to build gas turbine factories, etc., and thus, could not generate any income, let alone profits, for a long time, bringing many of these companies to the doorsteps of bankruptcies.*

2. *There were too many companies competing for the relatively small markets in key heavy industries, using loans secured with government guarantees.* None of them could have survived because their production volume was too small to be competitive vis-'a-vis their competitors overseas with years of experience in these old industries. For example, the

total market for vehicles in Korea in 1980 was of the order of approximately 250,000 ≈ 350,000 cars, buses, and trucks. The minimum production volume for passenger cars would be of the order of 200,000 ≈ 250,000 cars per platform. For this small market, three companies were competing. Also, there were three shipbuilding companies for this highly volatile market, competing with then leading shipbuilders in Japan. A couple of shipbuilders stopped the operation, while they were still in the process of building dry docks. The same was true in the machine tool business. A large number of companies were trying to make very conventional machine tools that have been dominated by foreign competitors. Apparently, the government officials thought that competition was a good thing, which would be under typical steady-state operating conditions. However, when the market size could not support so many competitors, it was not a good policy.

3. *Three or four major industrial firms were competing in the same industries.*

4. *Government officials, including civilian and military, were at a loss because they had not faced this type of crisis before.*

5. *There were no indigenous technologies in these basic industries.*

### 6.2 Solution

Based on the problems identified, the following functional requirements (FRs) were immediately identified:

- $FR_1$ = Increase the production volume to a competitive level
- $FR_2$ = Encourage mergers of companies in the same business as an emergency measure
- $FR_3$ = Strengthen R&D effort for these industries in Korea
- $FR_4$ = Strengthen the financial viability of major companies that are in these key heavy industries

The corresponding design parameters (DPs) were chosen as:

- $DP_1$ = Determination of the minimum production level
- $DP_2$ = Swapping of businesses so that only one or two company would be in a given industry (until the production level reached a competitive level)
- $DP_3$ = Strengthening of the R&D infrastructure in companies, universities and research institutes
- $DP_4$ = Conversion of bank loans into equities

### 6.3 Results

1. The Korean government adopted the recommendations made based on these FRs and DPs.
2. By 1985, these companies and Korea became competitive, domestically and globally.
3. Korea has become the 10th largest industrialized nation in the world.

This project lasted for about 30 days. A couple of months later the ROK government announced a new economic policy, adopting all the recommendations made.

## 7 Money Circulation for Economic Growth

PROBLEM[7] identification: The first step in Axiomatic Design is the identification of the problem in the customer domain. The problem we identified is the slow economic growth of a *imaginary* country in South America. Our goal is to solve the problem through the design of its taxation and economic policies that will *increase the velocity of money circulation.*

Economists have known for a long time that one way of promoting the economic growth of a nation is to increase the circulation of money (sometimes called the velocity of money circulation). Money circulates when people either buy or sell goods and services. Thus, the faster the circulation of money, the greater is the economic activity, hence faster economic growth. The question is how a taxation system should be designed so to increase the velocity of money circulation.

Poor people spend all their income but still cannot buy all the things required for decent living, because they make less than what is needed to maintain "middle-class standard of living". On the other hand, people in the top 1% spend as much money as they please but they cannot use all of their income, because their income is far greater than the amount of the money they need to maintain their luxurious lifestyle, and therefore, they circulate only a small fraction of their annual income. Rich people may simply deposit their money to collect interest on the money, which may not affect money circulation in a significant way. Our task is to transform the economy of this nation. We need to transform the problem identified in the customer domain into a set of FRs in the functional domain and a set of DPs in the physical domain as defined in Fig. 2 in order to design an economic system that will maximize the economic growth rate of the country by increasing the velocity of money circulation.

The following facts about this country are known: There are five income groups: A, B, C, D, and E. Group A is the lowest income group, B the second lowest income group, which makes twice as much as those in group A. Group C makes three times that of B. Group D makes five times that of Group C. and Group E makes 100 times that of Group D. Income of Group C is just enough to support a typical family. The population distribution in these economic income groups is as follows: A = 100,000; B = 5,000,000; C = 1,000,000; D = 50,000; E = 300. People in Group C spend all the money they make just to take care of their minimum expenses. Groups A and B need more money to achieve the middle-class living standard but do not have the necessary income. The goal is to design fiscal

[7] This fictitious design problem is chosen to illustrate how AD might be applied in solving non-technical problems, in particular, economic issues. The author is neither an economist nor a financial expert. This example is created with a pedestrian-level understanding of the subject matter for illustrative purpose to show how AD might be used in social sciences

and monetary policies so as to maximize the velocity of money circulation.

The new tax system will be designed to achieve the following three FRs:

- $FR_1$ = Maximize the velocity of money circulation.
- $FR_2$ = Invest in public infrastructure, including national defense.
- $FR_3$ = Provide incentives to all groups to work efficiently and effectively.

The DPs that can satisfy FRs may be stated as follows:

- $DP_1$ = Monetary policies
- $DP_2$ = Investment policies for the public good
- $DP_3$ = Fiscal policies

Note that $DP_1$ is chosen to satisfy $FR_1$, and so on.

These highest-level FRs and DPs must be decomposed so as to develop detailed designs that can be implemented, because $FR_1$, $FR_2$, $FR_3$ and $DP_1$, $DP_2$, and $DP_3$ are still conceptual and do not provide sufficient details for us to implement. The design matrix for this highest-level design may be represented as

| | $DP_1$ | $DP_2$ | $DP_3$ |
|---|---|---|---|
| $FR_1$ | X | x | X |
| $FR_2$ | 0 | X | X |
| $FR_3$ | 0 | 0 | X |

The above design matrix indicates that the design is a decoupled design. Therefore, we should change DP3 first, then DP2, and finally DP1 in order to satisfy the Independence Axiom. There are many unknowns in filling out the above matrix, but as we decompose, we must select policies so as to make the design of policies to be decoupled. To achieve the goal of having a strong economy, we need more details. Thus, we will decompose ($FR_1$, $FR_2$, and $FR_3$) as well as ($DP_1$, $DP_2$, and $DP_3$). Different designers may come up with different sets of lower level FRs, depending on how they decompose them based on their understanding of the problem and issues involved. It should be noted that the use of lowercase x for the relationship between $FR_1$ and $DP_2$ at this stage of design is to note that the influence of $DP_2$ on $FR_1$ appears to be weaker than other relationship. Further decomposition of $FR_1$ and $DP_2$ should clarify this qualitative reasoning.

We decided to choose the following second-level FRs to address the goal of maximizing money circulation, i.e., $FR_1$ (Maximize the velocity of money circulation):

- $FR_{1.1}$ = Give subsidies and/or tax credits to Groups A and B.
- $FR_{1.2}$ = Establish progressive income tax rate for Groups C, D, and E.
- $FR_{1.3}$ = Reduce the tax rate on the net income that exceeds the preceding year's income.
- $FR_{1.4}$ = Levy fixed % tax on all income groups for healthcare.
- $FR_{1.5}$ = Levy fixed % tax on all income for social security.
- $FR_{1.6}$ = Adjust the interest rate.

For $FR_2$ (Invest in public infrastructure, including national defense), we selected the following as the next level FRs:

- $FR_{2.1}$ = Invest in infrastructure.
- $FR_{2.2}$ = Fund national defense.
- $FR_{2.3}$ = Provide free education from primary to tertiary education.
- $FR_{2.4}$ = Invest in 5% of GDP in open R&D.
- $FR_{2.5}$ = Strengthen patent policies.
- $FR_{2.6}$ = Provide free public transportation.

For $FR_3$ (Provide incentives to all groups to work efficiently and effectively), we decided to choose the following as the next level FRs:

- $FR_{3.1}$ = Provide free education for primary, secondary, and tertiary education.
- $FR_{3.2}$ = Legislate a minimum pay policy that is tied to the inflation rate
- $FR_{3.3}$ = Promote merit-based reward system.
- $FR_{3.4}$ = Implement a generous overtime pay policy.

To satisfy these FRs, we need to select the means of satisfying them by choosing a right set of DPs in the physical domain.

One possible set of DPs that are chosen to satisfy the second-level FRs listed above are as follows:

- $DP_{1.1}$ = Special tax incentives for Groups A and B
- $DP_{1.2}$ = Progressive tax rate for Groups C, D, and E
- $DP_{1.3}$ = Tax Incentive system for exceptional achievers
- $DP_{1.4}$ = Healthcare taxDP15 = Social security taxDP16 = Interest rate
- $DP_{2.1}$ = Infrastructure fund
- $DP_{2.2}$ = Defense budget
- $DP_{2.3}$ = Strong public educational institutions
- $DP_{2.4}$ = Competitive R&D funding
- $DP_{2.5}$ = Innovation and patent policy for public good
- $DP_{2.6}$ = Public infrastructure
- $DP_{3.1}$ = Public education system
- $DP_{3.2}$ = Mandatory minimum pay system
- $DP_{3.3}$ = Civil servant examination system
- $DP_{3.4}$ = Overtime pay legislation

For the second level decomposition of FRs and DPs, we must construct the design matrix to be sure that we are satisfying the Independence Axiom. The design matrices must be either diagonal or triangular. If not, we have to select new DPs or re-arrange DPs until we do get either diagonal matrices or triangular matrices. For the purpose of this illustration, we will assume that they do satisfy the Independence Axiom.

In this example, the goal was to show that the fiscal and monetary policies can be established on a more rational basis based on Axiomatic Design. Once we have the decomposition of FRs and DPs completed, we can quantitatively simulate the design outcomes using the data provided on population and income distributions[8].

[8] After this article was written, Professor Jacqueline Clare Mallett, an economist at Reykjavik University, introduced me to the work of Irving Fisher (1912)[9]. The article states that if the velocity of money circulation increases, with other variables remaining the same, the price of materials (i.e., goods and services) must increase. One may then assume that the pay, which is typically a portion of the materials, including service, should increase as well. Thus, the "poor people" who sell the merchandise should get more income. The author's view of economics is that it is dealing with a highly coupled system. Thus, the matrix that relates

## 8 Creating a Globally Competitive University (an Open System)

Administration of universities[9] involves multi-disciplinary subjects, including management, humanities, and social sciences. University administration deals with all aspects of operating and nurturing a large tertiary educational institution for the public good. Its diverse roles include: education of people; training of future workforce; research on various issues such as finance and economy, society and societal functions, human aspirations, legal issues, ethics, morality, equality, fairness, economic and manufacturing competitiveness; and research on any issue that merits scholarly assessment; most important of all, financing the university operation through securing the budget and fundraising. Administrators of universities must also deal with the recruitment of top faculty and staff, admission of outstanding students, physical and cyber security, maintenance of its infrastructure, teaching and research facilities, communications within the university, and interaction with the world external to the university. To perform all these different tasks systematically and strategically, university leaders must establish strategic goals and design an operating plan that will require design thinking.

Few academic administrators and professors would think that one of the major barriers to making a university great is related to *design and design thinking.* Furthermore, many people think that they can improve their universities through hard work and implementation of experience-based ad hoc decisions based on past experience. These views may be valid if their goal is to maintain the status quo by enabling their universities to perform typical functions of a university (i.e., administration, teaching, and research) reasonably well. When their effort does not yield the desired results, they typically attribute the poor performance to lack of financial resources, poor quality of incoming students due to poor secondary education, meager government support, etc. In fact, many universities waste their limited financial resources by pouring money into causes that should not be supported.

The basic cause of poor performance at many universities is often attributable to wrong goals, ill-conceived policies and programs, and violation of the Independence Axiom, which may lead to confusion, endless meetings, repetition of past mistakes, and so on. In order to elevate a university to the best of its class, they should either modify or re-design their university after finding out the *"problems"* that need to overcome, which should be transformed into FRs. On the other hand, some leading universities may simply live off their old reputation that was established many decades ago. However, many institutions profess their desire to change and become a better institution by renewing themselves through innovation. In that case, they need to adopt *design and design thinking* advocated by Axiomatic Design.

Academic administration and leaders of universities must try to renew their institution periodically because their institutions are complex entities and their functions can deteriorate over a long period of time[10]. Furthermore, the world around them is continuously changing and the old functional requirements FRs may no longer be appropriate or pertinent. However, few start the process by defining the problem(s) and the functional requirements FRs that must be satisfied *independently* by selecting right design parameters DPs.Rather many academic leaders make *ad hoc* decisions based on the knowledge they have acquired by being a faculty member or an academic administrator. Sometimes they simply follow academic precedents that have been refined over many decades of university's existence. These practices are accepted as being normal. As a result, many universities change only at the margin. Thus, leading universities tend to attract the best faculty and best students as well as most donations, which enable them to maintain their long-standing reputation and competitiveness. Academic inertia is perhaps greater than any other inertia!

## 9 Case Study: KAIST

The example given here illustrates that non-profit organizations such as universities can be managed systematically to improve the institution by applying design thinking. The institution at which the design theory was systematically applied was the Korea Advanced Institute of Science and Technology (KAIST). In six years, KAIST became a leading university in science and technology in the world. In 2016, the Times Higher Education of the United Kingdom ranked KAIST as the 6$^{th}$ Most Innovative University in the world. In fact, KAIST was the only non-U.S. based university to be in the top 10[11].

### 9.1 Historical Background of KAIST

In 1970, the government of the Republic of Korea had decided to industrialize by moving into heavy industries such as shipbuilding, steel making, automobiles, machine tools, and electric-electronic equipment. As part of this vision, KAIST was established in 1971 as a graduate school under a special legislation for the purpose of supplying advanced technical human resources needed for newly established Korean heavy industries. KAIST is a quasi-public and quasi-private university in the sense that it had an independent board of trustees as the governing body like a private university but with heavy government control because the government provides the basic funding. It is a tuition-free institution. In 1986, it merged with an undergraduate college. They hired many excellent professors, mostly Korean Ph.D.'s, who earned their degrees from universities in the United States, by offering them salaries

the FR vector to the DP vector is a full matrix. In such a circumstance, different economists study one element of the design matrix since they cannot deal with the entire FR-DP relationship. What is being suggested in this paper is that economists should really "design" the economy to solve a given set of problems a priori and establish fiscal and monetary policies at the same time.

[9] The characteristics of open systems and closed systems are discussed in Appendix A

[10] The idea of "functional periodicity" is discussed extensively in [4, Chapter 5]

[11] According to a rating agency, QS, KAIST was the most improved university.

comparable to the U. S. university salary, which was then many times the prevailing salary of other Korean universities[12]. KAIST produced many graduates with advanced degrees, who have contributed to Korea's industrialization. More than 10% of professors in science and engineering throughout Korea are KAIST graduates, and many teach in other countries as well.

Notwithstanding the special support given to KAIST, the quality of KAIST education and research gradually approached an asymptote and was not competitive with the leading universities of the world. In fact, it was performing at the level of typical public universities, notwithstanding the special support provided by the Korean government and highly qualified students[13] and faculty. Korean government was concerned about the gradually deteriorating quality of education and research at KAIST. The board of trustees of KAIST and the Korean government hired a new president for the purpose of making KAIST a leading university in the world. He, with the help of others, redesigned the university so as to achieve the original goals envisioned by the founders of the university.

### 9.2 Problems Identified at KAIST in 2006

The first step in Axiomatic Design is the identification of the PROBLEMS in the Customer Domain. Through surveys of the department heads, faculty, alumni, students, and staff, the following problems were identified:

1. Although KAIST had its own board of trustees, the Korean government-controlled KAIST through the budgetary process. Therefore, KAIST was beholden to the whim of the ministries that controlled its budget. They did not have their own plan for KAIST's future. Many were content to live with what the government dished out to them rather than securing more resources to fully exercise their ultimate innate capability.

2. The size of the faculty remained at 400 for more than two decades, which was too small for the number of students at KAIST, i.e., 3,000 undergraduates and 6,000 graduate students. For reference, MIT has about 1,000 faculty members for a similar size undergraduate and graduate student body.

3. The quality of KAIST students was excellent, perhaps in the top 1% of any cohorts in any country. However, they were not challenged intellectually.

4. The quality of professors was excellent, but aging rapidly. Many of them received their education at leading universities, mostly from the United States. However, the median age of the faculty was 55, with a few faculty members under 40. Thus, the research productivity had been going down over the years. They could not hire younger professors since the government effectively froze the faculty hiring through their budgetary process. They could only replace professors when someone retired.

5. Most professors could generate research results and publish papers because they had many research students working for them. Since many professors tended to work on more or less similar research topics throughout their career rather than exploring new fields because KAIST measured research productivity by the number of papers published rather than the quality and creativity of their work. Each professor had a large number of bright graduate students, who could not graduate until they publish a paper in international journals based on their thesis work.

6. The physical facilities were deteriorating fast for lack of maintenance.

7. Since KAIST was located in Daejeon, about 100 miles away from Seoul, KAIST was becoming a regional university, since Korean people, including students, faculty, and staff prefer to live in the capital city.

8. Many of the professors at KAIST did not have meaningful collaborations with Korean industry, although Korea had world-class industrial firms, producing high technology products.

9. Once hired as a professor at KAIST, their job was guaranteed for life regardless of their performance since the tenure process was perfunctory.

10. KAIST had not increased its faculty size, blaming the government for not increasing their budget. The student/faculty ratio at KAIST was greater than that of MIT by more than two (2).

11. Ranking agencies put KAIST around the 200th ≈ 300th among global universities.

12. KAIST's primary role was to supply bright graduates to Korean industry, fulfilling the original goal envisioned by the founder of KAIST in 1971[14].

### 9.3 New Goals and Functional Requirements (FRs) Established in 2006

Based on the foregoing assessment of KAIST, a new set of goals and policies were established based on the functional requirements (FRs), design parameters (DPs), and process variables (PVs) created through the Axiomatic Design process. Some of the actions taken were as follows[15]:

[12] In 1971, the GDP per capita of Korea was only about \$300. In 2018, it is about \$30,000 or \$36,000 in purchasing power parity (PPP).

[13] The government supports all KAIST students, which include free tuition, free room, and board, and a stipend. A large fraction of KAIST students are the top graduates of special "Science High Schools". They represent the top 1% of high school graduates in Korea. One of the major benefits of becoming KAIST students used to be deferment from military service.

[14] It should be noted that in 1971, some members of the international advisory group, many from Stanford University, was against the idea of creating a Ph.D. program at KAIST, saying "why should KAIST produce PhDs when Korea cannot even absorb existing technologies?"

[15] Behind these policies and actions, there were concrete rationale and plans for implementation, which will not be elaborated in this paper.

1. Increased the faculty size from 400 to 630 by creating its own financial resources[16]. The goal was to reach 700 faculty members.

2. Allowed departments to hire as many professors as they could find under one stipulation: the newly recruited professor must meet the highest standard as scholars and teachers. The central administration checked only the quality of the faculty candidates irrespective of their specialization, gender, nationality, race, educational background, etc.

3. Increased the undergraduate enrolment to 1,000 students a year from 750 a year. A special arrangement was made with the government for additional budget for supporting these additional undergraduate students.

4. Adopted a "merit-based" salary system, replacing the "seniority-based system"[17]. Under this system, younger professors could make a higher salary than senior professors.

5. Increased the research overhead rate from 20% to 25%. [At leading U.S. universities, the overhead rate is over 50%.]

6. Secured private sector gifts and donations to build 14 new buildings with partial support from the government.

7. Actively recruited International students and women students.

8. Actively recruited international faculty.

9. Changed the language of instruction to English from Korean to English.

10. Required doctoral students to finish their degree in six years. After that period, they were asked to pay "tuition".

The results of these efforts were as follows:

1. In seven years, the overall budget of KAIST increased by 270% due to the increased research volume, while the direct government financial support for KAIST increased by about 10%.

2. From 2007 to 2013, 350 new faculty members were hired, increasing the faculty size to 630 from 400, with retirements.

3. The number of international students and faculty increased by about 10 to 15%.

4. The international ranking of KAIST jumped from around 200th to 40th, and some fields ranked in the 20th.

5. In 2016, KAIST was the only non-American university in the world to be ranked among the top 10 most innovative universities (actual ranking #6) by the Times Higher Education.

[16]This action was taken, in part, based on the fact that at many leading research universities including KAIST and MIT, only about 16% of the salary is used to pay professors. In 2007, there was enough non-essential use of the KAIST funds that KAIST could hire at least 10% more faculty during the first year of this policy. Since then, additional financial resources were secured to hire 350 more professors.

[17]This was a dramatic change in Korean culture, where almost everything was based on seniority.

## 10 Conclusions

1. During the past three and a half centuries, advances in science and technology have dramatically changed all aspects of society and human lives. It is anticipated that more profound changes will occur in all fields of human endeavor. In order to be certain that these changes do not create unexpected disasters, it will be good if human beings can design and control future advances to the maximum extent possible so as to avoid making major mistakes similar to some of those made in the past. Design and design thinking may provide useful tools to humanities and social science fields in developing correct and rational solutions in the future.

2. Humanities and social sciences are similar to natural sciences and engineering in that all these fields deal with the synthesis of systems as well as analysis.

3. Axiomatic Design theory has been used to re-design universities and a government agency with impressive results.

4. Based on Axiomatic Design, an industrial policy for heavy industries was designed for Korea in 1980 during the time of its economic turmoil. The ideas generated as part of the design process has played a major role in reviving the Korean economy.

5. A fictitious problem of increasing the velocity of money circulation was used to illustrate how Axiomatic Design might be utilized in fields outside of engineering such as economics.

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## A Open System versus Closed System

In engineering, we often create a closed system by selecting a set of DPs for a given set of FRs, eliminating or minimizing the effect of random variations. However, the issues related to humanities and social sciences appear to be extremely diverse and complex. Among the reasons that make these subjects particularly difficult are: the complexity of the subject matters, unstructured database, descriptive approaches, reliance on empirical arguments, difficulty in verifying assumptions, and lack of verifiable tests, among others. From the viewpoint of Axiomatic Design, the more fundamental reason for the difficulty in devising solutions for problems in humanities and social sciences is that these fields often deal with *"open systems"* rather than *"closed systems"*, whereas in engineering we deal primarily with uncoupled or decoupled *closed systems.* Therefore, to apply Axiomatic Design to subjects in humanities and social sciences, we must check if the system is an *"open system"* and then devise solutions accordingly. There are inherent differences between an open system and a closed system. For a *closed system*, the DPs selected to satisfy a given set of FRs are assembled to create a systems solution, keeping all other potential variables more or less constant. Therefore, for a *closed system*, we can select a DP that can satisfy a given FR. For a system with many FRs, we can select a set of DPs to satisfy the set of FRs that can satisfy the Independence Axiom. In this case, the relationship between the FR vector and the DP vector is either a diagonal for an uncoupled design or a triangular matrix for a decoupled design. In an *open system*, it is difficult to select a DP for a given FR, because many other variables may affect the selected FR. Some of these random input variables in an open system may act like DPs, making it impossible to control FRs with a selected set of DPs. *Thus, it is difficult to design an open system.* The fact that most humanities and social science subjects are "open systems" requires *additional constraints or modifications* to operate these open systems, which is discussed next.

### A.1 Conversion of an Open System to a Quasi-Closed System

In some cases, an open system may be converted into a "quasi-closed system" by limiting the acceptable bounds of potential DPs as follows:

1. Limiting acceptable variables through the constitution and common laws
2. Adopting rules and regulations (either written or traditionally accepted set) to rule out variables a priori
3. Dictating allowable behaviors (a common technique sometimes used by dictators)
4. Creating a culture for acceptable behavior

For example, a typical university, which is an open system, plans to generate a set of desired outputs, i.e., FRs, using certain DPs. However, the desired FRs can be affected by many unanticipated input parameters. To overcome this problem, a typical university establishes many regulations and rules in order to define the acceptable bounds on permissible inputs that are the permitted within the university. Sometimes, many committees are created to deal with extra DPs, which is one of the reasons why universities have so many committees. Another example is the government. The United States government is an open system that is bound by the U.S. Constitution and the laws established by the legislature. Many industrial organizations attempt to operate their companies as a closed system in order to prevent random variables being introduced inadvertently so as to attain their corporate objectives.

### A.2 Incentivization of an Open System To Make it Behave-Like a Closed System

One of the responsibilities of the leader of an open system (e.g., a university or a government agency) is to make the system attain the important goals of the open system by making it behave like a closed system. This can be achieved by designing and operating the system so that they can achieve the desired outcomes through *design and design thinking*, based on our understanding of the Independence Axiom and the Information Axiom. Sometimes, through an incentive system, we can co-opt an open system to convert potential random DPs of an open system to the desired DP so as to approximate its behavior to be that of a closed system. For example, in the 1960s to 1980s since the launching of Sputnik, (the first Earth-orbiting satellite) by the Soviet Union, many engineering schools in the United States tried to change engineering education to "engineering science" education. They regarded design to be outside of engineering science. This was the culture that was created in U. S. engineering schools, wrongly spearheaded by MIT's School of Engineering. The leaders of the MIT engineering school then believed that subjects such as design should be handled by industrial firms and trade-oriented engineering schools, because, according to their rationale, there is *no science base in design.* As a result, few leading universities hired design professors and conducted research in design, devoting their available resources to "engineering science", which mostly consisted of *analysis* rather than *synthesis.* Since there were not too many researchers in the field of design, they did not submit any research proposals to funding agencies such as the U.S. National Science Foundation (NSF). NSF, in turn, eliminated funding programs for design related areas, since there was no demand for research support. Universities, in turn, did not hire design professors because they could not get research support in the design field. Some design professors did not help the situation by claiming that design can only be learned through experience, i.e., "design was regarded as an experiential subject".

From the viewpoint of the NSF Engineering Directorate of the 1980s, strengthening design was a central issue in promoting the U.S.'s industrial competitiveness. Furthermore, the government is the biggest investor in new technologies, which require design expertise. To rectify this problem, support for design research was initiated in

1985 at NSF. Once NSF took this action, many universities started to emphasize design education and start hiring design professors. In other words, NSF, by allocating a relatively small budget for design research at universities, leveraged much larger resources available at universities into the design field. Similarly, by creating the Engineering Research Centers Program at NSF, with a small government funding, it leveraged to create a large research base for cross-disciplinary research at universities with funds provided by industry and universities.

## B Case Study: NSF Engineering Directorate

### B.1 The Story about the Design of the NSF Engineering Directorate:

The National Science Foundation (NSF) is a United States (US) government agency that provides research funding primarily to universities in the United States. It was established in 1950 to enable universities to continue to make the important scientific and technological contributions to the country as they had done during the Second World War. NSF supports research in science, engineering, and education. Its budget is relatively modest in comparison to other R&D agencies such as the National Institute of Health (NIH), Defense Advanced Projects Agency, and U.S. National Aeronautics and Space Agency (NASA). However, it is the largest agency that supports only extramural research at universities, whereas NIH and NASA have significant intramural programs. It supports research in physics, mathematics, chemistry, biology, materials, engineering, and education. The Engineering Directorate was established in the late 1970s. Before that, it was part of the Mathematics, Physics, and Engineering Directorate.

In the early days of its establishment, basic scientists dominated NSF, perhaps because, during the Second World War, scientists played key roles in developing new weapons. Beginning in the 1970s, the consensus was that NSF should strengthen the support for engineering research. However, NSF had difficulties in defining its role in engineering — many regarded engineering as an applied science. By 1984, the United States had formidable competition from abroad, especially in manufacturing related industries and NSF was under pressure to strengthen its engineering programs. To chart a new course for engineering, President Ronald Reagan appointed an engineering professor as the first presidential appointee in charge of the Engineering Directorate at NSF as Assistant Director (AD) of NSF for Engineering. The initial question was: What should he do to strengthen the engineering community of the United States?

### B.2 Introduction to the NSF Engineering Directorate

NSF was established to achieve the following three main missions: (1) to promote progress in science and engineering, (2) to provide health, welfare, and prosperity to the people, (3) to secure the national defense. In the early days of NSF, engineering was part of the Directorate for Mathematics, Physics, and Biology. Then, it became a separate directorate in the late 1970s. Even then, engineers at NSF defined its role as supporting "applied science" and thus, fields such as design and manufacturing were not supported. Furthermore, it dwelled on engineering issues of the first half of the 20th century in spite of the fact that microelectronics, semiconductors, and biology were revolutionizing the world of science and technology, in part because well-known engineering professors had undue influence on the NSF Engineering Directorate, emphasizing those topics that were important in the first half of the 20th century. This forced young professors to work on old engineering problems to get NSF funding. The people in the White House in the Reagan administration, who were responsible for science and engineering policies, thought that the NSF should strengthen its support for engineering R&D to make the United States more competitive in the world. This vision was implemented by the new AD for Engineering of NSF. There was major resistance to this change, mostly from some leading universities.

### B.3 Problems Identified in the Customer Domain:

The problems the new Assistant Director for Engineering identified through extensive consultation with professionals in industry, academia, and government were the following:

1. Although NSF mission was, as defined in the NSF Act of 1950, to (1) to promote progress in science and engineering, (2) to provide health, welfare, and prosperity, (3) to secure national defense, the NSF Engineering Directorate was primarily serving the interest of existing engineering education and research programs of universities. The NSF Engineering Directorate was organized like a mirror image of a typical engineering college and forgot about their main mission that was to deal with the future wellbeing of the nation.

2. Funding was given primarily to well-known senior professors in engineering who were solving (or resolving with slightly different approaches) the problems of the past to improve the accuracy rather than dealing with the future issues of engineering and technology in a rapidly changing world. Thus, young professors who were not well established for having contributed to "engineering science" had difficulty in receiving NSF grants. Therefore, to write a credible research proposal with many references to previous work, they tended to extend their doctoral thesis work rather than venturing into new challenging fields.

3. Research in design and innovation of technologies, which should be one of the cornerstones of engineering, were completely neglected.

4. Emerging and critical technologies were also totally neglected, although these areas held the promise of

creating future technologies and keys to the future wellbeing of the United States and the world. Many grants supported research on engineering problems of the first half of the 20th century.

5. The budget was allocated in proportion to the number of proposals received in a given area. Consequently, new areas and creative ideas did not get much funding, because the number of proposals in these emerging and critical areas was small and therefore, there was no budget allocated for newly emerging and innovative fields. For example, there was no funding for research in design or emerging technologies (e.g., biotechnology). As a result, many universities, in turn, did not hire professors in design and emerging engineering fields.

6. Cross-disciplinary research did not get any funding, including the fields in which the collaboration between academia and industry is of paramount importance.

7. Although NSF is a government agency that must deal with national issues, NSF Engineering was not providing funding for research in areas that are important for the U.S. competitiveness in the 21st century. Funding went to those who submitted thick proposals that received high scores in peer review rather than really important proposals with creative and risky ideas.

8. The number of women and minorities in engineering was totally inadequate because they shied away from engineering because of its traditional image, i.e., engineers wearing hard hats.

These were the problems that had to be dealt with to be certain that NSF was fulfilling its mission as outlined in the NSF Act of 1950.

### B.4 Design Solution: Defining Functional Requirements (FRs) in the Functional Domain

Based on the problems identified, the FRs for the NSF Engineering Directorate were defined as follows:

- $FR_1$ = Advance engineering science base.
- $FR_2$ = Support engineering fields where the science base needs to be developed.
- $FR_3$ = Support emerging technologies.
- $FR_4$ = Advance critical technology areas for U.S. competitiveness.
- $FR_5$ = Promote collaboration between universities and industry.
- $FR_6$ = Strengthen the support for young researchers, minority researchers, and women researchers.

### B.5 Constraints

There are many constraints when one attempts to re-direct any organization, especially government agencies. It is especially difficult when the FRs deal with newly emerging subjects for which there are no large groups of researchers and professional societies (e.g., at the time of reorganization, nanotechnology). Furthermore, if the budget has to be changed by more than a fixed amount, it has to be approved by the director of NSF, the Office of Management and Budget of the White House, and the Congressional Committee that oversees NSF, which typically take a long time. An equally important constraint was personal and financial because of the low government pay and four children attending private schools. Therefore, the reorganization had to be done during the first three months of his tenure at NSF. No one believed that such an ambitious re-direction of a government agency could be achieved in less than two or three years. However, the NSF Engineering Directorate was re-organized, received the approval of OMB and Congress for budgetary changes, and new policies were implemented in three months, a record that defied the prevailing culture of Washington! The new structure and policies of the NSF Engineering fundamentally changed the NSF engineering support structure.

When a new direction for an organization is implemented, what people often search for are the DPs and PVs without ever defining FRs. DPs, which are created to achieve FRs, are represented by means of an organizational chart. PVs are resources such as personnel and budget that are needed to support DPs. However, to design an effective and efficient organization, we must establish FRs first and then develop DPs. That is, in the design of organizations, DPs are the organizational entities that exist to achieve (or satisfy) a given set of FRs. For example, $DP_3$ that must satisfy $FR_3$ (i.e., "support emerging technologies") could be called the "Division for Emerging Technologies".

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