Introduction to Design

1

Nam Pyo Suh

Abstract

The human ability to design and invent has changed the world in a relatively short time—less than ten generations since the invention of the Watt steam engine in the eighteenth century, which led to the Industrial Revolution. Since then, the number of inventions and design artifacts has exploded to create the current technology-based world and the overall much higher standard of living for a population of about 7–8 billion in the twenty-first century that is about ten times larger than that of the pre-Industrial Revolution!

In the late nineteenth century and the twentieth century, the design of internal combustion engines created the automotive industry and the oil industry that dominated the world's economy for more than a century. The jet engines introduced in the mid-twentieth century shrunk the world—people can travel anywhere in the world in about 24 h. In the twenty-first century, semiconductors and advances in telecommunications have revolutionized all aspects of human lives. The advances in biotechnology are also improving the quality of life of many and are likely to create a new era of human history. All this progress has been possible because of the human ability to design, inspired by challenging goals and promising ideas.

Our ability to design creatively is likely to determine humanity's future. There are many challenges. We need to grow the economy, producing goods and services, to improve the quality of life, all while improving the environment. We also have to combat various old and new diseases through the design of better drugs and healthcare systems. The advances that have enriched and improved the quality of life have also created new challenges for humanity in the form of global warming and others, which must be addressed during the next few decades. The animal husbandry that has satisfied the human need for protein

N. P. Suh (✉)
M.I.T., Cambridge, MA, USA
e-mail: npsuh@mit.edu

N. P. Suh et al. (eds.), *Design Engineering and Science*,
https://doi.org/10.1007/978-3-030-49232-8_1

intakes of people is likely to be replaced by proteins derived from vegetables, partly related to human attempt to solve global warming problems and health issues. Solutions to all these issues depend on our ability to design.

What is design? Design refers to a set of creative activities to satisfy human and societal needs and goals through synthesis. Design is motivated and driven by three basic elements of human nature: inspiration, curiosity, and necessity to improve the quality of life through creation of something new and better. Sometimes, these three factors reinforce each other. Regardless of the motivating factor that initiates the design thinking and activity, the first thing the designer must do is to "establish goals" of the design task. Then, the designer must identify the problem(s) that must be overcome to reach the design goals. Finally, the designer must create useful and meaningful solutions to the problem identified.

Design and creativity have a symbiotic relationship. The ability to design generates creative solutions. Conversely, creative minds yield unique and appropriate designs. Axiomatic Design theory enhances the probability of strengthening this symbiotic relationship to create solutions that are better than random trial-and-error processes. Axiomatic Design (AD) provides a theoretical foundation for the creation of imaginative and optimum designs that satisfy the desired functional requirements (FRs) that the design must fulfill to solve the identified problem. The ability to state the FRs is a foundation for modern technologies and various non-technological systems.

The design is a series of transformational processes. It could be a routine process or an inspirational process of creating new ideas and solutions. Briefly, it begins with "design goals." In the customer domain, we define the "problem" we must address to achieve the design goals. After the problem is established, we create a set of FRs that we must satisfy to solve the problem identified. Then, we transform the FRs to design parameters (DPs), followed by the transformation of DPs to process variables (PVs). Depending on the nature of the system to be developed, DPs and PVs take on specific physical, informational, biological, and organizational entities.

The transformational process of going from problem definition to FRs, DPs, and PVs follows the same methods regardless of the specific nature of the design task. All of them must satisfy the Independence Axiom and the Information Axiom. When we complete the design, the resulting embodiment is a collection of DPs that constitute a system or product. We must check for physical compatibility, information flow, biological functions, and safe operations, among others, to assemble the final system.

To find an appropriate DP for a given FR or the right PV for the chosen DP, we must depend on the fundamental laws, principles, and known phenomena of science, engineering, and other relevant fields. The quality of design thinking and ideas depends on the designer's understanding of natural laws and principles as well as human aspirations, needs, and limitations. In scientific and technological fields, the relationship between FRs and DPs is often governed by natural laws, which may require mathematical modeling to predict the outcome. In general, the **uncoupled design** simplifies and enables the fulfillment of design goals. We can make right design decisions based on our understanding of design principles, natural laws, and the human needs.

Throughout the design process, we must seek inspirations to generate designs that are most imaginative, appropriate, and creative for the task identified or defined. Ultimately, through creative and rational designs, we advance the lot of humanity and even the natural world.

1.1 Human Creativity and Design

"Through design, human beings satisfy their curiosity, create solutions to satisfy the perceived needs, and fulfill human aspirations. Inspiration, logical reasoning, perspiration, and persistence enhances this creative process. The design axioms guide the creative thought process."

What sets humans apart from other creatures is "creativity" and their ability to conceive and create solutions through design, i.e., generation of solutions that have not existed hitherto through synthesis. It has taken many centuries to cultivate this human creativity. Until about 6,000 to 8,000 years ago, human beings lived in the Stone Age. Eventually, the Stone Age ended, not because humans ran out of stones, but they had found something better, i.e., iron. Thus, the new Iron Age was born. However, the subsequent advances in technology and science were slow. They had to wait many tens of centuries for science and modern technologies to emerge. In the mid-seventeenth century, people like Isaac Newton began to lay the foundation for science, and another 100 years later, inventors like James Watt started to create new technologies that led to the Industrial Revolution. Then, a new era for humanity has begun, accelerating the transformation of the world through the use of human brains. What humans have created in basic knowledge and technologies during the past three centuries is most impressive. Furthermore, the rate of new advances and innovation has been accelerating ever since, which has challenged many aspects of human and societal assumptions and practices.

"Design" is an intrinsic human activity, which enables people to develop solutions to the problem that they need to solve through synthesis, analysis, and discovery. Curiosity plays a major role in initiating and deriving these creative activities. Curiosity has its roots in human thought processes that culminate in raising the question: "WHY, WHY NOT, and WHAT IF?" In some fields that do not require manufacturing, materials, and long-term testing to answer these questions, such as the information technology industry, the transition from curiosity to implementation has occurred relatively quickly, as attested by rapid development of IT industry, accelerating the pace of innovation.

The design used to be done and is still practiced in many organizations, based on experience and trial-and-error processes, including extensive prototyping, building, and testing. Many companies depend on their expertise and accumulated database to design and manufacture their products. Good experience and know-how are invaluable in these processes, often generating a reservoir of knowledge and "trade secrets." People have also designed and created public organizations such as universities and governments, often through trial-and-error processes. It is simply amazing how much humanity has improved the quality of life and advanced technologies through these trial-and-error processes of creating new products, solutions, and, eventually, wealth. Humanity has generated many amazing products and processes through these empirical approaches. The human ability to design and create has culminated through such achievement as Apollo 11 that took human beings to the moon in 1969.

Notwithstanding the amazing human achievements of the past three centuries, depending only on experience and adopting the "design-build-test" process of creating new products or systems have their limitations. Such a process is slow and expensive because it requires extensive trial-and-error procedures, costly experiments, and testing of prototypes. In some cases, these purely experience-based approaches to design have resulted in unanticipated failures of the newly created system that resulted in the loss of human lives and extensive cost overruns. Strictly experience-based design approaches have led to failures due to the mistakes and inappropriate decisions made, especially when the new set of requirements deviates from the old ones. There are many well-known examples of failed designs due to these "design-build-test" practices in product and system development. Famous examples are airplanes that fell out of the sky, nuclear power plants that exploded, newly constructed airports that have incurred significant cost overruns and delays, and many costly failures of consumer products such as automobiles due to faulty ignition switches.

Design based on fundamental principles of design should augment experienced-based know-hows, which should assure the creation of successfully designed systems and products that work the first time around without repetitive redesigns and incremental changes to overcome design errors. Rationally designed products and systems based on design principles also simplify analysis and testing, reducing the time and cost associated with innovations of new technologies, products, and systems of all kinds, including organizations, software, and hardware.

Some people believe that design is an "experiential subject," which cannot be taught well at universities. They claimed that design could be learned only through experience. This "experiential school of design" has dominated the design field until fairly recently. As a result, many people engaged in the creation of new design solutions, including engineers, depended on repeated trial-and-error processes and their experience in creating new systems and products. They use the repetitious cycle of "design-build-test" and "redesign-build-test" in developing new products and systems, including organizations. This experience-based design practice is equivalent to attempting to improve the efficiency of jet engines without knowing the fundamental laws of thermodynamics. Similarly, design cannot be done rationally, minimizing mistakes, in the absence of fundamental design principles.

Axiomatic Design (AD) was advanced about 40 years ago to overcome and eliminate the costly trial-and-error processes of design. The goal was to enable us to make the right design decisions and avoid making mistakes and wrong solutions in the development of new products and systems. Since the advent of AD, many innovative products, processes, and organizations have been created quickly and reliably. Many people have become much more creative after learning AD. These results are not surprising, because the design axioms are distillations of common features found in rational designs. The axioms were discovered through the examination of past design decisions that had generated good designs and often, highly creative products. The purpose of this book is to teach AD to students in all fields of intellectual endeavor, who are interested in the synthesis of innovative systems and products.

To learn AD, students must acquire the "language of AD," i.e., definitions of keywords, axioms, mapping, domains, the Independence Axiom, and the Information Axiom. They are not difficult concepts to understand but must be able to follow the logical reasoning used in AD.

1.2 Design: A Basic Human Intellectual Instinct

The need to design exists in most fields of human endeavor. We encounter "design" in many different contexts and situations. Sometimes it is driven by human *curiosity* and by problems that must be solved. Design principles discussed in this book help in both of these situations. Curiosity arises when "something" violates the design principles. These principles also guide the process of creating solutions to the perceived problem.

The design is done to achieve a set of goals. In other words, without a clear set of goals, we cannot commence design. Once we define the goal, we can identify the problem that must be solved to achieve the goal. Based on the identified problem, the designer can establish FRs that must be satisfied to solve the problem. Then, the designer must look for design ideas and the corresponding DPs that can satisfy the FRs of the design. It is a creative process that could be lots of fun because the process of conceiving something new that no one else thought about in the past is a challenging and exciting endeavor. There can be many equally acceptable design solutions, but often, there is a superior design. The joy that follows when we come up with creative ideas can be intoxicating. Furthermore, the same design thinking that leads to innovative design applies to many different problems in many diverse fields!

This book presents the process and the principles that will lead to the creation of designs after we identify the problem—creatively, effectively, and efficiently—regardless of the specific field of application. AD leads to rational and useful design solutions in all areas of synthesis. By being able to identify weak or bad designs early, it prevents the creation of a design that is not acceptable, thus improving the efficiency of the design process. In practical terms, it means that a person who is good at dealing with design issues can be useful in many other fields where synthesis is essential.

The following are real design stories that illustrate how important it is to establish the goals and identify the problem that must be overcome to achieve the goal, leading to new design solutions:

Design Story 1.1:

An aspiring engineering student had to earn enough money to pay for his living expenses while attending a university in the United States because his parents, being recent immigrants to the U.S., could not support him financially. To support himself, he had to hold a series of odd jobs at the university. His first job was to work as a janitor, later moved up to be a telephone operator, lab assistant, and library assistant, working roughly 25 h a week during the academic year to pay for his room and food. He received the legal minimum wage for his work at the university. After his third year at the college, he was most fortunate to get a job in a small industrial firm near his university that manufactured disposal plastic products such as cups and dishes. The best part of the job was the pay! The hourly wage at the company was 120% more than the compensation for student assistants at the university. He felt rich!

Moreover, he was in charge of his project with flexible working hours so that he could attend his classes at school on Mondays, Wednesdays, and Fridays, while working at the company the rest of the week, including Saturdays. He was the only "engineer" in the small company, although he had not yet completed his undergraduate studies. He worked with a dozen or so skilled machinists and technicians, who taught him a lot of practical skills and know-how.

One day, the president of the company asked him to design a new product that could replace a competitor's product that had been used in vending machines for dispensing hot coffee. The young engineer then learned, for the first time, about the problem his boss identified, that had to be solved. The problem was the following: The company decided to replace paper cups used in vending machines with a plastic cup. However, the cup made of thin polystyrene sheet by vacuum-forming could not replace the paper cup, because the cup made of the plastic sheet was too hot to hold with a bare hand when hot coffee is poured into it. Furthermore, the cup did not have enough rigidity to be held by a hand when it contained hot coffee. The alternative was to use a thick foamed plastic sheet (sometimes called Styrofoam that had high thermal insulation) to make the cup, but it was not acceptable, because the wall thickness of the cup made of foamed polystyrene was too thick, limiting the number of cups that can be stacked in the vending machine. The president of the company assigned him to develop a new solution. It was an exciting challenge for the young engineer, who had not yet graduated from college.

The young engineer's solution was to satisfy two FRs, i.e., stiffness and thermal insulation, by laminating foamed plastic sheet with un-foamed straight polystyrene sheet to provide both the required thermal insulation and rigidity. In addition to creating the product, he also designed and built a continuous manufacturing system for mass production of the laminated plastic products. It took about 2 years to finish the project and go into mass production. The product was a major commercial success. The company did very well with the new invention, making many products. The U.S. Patent Office granted a patent for the product and processes. He received a bonus that was equal to his weekly pay, which was appreciated but did not make him rich!

Many years later after he became a professor at the same university where he was a student, he and his family visited one of the manufacturing plants of the company and found that the same machine he designed and built as an undergraduate student, a la a development engineer, was still being used to make the product, except that there were many more of them humming at the same time! He was happy to show what he did many years ago to his wife and daughters.

Design Story 1.2:

As the above design story unfolded, across the town, a recent graduate of the same engineering school got a job at a major teaching hospital. While working there, he had this *inspiration* that the hospital could use a computerized information management system. He realized that the hospital, which was well known for its advanced medical care system throughout the world, was inefficient in its operation because the hospital lacked an integrated information system because all the information was written by hand and stored in file cabinets by people. Such information could not be shared among different departments of the hospital without human intervention.

He designed and implemented a central software system for electronic record keeping as well as providing diagnostic assistance to medical doctors based on the data collected from various tests done on a patient. He established a new company in 1968 to make a software system for automation and management of hospitals and healthcare. His company might have been one of oldest software systems company in the world. (Note: Bill Gates started Microsoft in 1975.)

Initially, the company struggled but eventually received funding from a local venture capitalist. Now the company is the leading software company in the healthcare industry in the United States. The company did superbly well, making him and his wife one of the wealthiest couples in the country. He and his wife have become generous philanthropists, supporting many worthwhile causes at universities; hospitals; and various educational, civic, and cultural organizations in the United States and other countries. Many of the recipients of their largess were glad that he had that inspiration and started a new industry.

Design Story 1.3:

Another young engineer established his company that tested imported merchandise for big department stores in the United States for quality assurance. He had learned from one of his classmates that large department stores had a problem controlling the quality of merchandise they were importing from overseas. They needed the confidence that the products they were about to buy in large quantities from a vendor in other countries were of good quality. His company tested various merchandise (ranging from clothing, furniture to even medicine) at the request of department stores.

The manufacturer of the merchandise wishing to sell its product to a department store in the United States paid this testing company to test and certify the quality of their products. When his company approved the quality of the product, the department store purchased the merchandise directly from the manufacturer. It was a perfect arrangement for this testing company, i.e., testing done at the request of large department stores but paid for by the manufacturers of various merchandise that is trying to sell their products to the department stores.

His company designed and invented many new testing methods and machines. They also established the standards for an acceptable quality of various products, creating an extensive database. The company became a reputable and highly successful merchandise testing company in the world. One of the reasons for success of this company was the reputation and personality of the founder. He always had impeccable reputation for hard work, honesty, and the highest ethical standards. Later, he and his wife sold the company to a large company at a high premium. With their immense wealth, they became philanthropists, supporting many worthwhile causes at universities, hospitals, and needy students in many countries.

Design Story 1.4:

There are other interesting stories related to design. Recently, students at a well-known university organized a team to create a solar-energy-powered electric car to solve the problem of global warming caused by CO_2 emission. They came up with their unique design for the solar-powered electric car, learning about many issues related to developing such new products. The students would have done a better job if they had known more about fundamental aspects of the design of such vehicles and solar power. If they had defined the FRs of such a car first (i.e., in a solution-neutral environment) without letting the pre-conceived notion of what such a vehicle should be like, they would have created a better vehicle. They could have learned the lesson from those who designed the “Sunraycer” that won the 1,867-mile Pentax World Solar Challenge (Wilson et al. 1989). The Sunraycer team defined FRs *first* without any specific design in mind, whereas other competitors had decided on the physical configuration first without clearly defining the FRs of such a vehicle and then tried to optimize the design afterward. Doing so, they encountered too many problems due to the coupling of FRs.

Design Story 1.5:

A young professor at a leading university presented a seminar on how to manufacture thin, single-crystal III–V semiconductors without defects. The idea he offered for making thin semiconductors was creative and smart. It had the potential of manufacturing thin-film semiconductors that can be used to make devices.

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 a crystalline substrate by vapor deposition, the newly deposited material assumes the crystal structure of the substrate. After the deposition of several layers of the crystalline material, if we could separate the newly deposited crystal from the substrate, it could be used to make a memory or logic device. The *problem* was that it was difficult to peel off the newly deposited semiconductor layer from the substrate.

The young professor's idea, which he developed while he was working at IBM, was to satisfy two FRs *independently from each other*, i.e., the FR of growing thin-film semiconductors and the FR of separating the thin-film semiconductor from the substrate. To satisfy the second FR of separating a newly deposited semiconductor layer, an intermediate atomic layer of graphene was deposited first on the solid semiconductor substrate. The thin graphene sheet is a two-dimensional material and does not bond to any material perpendicular to its surface because the interatomic force of graphene is planar. Then, if the semiconductor material is deposited on top of the graphene by vapor deposition, the newly deposited semiconductor would then assume the structure of the substrate crystal below the graphene sheet, but not bond to the graphene. Hence, when the semiconductor material is deposited on top of the graphene layer, the crystalline structure of the newly deposited semiconductor material on the top of the graphene would be the same as the original substrate below the graphene layer. Then, the freshly deposited crystal on top of the graphene sheet can be peeled off to make thin semiconductor devices. If the design can produce atomic scale-thin semiconductors on a mass production basis, it may open up a new chapter in mass production of semiconductor devices.

Design Story 1.6:

Famous researchers and professors got together at a research institute, which was established by a generous gift given by a leading industrialist and an alumnus of the university, to discuss the progress made in the field of brain science and technology related to autism. They were bright people with impressive credentials. Young researchers and their professors made presentations in front of these experts assembled from many different regions of the world. They presented the results of various measurements, correlations, hypothesis, and models. They got into heated discussions to clarify multiple concepts presented. What was clear from the presentations and subsequent discussions was that they could not define the cause or the *problem* that lead to autism. Until they can identify the problem, their research is likely to take longer to find a cure for autism. Their research, which is in their early stages, needs to be conducted to determine the problem. They should perhaps do more research based on hypothesis to narrow down the probable cause of autism. To do this type of hypothesis-based research, they will probably need to adopt "design thinking" to make more rapid progress.

Design Story 1.7:

In 2019, one of the most challenging issues in the world is the "cyberattack" by hostile governments to disable computer networks or steal the information stored in the computer systems of other nations. Many countries are engaged in such hostile attacks, hoping to tilt the public opinion. They either try to steal or compromise the information stored in the computer system of the targeted institutions. Certainly, the attempt to influence the U.S. election has dislocated the U.S. political system in 2016. Corporations and institutions are spending a vast sum of money to protect their information system from those who are attempting to steal the secret information and strategic plans stored in their computer systems. In some cases, the goal of the attacker is to destroy or disable specific computers to render the entire information system malfunction and thus destroy the infrastructure of their competitors.

This kind of cyberattack is of primary concern for governments, corporations, and even individuals. The problem is how to deal with cyberattacks and safeguard the information systems from these intruders. The attackers may use email systems and the Internet system to penetrate the information system of the organizations they wish to compromise. One of the major design issues in cybersecurity is the continuing escalation of attacking strategy to avoid newly installed defense systems, which require a response system that periodically updates and adjust the defensive strategy. One design approach might be to attack the source of the cyberintruders at their base.

This problem can be solved only through the superior design of the software system that can identify the attacking system, protect its information system, mislead the attacking system to self-destruct, and, at the same time, disable the attacking computer system.

Design Story 1.8:

One of the most critical issues of the twenty-first century is global warming. If it is unchecked, the temperature of the earth atmosphere will rise, creating many unacceptable calamities such as flooding, the rise of sea level, creation of desert, and many others. One of the major causes is the anthropogenic emission of carbon dioxide (CO_2) by automobiles and electric power plants. A widely accepted goal is to limit the temperature rise to below 2 degrees Celsius relative to the temperature of the atmosphere before industrialization. Professor William D. Nordhaus of Yale University received the Nobel prize in economics for his work on how to reduce carbon emission. His idea was to introduce a carbon tax to limit CO_2 emission. In 2016, 196 nations signed the United Nations Framework Convention on Climate Change (UNFCCC). Its implementation has not been easy, some countries refusing to join in, citing that its negative impact on the economy and the high cost of replacing fossil fuels with solar and wind energy.

It is a classic design problem. There are many FRs we have to satisfy to solve this global warming problem. We need to identify all the FRs we have to satisfy and the corresponding DPs. The carbon tax, although a creative idea, cannot solve the global warming problem by itself. As we will demonstrate in later chapters, when there are more FRs to be satisfied than the number of DPs (in this case, the carbon tax), the design is not acceptable, i.e., the problem cannot be solved. We will show that the number of DPs must be equal to the number of FRs that must be satisfied to solve the global warming problem. Thus, the carbon tax alone will not bring about an acceptable solution to global warming! We have to identify all the FRs that must be satisfied and then develop an equal number of DPs, which will satisfy the FRs without coupling them to each other.

Question 1.1:

"What is the common element in all these stories? How are they related to the main subject of this chapter, i.e., why design?".

1.3 Importance of Knowing How to Define the Problem Based on Design Goals

Every design task, regardless of the specific field of application, has a set of goals. In the case of the environment, the goal may be the reduction of greenhouse gases, whereas, for the head of a university, the goal may be making the university one of the best in the world. In the case of product development, the goal may be to make the most efficient electric vehicle. The goal of the government may be to provide universal healthcare to all citizens.

Once the goal is determined, the designer must ask, "What is the PROBLEM(s) that has to be solved to achieve the goal?" Once the problem is defined, we can proceed with the design task by going through the following four-step transformational processes:

(a) understanding the problem that needs to be solved in the customer domain;
(b) defining functional requirements {FRs} that must be satisfied to solve the problem identified;
(c) identifying design parameters {DPs} to satisfy the {FRs};
(d) selecting process variables {PVs} that can satisfy the {DPs}.

This transformational process occurs over the four domains of the design world: the customer domain, the functional domain, the physical domain, and the process domain. The relationship between the domain on the left and the domain on the right is "What" versus "How." In other words, {FRs} with respect to {DPs} represent "what we want to achieve," whereas {DPs} are "how we are going to satisfy {FRs}." Figure 1.1 illustrates this transformational process.

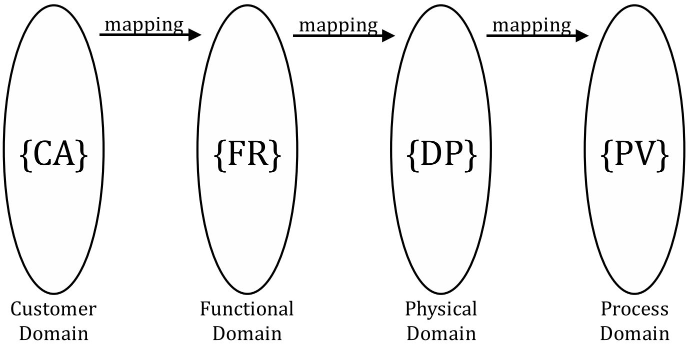

Fig. 1.1 Design is done to achieve the goals (i.e., the customer attributes, CA) stated in the customer domain. Typically, the PROBLEM that is preventing the achievement of the goal must be identified and solved. We state the goal in the form of functional requirements {FRs} in the functional domain that will solve the problem. Then we go through a series of transformational processes, i.e., from {FRs} to design parameters {DPs} in the physical domain, from the design parameters, {DPs}, in the physical domain to process variables {PVs} in the process domain. The terms DP and PV can be interpreted in different ways, depending on what we are designing, e.g., an organization rather than a machine

The importance of identification of the problem cannot be over-emphasized as the following story about the invention of the Watt steam engine illustrates: James Watt, who transformed the history of humankind, began his quest for mechanical power generation with the use of thermal energy by discovering the problem with then-existing Newcomen engine!

1.3.1 Invention of the Steam Engine by James Watt Changed the History of Humanity and Created the Science of Thermodynamics

From a historical point of view, the most critical invention made by human beings is the steam engine by James Watt. His invention was not only responsible for the Industrial Revolution in the eighteenth century but also chartered a new path for human history by awakening the human brainpower for scientific and technological thinking. The Watt engine freed humankind from hard physical labor and changed the trajectory of civilization through a series of scientific and technological advances that followed. Now 300 years after the invention of the Watt engine, science and technology are taking humanity to a hitherto unimaginable path that depends on science and technology, the outcome of which we cannot even fathom with any degree of certainty. The only thing we know for sure is that in the future, humankind will create new problems and new solutions that will accelerate the pace of change. The design will be central in this transformation of human history, as people will continue to use their creativity to design artifacts that will take humans to a new plateau of not only technological progress but also better understanding of humanity itself and societal fabric.

History attributed the beginning of the Industrial Revolution of the world to the invention of Steam Engine by James Watt in 1736. In some ways, James Watt was fortunate to be at the right place at the right time, in addition to being gifted with brainpower and persistence to solve a problem that led to his invention of the Watt steam engine. His genius was his ability to identify the problem (i.e., shortcomings) associated with the Newcomen engine (invented in 1712), which led to the invention of the Watt steam engine (1763–1775). At the time, the Newcomen engine was primarily used to pump water out of mine shafts.

History states that James Watt was asked to repair the Newcomen engine that belonged to the University of Glasgow. While repairing the machine, he found the major shortcoming with the Newcomen engine (see Fig. 1.2), i.e., its intermittent motion. As shown in Fig. 1.2, steam is injected into the cylinder of the Newcomen engine. Then, the valve from the boiler to the cylinder is closed, and cold water was injected into the cylinder to lower the temperature and condense the steam in the cylinder. The vacuum created in the cylinder due to condensation of the steam pulled the piston down. This downward motion of the piston, which was connected to the water pump of the mine, sucked the water from mine shafts. James Watt noticed that since one cylinder was used for both expansion and condensation of the steam, the Newcomen engine was slow and not efficient. This discovery of the problem by James Watt led to the invention of the Watt engine. His solution was to separate the two functions, i.e., expansion and condensation by adding a separate cylinder for condensation. This solution is consistent with the Independence Axiom of AD, which is a formalization and generalization of what James Watt did, although the origin of AD was not based on this observation of the Watt engine.

1.3.2 Design as a Common Human Activity in Many Fields

"Design is a universal human activity to satisfy human aspirations."

In 2006, researchers at KAIST (The Korea Advanced Institute of Science and Technology) identified the elimination of CO_2 emission from internal combustion (IC) engines as the central problem they must solve in order to alleviate the global warming problem. Electrification of ground transportation systems should eliminate about 30% of all anthropogenic CO_2 emission of the world by using electricity generated at more efficient electric power plants as well as using renewable energy sources such as wind, solar, and hydropower.

This goal of removing of anthropogenic emission of CO_2 has resulted in the invention of new kinds of electric buses, cars, and trains that receive electric power *wirelessly* from the underground power supply system to propel the vehicle. This technology is called the "On-line Electric Vehicle (OLEV)." The OLEV bus carries a small battery on board for operations of the vehicle on roads without the underground power supply system. The driver of the OLEV bus drives the vehicle

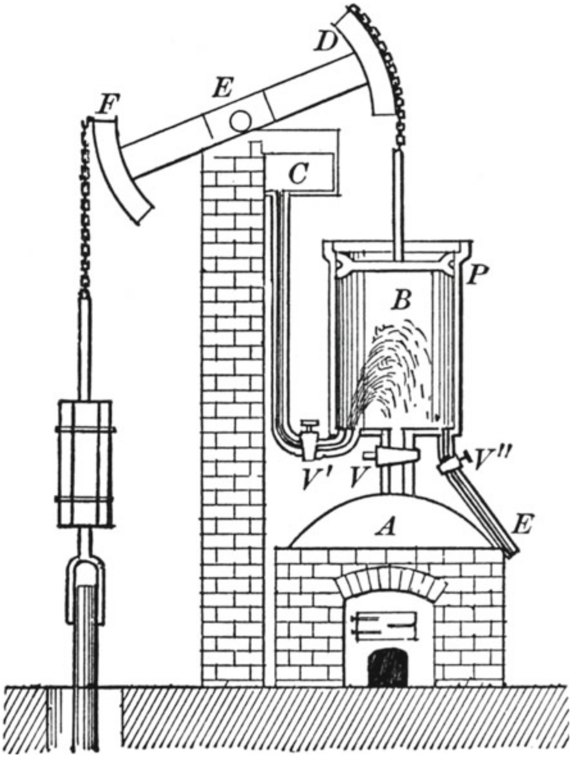

Fig. 1.2 Schematic drawing of the Newcomen engine. The sequence of operation: Hot steam is injected into the cylinder, followed by the closing of the valve. The piston of the cylinder then moves upward due to the internal pressure created by the steam. This piston is connected to the water pump of the mineshaft. When the steam in the cylinder condenses by the cold water injected into the cylinder, a vacuum was created in the cylinder, pulling down the piston. The downward motion of the piston pulled the piston of the water pump upward, pumping water out from the mineshaft. (Reproduced from Black and Davis 1913)

without ever worrying about recharging the battery because it is done automatically when the bus is on the top of the road with underground power supply system. Figure 1.3 shows a bus commercially operating in Gumi City in Korea.

In addition to the design issues related to technology, similar design needs exist in other fields such as organizations, economics, finance, public policy, and literature. For instance, a senior professor at a leading university got a telephone call from overseas, asking him to lead a university to the next level of academic excellence. He accepted the presidency of the university and redesigned the university through strategic planning with the support of some of the faculty members, eventually making it one of the best universities in the world. What the new president did first was to identify the problems the university had to solve through institutional transformation. After reaffirming the new goal of the university, he and

Fig. 1.3 OLEV bus in Gumi City in Korea

his team redesigned the university, including organizational structure, operational policies, financial structure, and personnel policies. They used the principles of AD. The university has indeed emerged one of the best innovative universities of the world.

The design is performed in many fields, although in some fields they may not call it "design" and use other synonymous phrases. It is interesting to note that recently, graduates of liberal arts colleges in many countries are eager to become writers of fictions, inspired by the work of Kazuo Ishiguro, the 2017 Nobel laureate who is the author of "The Remains of the Day." To write such a novel, the author had to design the book first before actually commencing the writing of the book.

Although the specific nature of their tasks appears to be vastly different, all of the people mentioned in this chapter have performed similar tasks! The first thing all of them had to do to achieve their goal was to identify the problem to be solved and then develop design solutions for the problem identified through a transformational process illustrated in Fig. 1.1. The engineers and scientists design their products, processes, and systems. The writers of fictions also design their book, i.e., identify the "problem (i.e., the theme of their story)," design the structure of the story to be written, and then write the narratives of the book. University administrators must also do similar things: design the goals, strategy, and policies, and organize the university for the execution of the plan.

Question 1.2:

Through DESIGN, humans have created modern society; fulfilled their aspirations, curiosity, technological and cultural advances; and extended human life. Unfortunately, people have also conceived the means of harming nature and human civilization through design. How do we design all of these different things? Are there common elements in all these designs?

In this introductory section of this chapter, we emphasized, repeatedly, the need to discover or identify the "problem," either before or after the goal of the design is established. Then the designer translates or transforms the problem into a set of specific objectives or goals the design must satisfy (or achieve). The goals are then transformed into specific FRs that must be satisfied through design in order to achieve the stated goals. Then, we have to search for specific means of satisfying the FRs, which is defined as DPs in AD. All designs must go through these steps. Fortunately, all designs, regardless of the field or the subject matter, involve similar thought processes and the same basic principles a good design must satisfy. In summary, to be useful in design, we must go through the actual process of designing and understanding the design process, similar to learning how to ride a bicycle, i.e., one has to try it, even at the risk of falling!

The process of the design described above applies in all fields that require design solutions. It is not a difficult task. Everyone can do it! In design, the experience can either be helpful or become a hindrance if the experience consists of purely random trial-and-error processes.

1.3.3 Two Different Solutions for the Same Problem

Space travel fascinates many people of all ages, both young and old. The idea of people going to the Moon was a big challenge in the 1960s. When Apollo 11 of the United States landed on the Moon for the first time, on July 20, 1969, it was a momentous and aspiring moment for all humankind. It gave confidence that human beings can claim space as part of the human habitat. It has undoubtedly inspired many young people all over the world to be interested in space travel and science.

In the early 1980s, the U.S. National Aeronautics and Space Administration (NASA) established the Space Shuttle Program in order to build a space transportation system primarily between Earth and the International Space Station. Figure 1.4 shows a space shuttle taking off the launch pad. It shows the orbiter vehicle (OV) that looks like an airplane attached to the external tank (ET), which carries oxygen and hydrogen in two spherical tanks inside the external tank. Two solid-fuel booster rockets are attached to the external tank on its two sides, which assist during the liftoff. The external tank, which is made of aluminum, has about half-inch thick polyurethane foam layer on its surface as thermal insulation in order to prevent the formation of ice on the cold surface of the external tank while waiting for launch. If ice forms, it can fracture during the ascent, which may hit the OV, damaging the ceramic tile on the OV that protects the vehicle from burning up during its re-entry into the earth's atmosphere. The surface area of the external tank is about the same as two football fields. The students, who visited the

Fig. 1.4 The space shuttle discovery and its seven-member STS-120 crew head toward earth's orbit and a scheduled linkup with the International Space Station. (Reproduced with permission from Petrushenka 2019)

manufacturing facility in Louisiana, U.S.A., where the external tank was being built, were duly impressed by the size of the external tank.[1]

The problem with the Space Shuttle Program was its enormous cost. In comparison to the cost of launching communication satellites using a rocket, the cost of launching it using the space shuttle was much more expensive. NASA justified the cost because the space shuttle was needed to service the International Space Station. In order to reduce the cost, it was decided to reuse the solid booster rockets. They jettisoned the rockets mounted on the external tank fall into the ocean upon completion of their mission during ascent. Then they have recovered the jettisoned rocket for future use.

Another solution to the reuse of the solid rocket is to let it descent along a pre-programmed trajectory back to the launch pad, which has been demonstrated in 2017 by Space X, a company founded by Elon Mask. Conceptually, this technology appears to be more elegant because it eliminates the need to search the ocean for the

[1]As part of the contract between a NASA contractor and MIT, one of the students under the supervision of a faculty member developed a method of putting on thermal insulation on the external tank, which significantly reduced the cost of manufacturing.

recovery of used rockets. We have two different designs to solve similar highest level FRs.

The FRs of the Space Shuttle Program involved many additional functions than the Space X because it had to serve the International Space Station and launching of satellites. However, the problem of recovering used rockets is similar at the highest level of the design hierarchy. The lower level of FRs and DPs was different, yielding two different solutions.

1.4 Designing Without Explicit Goals and Problem Identification is Analogous to Sailing a Sailboat Without a Rudder

In a major global company that makes steering systems for automobiles, the management assembled their technical and marketing leaders to review their strategic direction for the development of their next generation of new products. Their goal was to be more competitive in the market place, especially in light of the competition coming from Chinese companies that were offering similar products at a lower price. The people gathered in the conference room of the company were all experienced and bright people. Various ideas and solutions were proposed and discussed.

Their products may be classified into the following four different kinds of systems: purely mechanical systems, electro-mechanical systems, all electrical systems, and hydraulic systems. The price ranges from a few hundred dollars per unit to a few thousand dollars. After 3 h of intense discussion, the meeting was concluded without developing any new major ideas and decisions. They decided to have another meeting in about a month. Unfortunately, these unsuccessful meetings are often a common occurrence in many companies. It is highly probable that the meeting failed to produce any concrete ideas because they concentrated on lowering the manufacturing cost of their products rather than reviewing their design after clearly defining the PROBLEM.

The situation discussed above is similar to trying to steer a sailboat without a rudder. The sailor will not go very far, or even worse, may not turn to the home base!

1.5 A Summary of the Creative Process

The first step in developing innovative design typically requires the establishment of the need (or the goal) and the identification of the problem that must be overcome to achieve the goal.

Based on the identification of the goal and the problem, we establish specific FRs that our design must satisfy to meet the goal. The next step in design is to come up with DPs that will enable us to satisfy the FRs. Then, we configure the designed system through the integration of various DPs as an integrated system. The integrated system may consist of hardware, software, information systems, natural elements, and others such as sensors. In some ways, it is an obvious way of coming up with good designs.

Most people confront many problems, large or small throughout their life. They have to solve them through design and perhaps by other means as well. The difficulty is that often they are trying to find solutions without first defining the problem. They may come up with various and contradictory claims and counter-claims, aggravating each other. If we can define "what the problem is," it may be easier to develop solutions to the problem identified. The ability to define the problem can be acquired by accumulating broad knowledge base, experience, and design thinking. One of the goals of this design book is to teach those who are not yet initiated into the field of design the ability to identify and define the problem and FRs.

Once the FRs are defined, most people can synthesize their unique solutions, unless they can find a quick solution from their "library" of past solutions that are similar to the current problem. When there are no obvious past examples that can be adapted, people should seek a new solution through "design" with confidence without being intimidated. The decision to either adopt an old existing solution or create a new "solution" depends on one's knowledge base or experience or the confidence that one can create something new from scratch that will be superior to the existing system. Many people instinctively want to create their unique solution. That may be a good aspect of human nature.

1.6 Importance of Design and Design Thinking

Design and design thinking are essential in dealing with all aspects of any system. Design thinking implies that a system must be designed first before analyzed. Sometimes based on the analysis, we may have to go back to the original design of the system to improve the design. Unfortunately, sometimes, engineers are mired in an analysis of wrong designs rather than changing the design. Engineering education sometimes biases students' thinking by giving well-defined problems at the end of each chapter, without explaining the design that led to the problem. To repeat, design thinking emphasizes the need to design first, followed by analysis. This chapter outlined how one should begin the design process.

We design two kinds of systems: technical and non-technical. Much of this book deals with technical and scientific design. However, the design of non-technical systems such as government and universities has equally significant consequences on society and humanity as much as technical systems. Institutions and governments must be designed well for them to serve their constituents as well as intended. Unfortunately, this is not always the case. In short, “Design Thinking” is equally applicable to all designs.

When we deal with systems, technical as well as non-technical, we must deal with synthesis and analysis. In designing new systems or modifying old systems, it is often instructive to consider the synthesis (or design) issues first before delving into an analysis of a subset of the overall system. One can spend a lifetime analyzing a poorly designed system, because coupled systems, i.e., poorly designed systems, are often mathematically intractable. Unfortunately, more people in all intellectual persuasions tend to delve into an analysis of lower level issues and then become bewildered by conflicting details of a poorly defined or designed system. To reiterate the significant point of this chapter: identify the PROBLEM(s) of a system that must be improved (in the case of an existing system) and then establish goals in the form of FRs that must be satisfied. Then find DPs that can satisfy the FRs, before undertaking a detailed analysis of lousy design, thinking that optimization will improve the system. An optimized, poorly designed system is still a bad design!

In many professions, the precedents provide guiding lights, and therefore they look for similarities of a case with an old example for decision-making. For instance, not too many political leaders in many countries have a technical or scientific background. In the United States, many of them have legal or business backgrounds. Occasionally, there were exceptions. Two of the past presidents of the United States, Herbert Hoover (1929–1933) and Jimmy Carter (1977–1981), had technical backgrounds. Hoover was a mining engineer and Carter was a nuclear engineer who served on nuclear submarines in the United States Navy. Even today, they are regarded as honest and ethical people with deep convictions. However, historians might not see their presidencies as successful ones. During their presidencies, the United States encountered economic difficulties. The Hoover administration had to deal with the world’s worst depression of 1929. During the Carter period, inflation was out of control. Either they were unlucky or mismanaged the economy. Did they concentrate too much on individual detailed issues rather than the systems issues to develop suitable designs for economic policy? The simple conclusion may be that they focused too much on details before they really identified and understood the problems and then design their policies accordingly. We must identify the overall problem first and then design sound policies. Analysis of poorly designed systems typically is not enlightening. Accurate analysis of a poorly designed system cannot improve the poorly defined system. If the system is coupled, i.e., FRs are not independent, improving one FR may result in deterioration of other FRs, negating the intended effect.

It should be emphasized again here: The first step in developing innovative design typically requires the identification of the problem.

Once we know the problem, we establish the goals that our design must satisfy to solve it and other associated issues. (Sometimes, we set the goal first based on the “customer need” and then identify the problems that must be solved to achieve the goal.) These goals must then be stated as specific FRs that our design must satisfy. The final step in design is to come up with DPs that will enable us to fulfill the FRs.

The last step is to configure DPs through the integration of various DPs as an integrated system that may consist of hardware, software, information systems, natural elements, and others, such as sensors. In some ways, it is an obvious way of coming up with good designs. However, many companies have repeated the error made by some manufacturers, i.e., trying to be more competitive, without first discovering the specific problem faced by their company other than lowering the cost of manufacturing. This situation may not be only confined to manufacturing companies but also individuals as well.

Most people confront many problems, large or small, throughout their lives. They have to solve them through design and perhaps by other means as well. The difficulty is that often they are trying to find solutions without first defining the specific problem. They may come with various and contradictory claims and counterclaims, aggravating each other. If we can determine "what the problem is," it may be easier to develop solutions. The ability to define the problem can be acquired by accumulating broad knowledge base, experience, and design thinking. One of the goals of this design book is to teach the ability to identify and define the problem.

Once the problem is recognized and defined, most people can synthesize their unique solutions, unless they can find an immediate solution from their "library" of experience that is similar to the current problem. When there are no prominent past examples that can be adapted, people should seek a new solution through "design" with confidence without being intimidated. The decision to either adopt an old existing solution or create a new "solution" depends on one's knowledge base or experience or the confidence that one can create something new from scratch that will be superior to the existing system. Many people instinctively want to create unique solutions. That may be the meritorious aspect of human nature.

1.7 What is the Most Difficult Aspect of Learning Axiomatic Design?

Every era has certain businesses that dominate the economy. In the first half of the twentieth century, it was the automotive companies (such as Ford, General Motors, Toyota, and Daimler Benz). In the late twentieth century, manufacturers of computers (such as IBM and Microsoft) and semiconductor chips and integrated circuit devices (such as Intel) have dominated the economy and technology. In the first half of the twenty-first century, it was the era of high-speed Internet and social networking and telecommunication businesses (dominated by companies such as Amazon, Facebook, Google, Uber, and others) that have built their business using digital technologies and the Internet. In all cases, they were successful in creating new industries, because they could identify problems that need to be solved and came up with FRs and DPs for their businesses, using newly emerging technologies.

One of the most stumbling mental blocks in learning AD could be the lack of experience in defining the FRs for the problem identified in the customer domain. To some, defining FR is a trivial task, and to some others, it is a difficult task. To many, it is a new experience to think of design as the transformational process of going from problem definition to FR, going from FR to DPs, and from DPs to PVs. There could be many reasons for this difficulty—different depending on one's experience and educational background. Some people might have worked on problems someone else defined for them throughout their life. Students are often taught to solve the problem defined by others, especially in textbooks. In some countries, the college entrance examinations ask only analysis-oriented questions. Not surprisingly, students prepare for the exam accordingly. Also, in some cases, one might have spent most of their career, modifying, through trial-and-error processes, designs someone else has made. In many companies, high-level executives define the problem, and engineers/designers execute them. In universities, professors assign problems to be solved, and students are taught to solve them following well-established methods and processes. Also, throughout their education, students are taught that there is ONE correct solution, which is true in most cases of analysis-oriented subjects. However, in design, there can be many equally good solutions!

The best way of learning how to define the problem to be solved and establish a specific set of FRs is to go through the experience doing them a few times to internalize the process in one's brain. Pretty soon, it can become second nature to young students.

Design is ecumenical in the sense that the design methodology is not a field-specific subject. The same method and approach can be used in all fields that require synthesis and design, although the specific design task will depend on the nature of the problem and the FRs that we must satisfy. Some students claim that the most challenging part of learning and using AD is the process of coming up with FRs, which are derived from the problems that were identified in the customer domain. Some claim that they could delve into the design without specifying FRs, which may indicate that the person either modified or copied an existing design. When someone designs without specifying FRs, one may come up with a coupled design that does not withstand the test of times or fails to perform. One must invest time and effort to state FRs correctly and creatively. It is not difficult to learn how to state FRs, but it may take longer to state FRs than the designer has been accustomed to.

The basic rule in defining FRs is the following: Define FRs in a solution-neutral environment! That is, "DO NOT THINK OF THE SOLUTION FIRST BEFORE DEFINING THE PROBLEM AND THE FRs." When this simple rule is violated, the proposed design is simply an old reconstituted design.

Some designers and organizations spend "five minutes" in defining the design task and spend months or years to make the designed system work by correcting all the problems that continue to pop up because of the poor and unsystematic design practice. This practice leads to long development times and high costs. There are many well-publicized failures where a critical project failed to work, airplanes plunge into ground, cars stop all of a sudden leading to fatal accidents, and R&D projects had to be redone, all because the designers used their gut feelings to design some new products, purely based on their years of experience in designing systems and what they have seen before somewhere rather than defining FRs a priori.

Designing Orbital Space Plane (OSP)

A principal defense contractor in the United States received a government contract to design and manufacture the orbital space plane (OSP), which can replace the space shuttle that transported people and goods to the International Space Station. One of the primary goals of OSP is to reduce the cost and improve the versatility of space transportation. The manager in charge of the project decided to produce a better product at a lower cost. To achieve this goal, the visionary the leader of the OSP program chose to replace the past practice of repeating the "design-build-test" cycle of system development and production, because the company leadership found that such a practice is costly and invite major failures after they deploy the system. They hired a consultant to teach AD to their "lead engineers," about 250 engineers and scientists.

These highly experienced and skilled engineers and scientists learned AD rather quickly. However, it was much more challenging to teach experienced engineers and designers than undergraduate students because they tended to jump right into the physical domain, i.e., DPs and PVs, without ever defining what they want to achieve, i.e., FRs, explicitly. In many cases, many experienced designers and engineers often jumped right into solutions, i.e., DPs and PVs, without first establishing FRs and constraints, even when FRs are simple to state and in some cases, almost trivial. Sometimes, people try to state FRs after they come up with DPs, which is counterproductive in practicing AD. When FRs are not defined in a solution-neutral environment, the design may turn out to be a replication of a product that already exists. For innovation, it is of utmost importance to define FRs in a solution-neutral environment.

The experience of teaching AD has been that it is easier to teach undergraduate students than graduate students or experienced industrial engineers. The underlying reason might be that experienced people do not define FRs in a solution-neutral environment. They may instead think of a solution first based on their experience and justify their decision afterward.

In the corporate world, people who become top executives need the ability to define the problem and FRs from a systems point of view. They often have many competent people working for them who are well trained to solve specific problems if they are presented with well-defined problems. It is harder to find people who can define the problem the company needs to address. Even in academia, people who can lead an organization need the ability to identify the problem and create specific goals in the form of FRs. Sometimes, universities select students based on their ability to solve problems someone else defined for them, and then teach more of the same skill for another 3 or 4 years. Sometimes, the student rarely has the opportunity to identify the problem themselves and establish goals in the form of FRs.

1.8 List of Example Problems

Consider the following problems and think about how one might approach them to develop a design solution for each example. Some of these examples will require much thinking and work to develop the desired design solutions. In some cases, one may have to acquire some fundamental knowledge of the field by reading reference books or by getting information from the Internet. Most of all, one may have to THINK with an open mind in a *solution-neutral environment*! We should not forget is that all these design tasks can be achieved, given enough time and resources.

Example 1.1 Improvement of the Protocol System for Social Networks

Social networks (SN) such as Facebook and Twitter facilitate interaction between and among people as well as between people and business for fast social information distribution or disinformation. In the 2016 presidential election in the United States, certain groups or nations used these SN services to tilt the election by spreading distorted or fabricated information to American electorates. One of the issues we have to deal with is the privacy issue, because Facebook, for example, has accumulated so much data on individuals that some may use them for illegal purposes. How would we improve the protocol of SN to prevent such misuse of the SN systems?

Example 1.2 Water Faucet to Control Water Temperature and Flow Rate

We want to have a water faucet that will enable a person to control the water flow rate and the water temperature independently. How should we achieve these goals through the design of a new faucet?

Example 1.3 Operation of Emergency Room

In a typical emergency room (ER) of a hospital, as many patients as possible must be treated as quickly as possible. One problem faced by the hospital is that patients with many different kinds of illnesses come into ER without any prior notice, e.g., some because of the injury sustained in a car accident, another due to a flare-up of the chronic disease. Often, the doctors are so busy that patients must wait after checking in with the admitting nurse before the patient can see the doctor, especially if the illness appears to be chronic. Many hospitals use the FIFO (first in–first out) system to control patient flow in the ER unless someone is about to die, who should be given the highest priority. If one is to design a better triage system for the ER operation, what should the new system? Would an AD designer be able to create a better triage system to maximize the throughput rate of the ER?

Example 1.4 Global Warming

One of the societal goals is to solve the global warming problem by reducing anthropogenic CO_2 emission. Roughly 27% of CO_2 is generated by ground transportation systems and about 33% from electric power generating plants that burn coal. Suppose that our goal is the reduction of CO_2 as the primary design goal to deal with global warming. To achieve the goal, what specific actions would we undertake?

Example 1.5 Ski Bindings

Ski bindings enable a skier to transmit control loads from the boot to the ski to maneuver the ski while sliding on snow at varying speeds. One of the main problems is to avoid transferring loads from the ski to the boot that leads to injuries. They need to transmit control loads from the skier to the ski reliably and not transmit injurious loads from the ski to the skier. The solution is to have the binding release the ski from the boot under certain situations that lead to injury. Because the ski bindings do not perform these functions well, many skiers end in hospitals especially with knee injuries most to the ACL and from collisions after an inadvertent release of the ski by the binding. How would we solve this problem?

Example 1.6 3D Printing

One of the final outputs of design could be the manufacture of reliable goods. Some of these products have complicated three-dimensional shapes such as inside holes not connected to the outside surface. We have used, and often still use, various casting and machining processes to make these parts. The disadvantage of these traditional processes is the need to prepare expensive tooling, which necessitates that we make a large number of the same pieces to distribute the fixed manufacturing cost over a large number of parts to lower the unit manufacturing cost. How can we make these 3D parts using a general-purpose machine that can produce several products with minimal tooling and in small volumes on short notice?

Example 1.7 Money Circulation and Economy

To an engineer, it appears that one way of strengthening the economy is to increase the velocity of money circulation because the faster the money circulates, the higher will be the economic activity and increased economic growth. Thus, everyone within the economic system benefits as the velocity of money circulation increases. However, real rich people will only spend a small fraction of their wealth, whereas poor people do not have the money to spend. This situation limits the velocity of money circulation. Assuming that the wealth distribution is Gaussian, determine the ideal wealth distribution that will maximize the money circulation. As a designer, our task is to design several policies for increasing money circulation. State your FRs.

Example 1.8 Healthcare Delivery

A medical doctor has spent many years to deliver healthcare services to developing countries. One of the problems he has encountered is not the medical problem, but the logistics of delivery of medical care and medicine to remote areas. He is looking for "system engineers" who can solve the logistics problem working with MDs. What FRs should we try to satisfy in our design? How should we create a solution to this problem through the design of a system for delivery of medical care to remote regions?

Example 1.9 Global Warming

Many people in many countries are concerned about global warming. The Intergovernmental Panel on Climate Change (IPCC) of the United Nations determined that unless we can keep the temperature rise of Earth to within 2 °C relative to the temperature at the time of Industrial Revolution, many calamities will make the Earth much less habitable with more floods, hurricanes, forest fires, drought, and rising ocean submerging low lying lands. The consensus developed based on scientific data is that one of the major causes of these problems is the anthropogenic generation of CO_2. As a designer, what would you do to deal with this problem? What should be our goals to deal with the challenge created by global warming?

Example 1.10 Reduction of Plastic Consumption

A high-level executive of a major industrial firm that manufactures many products out of polymers (i.e., plastics) is searching for means of reducing the consumption of plastics to lower the cost of the company's products. Since the materials cost constitutes about 50% of the manufacturing cost, the executive reasoned that the company could lower the cost of their products by 5% if they can reduce the materials consumption by about 10%. Their products must look and perform the same as their current products. As a designer of manufacturing processes, develop a design for achieving the above-stated goal—first state the FRs you have selected.

Example 1.11 Mobile Harbor

Containerships carry as many as 16,000 containers (TEUs[2]) and cross the Pacific Ocean to deliver goods in containers to the United States and elsewhere. Many of these ships unload their containers in Long Beach, or Los Angeles harbors in California, which is then transported to the rest of the United States by freight trains because the Panama Canal was too narrow to accommodate these giant containerships. Now the Panama Canal has been widened, but the problem is not entirely solved, because the harbors in the eastern seaboard of the United States are not broad enough and deep enough to accommodate these large containerships. As a solution to this problem, mobile harbor (MH) was invented while visiting Singapore and developed at KAIST. The central idea for the MH is as follows: "Why should ships come into the harbor? Why not have the harbor go out to the ship?" Under this scheme, big container ships moor in deep waters rather than come into a harbor. The MH (see Fig. 1.5) that can handle 600 containers goes out to the containership to unload the containers and deliver them to their final destinations. MH has a relatively flat bottom rather than streamlined V-shape, which enables it to turn quickly in harbors, maneuver easily in shallow waters, and go to any place to unload the containers.

Fig. 1.5 Mobile harbor concept invented at KAIST (four mobile harbors are unloading containers from a large ocean-going containership in open sea to transport the containers from the ship to the shore)

To develop MH, we had to deal with two problems. The MH had to be firmly tied to the big containership during the loading and unloading of containers, so they move in unison in the rough and windy sea. A new design issue was how to tie the MH to the containership. Another problem is related to unloading the containers from the big ship to MH. The

[2]A **TEU** (20-foot equivalent unit) is a measure of volume in units of 20-foot long containers. For example, large container ships are able to transport more than 18,000 **TEU** (a few can even carry more than 21,000 **TEU**). One 20-foot container equals one **TEU**.

containers on the big containerships are lifted using a crane and steel rope. During the transfer of the container from the ship to MH, the container may oscillate due to the motion of the ship and MH. How should the containers be unloaded from the containership to MH on a windy day in a rough sea? What FRs should we satisfy?

In all of the above examples, better solutions may involve "design" of a new solution rather than adapting the past or existing designs. Some of these examples are not simple tasks and may require in-depth thinking and extensive work to provide the answer. They are given here to let the reader think about various issues involved in design. Many of the solutions will be systems that consist of many subsystems.

The purpose of this book is to teach the fundamentals of design to those interested in "developing superior design solutions." To achieve this goal, in the subsequent chapters, the design principles based on AD will be introduced with many examples and case studies. Many case studies show that projects executed based on the teachings of AD cost less and deliver a superior design.

1.9 Definition of Systems

The final output of design is a "system" that solves the problem and satisfies the perceived original need. A system is defined as an entity that generates a set of pre-determined outputs when a set of pre-defined inputs is supplied.

The operation of all systems consumes energy, i.e., the energy input to the system is higher than the energy output of the system. Some also are net consumers of materials and human resources. Some systems require financial resources to operate, and some are net generators of financial returns. The performance of a system is measured in terms of economic measures, or efficacy and fidelity in satisfying FRs, or social and human benefits.

Some systems are massive both in terms of the number of FRs they satisfy and their physical size. However, there is no relationship between physical size and the number of FRs they must fulfill. Some systems, such as semiconductor devices, are tiny physically, but they fulfill a large number of FRs. Some systems are measured in terms of people involved in operating the system.

Some systems are relatively simple, whereas some systems are complicated partly because of the number of FRs involved in a system and the nature of DPs chosen. Some systems are complex because they may not satisfy the FRs at all times. Sometimes a complicated system is also complex, but not always. For instance, the design of Boeing 787 is complicated because of the number of functions it must perform is very large as well as the number of parts that make up the airplane. However, they are not complex, because they satisfy their FRs with 100% certainty. On the other hand, the ignition key of a car manufactured by one of the largest automobile companies in the world could be extremely complex, if the probability of the key performing its functions is much less than 100%. Complexity increases when the system cannot satisfy FRs with 100% certainty.

The constituents of systems vary depending on FRs, DPs, and PVs. Exemplary system elements are physical elements, natural elements, software programs, biological units, humans, ideas (e.g., books), and some combinations of all of the above. Many systems operate within a set of constraints. There are two kinds of constraints: pre-existing external constraints and some constraints created during the design process or operation of the system.

1.10 Fundamental Principles of Design

The following two axioms constitute the basis of AD. All designs must satisfy them. We can separate good designs from unacceptable designs by checking whether or not they are consistent with these two axioms.

The Independence Axiom

Maintain the independence of FRs.

The Information Axiom

Minimize the information content.

Subsequent chapters explain and apply these axioms to various systems and problems.

1.11 Principle of Similitude of Systems

This book deals with many different systems, including mechanical, electrical, chemical, software, organizational, healthcare, and others. Once we understand the basic design principles and methodologies in one field, we should be able to deal with other design problems in many different fields. The reason we can treat many design problems in many diverse fields is that they are all systems with similar structures and characteristics. That is, the concept of design domain, the design axioms, and the design process apply to all design problems regardless of the specific field of application.

The Principle of Similitude of Systems may be stated as follows:

All systems follow the same design principles and processes, and therefore the same concept of design applies to all systems, although their specific functions, components, and usage may be domain-specific.

After students learn the materials presented in this book, they should be able to solve the 18 examples given in this chapter and be able to solve many other original design problems.

1.12 Importance of Knowing the Basic Laws and Principles of Science and Engineering

To be a creative designer of engineering artifacts, it helps if the designer has a strong background in basic disciplines of relevant engineering fields. Similar comments are equally valid for other disciplines. Without a strong knowledge of the related subjects, it is difficult to identify the problems that need to be solved and follow through the steps involved in the transformative process for the design of creative solutions outlined in this book.

The output of design is the functional requirements, {FRs}, which is what the designer wishes to satisfy through design. The inputs are the design parameters, {DPs}. If the design is related to physical things, the designer should have a fundamental understanding of natural laws and principles, constitutive relationships, and conservation principles. If the design involves information technology, the outputs are codes and background in algorithms should be invaluable. If the system is biological or medical, the designer should have background life science subjects such as biology. If the design is related to organizations, {DPs} may be organizational entities. After the design is completed, a more detailed mathematical modeling may be necessary to choose the correct values for DPs and PVs.

The results of the design we see are the assemblage of DPs. How DPs should be physically arranged is an issue that needs to be addressed, sometimes by examining the physical proximity in the case of mechanical design.

1.13 The Inverse Problem in Design: Extraction of Functional Requirements from Many Design Parameters

In the preceding sections of this chapter, the emphasis was on identifying the problem to be solved through design. In subsequent chapters, we will go through how the design can be done to solve the problem identified through the transformation of the problem to FRs, which are then transformed to DPs. Similarly, DPs will be transformed into PVs. We will show how FRs can be stated to represent the design task. We transform FRs to select appropriate DPs. This approach may be called the "direct" approach to design.

There is another approach to design, an "inverse" approach, i.e., going from existing designs to uncover the DP that can satisfy the desired FR. Usually, it is a difficult task to go from DP to FR, because a DP may satisfy many FRs. For example, the FR of a "coffee mug" can be many. It could be "hold hot coffee," "act as a paperweight," "commemorate a special event," and others. The fact that a DP can be related to many different FRs is one of the difficulties of "reverse engineering" because determining the FR from geometric shapes is challenging. However, with the enormous computational power of modern computers, we can manipulate a vast database and try many different combinations of existing DPs to satisfy FRs. In other words, the inverse method consists of going through a vast database of DPs to identify the design of a system that is close to the problem identified. This "inverse method" is possible because of the extensive data that can be processed by supercomputers and cloud computing. This approach is, in essence, the use of artificial intelligence (AI) to synthesize design solutions. With the increasing use of AI techniques, the inverse approach to design may be employed more in the future.

IBM has developed a machine named "Watson." Watson is an intelligent question answering (QA) computing system. IBM built it to apply natural language processing, information retrieval, knowledge representation, automated reasoning, and machine learning technologies to answers questions posed by people using natural language. It has access to 200 million pages of structured and unstructured content consuming four terabytes of disk storage. These machines can store an immense amount of data, which are used to answer questions posed by the user. IBM has been attempting to make Watson be the next generation of products that can generate new revenues for the company. It won chess games over the best human master chess player. Watson has been used in medical applications to guide medical practitioners as well. Google has its version similar to Watson that can provide answers to queries made by people. These technologies are possible because of large computers and easy access to the database produced by large networks and cloud computing. The difficulty lies in satisfying many FRs at the same time, which many design tasks require.

1.14 Optimization of an Existing System Versus Design of a New System

"Optimization of a poorly designed system yields yet another poorly designed system."

Many engineers, economists, and others in many different fields are engaged in the analysis and optimization of an existing system. They devoted significant effort to get the most out of existing systems, which were designed and have been used, sometimes, for decades.

There are many optimization techniques, mostly, mathematical, that have been developed. Typically, the mathematical approach is to express the problem in terms of an objective function with constraints. Even when there are many objectives, the problem is formulated for one objective function with many constraints for mathematical convenience and treatment. Such a brute force approach would not be applicable when an entirely new system must be designed to satisfy many FRs. James Watt would not have invented his steam engine if he tried to optimize the Newcomen engine.

1.15 Scope of the Book

The purpose of this book is to enable the reader to "design" on her/his own, with imagination and creativity, to satisfy human needs and societal aspirations. Human intellect is a powerful tool that enables human beings to achieve many things through design—it only requires the imagination and willingness to learn how the design should be done. This book outlines the steps involved in design based on AD to develop a rational design solution. The basic idea is to approach design systematically so as not to make wrong designs. There are well-known design mistakes that cost a great deal to re-do them to correct the errors, a la the design problem associated with control of Boeing 737 MAX. Many of these mistakes are often due to the coupling of FRs during the decomposition process. These coupled designs lead to accidents of nuclear power plants, crashing of aircraft, delayed construction of airports, and unreliable products.

This book presents the basic concepts involved in AD: the idea of four domains in the design world, the mapping between the domains, and the transformations involved during the design process. After the problem that needs to be solved is identified, the designer sets the ultimate goals of the design task in terms of functional requirements {FRs} and constraints (Cs). Then perform specific design tasks of identifying design parameters {DPs}. The idea of the design matrix is also introduced in this chapter. The design process, including the decomposition through zigzagging, is illustrated in this chapter. Many examples are given to clarify the new concepts presented.

The subject of "DESIGN" treated in this book is not limited to engineering, although many examples are derived from engineering and technology. Design is equally important in many other fields that involve synthesis to achieve a set of goals, such as in the design of software, organizations, and even in cooking gourmet foods. The same thinking and methodologies apply to all these subjects. That is, although the specific topics and subject matters are field-specific, all fields share the standard design process and the same design axioms.

1.16 Conclusions

The design is one of the most critical subjects in engineering. Synthesis of innovative products and solutions is the essential foundation for solving societal problems and advancing commerce, engineering, science, and social science fields. The ability to design well determines the quality of most things: products, processes, manufacturing, organizations, governments, technologies, the quality of life, and others.

Good designs depend, the foremost, on the quality of problem identification and definition. Once the problem is defined, the designer can proceed to the subsequent steps of design. The steps consist of the transformation of customer needs of the customer domain into functional requirements {FRs} of the functional domain, followed by transformation of {FRs} to design parameters {DPs} of the physical domain, and finally the transformation of {DPs} to process variables {PVs} of the process domain. The relationship between the domains is "What" and "How." The {FRs} in the functional domain is "what we want to achieve," whereas the {DPs} in the physical domain represent "how we are going to satisfy the FRs."

Similar design processes govern the design of diverse systems. A person who can design technical systems well can also apply the same skill to other design problems such as organizations, although specific issues are domain-specific.

Problems

1. In the twenty-first century, telecommunications and social network systems (SNS) have become the dominating information dissemination mechanism, displacing the printed media. As a result, the information distributed in SNS throughout the world can be corrupted by those with ill-intentions and nations as a warfare tool. Our job is to solve this problem to safeguard the system and make the information in the digital communication system from being corrupted. What FRs, would you satisfy this problem?
2. Faulty designs or poor designs cause many failures in various systems. The recent crash of Boeing 737 airplanes, the delayed opening of the new Berlin airport, and the Fukushima Daiichi nuclear power plant disasters are some of the well-publicized failures. These accidents occur despite numerous tests. What is the best way of preventing these failures?
3. If you are the president of your university, how would you improve the admissions process? What is the problem you are trying to solve? What functional requirements {FRs} should your university try to satisfy through their admission process?
4. Many companies are working on driverless automobiles. What functional requirements {FRs} should the designer of the automobile satisfy?
5. What do you think makes Starbucks so successful in selling coffee even though so many other companies had already been selling coffee before their emergence?
6. Define the FRs we must satisfy to teach AD well.

References

Black NH, Davis HN (1913) Practical physics for secondary schools. Fundamental principles and applications to daily life. Macmillan and Company, public domain

Petrushenka A (2019) The launch of the space shuttle. With fire and smoke. Against the background of the starry sky. Elements of this image were furnished by NASA. Photo licensed from Shutterstock, ID: 1480426817

Further Reading

Hatamura Y (2008) Learning from design failures. Springer

Senor D, Singer S (2009) Start-up nation: the story of Israel's economic miracle. Twelve Hachette Book Group

Suh NP (2001) Axiomatic design—advances and applications. Oxford University Press

Suh NP (2010a) On innovation strategies: an Asian perspective. The Glion Colloquium. https://glion.org/on-innovation-strategies-an-asian-perspective/

Suh NP (2010b) Theory of innovation. Int J Innov Manag (IJIM) 14:893–913. https://doi.org/10.1142/S1363919610002921

Suh NP, Cho DH (eds) (2017) The on-line electric vehicle: wireless electric ground transportation systems. Springer International Publishing

Wilson HG, McCready PB, Kyle CR (1989) Lessons of Sunraycer. Sci Am 260(3):90–97