INTRODUCTION TO DESIGN[1]

Big engineering design disasters, such as the explosion of the Space Shuttle Challenger, the Space Shuttle Columbia, the near melt-down at Three Mile Island Nuclear Power plant, the actual meltdown at the Chernobyl Nuclear Power plant, and the chemical plant failure in Bhopal, India, illustrate that the cost of failure is becoming more societally disastrous.

Airplane crashes, which result from design failures, and the Firestone tire/Ford Explorer disaster, illustrate how dependent we are on technology and how high the cost of failure is for poor design decisions.

Poor design practice results in a long design process. This is leading the United States to losing the technological superiority it held since the end of WWII. Since military and economic superiority are tied to technological superiority, this loss could mean the decline of the United States.

What is the problem with the traditional design approach and why develop a rational approach to design?

- **incorrect or excessive Functional Requirements (FR)**
- **alteration of the FRs during the design process,**
- **poor design decisions,**
- **inability to recognize faulty decisions prior to making faulty prototypes.**

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1. This section is largely adapted from Suh, N. P., The Principles of Design, chapters 1 & 2, Oxford University Press, 1990.

What is Design?

Design is a synthesis process.

Needs are fulfilled through creation of physical, informational, or organizational structures.

Structures could be a machine, a software program, an algorithm, an organizational chart, a system of electrical, mechanical, and software elements, etc.

Structures, such as a machine, are not necessarily purely mechanical. They may be a combination of mechanical, electrical, algorithm, and software elements. (This is called mechatronics.)

Given a set of specified inputs, the result of the design process has an output which satisfies the *perceived* goals.

Until very recently, design has been considered a *creative* process. The outcomes are desirable, but the process by which they are achieved were not understood.

Design can be broken into four components:

- **problem definition**
- **determining a physical embodiment of solutions**
- **an analytical determination of the feasibility of the solution**
- **a check on the fidelity of the final design.**

Design Space/Physical Space

Functional requirements (FR) constrain the Functional Domain. The Functional Domain contains the objective of the design process.

The objective of the design process is the question, "What do we want to achieve?"

The physical solution to the design problem exists in the physical domain.

The physical solution is the answer to the question, "How do we want to achieve the objective."

The physical domain is constrained by design parameters (DPs).

The design process maps the functional requirements onto the design parameters.

Which leads to the definition[1]:

"Design is the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through the mapping between the FRs in the functional domain and the DPs of the physical domain, through proper selection of DPs that satisfy FRs."

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1. **Suh, Principles of Design, Oxford University Press, 1990.**

Design Outputs

The output of the design process is Information. This is a growing area of understanding in the world of engineering and science (and is captured by the fledgling field of Information Science).

Hazelrigg[1] gives us three important definitions:

1. Knowledge: An agreed upon set of facts.

Knowledge is essentially the contents of a database, with elements such as F=ma. Knowledge can be defined as an understanding of the laws of nature and the ability to apply those laws to predict the behavior of physical systems.

2. Decision: An irrevocable allocation of resources.

The selection of design parameters for an engineering system such as a computer or an automobile constitutes an allocation of resources. Design is a decision-making process, and the selections of design parameters represent decisions.

3. Information: Information relates to a specific decision.

Quantitatively, it can be measured as the probability that the preferred choice in a decision will lead to the most desired outcome.

Information for a mechanical design takes the form of drawings, tolerances, assemblies, manufacturing techniques, parts lists, etc.

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1. Hazelrigg, G. A., Systems Engineering: An Approach to Information Based Design, pp. 3-4, Prentice Hall, 1996.

Problem Definition

Problem definition is a poorly understood part of design.

It is not unusual for engineers to impose a known solution on a new problem.

Failure to define the correct problem inevitably results in successfully solving the wrong problem!

This is actually worse than incorrectly solving the right problem.

The problem definition process is subjective (not objective). There may be many correct (but different) definitions to the same problem.

Identifying the share-holders in the design endeavor is important.

Customers (or potential customers) are very important share-holders.

The customer is always right. Unfortunately, the customer does not know what he wants or is not willing to pay for everything that he wants.

"Registering" the customer base is the starting point for a design.

Example: in the 1950s, automobile safety was considered important by consumers. However, they were not willing to pay for it. Rather, style was more important.

Problem Definition - Determination of FRs

Problem definition is driven by acquiring information. (see Suh, pp. 30-35)

A more experienced designer will have more information at his disposal. This designer will require fewer iterations to achieve an independent set of FRs than a less experienced designer.

There are two circumstances under which FRs are defined:

- **Develop a new design (solution neutral environment)**
- **Improve an existing design**

The second circumstance is the most likely situation that a designer faces. It is also the most comfortable.

The first circumstance is scary in that the designer starts with a "clean sheet of paper." What this means is that the designer must disregard all solutions that currently exist.

The first step in a clean design is to gather as much information as possible. From this information, a preliminary set of FRs are identified. It is to be expected that one or more iterations on FRs will be done. Each iteration on FRs brings more information into the process.

The second circumstance should not ignore FRs. If the exercise has not already been done, the FRs should be generated from the design. The questions, "What societal need does this product satisfy?" and "What are the FRs?" should be answered. The new requirements should be integrated into the existing FRs. If necessary, FRs should be made independent or, if they are unnecessary, abandoned.

Axiomatics in Design

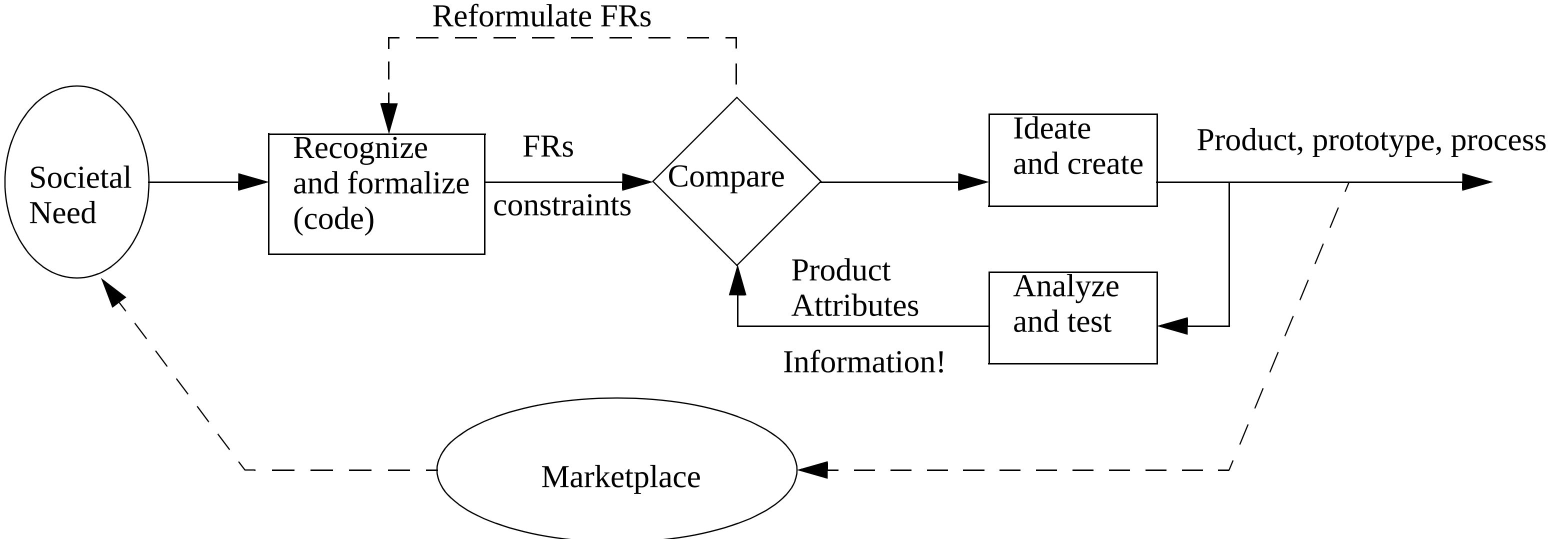
First step in putting science into design is to develop the fundamental axioms. Suh has determined these to be:

Axiom 1: The Independence Axiom

Maintain the independence of functional requirements (FRs).

Axiom 2: The Information Axiom

Minimize the information content.



The Design Loop

The design loop figure adapted from Wilson, D. R., An Exploratory Study of Complexity in Axiomatic Design, Ph. D Thesis, MIT, 1980.

The Performance Envelope

Designs which push closer to the edge of the performance envelope or which exist in environments for which little design data is available, are less safe. Design conservatively in these situations.

This impulse is complicated by the traditional design process. Poor decision making and a lack of a metric against which a design can be considered good or bad, result in costly designs.

Products will always be used outside the performance envelope (see any movie about a submarine for an example).

Engineers must make sure that their products function properly inside <u>any</u> reasonable performance envelope.

It is not sufficient to issue special "operator instructions" when a design flaw is encountered.

Most of these difficulties should be handled in the identification of Functional Requirements.

Constraints

Although both FRs and Constraints constrain the Functional Space and although they seem to be the same thing, they are slightly different.

A Constraint has a looser bound on it than an FR. It will be incumbant on the designer to distinguish between these in the problem definition.

An FR must be satisfied. A Constraint must be satisfied only if the design bumps into it.

For instance, minimizing cost is a Constraint. Meeting a specific cost is a Functional Requirement.

E.g., unit cost must be less than $1 versus unit cost must equal $1.

Fitting within a space envelope is a Constraint. An exact shape is a Functional Requirement.

E.g., unit must fit within 1 m by 1 m by 1 m space versus unit must mount to 1” radius hole pattern.

There are two kinds of constraints:

- **input constraints (constraints on design specifications)**
- **system constraints (constraints imposed by the system in which design solution must function)**

Note: DPs at a higher level in the design hierarchy may become Constraints on a lower level.

A problem which is highly constrained will have fewer solutions than one which is largely unconstrained.

Hierarchical Decision Making

The design process is a <u>hierarchical decision making</u> process.

Design is a synthesis process which is supported by analysis. The analysis helps remove some of the uncertainty from the decision making process.

A hierarchical decision making process is one in which decisions must be made in order. This is similar to a linear computer program.

Decisions can be made in parallel (called parallel path engineering). This is similar to organizing a computer program into a parallel program in which chunks of the code will run simultaneously on separate processors.

Nonetheless, the parallel process must synchronize periodically to pass information between the separate processes. In other words, the hierarchical nature of design can be relaxed somewhat. It cannot be entirely removed.

Entities which fail to recognize the hierarchical nature of design and organize themselves accordingly, perform design on an *ad hoc* basis. Although this can be successful, there is a limit to the efficiency with which this design is accomplished.

Entities which organize themselves scientifically to perform design will out-compete *ad hoc* entities.

Hierarchy of FRs and DPs

FRs and DPs have hierarchies and must be decomposed through the design process.

Identifying the second, third, etc. level FRs requires that preliminary DPs be generated for the first level FRs.

At the first level, the designer must choose the most important FRs and must choose a minimum set.

At the second, third, etc. level of definition, the designer can return to previous levels and recast the FRs so as to decouple or simplify them.

Although FRs are the "minimum set of independent requirements that completely characterize the design objective for a specific need," each designer may define the need differently. It is unlikely that two designers will choose the same set of FRs for a given need.

Therefore, FRs for a new design are not unique.

FRs can be seen to be an extension of the individual designer.

See Suh, pp. 37-38 for an example of FRs and DPs for a lathe.

Reverse Engineering

Reverse engineering involves deducing DPs and the FRs that they satisfy from an existing design.

Reverse engineering is a useful exercise on many levels.

Understanding DPs and FRs in the abstract is difficult. Through reverse engineering, a more concrete understanding can be developed.

Both good designs and bad designs are illuminated through reverse engineering.

This allows an engineer to avoid the mistakes of poor designers and emulate the successes of good designers.

How to reverse engineer...

Take stuff apart. Identify the critical components (these are the DPs). Identify the modules (these are the upper level DPs).

Once you have all of your DPs, determine what requirements these DPs satisfy. These are the FRs.

Brain-Storming

Brain-storming is a useful technique for quickly identifying a large number of possible solutions for a problem. It is an effective, methodical way to tap into the creative process.

A group of three or more people can generate many more ideas than the same number of people working independently.

Brain-storming also reduces the tendency to “lock in” to a single idea and ignore all other possibilities.

Competitive pressure usually compels a person to explore uncharted territory. An urge to “claim territory” by being the first to articulate an idea pushes the “brain-stormers” to formulate and articulate ideas at a pace that does not exist outside the brain-storming arena.

During brain-storming, the development of an idea should be discouraged. This prevents the development of ownership and the politics associated with “getting your ideas in front of your peers.”

Note: in the presence of non-competitive, unmotivated, or just plain dull people, brain-storming is a waste of time. But, these people should not be training to become engineers anyway and should be weeded out of the gene pool.

Brain-storming Methodology

1. Determine the topic and scope of the brain-storming session.

If you are planning to create the functional requirements that your design must satisfy, then state that objective clearly prior to the beginning of the session. It is OK to develop ideas that are not part of this objective. However, those ideas should be written down and tabled for the appropriate brain-storming session. For instance, if a design parameter occurs to you which satisfies a functional requirement that your peer has just articulated, write it down, but do not submit it as an idea for a functional requirement.

2. Each person, independently, spends two minutes writing down ideas. (Idea trigger)

3. Take a two minute break. (idea purge)

4. Each person, independently, spends 30 seconds writing down ideas.

5. One at a time, each group member reads <u>one</u> idea. So, you had better put forward your best idea on your first go, and you had better volunteer to go first!

If someone else reads "your" idea, you must cross it off your list. The session leader should write down each idea in a master list as they are read.

If an idea occurs to you while someone is reading a different idea, write it down. You can read your new ideas when your turn comes again.

When all ideas have been articulated, the brain-storming session concludes.

Separating Brain-storming Activities

The first brain-storming session should evaluate top level functional requirements.

The next brain-storming session should take each functional requirement and determine a list of possible design parameters to satisfy the FRs. In a large organization, each FR may be assigned to a separate team.

Often, in the discussion over DPs, new or modified FRs are evolved. It is OK in the beginning stages to return to the start and modify FRs.

Since design is hierarchical, once first level DPs have been determined, second level FRs must be developed, then second level DPs.

At each step, it is appropriate to undertake a brain-storming exercise.

As the bottom of the hierarchy is approached, it becomes less productive to engage in brain-storming.

Design Corollaries and Rules of Thumb[1]

The design axioms can be combined to yield thera and corollaries which are usually more useful than the axioms themselves. These can be seen design rules or rules of thumb. If the designer abides by the corollaries, he will automatically satisfy the axioms.

Corollary 1 (Decoupling of Coupled Design): Decouple or separate parts or aspects of a solution if FRs are coupled or become interdependent in the designs proposed.

Corollary 2 (Minimization of FRs): Minimize the number of FRs and Constraints.

Corollary 3 (Integration of Physical Parts): Integrate design features in a single physical part if FRs can be independently satisfied in the proposed solution.

Corollary 4 (Use of Standardization): Use standardized or interchangeable parts if the use of these parts is consistent with the FRs and Constraints.

Corollary 5 (Use of Symmetry): Use symmetrical shapes and/or arrangements if they are consistent with the FRs and Constraints.

Corollary 6 (Largest Tolerance): Specify the largest allowable tolerance in stating FRs.

Corollary 7 (Uncoupled Design with Less Information): Seek an uncoupled design that requires less information than coupled designs in satisfying a set of FRs.

1. **Verbatim from Suh, Principles of Design, Oxford University Press, 1990.**

Design Theora[1]

Theorem 1 (Coupling Due to Insufficient Number of DPs): When the number of DPs is less than the number of FRs, either a coupled design results or the FRs cannot be satisfied.

Theorem 2 (Decoupling of Coupled Designs): When a design is coupled due to the greater number of FRs than DPs, it may be decoupled by the addition of new DPs so as to make the number of FRs and DPs equal to each other, if a subset of the design matrix containing nxn elements constitutes a triangular matrix.

Theorem 3 (Redundant Design): When there are more DPs than FRs, the design is either a redundant design or a coupled design.

Theorem 4 (Ideal Design): In an ideal design, the number of DPs is equal to the number of FRs.

Theorem 5 (Need for New Design): When a given set of FRs is changed by the addition of a new FR, or substitution of one of the FRs by a new one, or by selection of a completely different set of FRs, the design solution given by the original DPs cannot satisfy the new set of FRs. Consequently, a new design solution must be sought.

Theorem 6 (Path Independence of Uncoupled Design): The information content of uncoupled design is independent of the sequence by which the DPs are changed to satisfy the given set of FRs.

Theorem 7 (Path Dependence of Coupled and Decoupled Designs): The information content of coupled and decoupled designs depends on the sequence by which the DPs are changed and on the specific paths of change of these DPs.

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1. **Verbatim from Suh, Principles of Design, Oxford University Press, 1990.**

Elements of Mechanical Design

Over the past several centuries, many specific elements have evolved, which cover the majority of the situations which occur in mechanical design.

These elements are grouped in categories, most of which are listed in Machinery's Handbook. This is not an exhaustive list, but it covers the basic mechanical and electromechanical elements in a mechatronic system.

- **Fasteners**
- **Gears and Sprockets**
- **Bearings and Bushings**
- **Shaft Couplings**
- **Brakes and Clutches**
- **Actuators (motors, solenoids, pneumatics, and hydraulics)**

Beyond the elements, there are many standard mechanisms, such as the four-bar linkage, the Scotch yoke, Watt's linkage, the Geneva wheel, Peaucelier's linkage, Tchebichoff's linkage, the gimbal mount, and the cardan joint.

Most of these mechanisms have their own design and analysis procedures and are covered independently in separate courses. These are beyond the scope of a basic course. Further, many of the more complex mechanisms may be made obsolete by a mechatronic replacement.

Mini-Design Problem

Design a gear-box for the FIRST CIM motor (specifications available at http://banebots.com/p/M4-R0062-12) which generates an output torque of between 5.5 to 6.5 Nm at the most efficient operating point. Output shaft should be 1/2 in hex, 2" long (as measured from the gearbox face), with an additional .25" by .375" diameter for seating in a bearing.

Pick the desired gear-box type (e.g., spur gear, planetary gear, worm and gear) and use the efficiency estimates from the class notes in your calculations.

Use only Bearings, Fasteners, Material Stock, and Spacers available from McMaster-Carr (http://www.mcmaster.com), and gears from Stock Drive (http://www.sdp-si.com).

Your final report should include a parts list, design drawings for all custom parts, part costs for off the shelf parts and materials, all gear box calculations, total materials cost for the entire gearbox, and an assembly level drawing showing the final product.

Deliverables for the mini-design project

The deliverable for the mini-design is a report (in memo format) which would allow a person not familiar with your design to fabricate and assemble it. Attached to the report should be

- **dimensioned engineering drawings for each part**
- **a drawing (not dimensioned) of the assembly to assist in determining your design intent**
- **a parts list and a bill of materials**

Report Format:

- **Introduction**
- **Discussion of design intent, including functional requirements**
- **Description of the design**
- **Bill of materials**
- **Drawings of all parts**

Semester Design Project

A common property which is needed in mechanical work is a body's moment of inertia. There are commonly available moment of inertia testers; however, they use passive principles to determine the measurement. These passive principles require calibration on spring contants or mass properties which may be difficult to control.

They also involve using externally measured properties (such as time), rather than incorporating sensors and actuators into the design. Gravity, whose variation is often ignored, is usually a fundamental quantity in the measurement.

Therefore, it is desired that a moment of inertia tester be designed, whose accuracy is equivalent to the available testers, but which includes sensor, actuator, and data acquisition elements to remove the need for external measurements. If possible, the testers should not need a calibration moment of inertia standard.

In order to limit the size requirements on the tester, the desired outcome is to measure the three principal moments of inertia of the Control and Sensor System (CASSy) platform.

If an external data acquisition system is desired to be used with the tester, assume that a 2 input, 2 output Siglab will be available for the measurement. If it is desired to include an active element (e.g., motor) in the design, an off-the-shelf power amplifier should be located and specified.