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# Design Record Graph and Axiomatic Design for creative design education

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**Abstract**

The authors have been offering a graduate level design course at the University of Tokyo. The students form groups of about 5 members to identify their own design goals and construct creative solutions to meet the product functional requirements (FRs). The course teaches Design Record Graph (DRG), a network diagram that starts with the product FR that divides into a number of sub-functions. The division continues until all functional elements are identified, and when every element functional requirement maps to a single element design parameter (DP), the design meets the independence axiom. The projects often start with heavily coupled designs that gradually turn into clean solutions towards their finalized design. The graph expression is easier for design students to get started with functional decomposition without having to work with design matrices.


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*Keywords:* Design; Education; Design Record Graph; Axiomatic Design; Independent Axiom

## 1. Introduction

The authors teach a graduate level course at the University of Tokyo, School of Engineering. The course title is “The Practice of Machine Design.” It teaches mechanical design in the conceptual stage. Formal language of the class, including discussions and presentations, is English, and it attracts foreign students throughout the school.

The course objective is a group project to identify a problem to solve within the school-life and define a creative solution for it. From the nature of this assignment, the student groups often find improvements for solutions that are already in place but with existing inconveniences.

The course instructions are modeled after the practice at Stanford University d.school. To the 5 stages of conceptual design, Empathize, Define, Ideate, Build, and Test, the course additionally elaborates


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between the Ideate and Build stages. The students analyze their proposed solutions with Design Record Graphs (DRGs). The next section explains DRG and how it relates to the Design Matrix in Axiomatic Design [Suh, 2001]. Section 3 explains common pitfalls students often encounter when they draw DRGs for the first time.

The DRG representation gives an easy entrance to the concept of “divide and conquer” which is also the foundation of Axiomatic Design. The simple node and arc diagram allows breaking down a product functional requirement into sub-functions and eventually into functional elements. When the independence axiom is met, the DRG shows a ladder like set of arcs across the functional and structural spaces. DRG is especially useful in teaching functional analysis to students not well trained in linear algebra.

## 2. Design Record Graph and Design Matrix

Brown pointed out the advantage of Axiomatic Design for teaching traditional design [2]. Park reported applying Axiomatic Design in conceptual design education [11]. Liu and Lu reported challenges for students in learning Axiomatic Design [8].

The concept of DRG was earlier called function-structure diagram (F-S Diagram) [Iino *et al.*, 2014] following the Stanford naming of function and structure diagrams [Leung *et al.*, 2005, Ishii and Iino, 2008]. Hatamura and Nakao separately developed the same concept [Nakao, 2003, Hatamura, 2006]. Stone and Wood developed the functional model [Stone and Wood, 2000] which has input and output identified for each function. To avoid confusion with this functional model, the diagram is now called DRG because it is intended more for describing the designer’s development of the design starting from the product functional requirement.

DRG is a directed graph with functional nodes in the left and structural nodes in the right. The two sides respectively show the hierarchy of functions and structures. The left-most functional node is the product functional requirement, also called the maximum functional requirement [Ishii and Iino, 2008]. The right end is the product. This graph representation, often used for mechanical design, is simple, easy to use and frequently used for other applications like service engineering, planning and software development.

The product functional requirement divides into sub-functions and continues dividing into smaller functions until they are divided into a set of Functional Elements (FEs). An FE maps across the border to the structure space to one or more Structural Elements (SEs). The SEs gather to form components and higher level assemblies until they all combine to define the right end product. Fig. 1 shows a typical DRG. This figure shows 4 layers of hierarchy in both the functional and structural spaces. There is, however, no set number of layers to draw in the graph. For conceptual design, 3 to 5 levels on each side are recommended.

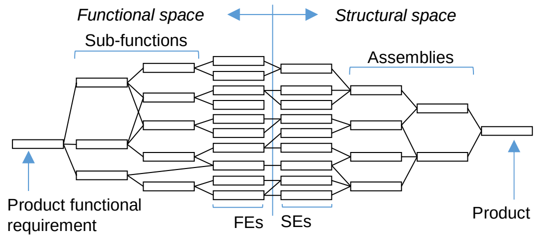


Fig. 1. Typical DRG

Axiomatic Design, on the other hand, relates Functional Requirements (FRs) to Design Parameters (DPs) in the formula Eq. 1 [Suh, 2001], where ***A*** is the design matrix. DRG relates to ***A***, such that FEs in DRG are the components of the FR vector, and SEs, those of the DP vector.

In constructing a DRG, students identify customer needs in the first decomposition level of subdividing the product functional requirement. Thompson pointed out that mixing customer needs with FRs can confuse the Axiomatic Design process [15]. Bragason *et al.* showed an example that had to map the customer needs first to FRs to complete the Axiomatic Design analysis [1].

DRG is not as rigorously defined as Axiomatic Design, e.g., the level of hierarchies in the functional and structural spaces do not have to match, and the designer is not concerned about correspondence of intermediate level nodes between the functional and structural spaces. The less structured nature of DRG may lead to confusion, but experienced designers can map customer needs in the first functional decomposition level to functional requirements in the second decomposition and repeat the subdivision to reach FEs. Well defined FEs state its requirement in the form of engineering metrics. DRG is easier for designers with less experience in linear algebra to start subdividing functional requirements.

The designer applying axiomatic design will strive to meet the independence axiom [Suh, 2001]. The goal is accomplished when the design matrix ***A*** is diagonal. This axiom in DRG means the arcs crossing the border from the functional space to the structural all have one to one correspondences, i.e., each FE has a single counterpart SE. In this case, unlike the DRG in Fig. 1, the arcs across the functional and structural space forms a ladder. Fig. 2 shows this concept.

$$\{\mathrm{FR}\} = [A]\{\mathrm{DP}\} \qquad (1)$$

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 & 0 \\ 0 & 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \end{Bmatrix} \qquad (2)$$

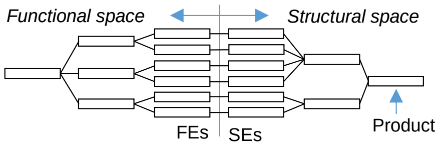


Fig. 2. Design Matrix and DRG of a design that meets independence axiom

In contrast, a coupled design in Axiomatic Design produces a DRG with multiply connected nodes across the functional and structural space boundary with multiplicity going in both directions. If the multiplicity is only in one direction, the design is decoupled. When a number of arcs across the functional and structural space boundary are not straight, slanted, or intersect, the students are guided to rethink their design decomposition to approach ladder-like connections. As Section 3.4 pointed out, the concern is when multiple FEs point to a single SE.

The designer should also avoid subdividing the structural space elements to a level too fine that the DRG boundary may look to form a ladder (uncoupled design). Excessive decomposition can hide interferences at higher component levels. Section 3.4 also explains this concern.

**Nomenclature**

| | |
|---|---|
| DRG | Design Record Graph |
| FE | Functional Element |
| SE | Structural Element |
| FR | Functional Requirement |
| DP | Design Parameter |

## 3. Modifications to Conventional DRG

Through experience of working with students in creating conceptual solutions to problems they identified, some modifications to conventional DRG will make working with them more convenient. This section lists these findings.

### *3.1. Subdividing parts to features*

Conventionally the SEs in the structural space are collections of all the parts of a finished product. Today, however, with the advancement of injection molding and material processing, a single plastic part can take complex shapes to satisfy a number of FEs. Take for example, the case of a cellular phone. It not only provides protection to the internal parts, but also shields electromagnetic noise from the outside with the metallic ingredient in its material, sometimes, provide windows for the internal LEDs to give status notification to the user, and defines the color and shape that attracts the user to make purchase.

The last point of defining the "looks" of a product is more important these days because technology is wide spread over the world and it is getting difficult to distinguish a good product by just the technical functions it provides. In other words, products that are built anywhere with the same product functional requirement have almost the same set of technical functionalities. Consumers are more inclined to make decisions on their purchase based on how the product appeals to them with the looks.

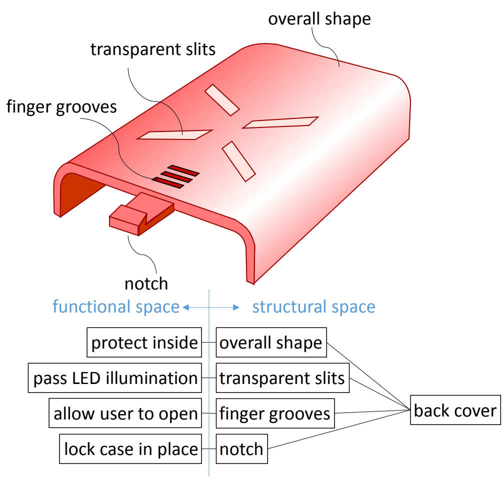


Fig.3. A single part, its features and FE-SE correspondence

Modern product parts force us to subdivide parts to the level of features. It means that the designer should divide a single part to the level of features to define the set of SEs for a product. See for example Fig. 3 for a common battery cover.

### *3.2. Including power sources*

Nakao *et al*. pointed out that mechanical engineers often forget about electrical power supplies to the product [10]. Almost all convenient products today run on battery cells, rechargeable ones or AC household power supply. If, however, a DRG includes the power supply in it, its existence clutters the diagram because electricity is needed for almost all functions. Fig. 4 shows sub-functions of a cellular phone that identifies the caller, lets the user know who is calling, and allows the user to take the call.

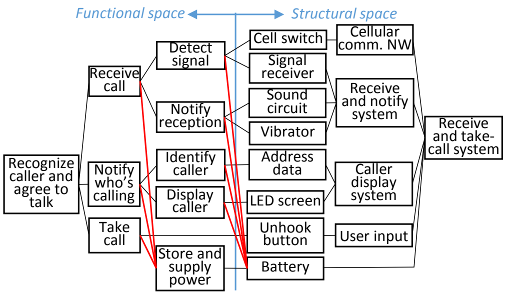


Fig.4. DRG for "recognize caller and take call" function of a cell phone

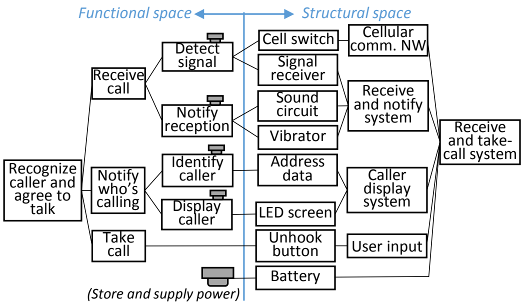


Fig.5. Alternate DRG for Fig. 4 with a battery symbol

The arcs in Fig. 4 shown in red are lines from the battery system. Their existence are important because failure of the battery system would take away all functions of a cellular phone. These cluttered arcs are a good sign of the design vulnerability that a single part can affect the whole product function; its failure is critical for the product function. In the conceptual design phase, however, presence of these arcs is unwanted. The suggestion is to replace the lines with battery symbols like shown in the next Fig. 5. The diagram is not cluttered while the important function of power supply is not forgotten.

### *3.3. Including of human factor*

70 to 90% of accidents are said to be caused by human factors [Hollnagel and Woods, 2005]. During the design phase, just like the tendency of mechanical engineers to forget about electricity, designers also tend to forget the reliance of the design on human recognition, judgement, and operation. Fig. 6 added the human factors to the "recognize caller and take the call" function. The nodes with round corners indicate human factors.

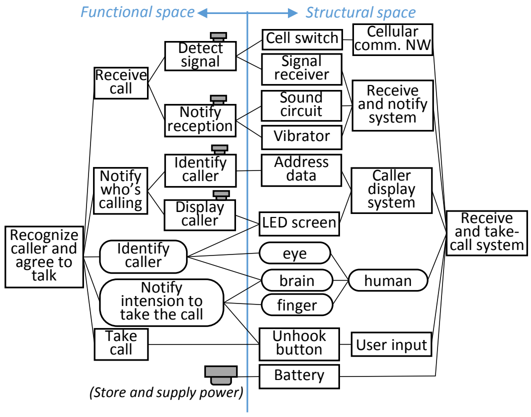


Fig.6. Alternate DRG for Fig. 5 with human factor

### *3.4. Interference in axiomatic design*

Interference with design is unwanted because they cause later problems, difficulty in product maintenance and hardship in operating the product. From the DRG viewpoint, satisfying a single functional requirement (FR/FE) with multiple design parameters (DPs/SEs) is not a source of problems, e.g., meeting the "notify reception" function with "sound" and "vibration" in Fig. 6.

The designer should be concerned when a single design parameter (DP/SE) is used to meet more than one functional requirement (FR/FE) (Fig. 7).

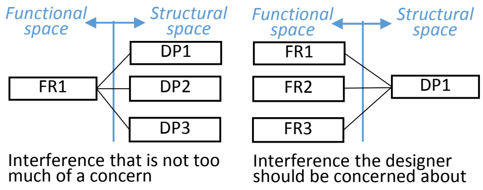


Fig.7. Multiple element correspondence and design concerns

A clear example of this is the battery in Fig. 4. If the battery dies, the cellular phone is just a plastic box with buttons that do not even work as a calculator. In a more extreme example, when all power sources were lost, Fukushima Nuclear Power Plant melted down three of its cores and released a large amount of radioactivity.

Section 3.1 also showed that if breaking down the parts in the structural space to a fine level, can accomplish a one-to-one correspondence between the FEs and SEs, or in axiomatic design, FRs and DPs. For example, the battery in Fig. 4 can be further broken down to each wire, or pattern on the PCB, that feeds power to each function, to make the design matrix look diagonal.

In such a case, the designer has to go up a level in the functional requirement and design parameter spaces to find interference in the component level.

## 4. Common difficulties in conceptual design

Graduate level students in the Mechanical Engineering Department have plenty of experience in drawing with solid modelers and producing 2D drawings for production. Common undergraduate design assignments come in the form of “Here are some examples. Now with a different set of design parameters, modify the design.” The students are thus used to the concept of producing similar products that follow already defined models.

At the early stage of the course, the students define or discover their own problems and later in the course, they find solutions to the problems, in other words, the class starts from the phase of defining the model. The students have no model to follow. Here are some common difficulties that the students face in the early stage of conceptual design when they have to start giving some shapes to their ideas:

### *4.1. Confusing functions with structure*

When the students start to build their first DRGs, it is common to write down descriptive nouns in functional requirement nodes. Nodes in the functional space typically take the form of verb + object, thus, there should be nouns in the left side also, however, they should not refer to the solution.

Examples of problematic function definitions are; “ball bearing” that should state “provide smooth coaxial rotation” or “oil cylinder” in place of “lift heavy objects straight up”. Minds unexperienced in creative design often runs to a conclusion given a functional requirement. In the designer’s mind, the only thing to provide smooth rotation is a ball bearing, thus a ball bearing itself defines the function for them. This is a block in the students’ minds which stop the search for other possible solutions that may lead to better results.

When faced with this type of confusion, the student is instructed to voice out the “function” of a ball bearing to write it down in the functional space node.

### *4.2. Difficulty in stating the why*

For DRG with the functional space in the left and structural space in the right, constructing the right side seems relatively easy for the students. It is probably because they can picture or see the parts in the right and imagine assembling them into larger assemblies. The difficulty is with the left side where there is no picture, Internet photo, or physical existence of the concept. The frustration may be rooted in engineering students being good in number crunching but not in literature.

Some students have hardships in both stating the real need, and going up a level in the functional requirement (left in functional space of a DRG) to state why you need that function.

One exercise often used in the class is to have the students state the product functional requirement of a cellular phone. What is the functional requirement of a cellular phone? The session typically starts with a student replying “To make a call.” Is that the FR for a cellular phone? You can still ask the question, “Why do you want to make a call?” Then they realize they just want to converse with a friend. Is that enough? Is it always a friend that you talk with on the cellular phone? After a few questions, thinking and answering, they finally reach a statement like, “To specify a receiver and converse with the person from anyplace after agreement." The phrase "from anywhere" is important to distinguish the functionality of a cellular phone from a ground line. "After agreement" is another feature of a cellular phone that is often forgotten.

One common way to find the FR at a higher level is to ask the question, "Why do you want that function?" Roth finds a way to identify the higher level functional requirement by asking "What happens if that functional requirement is met?" Although his book [Roth, 2015] does not specifically state it is a way to find a higher level FR, it shows how designers can ask that question to find what is really wanted.

### *4.3. Experience interfering with new ideas*

Students, and more often adult learners of DRG, have some experience with machine design. As they decompose higher level functional requirements into sub-functions, before reaching element functions, they often jump to conclusions that they will realize a high level function with what mechanism. The result is a function mapping to multiple SEs.

Although this interference is not too much of a concern as Fig. 7 shows, the concept creates a block in the designer's mind, taking away the chance for new ideas that may replace a conventional structural element with a different one.

When this happens, the student is guided to go back to the structural element and try to state its FE. The student then recognizes how to break down the higher level functional requirement that he/she mapped directly to a number of structural elements. This review is forcing the designer to zag back into the functional space from the physical space [Suh, 2001].

## Conclusion

The authors have developed a design education course that teaches how to construct DRG, a directed graph representation for mechanical design in the conceptual stage. The tool is easy to build using pen and paper, yet allows students to start giving shape to their conceptual design. This paper showed how DRG relates to the design matrix in Axiomatic Design.

This paper also proposed how to modify conventional construction of DRG to meet modern design, i.e., to break down parts to the level of features, include electrical power, and draw human factors in the graphs.

Novice designers have difficulty in stating "functions," however, this hardship is not unique to this graph representation and it always accompanies any methods intended for functional and structural analysis, including Axiomatic Design.

Drawing DRGs provides a relatively easy entrance to functional analysis for designers that may be reluctant to work with matrix representation of designs. It can serve to have students started with functional analysis and guide them towards Axiomatic Design.

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