DESIGN CREATIVITY EDUCATION IN AN INTERNATIONAL ENGINEERING CLASS

(DRAFT VERSION)

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ABSTRACT

Conventional engineering education in Japan encourages students to widen knowledge built upon work and research by our predecessors. Such education has been effective in producing design improvement for higher efficiency and performance, however, not so in coming up with innovative ideas. Building products from within common knowledge cannot surpass the consumer expectation. We earlier reported about our collaboration between mechanical and industrial engineering educators in finding similarities and differences in the designers' approaches in the two fields. Industrial designers, like mechanical designers, strive to meet the voice of customer (VOC) by dividing and conquering functional requirements. They also, unlike mechanical engineers, place the starting point of new designs outside the knowledge domain in efforts to define products that surpass consumer expectations. We call the starting point a discomforting seed. This paper reports our experience in educating foreign and native graduate students in mechanical engineering to have them recognize the discomforting seeds.

1. INTRODUCTION

Mechanical engineers typically have performed well in their math and science classes during their adolescence. Their school years are their starting point for building such knowledge like Newton's laws of physics, geometry, linear algebra and so on, to construct the base of their career. Once awarded with BSME, MSME, or similar degrees of alike, a mechanical designer has acquired skills in selecting an adequate diameter of bolts to hold down a cover of a pressurized vessel, finding the weakest spot of a mechanical structure, or perhaps suggesting alternate configuration or material of a structural element to improve the overall cost of ownership.

If we, however, turn our attention to the markets of automobiles or consumer products, we find that big hits are not defined by performance, reliability, or cost that mechanical engineers are concerned about, but rather aesthetics, brand images, or catchy tag words the industrial designers define [1].

Engineering researchers in the field of mechanical design have started to look into the upstream area of conceptual design, e.g., Lu and Liu pointed out subjective and abstract decisions made in the early stage of design [2], Wang and Tseng derived customer requirements from purchasing intention they have [3], and Christophe et als. defined structured knowledge for conceptual design [4].

In 2011, Nakao invited Satoshi Nakagawa to serve as a faculty member at the University of Tokyo in the Mechanical Engineering department. Nakagawa heads a universal and industrial design firm, tripod design. The collaborative work at the university led to findings that industrial designers, just like mechanical designers [5], strive to satisfy voice of customer (VOC) by identifying functional requirement (FR), determining design parameters (DP), and then isolating the FR-DP relations to remove design interference. The strategy has striking similarities with Suh's axiomatic design [6].

A difference between the two engineering schools lied in what motivates a designer to initiate a new design [1]. This paper elaborates on this difference, explains it with functional and structural tree diagrams, and discusses how mechanical engineers in the design field can learn from the field of industrial design. Starting from a new design motivation may lead to inventing new designs for the market or even creating a new market. We also report the results of our experiment in teaching the functional-structural approach to an international class of foreign (non-Japanese) and native (Japanese) graduate students at the University of Tokyo.

2. FUNCTIONAL-STRUCTURAL TREE DIAGRAM

Stanford University reported functional-structural diagrams (F-S Diagram) to semi-graphically express functional and structural analyses [7,8]. Given a FR or a problem to solve, the Stanford method starts from brain-storming that jots down seeds of ideas or concepts on pieces of paper, then collects the phrases into groups of higher concepts. The process then places the phrases into a value graph with the solution in the middle, alternate ideas above together with the ultimate question of "why," i.e., the overall FR of why the product exists in the first place. Below the solution in the middle is a structured hierarchy of how the product is broken down into VOC, engineering metrics to realize the VOC, and structural parts at the bottom to accomplish the engineering metrics.

Once the Value Graph is complete, then one can easily construct the F-S Diagram from the structured lower half of the Value Graph. The only elements missing are subassemblies that group the structural parts.

Hatamura and Nakao, independently from Stanford, developed "expansion of thoughts diagram [9,10]" that serves the same purpose. The method starts similarly with the Stanford Method by starting with "seeds of ideas" written or sketched on paper, with arcs drawn between them as soon as one recognizes a relation. The Tokyo Method then projects a collection of those mini-graphs onto a single diagram to construct the Expansion of Thoughts Diagram.

F-S analysis is much easier to understand with existing products, so we introduced the class to the concept with a product that the students are familiar with and easy to have their hands on during class, a cellular phone. A cellular phone plays an important role in a student's life and analyzing it has the effect of catching interest of the students. We guided the students by having them list all the parts they can find or imagine hidden. We had them then state the FR, i.e., to state the "why" for each part. Interestingly, many students forgot to mention the "case," one of the most important parts of the product. It tells how easy it is to lose the big picture once we are in an analysis mode. Figure 1 shows the F-S diagram of a cellular phone.

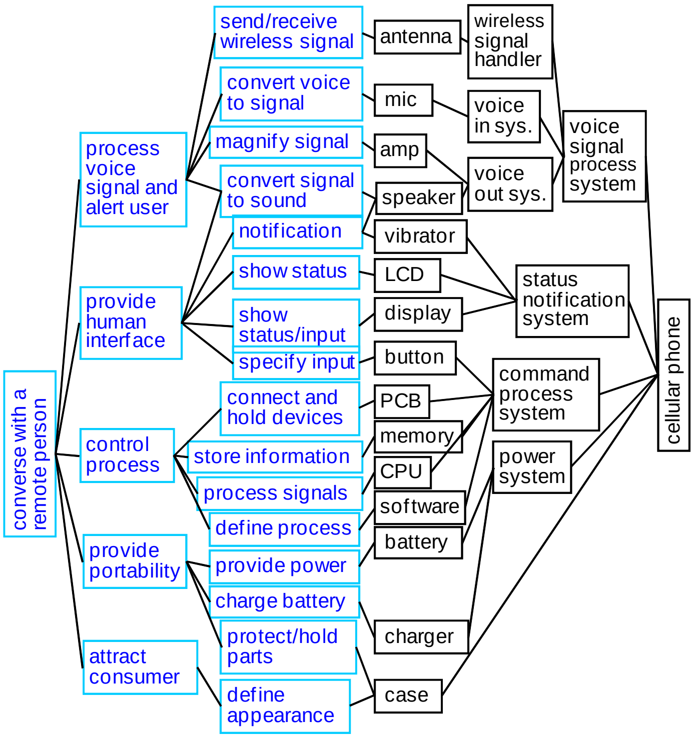

Fig. 1 F-S Diagram of a cellular phone

The second task we gave was to construct the F-S Diagram for a simple tool, a utility knife. We had the students work in groups of 4 to 5. This grouping turned out effective in encouraging otherwise quiet Japanese students to speak out. Section 6 reports more on this effect. A typical utility knife has seven parts. Figure 2 shows one disassembled. The complexity of the tool is ideal for a beginner in F-S analysis. Figure 3 shows the F-S diagram.

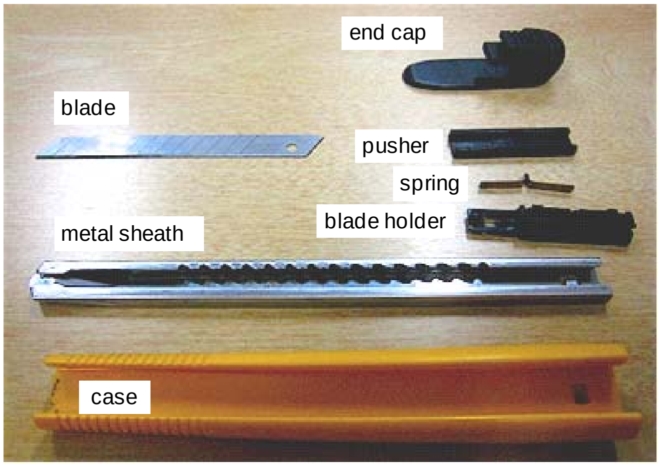

Fig. 2 Utility knife taken apart

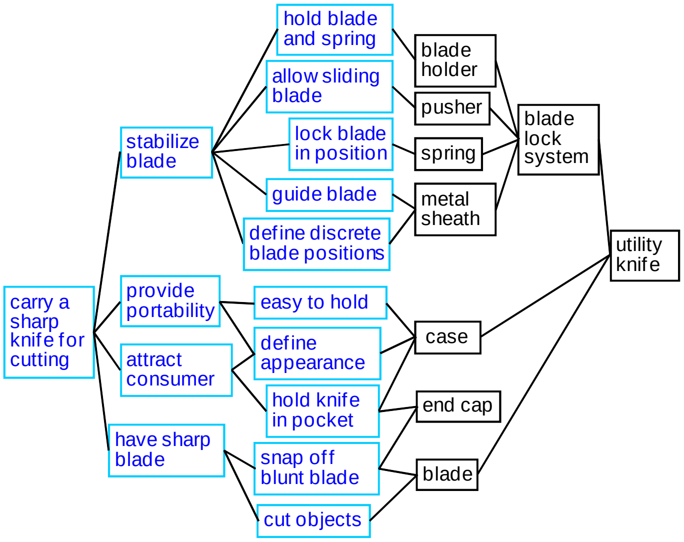

Fig. 3 F-S Diagram of the utility knife

Once we familiarized the students with F-S analysis, we took them to the next level by having them analyze a more complex product, the Air Swimmer. Air Swimmer was invented by William Mark Cooperation now based in California, US. It is basically a fish balloon filled with helium gas for buoyancy and two remotely controlled motors; one to wag its tail fin for forward propulsion and lateral turns, and the other to move a weight back and forth for controlling the overall pitch.

In addition to analyzing the structure and stating the FR of each part, we were interested if the students could find the right idea that states the overall FR. Most students stated "remotely control a fish-like object so it swims in air." We, however, were rather looking for the function of surprising people or having fun. Only 8 out of the 19 students had the word toy, fun, excite, or entertain in the overall FR. Figure 4 shows the this innovative new toy, the Air Swimmer, swimming in midair during a class session and Figure 5 its F-S diagram.

Fig. 4 Air Swimmer

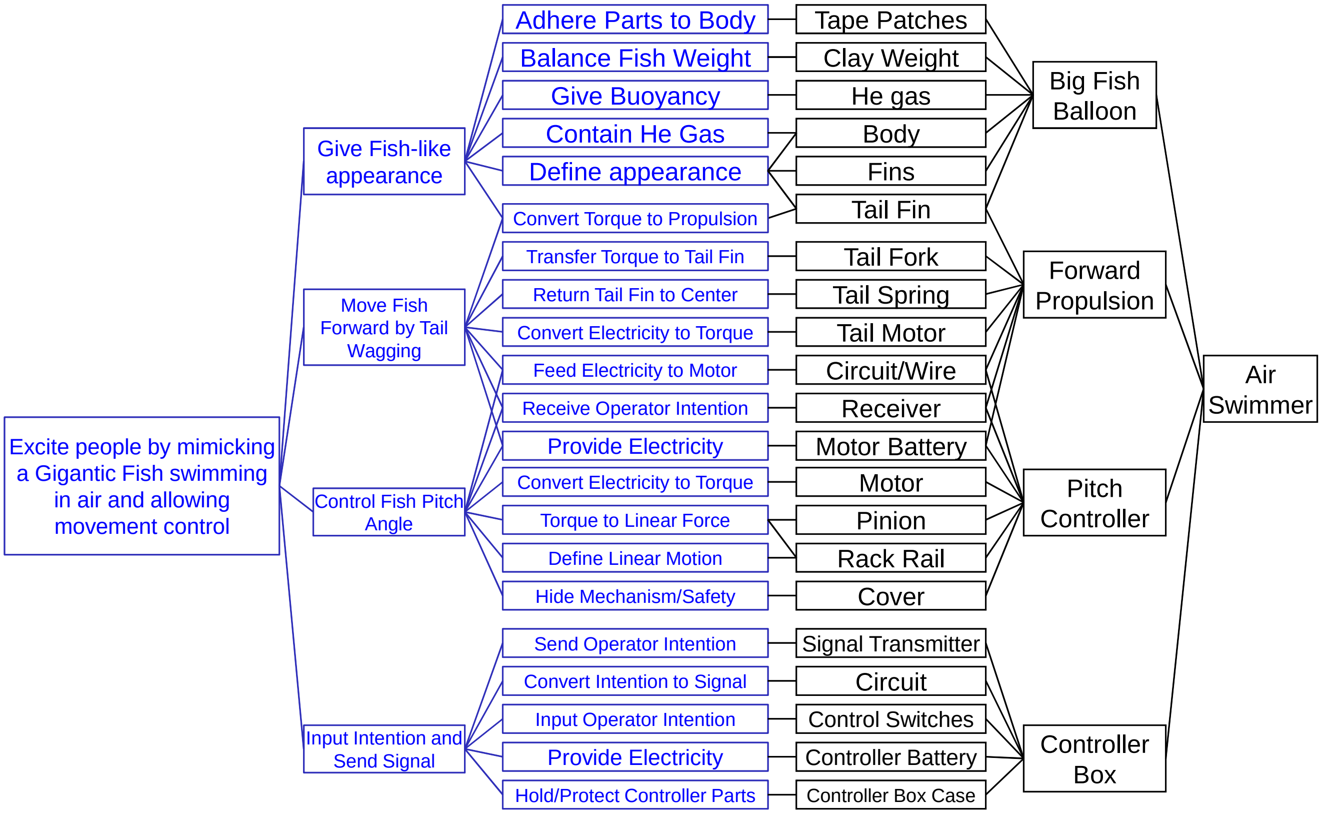

Fig. 5 F-S Diagram of Air Swimmer

3. PRODUCT APPEARANCE

Notice in both Figures 1 and 3, we noted "attract consumer" as main sub-functions of the products. With the rapid advancement of technology and INTERNET playing an important role in spreading information, products in the market hardly have any difference in performances like speed, accuracy, robustness, or reliability. In addition, expected life of a product is getting shorter each year with prices dropping and faster development of new models. In fact, once a product fails, it is often less expensive to purchase a new model than to pay for the labor of repairing the broken machine.

Take for example a cellular phone. Although its market is slowly invaded by smartphones, there are hundreds of models to choose from in the Japanese market (Figure 6).

Fig. 6 Storefront of a cellular phone shop

When a consumer chooses a model for purchase, he picks one up that attracts his taste, flips or slides it open, plays with the buttons, makes sure that key functions that he wants are present with the model, check out the illumination upon receiving a call, and then decides to make the purchase.

The consumer, unlike old days when we were so concerned about reliability, speed, and many other engineering metrics, seems only to be concerned about the looks and ease of use. They are such attributes that are difficult to quantify and hard to teach to students in mechanical engineering.

The above trend of people basing their choice on looks projects the future. It is a scary future for mechanical engineers that if we continue to teach conventional manufacturing engineering, products that serious mechanical engineers design will go out of style. A good example that shows the threat is Apple's new iPad. The smooth look around the edges of the backside, shown in Figure 7, comes from continuous curvature the surface has. The matt finish of the surface does not allow us to see it but if it was shiny and reflective, we would see reflections of straight edges being tangentially continuous in the reflection [11]. If the surface was only tangentially continuous, like with a flat plane to a cylindrical surface, the reflection of a straight line will have a sharp bend right at the edge. A production engineer in this case will argue that the continuous curvature design will result in added cost due to the difficulty in defining tool paths that generate a curvature continuous surface.

Fig. 7 iPad has continuous curvature on its edge

A similar argument holds for MacBook Air with screws on the back plate opened so their flat heads are flush with the curved surface. Again, a production engineer will argue the added cost in having to open threaded holes at different angles instead of approaching all the threads from one direction. Such a conventionally cost-saving approach will leave the product with small wedge-shaped cavities above all the screw heads.

Although mechanical engineering courses do not teach art and how to produce shapes and colors that capture the mind of the consumer, we must recognize the importance of product appearance for making better sales in the market.

4. IMPROVEMENT OR INNOVATION

The Japanese industry grew to the second place in GDP, now third after China, with continuous efforts in improving products and manufacturing methods. If we look at modern day products, we can find plenty of Japanese products being the best of their kinds, however, most of these products are improvements from originals invented overseas.

This section explains how improving a product relates to the F-S Diagram and what it takes to go over the hurdle to the next step of innovation. The following discussion is hypothetical that without knowing what the designer went through in inventing Air Swimmer, we just illustrate how improvement, innovative ideas, and inventions come about.

First we will discuss improvement. Imagine that the “Tail fork” mechanism in Figure 5 was not present. Assume the designer wants to use an easy form of energy for propulsion, that is torque from an electrical motor. To generate a wagging motion, the designer has to convert torque into a near linear motion. What would naturally come to a mechanical engineer’s mind is a linkage design or a gear assembly. Such sturdy but traditional designs are heavy and pose severe penalty in keeping the fish as light as possible so it can float with small volume of helium. The FR is to “convert rotary motion to near linear motion.”

The designer then realizes that the joints do not have to be tight, and that as long as force is transferred and the joints do not fall apart, a linkage can slide relative to another. The bottom diagram in Figure 8 shows the solution employed with Air Swimmer. This case is an improvement where the FR remains the same and the solution performs better.

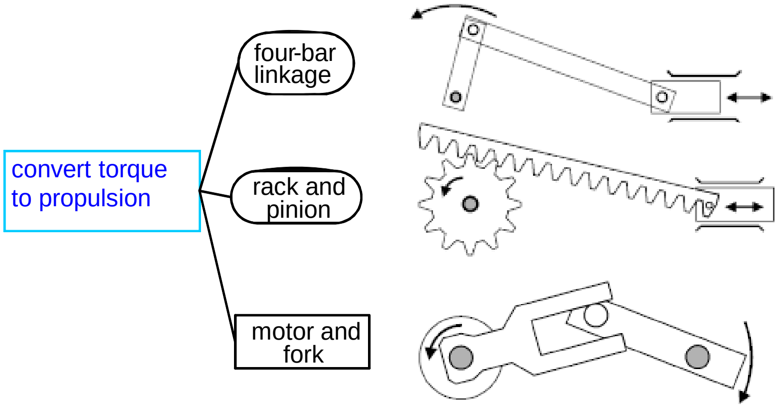

Fig. 8 Improving mechanism for near linear motion

A poor practice here is to state the FR with a solution the designer has nearsightedly locked his mind on, e.g., “Use linkage to generate near linear motion from rotation.” The FR has to be stated in a way that does not restrict the solution.

Starting from a set FR can lead to improvement as we saw above. At the same time, however, as long as the FR is set, solutions will not venture out from the world that the requirement describes.

For the designer to come up with innovative ideas, he will have to look at FR’s at higher level. The F-S diagram in Figure 5 has 4 high level FR’s, namely appearance, propulsion, pitch, and control. Let’s take the propulsion requirement of “Move fish forward by tail wagging” and assume it was not set at a certain instance of the design. The designer has to give the floating fish some force to move it forward and make turns. A way that instantly comes to the mind of most mechanical designers is to use two screws like with a boat, or a single screw with a rudder for direction control.

If it was adopted for the Air Swimmer, conventional ways of pushing and turning the fish with 1 or 2 screws would not have made the product so appealing. It would have been more like a fish-shaped submarine moving through air.

The tail wagging method is elegant with less weight and of course, adds outrageous fun to the looks of the toy.

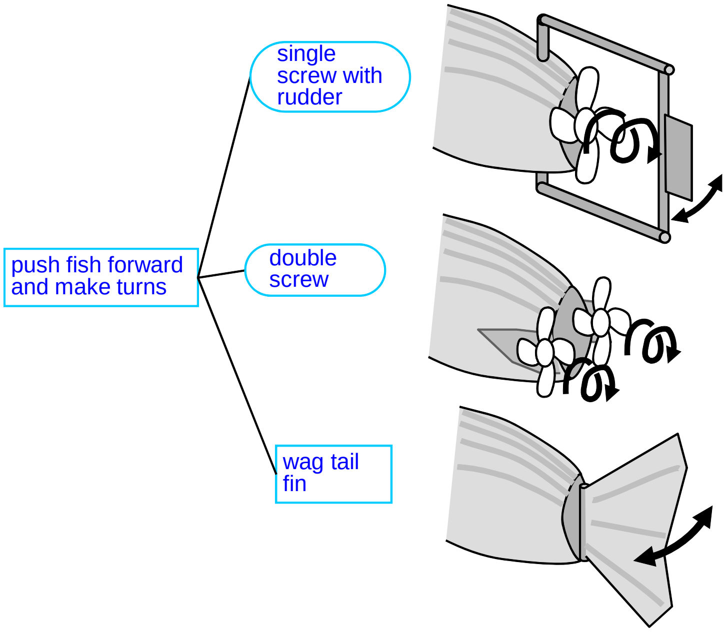

Fig. 9 Improving FR for propulsion and turn

Note that the sub-nodes in Figure 9 are colored blue. They are still FRs at low level that the designer has to decide how to realize with what structures.

Once we reach this level, we find that we are striving to come up with an innovative idea, i.e., to make something happen with a way that others did not think about before. Tackling nodes at higher level in the FR hierarchy can lead to innovative ideas.

So far, however, the overall FR has not changed. Every industrial product has, whether stated well or not, a fixed overall FR. Looking at Air Swimmer, we recognize that it is a totally new innovation with an overall FR that never existed before. What it did in terms of an F-S Diagram is that it defined a totally new overall FR.

Given an overall FR, sensing the discomforting seed is the first step in coming up with an innovative idea [1]. An innovative idea may redraw the entire F-S Diagram with just the leftmost first node being the same. In contrast, recognizing a discomforting seed with life in a way never acknowledged before can lead to a real innovation. Such an innovation defines a totally new overall FR and a new F-S diagram expanded to its right. An existing F-S Diagram cannot lead to total innovation.

5. IDENTIFYING THE RIGHT FR AND INNOVATION

For the class, we aimed at arming the students with skills for running F-S analysis and improving existing designs or better yet devising design innovations. The final assignment we gave was a free-topic project for final presentation where each student will find an innovation and present a solution to the class. Among the 19 projects proposed, 12 either put together a number of functions into a single product, or just reworked an existing one, perhaps a result of incomplete market research. 4 proposals were innovative ideas, i.e., new ways to realize FR's that existed before. They were:

- A new way to scrape white meat of a coconut
- A new way of waking up a person at a preset time

- Allowing pulling an AC socket out
- Digitizing and retrieving handwriting into the computer

3 students identified overall FR's that did not exist before. Here are the brave projects.

- A way to push a soap pump without letting the soap out
  (to retract the pump without letting the soap out)
- Making use of cold water when waiting for the shower to get warm
- A mattress that warms the feet area quickly in the winter without external heat source nor power

Figure 10 shows how the students performed in terms of stating the right FR of excitement in the Air Swimmer F-S Diagram and presenting innovation or innovative ideas for the projects. 5 out of the 7 students (71%) with innovation or innovative ideas had reported the right overall FR of excitement in the Air Swimmer F-S Diagram. Another look at the results shows that 63% (5 out of 8) of the students that mentioned excitement in the Air Swimmer F-S Diagram came up with innovation or innovative ideas. So, without any formal proof, we report that students who gained good skills in identifying the right FR came up with innovative ideas or innovations given free project assignments.

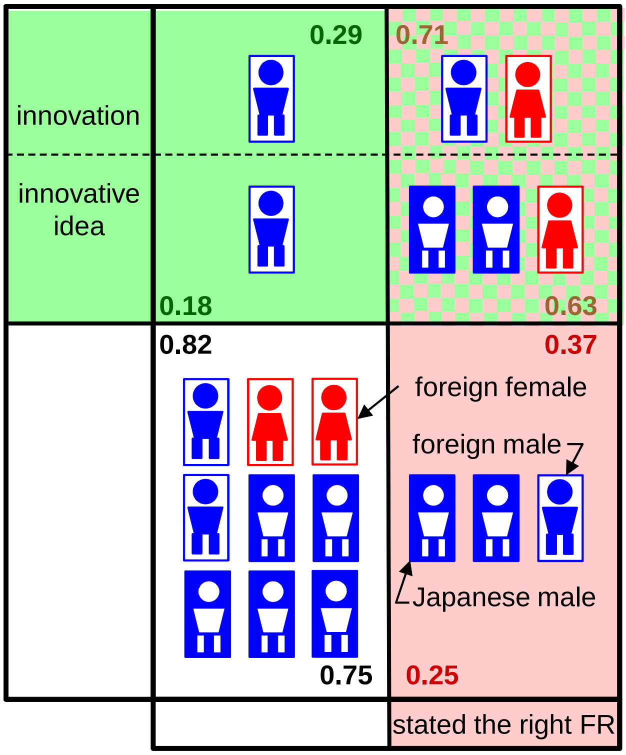

Fig. 10 Correlation of students with innovation and the right FR identification

This fact encourages students as well as designers in the field. How to build one's innovative skills has been asked many times but without clear guidance in where to begin. We claim that practice in identifying the right FR is a good starting point in gaining skills for innovation.

Also, of the 7 innovative students, 2 were female and 3 were Japanese. Again, without formal proof, we state that at least in our class, nationality or gender did not show significant difference in terms of the ratio of students that gained the first steps in innovation.

6. IDENTIFYING THE RIGHT FR AND INNOVATION

The class "Practice of Machine Design" met every Friday from 13:00 to 14:30 and was offered to graduate students in the Mechanical Engineering Department at The University of Tokyo. The class had 8 Japanese students and 11 foreign. Table 1 shows the breakdown of the class members.

Table 1 Members of the class

Country	Male	Female	Total
Japan	8		8
China	2	3	5
Thailand	2		2
Indonesia	1		1
Korea	1		1
Sri Lanka		1	1
Switzerland	1		1
Total	15	4	19

We also had another purpose for the class; to offer an English class to foreign students and at the same time, improve English skills with Japanese students. Fukui reports that Japan has the worst level of skills in English [12]. The fact is now catching serious attention by Japanese teachers but there is a lack of educators with high enough English skills to offer classes in English.

When we had the students work in groups, we carefully formed the groups so there was no group of Japanese only. With the relatively large number of Chinese students, we took the same measure against them.

Foreign students were generally outspoken. It is probably a personality that pushed them to study overseas in the first place. Japanese students, perhaps from the culture that value "silence is golden" at the beginning were very quiet. The above grouping, however, worked well and many of the Japanese students started to speak out and some would even raise their hands to state their opinions.

7. CONCLUSIONS

- Conventional engineering education teaches ways to improve an existing solution or to invent different ways of meeting fixed FR's at low levels. They are alternate DP's.
- Questioning FR's at higher levels leads to innovative ideas
- A totally new innovation is one that defines an overall FR that nobody imagined before
- Students with keen eyes in defining FR's tend to challenge innovations
- Nationality or gender did not make significant difference in terms of the ratio of innovative people
- Having students work in groups of mixed culture is effective in raising the outspokenness of all members

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REFERENCES

[1] M.Nakao, S.Nakagawa, K.Iino, Designs that surpass imagination are born from discomfort outside the knowledge domain, 2012 Annals of CIRP.

[2] S.Lu, A.Liu, Subjectivity and objectivity in design decisions, 2011 Annals of CIRP, 60(1):160-164.

[3] Y.Wang and M.Tseng, Integrating comprehensive customer requirements into product design, 2011 Annals of CIRP, 60(1):175-178.

[4] F.Christophe, A.Bernard, E.Coatanea, RFBS: A model for knowledge representation of conceptual design, 2011 Annals of CIRP, 59(1):155-158.

[5] K.M.Donaldson, K.Ishii, S.D.Sheppard, Customer Value Chain Analysis, 2006, Research in Engineering Design 16: 174–183 DOI 10.1007/s00163-006-0012-8

[6] N.P.Suh, Axiomatic Design: Advances and Applications, 2001, Oxford University Press, New York.

[7] P.Leung, K.Ishii, J.Benson, Modularization of work tasks for global engineering, 2005, Proceedings of IMECE2005, ASME, IMECE2005-82137

[8] K.Ishii and K.Iino, Value Creating Design (in Japanese), 2008, Yokendo, Tokyo, Japan

[9] Y.Hatamura, Decision-Making in Engineering Design, 2006, Springer-Verlag, London, originally published in Japanese, Koshite Kimeta, 2002, The Nikkan Kogyo Shimbun, Tokyo Japan.

[10] M.Nakao, Study of Creative Design (in Japanese), 2003, Maruzen, Tokyo, Japan

[11] G.Farin, Curves and Surfaces for CAGD, Academic Press, San Diego, US

[12] K.Fukui, Aiming at escape from the world's worst English level, a presentation made April 6, 2012, at The University of Tokyo, ME Department, ME Seminar