Inquiry-Based Student Learning

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Abstract

In the traditional engineering curriculum, students are presented with and tested on factual knowledge. Very little emphasis is placed on their thought process, which is more important as it can lead to inventions and innovations. This attitude is reflected in the common answer "I don't know" from the students who do not spend any effort or time to think. The engineering programs at St. Louis and Fairfield Universities have the common objective: *Enable the development of conceptual engineering reasoning abilities*. In other words, our goal is plant the seeds of reasoning that develop the student's intellectual independence.

We adopted a teaching model, which involves developing an appreciation for the design process and the functionality. Students developed thinking skills though cognitive inquiry based on "Identify an interesting configuration – Understand the core concept/functionality – Observe similar configurations." After this exercise, students understand the concept, identify new situations and apply the concept. The students can then observe new everyday things in their environment and create a library of possible innovative ideas. The paper describes a teaching model with several illustrative examples. The examples cover a wide range of topics from engineering concepts to design. Also, included are case studies with our students dealing with cognitive inquiry of objects based on concepts and functionality.

1. Introduction

As more and more pressures are brought to bear on the engineering programs to stay within a 'four-year' undergraduate degree program, more interest has been given to the student's ability to learn the fundamental engineering concepts. The question of student learning has surfaced in the pre-college education for science many years ago, as described in the text, 'Learning How to Learn' (1). Rutherford and Ahlgren (2) in their excellent book 'Science for All Americans," broach the subject of learning. A fundamental premise of their book is that "the schools do not need to be asked to teach more and more content but rather focus on what is essential to scientific literacy…" They also found that even academically talented students had a limited or distorted understanding of the scientific concepts indicating that the teaching model was flawed. They also found that teaching that attempted to solely impart to students the accumulated knowledge of a field leads to very little understanding and will not lead to the development of intellectual independence.

Through the efforts of our students, we have determined that a method of conceptual inquiry is an effective teaching model for engineering students. Within a 'four-year' undergraduate degree program, students cannot possibly learn the content of the field but must be given the essential concepts and understand how to apply the concepts. In addition, students must be given a variety of contexts in order to express their conceptual understanding. Inquiry of tangible objects, related to the conceptual functionality, is the premise of our investigation and subsequent teaching model.

2. Theory of Inquiry

2.1. The Basic Model

The cognitive thought process is the progressive iteration between two spaces of knowledge (refer Fig. 1). The output of a design process is generally a physical object or group of objects, which are termed as *configurations.* In this model, the outputs at different stages as the process unfolds can be thought of as elements in *configuration space.* The model must be balanced by another space, called *concept space,* which contains the ideas or concepts that provide the basis for the elements of configuration space. The design process can be viewed as an iterative process of moving from configuration space to concept space, making changes or movements within concept space, and then moving back to new points within configuration space corresponding to further creative generation of configurations based on these new ideas.

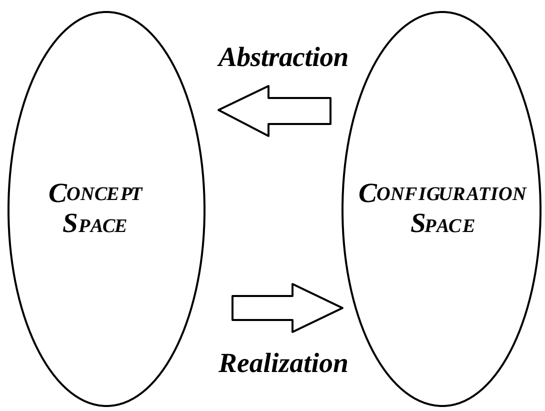

Fig.1. Concept-Configuration Space Model (3).

The process of moving from configuration space to concept space can be thought of as *abstraction.* It is a generalization process by which the real need is distilled or fundamental governing concept is discovered. Movement from concept space to configuration space can be thought of as *realization* or *particularization*—bringing to reality, in particular physical form.

2.2. Abstraction

Abstraction is essential in open-ended problem formulation because it requires the suppression of non-essential, and typically highly detailed information, thereby permitting only the most fundamental information to be considered (4). This conceptual understanding is the key to change or improve the existing configuration. A common problem among engineering graduates is their inclination to remain in the configuration space, as it requires less cognitive effort. In other words, they identify the required end product rather than emphasize the need or concepts. The established goals such as “design a shaft,” “design an encoder” or “design a ship canal.” These statements quickly evoke existing configurations in our minds. Our natural inclination is to take these general configurations and make them more concrete. However, recalling existing configurations tends to fixate the designer onto similar and common solutions and prevent the conception of highly innovative and effective products.

To suppress the tendency of being configuration- or object-oriented, the designer must always begin by abstracting from the configuration to define the real need - the benefit sought by the customer, or core concept – the science or technology behind the product. The need for a shaft, for example, can be defined as “transmitting torque.” Or the fundamental concept behind shaft design can be “provide required torsional rigidity while allowing for required safety factor.” Leading businesses also follow a similar abstraction in defining their core business in terms of customer needs. Kodak, for instance, defines its core business as “imaging,” which includes digital photography. Such definition facilitates the discovery of new potential markets. Similarly, abstraction allows the creation of innovative products.

Any design can be viewed as a system that interacts with its environment by the means of inputs and outputs. Thus, at a conceptual level, the functionality can be defined by identifying the input-output relationship. The inputs and outputs can be classified into five categories, namely energy, material, information, generalized forces (includes moments) and generalized displacements (includes rotations). The later two categories are included to easily understand some of the mechanical engineering tasks. The routes, through which the inputs are processed by the design to create the outputs, are called *transmission paths that includes the processes of transfer, transmit, and transform.* Thus, tracing the transmission paths is a crucial step in identifying functionality.

2.3. Abstraction – Example

Let us examine a task statement, that of “design a ship canal to connect two bodies of water.” The first thought that comes to mind is digging a simple “moat,” which is a possible solution when the water level of the two seas is the same. An example is the Suez Canal, which connects the Mediterranean with the Gulf of Suez at the head of the Red Sea. Because it is a sea-level canal, the elevation of a ship does not change during its journey. The Suez Canal remains the world’s longest canal and can still be widened or deepened relatively easily to accommodate bigger ships.

After building the Suez Canal, the French tried to build the Panama Canal to connect the Caribbean Sea with the Pacific Ocean. Their attempt to dig a sea-level canal lasted for nine years, but ended in failure. This led the Americans to build the Panama Canal with locks that raise and lower the waterway by about 85 ft. When a ship enters a lock in the canal, the gates are closed behind it, the water level raised or lowered, thereby changing the elevation of the ship. Then the next set of locks ahead of the ship opens to allow the ship to proceed. This way, the locks eliminate the need for maintaining constant water level in the canal. Thus, a better definition of the original design task might have been "to connect the two bodies of water." Note that the last statement is less configurational (no "canal") and more functional ("connect").

If we investigate the need further—by asking, "do we really want to connect the two bodies of water?"—then the answer reveals that the real need is "to transport ships across a landmass in a cost- and time-effective manner." The designers at Ronquiéres in Belgium utilized this insight in constructing a system for transporting ships across a 1-mile stretch of land with a 220-ft rise between Brussels and Charleroi. The gradient for this system is much larger than the Panama Canal's, which elevates ships by 85 ft over about 2 miles. Due to the steep gradient, it was difficult to implement a canal system that uses locks to raise the waterway. The designers conceived a novel system that uses 300×40-ft water-filled railroad cars to transport ships up and down the five-degree slope. Had the designers followed the natural instinct of designing a ship canal that connects two bodies of water *with water,* they would have ignored innovative solutions such as the "canal on wheels." Therefore, it is necessary to understand the need in functional terms before moving to configuration space.

2.4. Realization

The elements of configuration space are the representations of physical objects motivated by the conceptual elements of concept space, which bring some real form to the thoughts created in concept space. A concept can be realized in terms of several configurations. The student is faced with the challenge of considering several configurations in a systematic manner. The morphological matrix methodology aids in documenting the process. It started some fifty years ago (5) and it is still popular today as an important step in the engineering design process (6,7). The morphological matrix represents a methodology for organizing alternative configuration for each concept/function/sub-need of a system and combining them to generate a great number of configurational variants each of which can potentially satisfy the system-level need.

The basic format for a morphological matrix is a grid of columns and rows. The first column lists the relevant functions/concepts/sub-needs and the row adjacent to each function lists the possible configurations that will achieve the function. In developing the matrix, the students can use both sketches and text to represent the configurations. Once the matrix is established, the student must combine the individual solutions into effective conceptual designs. The morphological matrix methodology is an excellent way to record information about the solutions for the relevant functions and aid in the cognitive process of generating the system-level design solution. This methodology is not a replacement for creative thinking but a structured means for developing as well as documenting, design alternatives. It allows the student to consciously explore design alternatives without confining them to the human short-term memory limitations.

2.5. Realization – Example

In the case study, the task is to design an "Air Vest" which protects a rider of an open-air vehicle in case of an accident. The vehicles under consideration are motorcycles, bicycles, ATV, snowmobiles and go-carts (8). The primary transmission paths are the mechanism through which the impact force is attenuated, the force attenuation agent (air or foam) is transmitted, information about impact is identified and processed, and information about road conditions is provided to the rider. Tracing these transmission paths resulted in the following functions: Attenuate impact force, store, release, transmit and contain the attenuation agent, detect accident, provide activation signal and provide visibility. The configurations for each of the function in the Air Vest example are summarized in Table 1.

Functions	**Solution Alternatives**		
	Solution #1	**Solution #2**	**Solution #3**
Attenuate the impact force	Gas	Liquid	Solid
Store attenuation agent	Compressed state	Individual chemical elements state	
Transmit attenuation agent	In-chamber (no transmission required)	Piping	
Contain attenuation agent	Single chamber	Multiple chamber	
Detect accident	Accelerometer + Electronics	Snap-off tether	
Provide activation signal	Mechanical signal	Electrical signal	Chemical signal
Provide visibility	Rigid window	Flexible window	

Table 1. Air Vest - Morphological Matrix (9).

3. Nurturing Inquiry

Based on our understanding of the concept/configuration model, we adopted a teaching model based on inquiry. These exercise are focused on improving the students' understanding of the two space inquiry model and establishing thinking pattern in terms of iterative movement from the two spaces.

3.1 Understand the importance of the consciously following the inquiry-based model

First Year students design certain devices based on needs that are purposely left open-ended. Typical examples include "Design a device to make a hole 2.5cm in diameter by 35cm deep in concrete” and “Design a toy for blind children.” These exercises show that it is difficult to detach from the experience base. For instance, most students design a device to drilling the hole with a conventional drill bit. Alternatives such as drilling with pneumatic or hydraulic energy, or laser are not considered. Students realize the need for considering alternatives after careful abstraction.

3.2 Understanding the importance of functionality:

Prior to the introduction to the design process, the students describe some objects for function. Typical items included a plastic gear from a toy car, sheet-metal key for setting a door lock, protective eyewear needed after an eye examination and a tilt-leg from a computer keyboard. Student responses show minimal insight to good conceptual understanding depending on their experience level.

The students realize very quickly that the configuration does not give much information unless from experience the functionality is known. This form of cognitive realization is an important first step for the students to understand the significance of the functionality of design. For example: Plastic Gear from a toy car- the students easily identified the ‘object’ as a gear. This object was one the few that actually was described using engineering terminology. However they could not give its functionality because they did not know how it was used. These ‘object’ lessons have a lasting impact on the students’ understanding of the importance of conceptual functionality.

3.3 Concept/Configuration Observation

The students start the process with observing a certain technical details or new design (typically configuration space). A set of sample questions are used to prime their inquisitiveness and initiate the process:

1. Why does an aluminum foil have a shinny side and a dull side?
2. Draw the external shape of 5.25” and 3.5” floppy disks. What are the fundamental differences in their geometry?
3. What is the purpose of counter-weight on elevators and bridges?
4. A caster for a chair is shown in Figure 3. What happens if the offset is not present?

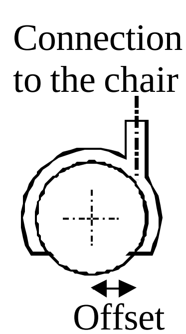

Fig. 3. Caster connection to the chair

Answering these questions results in a deeper understanding of a few key concepts and the functionality behind the design details. Note that they moved from the configuration space to the concept space during this activity. Thus, it reinforces the link between concept and configuration spaces. For instance, while answering the first question, the students may discover that the difference in surface finish is the key for an effective heat transfer design. For heating food, the shiny side should be placed towards the food, so it reflects radiant heat back to the food while the dull side absorbs the external heat. This configuration thus creates a bias in the radiation heat transfer.

After this understanding, students are encouraged them to identify new configurations that use the same concept. The same concept has been used in the design of chocolate wrappers and car sunshades, where the glossy outside radiates heat away to keep the chocolate or the car's interior cool.

This concept of bias in the radiation heat transfer can be used in synthesis of new designs. For instance, the students can understand that the design of space suits poses an interesting challenge. Without an appropriate space suit, an astronaut's body heats up due to solar radiation when facing the sun and loses heat when in the shade. The temperature fluctuations could reach ±400°F. In this particular application, the critical parameter is "block the solar radiant heat from entering the space suit while reflecting the body heat back." In other words, the design must integrate the features of chocolate wrappers to keep the external heat away with the features of cooking foil to retain internal heat. NASA uses a multi-layered double-shiny foil to achieve this task. The same principle is used for thermal shielding of spacecraft components and in building insulation.

4. Conclusions

The Inquiry-Based model presented in this paper has been a successful method for developing the cognitive thought process. Building on a design methodology, the model helps students develop intellectual independence by an iterative process between two spaces of knowledge: concept space and configuration space. The study has found that engineering students have a natural curiosity for tangible objects. The model proposed builds on the natural inquisitiveness of students to develop an appropriate understanding of engineering concepts through object-oriented functionality. Consequently, the critical thinking skills of the student evolve from a monistic level to a multiplistic level.

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