An Engineering Imagination Training Paradigm based on Conceptual Combination Theory

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INTRODUCTION

The purpose of this study is to propose a conceptual combination training paradigm for enhancing engineering imagination. Engineers must possess an ability to design a system, component, or process to meet desired needs [1]. Engineering design can be defined as a search for a satisfying solution to a problem that is facilitated through a conversion of customer requirements to design description [2]. This search is necessarily based on various information processing activities. Most new product and process designs are variants of previous designs. Understanding the retrieval, transfer, storage, and flow of information in human cognitive system during the design process is important for developing methods and tools to facilitate engineers' generation of new and satisfactory solutions to a problem. In this study, conceptual combination is proposed to be the cognitive mechanism that brings about imaginative and innovative design solutions. Based on this premise, an imagination training paradigm is proposed and guidelines and procedures for imagination training are outlined for facilitating engineering creativity.

1. CONCEPTUAL COMBINATION AND ENGINEERING CREATIVITY

Original design ideas for an engineering problem invariably springs from an individual's head. In the present study, conceptual combination is proposed to be the underlying cognitive process that generates the new ideas in human brain. Conceptual combination referred to joining of two or more than two concepts to generate a new idea. It is believed to be the most wonderful merit of the human mind [3]. At neurological level, conceptual combination is made possible because a neuron in human brains can be linked to many other neurons unconsciously or deliberately [4], and the meaning of an object or event is determined by its activation pattern of neurons [5].

In engineering, many innovative ideas were indeed conceived and created through conceptual combination. For example, the Blackberry was first conceived by joining of two concepts: cell phone with email [4]; mirrors were added to elevators as a means to distract people' attention on the slowness of elevators [6].

1.1 Distinction between imagination and creativity

One of the most important tasks for engineers is to solve problems creatively. Thus, creativity is a criterion for evaluating all engineering solutions. However, creativity springs from imagination. In the

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present study, the distinction between imagination and creativity will be highlighted so that conditions that enhance engineering imagination can be better understood. Creativity is defined as the process that a socially valuable new product was produced, whereas imagination is defined as the process that a new ideas emerged in the mind. This distinction is important because creation of a novel and appropriate product that is valued by the society is often a very long and complex process. Factors that affect creativity include not only an individual’s personal characteristics such as ability, personality, and motivation, but also social, intellectual, and technological resources to support such endeavour [7]. Simonton [8] thus argues that highly creative achievement is determined by a multiplicative rule composed of many personal, social and environmental factors. Absence of one of required factors would render the creative efforts futile. Imagination, on the other hand, occurs in one’s head.

According to Wallas [9], there are four stages in creative process: First, the preparation stage, during which the individual sensed the problem and searched for the solutions but failed; second, the incubation stage, during which the individual put aside the problem and shifted their attention to some unrelated activities; third, the illumination stage, during which the solution to the problem suddenly appeared to the individual’s mind, and the last stage is the verification stage, during which the individual would carry out all the required tests to see if the idea could work. These four stages require different cognitive engagement and social participation. For example, learning and searching for information are the major cognitive activities in the preparation stage. Implementation of the idea and testing how it accomplishes the goals usually require collaborative works and investment of material and financial supports from society. Among the four stages, only the incubation stage and the illumination stage occur primarily in human brain. The ways the brain works to bring about the illumination is through the act of imagination. Imagination therefore is a kind of mental activity through which new ideas are generated. Conceptual combination is proposed to be the cognitive mechanism that human brain creates new ideas.

In his seminal paper “blind variation, selection and retention”, Campbell [10] argues that random variation is the basic mechanism organisms cope with uncertain environment. For example, mutation is the major mechanism virus adapt to the harmful environmental factors. Humans are blessed with a magnificent brain that can perceived the environment, store their learning and experiences, and retrieve information to help understand and solve problems facing them now and in the future. By manipulating information in the brain, simulating the possible environmental changes, humans, unlike lower organisms, can think and plan their coping responses in advance. The way human brains work to create new knowledge is by random combination of ideas in the brain. Ideas automatically collide to each other randomly and some patterns may emerge unexpectedly and shed light on the puzzled mind. Later, Mednick & Medinick [11] argued that creativity lies in people’s ability to associate two or more than two remote ideas and designed the Remote Associate Test as a creativity measurement instrument. After reviewing extensive empirical evidence from psychological literature, Simonton [12] used the theory of constrained stochastic process to account for scientific creativity. He pointed out that the road to scientific discovery is filled with uncertainty and luck. Logics and systematic thinking provide not much help. They are useful primarily after the discovery to provide proofs and explanations for the validity of the discovery. Based on his analysis, Simonton pointed out two factors that contribute to scientific discovery. The first one is the domain knowledge where each scientist can sample a small portion of it as the target of the study. The second factor is the scientists who evaluate the existing knowledge in the field of their study, and try to find new and useful knowledge via the combination of knowledge shared in their scientific community. In the theory of constrained stochastic process, the random combination of ideas that lead to scientific discovery proceeds in two steps. One is ideation, which refers to the generation of possible ideas; the other is elaboration, which refers to further explanation and refinement of the ideas. Scientists usually work on more than one project at a time. The cross-talk from these diverse projects may produce some novel reformulations and discoveries.

Technological innovation is founded on scientific knowledge. The difference between technological innovation and scientific innovation is, according to Simonton, that technological innovation is less constrained because usually there are numerous possible solutions to a technological problem. Conceptual combination therefore is also proposed to be the basis for engineering imagination. There is empirical evidence that random variation and conceptual combination are crucial for the emergence of original technological solutions. Namely, combining two or more than two seemingly unrelated concepts will increase the chance of finding an original solution to an engineering problem. For example, Zeng et al. [6] found that remote association of concepts from different domain spawned more creative mash-up web service design ideas in the domain of information technology, when compared to intradomain mash-up web service design. The purpose of this study is thus to propose a conceptual combination training paradigm for promoting engineering imagination

1.2 Interpretation: Emergence of new ideas from conceptual combination

When two seemingly unrelated objects or events occur together, an interpretation process would be activated automatically in human cognitive system aiming to find meaning for the co-occurrence of objects or events. Finding a way to connect two terms meaningfully is called relational thinking, a kind of abstract thinking [13]. This interpretation process is the cognitive mechanism that produces new ideas from conceptual combination. It is found that there are three kinds of interpretation people use to associate two unrelated words: 1. conjunctive interpretation, 2. property transfer, 3. relational interpretation [14]. In conjunctive interpretation, new ideas emerge from finding property overlap from concepts to be combined. For example, "vitamin C" is the concept merged from combination of the pair of concepts "*orange–apple*." In property transfer interpretation, new concepts emerge from giving the property of one concept to another concept. For example, combination of two concepts: "*corn–light*" may produce a response: "the corn-shaped desk lamp." In the relational interpretation, a mediating concept is used to link two concepts such that the initially unrelated concepts become related. For example, "*lavender–coffee*" may produce response such as "drinking coffee in a lavender garden." Note that novelty of new concepts emerged from different type of interpretation can be quite different in terms of whether the original concepts was modified, or whether the new concept entails the original concepts and create a broader meaning. Horng & Wang [15] identified another two subtypes of interpretation for conjunctive interpretation and discovered three subtypes of relational interpretation. Other than finding a common property for the two concepts in conceptual combination, the mapping/conjunction between the two concepts can also occur at a more global level, or at structure level. This type of mapping is usually accomplished by analogy. A very unique type of conjunctive interpretation is "negation", the new concept is obtained by a negative interpretation of the common property found between two concepts, for example, "darkness" as a response to the property "brightness" derived from *light-rationality* pair. Horng & Wang also further classified participants responses to relational interpretation into three types of relation: thematic relation, causal relation, and hierarchical relation. The examples for these types of interpretation are given in Table 2.

1.3 Conditions that spur originality in conceptual combination

Not all ideas emerged from blind variation and combination of concepts is original. That is why Campbell [10] had to include a selective retention procedure in his theory of blind variation in knowledge creation process. Previous studies have found several factors that might affect the novelty of interpretative outcome in conceptual combination. For example, ontological category of the concepts may affect what kind of interpretation is more likely. Objects that belong to the natural kind such as "water" all possess defining or characteristic features/properties. In contrast, objects that belong to the artifact kind such as "table" usually do not have defining property. Bock & Clinton [16] indeed found that noun-noun pairs of the natural kind elicited significantly more property related interpretations than noun-noun pairs of the artifact kind, whereas noun-noun pairs of the artifact kind elicited significantly more relational interpretations than noun-noun pairs of the natural kind. Other factors that affect the outcome of conceptual combination include the number of times the interpretation process is repeated, the abstractness of the concepts to be combined, or the types of interpretation. Evidence suggests that the more attempts one made to interpret a noun-noun pair, the more original the emergent new concepts are [17]. Combining concrete nouns with abstract nouns may enhance the originality of emerged new concepts [18, 6]. The more analogy one used in interpretation, the more original the emerged new concepts may be [15].

In practice, a creative product or idea that come to actualization may requires many iterations of conceptual combination and incorporate many different concepts. For example, Wang, Horng & Chen [19] interviewed 21 persons who were R&D professionals, industrial designers, or business owners about how the breakthrough ideas occurred to them. The data showed that the mean number of concepts that were combined to generate the new ideas was 9.90, and the number of types of interpretation they used in conceptual combination was 2.1. Thus, for conceptual combination to produce original outcome, a simple formula is given as follows:

$$\textbf{\textit{Imaginativeness}} = f\,(C_i * C_j * I * O) \qquad (1)$$

According to this formula, idea I (Ci) and idea j (Cj) are two disparate, unrelated concepts, probably come from two very different domains. These two ideas (or more than two ideas) must have a chance to meet in one's head. One or more than one interpretation (I) must be applied to combine these concepts. And O is an individual's decision bias to favor or retain certain types of outcome yielded by conceptual combination. Imaginativeness of an idea emerged from conceptual combination is a product of these four factors within an individual. Based on this simple formulation and Campbell and Simonton's theory, design guidelines for any program that aims to stimulate originality from conceptual combination can be outlined as follows:

1. A random process has to be included to attract disparate and remote concepts to be considered together,
2. The remote concepts are conceived in a relatively abstract level,
3. Different types of interpretation are tried to combine the concepts meaningfully, and
4. The selection criteria that value and retain original ideas for further consideration must be cultivated.

For facilitating engineering imagination, implementation of these guidelines means engineers have to be educated to have broad interests in diverse topics of issue so that they have a rich repertoire of knowledge from different domain. Or, engineers must be open enough to entertain ideas and concepts from other domains and are willing to conceptualize their technological problems from a broader environmental, social and cultural perspective so that a technological problem can be framed in a more abstract way. Practice on different types of interpretation in conceptual combination can be provided to stimulate engineers' imagination and abstract thinking. To facilitate collision of novel concepts in the head, opportunities to collaborate with colleagues can be very helpful. A training paradigm specifically aiming at facilitating random process in conceptual combination is proposed below.

2 DESIGN OF A PRIMING PARADIGM FOR STIMULATING ENGIENERING IMAGINATION

A priming paradigm was proposed to serve as the bed for brooding conceptual combination activities in the brain. It is suggested that prior to any engineering design project, cross-domain conceptual combination tasks can be used to facilitate the random activation of remotely associated ideas in the brain and prime the cross talk of ideas in one's brain..

2.1 Use of priming paradigm to facilitate random process in memory

Priming is an experimental technique used in psychological experiments. According to spreading activation theory of human memory system [5], concepts and traces of experiences are stored in memory like an interconnected network. Memory contents are represented as nodes; and relations between or among concepts are represented as links. When an external stimulus activates the concept in the network, its activation will spread to other nodes through the associated links. When the accumulated activation value of a node in the network reaches the threshold, it will enter the conscious zone of human cognitive system. Those nodes with activation value below threshold cannot be consciously detected by the individual, but it nevertheless exerts influences on the person's information processing. In psychological experiments, below-threshold primes can be presented to the individual before the performance of target task. If the person's performance on the task is facilitated by the prime, it indicates a positive priming effect. If the performance is handicapped by the prime, it is a negative priming effect.

It is suggested that prior to any creative endeavor, priming technique can be designed to facilitated random process in human memory. If priming activity is used as a prelude to the following engineering design task. It is very likely that remotely associated ideas may be activated consciously or subconsciously. At the surface level, the priming task appears unrelated to the following targeted activity. But the brain can be mobilized and information in the memory be stirred up. Specifically, conceptual combination practice is expected to loosen students' or engineers' mind set and make connections with far and unrelated ideas.

2.2 Construction of cross-domain materials for conceptual combination tasks

Depending on the goals of an engineering project, concepts from different domain can be sampled to construct the conceptual combination task. A conceptual combination task must include at least two concepts from two different domains. For example, if the concepts are classified into natural, artefact, or abstract kind, concepts from the same ontological category (natural-natural or artifact-artifact type of concepts, as shown in Table 1) will be avoided. However, there is evidence that inclusion of abstract concepts can facilitate the emergence of original ideas from conceptual combination [15], the abstract-abstract kind of conceptual combination task can be retained as a means to facilitate participants' abstract thinking ability. Conceptual combination tasks that include more than two concepts from different domains are also viable. Tokens that are used in conceptual combination task can be either words, pictures, real objects, or events.

Table 1. Examples of cross-domain noun-noun pairs for conceptual combination tasks

First noun/second noun	Natural	Artifact	Abstract
Natural	---	hair-bucket	cactus-power
Artifact	spoon-Star	---	mirror-lightness
Abstract	group-time	meaning-car	motion-pleasure

2.3 Interpretation training and instruction on the nature of engineering creativity

Instruction, in the form of a short course, will be provided to explicate the nature of engineering creativity, and the role of conceptual combination in engineering imagination. Examples of engineering innovations obtained from conceptual combination will be used to illustrate how combination of concepts can lead to breakthrough in conception of new ideas for a problem. Besides, how to combine seemingly unrelated concepts to produce new ideas will be illustrated by examples (as illustrated in Table 2).

Table 2. Examples of types of interpretation in conceptual combination

Type of interpretation	subtype	New concept	Interpretative process
Apartment-Dog			
Conjunctive Interpretation	common property	vulnerable	Both can be destroyed easily
	analogy	small & messy	His apartment looks like a dog house
	negation	large and tidy	
Property transfer		an apartment that barks	The door bell of the apartment barks when you press it.
Relational Interpretation	thematic relation	apartment dog	Dog living in an apartment
	causal relation	dog friendly apartment	The apartment allows dogs.
	hierarchical relation	human society	Humans build apartment and use watchdog to protect their apartment
Interpretation failure		vicious	A hungry dog is dangerous

Students will be required to practice making different types of interpretation for a given conceptual combination task. An example of conceptual combination worksheet used for training is illustrated in Table 3.

Table 3. An example of conceptual combination training worksheet

Noun-Noun Pairs	Type of Interpretation	New concept	Interpretative process
spoon-star	conjunctive interpretation		
group-time	analogy		
meaning-car	negation		
cactus-power	property transfer		
mirror-lightness	thematic relation		
hand-airplane	causal relation		
balloon-winter	hierarchical relation		

2.4 Training procedure and implementation of the program

A generic form of training procedure includes an instruction on the nature of creativity, imagination and engineering innovation, an introduction on the role of conceptual combination on imagination and various types of interpretation that are conducive to emerged new ideas, and then practice on conceptual combination and interpretation. It is suggested that conceptual combination practice takes place prior to initiation of any engineering project that is aiming for new invention of products or procedures, to allow for an incubation period during which spreading activation is to occur in the brain. To implement the conceptual combination training program in curriculum, various forms of curricular designs can be assembled to meet the specific goal of the task at hand. The recommended necessary elements of program includes: 1. an introduction to the nature of the creative thinking process and the role of conceptual combination in idea incubation and illumination, 2. explanation and examples of different types of interpretation process that brings about new concepts in conceptual combination. 3. practicing conceptual combination and various types of interpretation. 4. sharing and providing feedback on participants' performance in conceptual combination, 4. a period of incubation, and then 5. applying conceptual combination to solve a technological problem. The training can takes place individually or in small group. The training program takes at least 3 hours. It can be extended to various length. After the training, 10- to 20-minute mini-courses can be provided intermittently as additional practice or as warm-up activities before any project.

3 SUMMARY AND ACKNOWLEDGEMENT

Various methods for training engineering creativity have been proposed before. For example, Triz [20,] is a widely used systematic way for engineering innovation. However, most of these methods may be effective only for accumulative type of innovation within an existing technology. For revolutionary breakthrough, ideas from more than one domain must be sampled and joined together to give an old thing a completely new conception [21]. Conceptual combination is a basic cognitive mechanism by which humans can generate new ideas from old, unrelated information. Conceptual combination using materials from diverse domain has been found to be effective for promoting engineering creativity [6]. A conceptual combination training paradigm is proposed in the present study. The program is grounded on theories and evidence obtained from psychological studies on creative thinking processes and conceptual combination. In conceptual combination, new ideas emerged through individuals' interpretative efforts to make sense of novel experiences they might encounter in life. Training designed to facilitate this interpretative efforts is expected to enhance engineering students' ability to do abstract, relational thinking. Conceptual combination tasks that composed of concepts from different domain are recommended to facilitate remote associate. The priming paradigm is used to facilitate random processing of stored information through the mechanism of automatic spreading activation of human cognitive system. The effectiveness of the proposed training program can be tested by experiments. Different versions of the training materials and procedures can be designed to meet different goals of education and engineering projects.

However, conceptual combination that occurs in an individual's head is severely constrained by that individual's store of knowledge and experiences. To overcome this limitation, collaboration is encouraged so that ideas from different brains may meet and combined to produce something beyond one's imagination. The last point to make is that the effectiveness of the current model relies on a random process in the brain. How successful and how soon one can find the right conceptual combination is a matter of chance. However, as a rule of thumb, the prepared minds always have a better chance.

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