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INFLUENCE OF ANALOGICAL DOMAINS AND ABSTRACTION LEVELS ON NOVELTY OF DESIGNS

S. Keshwani[1], A. Chakrabarti[1]

[1]CPDM, Indian Institute of Science, Bangalore, India

Abstract: The overall goal of this work is to improve creativity of technical products by supporting novelty of designs. Analogy - an important aspect of creative thinking, is studied for its influence on novelty under the influence of two parameters: ‘distance between source- and target-domain’, and ‘abstraction level’. Two studies are conducted to test the influence of these two parameters on novelty of designs. Analogical domain is varied as: biological-, cross- and in-domain. Here, biological-domain analogies are those drawn from biological domain; cross- and in-domain analogies are drawn from engineering domain. ‘Level of abstraction’ of an analogy is defined here as the relative depth at which an analogy is explained, and is varied as deep, shallow and surface levels of abstraction. Statistical analysis showed that cross-deep and biological-surface analogies generated the most novel designs when compared to other abstraction levels within cross and biological domains respectively. Overall, cross-domain analogies were found to generate most novel designs as compared to other domains.

Keywords: *analogical abstraction, analogical domains, design for novelty*

1. Introduction

Use of analogies in design have resulted in invention of many new and successful products (Holyoak & Thagard, 1996; Chakrabarti et al., 2005), like velcro, self cleaning paints and dry tapes (Wilson, 2010). Since a major goal of design research is to enhance creativity of products, this research aims at supporting novelty – a central aspect in creativity. This is intended to be done by providing analogies as stimuli for generation of novel ideas. This work studies the influence of two classifications of analogies viz. distance between analogical domains and abstraction levels on the novelty of designs; this will help in identifying appropriate classes of analogies for stimulating greater novelty in design.

2. Literature Review

Analogy involves **accessing** and **transferring** elements from familiar categories in order to use them in the construction of a novel idea (Gentner, 1989). Creation of analogy requires establishment of similarity of relations between two domains i.e. the ‘source-domain’- domain from which the analogy is drawn, and the ‘target-domain’- domain to which the analogy is applied. Sections 2.1 and 2.2 provide review of two bases of classification of analogies that have been proposed in literature.

2.1. Conceptual distance between the source- and target-domains of an analogy

The parameter 'distance between source- and target-domains' has been defined in this work as the *conceptual closeness between the two domains*. Depending on the *conceptual closeness* between two domains, analogies can be classified as the near-domain and far-domain analogies (Holyoak & Thagard, 1996; Perkins, 1997). Far-domain analogies have greater impact on novelty than near-domain analogies (Ward, 1998; Dahl & Moreau 2002). With this as the basis, it can be hypothesised that novelty of designs generated using analogies from various analogical domains should vary as $N_{\text{farther-domain}} > N_{\text{far-domain}} > N_{\text{near-domain}}$. Assuming design problems are from engineering domain, it is argued that analogies from biological domain, being farther from engineering domain, will produce more novel designs over analogies from engineering domain. Case-studies leveraging biological examples (Walters et al., 2013; Chena et al., 2012) and biological knowledge (Keshwani et al., 2013; Wilson et al., 2010), as well as computational approaches to access and use biological analogies in engineering design (Vattam et al., 2011; Shu, 2010; Chakrabarti et al., 2005) show the potential of biological analogies in generating novel solutions. However, little has been reported that compares novelty of designs generated using biological analogies with those of far- and near-domain analogies from engineering domains. Therefore, this work compares relative novelty of designs generated using analogies from three domains – in-domain (near), cross-domain (far) and biological-domain (farther). One of the hypotheses of our research, therefore, is that the novelty of designs generated using analogies from these domains will vary as: $N_{Biological} > N_{Cross} > N_{In}$, where N_x = novelty of designs generated using analogies from domain x. These domains have been defined here as follows: biological-domain - phenomena occurring within an organism, or during its interaction with the environment; cross-domain - phenomena occurring within a technical product, or during its interaction with the environment, where the domain of the product is different from domain of the problem (target) to be solved; in-domain - phenomena occurring within a technical product, or during its interaction with the environment, where the domain of the product is similar to that of the problem (target) to be solved.

2.2. Levels of abstraction of an analogy

'Levels of abstraction' of an analogy has been defined here as the relative depth at which an analogy is explained. Mak & Shu (2004) describe it as the nature of description of a phenomenon. Different levels of abstraction of an analogy are achieved by using different sets of constructs to describe the analogy. Some instances of these constructs are: (a) the parts that constitute a system, (b) how parts interact with each other and the surroundings, (c) why parts interact in the way they do, and (d) the outcome of the interactions among parts. Together, these constructs explain the overall working of a system. Once these constructs are identified, they can be varied to explain the same analogy at different depths (i.e. different levels of abstraction). An example of analogy at a lower abstraction level is: *Polar bears have thick hollow furs. These furs help polar bears to survive in the cold*; an example of this analogy at a higher abstraction level is: *Thick hollow furs insulate polar bears and prevent heat loss from their body. This helps polar bears to survive in the cold*. We argue that the level of abstraction at which an analogy is described influences the constructs that are transferred from the source to the target domain; the constructs transferred are the ones responsible for novelty.

Earlier studies (Mak & Shu, 2004; Cheong et al., 2012) compared the constructs transferred from the source- to the target-domain at different levels. They did not, however, study the influence of varying the levels of abstraction on the novelty of design outcomes. Studying this will provide a basis for identifying the appropriate levels for abstraction for fostering enhanced novelty in designing. One aim of our research, therefore, is to compare the novelty of designs generated from analogies described at different levels of abstraction. Studies showed that concepts ideated at higher levels of abstraction are more novel over those ideated at lower abstraction levels (Srinivasan & Chakrabarti, 2010; Sarkar & Chakrabarti, 2011). Therefore, it is hypothesized that the transfer of constructs at higher levels of abstraction from the source- to the target-domain will lead to designs of greater novelty.

3. Research Hypotheses and Objectives

Based on the issues raised in the literature, the following research hypotheses have been framed:

h1. Novelty of designs generated using analogies from biological-, cross- and in- domain will vary as : $N_{Biological} > N_{Cross} > N_{In}$, where N_x = novelty of designs generated using analogies from domain x.

h2. Novelty of designs generated using analogies described at different abstraction levels will vary as: $N_{high\text{-}abstraction\text{-}level} > N_{medium\text{-}abstraction\text{-}level} > N_{low\text{-}abstraction\text{-}level}$, where N_y = novelty of designs generated using analogies described at abstraction level y.

The following are the associated objectives (O1-O2) of this research:

O1. To study the influence of analogical domains on novelty of designs.

O2. To study the influence of abstraction levels of analogies on the novelty of designs.

4. Methods to Classify Analogical Domains and Abstraction Levels

Before conducting experiments to test the hypotheses, it was necessary to identify methods to classify analogies on the basis of analogical domains and abstraction levels. As analogical domains are in a continuum (Perkins, 1997), it is difficult to categorize an analogy into a particular domain. Therefore, in order to classify analogies into in-, cross, and biological-domains, two bases (i.e. characteristics) have been proposed: a) parameter of interest e.g. temperature; b) its context e.g. buildings (Table 1). Using these bases of classification should enable selection of analogies belonging to each domain. For each problem, two categories were identified by varying each basis, and one analogy was drawn from each category. So, a total of two analogies were selected for each domain.

Table 1. Bases of classification of analogies into biological-, cross- and in- domains

Domain	**In-domain**		**Cross-domain**		**Biological-domain**	
Category	**1**	**2**	**1**	**2**	**1**	**2**
Problem: Temperature Controlled Buildings	Temperature control in buildings and its materials	Optimization of *other parameters* in buildings and its materials	Temperature control in *other devices*	Optimization of *other parameters* in *other devices*	Temperature control in *nature*	Optimization of *other parameters* in *nature*

Gentner et al. (2001) identified two levels at which similarities can be found in analogical reasoning: superficial and relational. Using this view, Mak & Shu (2004) proposed abstraction levels of analogies that varied from: form – the superficial level, to principle – the causal level. Cheong et al. (2012) also implemented this view by using abstraction levels that varied from entity – the superficial level, to strategy – the causal level. Therefore, we implemented this view in our work, and varied the levels of abstraction to construct analogies from superficial to increasingly causal level using SAPPhIRE model of causality (Chakrabarti et al., 2005; Srinivasan & Chakrabarti, 2010) – an empirically validated model that provides a richer description of causal relations. Using SAPPhIRE model, three levels of abstraction of analogies are proposed to explain an analogical description: surface – includes part, organ and action constructs, shallow – includes physical effect and physical phenomena and action, deep –input, state change and action constructs. While deep abstraction level explains changes in the property of the system and environment after their interaction, surface abstraction level describes only the parts of the system and conditions associated with those parts. Therefore, the order of abstraction level of analogies varies as deep > shallow > surface. However, without using lower level constructs, it is difficult to describe an analogy in a manner that can be understood by designers, especially when the analogies are complex and involve multiple phenomena and state changes. Therefore, definitions of abstraction levels are modified by adding lower level constructs to each. The modified definitions of these abstraction levels are: surface: it includes part, organ and action; shallow-it includes part, organ, physical effect, physical phenomenon and action; deep- it includes part, organ, physical effect, physical phenomenon, input, state-change and action. An example of analogy described at the three abstraction levels is as follows:-

Deep Level: Elephants use ears (part) to blow air around them during the hot weather. Blowing air causes evaporation (physical effect), which creates cooling (physical phenomenon). Ears also have blood vessels (part). The higher the surface area of ears, the greater is the heat loss (physical-phenomenon). Cooler blood is circulated through the body (state-change) resulting in cooling (action).
Shallow Level: Elephants use their ears (part) to blow air around them in hot weather. Blowing air causes evaporation (physical effect) and hence cooling effect (physical phenomenon). Ears also have blood vessels (part). The higher the surface area of ears, the greater is the heat loss (physical-phenomenon). So, elephants keep themselves cool in summer (action).
Surface Level: Elephants move their ears (part) frequently in summer. The ears also have many blood vessels (part). In this way they keep themselves cool in summer (action).

5. Experimental Procedure

Two studies Study-1 and Study-2 were conducted to test the hypotheses. Study-1 included 18 subjects – all M.Des. students at Indian Institute of Science. Study-2 included 18 subjects – 8 researchers, 8 designers, and 2 with BE in Mech. Eng. This difference in educational qualification of the subjects across two studies was due to availability of the subjects to each experiment. The experimental procedure followed was the same across both studies. Each study consisted of two experiments - E1 and E2 - conducted within a span of a week. Details of experiments E1 and E2 are:
Experiment E1: Nine teams viz. t1-t9, of two subjects each, were randomly created. A design problem P0, along with 3 analogies – one each from biological-, cross-, and in-domain, were given to each team. Each team was asked to generate as many solutions to the problem as possible, using the given analogies as inspiration, in 40 minutes. The solutions, presented in the form of annotated sketches, were evaluated by the authors of this study, for novelty of the concept-space generated (Srinivasan & Chakrabarti, 2010, Section 6). Based on the scores of novelty of concept-space obtained by each team, the authors labelled the three teams (t1, t2 and t9, see Table 2) that obtained the highest novelty scores as 'Excellent-Performers', the three teams (t3, t5 and t8, see Table 2) with the lowest novelty scores as 'Bad-Performers', and the remaining three teams as 'Medium-Performers' (Table 2). Three groups G1, G2 and G3 were created, each consisting of an Excellent, a Medium, and a Bad-Performer, (for instance, G1 consisted of t3, t4 and t1). The motivation behind formation of groups with similar average performance was: the authors intended to compare the performance of these groups among each other to study the influence of abstraction levels and domains on novelty of designs. Formation of groups in this way helped to average out the effect of performance of individual teams on the results obtained subsequently from experiment E2.
Experiment E2: Without changing the team constitution, team numbers were changed in experiment E2, e.g. teams in group G1 were numbered as T1, T2 and T3 (Table 2). E2 involved 3 design problems P1-P3, conducted in three sessions S1-S3, each 40 minutes long. Each problem was paired with a set of two analogies belonging to a specific domain and abstraction level combination (e.g. bio-deep) but with variation in one of the two bases. Subjects were asked to generate as many solutions as possible to a given problem, and express these in the form of annotated sketches.
Table 3 shows the design of experiment in E2, where each row summarises sessions S1, S2 and S3. Following example shows how the details of each session within a row can be read from this table. Session S1 in serial no. 1 (Table 3) can be read as (all bold and underlined) 'Within Group G1, Team T1, in session S1, solved problem P1, using analogy from biological-domain described at deep abstraction level'. Similarly, all other details of all other sessions can be understood. The strengths of this design of experiment were: a) influence of individual performance of teams was averaged out, as each group consisted of an excellent, a medium, and a bad-performing team. b) for analogies belonging to each domain and abstraction level combination (for instance, bio-deep), all three problems were solved in all three sessions. So, the influence of problem variation and performance of group due to tiredness on results was averaged out; c) keeping domain as a constant parameter, the influence of deep, shallow and surface abstraction levels on the results can be compared. For instance, across serial nos. 1 to 3 in group G1 (Table 3), keeping 'biological-domain' as constant, the influence

of deep, shallow and surface abstraction levels can be compared on the results. Similarly, keeping abstraction levels as constant, the influence of analogical domains on the results can be compared.

Table 2. Evaluation and renaming of teams in experiment E1 in Study-2

Team No. In E1	Novelty of CS	Performance	Group	Team No in E2
t3	1.5	Bad	G1	T1
t4	3.333	Medium	G1	T2
t1	5	Excellent	G1	T3
t8	1.5	Bad	G2	T4
t6	3.5	Medium	G2	T5
t9	4.5	Excellent	G2	T6
t5	1.667	Bad	G3	T7
t7	3	Medium	G3	T8
t2	3.667	Excellent	G3	T9

Table 3. Design of experiment-E2 for Study-1 and Study-2

Serial No.	Group	Teams	Session	Problem	Domain	Abstraction
1	**G1**	**T1**,T2,T3	**S1,**S2,S3	**P1**,P2,P3	**Bio**	**Deep**
2	G1	T2,T3,T1	S1,S2,S3	P3,P1,P2	Bio	Shallow
3	G1	T3,T1,T2	S1,S2,S3	P2,P3,P1	Bio	Surface
4	G2	T5,T6,T4	S1,S2,S3	P2,P3,P1	Cross	Deep
5	G2	T6,T4,T5	S1,S2,S3	P1,P2,P3	Cross	Shallow
6	G2	T4,T5,T6	S1,S2,S3	P3,P1,P2	Cross	Surface
7	G3	T9,T7,T8	S1,S2,S3	P3,P1,P2	In	Deep
8	G3	T7,T8,T9	S1,S2,S3	P2,P3,P1	In	Shallow
9	G3	T8,T9,T7	S1,S2,S3	P1,P2,P3	In	Surface

6. Data Analysis

This section presents the details of evaluation of sketches generated in experiment E2 in both studies. Their evaluation was done by the authors of this work, using the approaches described below:

- Approach A1 (Novelty of Design Concepts, from Sarkar & Chakrabarti, 2011): It identified 'highly-novel' concepts generated in a design session, thereby giving the proportion of concepts generated with high novelty in a design session.
- Approach A2 (Novelty of Concept-Space, from Srinivasan & Chakrabarti 2010)**:** It evaluated the overall novelty of all the concepts (concept–space) produced in a design session.
- Approach A3 (Variety of a Concept-Space, from Pal & Chakrabarti, 2014)**:** It evaluated the overall variety of concepts generated.

While A1 and A2 are two complementary approaches for assessing novelty; A3 assesses variety, an indirect measure of novelty (Dylla, 1990; Srinivasan & Chakrabarti, 2010). Units of analysis, used in this work, are given below.

1. $[HNC]_{TiPj}$,: This unit of analysis, calculated using Approach A1, signifies the Number of Highly-Novel Concepts generated by Team Ti for Problem Pj. To mitigate the influence of problem on the number of [HNC] generated, the data was normalized wrt to problem Pj.
2. $P[HNC]_{TiPj}$: This unit of analysis, calculated using Approach A1, signifies the Proportion of Highly-Novel Concepts generated by Team Ti for Problem Pj. As the total number of concepts generated by each team were different, so it was essential to calculate the proportion of total concepts generated by each team was that was highly novel. This was done to compare the number of highly-novel concepts generated across different teams.
3. $N(CS)_{TiPj}$: This unit of analysis, calculated using Approach A2, signifies Novelty of Concept-Space generated by Team Ti for Problem Pj in a design session. While [HNC] and P[HNC]

capture peak novelty, N(CS) calculates average novelty of all concepts generated in a design session, thereby complementing each other. As some problems may be common in market over the other, N(CS) is influenced by the problem. So, $N(CS)_{TiPj}$ was normalized wrt problem Pj.

4. $V(CS)_{TiPj}$: This unit of analysis, calculated using Approach A3, signifies the Variety of Concept-Space generated by Team Ti for Problem Pj. While [HNC], P[HNC] and N(CS) capture novelty, V(CS) calculates the average difference among all the concepts generated in a design session. This is an indirect measure of novelty. As it might be easier for the subjects to generate different types of concepts for one problem as compared to other, leading to greater V(CS) generated for former problem, $V(CS)_{TiPj}$ was normalized wrt problem Pj.

These units of analysis were calculated for each team in each session. Using these, units of analysis were calculated for each analogical input (Table 4 shows the example calculation of overall novelty and variety for cross-surface analogy in Study-1). Units of analysis for an analogical input from Study-1 were added to corresponding units of analysis from Study-2 to get overall values for each input.

6.2 Example of concepts generated in design session

An example problem given to the subjects during experiment E2 and concepts generated by them are presented here. Problem P1: Develop concepts for buildings that can adjust to a comfortable temperature automatically in all climatic conditions (with minimum use of energy).

Concept Sketches: Figure 1 shows three concepts generated by using the analogy described at three abstraction levels in section 4. Figure 1A shows metallic conductive tubes embedded within the walls of building. These tubes carry liquid that absorbs heat from the walls in summer and releases heat in winter. Figure 1B shows similar concept as in Figure 1A with an extra layer of glass on wall that allows only a certain range of heat intensity to pass through it. Figure 1C shows a concept in which walls are built as movable fragments. The fragment that gets heated up in sun is replaced by a cooler fragment, while the hot fragment moves in shadow to lose heat.

7. Results

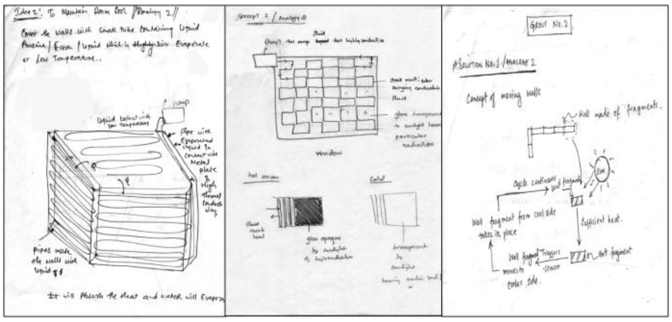
This section presents statistical analysis of novelty and variety scores of analogical inputs, which was done using Kruskal-Wallis H test. Post–hoc comparison after significant Kruskal-Wallis H test was also done using Turkey's test. For k-1= 2 degrees of freedom in Kruskal-Wallis H test, $\chi^2_{.975} = 7.38$, $\chi^2_{.95} = 5.99$ and $\chi^2_{.90} = 4.61$. Following are the key results obtained from Kruskal-Wallis H test:

Within biological-domain, significant difference was found across deep, shallow and surface levels in terms of the number of [HNC] at 97.5% confidence level ($H = 9.57 > \chi^2_{.975}$) and N(CS) at 95% confidence level ($H = 6.43 > \chi^2_{.95}$). Within the cross- and in-domain, no significant difference was found across deep, shallow and surface levels for any unit of analysis ($H_{max} < \chi^2_{.90}$). Within deep level, significant difference existed in V(CS) across biological-, cross- and in-domain analogies at 95 % confidence level ($H = 6.04 > \chi^2_{.95}$). Within shallow and surface abstraction levels, significant difference did not exist across biological-, cross- and in- domains for any unit of analysis ($\chi^2_{.90} < H_{max\ for\ shallow\ level} = 5.08 < \chi^2_{.95}$; $\chi^2_{.90} < H_{max\ for\ surface\ level} = 5.24 < \chi^2_{.95}$). Overall, irrespective of abstraction levels, significant difference existed across biological, cross and in domain analogies in terms of N(CS) at 95% confidence level ($H = 6.88 > \chi^2_{.95}$) and V(CS) at 97.5% confidence level ($H = 11.13 > \chi^2_{.975}$). Significant difference was not found across the abstraction levels when domains were disregarded ($H_{max} = 1.67 < \chi^2_{.90}$).

Post–hoc evaluation using Turkey's HSD test (calculated at 0.1 level of significance) indicated the following results (it is conducted on those pairs that show significant difference in Kruskal-Wallis H test): within biological-domain, surface level indicated higher N(CS) as compared to deep level; within deep level, cross-domain analogies indicated higher N(CS) as compared to biological-domain; Overall, when abstraction levels were ignored, cross-domains indicated greater N(CS) as compared to in-domain.

8. Discussion

This section explores probable causes for the results obtained in this work. It was found that within biological domain, surface level indicated higher N(CS) as compared to deep level. Probable cause behind this observation might be: all designers who performed the experiment were from engineering background; therefore, based on their limited understanding of the biological domain, they could transfer only superficial elements into the target, leading to greater novelty while using analogies described at the surface level of abstraction as compared to those described at deep level. Helms et al., (2009), Cheong et al., (2012) observed that, engineers transferred superficial aspects of biological analogies and found it difficult to transfer causal relations of those analogies. It was also found that within deep level, cross-domain analogies indicated higher N(CS) as compared to biological-domain. Subjects, being engineers, might have been relatively more familiar with analogies from cross-domain (which is still an engineering domain, albeit a different one from the target domain) as compared to biological-domain. Therefore, they might have found it easier to transfer cross-domain analogies at higher abstraction level, leading to greater novelty. Overall, when analogical abstraction levels were ignored, analogies from cross-domains indicated greater N(CS) as compared to in-domain analogies- an observation made by researchers like Ward (1998), Dahl & Moreau (2002), Chan et al. (2011). However, no significant difference was found between novelties of designs generated using analogies from cross- and biological-domains- an observation that shows the potential of biological analogies in generating novel solutions even though subjects found it difficult to transfer them into their concepts.



A. Concept inspired using deep level analogy B. Concept inspired using shallow level analogy C. Concept inspired using surface level analogy

Figure 1. Examples of concepts generated using deep, shallow and surface analogies

Table 4. An instance of novelty and variety scores due to cross-surface analogical input in Study-1

Team, Session, Problem	Domain-Abstraction	$Nor(HNC)_{TiPj}$	$P[HNC]_{TiPj}$	$Nor(N(CS))_{TiPj}$	$Nor(V(CS))_{TiPj}$
T4,S1,P3	Cross-surface	0	0	0.74	0.45
T5,S2,P1	Cross-surface	0	0	0.75	0.99
T6,S3,P2	Cross-surface	0.067	0.767	0.81	1.04
Net value for Cross Surface analogical input in Study-1		0.067	0.767	2.3	2.48

9. Conclusions

This study presents an initial framework as to how much to abstract or concretize an analogy belonging to particular domain in order to obtain more novel design outcomes. The main learnings from this research are: a) far-domain analogies (be it biological or cross) produce more novel designs as compared to near domain analogies, although it is not clear which analogy (biological or cross) in far domain produces greater novelty owing to difficulties faced by the subjects in understanding and transferring biological analogies; b) it can be implied from the results that designers who take inspiration from nature to design novel products require training to make use of biological analogies; c) if designers are using an analogy from cross-domain, they are more likely to generate novel designs when the analogy is described at greater depth. Limitations of this work include: a) the analogies for problems P1-P3 were searched primarily using the Internet. This choice of analogies made by the authors might have influenced the results; b) the measures of evaluation of novelty required that the concepts generated in design experiments be compared with existing products (satisfying the same function) in the market, again found through the Internet. Although a thorough search was done to find existing products for comparison, the list cannot be claimed to be exhaustive; c) inclusion of lower level constructs of SAPPhIRE model in defining of deep and shallow abstraction levels would have influenced the results. Future work includes exploring causes behind the observations and studying the patterns of transfers from source to the target domains using the analogical inputs proposed in this study.

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