On the Role of Analogy in Resolving Cognitive Dissonance in Collaborative Interdisciplinary Design

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Abstract. Analogies play multiple roles in cognition. In this paper, we explore the roles of analogy in collaborative interdisciplinary design. We describe two analyses of a case study of a design team engaged in biologically inspired design. In the first analysis, we sought to understand the multiple roles of analogy in interdisciplinary design. The goal of the second analysis was to understand the relationship between analogy and collaboration. During this latter analysis, we discovered another, unexpected, role for analogy: resolving cognitive dissonance. Cognitive dissonance typically refers to the mental discomfort a person experiences when simultaneously holding two conflicting goals, values, beliefs, thoughts or feelings. We observed that interdisciplinary design teams too have cognitive dissonance. We also observed that analogies play an important role in helping induce shifts in the perspectives of teammates, align their mental models, and thereby resolve the cognitive dissonance in interdisciplinary design teams. We discuss some implications of our observations for developing case-based systems for collaborative interdisciplinary design.

Keywords: analogical reasoning, cognitive dissonance, collaborative work, interdisciplinary design, design teams.

1 Background, Motivation and Goals

In 1957, Leon Festinger [1] famously introduced the notion of cognitive dissonance into the literature on cognitive psychology. Cognitive dissonance refers to the mental discomfort a person experiences when simultaneously holding two conflicting goals, values, beliefs, thoughts or feelings. Festinger suggested that when a cognitive agent suffers from cognitive dissonance, he tries to reduce the dissonance. Consider, for example, the famous parable of the fox that tried to grasp a bunch of grapes. When the fox failed to reach the grapes, he suffered from a cognitive dissonance between two thoughts: wanting the grapes and the failure to reach them. To reduce the cognitive dissonance, the fox surmised that the grapes must have been sour and therefore not worth reaching! Over the last fifty years, cognitive dissonance has become a classic theory in cognitive science.

Although cognitive science typically views individual humans as cognitive agents, social aggregates of humans, such as teams, organizations, and nations, too may be

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viewed as cognitive agents. Consider as an example Ireland, the host country for this conference. Like any cognitive agent, Ireland perceives its environment and acts on it in the pursuit of its goals; it also acquires, organizes, accesses and uses knowledge to decide on appropriate actions; and so on. Indeed, the cognitive science literature is replete with examples of viewing, if only implicitly, social aggregates of cognitive agents themselves as cognitive agents. Sylvan et al. [2] explicitly viewed Japan as a cognitive agent in modeling its decision making related to energy security. Given that social aggregates of humans, such as nations, organizations and teams, can be viewed as cognitive agents, we posit that such social aggregates too may have cognitive dissonance.

This notion of cognitive dissonance in social aggregates of humans seems intimately related to how humans work, play, and live. Consider as an example how humans design. Most design is collaborative in practice: designers typically work in teams. It follows that a design team may suffer from cognitive dissonance due to the conflicting goals, models and thoughts of its members, and that the team will employ cognitive strategies for reducing the dissonance. Further, design often is interdisciplinary in practice: members of a team working on complex system design, for example, may have very different knowledge and expertise. It follows that interdisciplinary design teams in general may suffer from deep cognitive dissonance because of the deep conflicts in the metaphors, models and methods used by its members.

This notion of cognitive dissonance in design cognition raises another question: what cognitive strategies may an interdisciplinary design team use to resolve its cognitive dissonance? Recently, Spitas & Badke-Schaub [3] presented a preliminary information-processing model of cognitive dissonance in interdisciplinary design teams in terms of flow of ideas in "synaptic networks." Our work described below suggests that interdisciplinary design teams use analogies as a mechanism for reducing cognitive dissonance. Informally, this makes sense when one considers "analogy as the core of cognition" [4,5] and especially of creativity [6,7]: Given that analogy is a core process of cognition, we would expect it to appear throughout human behavior; we would especially expect analogy to be prevalent in creative design.

In this paper, we describe two related analyses of a case study of a design team engaged in biologically inspired design. We chose this context for our study because biologically inspired design is intrinsically interdisciplinary (because it entails analogies from biology to a design domain), and collaborative (because most designers are novices in biology and most biologists are naïve about design). In the first analysis, we sought to relate the case study to prior research [8] that described multiple roles of analogy in biologically inspired design. The goal of the second analysis was to understand the relationship between analogy and collaboration. It is during this latter analysis that we unexpectedly discovered the role of analogy in resolving cognitive dissonance. We also discuss the implications of our findings for developing case-based tools for collaborative interdisciplinary design.

2 Biologically Inspired Design

Biologically inspired design (also known as biomimicry) is an important and widespread movement in modern design [9-11]. The paradigm espouses the use of analogies to biological systems for generating conceptual designs for technological systems. One prominent example is the design of windmill turbine blades inspired by the design of humpback whale flippers [12]. The designers adapted the shape of the whale flippers—specifically, the bumps on their leading edges—to turbine blades, creating blades that improve lift and reduce drag, increasing the efficiency of the turbine [13].

The rapidly growing movement of biologically inspired design has led to the development of several case-based interactive tools for supporting its practice, including Biomimicry 3.8 Institute's [14] AskNature, Chakrabarti et al.'s [15] IDEA-INSPIRE, and Vincent et al.'s [16] BioTRIZ. DANE (http://dilab.cc.gatech.edu/dane/) [17], for example, provides access to a digital library of functionally indexed multimodal and structured representations of biological and technological systems for idea generation in conceptual design, and Biologue [18] is an interactive tool for collaborative tagging of biology articles with semantic tags and for accessing biology articles based on the semantic tags. All these case-based tools are based on the fundamental assumption that biological analogies are useful mainly for the task of design idea generation in the conceptual design of technological systems.

However, empirical studies of biologically inspired design indicate that analogies play multiple roles in biologically inspired design. By the "role" of analogy, we mean the "function" of analogy in the design process, i.e., the design task or subtask that the analogy addresses. For example, Christensen & Schunn [19] identified three functional roles of analogy in engineering design: problem identification, problem solving, and concept explanation.

Vattam, Helms & Goel [8] identified multiple roles of analogies in biologically inspired design, including "*solution generation*, *evaluation*, and *explanation*". Analogy for solution generation occurs when an analogue is used to transfer a mechanism or decompose a design problem. Analogy for evaluation occurs when an analogue is used to assess the candidate design. Analogy for explanation occurs when an analogue is used to explain some part of a design solution.

Helms, Vattam & Goel [20] identified problem formulation as another role analogy in biologically inspired design, and Helms & Goel [21] identified design problem reformulation as yet another role of analogy in biologically inspired design. While analogy for problem formulation occurs when an analogue is used to identify and specify a problem, analogy for problem reformulation occurs when analogy is used to revise a problem formulation.

3 A Case Study of Biologically Inspired Design

Georgia Institute of Technology offers a course on biologically inspired design that provides the context for our case study. ME/ISyE/MSE/PTFe/BIOL 4740 is a yearly, interdisciplinary, project-based undergraduate class taught jointly by biology and engineering faculty in which mostly senior-level design students work in small teams of 4-5 on design projects. The class is composed of students from biology, biomedical engineering, industrial design, industrial engineering, mechanical engineering, and a variety of other disciplines. The projects involve identification of a design problem and conceptualization of a biologically inspired solution to the problem. Yen et al. [22] provide details of the project-based learning and teaching in this course.

We performed a participant observation of a design team in the Fall 2010 session of the course. This entailed one of the authors of this paper (Wiltgen) taking the course and engaging in all activities expected of a student, including attending lectures, doing homework, and participating as a design team member in the observed design team. Wiltgen's team consisted of five people representing five different majors: architecture, biology, computer science (Wiltgen), mechanical engineering, and industrial engineering. In this paper, we will focus on what we call the Shark Attack project that was developed by Wiltgen's team. The goal of this project was to prevent shark attacks off the coast of the United States without harming the sharks. The team designed an underwater sound-based shark repellant device inspired by the snapping shrimp [23,24], a small shrimp with the ability to create loud, underwater sounds using one of its claws, which it uses to hunt prey and communicate with other snapping shrimp. The final design worked by emitting sounds that are generated by the same cavitation mechanism that the snapping shrimp uses to create sound, but at a frequency that sharks dislike.

4 Roles of Analogy

The first research question in this paper pertains to the roles of analogy in biologically inspired design: for what design tasks does a collaborative, interdisciplinary team use analogies? Based on our prior research [8], our initial hypothesis was that analogies will address the tasks of what we now call design idea generation, design concept evaluation and design concept explanation. Our analysis added the role of domain concept explanation.

4.1 Method

Several kinds of data were collected during the participant observation: audio recordings of team discussions, e-mail communications amongst the team, design artifacts (including some class assignments), and field notes of class sessions. For this paper, we focus strictly on the audio recordings and transcripts derived from those recordings. The audio recordings cover in-class team activities and out-of-class team meetings. We transcribed the recordings into written form. Once transcribed, we analyzed transcripts related to the first design episode, looking for instances where an analogy explicitly occurred. Phrases such as "like <X>" where used to identify passages. Once the instances were identified, we then categorized the instance by its role.

4.2 Preliminary Results

Table 1 summarizes our preliminary results pertaining to the roles of analogy in biologically inspired design. The table provides three rows per covered role of analogy: identification of the role, definition of the role, and an example of the role. We identify each of the five team members by their major: CS for computer science (Wiltgen), ME for mechanical engineering, ARCH for architecture, BIO for biology, and IE for industrial engineering.

Table 1. Roles of Analogy

Role: Design Idea Generation
Definition: A problem is defined and then an analogy is used to meet the parameters of that problem.
Example: In one class session, ME used the source analogue of the flying fish to address the problem of drag in maglev trains: *ME: "So, what I was thinking about was using these fins off the flying fish on the side of a maglev train to also create a little bit of lift where you, you actually use the air resistance to help you get over the actual friction and move more efficiently"*
Role: Design Concept Evaluation
Definition: An analogue related to the design solution is used to infer the quality of the design.
Example: In this snippet of a discussion from an out-of-class meeting, only IE and CS are present. As we interpret this snippet, IE brings up an argument for why sharks would not get desensitized to the sound created by the team's design. Here, we present an edited version of the transcript to ease readability. In Table 3, we present the unedited transcript. (Actually, this example was derived from the analogy identified in the second analysis. However, this makes little difference to our results.) *IE: "the whole thing on like desensitizing the sharks I mean sharks don't eat humans you know"* *CS: "right"* *IE: "they're not their food source huma- we're not their food source so does that mean that they've already been I mean it's not like they've been de- desensitized to human sound right now anyways right?"* *CS: "mmm"* *IE: "so do we really have to worry about them them being desensitized? Since I mean humans basically are like decoys in a sense already ((CS says "right" overlapping with the ready part of already)) in the fact that they don't get anything out of it"* *CS: "right"* *IE: "so if they haven't been desensitized already then"*

Table 1. (*continued*)

Role: Design Concept Explanation
Definition: An analogy is used to explain the entirety or some aspect of the design solution.
Example: In this example, ARCH is describing a component of the design solution: a proximity sensor that would turn on the sound generator only when a shark passes nearby. She makes an analogy to a "fish monitor" to explain her solution component to the team. *ARCH: "Let's say it comes within a certain boundary of the coast like a large organism."* *ME: "Yeah"* *ARCH: "Cause I mean there's already things that like"* *ME: "Let them come off the-"* *ARCH: "Can detect large organisms. You know, like a fish monitor if you're going fishing it can-"* *CS: "Yeah"* *ARCH: "And then so if there's like a large organism that passes through maybe then it triggers something."*
Role: Domain Concept Explanation
Definition: An analogy is used as an explanatory tool to help build an understanding about a biological concept.
Examples: In this example, ME had previously presented a magnolia leaf as his found object. A magnolia leaf has two distinct sides, a top, waxy side and a fuzzy brown bottom side. In his explanation of the leaf, he could not explain the bottom side, so the team set forth to generate an explanation. BIO tried to explain the bottom of the leaf by making an analogy to an umbrella, where water collects on the umbrella's underside. He proposes that the fuzzy-like bottom side of the magnolia leaf helps it overcome this problem: *ME: "Yeah, there's not really a lot about the brown on the bottom."* *BIO: "What I'm thinking is, uh, you- you just mentioned that kinda good for the umbrella"* *ME: "Yeah"* *BIO: "Yeah, cause uh, yeah I agree with you. Cause uh, all the umbrellas I think I've kinda experienced that if the water pours out then the water kinda, kinda getting into like underneath of the umbrella."* *CS: "Huh"* *BIO: "But if it's [[inaudible]] stuff then that kinda prevents the water going underneath, so I think that's [good]"*

Thus, our study confirms that analogies play multiple roles in biologically inspired design, including design idea generation, design concept evaluation and design concept explanation. In addition, our study shows that analogies in biologically inspired design also play a role in explaining novel domain concepts. Consistent with Christensen & Schunn [19], we posit that the use of analogies for domain concept explanation is more likely to occur in interdisciplinary design teams because the team members are more likely to begin with different concepts and models of the world.

5 Cognitive Dissonance and Perspective Shifts

The articulation of an analogy by one member of a design team typically results in transfer of the knowledge to other team members and assimilation of the knowledge in the receivers' mental model. We will call this Transfer Analogy. Transfer Analogy appears to be a natural extension of current theories of analogy [e.g., 7]. However, in design concept evaluation, the goal of analogy appears to help a teammate look at the current issue under discussion from a different perspective. We will call this type of analogy Change Analogy. We hypothesize that a teammate may use a Change Analogy as a means of persuading other teammates to view the current problem from a different perspective when there is a cognitive dissonance on a design team.

5.1 Method

We discovered Change Analogy through analysis (conducted after the analysis presented above) of a discussion by the same team in the same Shark Attack project as before. We used the audio file of the discussion and a partial transcript of that audio file in various stages of our method. We analyzed our data in three steps: (1) identify instances of analogical reasoning; (2) for each instance of analogical reasoning that we chose to investigate, understand what changes in knowledge occurred in the speaker of that instance before the occurrence of the instance; and (3) determine if there are any relationships between steps 1 and 2.

We pursued these goals through a variety of techniques. For step 1, we first listened to the audio recording to identify all possible instances of articulated analogies. Then, we selected a specific instance of articulated analogy for further analysis. We coded this instance of articulated analogy (and related passages) using a scheme inspired and informed by Richland et al.'s [25] method for identifying analogies in a discourse. We used these codes to decide whether to accept or reject the instance as a true analogy. For step 2, we used a coding scheme that characterized contents of passages in the transcript in terms of attributes and relationships. Each passage could have zero to many such codes associated with it. We primarily coded only those passages spoken by the speaker of the selected instance of articulated analogy and those passages spoken by others that we felt were important to understanding that speaker's passages. Finally, for step 3, we reviewed our codes, looking for changes in the knowledge of the speaker who articulated the selected instance of analogy. We surmised that the changes in knowledge that occur before the selected instance of articulated analogy might be related to that instance.

5.2 Preliminary Results

Table 2 and Table 3 display sections of the transcript. We use the same speaker identifiers in Table 2 and Table 3 as in Table 1. The discussion in Table 2 occurred before the discussion in Table 3. Table 2 shows an articulation of knowledge by CS (Table 2 Passage Numbers 6 and 8) that we identified as meaningful and some discussion around it. We believe that this articulation of knowledge is at least a contributing factor to IE's identification of a cognitive dissonance. Table 3 shows the analogy that IE articulated. We note that some passages occurred between these two transcript sections.

In both tables, we divide our passages by turns of speaking. We will describe Table 3's columns. From left to right, the columns show the following: a uniquely identifying number for the passage (set to a table-relative number for this paper), the speaker of the passage, what was spoken for the passage, and any analogy-related codes that were created for the passage. Table 2's columns are a subset of Table 3's columns and have the same meaning.

The symbols used in the Spoken column in both tables were derived from Du Bois et al. [26]. <X-UNKNOWN-X> refers to indecipherable speech and that the transcriber could not distinguish the number of syllables in that speech. <X content X> refers to uncertain words or phrases, and <X content X><X2 other-content X2> displays possible alternatives when they exist. X: in the speaker column means an unknown speaker. ((?)) signifies that the transcriber felt the preceding text was a question. ((CONTENT)) is a transcriber comment. [content], [[content]], etc., refer to overlapping speech. We vertically align overlapping speech by the left-most bracket; the right-most brackets always end at the end of a word; and the number of brackets identifies the particular instance of overlapping speech.

The analogy in Table 3 is between the human-shark system and the decoy-shark system. We derived the relationships in both systems from our codes in Table 2 with the exception of Decoy makes Sound. However, we feel this relationship is appropriate because the team was discussing a decoy that would use sound to attract sharks. There is an error in the mapping identified in Table 3 P# 5. The human-shark system part should be "sharks don't get anything out of attacking/eating (?) humans". We put a (?) because we are not exactly sure what precisely IE meant here. Although he does not articulate all of his thought, we conjecture that IE transfers the "not desensitized to" relationship between Sharks and Sound.

Now consider our data as it relates to the process of resolving the cognitive dissonance between IE and CS on the team. IE received CS's articulation of knowledge that revealed to IE that his mental model was different from CS's mental model. At some later point, IE decided to reconcile this difference, i.e., to convince CS to change his mental model to be aligned with IE's mental model. IE attempted to do so by articulating an analogy. Thus, CS's articulation of knowledge provoked analogy making by IE. IE recognized a conflict with his knowledge and sought to fix it not by changing his own knowledge but by attempting to change the knowledge of the articulator (CS).

Table 2. Section of the Transcript Showing CS's Knowledge Articulation. (The Passage Numbers are relative to Table 2 only.)

P#	**Speaker**	**Spoken**
1	IE:	huh ((?)) I don't know <X for ((SOUNDS LIKE FUR)) X> but then if <X we're X> just focusing on sound
2	CS:	mhm
3	IE:	do we have to worry about the other two ((?)) like once we've successfully like attracted them or repelled them using sound
4	CS:	mhm
5	IE:	do we really have to worry about what they see or smell afterwards ((?))
6	CS:	we might if they get desensitized like if that if that question is true that it it'll attract them and then they'll go <X well X> there's nothing here and go somewhere else
7	IE:	<X mhm X> ((HARD TO HEAR. IT IS POSSIBLE THIS IS JUST A NOISE AND NOT IE))
8	CS:	then we might want to have in our solution talking about solutions something that uh you know creates smell or creates uh uh something that looks like a <X seal X> or something like[that] you know
9	IE:	[right]
10	IE:	<X yeah X> cause I was thinking like our the purpose of our solution is to like if you're talking about attracting them we're <X trying to attract them X> as far away as needed
11	CS:	mhm
12	IE:	so that they won't be attracted to human sound right ((?))

Table 3. Section of the Transcript Showing IE's Articulated Analogy. (The Passage Numbers are relative to Table 3 only.)

P#	Speaker	Spoken	Analogy Codes
1	IE:	the whole thing on like desensitizing the sharks I mean sharks don't eat humans you know	
2	CS:	right	
3	IE:	they're not their food source <X huma-X> we're not their food source so does that mean that they've already been I mean it's not like they've been de-desensitized to human sound right now anyways right ((?))	Relationship: (human-shark system) sharks don't get anything out of attacking/eating (?) humans Relationship: (human-shark system) sharks are not desensitized to sounds humans make
4	CS:	<X mhm X><X2 mmm X2>	
5	IE:	<X so X> do we really have to worry about them them being desensitized ((?)) since I mean humans [basically] are like decoys in a sense al[[ready]] in the fact that they don't get anything out of it	Source object: human-shark system Target object: decoy-shark system Relationship: (decoy-shark system) sharks don't get anything out of attacking/eating (?) decoys Mapping: (human-shark system) sharks don't get anything out of attacking/eating (?) LIKE (decoy-shark system) sharks don't get anything out of attacking/eating (?) decoys
6	X:	[<X-UNKNOWN-X>] ((SHOULD BE CS BUT THIS MAY JUST BE A NOISE))	
7	CS:	[[right]]	
8	CS:	right	
9	IE:	so if they haven't been desensitized already then	Transfer: (human-shark system) sharks are not desensitized to sounds humans make THEREFORE (decoy-shark system) sharks are not desensitized to sounds decoys make

6 Implications for Case-Based Technology

Our findings have several implications for developing case-based technology to aiding biologically inspired design in particular, and interdisciplinary collaborative design in general. The current generation of case-based tools for aiding biologically inspired design – such as AskNature, IDEA-INSPIRE, DANE, etc. – were designed only for the task of design idea generation. This provokes two questions: (1) To what extent do current case-based tools already serendipitously support other tasks? (2) How may one adapt current case-based technologies to address another task?

We will consider these two questions relative to DANE [17] and Biologue [18]. We briefly described both tools in Section 2: While DANE provides access to a library of conceptual models of biological and technological designs, Biologue provides access to a library of biology articles that contain descriptions of biological systems in natural language. Biologue articles too are annotated with conceptual models, but they are skeletal compared to the detailed models in DANE.

First, let us consider the tasks of design concept explanation and domain concept explanation. We posit that DANE's conceptual models already serendipitously support the task of design concept explanation and also provide partial support for the domain concept explanation task, so one may not need to adapt DANE for it to address these tasks. However, Biologue's skeletal models may be less effective for these tasks, and so it may benefit from adaptation. We conjecture that we could use DANE-like conceptual models to add the two functionalities to Biologue; that is, we could annotate the articles in Biologue with the DANE-like conceptual models of the biological systems and concepts described in the articles. In fact, we are currently developing an AI agent that can automatically derive DANE-like conceptual models for the biological design described in Biologue's articles.

Now let us consider how we may adapt DANE for the task of design concept evaluation, a task it does not serendipitously support. At present, a user interacts with DANE by browsing models or creating/editing models. Let us suppose that a user could also input a design problem and associate it with a conceptual model of the proposed design. We conjecture that an AI agent could (a) use DANE's schema for checking the structure of the conceptual model of the proposed design for consistency, and (b) use DANE's other conceptual models for checking the contents of the conceptual model of the proposed design for correctness.

6.1 Case-Based Techniques for Addressing Cognitive Dissonance

The problem of developing a case-based technique for reducing cognitive dissonance in collaborative interdisciplinary design is more complicated as well as more subtle. Cognitive dissonance on a design team may be healthy (at least to some degree) because it reveals that the team members have different mental models and starts the process of aligning their mental models with one another's. Thus, instead of reducing the occurrence of cognitive dissonance, we want to focus on how to address cognitive dissonance once it is manifested in a design team. Given our finding about analogy as a cognitive strategy for addressing cognitive dissonance, we want to make analogies more effective so that they may more readily help persuade team members to shift their perspectives and align their mental models. But this raises another question: Why are some analogies not effective? This question likely has several answers, but one answer surely is that some analogies are just not very good. This suggests a way in which case-based techniques could help address cognitive dissonance: effective analogy evaluation. It is noteworthy that while there has been a significant amount of work on analogy generation, there has been relatively little research explicitly on analogy evaluation.

Yen et al. [22] found that designers struggle with (a) articulating why a biological analogue is appropriate for a given problem and (b) consistently explaining why one biological analogue is better than another. To support designers' evaluation of biological analogues, our laboratory has developed a simple tool called a T-Chart that enables designers to compare the similarities and differences between a design problem and a biological analogue along multiple dimensions such as function, operating environment, constraints, and performance criteria [27]. Preliminary evidence indicates that T-Charts help designers better evaluate the appropriateness of biological analogues to design problems.

7 Future Work

The current work raises several questions for exploration. The first set of questions pertains to the generalization of our findings. What other empirical evidence exists for cognitive dissonance in social aggregates of humans such as teams, organizations and nations? How can we collect this evidence? Similarly, what other empirical evidence exists for the use of analogies to reduce cognitive dissonance in cognitive agents at various levels of social aggregation from individual humans to nations? How can we collect this evidence?

The second set of questions relates to case-based techniques and tools for addressing cognitive dissonance once it is manifested, and in particular, for effective analogy evaluation. We are presently developing a new technique for automatic evaluation of analogies in biologically inspired design, including the conceptual design that results from such an analogy [28]. This technique uses multiple strategies for analogy evaluation such as requirement checking, model checking, and qualitative analysis and simulation. As part of its evaluation, this technique will generate justifications for why an analogy is good or bad. We hypothesize that this kind of analogy evaluation resulting in justifications could potentially help address cognitive dissonance on a team because it should lead to better and more persuasive analogies.

8 Conclusions

In this paper, we reported on an empirical study of collaborative, interdisciplinary design. It is important to ground the development of case-based theories, techniques and tools in empirical studies of human behavior for at least two reasons. Firstly, empirical grounding of case-based tools increases the likelihood that humans will actually use them. Secondly, observations of human behavior sometimes lead to new inspirations for theory construction.

Our observations of human practices in biologically inspired design seem to present four kinds of opportunities for constructing theories of case-based reasoning. Firstly, our work suggests that analogies are useful for the tasks of design idea generation, design concept evaluation, design concept explanation, and domain concept explanation. Other studies indicate that analogies are also useful for problem formulation as well as problem reformulation. These findings raise questions about how can we repurpose existing case-based tools or build new case-based tools for these design tasks.

Secondly, our empirical studies indicate that cognitive dissonance occurs not only in individual humans as Festinger originally postulated, but also in interdisciplinary design teams. The degree to which this finding can be generalized to other human activities or other human social aggregates is presently unclear. However, it seems clear that yet another role of analogy is to reduce cognitive dissonance in human teams.

Thirdly, and more specifically, analogy is not only a mechanism for transfer of knowledge from a familiar situation to a new situation, but also a cognitive strategy for reducing cognitive dissonance on a team. In particular, analogy is also a strategy for inducing shifts in the perspective of a teammate and alignment of mental models when the mental models of teammates are not well aligned. This raises the hard question of how we can develop techniques for persuading a teammate to shift perspectives, align mental models, and thereby reduce cognitive dissonance on interdisciplinary design teams once the dissonance manifests itself. We expect that articulation of stronger, well-justified analogies would be more persuasive in inducing teammates to change perspectives. Thus, we are exploring a technique that relies on analogy evaluation: it critiques analogies and generates justifications for why they are good or bad.

Finally, and more generally, analogy is not only an internal cognitive process, but it is also situated in the external physical, information and social worlds of cognitive agents. Nersessian & Chandrasekharan [29] found that some analogies are situated in the world. Kokinov & Petrov [30] and Kulinski & Gero [31] found that analogy construction depends in part on external representations of artifacts. At last year's ICCBR conference, we presented a paper that showed that analogies in biologically inspired design typically are situated online [18]: Given a design problem, design teams typically find relevant biological analogies on the Web instead of retrieving them from their long-term memories. In the present study, we found that analogies often are situated in teamwork. This raises the deep question of how can we build new theories of analogy that take into account the affordances and constraints of the physical, information and social worlds in addition to the internal mental worlds of cognitive agents.

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