A Methodology for Supporting 'Transfer' in Biomimetic Design

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1. INTRODUCTION

A non-toxic anti-fouling coating for ships has been developed using shark scales as inspiration (Kesel and Liedert, 2007); a micro robot has been modelled after the locomotion of water striders (Suhr et al. 2005); composite beams have been created following the structure of plant stems (Milwich et al. 2006). These recent outcomes of biomimetic research illustrate but a small proportion of the productivity that can be generated from circulation of knowledge between biology and engineering (Schmidt, 2005).

It is possible to envisage a much broader use of structures and processes abstracted from nature in solving technical problems, when engineers have better access to existing biological knowledge, in terms of it being structured and interpreted in a way that makes this knowledge better tuned to the needs of the engineer. Even well-known biological solutions can trigger innovative solutions in engineering if the knowledge is available at the right time and in the right form – a common language with which the functionality of both biological and engineered systems could be expressed. Thus the progress in the development of interfaces between biology and engineering promises to have substantial synergetic benefits. One possible step in that direction is the adaptation of means for systematic solution-finding in engineering using biological knowledge. Recent attempts focus on tools belonging to TRIZ, a set of methods for systematic invention, especially contradiction analysis (Hill, 2005; Vincent, 2006). But besides TRIZ, results from advanced design research offer further possibilities, for example representations for structuring design knowledge. Once adapted to capturing functional knowledge about biological systems these could become powerful means for more systematic biomimetic transfer. In addition, the integration of a flexible approach for biomimetics into design methodologies could encourage more widespeard use of biological models. Available approaches span from biomimetics as an important, single tool to be used in the solution finding process (Vincent, 2006), to approaches that offer a complete process for biomimetic design (Hill, 2005).

The overall objective of this paper is to understand and support the biomimetic design process, in particular its critical step of biomimetic transfer[2].

In order to achieve this, we need to understand:

- the essential steps of the biomimetic process, and
- how and at what levels of abstraction of knowledge biomimetic transfer* – the core of the biomimetic design process – takes place.

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[1] The work presented here has been primarily carried out at the Centre for Product Design and Manufacturing, Indian Institute of Science, Bangalore, India. The design experiments carried out in Germany, as reported in this paper, have been carried out at the Bremen University of Applied Sciences.
[2] Transfer is defined as the reproduction of information from a model of a biological system in a model or prototype for a technical system. This understanding is based on Schmidt's description of biomimetics (2005, discussed further in Section 2 of this paper).

In order to identify the essential steps of the biomimetic design process, various biomimetic design approaches available from literature are reviewed, and those steps that are common across these processes are identified as essential steps for the biomimetic design process.

In order to facilitate analysis of the transfer process, the functionality of 20 biomimetic pairs, each containing a biological system and the technical system analogically learned from the biological system (details of these pairs are already available from literature) are modelled. The means of modelling used is the SAPPhIRE model of causality (Chakrabarti et al. 2005) – a model that uses multiple levels of abstraction of knowledge in order to explain how a system works to fulfil its goals. For each biomimetic pair analysed, the SAPPhIRE model of the biological system is compared with that of the corresponding technical system in order to understand the level of similarity between the two systems; this informs us about the levels at which biomimetic transfer actually took place in these pairs. Using the SAPPhIRE model, the levels of abstraction at which transfer seems to have taken place in these biomimetic pairs were distinguished; as a result, four distinct classes of biomimetic transfer that actually took place have been identified, and another level of transfer that is theoretically possible no no actual cases were observed, has also been postulated.

Based on the SAPPhIRE model, the findings from the above biomimetic transfer analysis, and the essential steps for biomimetic design identified in this work, a set of guidelines for a systematic biomimetic design process is proposed. The focus is especially on supporting the step of biomimetic transfer in this process. The guidelines are evaluated for their effectiveness in inspiring greater fluency in biomimetic design and transfer, using multiple technical design problems by multiple designers from India and Germany.

2. LITERATURE SURVEY

Even though research on its methodology has started to grow seriously only over the last decade, biomimetics is increasingly being envisaged as a design method with great potential for industrial research and development. Below, approaches to biomimetic, design methodologies and tools are reviewed.

Nachtigall (2002) distinguishes between two different perspectives on biomimetics: “technical biology” and “biomimetics”. He defines technical biology as “understanding nature with the means of technology” and biomimetics as “learning from nature for technology”. These approaches can be perceived as distinct perspectives, but each contributes to the growth of the other.

Schmidt (2005) elaborates on the concept of the interdisciplinarity and its implications for the philosophy of science, with biomimetics as a primary example. Schmidt points out that biomimetics involves an interdisciplinary circulation of knowledge rather than a unidirectional transfer. Only a part of biology knowledge as well as engineering knowledge is circulable; thus biomimetics does not start from biology or from engineering as a discipline, but from a rather undefined centre. Furthermore, for reasons best illustrated by the difference between map and territory (Korzybski 1933), a person will never have nature itself in mind nor a technical system, but ideas of nature and technical systems. The phrase “transfer from nature” obscures the fact that knowledge is instead transferred from a model of nature to a model of a technical system. This transfer process influences the model of nature too. Furthermore, some models become prototypes for a factual implementation, which also retro-acts on the models. Besides model transfer, propositions, operations, methods, standards and metaphysics diffuse between and beyond the involved disciplines. Schmidt distinguishes three kinds of circulation in recent biomimetics: (1) a circulation of constructions referring to structures, forms and materials based on a static understanding of nature, for example honeycombs being used as a prototype for optimization of components, (2) a circulation of functions, in which new functions and processes are learnt from nature, for example the transfer of the self-cleaning function of the lotus leaf to paint (Barthlott and Neinhuis, 1997) and (3) a nomological-mathematical circulation abstracting knowledge about processes, information and chaos based on a dynamic and evolutionary understanding of nature, for example genetic algorithms. Schmidt's distinction between construction and function biomimetics seems to become blurred in recent biomimetics as constructions are observed from the point of view of their functions, and from an increasingly more kinematic or even dynamic perspective. However, the description of biomimetics as circulation of knowledge is important to be kept in mind, as most methods and tools for supporting biomimetics describe only unidirectional transfer.

To aid biomimetics projects, Gramann (2006) proposes a relatively basic and practical procedure beginning with a technical problem. It has the following steps:

- Formulate a search objective, either in terms of a function or of constraints.
- Search for and assign a set of relevant biological systems: This step requires biological knowledge. Gramann offers an association list relating function categories and biological examples to aid search in biological literature.
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- Analyse the biological systems: often the knowledge available in literature is not sufficient for carrying out this step, and may require carrying out new experiments – a task of technical biology, as defined by Nachtigall.
- Evaluate the systems using the following steps:
  - Is the derivation of a technical analogy possible? If this is the case, the next steps are transfer and implementation of the analogy. Otherwise, the following step of evaluation is carried out.
  - Is the chosen level of abstraction right? If this is the case, the next step of evaluation is to be carried out. Otherwise, analysis of the biological systems has to be repeated at another level of abstraction.
  - Is the search objective realistic? If no technical analogy could be derived although the search objective is realistic and – as confirmed by the preceding step of evaluation – the level of abstraction was chosen right, the search for biological examples should be repeated more comprehensively, otherwise the search objective has to be reformulated.

Gramman's procedure focuses on the engineering pole of biomimetics rather than on circulation. It does not include any specification of how "derivation of technical analogies" and "transfer" should be pursued. According to Gramann in the step of analysis structural information has to be related to physical explanations. This implies that the kinds of information transferred are structures for which a physical explanation was found.

Hill (2005) proposes an orientation model for biomimetics divided into two parts: goal setting and solution identification. Based on contradicting demands identified in the goal setting part, the solution identification part comprises the following steps:

- Determine the basic function(s) underlying the contradicting demands. To support this, Hill provides biological function categories similar to the function categories of Rodenacker (1976) – the basic functions of form, change, transfer, store/balk, separate/connect, support/carry and the basic flows of material, energy and information.

- Identify relevant biological structures with same or similar functional characteristics. This step is supported by a catalogue of biological structures sorted according to the basic functions.
- Compile the identified biological structures in a table; analyse each to extract the underlying principles and make preliminary solution associations for each biological structure.
- Transfer the preliminary solutions into technical solutions according to the requirements and conditions of the goal (economic, technical-technological, ecological, social…).
- Vary and combine relevant characteristics of these solutions; enlist alternatives of each characteristic (size, number, situation, form, material, surface, transaction type, kind of conclusion) into a morphological table and identify possible combinations of these characteristics.
- Using common evaluation methods, evaluate the solution elements or complete variants to select the best.
- Elaborate the chosen solution.

Hill mentions that is the “structure elements” and “principles” that are transferred. However, “transfer” is not specified in any detail.

Vincent et al. (2006) developed a database of biological effects using the TRIZ set of methods, in particular contradiction analysis and the system operator(Terninko et al. 1998). With the aim of developing a synthesis of TRIZ and biomimetics, they first analysed biological solutions in terms of the contradiction matrix. Therefore actions in biology have been described using a logical framework that is based on the substance-field system of TRIZ. This is captured in their sentence “things (substances and structures) do things (requiring energy and information) somewhere (in space and time)”. Thus the basic constructs for describing biological actions are substance, structure, energy, information, space and time. These constructs are used to reorganize the TRIZ contradiction matrix. The result is a modernized contradiction matrix (called PRIZM) in which the formerly 39 conflicting parameters are categorised by the above six constructs. According to the authors, it has the advantage of being clearer and more logical than the old contradiction matrix as all fields are filled and the constructs of the action representation are used. Nevertheless, the representation is not as detailed and precise as before. Using a tool based on this, 2500 conflicts and their resolutions in biology are analysed. The 40 TRIZ solution principles have been found to be sufficient to describe the biological solutions, but they are now assigned to the conflicts in a different way. The resulting Matrix is called BioTRIZ matrix. As the inventive principles are possible to be summarized within the six constructs, Vincent’s group has been able to infer the following about the means by which conflicts were resolved in these systems: For scales up to 1m, information and space are found to be the most common means for conflict resolution in biology, whereas in technology, energy and materials have been used more often. Therefore they concluded that a large number of new technical solutions involving information and space can potentially be learned from biology..

In a further step, Vincent et al. (2006) developed a framework for capturing biological data in a way compatible with technology. Biological data is subdivided corresponding to the technical functionality and its requirements. Auxiliary conflict matrices for biological structures and environments and for causes and limits of actions have been developed for the purpose of taking into account the primary TRIZ components “function”, “effect” and “conflict”. The resulting chunks are described in terms of object parts, the environment in which the objects operate, the limits and causes of an action, the ultimate purpose of the action, and the resources and auxiliary systems.

The above work aims at making biological principles available in TRIZ solution processes, resulting in a model of the biological functionality for use in databases to support the designer. It, however, does not address the issue of specifiying steps of the transfer process. While the functional model used in this work allows integration with the contradiction matrix, it does not make any attempt to relate the constructs of the model in a logical manner, e.g., how structural attributes, physical effects and functions relate to one another.

In their work on the use of analogies for developing breakthrough innovations, Schild et al. (2004) propose a systematic approach for finding analogue solutions to a given problem. It comprises the following steps:

- Problem formulation at an adequate level of abstraction: To arrive at a practical problem definition, consider the following aspects
    - Identify general conditions important for the success of a solution
    - Identify contradictions, break problem down into sub problems, consider the relations between sub-problems
    - Integrate the views of customer
- Evaluation: Is a search for analogies promising? Is the problem a creative problem or is it well structured and can be solved by a known algorithm?
- Search for analogies: Follow these steps
    - Begin with the knowledge of the team
    - Evaluate: Which search strategy should be used?
    - Search: Ask people in the social network when the problem definition is vague'; for more concrete problems, search in existing databases.
- Verification and evaluation
    - Verification: Is the analogue system well understood? Are relevant structures and functions identified?
    - Evaluation regarding transferability: Four levels of transfer are proposed:
        1. Direct transfer of an existing technology to a new context,
        2. Transfer of structure,
        3. Partial transfer of functional principles, and
        4. Use of an analogy as idea stimulus
    - Consider technical and commercial success factors to develop a suitable solution

This process is not necessarily linear – feedback loops or repetition of activities may have to be carried out, for example when new requirements are discovered.

Although this systematic approach for finding analogue solutions is not specific to biomimetics, it contains two special features that are particularly useful for biomimetic design processes. First, the evaluation of whether a search for analogies is promising is often forgotten in pure biomimetic design processes. Second, the step "verification and evaluation of analogous solutions" specifies analogue transfer by distinguishing the four levels of transfer described above.

2.1 SUMMARY OF BIOMIMETIC PROCESSES

Biomimetic procedures of Gramann (2006), Hill (1997, 2005) and Schild et al. (2004) are compared in this section. It is found that these biomimetic procedures have the following steps in common:

- Formulate search objectives

- Search for biological analogues
- Analyse biological analogues
- Transfer.

Table 1: Comparison of three approaches for the procedure of doing biomimetics. Column 4 shows the essential steps abstracted from the steps listed in the same row.

Gramann	**Hill**	**Schild et al.**	**Summary**
Formulate a search objective	Determine the basic function(s) underlying the contradicting demands	Problem formulation including success factors, contradictions and the views of the customers	Formulate a problem/ search objectives
		Evaluation: Is a search for analogies promising?	
Search for and assign a set of relevant biological systems	Identify relevant biological structures	Search for analogies: Ask people in the social network or search databases	Search for biological analogues
Analyse the biological systems	Analyse the biological structures: extract the underlying principles, associate preliminary solutions	Verification: Is the analogue system well understood?	Analyse the biological systems
Evaluate the systems, whether a transfer is possible, else review the previous steps	Transfer the preliminary solutions into technical solutions	Evaluation regarding transferability: 4 levels of transfer are proposed	Transfer
Implement the analogy	Vary and combine relevant characteristics of these solutions		
	Use common evaluation methods to select the best		
	Elaborate the chosen solution		

The following steps are different among the procedures:

All procedures contain some evaluation phases. But their positions in the process differ: The procedure of Schild et al. (2004) is the only one that includes an evaluation of whether or not a search for analogies is promising. In Gramann's procedure, an evaluation is conducted only if the derivation of a technical analogy of the biological system fails. Based on the results of this evaluation, he proposes iterations of his procedure from suitable previous steps onwards. In Hill's procedure, analogue solutions are derived from all examples, and an evaluation is conducted only at the end after varying and combining structure elements.

By analysing the above procedures using the systematic design process of Pahl and Beitz (1996), we conclude the following. All the above procedures are intended to support the phase of conceptual design. Hill's procedure also includes guidelines for problem analysis and for transition to embodiment design. In contrast, the procedure of Schild et al. provides specifications for problem analysis, but not for embodiment design, while Gramann's procedure focuses on conceptual design and begins after the problem is already analysed.

Regarding implementation of the common steps, the following differences are found among the procedures:

- Basis for search for analogues: Gramann proposes to use either function or similarities in constraints as the basis for the search. Hill's guidelines recommend identification of contradicting parameters; these are used only to identify an underlying basic function and not as separate search criteria. Schild et al. do not specify any search criteria.

- Support for the search: Search is supported with an association list based on functions and fields in Gramann's approach, and with catalogue sheets sorted according to relatively abstract function-flow combinations in Hill's approach.
- Analysis: According to Gramann, relating structural information to physical explanations is required for analysis, while Hill suggests abstracting the principle of the identified structures; Schild et al. recommend identification and understanding of relevant structures and functions as the basis for analysis.
- For Transfer, no guidelines are specified in Gramann's and Hill's procedures. Schild et al. go a bit further by describing the four levels at which transfer may be possible.

The biomimetic design processes examined above provide some formalisation for problem formulation, search of analogues in biology and evaluation of those analogues. The transfer of abstracted principles and structural requirements are also mentioned, but no specific guidelines have been proposed for systematically supporting the process for the transfer step. Formalising this step should help advance this as well as the other steps of the biomimetic design process.

2.2. SUMMARY REGARDING DATABASES

There is considerable variation in opinion among researchers as to how a biological database should be structured and used for aiding designers in a biomimetic design process. Vincent (2006) and Hill (1997) both structure the information in biological examples to develop databases for use in biomimetic design, while Gramann questions such an approach because of the vast amount of and variety in biological knowledge. Furthermore he argues that descriptions of biological systems can hardly include all the information required for any technical request that may be associated with them. His answer is not to structure the information in biological examples, but simply to create an association list relating function-field combinations and biological examples.

A similar but more comprehensive approach is chosen by Shu et al. (2007), who used the enormous amount of biological information that is already available in natural-language format, such as books, journals, etc. They developed a method that uses natural language processing to extract relevant biological phenomena from these existing sources of biological knowledge. They use a natural language model (i.e. subject-verb-object) to identify "bridge verbs" to connect biology and engineering lexicons, and bridge cross-domain terminology for searching biological knowledge to support biomimetic design. Once relevant biological phenomena are found, designers can apply analogical reasoning to transfer knowledge from the source domain (i.e., biology) to the target domain (i.e., engineering).

Hill's catalogue sheets capture knowledge about biological structures and their functions, while the database by Vincent et al. describes biological effects more comprehensively. One central problem in this approach is the distribution of biological functionality over several levels of scale and complexity, most often described in a hierarchical fashion. The quest for an adequate functional representation of biological systems that is suitable for the purposes of engineering design seems to be a central, unsolved problem. In the descriptions in Hill's catalogue sheets and in Vincent et al.'s database, there is no explicit and objectively defendable relationship between function and structure of biological systems. Functional representations from product design, like the SAPPhIRE model used in this work, might be helpful to resolve this issue. SAPPhIRE model, which is used as a behavioural language in IDEA-INSPIRE (Chakrabarti et al., 2005), has been developed with the specific purpose of describing the functioning of both technical systems and natural systems.

Furthermore, the characteristics of transfer and transferred knowledge need to be identified in order to support, e.g. develop database structures to provide required knowledge, to aid the transfer process.

2.3 PROBLEM SPECIFICATION

Based on the above review of literature, the main issues to be addressed in this work are identified as follows:

- Is the SAPPhIRE model adequate for capturing transferred knowledge?
- In terms of SAPPhIRE: What kind of knowledge is transferred? How can the transferred knowledge be classified?
- How can the transfer process be specified?

3. RESEARCH METHODOLOGY

To arrive at a formalization of and guidelines for biomimetic transfer, it is necessary to analyze biomimetic transfer processes and their outcomes. However, while a variety of cases of transfer are reported in literature, accounts of the transfer processes used in these have not been reported. To circumvent this problem, these cases have been analysed to understand the outcomes – the biological systems and the artefacts developed with inspiration or learning from these biological systems – and the similarities between them. The assumption has been that the similarity between the two systems would throw light upon the level at which transfer took place. The transferred knowledge is then classified, and guidelines developed from this knowledge to support enhanced fluency of transfer. Finally, a series of design experiments are carried out to evaluate these guidelines by comparing the performance of designers when they use these guidelines in carrying out biomimetic design, with that when they use the general biomimetic guidelines extracted from existing approaches (taken as the benchmark).

Note that there is no immediate access to biological systems themselves but to models of biological systems. Therefore it seems difficult to analyze directly the relations between biological systems and corresponding, analogically developed technical systems. Thus we compare models of the functionality of the biological systems (i.e. how these systems work to promote their survival and reproduction) and that of the artefacts created using these systems as biological analogue. The source functionality in the biological system as well as the correspondingly developed functionality in the technical system is modelled in terms of the SAPPhIRE model of causality.

The SAPPhIRE model was developed for capturing the functionality of systems in general – systems that use physical phenomena for attaining their goals. It was originally developed for supporting product design, by providing causal descriptions of systems – both biological and technical – as stimuli for inspiring ideation for designers searching for solutions to design problems (Chakrabarti et al., 2005). The SAPPhIRE model consists of the following constructs (Srinivasan and Chakrabarti, 2009):

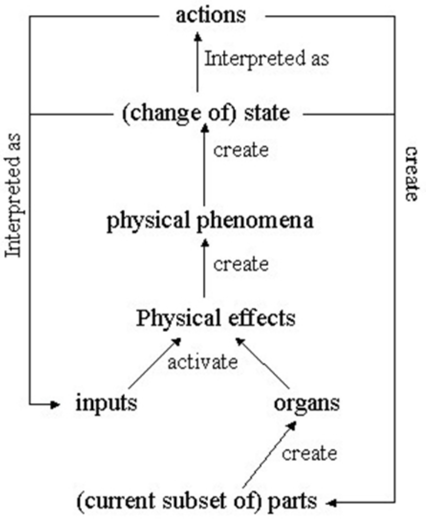

Figure 1: The SAPPhIRE Model of Causality

Parts: A set of physical components and interfaces that constitute the system of interest and its environment.
Physical phenomenon: An interaction between the system and its environment.
State: A property time of the system (or its environment) that is involved in an interaction.
Physical effect: A principle of nature that underlies/governs an interaction.
Organ: A set of properties and conditions of the system and its environment required for an interaction between them.
Input: A physical variable that crosses the system boundary, and is essential for an interaction between the system and its environment.
Action: An abstract description or high-level interpretation of an interaction between the system and its environment.

The relationships between these constructs are as follows: Parts (P) of a system and its surroundings *create* organs (R), which are the structural requirements for a physical effect (E). A physical effect is *activated* by various inputs (I) on the organs and *creates* a physical phenomenon (Ph), and changes the state (S) of the system. The changes of state are *interpreted* as actions (A), as new inputs, or as changes that *create/ activate* parts (Figure 1).

Based on the assumption that using the SAPPhIRE constructs, all transferred knowledge can be captured and distinguished into useful and causally-related categories, the SAPPhIRE models of the biological and corresponding technical systems are taken as estimators of the biological and the analogically learned technical functionality.

In order to identify and select a reasonable number of examples of such biomimetic pairs, a large number of such cases have been collected from literature, and modelled using the SAPPhIRE constructs (Table 2 shows an example pair). These are then pruned to a final list of twenty example pairs, based on the criterion that the description should be sufficiently detailed to enable creation of SAPPhIRE models of the functionality of the pair. In most of the examples, several SAPPhIRE instances have been required for describing the functionality, each instance explaining, for example, how one state change took place in a sequence of state changes embodying a given action.

The SAPPhIRE constructs of each biomimetic pair are then compared and analyzed in order to assess the role of each single construct in the transfer process. They are classified and labelled according to two classifications:

1) Each SAPPhIRE construct of the biological system is compared with that of its corresponding technical system to determine how similar the two systems are for that construct. Five different levels are used to express the degree of similarity: (1) different: 0% similarity, (2) somewhat similar: 25% similarity, (3) similar: 50% similarity, (4) very similar: 75% similarity and (5) same: 100% similarity.

2) An evaluation of the transfer operation is then carried out. Constructs are categorized as “transferred” if the following conditions are satisfied:
    - Parts: if material and structure were copied or mimicked.
    - Organs (as well as attributes, as discussed in Section 4.1): if these are found to be very similar to those of the biological system and achieve a similar function.
    - Inputs: if they were introduced to the technical system due to learning from the biological model.
    - Phenomena and state changes: if the learning was not about how a phenomenon or state change can be achieved, but about by which phenomena/state changes a function can be achieved.
    - Actions: if a similar or the same action was part of the sequence of actions in both the biological and the technical system.

Transfer of physical effects is considered impossible as these cannot be copied directly; the same physical effects would be activated only if appropriate organs and inputs were transferred and brought together.

Constructs are labelled as “given”, if the value of the construct is already fixed by the formulation of the technical problem. Constructs are labelled as “changed”, if an adapted version of their value in the biological example occurs in the artefact.

Each label is then given a score: every SAPPhIRE construct labelled as only “transferred” is scored as having 1 “transfer”-point. If a construct was labelled “transferred” as well as “changed”, 2/3 “transfer”-point is given. If the transfer is considered as the result of another transfer, 1/3 “transfer”-point is given. This gradation was used to emphasise those constructs that seem to have been central to the transfer. Any label “given” is graded for 1 “given”-point. Here combinations with other labels are not considered. The question asked is which constructs are generally influenced by constraints or requirements. The label “changed” is given 1 “changed”-point. If it is ascribed in combination with other labels, 2/3-“changed”-point is given.

The comparison of the similarity, as described above, is not yet very objective as it is unclear what the different degrees of similarity mean for the different constructs. The labels “given” and “changed” turned out to be too arbitrary because of the lack of clarity in their definitions and lack of knowledge about the transfer processes. Besides, there are still some contradictions regarding the classification of constructs as “transferred”: Transfer of parts or organs necessarily involves transfer of other constructs, but it is not always possible to say at which construct the transfer began. As one SAPPhIRE instance describes an action on several levels of abstraction, it made more sense to use the SAPPhIRE model to distinguish levels of abstraction in biomimetic transfer. Thus four classes of transfer were obtained using SAPPhIRE model as the basis:

- Copy parts: Parts are copied in order to transfer all actions of a biological example. An example is the case to produce the biological material nacre/mother-of-pearl using technical means.

- Transfer attributes: One or several attributes are transferred in order to achieve an analogue action. Shaping a car according to the body shape of box fish is an attribute transfer – a drag reducing effect of the shape is assumed, but the exact organs can not be identified.
- Transfer organs: One or several organs are transferred in order to achieve an analogue action. For example microstructures and material properties of plants have been transferred to achieve the self-cleaning effect of the lotus plant.
- Transfer state changes: A sequence of state changes or actions or a single state change is transferred in order to achieve an analogue state change or action. Computer Aided Optimisation (CAO) mimicking the growth of trees to reduce tension in mechanical components is a result of a state change transfer, while the organs involved in the growth of trees are not in focus.

All twenty biomimetic pairs are then analysed to identify whether any of these four classes of transfer took place. A fifth class can also be proposed where an action is transferred:

- Transfer a new action: A new action is learned from the biological example.

However, transfer of action usually does not occur in biomimetic processes that begin with a technical problem, where the required action is already determined and specified, unless the action originally posed is changed by the user after seeing action involved in the biological example for its greater suitability to the goals which the technical problem is meant to fulfil

If a function includes more than one instance of the SAPPhIRE model for action and state-change transfer, a distinction between transferring a sequence of state changes or actions and transferring a single state change or action is possible. Transfer of a sequence of actions could also occur in biomimetic processes that begin with a technical problem. Correspondingly in organ transfer, a combination of organs may be transferred instead of a single organ.

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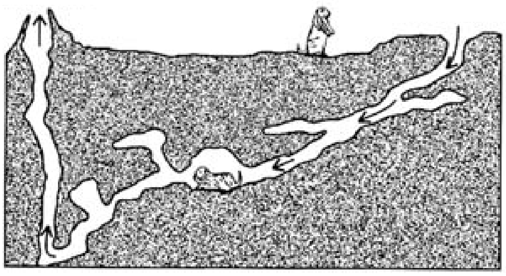

Figure 2: Prairie Dog Den (Nachtigall 2002)

For each biomimetic pair analysed, the description of the functionality has either been found from literature, or from popular science descriptions on the internet.

Table 2: The prairie dogs den (See Figure 2) and the correspondingly learned ventilation system (Nachtigall 2002) described in this research in terms of the SAPPhIRE model

	Biological System	Technical System
System under consideration	Ventilation System: Prairie Dog Den	Ventilation System: Building

Parts	Den: Heightened entrance, Plain entrance	Building: Roof with an opening, Opening on the side of the building
Organs (further parameters, adequate values)	Obstruction created by heightened entrance	Obstruction created by building
Input	Wind	Wind
Physical Effect	Bernoulli’s effect	Bernoulli’s effect
Phenomena	Reduction of static pressure on heightened entrance	Reduction of static pressure on roof
Change of State	From given pressure to lower pressure on heightened entrance, no change on plain entrance	from given pressure to lower pressure on roof, no change on side opening
Action	Generate pressure difference between entrances	Generate pressure difference between entrances
Parts	Den, Air in den	Building, Air in building
Organs (further parameters, adequate values)	Fluidity and density of air, spatial connection and flow path between entrances formed by den	Fluidity and density of air, spatial connection and flow path between entrances formed by building
Input	Pressure difference between entrances	Pressure difference between entrances
Physical Effect	Bernoulli effect	Bernoulli effect
Phenomena	Low pressure on entrance sucks air out of den	Low pressure on entrance sucks air out of building
Change of State	From air in rest to airflow	From air in rest to airflow
Action	Generate ventilation in the den	Generate ventilation in the building

4. RESULTS:

4.1 MODIFICATION OF SAPPhIRE MODEL AND AN EXPLANATORY EXAMPLE

For modelling biomimetic examples, the SAPPhIRE model has been slightly modified. Two more constructs are added: *premises*, as introduced by Chakrabarti and Taura (2006), and *attributes*. The SAPPhIRE constructs, including the two new constructs, are used in the way described below. Absorption of infrared radiation in the window cells of the “babies’ toes” leaves provides an illustrative example (Nachtigall, Bluechel 2000). These plants are also called window plants and correspond to the genus *fenestraria*.

- *Parts* are a set of physical components and interfaces that constitute the system or its environment. They may therefore belong either to the organism or artefact under consideration or to its environment. A distinction between the organism and its environment would be relatively arbitrary as it is a distinction due to the focus and interest of the observer. In the example, the parts include the aqueous cells on the top of a babies toes leaf and the water contained in these cells.

- *Attributes* belong to the parts, and include organs. But as organs are mentioned separately, the attribute constructs are used to describe only those properties that are not necessary for activating the effect under focus. Thus there is one possible reason for mentioning an attribute: It can act as an organ for a different, closely related action which is not under focus in the description under analysis; since the attribute is relvant for a closely related action, it may be interesting to a designer as it can fulfil further, related requirements or constraints. An attribute of the babies toe's leaf is the form of the transparent area on the top – it is not required for the action under focus here – absorption and transmission of light. But it substantially affects *how much* light is absorbed at a given position of the sun and how the light is *distributed* by refraction within the leaf. Both may be represented in other SAPPhIRE instances and is reduced to an attribute for the action under focus here.

- *Organs* are a set of properties and conditions of a system and its environment required for an interaction between them. These are part attributes that are necessary for the activation of the physical effect. The organ for absorption of light is the absorption coefficient for infrared light of the aqueous cells and the water. As the transparency of the material is also necessary for the effect to take place at a depth within the material, the attenuation coefficient is also required. A qualitative specification of the values of both coefficients may also have to be used in absence of quantitative information, such as: the absorption coefficient has to be relatively high, while the attenuation coefficient ought to be low.

- *Inputs* are physical variables that cross the system boundary, and are essential for an interaction between a system and its environment. They are material, energy or signal flows activating the physical effect by acting on the organ. In the example, the input is sunlight.

- Physical effects are principles of nature that underlies/governs an interaction. The physical effect used in the example is the Beer-Lambert law relating absorption of light to the properties of the material through which the light is travelling.

- *Phenomena* are interactions between a system and its environment. These are the consequences of the physical effect activated due to an input on the organs, as specified earlier. The absorption effect in the babies' toes' window cells results in transmission and reflection of sunlight, in absorption of infrared light, and increase of (heat) energy in the aqueous cells.

- The *State* are the properties at an instant of time of a system, that are involved in an interaction. A state change can be expressed in the form "from state1 (before the physical effect was activated) to state2 (afterwards)". The change can be in the input flow or in the parts. Several state changes may have to be described. State changes can be interpreted as actions or new inputs for further SAPPhIRE instances; these can even create or activate parts. In the example, the following state changes are used: from given energy to higher energy in the window cells; from given spectrum of light outside the plant to spectrum with lower infrared intensity inside. The former state change can become an input for a further SAPPhIRE instance on the irradiation of warmth by the window cells, the latter for instances on the processes inside the leaf.

- *Premises* are sometimes necessary to aid in the interpretation of a state change as an action (Chakrabarti, Taura, 2006). Premises provide an explanation as to how a state change can be interpreted as a specific action, and thereby provides the latitude for a designer to express the needs of the design at any level of abstraction while still being able to solve it at well-posed levels of abstraction such as state changes. In the example of the babies' toes leaf, no premise is required to interpret the state change into an action. But in a SAPPhIRE instance describing the decrease in air density due to warming, the premise "surrounding air stays cool" allows one to interpret the state change into the action "increase buoyancy of air".

- *Actions* are abstract descriptions or high-level interpretations of an interaction between a system and its environment. They often express the purpose of the system, but not always. Sometimes SAPPhIRE instances are even used to describe the problem solved by the system. In these cases the action summarises the problem. The action taking place in the window cells is to "transmit and filter light". (Chakrabarti et al., 2005).

In the explanation of actions for some biological systems, the required physical effects and organs are known only in a broad sense. The organ construct is used to describe attributes related to the phenomenon, state change or action, and the attribute construct in these cases is used for describing those properties of the system which may not be directly related to the effect. If a simplified physical model allows a vague explanation or description of the phenomenon or an effect involved on the molecular scale without explaining the macroscopic phenomenon comprehensively, the effect may be noted. We call this way of using the SAPPhIRE model the fuzzy SAPPhIRE model and is marked by italic fonts. A typical example for the use of the fuzzy SAPPhIRE model is the description of a fluid-flow around a complex three-dimensional body. The form of the body is classified as the attribute and Navier-Stokes-Equations are a law that may enable a numeric calculation of the flow. Thus Navier-Stokes-Equations is mentioned as the effect.

Furthermore, it sometimes appeared useful to describe a system on a relatively abstract level, when the physical effects' level provides too much detail. One example for this is a description of communication among dolphins: it was crucial for the transfer to understand which characteristics of the signal help to overcome which problem of under-water communication, but not the physical phenomena and effects responsible for generating and sensing these signals. In such cases, only parts, inputs, state changes and actions, and occasionally premises and some attributes related to the state change are specified. This adapted model can also be used to summarize several SAPPhIRE instances on the physical level into one SAPPhIRE instance at a more abstract level. This enables organizing functionality in organisms into hierarchies. As descriptions of function usually focus on causality at a certain level of abstraction and within a constrained range of scales, the abstract instances are used to summarize actions where the physical effect is not of interest or on much smaller scales. In these descriptions, only a sequence of state changes or actions and some related attributes are captured without complete causality or physical explanation up to the lowermost levels of abstraction.

4.2 RESULTS OF THE ANALYSIS

The overall similarity at the level of each SAPPhIRE construct, between the biological and the technical systems considered in the twenty biomimetic transfer cases used in this work, is expressed using a "degree of similarity" scale (between 0%-100%), as explained in Section 3. At each SAPPhIRE level, each SAPPhIRE instance expressing the biological systems in the above cases is compared with the corresponding instance in the technical systems, and based on the degree of similarity between the instances, a degree of similarity value is assigned; these values are added up and divided by the number of instances to obtain the overall similary between these systems at this SAPPhIRE level of abstraction. The degree of similarity for each construct is shown in the second row, Table 3. The biggest similarities between biological and technical examples are found at the "physical effects" level. Regarding "actions" and "premises" the similarity is also over 90 percent. The constructs "change of state", "input", "organs", "phenomena" and "attributes" show similarities between 60 and 80 percent. The least similarity is found for parts.

Note that while there can be similarity at multiple levels of subtraction between the stimulus (i.e. biological instance) and the target (i.e. the corresponding instance in the resulting technical solution), the transfer is taken to have happened at the highest levels of subtraction among these. "Transfer Frequency" (Row 3, Table 3) is used to assess the number of instances in which transfer happened, for each level of abstraction. Transfer Frequency for a given level of abstraction is calculated by adding the "transfer points" (Section 3) for that level of SAPPhIRE abstraction for each SAPPhIRE instance.

Most often the constructs "organs" and "action" are labelled "transferred" – transfers of these constructs were found in more than 50 pairs of SAPPhIRE instances (even though there are only twenty biomimetic transfer cases, many of these cases have multiple SAPPhIRE instances to explain their action). The overall number of pairs of SAPPhIRE instances in the twenty biomimetic cases has been found to be 81. Just over 10 transfers are found for "phenomena", "parts" and "state changes".

The numbers in Rows 4 and 5 in Table 3 are the sum of the "Given" values (for Row 4) or "Change" (for Row 5) values for each construct from all the SAPPhIRE instances of the biomimetic pairs. The inputs (as explained in Section 3) are classified as "given" in 30 out of 81 cases (i.e., inputs are pre-specified in the problem statement itself), and actions are found to be "given" in 22 out of 81 cases. This shows that both input and Action are pre-specified in the problem statements. "Change" seems to have taken place in very few instances.

A biological example and a technical system can either use the same physical effect or different physical effects. One criterion for the selection of the examples was that they should involve a biomimetic transfer. As transfer is more apparent in examples where physical learning took place, the probability was high that the physical effects are the same instead of different. This may explain the similarity of biological and corresponding technical system concerning "physical effects". Several circumstances contribute to the similarity in actions. First, SAPPhIRE models of the biological and technical systems in the cases were developed by the researcher in parallel. Thus only those actions of biological systems were modelled that have a counterpart in the technical system. Second, because of that technical context, the state changes of the biological example were interpreted into actions in a similar way as in the technical example. Third, similarity of actions is a requirement for biomimetic design: If no state change in the biological example can be interpreted as the desired action of the technical solution, a transfer is not worthwhile. Further explanations, premises occurred too seldom to draw conclusions from their similarity. But the finding of least similarity in "parts" reflects that copying parts usually does not make sense in biomimetics as biological structures are too complex and requirements and constraints of a technical system differ substantially from those of biological systems.

The analysis about transferred constructs shows that most often "organs" and "actions" are transferred and "input" is typically given by the problem description. However, the high frequency of transferred actions is probably caused by the fact that transfer of any construct from one to another SAPPhIRE instance often leads also to transfer of the action.

Table 3: The results of the analysis: The percentages in line 1 correspond to percentage of similarities in the different constructs between the biological and technical descriptions. The numbers in lines 2-4 indicate how often the constructs were labelled with the respective label (see Section 3 on "Research methodology").

		Parts	Attributes	Organs	Input	Physical Effect	Phenomena	Change of State	Premises	Action
Similarity	Overall degree of similarity in percentage	50.88	62.50	70.89	73.58	96.18	68.48	78.20	92.39	95.21
Transfer	Transfer Frequency	10.17	1.00	53.33	3.00	3.67	11.33	10.33	1.33	53.00
	Overall number of value "given"	8	0	10	30	1	1	3	0	22
	Change Frequency	2.33	0.00	11.00	0.00	0.00	0.00	0.00	0.00	1.67

Table 4 shows the classes of transfer that took place in the twenty biomimetic cases analysed. The most important finding is that all four classes of transfer proposed in Section 3 have been found to have taken place in these cases. Most of the transfers have been found to be organ-transfers, followed by the closely related attribute transfers. Two state-change transfers are found. One case related to material is found, and is categorised as a transfer of parts.

Table 4: The different classes of transfer and the number of times they occurred in the 20 biomimetic pairs

Classes of Transfer	Number
Sub function/State change	2
Organs	10
Attributes	7
Parts	1

5. GUIDELINES

In this section, we describe two sets of guidelines. "Guidelines Standard" has been developed to encapsulate the generic steps of the biomimetic design process proposed in Section 2.1, and the recommendations specific to each of these steps as found from existing literature. "Guideline with SAPPhIRE" is proposed to follow the same generic steps as in Guideline Standard, but with specific guidelines for using SAPPhIRE constructs as part of the process in all the stages. Also, the five classes of transfer proposed in this work in Section 3, are recommended to be systematically used in the analysis and transfer stages. This is expected to lead to a greater number and variety of biomimetic design alternatives.

5.1 GUIDELINE STANDARD

The standard guidelines were summarised from literature findings.

1. Problem analysis
    - 1.1. Identify the required *function* from the problem description
    - 1.2. Identify the most important *requirements* and *conditions*

2. Analysis of the biological example
    - 2.1. Identify relevant *functions* of the biological example
    - 2.2. Identify solution *principles* in the biological example (abstract and concrete ones)
    - 2.3. Identify *structure* of the biological example related to the *principles*, if any

3. Transfer
    - 3.1. Use biological *principles*/ *structures* into solutions for the problem
    - 3.2. Adapt the solutions to the *requirements* and *conditions* of the problem.

5.2 GUIDELINE WITH SAPPhIRE

1. Problem analysis
    - 1.1. Identify the required *function* from the problem description.
    - 1.2. Identify the most important *requirements* and *conditions*.
    - 1.3. Identify which *parts*, *attributes* and *inputs* are already determined by the problem description.

2. Analysis of the biological example
    - 2.1. Identify relevant *actions* and *instances* of the biological example
    - 2.2. Evaluate for each *action/instance*: Which kinds of transfer are most promising?

      Kinds of transfer:
        - a) Transfer a *sequence of actions*
            - if a direct technical implementation of the actions using existing artefacts is feasible and desirable
            - if knowledge about how the *actions* are achieved in biology is not necessary for an implementation
        - b) Transfer (a sequence of) *state changes*
            - if a technical implementation of these *state changes* is feasible and desirable
            - if knowledge about the physical background of the *state changes* in the biological example is not necessary
        - c) Transfer *organs* and *inputs*
            - if you want to transfer the *physical effect* and *phenomenon* of an *action* and understanding of the related *organs* is available
        - d) Transfer *attributes* and *inputs*, trying to achieve the *physical effect*
            - if you want to transfer the *physical effect* and *phenomenon* of an *action* and the *organs* are not yet known (not given in the SAPPhIRE description)
        - e) Copy *parts*
            - if you want to make use of all *functions* of the parts and if the *parts* are not too complicated
            - if no other way of transferring the *parts' functions* can be found

    - 2.3. If you want to transfer a *sequence of actions* or *state changes* (Transfer types a or b above)

    - Identify the transferable *state changes* or *actions*
    - Go to Step 3.1. (Transfer)

2.4. If you want to do a transfer at the *attribute*/*organ* level (Transfer types c or d above)
    - Identify which *attributes*, *organs* and *inputs* you want to transfer. These are the transferable elements.
    - Go to Step 3.2. (Transfer)

2.5. If you want to copy *parts* (Transfer type e)
    - Identify all materials and the exact arrangement of materials
    - Go to Step 3.3

3. Transfer

3.1. If you want to transfer a *sequence of actions* or *state changes*
    - Find implementations from technology providing these *actions* or *state changes*

3.2. If you want to do a transfer at the *attribute*/ *organ* level
    - Use transferable elements into solutions for the problem or parts of the problem
    - Adapt the size, orientation and further variables of the transferred elements to the *parts*, *attributes* and *inputs* given by the problem description and to the *requirements* and *conditions* of the problem

3.3. If you want to copy *parts*
    - With this kind of transfer the arrangement of materials already is the final solution

3.4. Maybe some single transfers of (sequences of) *actions* or *state changes*, *organs*, *attributes* or *parts* do not solve the problem completely but parts of it. Put them together into as many complete solutions as possible.

Appendix I contains the Glossary of Definitions for the terms in italic above.

6. EVALUATION

The two guidelines have been evaluated by a set of design experiments, in each of which designers have been asked to find solutions to a given design problem. The designers have followed the guidelines while using a given description of one analogue biological example.

6.1 EXPERIMENTAL SETUP

The design experiments have been carried out in two consecutive design sessions. In the first session, four designers participated; two of them, within what will henceforth be referred to as Group 1, individually solved Problem 1 (see Table 5 below), while the other two, in Group 2, solved Problem 2. Each designer worked individually, carrying out the design task using a natural language description (Appendix II) of a specific, given analogue biological example and the standard biomimetic guidelines described in Section 5.1. The design task and the biological example have been kept the same for all members of one group. In the second session, the same four designers participated; the designers in Group 1 had to individually solve the design task which the members of Group 2 had solved in the first session, using the description of the corresponding biological example but using the Guidelines with SAPPhIRE described in Section 5.2, and vice versa (Shown in Table 5). In this second session, a SAPPhIRE description is also added to the description of the biological example used in the first session. It contains the information from the example description and information that can be inferred from it, but provided in a SAPPhIRE structure (See Appendix II). Before each session, an introduction to the respective guidelines is given by the researchers, followed by an example problem solving session coached by the researchers in which all the designers participated, to make sure each designer understood the general task and the guidelines. The participants are then provided the design task to be carried out and are asked to develop as many solutions as possible; no time constraint has been imposed. The designers are asked to mark every description or sketch which they consider a solution, with a unique serial number. While they have not been allowed to speak among themselves, the designers could ask for any clarification to the researchers who acted as the experiment supervisors. Between the sessions also, the designers have been asked not to speak about the problem they worked on to anyone else. The second session took place several weeks after the first session.

The number of biomimetic and feasible solutions for each given problem developed by the designers is taken here as an estimator for the performance – of the usage of the respective guidelines and associated descriptions of the stimuli. The solutions proposed by the designers have been reviewed and classified by a team of three people with engineering background to make sure that the team is able to assess technical feasibility of the solutions and that the review is not biased to a single reviewer. For each solution developed, the team had to decide first whether the respective design solution can be considered a *feasible* solution in the sense that it tackles the problem of the design task, and a technical implementation can be imagined that would solve the problem. Second, it was decided whether the design solution can be classified as biomimetic, i.e., whether there is any aspect of the solution that is not contained in an earlier solution developed by the same designer in the same session but is learned from the biological example. For any of these decisions, the members of the team had to discuss among themselves until they came to a consensus. In the cases where consensus could not be reached, as that the cases could be classified differently based on different but internally logical interpretations, half points were given, see Table 9-10.

The designers' educational background was either in engineering, product design or in biomimetics (see Tables 7-8 below). The design tasks were developed from biomimetic examples from the examples list. They comprised an aerodynamics problem and tasks to illuminate or aircondition houses (see Table 6 below).

Table 5: Design Sessions

Groups	Design Sessions	
G_1	Problem 1 Biological Example 1 Standard Guideline	Problem 2 Biological Example 2 SAPPhIRE Guideline
G_2	Problem 2 Biological Example 2 Standard Guideline	Problem 1 Biological Example 1 SAPPhIRE Guideline

Table 6: Problems and Biological Example

Problems		Biological Examples	
Problem 1 (India)	Develop concepts for hindering or at least reducing	Biological Example 1	Top feathers on the wings of sea-gulls – reverse

	the stall effect in aircraft.	(India)	flow brakes hindering stall
Problem 1 (Germany)	Develop a house for hot areas/ desert. It should implement following solutions: • Natural illumination inside the house in daytime • Keep temperature low	Biological Example 1 (Germany)	The window plant/ babies toes' leaves – a leave with a light filtering and distribution system, as well as a heat conduction system
Problem 2	Develop concepts for the ventilation and acclimatisation of a building.	Biological Example 2	Ventilation chimneys of termites mounts – a ventilation system using sun energy

Table 7: Designer's Background (India)

Team	**Designers**	**Education**	
		Bachelors	**Masters**
G_1	D_{11}	Mechanical	PD
	D_{12}	Mechanical	PD
G_2	D_{21}	Mechanical	PD
	D_{22}	Mechanical	PD

Table 8: Designer's Background (Germany)

Team	**Designers**	**Education**
		Bachelors
G_1	D_{11}	Biomimetics (4th semester)
	D_{12}	Biomimetics (4th semester)
G_2	D_{21}	Biomimetics (4th semester)
	D_{22}	Biomimetics (4th semester)

6.2 RESULTS

All but one designer came up with more solutions when using Guideline SAPPhIRE and a SAPPhIRE description of the biological example, than when using Guideline Standard and a non-SAPPhIRE description of the biological example. Similar trends can be observed for the number of biomimetic and feasible solutions (see Tables 9-10 below). The overall increase in the number of biomimetic and feasible solution concepts due to the SAPPhIRE model and guidelines was about 60%.

Since attribute is a superset of organs, SAPPhIRE guidelines and design experiments treat transfer at these two levels as part of the same level of transfer, giving three possible transfer levels: parts, attributes/organs, and state changes. All these three levels of transfer have been found to have been carried out in the design experiments, both in Germany and in India, see Tables 14-15. An example of a solution embodying each level of transfer for a given problem is shown in Figures 3-5. The stimulus used is shown in Appendix II.

As shown in Figure 3, the outer thick wall protects from the sun and absorbs most of the heat energy. Heat that is conducted to the inside air, and is dissipated by the air that rises up due to density change. The rooms inside the thick wall will always remain cool and conditioned, which will prevent heat from the surroundings to penetrate inside the room. Also in the night, the thick wall which contains heat energy will dissipate heat to surroundings and thus prevent the inside room from catching cooler temperature fast.

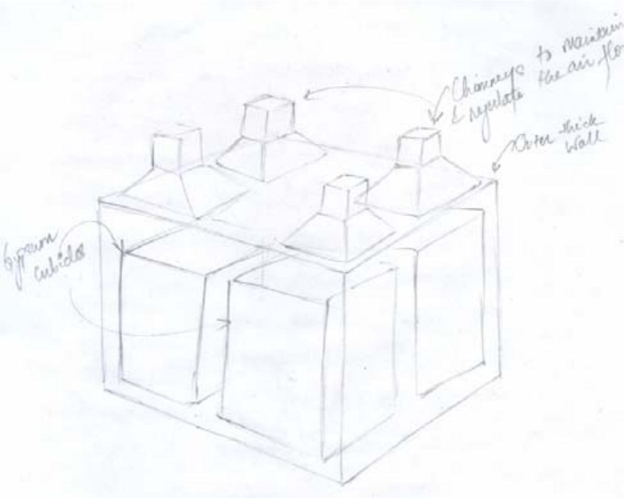

Figure 3: Organ Level Transfer

The following organs are transferred to obtain the solution in Figure 3:

- Heat absorbance of material
- Dissipation co-efficient and heat capacity of chimney material
- Contact area of wall and air.

Figure 4 provides an example of transfer at the state change level for the same problem and stimulus, where the walls of the window should get heated due to the sunlight and heat the air inside the room; this would then increase the volume of the air and decrease its density, so the air would tend to rise up. Also due to the varying cross section of the room, the flow of air would be regulated. With a decrease in area, the air would move faster. The pressure drop created in the living room would try to suck air from the underground room. When the air from the underground room rushes to the living room, outside air would flow into the underground room, resulting in ventilation.

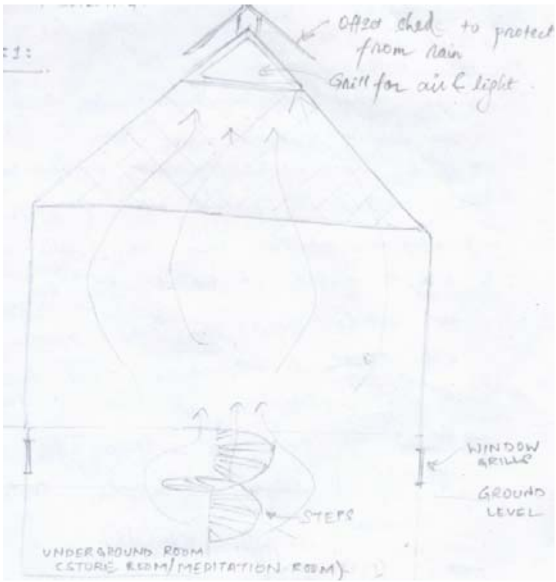

Figure 4: State Change Level Transfer

The following state changes are transferred to obtain the solution in Figure 4:

- From given temperature to higher temperature
- From given density to lower density

Figure 5 shows an example of part level transfer for the same problem and stimulus. Temperature regulated due to air motion around the building floor walls.

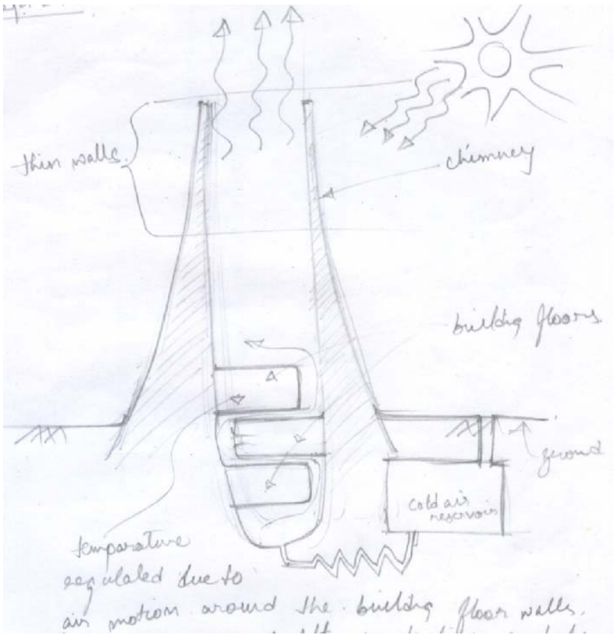

Figure 5: Part Level Transfer

The following parts are transferred:

- Walls of termites' mound and ventilation chimney
- Core of the termite’s mound, cool air sucked in from the cellar
- Ventilation chimney, attached material in chimney, air in ventilation chimney

The stimulating effect of the SAPPhIRE support showed almost no variation between Germany and India (see Tables 11-13 below). However when this result was analysed in greater detail, the effect seemed to vary: While in Germany the use of the developed guidelines led to a substantial increase in the number of state change transfers and only to a slight increase in the number of organ transfers, in India only the number of organ transfers increased (see Tables 14-15).

In both countries, the SAPPhIRE guidelines seem to encourage unfamiliar ways of thinking towards biomimetic transfer: the biggest increase respectively took place in the organ transfer category that seemed to encourage very few transfers when the standard guidelines were used (Table 14 and 15 below). From the overall summary regarding transfer categories (see Table 16 below) the increase in organ transfers by more than 100% seem to be the most prominent gain from using SPPhIRE Guidelines.

Note that the differences between results from Germany and India could be due to the difference in problems used (first problem was different across the two countries), the difference between the type of designers used, or due to the small number of designers involved in the study.

On the whole, the results indicate that the SAPPhIRE models and guidelines compared to the natural language descriptions and standard guidelines seem to encourage considering unfamiliar kinds of transfer; in particular they seem to support transfer and thinking at a physical level which results in a much higher number of organ level transfers.

Table 9: No of solution generated by individual designers with standard and SAPPhIRE Guideline in Germany

	Designer 1				Designer 2				Designer 3				Designer 4			
	T	B	F	B+F	T	B	F	B+F	T	B	F	B+F	T	B	F	B+F
P_1	4	2.5	4	2.5	4	3	4	3	**9**	**5.5**	**9**	**5.5**	**6**	**4.5**	**6**	**4.5**
P_2	**8**	**4.5**	**7**	**4.5**	**6**	**4**	**6**	**4**	4	4	4	4	4	2	4	2

Table 10: No of solution generated by individual designers with standard and SAPPhIRE Guideline in India

	Designer 1				Designer 2				Designer 3				Designer 4			
	T	B	F	B+F	T	B	F	B+F	T	B	F	B+F	T	B	F	B+F
P_1	2	2	2	2	3	3	3	3	**5**	**5**	**5**	**5**	**6**	**6**	**6**	**6**
P_2	**3**	**3**	**3**	**3**	**2**	**2**	**2**	**2**	3	3	3	3	3	2	3	2

Numbers with normal face: Those obtained With Standard Guideline
Numbers with bold face: Those obtained With SAPPhIRE Guideline

P_1 – Problem 1
P_2 – Problem 2

T – Total Number of Solutions
B – Biomimetic Solutions
F – Feasible Solutions
B+F – Biomimetic and Feasible

Table 11: No of solutions with standard and SAPPhIRE Guideline in Germany

	Standard Guideline	SAPPhIRE Guideline
T	16	29
B+F	11.5	18.5

Table 12: No of solutions with standard and SAPPhIRE Guideline in India

	Standard Guideline	SAPPhIRE Guideline
T	11	16
B+F	10	16

Table 13: Overall no of solutions with standard and SAPPhIRE Guideline

	Standard Guideline	SAPPhIRE Guideline
T	27	45
B+F	21.5	34.5

Table 14: No of solutions according to categories of transfer with standard and SAPPhIRE guidelines (Germany)

Transfer	Guideline Standard	% of Each	SAPPhIRE Guideline	% of Each	Ratio of No. of Solutions (SAPPhIRE/Guideline)
Part	1	8.7	0	0	0
Organ	9.5	82.6	15	81.1	1.6

State Change	1	8.7	3.5	18.9	3.5

Table 15: No of solutions according to categories of transfer with standard and SAPPhIRE guidelines (India)

Transfer	Guideline Standard	% of Each	SAPPhIRE Guideline	% of Each	Ratio of No. of Solutions (SAPPhIRE/Guideline)
Part	3	30	3	18.75	1
Organ	2	20	10	62.5	5
State Change	5	50	3	18.75	0.6

Table 16: Overall no. of solutions according to categories of transfer with Standard and SAPPhIRE guidelines

Transfer	Guideline Standard	SAPPhIRE Guideline
Part	4	3
Organ	11.5	25
State Change	6	6.5

6 SUMMARY, CONCLUSIONS AND FUTURE WORK

The work described here yields the following major reaults:

- A generic biomimetic design process
- A generic set of biomimetic transfer levels
- A validated set of guidelines to encourage greater ideation fluency in the biomimetic design process.

One the whole, the SAPPhIRE models and guidelines compared to the natural language descriptions and guidelines seem to encourage considering unfamiliar kinds of transfer; in particular they seem to support transfer and thinking at a physical level which results in a much higher number of organ transfers.

The following attributes of the SAPPhIRE model and the design process might account for the increase in the number and variety of biomimetic and feasible solutions vis-à-vis use of natural language descriptions and guidelines. SAPPhIRE guidelines describe how to come to principles at several levels of abstraction. Also, different descriptions of the same material may activate a different range of associations. This might be especially valid as the SAPPhIRE models introduce a completely different structuring of the information about a biological system.

However, the following factors may also have influenced the results. The SAPPhIRE guidelines usually were the second guidelines to be tested. If there was a training effect due to the first design experiment, it might have caused more solutions. A counter-reason is that designers often put in more effort to design tasks that are given first, and far less to those given afterwords, leading to less number of solutions when using SAPPhIRE guidelines. However, a measurable training effect or fatigue effect is improbable as the second session was usually carried out several weeks after the first session.

Furthermore the introductory explanation and pilot study included an explanation of the SAPPhIRE model as part of the second session. By thinking about the constructs of the model more areas of the memory of the designers might have been activated.

The detailed analysis of the design experiments points to aspects that could have stirred creativity, especially the number of organ transfers increased. Therefore, the increase in biomimetic and feasible solutions might be explained by the fact that the SAPPhIRE models provide a more detailed physical explanation and that the SAPPhIRE guidelines force the designers to explicitly think about the physical effects involved in the biological functions.

The benefit of the categories of transfer was demonstrated by the design experiments with the SAPPhIRE guidelines. But this categorization seems to make sense well beyond increasing design performance. Especially the distinction between organ or attribute transfers and state change transfers can be easily applied onto artifacts in which the biological source function is known. No knowledge about the design process is required. It should also help explain which kind of knowledge is transferred in biomimetics.

The resemblance of the distinction among “part transfer”, “organ transfer” and “state change transfer” with the distinction of Schild et al. (2004) among “transfer of a known technology into a new context”, “transfer of structure” and “transfer of functional principles” is apparent. However the definition of “(combinations of) organs” and “(sequences of) state changes” is more specific than “structure” and “functional principles”.

The SAPPhIRE model seems to be paricularly useful when a technical biologist is able to out a specific functions of an organism and is looking for a language for describing each function in technical terms. As our results show, a designer using such a description and an adequate design process is likely to come out with more possibilities than a designer working with a purely verbal description. Thus the SAPPhIRE model offers a specification for capturing knowledge in biological principle databases.

ACKNOWLEDGEMENT

Special thanks to Professor Labisch and Daniel Matz for their help in the conduction and evaluation of the design experiments as well as to Paul Bohmke, Katharina Haag, Sebastian Möller, Nina Sauthoff from Germany and Pankaj Upadhyay, Urvesh Avinash Bharambe, BSC Ranjan and Geo Paul from India for their participation and feedback.

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APPENDIX I: Glossary

Conditions : An arrangement that must exist before something else can happen.

Function: Descriptions of what a system does: it is intentional and at a higher level of abstraction than behaviour.

Instance – A (SAPPhIRE) instance is the SAPPhIRE description belonging to one single action

Relation: A situation of something in comparison to or with respect to another thing, i.e. inside, outside, over, under,…

Requirements: Requirements describe what designers try to satisfy with or in their design.

Sequence of actions – since a certain function may include several SAPPhIRE instances, these instances to gether specify a sequence of the actions that together describe the function.

APPENDIX II: AN EXAMPLE OF PROBLEM AND RELEVANT BIOLOGICAL EXAMPLE WITH NATURAL LANGUAGE AND SAPPhIRE DESCRIPTION

PROBLEM STATEMENT:
Develop a concept for the ventilation and acclimatisation of a building.

Biological example

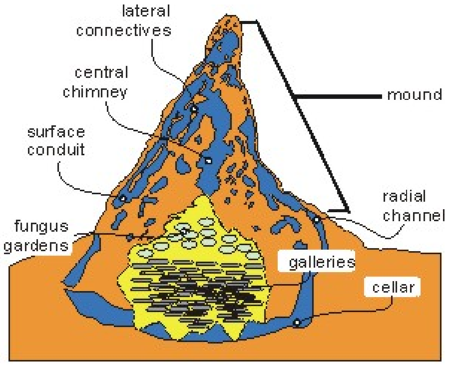

Figure A1: Overview: Termites' mound without ventilation chimney (Turner 2001)

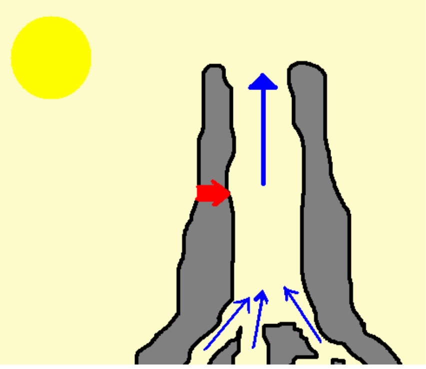

Figure A2: Schematic illustrations of a ventilation chimney's working principle

NATURAL LANGUAGE DESPCRIPTION:

Some termite species attach chimney-like constructions to their mounds. Due to solarisation these chimneys become very warm over the day. This heat is transmitted to the air within the chimneys. The density of the heated air decreases because of thermal expansion and the air rises and partly leaves the mound through pores. Because of the resulting decrease of pressure air is sucked out of the mound’s core (nest) into the chimney and cool air from the “cellar” is sucked into the mound’s core. Hot air from the environment and inside the mound refills the cellar and is cooled down there. Thus ventilation is established and the nest in the mound’s core is cooled down to a moderate temperature. The termites regulate this ventilation by changing the chimney’s diameter. Therefore they attach material to the chimney’s inner walls and remove it again when required. Correspondingly the air flow through the chimney is reduced or increased.
Furthermore the low thermal conductivity and the high thickness of the walls lead to a heat regulation. Indeed the walls of the termites’ mound become hot over the day due to solarisation. However this takes so much time that the mound is overshadowed before the heat reaches the nest in its core. Then the heat flow changes its direction and the heat is emitted to the environment again.

SAPPhIRE DESCRIPTION:

Ventilation due to ventilation chimneys	
Parts	Walls of termites' mound and ventilation chimney
Organs	Absorbance of material
Input	solarisation at chimney
Physical Effect	Absorption
Phenomena	absorption of sun light, increase of energy in chimney
Change of State	Chimney (outer surface): from given energy to higher energy
Action	Absorb solarisation
Parts	Walls of termites' mound and ventilation chimney
Organs	Dissipation coefficient and heat capacity of chimney material
Input	Absorbed energy
Physical Effect	Dissipation
Phenomena	A part of the energy is converted into heat, the mound is heated
Change of State	from given temperature to higher temperature
Action	heat chimney surface
Parts	termites' mound: wall of ventilation chimney
Organs	thermal conductivity of chimney, low thickness of chimney wall, heat capacity of chimney material
Input	temperature change on outer wall, temperature difference
Physical Effect	heat conduction effect (Fourier's law), heat capacity effect
Phenomena	Heat conduction, temperature increase on inner surface of chimney
Change of State	from given temperature difference to lower

	temperature difference
Action	heat chimney inner wall
Parts	termites' mound: ventilation chimney, air in chimney
Organs	heat transfer coefficient of chimney wall, contact area wall-air, heat capacity of air
Input	temperature difference chimney-air, time
Physical Effect	heat transfer effect, heat capacity effect
Phenomena	transfer of heat energy to air in chimney
Change of State	air in chimney: from low temperature to higher temperature
Action	heat air in chimney
Parts	fixed amount of air particles in chimney
Organs	Ideal gas properties of air
Input	increase of air temperature
Physical Effect	Ideal gas law
Phenomena	increase of volume
Change of State	from given density to lower density
Action	Decrease density of air in chimney
Parts	Termites’ mound, ventilation chimney, air in chimney, mound, cellar and in the environment
Organs	density (inertia), fluidity of air, orientation of chimney/ flow path for convection, force of gravity
Input	Decrease of density of air in chimney
Physical Effect	Convection effect
Phenomena	air rises and sucks further air up
Change of State	from no movement to movement
Action	ventilate air in mound and environment
Heat exchange in the core and in the cellar of the mound	
Parts	Core of the termites mound, cool air sucked in from the cellar
Organs	Heat transfer coefficient and contact area between air and the core, heat capacity of core
Input	Temperature difference between core (warm) and air (cool), time
Physical Effect	Heat transfer effect
Phenomena	Transfer of heat to air
Change of State	Mound: from higher temperature to lower temperature
Action	Cool down core of the termites mound
Parts	Earth of cellar and surrounding, hot air sucked inside the channel network
Organs	Heat transfer coefficient and contact area between air and earth, heat capacity of earth
Input	Temperature difference between earth (cool) and air (hot), time
Physical Effect	Heat transfer effect

Phenomena	Transfer of heat to earth
Change of State	Air: from higher temperature to lower temperature
Action	Cool down incoming air

Regulation of the ventilation by attachment of material	
Parts	Ventilation chimney, attached material in chimney, air in ventilation chimney
Organs	Diameter of chimney, friction coefficient between air and chimney walls
Input	Air flow in chimney (velocity) - convection
Physical Effect	Tube flow effect
Phenomena	Energy loss of airflow
Change of State	From given kinetic energy to lower kinetic energy in airflow
Premise	Ants regulate the diameter
Action	Regulation of airflow

Heat regulation due to the thickness of the walls	
Parts	Wall of termites' mound
Organs	Low thermal conductivity of wall, high thickness of chimney wall, heat capacity of chimney material
Input	temperature change on outer wall, temperature difference
Physical Effect	heat conduction effect (Fourier's law), heat capacity effect
Phenomena	Slow heat conduction, temperature increase inside mound
Change of State	from given temperature difference to lower temperature difference
Action	heat mound slowly

Parts	Walls of the mound
Organs	heat transfer coefficient between chimney wall and air in the environment
Input	Shadow (late afternoon), cooling of the environment, warmth of the walls
Physical Effect	Heat transfer effect
Phenomena	Heat transfer from the walls to the surrounding air
Change of State	From given temperatures to higher temperature of surrounding air and lower temperature of the mound
Premises	Walls are thick enough to hinder overheating in the time of solarisation till the heat flow changes its direction
Action	Keep the nest in the core of the mound cool