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TECHNOLOGY-PULL AND BIOLOGY-PUSH APPROACHES IN BIO-INSPIRED DESIGN - COMPARING RESULTS FROM EMPIRICAL STUDIES ON STUDENT TEAMS

H. Hashemi Farzaneh, M. K. Helms, C. Muenzberg and U. Lindemann

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1. Introduction

"Biology has at least 50 more interesting years" (James D. Watson). The famous Nobel Prize winner James Watson probably downplayed biology's pool of still unknown interesting biological systems. However, it is not only the unknown that makes biology a very interesting discipline. For technical product development, for example, already known biological systems hold an enormous potential to solve technical problems. One of the most famous examples is VELCRO®, which was invented by the Swiss engineer George de Mestral and is inspired by the burr [VELCRO 2015].

How can engineering designers know about, understand and make use of these biological systems?

In the past decades, researchers have developed approaches to answer this question. They have developed a number of procedures that suggest procedures for bio-inspired design (e.g. [Lindemann and Gramann 2004], [Helms et al. 2009], [Lenau et al. 2010]). These procedures can be differentiated by two distinct starting points.

Firstly, a bio-inspired design process can be initiated by a technical task or problem - this approach is commonly addressed as problem-driven [Goel et al. 2014], technology pull or top-down approach [VDI 2012]. Designers start with a technical problem or task and search for a biological system that provides a biological "solution" to a similar problem. The biological solution is then abstracted and transferred to the technical domain to develop a concrete technical solution.

Secondly, a bio-inspired design process can be initiated by a biological solution - this approach is commonly addressed as solution-driven [Goel et al. 2014], biology-push or bottom-up approach [VDI 2012]. Designers start with a biological solution and search for possible technical applications. Then the process is similar to the first approach: the biological solution is abstracted, transferred to the technical domain to develop a concrete technical solution.

Researchers report differences between these two approaches: For example VDI [2012] claims that the biology-push approach has the potential to develop future technology, whereas the technology-pull approach aims at optimizing existing technical products. Moreover, Goel et al. [2014] report that most successful bio-inspired design projects are based on biology-push approaches. On the downside, Helms et al. [2009] found that biology-push approaches lead to fixation on the biological system as they prevent design teams to regard additional biological system as possible sources for inspiration.

However, apart from the findings from student projects in a bio-inspired design course summarized by Goel et al. [2014], few studies exist that explicitly compare technology-pull and biology-push approaches. This work therefore aims at deepening the knowledge on the two bio-inspired design approaches by closely studying two design teams: one team follows a technology-pull; the other team follows a biology-push approach. The results are compared to the findings reported by Goel et al. [2014]. As we hypothesize that knowledge in biology is necessary to optimally use bio-inspired design, the student teams consist of an equal number of participants from the two disciplines. To facilitate the communication between the different disciplines and support search and transfer of bio-inspired analogies, the teams use KoMBi (communication model for bio-inspired design).

This work is structured as follows: In section 2, we give an overview on procedures focussing on technology-pull and biology-push approaches. Moreover, we explain modelling and use of KoMBi. Section 3 explains the research approach including data collection and analysis. In section 4, we analyse the procedures adopted by the two teams observed in this study. The results are compared to the findings of Goel et al. [2014] in section 5. A summary and outlook conclude the work in section 6.

2. Background

In this section we give an overview on procedures for the technology-pull and biology-push approach to bio-inspired design (2.1). We relate the procedures to model, search and transfer phases that we will use to analyse the results from our study. Then we introduce KoMBi (communication model for bio-inspired design), a modelling approach that the teams of our study use.

2.1 Technology-pull and biology-push procedures

Researchers have developed a number of procedures to describe and prescribe technology-pull and biology-push approaches in bio-inspired design. Table 1 shows exemplary procedures. The numbers indicate the sequence of the phases. Still, the described procedures explicitly include the possibility for iterations. The described bio-inspired design phases can be assigned to superordinate phases of modelling, search and transfer:

Table 1. Procedures for technology-pull and biology-push approaches in bio-inspired design

	Model (1)	Search	Model (2)	Transfer
Examples for technology-pull procedures				
Lindemann and Gramann [2004]	1) Formulate the intention/ the target	2) Correlate biological systems	3) analyse the correlated systems	4a) is it possible to deduce a technical analogy? 4b) realise the technical solution 5) is the degree of abstraction adequate? 6)is the intention realistic?
Lenau et al. [2010]	1) Problem definition phase	2) Search phase	3) Analysis phase	4) Principle phase 5) Design phase
Example of a biology-push procedures				
Nachtigall [2010]	1) Biological research 2) abstraction of a principle			3) technical application
Example of a general procedure for both approaches				
VDI [2012]	1) analysis			2) analogy/ abstraction 3) project/ design of experiments 4) experiments/calculations 5)prototype construction/ manufacturing 6)application tests 7) overall evaluation

In this work, we use the term "model" to describe the abstracted representation of a biological system or technical system or task. The first model phase is described as problem formulation in technology-pull procedures [Lindemann and Gramann 2004], [Lenau et al. 2010]. For biology-pull approaches, research and abstraction activities are described by Nachtigall [2010].
Procedures specifically developed for technology-pull approaches describe a subsequent search phase to discover biological systems. Then, they name a second model phase in which the biological system is analysed [Lindemann and Gramann 2004], [Lenau et al. 2010]. The two procedures applicable for biology-push approaches do not include separate phases for searching and analysing a technical application.
The transfer phase is detailed by all procedures depicted in the table. They include the design of a technical solution, but emphasize different activities: Lindemann and Gramann [2004] developed a decision flow chart for determining the most adequate level of abstraction of analogies. VDI [2012] details evaluation and testing activities.

2.2 KoMBi (communication model for bio-inspired design)

In research, models and visualization approaches have been used for bio-inspired design. Examples are SAPPhIRE and DANE which have been developed based on a technical engineering design perspective [Chakrabarti et al. 2005], [Vattam et al. 2011].
KoMBi additionally incorporates a biological perspective: based on features identified in biological and technical models, guidelines for modelling and visualizing technical and biological systems have been developed in previous work [Hashemi Farzaneh et al. 2015, 2016]. To minimize the effort for the engineers or biologists using the guidelines, the features are integrated into two modelling steps: "system description" and "system behaviour & properties". KoMBi aims at representing information in a way that it is understandable for both engineers and biologists. Thereby, communication and collaboration is sought to be supported. Moreover, KoMBi can be used to map between the labels of elements and relations of the technical and biological systems. This functionality can explicitly support the search and transfer in bio-inspired design.

3. Research approach

As explained in section 1, the aim of this work is to acquire additional knowledge on technology-pull and biology-push approaches in bio-inspired design. We therefore pose the question:
1. What are the differences between teams adopting a technology-pull and a biology-push approach?
Moreover, we compare the results from our study with findings reported by Goel et al. [2014] from student design teams:
2. How do the results relate to the findings of past studies with student teams from a bio-inspired design course [Goel et al. 2014]?

3.1 Data collection

Two bio-inspired design projects were set up with biology and mechanical engineering students. In each project, two different biology and two different mechanical engineering students collaborated on a bio-inspired design task. In the following, the selection of the participants and the projects' materials and process are described.

3.1.1 Participants

The participants were students in the 3rd or 4th year with a major in mechanical engineering or biology. These participants were selected as they possessed knowledge in their discipline from their 2-3 years of study. They were employed at the research institute as student assistants and could therefore be observed more closely in a six month project than a team of professionals working for another company or research institute. The participants had no experience in using KoMBi in a long-term project before the start of the study.

3.1.2 Materials and process

The projects had duration of about six month each in order to enable a realistic task and time frame. One of the teams was given a technical problem description: The task was to transport fragile goods in moving boxes. This "technology-pull" team was asked to search for biological systems as inspiration to develop a technical product. The other team ("biology-push" team) had to develop an application for a given biological system: The team received information about the toe pads of tree and torrent frogs and was asked to search for technical application fields and to develop a technical product. The deliverable of both teams was one or several prototypes of the developed product.

An additional difference between the teams is the testing of a software prototype of KoMBi by one team which is not discussed in this work: The biology-push team used the prototype; the technology-pull team documented the model manually and with common software tools (e.g. Microsoft PowerPoint).

There were meetings with the researchers approximately every two weeks in which the projects' progress was discussed. Apart from these meetings, the teams organized their collaboration by themselves. They worked independently, but could contact the researchers if questions arose. At the beginning of the project, the teams received instructions on the use of KoMBi in each phase of the project: The teams were asked to follow the technology-pull (task transportation of fragile goods) or biology-push (task tree frogs) process shown in Figure 1. The process includes the phases "model (1)", "search", "model (2)" and "transfer" discussed in section 2.1. The subsequent phases of the project were later phases of the product development process and less specific to bio-inspired design.

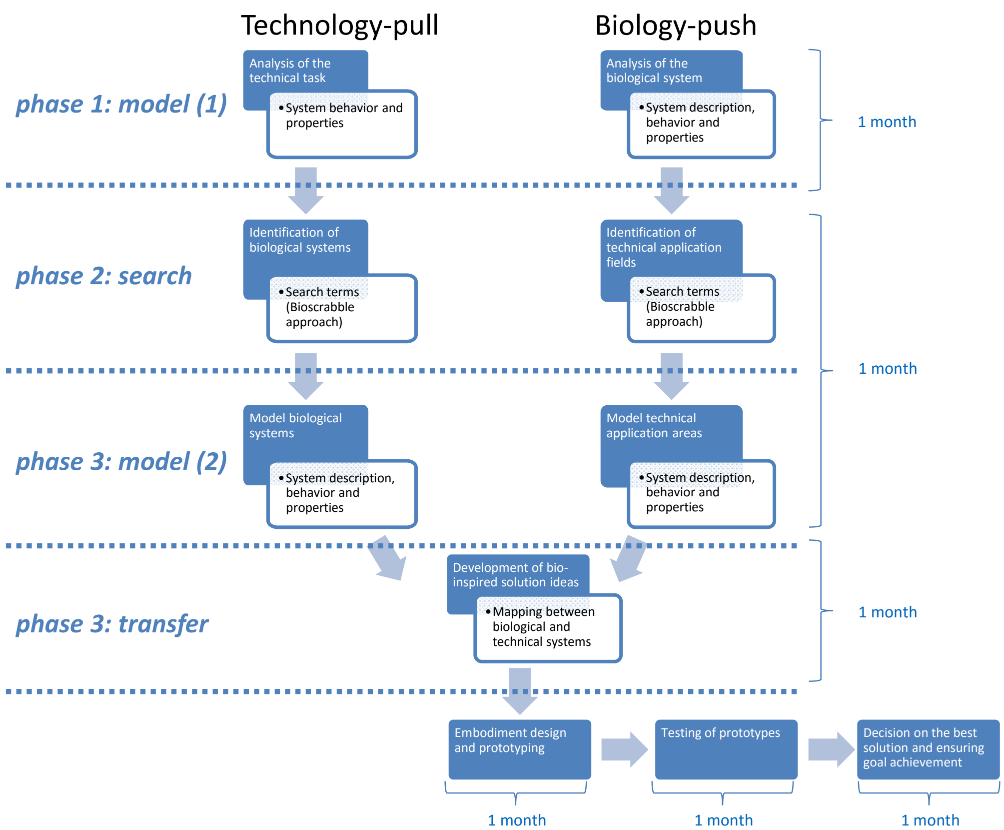


Figure 1. Prescribed product development process and use of KoMBi

In the first model phase, the team using the technology-pull approach had to analyse the technical task, the "transportation of fragile goods", and model the desired system behaviour and properties. As the technical task was a problem description and there was no embodiment, the team was not asked to model a system description. The team following the biology-push approach had to analyse the biological

system "tree and torrent frogs' toe pads" by doing a literature research and consequently model system description, behaviour and properties of the frogs' toe pads.
In the search phase, the technology-pull team had to identify biological systems which can be used as analogues for solving the technical problem "transportation of fragile goods". This was done in an internet and literature search supported by the BIOscrabble support [Kaiser et al. 2014]. The biology-push team had to identify technical application fields for which the biological system "tree and torrent frogs' toe pads" can provide an improvement. To identify technical application fields, the team had to do an internet and patent search on existing technical devices and analyse improvement potential. They also used the BIOscrabble support – which was adapted for the search in biology-push bio-inspired design.
In the second model phase, the technology-pull team had to model KoMBi system description, behaviour and properties of prospective biological systems. The biology-push team had to model KoMBi system description, behaviour and properties of prospective technical application fields.
In the transfer phase, both teams had to develop bio-inspired solution ideas based on the mapping of technical and biological systems using KoMBi.
In the subsequent phases, a number of selected solution ideas had to be detailed and prototypes had to be designed. These prototypes were tested. Then, the teams had to evaluate the prototypes and decide on the best solution. They ensured the envisioned goals were achieved by analysing the chosen solution and defining further development steps.

3.2 Data analysis

To compare the technology push and biology pull approach, we analysed the documents produced by the student teams during the project. To analyse the use of KoMBi in a technology-pull and in a biology-push product development process, we regarded the models the teams developed in the different phases of the project. We analysed how the teams used KoMBi in developing product development models, such as a requirements list, for example. Moreover, we examined which elements of KoMBi were re-used in product development models. For example, if terms from KoMBi elements were used for the search for biological systems, we regarded whether the search with these terms resulted in biological systems used as inspiration by the team.
Additionally, we compared our findings to the procedures reported by Goel at al. [2014]. They observed interdisciplinary teams of four or five undergraduate students including at least one student of biology and several engineering students. The team projects were conducted in the frame of a bio-inspired design course. There were teams following a technology-pull or problem-driven procedure (e.g. based on the technical task to design a levee). Other teams followed a biology-push or solution-driven procedure (e.g. based on the biological system "snapping shrimp") [Goel at al. 2014].

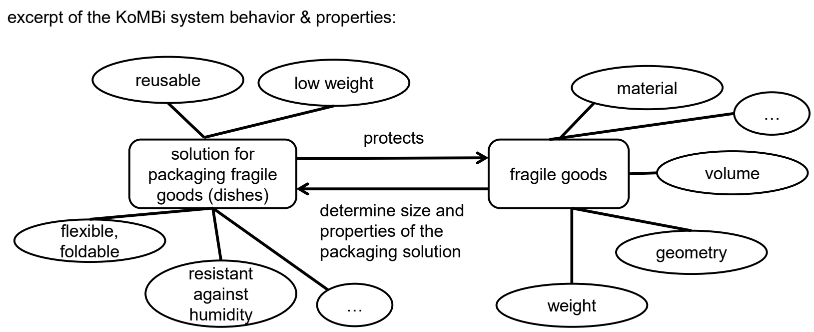
4. Analysis of the procedures and use of KoMBi by the technology-pull and biology-push team

In this section, we answer the first question posed in section 3 based on the analysis of the data acquired in our study:
What are the differences between teams adopting a technology-pull and a biology-push approach?
In the following we compare the procedure and use of KoMBi by both teams in each project phase - Model (1), search, model (2) and transfer. The procedure is depicted in Figure 7.

4.1 Model (1) phase

As Figure 7 shows, both teams started with a KoMBi model of the system they were given as a starting point: The technology-pull team modelled system behaviour and properties of the technical task. Figure 2 shows a translated excerpt: As there was no embodiment at that stage, their system behaviour contained no system elements, only the system "solution for packaging fragile goods" as a whole. Instead, the team modelled a high number of properties and relations of the type "impacts on". As can be seen in Figure 7, the team consequently used a high number of properties and relations to develop a requirements list (translated excerpt in Figure 2).

The biology-push team modelled the system description with system elements in addition to system behaviour and properties of the biological system tree and torrent frogs' toe pads. Figure 3 depicts a translated excerpt: In comparison to the technology-pull team, the focus of their model is more on the different system elements, their relations and changes than on their properties. Moreover, a number of properties are mathematic equations which cannot be used directly for a search. The number of KoMBi elements used in phase 2 is therefore lower in comparison to the technology-pull team. The biology-push team did not develop a requirements list.



excerpt of the requirements list:

requirement	value	description
stability		resistance, stiffness, no unintended warping/ folding
load	max. 10 kg	
length/width/height	100/100/100 [cm]	
…		

Figure 2. Technology-pull team: translated excerpts of KoMBi model (1) and requirements list

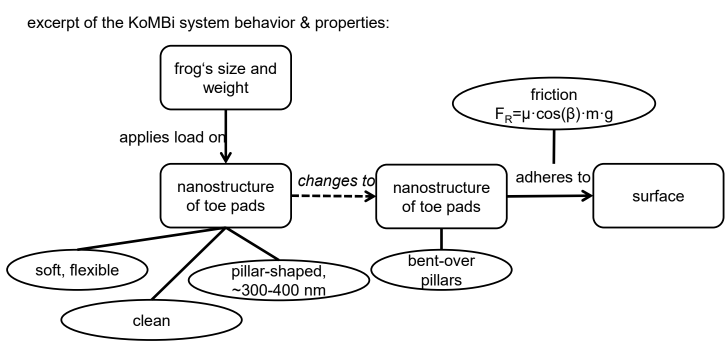


Figure 3. Biology-push team: translated excerpt of KoMBi model (1)

4.2 Search phase

Based on their requirements list, the technology-pull team developed search criteria and search terms. The biology-push team directly developed search terms based on their KoMBi model. Figure 4 shows translated excerpts from both teams. In the following, both teams proceeded similarly: They varied their original search terms formulating keyword variations as requested by the BIOscrabble approach [Kaiser et al. 2014].Then, they combined several search terms and performed the search, either in internet databases for biological publications (technology-pull team) or for technical patents (biology-push team). The teams discussed the found publications or patents and selected a set of biological systems or technical application areas. For the selection, the biology-push team conducted a formal evaluation: Each team member rated all application areas with points (0-3) with regards to the criteria "Do the frogs' toe pads fulfil the challenge of the application area?" and "Does it provide potential for improvement in comparison to existing solutions?" The technology-pull team used a set of KO-criteria based on the requirements list to select biological systems. The team used the criteria feasibility, costs, availability, low volume, adaptability, stability. Except the criterion adaptability, all criteria are considered technical and concrete – they can be used to select a further developed technical prototype, but not a biological system. This indicates a subjective ad-hoc selection of biological systems.

Technology-pull team: search criteria and terms

search criterion	weighting
flexible (adaptive, foldable)	9
light	4
…	

search term	varied search terms
flexible	elastic, deformable, strechy…
protect	defend, secure, guard…
light	lightweight, buoyant, ultra-light
…	

Biology-push team: search terms

search term	varied search terms
adhere	attach, glue, hold…
self-cleaning	self-purification, self-purge…
anti-slip	anti skid, grip, nonslip…
…	

Figure 4. Translated excerpts of search criteria and search terms

4.3 Model (2)

As a result of the search phase, the teams selected eight biological systems (technology-pull team) or five technical application areas (biology-push team). They modelled KoMBi system description, behaviour and properties of the selected biological systems or technical application areas. Figure 5 shows a translated excerpt of the sea anemone's system behaviour and properties modelled by the technology-pull team. Figure 6 depicts a translated excerpt of the technical application area "shoe" modelled by the biology-push team. It was observed that the level of detail was lower in comparison to the KoMBi model developed in the first model phase. This can be explained by the higher number of systems modelled or by the fact, that the teams already had ideas on which aspects to focus.

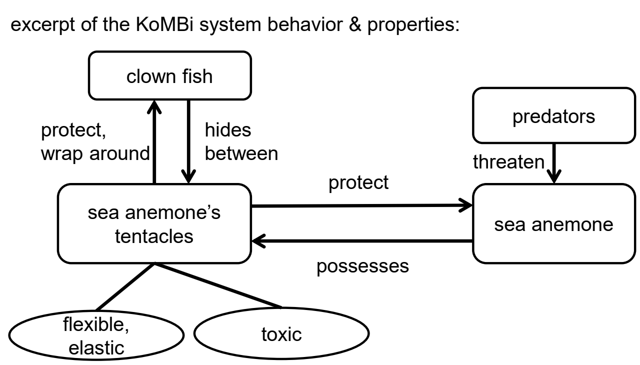


Figure 5. Technology-pull team: translated excerpt of KoMBi model (2)

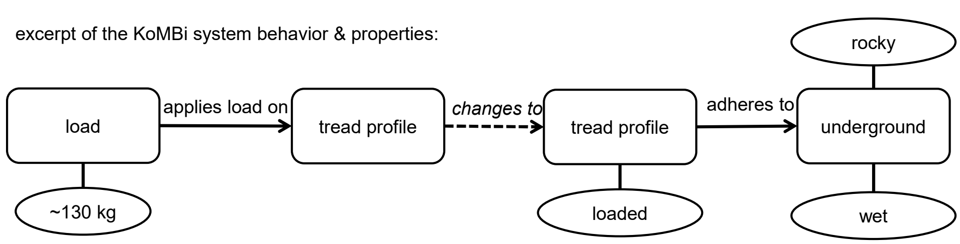


Figure 6. Biology-push team: translated excerpt of KoMBi model (2)

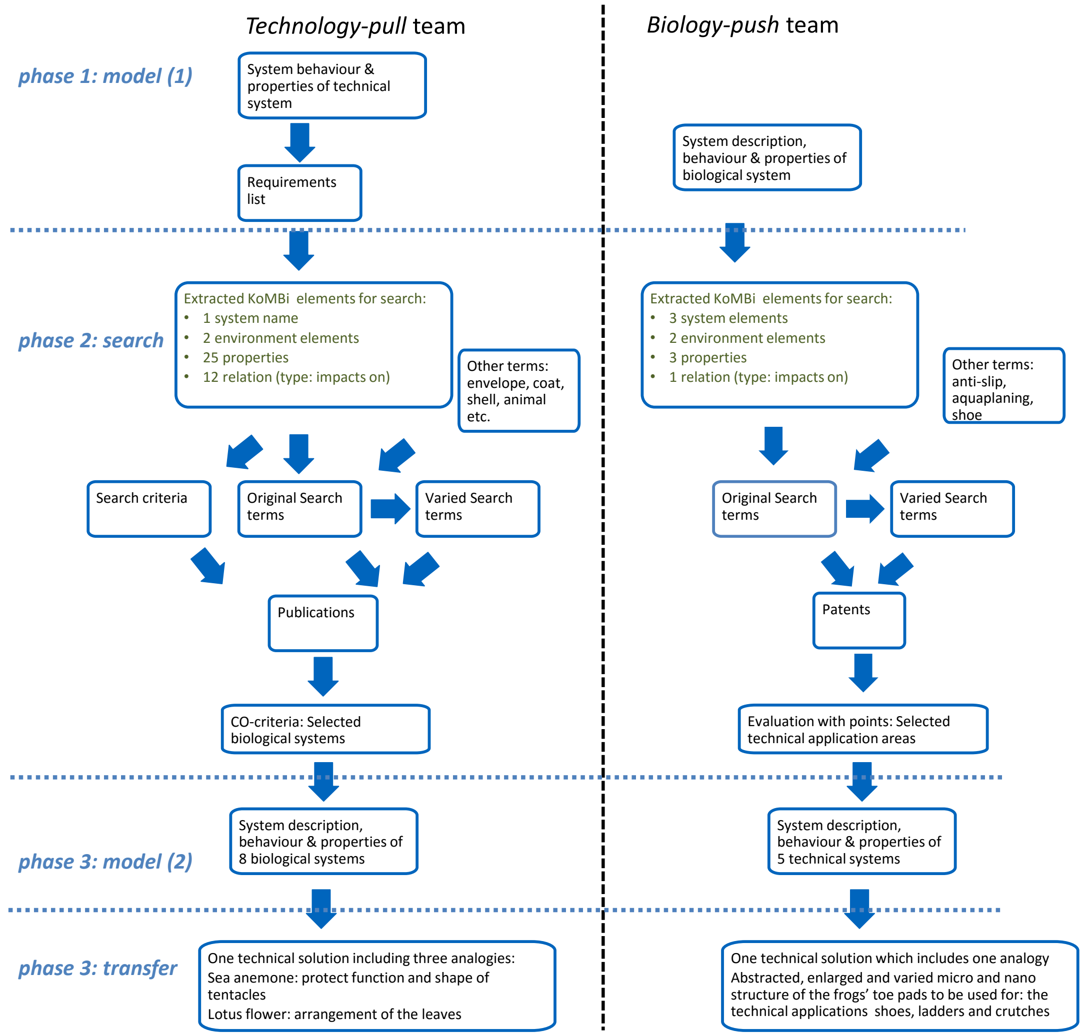


Figure 7. Procedure and use of KoMBi by technology-pull and biology-push team

4.4 Transfer phase

Based on the models, the technology-pull team transferred analogies to develop solution ideas for their technical task (transportation of fragile goods). The technology-pull team transferred the "protect" function of the see anemone for a device to transport fragile goods in moving boxes. Moreover, they transferred the arrangement of the lotus flower leaves for their device. In addition, they imitated the sea anemone tentacles' shape to develop their device. It has to be emphasized that the sea anemone's shape is not related to its "protect" function (see Figure 5). The biology-push team transferred analogies to develop solution ideas for the modelled technical application areas based on their biological system (tree and torrent frogs' toe pads). The biology-push team abstracted, enlarged and varied the shape of the micro and nano-structure of the tree frogs' toe pads to develop several non-slippery surfaces. The surfaces can be used for shoes soles, crutches, ladders or other technical applications. In comparison, the technology-pull team sub-divided their task into sub-tasks and used three different biological analogies to solve the different sub-tasks. The analogical transfer was conducted on a rather abstract level (function, arrangement) or unrelated level (shape of the sea anemone). The biology-push team only used the given biological system for analogical transfer. They transferred analogies on a rather concrete level - imitating the frogs' toe pads micro- and nano-structure. Moreover, they did not focus on one technical task as the technology-pull team, but developed a technical application for several solutions.

5. Comparison to findings from past studies of student teams

In this section, the results are compared to the findings by Goel et al. [2014]. We address the second question posed in section 3:

How do the results relate to the findings of past studies with student teams from a bio-inspired design course [Goel et al. 2014]?

Goel et al. [2014] describe a technology-pull and a biology-push analogical process of bio-inspired design. Table 2 shows the comparison of the procedures adopted by the teams observed in this study to the processes described by Goel et al. [2014].

Table 2. Comparison to the analogical processes of bio-inspired design [Goel et al. 2014]

	Technology-pull		Biology-push	
	Goel et al. [2014]	Team "Transportation of fragile goods"	Goel et al. [2014]	Team "tree frogs"
Model (1)	Problem formulation	Problem model, requirements list	Biological solution identification and definition,	Biological system model
			Principle extraction	No principle extraction
Search	Problem reframing,	Formulation of search terms and criteria	Solution reframing	Formulation of search terms and criteria
	Biological solution search	Search for biological publications	Problem search	Search for patents
		Selection of biological systems based on co-criteria		Selection of technical application areas based on an evaluation with points
Model (2)	Biological solution definition	Model of biological systems	Problem definition	Model of technical application areas
Transfer	Principle extraction	Identification of 3 analogies (abstract level)		Identification of one analogy (concrete level)
	Principle application	Development of one compound solution to the given task	Principle application	Development of one solution applicable in several technical application areas

As the table shows, the overall procedures observed in this study are similar to that observed by Goel et al. [2014]. However, two major differences were found: Regarding both approaches (technology-pull and biology-push), we observed an explicit selection process at the end of the search phase. This selection process is not described by Goel et al. [2014]. However, we found the selection process crucial: In a search, a high number of biological publications (technology-pull) or technical patents (biology-push) are found. A selection is necessary as it is not possible to analyse all search results in detail. Moreover, the selection process is subject to errors - as described in section 4, the technology-pull team used inappropriate co-criteria and subjectively excluded promising biological publications.

A second difference only accounts for the comparison of the biology-push approach: We found that the team of our study reassessed the biological system after modelling technical application areas. Then, the team extracted one analogy and transferred the micro- and nano-structure of the tree frog's toe pads to a polymer surface. The team did not explicitly extract one abstracted principle before the search phase as Goel et al. [2014] observed for their teams. Instead they formulated the concrete system behaviour and properties for the tree frogs adhesion on wet surfaces. They searched with search terms based on these concrete models.

In addition to the procedure of analogical processes, Goel et al. [2014] described several observations made throughout the team projects. One is "problem-decomposition and compound analogies": Goel observe the decomposition of the design problem to sub-problems and the solving of the sub-problems with partial solutions based on analogies from different biological systems. In our study, the same observation is made for the technology-push team: As explained in the previous section, the team based its solution for a device for the transportation of fragile goods on three different analogies. However, the biology-push team did not use compound analogies. This is in line with another observation of Goel et al. [2014]: In their studies, they observed that biology-push teams fixated on the biological system. Still, to describe the behaviour of the biology-push team in this study, the term "fixation" is not adequate: The team only regarded one biological system for analogical transfer, but the team still varied the transferred micro- and nano-structure and developed several prototypes.

6. Conclusion and outlook

In this work, we conducted a six-month study with two student design teams consisting of two students of biology and two students of mechanical engineering. One team followed a technology pull (problem-driven) approach, the other one a biology-push (solution driven) approach. We compare the two approaches to findings from past studies reported by Goel et al. [2014]. We find an overall similar procedure which differs in two aspects: our teams used explicit selection methods and the biology-push team only extracted a biological principle (analogy) after defining a technical application area. For future work, the use of selection methods in bio-inspired design has to be further explored and possibly supported as the selection of biological systems and technical application areas is crucial for the further development. Moreover, we found differences in the abstraction level of analogies and the type of technical solution developed by the technology-pull and biology-push team. These differences have to be further explored in future studies.

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Helena Hashemi Farzaneh, research assistant
Technical University of Munich, Institute of Product Development
Boltzmannstr. 15, 85748 Garching, Germany
Email, hashemi@pe.mw.tum.de