What is Abstraction in Biomimetics?

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Abstract
Abstraction is widely seen as an essential methodological process in biomimetics. Any ontology-based tool for biomimetics should support this cognitive process, but what exactly it consists in is not well understood. The paper analyses various descriptions of the role of abstraction in the biomimetic research project from engineering guidelines and the biomimetic literature, together with their ontological implications. It is argued that even if this is currently not universally accepted in the biomimetic literature, the traditional meaning of disregarding unimportant detail is a good approximation to what happens in the abstraction steps in biomimetic research processes. Even closer comes the converse description of abstraction as focussing on relevant aspects.

Keywords
biomimetics, cognition, methodology, abstraction, concretisation, heuristics, models

1. Introduction

Biomimetics is a field of research that tries to learn from nature to develop improved technical solutions. More specifically, biomimetics is said to be the "interdisciplinary cooperation between biology and technology or other innovative fields in order to solve practical problems through the functional analysis of *biological systems*, their *abstraction* into *models* and the transfer and application of these models to the solution" (ISO 18458:2015, p. 2, emphasis in the original [1]). It is, therefore, generally acknowledged that abstraction plays an important part in biomimetics. There is also a consensus that the abstraction starts from some biological entity, here called a "biological system", which is often an organism, but can also be a part, trait or behaviour of an organism, a biological process like evolution, a plurality of organisms like a swarm of birds or a school of fish, or artefacts or products of animals like nests, eggs or spider silk. It is less clear, however, what exactly abstraction is and how it works, and what the product of abstraction (here called "model") actually consists in.

This paper surveys various statements on abstraction from the biomimetic literature and suggests a reconstruction of the respective cognitive processes and their underlying ontological structure. I argue that abstraction in biomimetics is close to the traditional understanding of abstraction as a cognitive act of not considering certain properties. To show this, I will review

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statements about abstraction in biomimetic guidelines (section 2) as well as in descriptions of the biomimetic research process in the biomimetic literature (section 3). I will then discuss how my suggestion relates to the findings in the literature (section 4). Section 5 concludes the paper.

2. Abstraction in the VDI guidelines

As a research area with a heavy technical orientation, biomimetics often refers to guidelines and norms developed by such institutions as the International Standardisation Organisation (ISO) or the Association of German Engineers (Verein Deutscher Ingenieure, VDI). In fact, the VDI pioneered the production of guidelines in the field and prepared the path for the ISO [2][3]. The VDI guideline VDI 6220-1, on the conception of biomimetics and its strategies, originally published in 2012, has been updated in 2021 and a second part, VDI 6220-2 on the biomimetic development process, has been added in 2023 [4][5][6].

VDI 6220-1 (2021) adapts the definition of biomimetics given in ISO 18458 (quoted above) that puts the "abstraction into models" centre-stage, where these models are derived "through the functional morphological analysis of biological systems" and "the transfer into and application of these models to the solution (p. 5). Like its predecessor, VDI 6220-1 (2012), it defines abstraction as an "inductive process in which a general conclusion is drawn based on the observation of a specific object" (p. 4). This is strange, as such generalising inferences are standardly called "induction" in logic. An inductive reasoning process could, e.g., lead from "This swan is white" to "All swans are white" – i.e., from the observation that one instance (or more) of a certain kind has a certain property to the conclusion that all instances of a certain kind have this property. Another variant would lead, e.g., from "Swans can fly" to "Birds can fly" – i.e., from the statement that a certain property applies to a species to the statement that this property also applies to a genus of this species. Neither of these two variants would probably be considered an abstraction. It goes without saying that such inductions are important but not deductively valid and theoretically difficult to justify, as black swans and penguins show for the two examples mentioned here. Alternatively, one could consider non-standard ways of induction that do not infer universal statements but generic statements like "Typically, birds can fly". Such a result would allow for atypical exception cases. But this is also not the intended product of abstraction processes in biomimetics, where the result of abstraction processes are rather new descriptions of the design problem or a description of the design solution.

In a note to the definition of abstraction, VDI 6220-1 (2012) and ISO 18458:2015 add: "In biomimetics, this conclusion is ideally a physical context for describing the underlying functional and operating principles of the biological model." VDI 6220-1 (2021) echoes a variant of this: "In biomimetics, this conclusion is ideally a physical context for describing the underlying form–function relationships and operating principles of the biological system." This is verbally repeated in VDI 6220-2. Taken at face value, both variants commit the same category mistake, as conclusions of inference steps are propositions, which may be *about* physical contexts but not identical to them.

Describing abstraction as a variant of generalisation does also not fit well to the idea that abstraction is a process that leads to a model. A model is defined by VDI 6220-1 (2021) as a "coherent and usable abstraction originating from observations of biological systems" (p. 6; no such definition in the 2012 version). Standardly, the guideline distinguishes two variants of biomimetic research and development projects, which are labelled “technology pull” and “biology push”, respectively. A “technology pull” project starts from a technological problem and looks for a biological solution that can help to realise that function. In contrast, a “biology push” project starts from a biological observation and tries to implement this in a market-viable product. The biomimetic process “goes through several abstraction steps and modifications” (p. 7), and it is not complete “without performing a systematic analysis, abstracting, or transferring an operating principle” (p. 8). The biomimetic development process is characterised as consisting of three steps – also referred to as the “three A” (p. 13):

- First step: “A shape–function analysis of a biological system is carried out (analysis)”.
- Second step: “The biological system is abstracted to a model (abstraction)”.
- Third step: “The model is transferred and applied to develop a solution or product (application)” (p. 9).

Abstraction is said to be “of great importance”, because “biological systems are generally highly complex” (p. 15). Abstraction always starts with the “biological model”, i.e., an organism or some part or behaviour pattern of it; the abstraction phase will then lead to “explanatory approaches in the form of form–function relationships” (p. 18).

The conceptual framework of VDI 6220-2 is based, to a large extent, on VDI 6220-1 (2021). Indeed, VDI 6220-2 (2023) only slightly deviates from VDI 6220-1 (2021) when defining abstraction as a “process in which a generalised conclusion is drawn from the observation of a specific object”. For sure, the words “abstract” and “abstractions” are used (and sometimes misused) in multiple senses (just compare the usage of these words in modern art and set theory, where it refers to constituting a set by means of a predicate). Consequently, but somewhat clumsily, VDI 6220-2 goes on to make explicit the process–product ambiguity of the word “abstraction” (“This also includes the result of this process”). In fact, like “observation”, “explanation” or “perception” and other words ending in “-tion”, “abstraction” can refer to both a certain cognitive process and the result of this cognitive process. To the surprise of the reader, another note to the definition quoted above reports on the classical philosophical sense of abstraction: “‘Abstraction’ is also referred to as the mental removal of some features or properties of an object or system that are not relevant to the aspects of its behaviour under investigation.” (p. 3)

VDI 6220-2 (2023) describes the biomimetic development process by means of the so-called “biomimetic spiral” (p. 8). In this process description, “analysis”, “abstraction” and “application”, the three phases already mentioned in VDI 6220-1, are supplemented by a preceding “arrangement” phase (“Aufbereitung”). Abstraction is identified as an important step for both variants, “biological push” and “technology pull”. The goal of a “technology pull” development process is described as “abstracted effect principles” (p. 8). This is reached in the “abstraction phase” through “an understanding necessary for the technical implementation […] for the selected biological solution principle”, which is reached through “an abstraction process” (p. 9), in which “the individual effect principles for the desired function are worked out in detail, starting with a literature search and, if possible/necessary, through detailed biological investigations”; the result is finally “transferred from biology to technology through a further translation step”, e.g., through the construction of demonstrators (p. 10) – i.e., 3D-models that show that the hypothesised structure of effect principles (sometimes also called “working principles”) does, in fact, lead to the intended behaviour of the system.

In contrast, in a “biology-push” process, the abstraction phase aims at finding “an application in technology”. Later, an “abstraction in principle” is said to be necessary, in which “[t]he solution principle is described by means of models” (p.12). When “abstracting and thus detaching the biological principle from its initial context”, the biomimetic researcher is advised to consider the “different preconditions and adaptations” prevailing in biological systems (p. 13).

3. Abstraction in the biomimetic literature

To shed further light on these unequal findings, I will now look at three descriptions of the abstraction process from the biomimetic literature, in particular at the accounts of Werner Nachtigall (subsection 3.1), Kristina Wanieck (subsection 3.2), and Manfred Drack and colleagues (subsection 3.3).

3.1. Nachtigall

Werner Nachtigall is probably the most prolific author of books on biomimetics in the German-speaking world. From a meta-theoretical perspective, his book on “Biomimetics as Science” [7] is probably the most important one (all translations are mine). Already in the subtitle of his book, Nachtigall makes it clear that he sees abstraction (“Abstrahieren”) as a constitutive step of the biomimetic research process. This step consists in the “abstraction of general principles from ‘original data from biology’” (“Abstraktion allgemeiner Prinzipien aus den ‘biologischen Originaldaten’”), and it is these “abstracted principles of nature” (“abstrahierte Naturprinzipien”, vii), which will then be used in the technical setting (vii). Sometimes Nachtigall simply talks about “Prinzipabstraktion” (e.g., 72). These principles are thought of as being real elements of nature, out there to be discovered by biologists, to be explained in theoretical terms and then to be transferred to the domain of engineering.

Nachtigall dedicates the whole part B of his book to abstraction from biological findings and the discussion of general principles. For him, the crucial point in abstracting such a general principle from nature is the construction of a model (p. 79); the model is then called a “prinzipienabstrahierendes Modell” (p. 80) or “modellhafte Prinzipabstraktion” (p. 85). The process is sometimes called “Modellabstraktion” (p. 84), but this whole terminology is never explicitly introduced and very variegated. The next steps in the biomimetic research process lead from the “abstracted, still biological model” to a “technically abstracted, already technical model” (p. 87). According to Nachtigall, the step from the biological data and the abstracted model is mediated by analogy (p. 96). Nachtigall quotes Zoglauer [8] who sees a model as “simplification and abstraction of an original” (“Vereinfachung und Abstraktion eines Originals”, p. 98). While being constitutive of models, abstractions can also contribute to the limitations of models (p. 100). Nachtigall goes on to define models (in the context of biomimetics, that is) as “simplifying abstractions of biological substrates, i.e., of structures or functions or the connections of structures with functions”; more concisely, he says that a model is “the analogical abstraction of an original” (p. 105). He also talks about the “abstraction of a biological species by way of generalising induction” (“Abstraktion einer biologischen Art durch generalisierende Induktion”; p. 42, Fig. 4.7).

Next to the models of principles, which show how something works, Nachtigall also speaks about functional models ("Funktionsmodell", p. 109) and, as a subkind of these, cybernetic models ("kybernetische Modelle", p. 113). Nachtigall implicitly admits of degrees of abstraction when he talks about "half-abstract" things ("das halbabstrakte Schaubild", p. 19), and he also mentions "levels of abstractions" ("Abstraktionsebenen", p. 179), possibly referring to structures and functions as possible objects of abstraction.

In Nachtigall's picture, abstraction is supplemented by the reverse process of concretisation ("Konkretisierung einer Vorstellung"), which yields "a concrete instead of an abstract basis of deduction" (p. 106). But this term is only very rarely used and never explicitly introduced (the only other occurrences being "technisch konkretisiert", p. 185, and "Konkretisierungsverfahren", p. 190).

3.2. Wanieck

Wanieck's introductory textbook [9][10] contains a detailed description of the biomimetic development process with interesting details with respect to abstraction. In particular, she stresses that "the degree of abstraction varies" ([10], p. 9). She distinguishes three "level[s] of abstraction of biological knowledge" and claims that "[w]ith an increasing level of abstraction, the proximity to the natural model decreases, but the potential for application increases" (Figure 2.1 on p. 9 and other places; see my Table 1).

Table 1
Wanieck's three "levels" (extracted from Wanieck [10], pp. 9–10)

Level of abstraction and aspect	Example	Biological model
Level 1: Form–Function	Velcro fastener	Burdocks
Level 2: Physico-chemical principle	Lotus effect	Lotus leaves
Level 3: Innovative principle	Structuring of surfaces	Lotus leaves

In the case of the Velcro® tape ("hook and loop fasteners inspired by burrs"), she says that the abstraction level is "low", because "the similarity to the natural model is high and the application potential ranges in the context of the connection of two surfaces or objects – in nature and in technology" (p. 9). In the case of the Lotus effect ("self-cleaning properties of the Lotus plant"), she diagnoses "a higher level of abstraction", which "means that the closeness to the natural model is lower than with Velcro fasteners, as the structures of the lotus surface are no longer emulated 1:1" (p. 10). It is not clear, however, whether this comparison to the Velcro case is really accurate. For sure, the structures transferred in the Lotus case are much smaller and not visible to the naked eye, but also in the case of the Velcro fasteners, the form of the hooks and loops is not simply copied from the biological paradigm, but adapted to the technical context in which it is then used.

Finally, at "abstraction level three, knowledge about biological systems is abstracted to general innovative principles, which primarily serve the generation of ideas". As an example, she again refers to "the phenomenon of surface structuring known from the lotus plant", which "can also be understood as an innovative principle that can be applied in various areas", allowing "new functions to be integrated into products that are not directly related to the cleanability of surfaces, but rather serve, for example, to improve haptics, coloring, or transferring information" (p. 10).

Wanieck's description of the three levels insinuates the idea that abstraction comes in *degrees*. On the other hand, the descriptions of the three levels rather pick out different *aspects* that could be abstracted from a given biological paradigm. Her first level, the form–function analysis, seems to focus on those aspects studied by morphology (from Greek *morphê*, form) and their connections to functions. The second level concerns an analysis in terms of physical or chemical laws, which might come with a certain reductionist impetus. The third level, finally, is about more general (and more vague) strategies the engineer could pursuit to find new solutions, which still leaves a lot of questions open to be answered. Inspired by the Lotus leaf or other biological phenomena, structuring a surface might be a helpful hint, but then there is still the question *how* to structure it.

Wanieck describes biomimetics as a process consisting of eight steps ([10], p. 19–27). In two of these, she sees abstraction at work; these are "problem abstraction" (step 2) and "abstraction from biology" (step 6). The purpose of problem abstraction is to turn the "solution-neutral problem description", or the "targeted solution described as a function" (p. 20) found in the first step into an "abstract description of the problem that can be transferred to biology" (p. 24). This is needed because "technical terms are not suitable 1:1 for searching in biology", and "the problem or objective function[1] must be formulated in such a way that biological models can be searched for"; again, "different levels of abstraction and functions" can be chosen to process this step. As tools to support this step, Wanieck suggests using the Biomimicry Taxonomy[2] and the association list described by Gramann [11].

The second abstraction step is "abstraction of biology" (p. 26) or, more appropriately, "abstraction of biological findings" (p. 31). In this step, "biological functions are translated into the technical context"; this results in a "description of the biological phenomenon as a physical–chemical functional principle", in which "the biological principle is detached from the biological model and broken down to a physical–chemical function", such that "the principle can be made usable for a technical application" without the biological model itself becoming part of the solution in technology (p. 26). As there is "no general approach" to be followed for this step, Wanieck warns that "the work of abstraction requires time and expertise"; she advises biomimetic developers "to describe functions in the biological system by the main components of energy, material, and information flow", or to "ask in general terms what is responsible for the observed function", where the answer should be expected "at different levels of scale", and to search support from a biologist (p. 26).

3.3. Drack et al.

Following the lead of the VDI guidelines and authors like Nachtigall, Drack et al. [12] agree that abstraction is an essential process in biomimetic research. Following their description, biomimetics proceeds by abstracting functions and working principles from biological models,

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[1] In the German version [9], p. 22: "zu erreichende Zielfunktion".
[2] Cf. https://www.asknature.org/resource/biomimicry-taxonomy. In the older German version of the book ([9], p. 24), Wanieck also refers to the "BIOlogy Inspired Problem Solving" (BIOPS®) online dictionary, which, however, has since disappeared from the internet.

transferring them to the engineering domain and, subsequently, integrating them into constructions and, finally, market-viable products. In particular, Drack et al. write:

- "Engineers are typically challenged by a task which they attempt to solve by some manner of construction. In a typical textbook case, the workflow leads from the abstract level to ever more tangible solutions. Accordingly, this work flow encompasses the successive levels of: (1) task, (2) function, (3) working principle, (4) construction, and finally (5) the overarching system." (p. 2)
- "The overarching system and the construction in the biological model show many features that are typically not transferred. For instance, the material or the particular shape of the bur [...] are not used in Velcro®. Rather, they are abstracted." (p. 5)
- "As research progresses, more and more features that are found to be irrelevant for the particular goal are left aside. Correspondingly, the complexity of the investigated item decreases and the degree of abstraction increases [...]. The specific boundary conditions (e.g. particular shapes and material properties) in the biological system are successively abstracted and the inherent functions and working principles become exposed." (p. 7; omitted from the quote is a reference to a definition of abstraction from Psillos [13] that is quoted below)
- "Note that the levels of function and working principle do not involve particular sets of parameters—material, geometrical or otherwise. Later along the time line, during the application phase, ever more detailed engineering images are produced. Graphical representations can be understood as a continuous chain reflecting the degrees of complexity and abstraction along the biomimetic process." (p. 9)

According to the picture emerging from these quotes, the biomimetic research process steers through different stages of, first, increasing abstractness in order to abstract functions and working principles, followed by stages of decreasing abstractness in the construction process proper (cf. their Fig. 3 on p. 7). This seems to be exactly abstraction in the sense of disregarding detail, or, in the words of note 2 of VDI 6220-2 (2023), "the mental removal of some features or properties of an object or system that are not relevant to the aspects of its behaviour under investigation". This understanding of abstraction can be corroborated by referral to the understanding of abstraction in other areas. In a forthcoming glossary of biomimetic terms, Drack et al. list several definitions of abstraction both in general language and in relevant domains, like philosophy of science, engineering and architecture [14]. These definitions all converge on the central point that abstraction should be thought of as a process of excluding properties or other details:

- *Oxford English Dictionary* (out of a list of seven possible meanings): "The action of considering something in the abstract, independently of its associations or attributes; the process of isolating properties or characteristics common to a number of diverse objects, events, etc., without reference to the peculiar properties of particular examples or instances." [15]
- Philosophy of science: "The removal, in thought, of some characteristics or features or properties of an object or a system that are not relevant to the aspects of its behaviour under study." (Psillos [13])

- Engineering: “Ignoring what is particular or incidental and emphasizing what is general and essential.” (Pahl et al. [16])
- Architecture: “Omission or severe simplification of details in drawings of a building or landscape leaving essentials of massing, form, and solids, so that the basis of a design can be explained.” (Curl [17])

Inspired by Nachtigall’s use of the term, Drack and Jansen [18] adopt the term “concretisation” in order to describe the inverse process of adding detail, which is important for both engineering in general and biomimetics in particular.

4. Discussion

This review of a small selection of the biomimetic literature shows a consensus that abstraction is central to the biomimetic research process. As it turned out, however, there is no consensus about what exactly abstraction is in the context of biomimetics. It seems clear, though, as the VDI 6220-2 notes, that “abstraction” can both refer to a process and its product. As a process, abstraction starts from something and ends at a certain result:

- As to the starting point, there is consensus that is in the domain of biology; it is the “biological model”, an organism or a certain part of it or a behaviour pattern that it displays (or a product of such behaviour).
- The result, or product, of the abstraction process is called “model”, “principle”, or “function” and “operating principle” or “efficient principle” in different texts.
- The process itself is characterised as a cognitive process; it is sometimes described as a generalization and sometimes as disregarding unnecessary detail.

The findings regarding the endpoint of the abstraction process suggest that, in fact, the characterisation of the abstraction process as a process of disregarding unnecessary detail is fundamental. Conversely, the abstraction process could also be described as focussing on the relevant details. If the abstraction process starts from a finite set of information, both descriptions might be equivalent. Both the process of disregarding certain aspects and the process of focussing on certain aspects yield smaller sets of information. Still, it might be psychologically more adequate to say that researcher focus on the relevant aspects instead of thinking of the irrelevant aspects that they are irrelevant and can be disregarded. However, if the starting point is an infinite set of information, like the set of potential information to be gained about a concrete material object like an organism, the results of focussing and disregarding are clearly different: Disregarding finitely many aspects from an infinite set of information still leaves one with an infinite set of information, while focussing on finitely many aspects from these infinite set of information clearly yields a finite set of information (see Table 2). Focussing on relevant detail is thus an even more accurate description of what is going on in abstraction processes.

Table 2
Contrast between focussing on relevant detail vs. disregarding irrelevant detail

Starting point	Result of disregarding finitely many aspects	Result of focussing on finitely many aspects
Finite set of information	Smaller set of information	Smaller set on information
Infinite set of information	Infinite set of information of the same cardinality	Finite set of information

This understanding of abstraction fits well to the ontological characterisation of functions and operating principles as abstract properties that are borne by the concrete organisms that biomimetic researchers analyse – but are then cognitively isolated from their bearers and abstractly described and analysed. This understanding also fits to the claim in many texts that the objects of thought or research can be more or less abstract. As we can ignore more or less properties, the abstract and the concrete will constitute a range of more or less abstract or concrete models, which are bounded on the side of the concrete by the concreteness of the actual material objects, be they biological or technical, in the actual world. Ignoring unnecessary details can happen in at least four ways which follow distinct ontological patterns:

- **Specificity.** If an entity can be correctly described by a term *T*, it can be correctly described by any hypernym of *T*. The higher up the species–genus hierarchy the hypernym is located, the less informative the description will be.
- **Granularity.** An entity can be partitioned in more or less detailed granular partitions [19]. An organism can be described as an organism among other organisms, as a complex of organs, as a complex of molecules, as a complex of atoms, or as a complex of sub-atomic particles. Approximatively, it could be said that the coarser the partition, the less detailed the description is.
- **Variabilisation.** Given a property of a certain kind, we can disregard which specific property this is and use the description of the kind only. E.g., instead of ascribing the determinate colour *purple*, we can ascribe the less determinate colour *red*, or the determinable property *coloured*, i.e., say that there is some colour but we do not say which one.
- **Entirely disregarding certain properties.** If an entity can be correctly described as having all of a set of properties $\mathbb{P}$, it can also be correctly described as having any subset of $\mathbb{P}$. This, again, goes along with a lack of information.

In addition, one might think of means–end hierarchies, causal chains or hierarchies of constitution levels as possible dimensions of 'abstraction'. However, with any of these it is not as clear whether switching between levels in these hierarchies goes along with restricting oneself to less information; one rather deals with different pieces of information on different levels in these hierarchies.

Loss of information is not necessarily a bad thing, because, as Drack et al. [12] point out, an increase of abstractness comes along with a decrease of complexity, which may be very welcome in a research context, as long as all relevant information is covered. Wanieck's distinction of three levels of abstraction which I describe above (Table 1) seems in part to reflect different levels of granularity: The form–function aspect can mostly be found at the granular level of body parts of organisms, while physico-chemical principles could be localized at the molecular or sub-molecular level. However, physical principles, like the law of the lever, would also be situated at the mesoscopic level. Even more difficult is it to integrate the suggested third abstraction level (abstracting an "innovative principle") into the granularity logic. Rather, it disregards a lot of detail if, instead of copying the specific surface structure of the lotus leaf one thinks of structuring surfaces in general. Thus, Wanieck's levels are also compatible with viewing abstraction as disregarding detail or focussing on relevant detail.

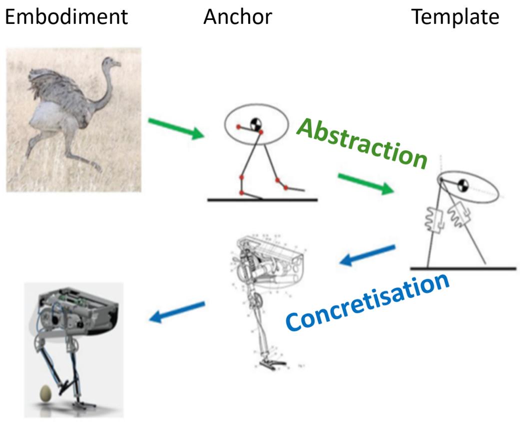

Figure 1: Development process of the walking robot eNandu. Modified from VDI 6220-2 (2023) [6], p. 23; some of the drawings are taken from the patent specification DE102018103892B4.

Moreover, while it contradicts the official definition of abstraction given in the VDI guidelines, seeing abstraction as disregarding unimportant detail fits nicely to an example mentioned by the VDI 6220-2 (2023), namely the eNandu project ([6], p. 23–24). This project applied the so-called template-and-anchor approach (see Figure 1). An early publication describing the template-and-anchor approach explicitly describes the template as "the simplest model (least number of variables and parameters) that exhibits a targeted behavior" ([20], p. 3325). As the case in question in this publication is "legged motion on land", the template is said to be "a model created by 'trimming away' all the incidental complexity of joints, muscles and neurons", while the anchor is described as "a more realistic model fixed firmly or grounded in the morphology and physiology of an animal", which is not only "more elaborate", but "must have embedded within it the behavior of its templates" (ibid.). The various stages of the development of the eNandu (depicted in an idealised manner in Figure 1) mirror these cognitive steps: From the concrete and complex biological model (called an "embodiment"), the nandu, an anchor model is abstracted that describes the mechanism of nandu movement. The anchor model is then transformed into an even more abstract – i.e., less detailed – model, the template. In the terms of Drack et al., the template is the "pivot" ([12], p. 7 and Figure 7 on p. 8) that is the culmination of the biological research into the motion process of the nandu (and other species), and the starting point of the engineering design process. During this process, the template is again enriched by adding more specifications via a technical anchor model to the design or construction plan, from which finally the concrete technical embodiment is produced.

Finally, we can also explain why some biomimetic researchers (like the authors of the VDI guidelines) may think that abstractions are generalisations. For sure, the development steps in the eNandu development are not well described as inferences from “This *F* is *G*” to “All *F*s are *G*s”, or to “Typical *F*s are *G*s”. Removing and adding detail is a much better description of what happens here. A possible motivation for why the VDI guidelines nevertheless think of abstraction as generalisations might be that models with fewer specifications may fit more cases. In the eNandu case, e.g., the template model fits both to the biological and the technical embodiment, while the more detailed technical anchor model fits to the technical embodiment only (i.e., to the eNandu) and not to the biological embodiment (the nandu). That less detail comes with wider applicability is, however, at best a rule of thumb. It is not at all necessary. If a model already fits to all cases in question, eliminating even more features will not lead to a model fitting more cases. Also, the elimination of features from the model can come with loss of explanatory and predictive power. Hence, there will be trade-offs between generality and usefulness of models. Biomimetic research will aim at models that are abstract enough to be understandable for researchers and transferable to the technical domain. But of course, the models need to be concrete enough to have the desired explanatory power, that then translate into the desired causal capability within the technical embodiment.

5. Conclusion

I have shown that while there is a large consensus in the biomimetic literature that abstraction is a crucial element to the biomimetic research process, there is no consensus, and maybe not even a clear understanding, of what abstraction is in the biomimetic research process. As I have shown, the understanding of abstraction varies from understanding it as a kind of generalisation to the more traditional account of disregarding irrelevant detail. I have shown how this traditional understanding, and more accurately its converse description as focussing on relevant detail, fits well to the role ascribed to abstraction in the biomimetic literature, and to what is supposed to happen in the abstraction steps in biomimetic research projects. Self-descriptions of engineers sometimes lack clarity and rigour (for an analysis of one example, cf. [21]). The present study shows that this is also the case for the self-descriptions of biomimetic researchers, which comprise both biologists (and other scientists) and engineers. An interdisciplinary collaboration with philosophers, and maybe cognitive psychologists, can help to better understand the biomimetic research process and its contents, and how this important cognitive process can be adequately modelled by means of an ontology.

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