Building a Biomimetics Core Ontology using OBO Foundry Principles

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Abstract
Biomimetics is an interdisciplinary research area that analyses biological phenomena to develop innovative technical solutions. It requires connecting and reasoning about diverse bodies of knowledge from both biology and engineering. However, existing semantic resources fall short of the requirements for a full-blown domain ontology. To address this gap, we used the OBO Foundry Principles to develop a core ontology for biomimetics. The resulting core ontology is based on the Basic Formal Ontology (BFO) and aligns with the OBO Foundry ecosystem. It is intended to serve as a semantic backbone for biomimetic research and future biomimetic application ontologies in academia and industry. We suggest definitions for central classes and populate them with the classes of existing OBO Foundry ontologies. The ontology is implemented in OWL and available online.

Keywords
biomimetics, core ontology, function, biological model, biologically inspired design, OBO Foundry

1. Introduction

Biomimetics is an interdisciplinary research area that analyses biological phenomena to develop innovative technical solutions. It has been defined as the endeavour to find innovative engineering solutions "through the abstraction, transfer, and application of knowledge gained from biological models" [1]. As such, biomimetics focuses on (i) biological entities, (ii) technical artefacts, (iii) biological strategies, and (iv) the natural laws and principles behind these strategies. In other words, it requires connecting and reasoning over diverse bodies of knowledge from both biology and engineering. For some time, there has been considerable research interest in using computer-aided methods to support biomimetic research processes [2, 3]. As we have shown in a previous paper, existing semantic tools/resources fall short of the requirements for a full-blown domain ontology [4].

To address this gap, we used the principles for ontology development provided by the Open Biological and Biomedical Ontologies (OBO) Foundry to develop a core ontology for biomimetics. The resulting ontology is based on the Basic Formal Ontology (BFO) and integrates into the OBO Foundry ecosystem. This ontology can serve as a semantic backbone for the

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biomimetic research and development process and future biomimetic application ontologies in academia and industry. For instance, it could be used to support design projects or literature research by introducing a machine-readable representation and knowledge integration across different biomimetic applications.

What we present here is very much a work in progress. The current version of the ontology is intended to annotate biological models, technical artefacts, and working principles, which we discuss accordingly. Ultimately, the intended use cases include establishing a *lingua franca* in biomimetics and annotating biological and technical data with biomimetics metadata. To illustrate this, we can use the well-known Velcro© hook-and-loop fastener [5], which was developed by the French engineer George de Mestral after he observed that burdock seeds stuck to woolen socks and the fur of his dog. To describe this biomimetic product from an ontological point of view, we should identify: the technical artefact, its intended function, the biological model, the so-called working principle (or dispositions) that fulfils this intended function, and the process which realises both the disposition of the biological model and the function of the Velcro© tape. All these entities could be represented in structured data and queried. The ontology should support answering questions like the following:

- Which organisms provide biological models for a certain technical function?
- Which working principles can be used to implement a certain technical function?

Moreover, the ontology should be able to align with other BFO-conformant ontologies, and can be used to build application ontologies by researchers in academia and industry, and ontology designers and developers. For instance, a biomimetic ontology intended for use in material science, bridging from biological material to engineered biomaterials, can be built upon this core ontology.

The paper is organized as follows. In Section 2, we provide general information on the biomimetic research process and provide information on the existing semantic resources in biomimetics. Section 3 details the methods and materials used, including the reuse of classes and formal relations. Section 4 suggests definitions for central classes and patterns for modelling biological phenomena, functions, and working principles. Section 5 offers a discussion of the findings, and Section 6 concludes by sketching our plans for future work.

In this paper, class names are written in *italics* along with their corresponding namespaces, e.g., *BFO:material entity*. Upon the first mention of a class name, we also cite its OBO ID as a unique identifier within square brackets, e.g., *material entity* [BFO:0000040], where the full IRI (Internationalized Resource Identifier) of a class, e.g., for *BFO:material entity,* http://purl.obolibrary.org/obo/BFO_0000040, is hyperlinked to the reference information within the square brackets. Relations, together with their namespace, are written in bold, e.g., **BFO:concretizes**. We often refrain from citing the namespace of **rdfs:subClassOf** and **owl:equivalentClass**. Lastly, the logical connectors are in small all-caps, e.g., NOT or SOME.

The OWL file of the version presented here is available at https://github.com/BiomimeticsOntologies/BiomimeticsCore.

2. Background

2.1. The Biomimetic Research Process

Biomimetics is defined as an "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" ([6], p. 2, italics in the original). A product is considered biomimetic if and only if its design results from a three-step process: analysing a biological system's function, abstracting it into a model, and applying that model to the product's design [6]. Although the three-step process remains the same, the starting point of a biomimetic project can vary: (i) in a technology-pull approach, solutions for technical problems are sought in nature, whereas (ii) in a biology-push approach, biological discoveries inspire the design of new technologies [7]. Regardless of the starting point, transferring biological knowledge to the technical domain is essential, as developing new ideas is a prerequisite for application-oriented research [1].

According to the conceptual framework developed by Drack and colleagues [5, 8], which is built on the engineering design approach of Pahl et al. [9], there are five levels to be analysed on the side of both biological models and technical artefacts: (i) the *overarching system*, a biological or engineering system, (ii) the *construction* level, where the concrete parameters of the interacting entities are specified, (iii) the *working principles*, which are the abstract causal relations operating at the construction level, (iv) the *function* in question, which is sought to enable a part of the construction, and, finally, (v) the *task*, which is either the intention with which a machine, device or process is being designed, or, in the context of biological systems, the biological function of the feature in question. Similar accounts are also reflected in self-descriptions of biomimetic researchers, be it in textbooks [10, 11] or in official guidelines and norms for biomimetics, as provided, e.g., by the German Association of Engineers (VDI) or the International Standardization Organisation (ISO) [1, 6, 7]. We conducted a survey of biomimetic research projects, which confirmed that these steps and the mentioned entities are indeed at stake in typical biomimetic research projects. Some preliminary results have been published in [12].

According to this framework, the most important modelling challenges are the representation of biological models, function, and working principles. Biological models and the technical artefacts in a biomimetic project may have different tasks to perform and may display different constructions [5]. The general idea, however, is that functions and working principles are of the same kind in the biological model and the technical artefact, and that these are thus at the core of biomimetic knowledge transfer. Thus, biomimetics mainly helps with the identification of working principles that explain how the function in question is fulfilled in the technical system. An ontological analysis of this framework concludes that the core components of biomimetics are functions, working principles, and the technical and biological systems in which functions and working principles inhere. The goal of a biomimetic research project is to design technical artefacts with specific technical functions, whose working principles are derived from biological dispositions. In a technology-pull biomimetic research project, biomimeticians seek a working principle that fulfils a technical function, which inheres in the technical artefact at hand. When they find a biological entity whose certain disposition aligns with the technical function, the working principle that fulfils the biological disposition can be transferred into the technical realm. Once the working principle is understood, it is applied to the technical artefact with specifications for its material and other characteristics.

2.2. Existing Semantic Resources

Several tools have been developed to support the biomimetic development process [2, 13–15]. Some serve as inspiration tools, such as Bio-Inspired Design and Research Assistant (https://github.com/nasa-petal/bidara), which is a GPT-4 chatbot that provides inspiration for researchers to apply biomimicry principles, while others aim to structure the domain, such as the BioMimetics Ontology [16], which organizes the domain by trade-offs in biology and technology using a TRIZ-based approach.

Yargan and Jansen [4] analyse nine tools that aim to semantically structure the domain of biomimetics, and check the potential of the tools to serve as (part of) an ontology or for being re-engineered for this purpose. The result of the evaluation was mainly negative: (i) no existing resource can adequately represent biomimetic knowledge due to its content, scope, or structure, and (ii) there are significant shortcomings that impede their effective use and reuse as ontologies. Key issues include: insufficient or a lack of documentation; the absence of a taxonomy as a backbone; frequent logical inconsistencies; unclear and unsystematic labelling conventions; and limited machine-readability and interoperability. While most resources offer some degree of extensibility, the overall lack of adherence to ontological best practices hinders their potential to serve as robust computational tools for the biomimetic development process.

As shown in Section 2.1, biomimetics has its own categories that warrant a structured representation of biomimetics knowledge. However, the central entities of biomimetics—function, working principle, and construction—are not consistently and ontologically analysed across existing semantic resources [4]. Furthermore, all these core entities should be elaborated in relation to the unique characteristics of the biomimetics domain. For instance, as there is no unified account of functions, which is indeed not needed [17], so-called "biological functions" must be represented as dispositions. Accordingly, a core ontology for biomimetics should capture dispositions of biological entities, functions of technical artefacts, and the working principles that fulfil both, as well as processes that realize them.

3. Methods

For developing our core ontology, we apply the Open Biological and Biomedical Ontology (OBO) Foundry Principles (obofoundry.org). These principles, established on a collection of best practices for ontology development, are meant to provide a suite of orthogonal and interoperable ontologies. In particular, we use the Basic Formal Ontology (BFO) as a top-level ontology, from which all our classes hang down. BFO meets the standards set by ISO/IEC 21838-1 for top-level ontologies and promotes interoperability, standardization, and reuse among ontologies (github.com/bfo-ontology), including the ontologies within the OBO Foundry and the Industrial Ontologies Foundry (IOF; oagi.org/pages/industrial-ontologies). While the OBO Foundry provides a repository of ontologies for the biological and biomedical sciences, the IOF aims at a suite of ontologies for the industrial domains, the two sides between which biomimetics has to bridge.

The ontology has been implemented in the Web Ontology Language (OWL, w3.org/OWL) using the Protégé 5.6.5 editor (protege.stanford.edu). We employed two methods for ontology reuse. First, we used Protégé's ontology importing wizard to insert BFO as a whole with all classes, their IRIs, labels, definitions, and other annotations. Second, in all other cases, we imported single classes (see Section 4 for examples). For this, we used the OntoFox tool ([18], ontofox.hegroup.org) that builds on the Minimum Information to Reference an External Ontology Term (MIREOT) method [19]. Finally, we used HermiT 1.4.3.456, an automatic reasoner available in Protégé, to test the logical consistency of the ontology.

We also aim to reuse relations that have established themselves as standards in the OBO Foundry. We use the relations that are part of BFO and import some relations from other OBO Foundry ontologies, namely **is about** [IAO:0000136] from the Information Artefact Ontology (IAO) and **is specified output of** [OBI:0000312] from the Ontology of Biomedical Investigations (OBI). As a class import from OBI included **participates in** [RO:0000056], we also had to import this relation from the Relation Ontology (RO), which we stated to be equivalent to the homonymous BFO relation [BFO:0000056], as there seems to be no semantic difference between them. The only additional relations we employ are the **has trigger** relation and its inverse, **trigger of** that have been suggested by Röhl and Jansen [20], originally presented as **has trigger$_D$**. The **has trigger** relation holds between a type of disposition *D* and a type of process *T* if and only if instances of *T* are suitable to trigger the realization of the instances of *D.*

4. Results

In the following, we will discuss the building blocks for a core ontology for biomimetics and explain which classes are imported from the OBO Foundry ontologies, starting from the biological entities that can serve as biological models (Section 4.1), and then proceeding to the engineering side of the technical artefacts to be developed.

4.1. Biological Entities as Biological Models

In biomimetics, biological models are studied to learn working principles for certain functions that can then be transferred to and implemented in technical artefacts. To model these, we need classes for biological entities, in particular organisms, their parts, aggregates thereof, and substances and artefacts produced by them.

Biomimetic guidelines typically suggest that organisms, biological processes, materials, structures, and functions can serve as biological models from which the engineer can learn [1]. A survey of examples showed that a biological model can be also an organism aggregate, e.g., a collection of reeds; an organism part, e.g., wavy whiskers; a material entity constructed by a single (non-human) animal, e.g., a bird nest; a material entity constructed by an aggregate of (non-human) animals, e.g., a termite mound; or a material entity secreted or produced by an organism, e.g., spider silk or eggs. The biological entities in a biomimetic research project, then, range from single cells and their parts to organisms and their aggregates, and from organism substances to portions of tissues, and they can even include biological processes like evolution. As a result, they are not restricted to types of *BFO:object* [BFO:0000030] or *BFO:object aggregate* [BFO:0000027], as an ecosystem or a collection of organisms without a membership relation, are also biological entities that are types of *BFO:material entity* [BFO:0000040]. Due to the categorial diversity, we cannot sensibly introduce a class named "biological model", as this class would comprise instances from various BFO top-level classes. If biological models can also be found in the BFO occurrent branch, we cannot even introduce a role "being used as a biological model", as within the BFO framework, roles can be borne only by independent continuants.

Organisms in biomimetics include any living beings, such as halophiles, blue-green algae, and cats. We decided to import *OBI:organism* [OBI:0100026], as OBI also uses BFO as a top-level ontology. There are several issues worth mentioning, though. *OBI:organism* has many subclasses taken from the NCBI Organismal Classification (NCBITaxon), which is not itself conformant to BFO. Also, NCBITaxon does not conform to the OBO Foundry naming conventions; e.g., the class *viruses* [NCBITaxon:10239] has a class label in the plural. Moreover, it is at least debatable whether viruses can be considered to be organisms or living beings in the same way that, say, cats or bacteria are. In this case, however, we defer our own judgement and follow the consensus reached in the NCBITaxon and OBI communities. An *organism* class can function as an interface to biological taxonomies like these when needed. Likewise, the superclass of *organism* can be debated. Organisms are listed as examples for *BFO:object* in the elucidations of this class in BFO 2020 (and also in [21], p. 91), but OBI subsumes *OBI:organism* under *BFO:material entity*. Again, we follow the consensus of the OBI community here.

Organism part. As in the example of wavy whiskers, also organism parts can serve as biological models. Organism parts can include the eye, leaf, tail, parenchyma tissue, cell, cellular component, cell membrane, and DNA. These examples span several levels of granularity and, thus, the domains of different OBO ontologies. For this reason, we import *GO:cellular component* [GO:0005575], *UBERON:anatomical structure* [UBERON:0000061], *UBERON:anatomical collection* [UBERON:0034925], and *PO:plant structure* [PO:0009011], to serve as bridge classes to more specialised OBO ontologies.

Organism aggregates. In some biomimetic examples, collections of organisms or their products serve as biological models. We can distinguish between two kinds of such collections. (1) Collections of organisms of the same species, such as a collection of reeds that can provide a biological model for absorbing sounds [22]. (2) Collections of organisms of different species (or parts of them), such as the system out of the burdock plant and dog (or burdock seed and dog fur) that served as the model for the Velcro© technology [5]. We selected *PCO:collection of organisms* [PCO:0000000] for representing the organism aggregates and two of its subclasses, *PCO:single-species collection of organisms* [PCO:0000018] and *PCO:multi-species collection of organisms* [PCO:0000029].

Animal artefacts. Gould [23] defines animal artefacts as "any creation on the part of an animal, using and/or modifying available materials, which is useful to it or its offspring" (p. 249). Bird nests, spider webs, and beaver dams are such objects. Here, we can observe a clash between ordinary language and biology: While from the point of view of biology, humans are special animals, ordinary language here uses the word "animal" to refer to non-human animals only. From the biomimetics perspective, a distinction between products of humans and non-human animals is essential, because only the latter would be used as biological models for biomimetic research. We found that *ENVO:construction* [ENVO:01001813] is the best choice to represent both technical and animal artefacts, as it subsumes both *ENVO:animal construction* [ENVO:02000154] (which is said to be synonymous with *non-human animal construction*) and *ENVO:human construction* [ENVO:00000070], which are imported and stated to be disjoint. We do not import the subclasses of *ENVO:animal construction*, but these can, of course, be used by more specialised biomimetic ontologies. Note that the producing agents can be individual non-human animals, as in the example of the bird nest, or aggregates of non-human animals, as in the example of the termite mound. In the former case, the agent would be an instance of *OBI:organism* AND (NOT *human*), whereas the agent of the latter is an instance of *PCO:collection* *of organisms* AND (NOT *PCO:collection of humans*). Representing the biological models with this distinction would be more accurate.

Organismal substance. A successful core ontology should differentiate the organismal substances that are secreted or produced by an organism, and the constructs that are built with the secretions and products of the organisms. For instance, the saliva of a swiftlet and the nest built with its saliva should be treated differently. There are two candidate classes: *UBERON:organism substance* [UBERON:0000463] and *SDP:portion of organism substance* [SPD:0000008], which share the same definition. *UBERON:organism substance* has the advantage to come with 138 subclasses that are not restricted to spiders, unlike the SDP classes (as of March 18, 2025). However, *SDP:portion of organism substance* is favourable as it is in keeping with the OBO Naming Conventions [24]. Accordingly, the saliva of the swiftlets is a subtype of *SDP:portion of organism substance*, while its nest, built with this saliva, is a subtype of *ENVO:animal construction*. The secretions and products of the organisms include enzymes, hormones, sweat, faeces, pheromones, nectar, saliva, silk, and resin, so they cannot be limited to animals. However, neither class includes the substances specific to plants. *PO:portion of plant substance* [PO:0025161] addresses this gap and can be subordinated to a class representing organismal substances. For this reason, we chose *SDP:portion of organism substance*, excluding its subclasses, and introduced *PO:portion of plant substance* as a subclass.

Biological processes: From an ontological point of view, the modelling of processes derived from nature is particularly challenging, as they do not seem to be based on the properties of material objects. A famous example in question is the Evolution Strategy [25, 26] that applies trial-and-selection approaches to the development of technical solutions, inspired by the evolutionary processes in the sphere of biology. On the background of BFO, it is prohibitive to ascribe dispositions to processes like *evolution*, *mutation*, or *selection*, as a disposition can only inhere in one or more independent continuants, whereas the realizations of a disposition are processes. However, though the Evolutionary Strategy is not itself an object, it cannot be implemented without objects, and these objects need to have the dispositions in question, which will produce an adaptive development when realized in a relatively stable environment. For biological evolution, the main participants would be genes (or their biochemical constituents) that have the disposition to mutate, but normally to reduplicate faithfully and to be inherited by the next generation of their bearers, where they can lead to adaptive behaviour in the given environment. In the technical application of the Evolutionary Strategy, it is the actions of the engineer that lead to changes in the construction, the selection of the most successful items, and the repetition in the next round. On the engineering side, the "genes" are mainly calculation units in the mind of engineers or in computers. The resulting engineering construction can be physical or computational units. In any case, the actions of the engineer or the computer are guided by the evolutionary algorithm, and we are dealing with dispositions of humans or computers, respectively.

4.2. Technical Artefacts and Their Functions

We now turn to the technical side of biomimetics and discuss technical artefacts, (technical) functions, and working principles.

Technical artefacts. Intentionality is a key notion in the discussion of technical function: What distinguishes entities in biological and technical realms is that the ones in the latter are driven by intentionality. More explicitly, a technical artefact is a concretization of a plan that is manufactured with the intent to perform a function [27]. Genetically modified organisms (e.g., the OncoMouse or GM-varieties of soybean), or organism parts (e.g., edited myostatin genes), as well as portions of tissue when maintained or cultured outside of an organism in laboratory settings (e.g., the HeLa cell line), are in this respect also technical artefacts. This shows that biological material entities and technical material entities are not disjoint classes [28]. Normally, however, biomimetics research is considered to have a non-living target. For this reason, (i) *ENVO:human construct* alone cannot represent all the technical artefacts, even if it is enlarged with *ENVO:manufactured product* [ENVO:00003074] and *ENVO:facility* [ENVO:03501288]; (ii) the class, which includes technical artefacts, cannot be disjoint from *OBI:organism*, which, notably, includes *OBI:genetically modified organism* [OBI:0302859] as a subclass, or from the classes that represent organism parts. Class hierarchies with multiple inheritance are inevitable when representing the intersections of biology and technology; while they are to be avoided in the asserted ontology, they should be allowed for in the inferred statements.

Another key point to consider is the distinction between the biological and technical realms that organisms and their aggregates, organism parts, organismal substances, and animal constructs are all of *BFO:material entity*, while biomimetic products include both methods, e.g., the Evolution Strategy [25, 26], or abstract constellations, e.g., artificial neural networks, as well as concrete products, e.g., Lotus-Effect® coatings [1]. Thus, a technical artefact can be constituted by physical or digital entities. When a technical artefact is an information entity, a strategy or an algorithm, it can be represented under *IAO:plan specification* [IAO:0000104] which is a subclass of *BFO:generically dependent continuant* [BFO:0000031].

Technical functions. Biomimetics is often regarded as a research field that seeks to transfer biological functions to the technological domain to develop innovative technical solutions [1]. This suggests the need for a unified framework for function that encompasses both biological and technical functions, as Drack et al. [5] have indeed proposed. However, Yargan and Jansen [17] argue that no unified account for functions in biomimetics should be assumed, for the following reasons. First, neither in biology nor in technology is there a consensus on what a function is, and there is no convincing account for a unified account of function bridging both domains, which would be required for a bridge discipline like biomimetics. While this is, of course, not a cogent argument, speaking of ‘biological functions’ could be seen as dispensible, because it is the respective dispositions of biological entities which are really of interest for engineering. We can thus restrict the talk about functions to technical functions. Thinking in terms of biological functions can, however, be of important heuristic utility. First, because features that are selected for by evolution are most likely also optimised for survival in a given environment. Second, because having a certain function brings within good reasons to believe that there is also a respective working principle to be found.

Working principles. While we do not require a unified class for both biological and technical functions, we think that working principles are, in fact, “transferred” from the biological to the technical sphere. We therefore need a description of working principles. According to Pahl et al. [9], working principles are the causal principles that bring about the intended effects. While there is a wide consensus in engineering design that the central step in the design process is the search for working principles to be combined with the resulting working structure of the device to be constructed, there is hardly any discussion of the ontological analysis of working principles in the engineering literature. Elsewhere, we argue at length that working principles are best understood in terms of dispositions [20, 29]. Like we did for the biological models, we do not introduce a class comprising all working principles, but use *BFO:disposition* together with other classes to represent knowledge about working principles as knowledge about dispositions. In contrast to *BFO:function*, the domain of a disposition or its bearer is in no way part of the elucidation of *BFO:disposition*; thus, we do not have to distinguish between dispositions that are natural and those that are the result of human design (for the latter, see [30], though). Moreover, for BFO all dispositions are intrinsic dispositions, as dispositions are due to the physical make-up of their bearers.

We have, however, to account for various varieties of knowledge about working principles (or dispositions) that are used by engineers. We do so by providing patterns to represent different "classifying criteria" for working principles: working material, working geometry, and working movements mentioned by Pahl et al. ([9] p. 94). Botchler [31] seems to conceive of these as three subtypes of working principles. In contrast, we think that they have to be construed as three different types of knowledge about the dispositions involved. In some cases, it might be advisable to combine these varieties of knowledge with each other. For these patterns, we employ the BFO framework plus a newly introduced relation **has trigger** and its inverse, **trigger of** (following [20]), and a class *portion of material* as a subclass of *BFO:material entity*. In addition, we import *PATO:shape* [PATO:0000052] and *PATO:size* [PATO:0000117], together with their subclasses, under *BFO:quality*.

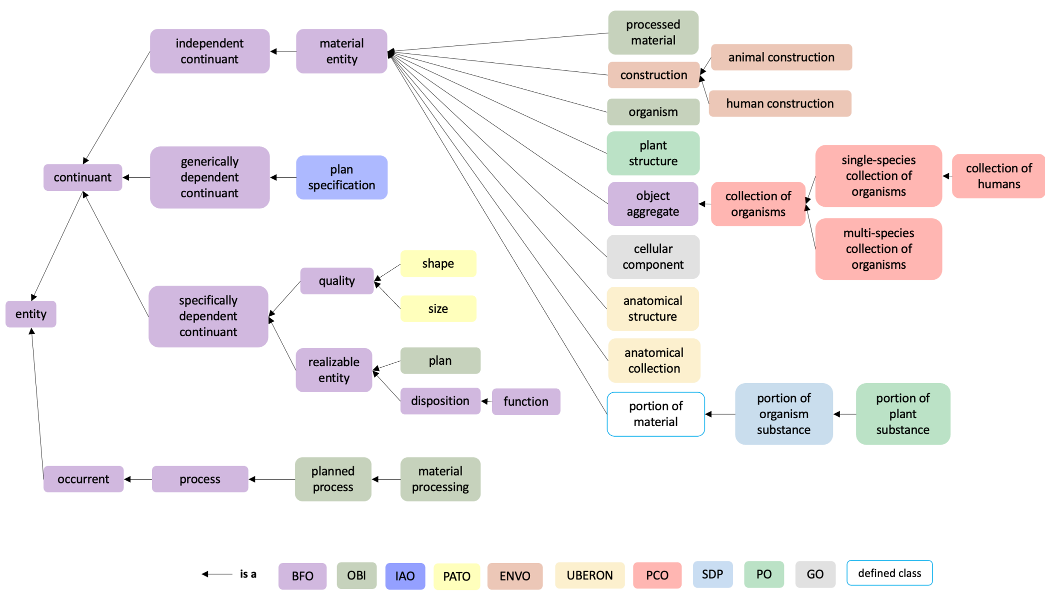

Figure 1. Classes from OBO Foundry ontologies imported for our biomimetics core ontology

5. Discussion

Figure 1 shows the overall classes in the ontology. The ontology provides a consistent framework that can be extended to full-fledged reference ontologies or application ontologies. It supports interoperability among and integration of various interdisciplinary works on biomimetics. To illustrate how to put the ontology to work, we will apply these core classes to the example of the wavy whiskers. Seals can track their prey by using their whiskers, which are extremely sensitive to water movements. The unique undulating shape of the whiskers reduces vibrations caused by the seal's own swimming by cutting down on background noise; which makes the whiskers much better at detecting the tiny water disturbances left behind by escaping prey [32]. Being a biology push example, this phenomenon has been used in technology, where sensing the flow or reducing the drag is important [32].

Our ontology can represent this biomimetics example as follows. The biological model used here is an organism part, namely the whiskers of the seals. The disposition of the whisker is to sense and follow the wake of escaping prey, which can be abstracted to the disposition to minimize self-generated vibration. This disposition also inheres in the technical artefacts produced by biomimetic projects based on this phenomenon. The process is exhibiting vortex-induced vibration. This process can also be realized by the technical artefact, say, an underwater cable which is designed in the undulating whisker shape in order to suppress VIV-induced lift and drag forces [32]. The working principle employed can be represented as a complex disposition inhering in both the seal's whisker and the cable [29]. The representation must include the specific shape of the whisker. Altogether, we arrive at the following axioms:

seal **subClassOf** *OBI:organism*

whisker **subClassOf** *UBERON:anatomical structure*

wavy whiskers **BFO:has continuant part** SOME *seal*

seal-whisker-like waviness **subClassOf** *PATO:shape*

seal with wavy whiskers **equivalentClass** (*seal* AND (**BFO:has continuant part** SOME (*whisker* AND (**BFO:bearer of** SOME *seal-whisker-like waviness*)))

disposition to minimize self-generated vibration **subClassOf** *BFO:disposition*

seal with wavy whiskers **BFO:bearer of** SOME *disposition to minimize self-generated vibration*

exhibiting vortex-induced vibration **subClassOf** *BFO:process*

disposition to minimize self-generated vibration **BFO:has realization** ONLY *exhibiting vortex-induced vibration*

underwater cable **subClassOf** *ENVO:human construction*

underwater cable with seal-whisker-like waviness **equivalentClass** (*underwater cable* AND **BFO:bearer of** SOME *seal-whisker-like waviness*)

underwater cable with seal-whisker-like waviness **BFO:bearer of** SOME *disposition to minimize self-generated vibration*

We based our analysis of biomimetics on the engineering theory of Pahl et al. [9]. This account of engineering design has been developed on the background of (and for the needs of) mechanical engineering. It might be questioned whether this account is broad enough to cover all variants of biomimetic research projects. In particular, the working principles discussed by Pahl et al. are mainly restricted to physical mechanisms. In biomimetics, chemical effects or still other strategies might be relevant as well, e.g., catalysis and redox reactions. Our approach is, however, able to accommodate these examples, as dispositions are in fact not restricted to the realm of physics, but may include chemical dispositions and others.

When applying the OBO Foundry principles, we encountered several challenges. One key issue arose when importing the relations. We based our ontology on the current BFO 2020 version, which contains temporalised relations. However, imported ontologies may still rely on legacy versions of BFO and consequently include some relations from RO. While BFO 2020 and RO share the same relation names, their underlying semantics may differ, such as in the case of **RO:concretizes** [RO:0000059], which we consider to be a subrelation of **BFO:concretizes** [BFO:0000059], which has the wider domain.

Several issues arose when importing the classes. First, despite the postulated orthogonality of OBO Foundry ontologies, we often had to choose between several candidates. In this case, we usually preferred the class from the ontology with the more pertinent domain competence. Second, not all OBO Foundry ontologies are really conformant with the OBO Foundry principles. There are, e.g., violations of the OBO naming conventions (plural class labels, ambiguous class labels), and undefined domain and range of relations.

Third, candidate classes could come with unintended subclasses. E.g., *OBI:organism* includes *NCBITaxon:Viruses* [NCBITaxon:10239] from the NCBI Organismal Classification (ebi.ac.uk/ols4/ontologies/ncbitaxon), while it could be argued that viruses are not even living beings, let alone organisms. As it cannot be the task of a core ontology for biomimetics to decide such issues, we often refrain from importing all the subclasses of classes that are of interest to us.

We also encountered the opposite problem that the superclass of certain classes was not debated. For example, the BFO literature suggests that organisms should be classified under *BFO:object* ([21], p. 91), but most of the OBO Foundry ontologies that have an organism class prefer to classify them under *BFO:material entity*. In this case, we again followed the domain ontologies, where we assumed more competence for factual issues.

Another issue was that some classes seemed to be importable according to their labels, but their definitions were restricted to the domain of the ontology; for instance, the subclasses of UBERON are limited to animals, although the definitions of the classes can encapsulate plants. The opposite problem, already mentioned above, occurred with *ENVO:animal construction*, where the definition fits our purpose, but the class term is misleading from a taxonomic perspective, as it is intended to comprise non-human constructions only. Identifying appropriate classes for cells and eggs proved challenging, as not all cells qualify as organisms, and genetically modified cells can be organisms or part of an organism. Often, a systematic treatment of certain domains was missing from the OBO Foundry ontologies. Sometimes, there are huge branches of interesting classes that could be reused in surprising domains, such as ENVO for representing technical artefacts, or PATO for shapes and sizes. However, such specialised branches for entities that are not peculiar to this domain could restrict the availability of subclasses, and could lead to orthogonality problems in the future.

6. Conclusion and Future Work

In this paper, we presented the core for a reference ontology for biomimetics. The ontology was developed in line with the good practice principles of the OBO Foundry. In particular, we used BFO as the top-level ontology and imported it as a whole. To warrant interoperability within the OBO Foundry ecosystem, we imported additional classes and relations from several OBO ontologies when available.

At its current stage, the ontology has neither been evaluated by a broader community nor tested in practical use cases. Its assessment has so far been limited to automated reasoning checks for internal consistency and expert feedback from two domain specialists, focusing on domain coverage and the appropriate reuse of existing OBO terms.

Future work will focus on both evaluation and expansion. On the one hand, we aim to evaluate the ontology by sending out our term lists to domain experts and have them check them based on their knowledge of the domain. Also, real-world applications are needed to assess the ontology's performance in practical biomimetic research and design tasks. On the other hand, modular extensions are planned to tailor the ontology to specific areas of biomimetic research (e.g., locomotion, surface structures, coloration, or self-healing capabilities) as well as to particular biological models (e.g., water plants, sharks). These modules will allow users to adapt and reuse the ontology for a broad range of biomimetic problems. What is especially undeveloped in the current state of our ontology is the hierarchy of process types. Process types are crucial, because they link technical functions and biological dispositions, if both kinds are realized by the same type of processes. We also want to build bridges to existing repositories of biomimetic knowledge, like the Ask Nature database (asknature.org) [33]. This can be done by re-engineering the so-called Biomimicry Taxonomy used to structure the database [34] as a hierarchy of process types. We also want to test how far other hierarchies of processes could be integrated, which, for example, have been suggested for the analysis of technical functions. Finally, like the Biomimetics Ontology [16], we plan to connect with the heuristic trade-offs of the TRIZ principles and to apply the core ontology to real-world examples, starting from the case studies we conducted. Finally, we will reach out to biomimetic communities to use our core ontology to model biomimetic knowledge. The ultimate goal will be the development of a reference ontology for biomimetics, or, rather, a suite of hierarchical and orthogonal ontology modules that can, step by step, exhaust the biomimetic domain.

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Declaration on Generative AI

The authors have not employed any Generative AI tools.

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