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Bio-Motifs: A Framework for the Design of Discrete Architected Materials and Structures Inspired by Nature

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Abstract

Despite the enormous potential of leveraging the rich information embedded in biological form, and the rising interest in bio-inspired design, there is no generalized, accessible computational design tool that enables it. This brief perspective seeks to identify the reasons for this gap and proposes a framework to address it. This framework consists of three pillars: (i) knowledge graphs, (ii) mathematical models, and (iii) data and information. Large Language Models and Machine Learning are proposed for integrating the three pillars of the framework into a software platform that is modular, interoperable, accessible, and results in manufacturable designed objects. This framework is proposed within the context of nine types of distinct architected materials, introduced here for the first time as "Bio-Motifs", with examples from ongoing work shown to elucidate the underlying concepts. This work also identifies the key challenges with the aim of stimulating future work in the research community to tackle the open questions the proposed framework raises.

Introduction

"*Cell and tissue, shell and bone, leaf and flower, are so many portions of matter, and it is in obedience to the laws of physics that these particles have been moved, molded and conformed…Their problems of form are in the first instance mathematical problems*."
-D'Arcy Thompson, *On Growth and Form*, 1917

In his seminal work *On Growth and Form*, D'Arcy Thompson convincingly demonstrated the value of integrating biology, mathematics, and physics when seeking to understand the underlying basis for biological structure. This desire to correlate form and function in nature continues to drive research a century later [1], with recent offshoots into the engineering sub-domains of Bio-Inspired Design (BID) [2] and biological materials science [3], [4]. One of the early demonstrations of the use of computing in mimicking biological form was in the late 1990s, when a computer program demonstrated how geometric design objectives can be leveraged to generate stick-figure like organic forms using simple line-drawings [5]. In the 25 years since, computational design has made great strides, but computational tools for BID have been typically limited to an individual organism or natural process serving as inspiration for a single application [6]. Additionally, commercial Computer Aided Design (CAD) tools do not embed bio-inspired design principles [7]. To this day, there are no general-purpose, accessible, and user-friendly form-generating computational tools for BID, which drives researchers and practitioners to create their own boutique tools for each new application. It may be argued that there are three primary reasons for this gap:

i. Scope and translation: A key challenge for generalizing BID tools stems from the sheer magnitude of organisms, forms, and functions in biology. A design capability for the generation of bone-like structures for lightweighting [8], to cite one example, cannot be readily leveraged for designing a sea sponge-inspired lattice for energy absorption [9]. This results in single-function design capabilities that have limited general use.

ii. Methods over form-generating tools: Most of the literature in BID delineates along two categories: the first emphasizes methodology and framework [2], [10], [11], [12], [13], while the second focuses on applying these frameworks to develop applications based on specific organisms – like the scales of the pangolin inspiring armor design [14], [15]. In other words, BID is widely seen as a process to be implemented in specific cases, not a broad capability enabled by tools that generate manufacturable designs, a key need for applications that embody BID.

iii. Convergence: Computational BID requires merging structure-function relationships in biology with algorithms that account for physical laws. This involves integrating fundamental concepts from biology, mathematics, and physics, within a computational framework, along with expertise required for application and manufacturing. Integration across these fields is challenging due to different semantic and logical constructions within each domain. These challenges of convergence have been well recognized in the domain of biomimetic architecture [16]. Further, from a design perspective, it is easier to use topology optimization to design a lightweight bracket [17] or to select among stiff lattices already available within design libraries [18], than to abstract design principles from naturally evolved bone structures [19], where biological, mathematical, and physical relationships are challenging to isolate.

The proposed Bio-Motifs framework addresses each of the three challenges above for BID applications focused on discrete structural forms, one of the primary applications of BID (section 2). The framework consists of three main elements: graphs, models, and data (section 3), and implementation requires integration of these into one platform (section 4). This framework is far from complete, in fact key challenges need to be addressed before it can be fully realized (section 5).

Bio-Motifs

To address the challenge of scope, this work is limited to discrete structural forms found in nature. These forms, such as the cellular structure of honeycomb and the open-cell foam geometry of trabecular bone have found engineering application in the domain of architected materials, a class of materials that derive their properties from more than just their base composition, by leveraging geometry, open space and interfacial phenomena, among other mechanisms [20], [21]. For the purposes of simplification, we borrow a distinction developed in computational geometry to contrast discrete forms of interest in this work against continuous forms [22]. Broadly speaking, continuous form addresses the overall shape of structures, such as the form of a shark's body, while discrete form is concerned with repetition, pattern and arrangement, such as the denticles that constitute shark skin [23]. In this work, we proposed nine distinct forms, termed here as Bio-Motifs, and shown in Figure 1.

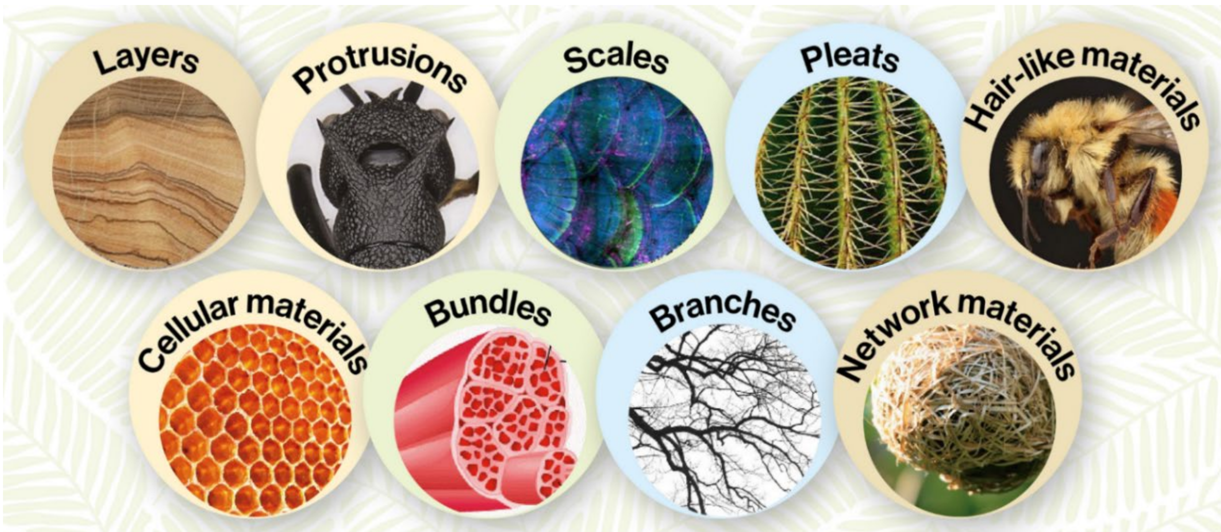


Figure 1. The nine Bio-Motifs identified in this work, from planar layers to surface features to 3D architectural structures

We propose that each of these nine Bio-Motifs meets three criteria simultaneously:

i. it can be represented as the patterned repetition of a fundamental geometric unit,
ii. this unit and its repetition are amenable to representation via algorithmic design, and
iii. the Bio-Motif has emerged across multiple species or biological contexts, enabling a comparative approach to study its function(s)

This separates Bio-Motifs from prior work that has identified structural elements and patterns in nature, but without an emphasis on geometric representation to enable general computational design [24], [25], [26], [27], [28], or with a narrow focus on specific structures [29], [30]. The focus on discrete forms that meet the above criteria, while proposed in part to limit scope, also has other benefits. Discrete forms are amenable to a comparative approach because life has converged on these forms across a wide taxonomic range for similar functions – to cite one example, hair-like materials are used for particle trapping by bees (for gathering pollen) [31], ants and spiders (for gathering soil for camouflage) [32], and filter feeders (for suspension feeding) [33]. As has been previously argued [34], [35], a comparative study of converged structural traits is likely to yield a deeper understanding of *why* morphological features have the functional benefits attributed to them, and therefore result in a higher likelihood of success for BID. Continuous form has also been shown to be readily amenable to topology optimization [36], which is arguably a more effective alternative to bio-inspired algorithmic or parametric design, and for which there are several mature techniques already integrated into commercial software – in contrast, there are no available equivalents for the Bio-Motifs shown here.

Geometrically speaking, layers are arguably the most fundamental Bio-Motif since they enable symmetry breaking [37] by partitioning space into more than one constituent. Protrusions, scales, pleats and hair-like materials develop on the external layer of biological form, while cellular materials and bundles are space-filling. Branches and network materials are system level assemblies of form. The boundaries between Bio-Motifs are more diffuse than suggested above, in more ways than one. Protrusions differ from hair-like materials in having lower length-to-width aspect ratios (<1). In hair-like materials, this ratio is generally one to two orders of magnitude greater. However, a low aspect ratio hair-like material may approach a protrusion. Nature also commonly combines Bio-Motifs – a cactus contains both pleats and hair-like spines. One Bio-Motif may also contain another within it – the spines of the sea urchin, for example, contain cellular materials within it [38], [39]. Feathers feature barbs branching off a central shaft, with tiny hair-like barbules at their ends. Each feather in turn is similar to an overlapping scale – indeed feathers and scales are homologous structures, sharing common ancestry, with the former believed to have transformed from the latter over a series of gradual morphological changes [40]. The overlapping nature of the Bio-Motifs proposed here is indicative of their evolutionary connections but does not detract from their clear geometric distinction in the vast majority of cases. From a designer's perspective, having access to the tools that enable the generation of each Bio-Motif independently is a necessary precedent in enabling their combination in the different ways nature demonstrates.

The Framework

The proposed vision for a computational design tool for Bio-Motifs is shown schematically in Figure 2 following an example of a designer seeking to develop a system for optimizing branching flow. To address this need, two main parts need to be developed: (i) a design ontology and (ii) a design platform, with models connecting them to each other and to the user. To realize this vision, we propose that three fundamental capabilities need to be developed: structure-function-application knowledge graphs, analytical models, and data and information.

Structure-Function-Application Knowledge Graphs

Structure–function relationships are commonly identified in the biological literature through extensive study of organisms and their environments and have also been studied in a design context as proposed in Gero's Function-Behavior-Structure framework [41] and the DANE knowledge-based design environment that captures this information for specific organisms [42]. However, their connections to applications for BID of architected materials are more tenuous. Consider the structure-function map generated in Figure 3 for one specific Bio-Motif: pleats. A detailed literature review was needed to arrive at a map in Figure 3, which demonstrates the high level of functional integration which exists in biological systems. While useful for exploring potential applications, it fails to relate specific structures to functions robustly – nor does it give an engineer confidence to leverage pleats in computational design, especially given the often tangled nature of structure and function. Knowledge graphs relating Structure, Function, *and* Application (SFA graphs) can help address this gap.

SFA graphs that connect function to application provide a clearer pathway for practitioners implementing a BID approach. A challenge in generating SFA graphs, however, is the need to identify and converge primarily semantic information over a wide body of biological and engineering literature. Table 1 shows an SFA table generated manually after over 80 hours of reading and synthesis, identifying a few functions and applications for selected Bio-Motifs. Not only do these tables require a significant amount of time to generate, but they also do not include details of the design of the Bio-Motif in question. Consider a hair-like material, for example: was it straight or branched? Was the distal (terminal) end simple, triangular-shaped, hooked, forked, or some other structure? The application examples also only include a small subset of the true potential of hair-like materials, which in nature are used for a wide range of functions beyond particle trapping, including sensing [43], locomotion [44], thermoregulation [45], surface adhesion [46], camouflage [47], as well as combinations of these functions. It also does not include specific geometric information for any given Bio-Motif. While there have been prior attempts to process natural language for BID [48], [49], there has been, to the best of our knowledge, no such use of Large Language Models (LLMs) for generating SFA graphs and including geometric information that models can act upon, going beyond purely semantic web-based search tools such as AskNature.org [50]. Generating SFA graphs manually, while feasible, is impractical for addressing most BID challenges, but this approach can leverage LLMs to accelerate development and refine these SFA graphs. Knowledge graphs so generated can be leveraged for purposes even beyond that of BID, and correlated to phylogenies, geographical location, environmental conditions, evolutionary history and even to digitized biological information such as that contained in images and videos.

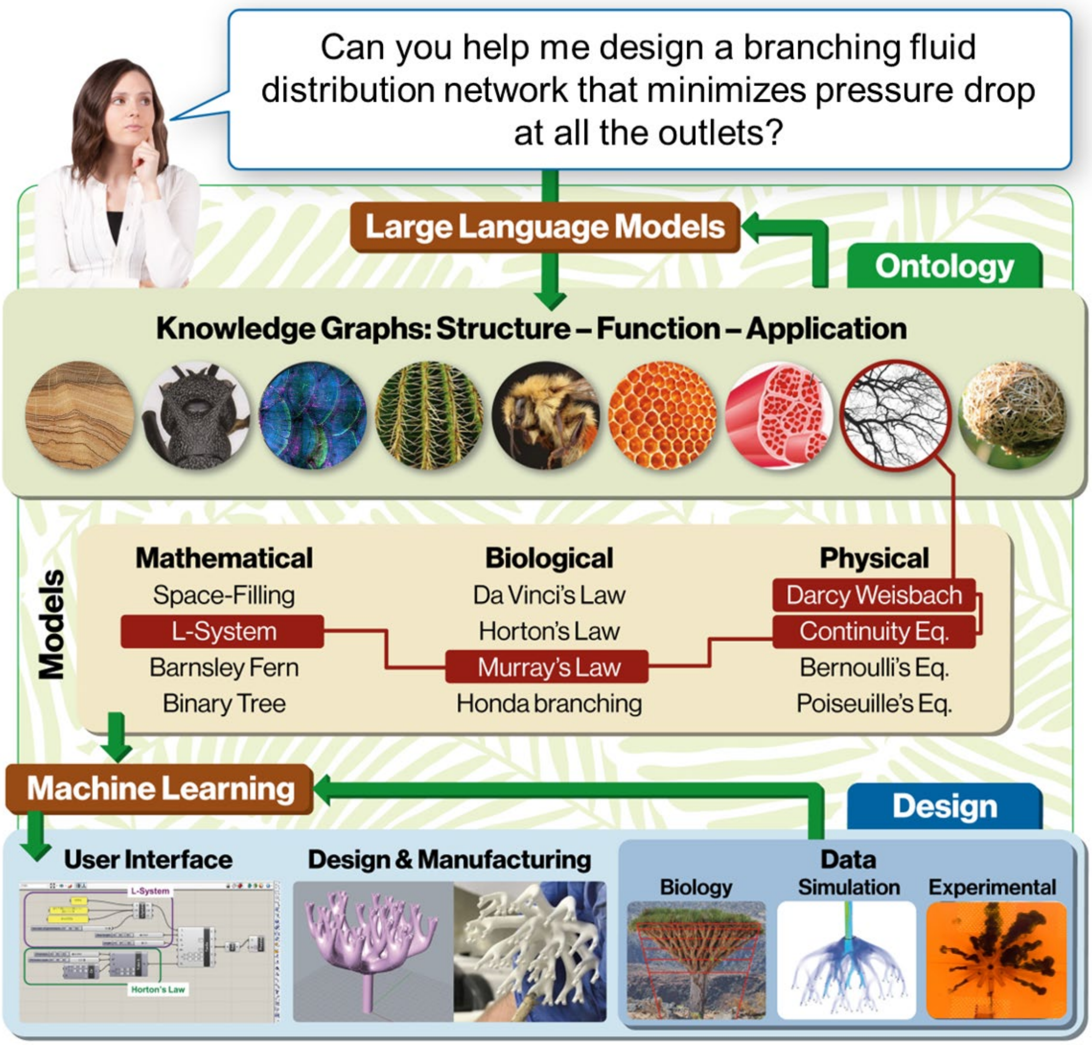


Figure 2. The information flow within the proposed framework, from a designer's question to design solution, demonstrated here for a specific question requiring branching design

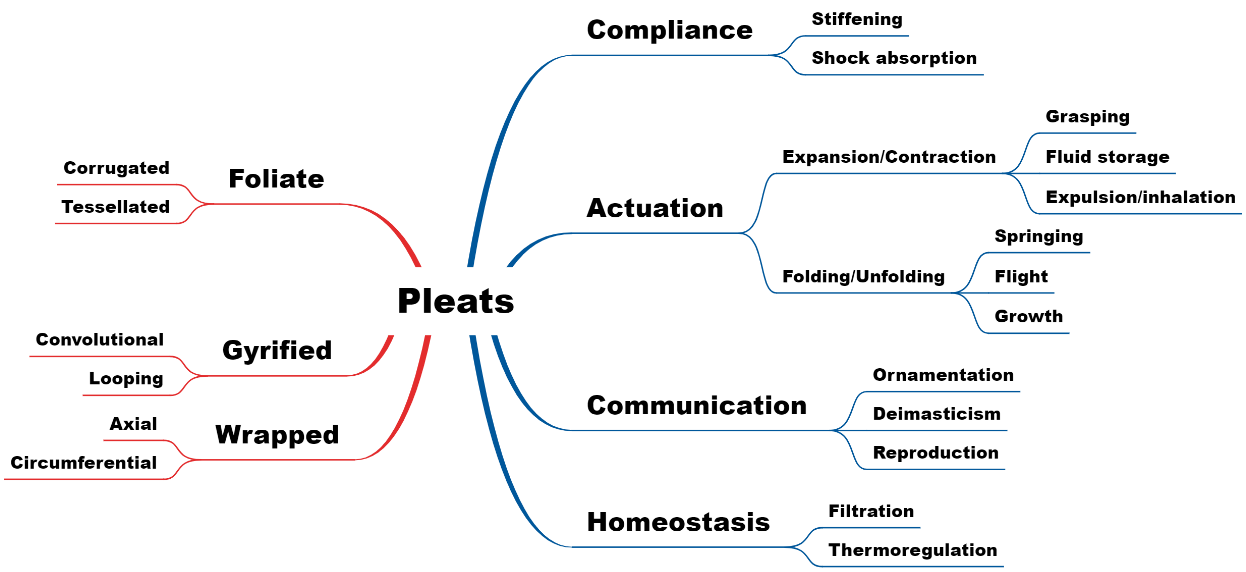


Figure 3. An example of a structure (left) – function (right) classification for a Bio-Motif, from a designer's perspective, developed here for pleats

Table 1. Structure-Function-Application (SFA) relationships identified after 80 hours of literature synthesis

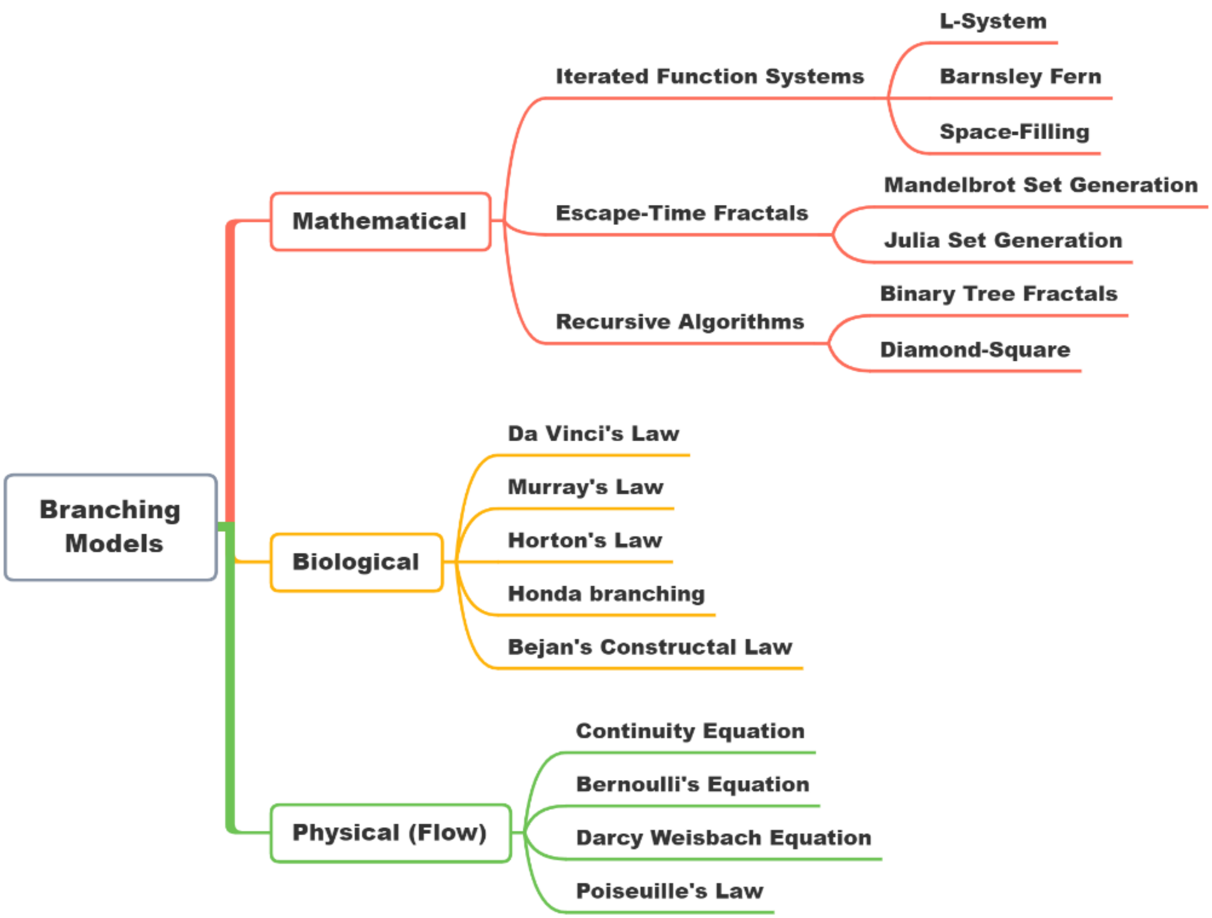
Bio-Motif (S)	Biological Function (F)	Engineering Application (A)
Scales	Protection [14], [51]	Armor plates [52]
	Load redistribution [53]	Anisotropic Load transfer [54], friction mobilization [55]
	Hydrodynamics [56]	Skinsuits
Hair-like materials	Particle trapping [23]	Lunar dust mitigation [24], drug delivery [26]
Protrusions	Hydrophobicity [31]	Self-cleaning surfaces [28]
	Abrasion resistance [57]	Geotechnical engineering [58]
Network Materials	Trapping [59]	Fiber manipulation [60], composite infiltration [61]
Branches	Vitamin transfer [62]	Water transportation [54]
	Nutrient absorption [62]	Foundation and anchoring elements [58]
Pleats	Filtration [63]	Water purification [64]
	Coupling [65]	Sandwich structure [66]
Layers	Growth rate [67]	Sequence Identification [68]
	Functionally graded hardening [69]	Bone grafting [70]
	Protection [69]	Impact toughness [71]

Analytical Models

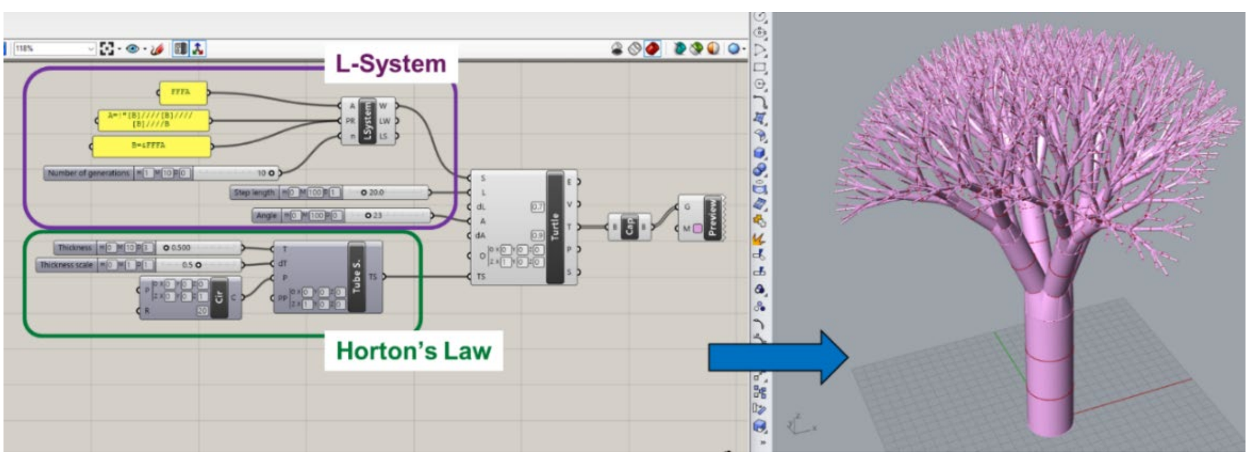
The generation of SFA knowledge graphs, while essential, is insufficient since it is limited to semantic data and does not directly address the need for models. In the context of this work, a model is any formulation that represents, generates, constrains or optimizes the structure or the functional performance of the Bio-Motif for the application under consideration. As shown in Figure 2, this is a critical bridge between the ontology and its implementation in a computational platform. For some Bio-Motifs and applications, such as branching for fluid flow, there is a wealth of knowledge in all three domains (mathematical, biological, and physical) to draw from, as shown in Figure 4a. For example, several mathematical branching algorithms have been developed, many of which, such as the L-system and fractal branching, have been used for studying specific phenomena and structures in nature [72], [73]. In addition, several bio-inspired "laws" such as Murray's law, have been proposed, relating different branch parameters to each other [74], [75], [76]. Finally, there is a vast body of literature in fluid mechanics, with mathematical relationships between channel geometry and flow performance [77]. LLMs can also be used here to identify the relevant physics and associated models, which can be verified against expert knowledge. Since these models embed relationships between geometric parameters and physical variables, they are ideal for implementation in a design platform, a preliminary example of which is shown in Figure 4b for a branching structure realized with the Grasshopper plug-in in the Rhino design software [78]. This approach also makes models amenable to evaluation against manufacturing constraints [79].

Data and Information

In addition to knowledge graphs and analytical models, there exists a vast body of empirical data. In the context of this work, these datasets may have been generated by biologists (measuring the dimensions of a particular morphological feature, for example), biological materials scientists (measuring the morphology's interaction with environmental variables), or engineers (generating data from experiments and simulation) [80][73]. Machine Learning (ML) algorithms can be used to fuse information from these diverse sources to support tasks such as classification, regression, and clustering [80]. While it is possible in some cases to generate designs directly from models (branching structures from the L-system algorithm [73], for example), there are several morphological features for which such models are not feasible or, when available, cannot adequately capture relevant interactions between geometry and physics. This is where ML methods may prove crucial in identifying parameters of interest and suggesting optimum ranges for the values assigned to them. This final pillar of the framework also enables the evaluation of a generated design against desired objectives and design constraints, and in so doing also informs the framework itself with additional data.



(a)



(b)

Figure 4. **(a)** Models of branching from different perspectives: Mathematical, biological, and physical, assisted by AI (Chat GPT 3.5); and **(b)** example of implementation of rules in a design framework in Rhino [78] to generate branching structures – reproduced from prior work in [81] under a CC-BY-4.0 open access license

Implementation

The three pillars of the framework discussed previously, along with their Artificial Intelligence (AI) foundations, are summarized in Figure 5. However, the mere development of these pillars is not adequate – they need to be implemented within an actual, design generating platform. This platform must have the ability to address at least four requirements, discussed below.

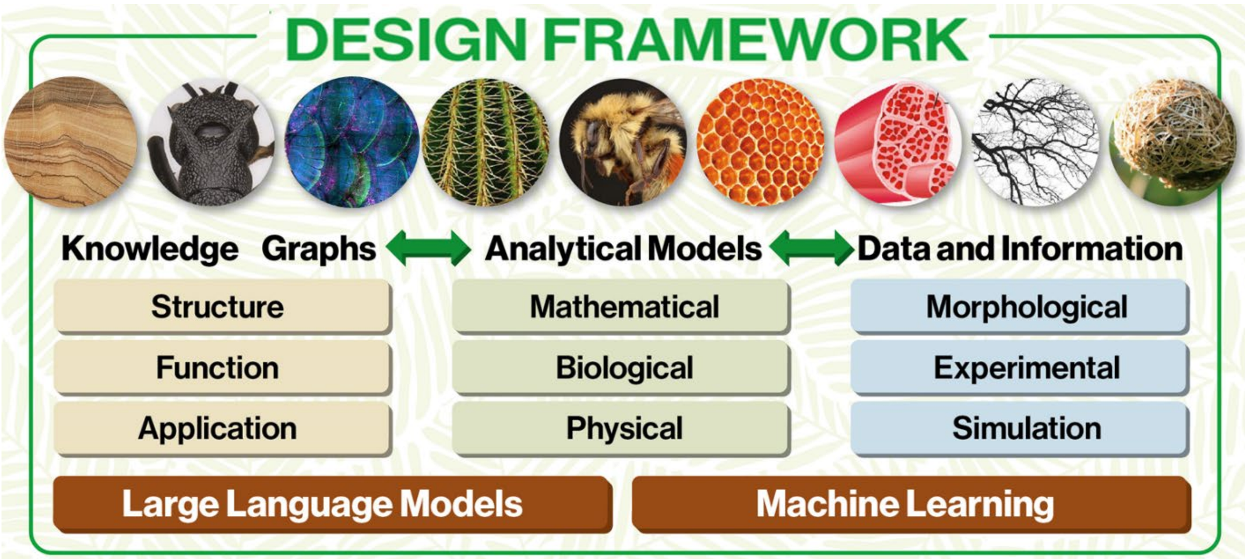


Figure 5. Design framework for AI-enabled platform that combines mathematical, biological, and physical models with knowledge graphs and data

- Modularity: The framework proposed here is a multi-level, modular concept. This is apparent not just at the level of the Bio-Motifs' SFA (e.g., selecting a specific shape of hair-like material [82] for trapping a given family of particles) but also at the level of model selection (e.g. modeling particle adhesion with van der Waals forces [83]). Any implementation thus needs to enable the selection of specific combinations on the SFA and model landscape. AI also needs to be integrated into the platform itself so that the user does not have to work in multiple environments.
- Interoperability: While designs can be generated, constrained, and optimized algorithmically by leveraging analytical models, in several cases, the analysis may need to leverage empirical data, simulation (such as Finite Element Analysis), or ML methods applied to data, image, and language processing. Further, the platform's outputs should be easily translatable to Computer Aided Design (CAD) formats for manufacturing. Any design tool should therefore either have access to these aspects within the platform itself or enable interoperability with other platforms.
- Accessibility: In addition to the convergence of ideas and approaches, this platform is unlikely to meet the stated vision unless it is widely accessible and built by a community of interested individuals. As a result, it is vital that the selected platform be affordable, require limited programming expertise, and be easy to customize.
- Manufacturability: The ultimate success of this framework will be measured by its ability to be used by students, researchers, and practitioners to address a wide range of real-world challenges. This will only be feasible if the resulting designs are manufacturable, which can be particularly challenging given the complexity of most bio-inspired designs, a key reason why additive

manufacturing is a promising approach to fabricating them [7]. Independent of the manufacturing process, any design platform that implements the above capabilities needs to also allow for process-specific design constraints and be able to export a wide range of files for manufacturing. These constraints can be implemented within the mathematical form generating algorithms as design bounds – for example on the thinnest wall or the largest part size that is manufacturable for a given additive manufacturing process and build orientation.

Discussion

The framework proposed in this work is not without its challenges that would need to be addressed for it to perform as envisioned. Three of these, which we believe are the key hurdles in realizing this work, are identified below, along with recent progress in the literature in these areas that gives us confidence that the community is on a path to addressing these.

- Ontology Development: An ontology containing the SFA maps as described here is challenging to realize for two reasons. The first challenge has to do with the sheer scale of knowledge synthesis needed for this effort. For this, we follow others [84] in advocating for a unification of LLMs and knowledge graphs for Bio-Motifs. However, the use of LLMs raises a few questions: how does one manage information from sources numbering potentially in the thousands for a given Bio-Motif, while ensuring their accuracy and without violating copyrights? These are ongoing discussions in the AI community, with different proposals recently forwarded by researchers specific to LLM usage [85].
- Data Organization and Integration: For any given Bio-Motif, there is a vast library of data – the challenge is organizing and integrating the relevant datasets into this framework. A promising approach for this is in using LLM multi-agent collaborations as demonstrated recently for mechanics problems by Buehler and co-workers [86]. Recently, a plug-in has been developed for embedding an LLM as a co-pilot specifically in Grasshopper for parametric design [87] – it is conceivable that this may be extended for the ideas proposed in this work.
- AI Implementation: Lastly, the ML strategies proposed here have yet to be reliably demonstrated in the context of BID of architected materials, but emerging tools in generative AI are showing the potential to handle the requirements of converging information of different types from varying sources [88]. It is highly likely that further progress in this direction will enable the kinds of knowledge synthesis the Bio-Motifs framework seeks to realize.

Conclusions

The realization of a practical, generalized computational BID tool is hindered by challenges of scope, the need for convergence across mathematical, biological, and physical domains, and widely dispersed models, data and information types. This work proposed a framework consisting of three pillars: (i) knowledge graphs, (ii) models, and (iii) data and information, with LLMs and ML as the tools to integrate them into a software platform that is modular, interoperable, accessible and results in manufacturable designed objects. Ongoing work by the authors is exploring the concurrent development of the framework proposed here, along with its implementation for addressing specific challenges in engineering and answering questions in biology. One such effort involves using LLMs for generating SFA graphs for scales, by drawing on biological and engineering literature. Another effort is exploring how mathematical, biological and physical models can be integrated for the design of branching structures for optimizing fluid flow distribution.

Supplementary Materials

Interested readers can subscribe to our "Bio-Motifs" Substack to get updates on and participate in the development of the framework articulated here at https://biomotifs.substack.com/

A 5-minute video summary of this paper is available at this link: https://doi.org/10.5281/zenodo.18675222

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