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Mathematically characterizing natural systems for adaptable, biomimetic design

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Abstract

Biomimicry, used increasingly to make engineering advances, remains underutilized on the scale of the built environment. Drawing from a systems engineering foundation, this research characterizes biomimetic design by the natural principle *form follows function*. By identifying and manipulating the mathematical functions that govern the resulting natural form, this research explores how built structures can best capture the fundamental functions of an organism. Studying an organism's form, processes, and habitat can lead to the development of structures that are able to adapt to changing trends and standards over time. An example is provided from the authors' current project, which involves structurally modeling the *Turritella terebra* seashell and conducting parametric studies to determine which of its characteristics allow for its adaptability. These adaptability parameters can be mapped to analogous characteristics in structural design.

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1. Introduction

Biomimicry is a design method that draws on the inspiration of Nature for more sustainable solutions to human challenges. Nature has 3.8 billion years' worth of time-tested patterns and strategies, which engineers can learn from

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and apply; many human problems have already been faced and resolved in one form or another in Nature. For the sake of organization, behaviors of natural systems are broadly generalized into ten principles [1], which cover concepts such as an efficient use of energy and resources, the recycling of all materials, system resilience, and optimization and cooperation, among others.

One principle that is of particular relevance for adaptable infrastructure design is *form follows function*. While this phrase is widely recognized as originating from modern, industrial architecture (20^{th} century), this concept draws from the theory of evolution (e.g., as described by the overlap in Lamarck and Darwin's theories in the 16^{th}-17^{th} centuries). Nature shapes its structural forms to help meet functional requirements, rather than adding material and energy to produce similar outcomes [1]. Natural structures are honed and polished through natural selection, resulting in systems that are effective, efficient, and multifunctional to meet each organism's performance demands [2]. When abided by, this principle carries potential for a more sustainable built environment.

The term *bio-inspiration* has been popularized in many disciplines, and as the term suggests, designers often draw qualitative, conceptual ideas from Nature. While biomimicry suggests an inherent quality of sustainability in a design, bio-inspiration is a term which encompasses a broader source of creativity (e.g., biomorphism, biophilia, and bio-utilization, which are all forms of bio-inspiration, but are not intrinsically sustainable) [3]. The next step in biomimicry research and practice is to add rigorous quantitative analysis to justify and support biomimetic designs for sustainability.

Using structural engineering tools and methods, our research explores natural systems through a bottom-up approach to reveal system properties of organisms. By pinpointing which emergent properties are the root of structural form, we have the opportunity to create simplified models of complex systems that are mathematically based. In other words, we can better understand the mathematical functions underpinning natural forms, and vice versa.

In this paper, we explore the principle of *form follows function* in common systems from various engineering disciplines. To describe the physical behavior of a system, a mathematical model called a *governing equation* is often used [4]. Governing equations are frequently seen as differential equations obtained by substituting a system's constitutive relationships into more general laws of physics. For example, the governing equations of mechanical systems are expressions of Newton's Second Law, while those of electrical systems are representations of Kirchhoff's Voltage and Current Laws. In these sorts of analyses, we are primarily interested in a system's behavioral response to various inputs. By extrapolating this idea of mathematical description to natural systems, our research investigates the effect of organisms' structural parameters on adaptability over time.

1.1. Governing equations of woodpeckers and harmonic oscillators

In classical mechanics, the dynamic motion of a system can be characterized by three simple elements: a spring, a mass, and a damper. Modeling a mechanical system with these parameters enables representation of not only its potential energy and energy dissipation capabilities, but also captures intrinsic characteristics of the system, such as its natural frequency, and consequently the time it takes return to a steady state response after a disturbance. Understanding this level of detail is important in many structural applications, as unintentionally vibrating a system at its resonant frequency can cause catastrophic failure (e.g., Tacoma Narrows Bridge collapse in 1940).

The dynamics of many mechanical systems can be characterized as harmonic oscillators, which is a system that experiences a displacement and fluctuates around its equilibrium point. Depending on the values of certain parameters, a system can exhibit various response behavior. For example, the sole value of the damping ratio (a constant dependent on the physical specifications of the spring, mass, and damper) can determine whether the system will return to a steady state value without oscillating past its equilibrium point, or if the system will return to a stable configuration at all. In cases with a driving force, oscillation amplitudes may even gradually increase until overwhelming internal forces cause the system to fail.

The governing equation of harmonic oscillators is often portrayed as

$$m\ddot{x} + c\dot{x} + kx = F(t) \tag{1}$$

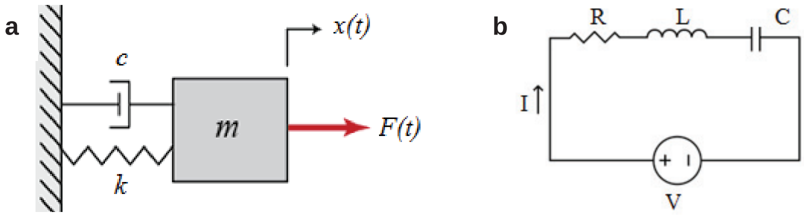

Fig. 1. (a) Simple diagram of a spring-mass-damper system; (b) Diagram of a simple RLC circuit in series

where *m* represents the mass, *c* is the damping constant modeled as a dashpot and resists motion via viscous friction, and *k* is the stiffness of the system modeled as a spring (Fig. 1a). By parameterizing a mechanical system in this manner, a space of infinite possibilities of different systems and response behaviors can be created by adjusting either the element specifications or the input force.

Woodpeckers baffled scientists for some time, as these birds avoided concussions even with pecking speeds of 6-7 m/s and decelerations of 1000 g [5], which is, conservatively, more than 100 times the acceleration that causes loss of consciousness in humans [6]. It has since been discovered that the woodpecker has a unique musculotendinous tissue as well as spongy bone in its skull which act as shock absorbers and protect its brain from extreme vibrations [7]. Additionally, the woodpecker has a comparatively long, heavy, and rigid tail, which it presses against the tree trunk to maintain balance while drumming [7].

The woodpecker can be modeled in elemental form as a spring-mass-damper system, as its input force and oscillating motion are visible and measurable. When the bird drives its beak into a tree trunk, the impact energy is dissipated by the bird's muscles and unique skull structure [8], while its rigid tail acts as a spring. Yoon and Park [7] illustrate an insightful, simplified (the tail is not included, for example) mechanical model of the woodpecker's head structure, and even depict a kinematic model of the bird during drumming. In the framework of *form follows function*, the woodpecker has evolved to have a chisel-like beak (form) for drilling into wood to eat insects (function). In parallel, its spongy skull bone and rigid tail (forms) aid in protecting the woodpecker from damage from impact (function).

Finite element analysis (FEA) is another engineering tool that has been used to study organisms. FEA is useful for studying complex behavior and interactions between various materials and capturing local phenomenon. In addition to the elemental model discussed above, the woodpecker has also been modeled with FEA for more precise insight on the dynamic response of its high-impact pecking [5,8,9].

These biomimetic studies of the woodpecker have led to the development of a new shock-absorbing system capable of protecting micro-machined devices from large accelerations and high frequencies caused by mechanical excitations. Inspired by the skull structure of the woodpecker, this system has a failure rate of 0.7% at 60,000 g, which is nearly 40 times less than the conventional method, which has a failure rate of 26.4% [7].

1.2. Governing equations in other systems

Governing equations are used to characterize non-mechanical systems as well. For example, similar governing equations are used to characterize electrical systems, in which parameters are directly analogous to parameters in mechanical systems (see Table 1). A diagram of a RLC circuit in series is shown in Fig. 1b. The governing equation for this circuit with a constant input voltage has the form

$$\ddot{i} + \frac{R}{L}\dot{i} + \frac{1}{LC}i = 0 \quad (2)$$

Governing equations are also used in fluid flow and heat transfer, among other topics. By applying mathematical analysis to natural systems, our aim is similar: to capture the behavioral response of a system depending on variable input parameters. But instead of measuring the displacement or resulting current in human-made mechanical or electrical systems, we aspire to quantitatively understand the behavior of structural growth in natural systems as environmental factors change. Studying organisms' forms based on their "inputs" is a bottom-up approach to biomimicry that may reveal system parameters that give rise to emergent properties. By searching for the roots of a morphology, we can discover forms that follow functions that are mathematically based—or, natural forms that follow mathematical functions.

In the case study described below, we use engineering mechanics to explore the adaptable growth of a seashell during different stages of its lifecycle. Our research investigates how the mollusk's changing functional needs influence the growth in shell formation and how the system is able to adapt to these changing performance demands.

Table 1. Analogous elements between mechanical and electrical systems.

Input variable (Effort)	Output variable (Flow)	Inductance	Compliance	Resistance
force (F)	displacement, velocity, acceleration ($x, \dot{x}, \ddot{x}$)	mass (m)	spring (k)	damper (c)
voltage (V)	current (i)	inductor (L)	capacitor (C)	resistor (R)

2. Case Study: Learning adaptability from a seashell

Mollusks seldom develop ill-fitting shells; on the contrary, the seashell's inhabitant is capable of adapting the structure (enlarging, primarily) as necessary to meet its needs as the mollusk's body expands. While "appropriate growth" is just one form of adaptability, we can use this simple growth model as a starting point for characterizing adaptability in structures.

Adaptability is of particular importance in the built environment, as accentuated by two studies. First, a study in Minnesota found that about 60% of all building demolitions are due to obsolescence, the lack of suitability for desired use. While this study was contained in St. Paul, there is no reason to consider that results would be different across the U.S. [10]. This large percentage suggests that the current way that our structures are designed is inadequate for meeting our long-term service needs. Human inhabitants and their belongings cycle through a structure every 30 years or so, but structures are designed to last for hundreds of years [11]. As these replacement rates are incongruous, it is essential that the structure and its site are designed to allow for change. Second, if our construction industry is viewed as a closed-loop cycle, 92% of building materials can be generated from renovations and demolitions [12]. Unfortunately, as the industry stands, these materials are treated as waste. If we can design not only our structures but also our structural components to inherently stimulate adaptability, we can increase the lifespan of structures while reducing the impact of the building industry on the natural environment.

2.1. Characterizing the gastropod's form

In our research, the properties of a seashell are parameterized to discover their effect on the shell's adaptable growth through time. The *Turritella terebra* seashell is investigated as a case study for its simple growth pattern. The *T. terebra* is a long, spiraled gastropod that grows in length and diameter as the mollusk ages. As the shell grows, the animal is capable of depositing material at the edge of the aperture, which is the opening in which the animal lives. This gradual deposition of primarily calcium carbonate connects the current to the previous rotations, creating sutures. The build-up of material creates and lengthens the spire over time. Some simple terminology to identify the shell's features are shown in Fig. 2a.

The geometric form of gastropods has been explored and characterized by scientists as early as 1838 [13], for purposes such as paleontological reconstruction of shells [14,15], mathematical exploration [16] and architectural study of natural forms [17], as well as advancement in the precision of artistic generation [18–20]. In a way similar to how the systems described previously are mathematically and parametrically characterized, the morphology of the gastropod can be described as a series of equations where the magnitudes of certain variables directly affect the generated shape of the shell. For example, the helico-spiral, the spiraled axis along which the shell adds material, can be characterized by two angles and a variable radius (see Fig. 2b). The gastropod's mechanical properties have also been investigated by many researchers [21–23], which are used in this research to illuminate factors influencing adaptability through a structural engineering approach. Understanding an organism's background is critical in biomimicry, as its environmental surroundings and survival instincts can inform, for instance, what types of loads its structure carries and reason for its growth pattern.

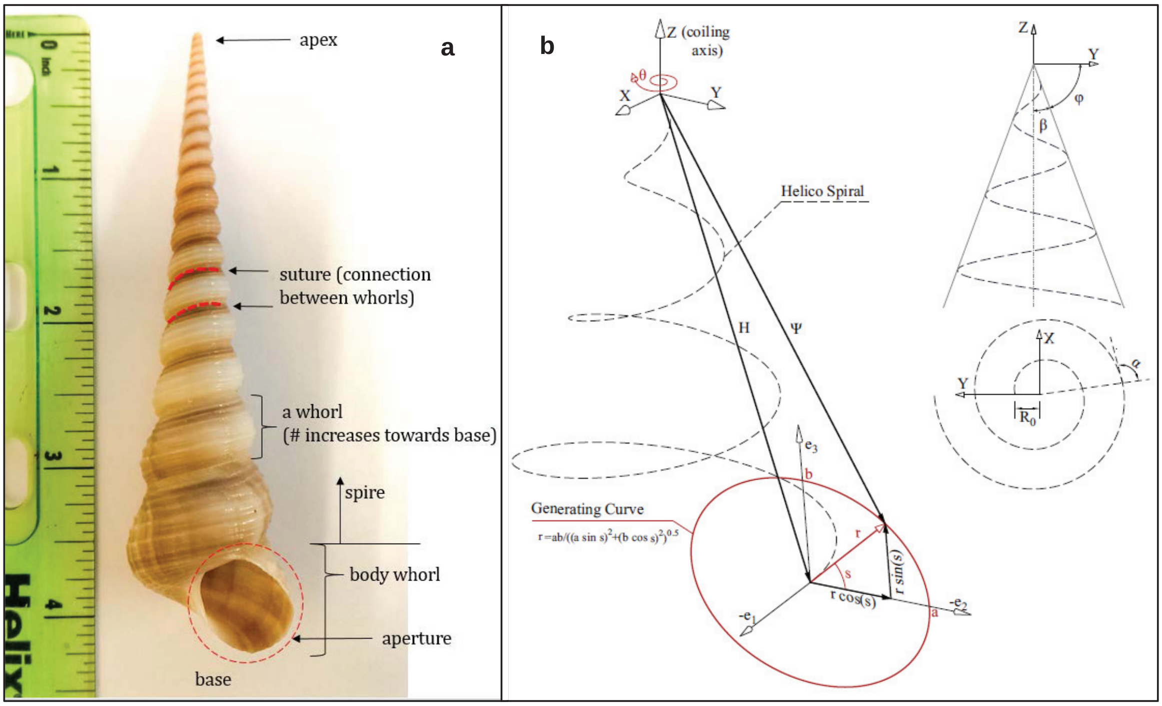

Fig. 2: (a) Terminology of shell features; (b) Select parameters that define the gastopod spiral ([24], with permission)

2.2. Structural applications and parameterization of gastropod adaptability

The next steps in our study of the quantitative biomimicry of the mollusk shell is to apply structural engineering tools. By integrating the mechanical properties of the shell as found in empirical and experimental studies, we created a finite element (FE) model of the gastropod. Due to the previously parameterized geometry, various morphologies are easily represented in three-dimensional graphical form. Finite element modeling involves subdividing the system into smaller parts in order to simplify complex equations, geometries, and phenomenon and explore solutions at a local level. Here, the FE analysis used is based on Hooke's Law,

$$F = kd \qquad (3)$$

The equation for Hooke's law is a simplification of the mechanical governing equation described above, with a focus on the stiffness k and displacement d within the linear-elastic region of the material under compressive forces.

We derived a mathematical model from the series of geometrical equations described earlier. This model accepts geometric variables as inputs and outputs a 3D representation of the shell that the variables define. This shell generation was then converted into a structural analysis model by applying material properties, external loads (forces), and boundary conditions. To validate the FE model, we conducted physical tests on shell specimens. Forces and boundary conditions in the physical tests are simulated in the model. We ensured model validity by comparing the displacements and strains calculated by the model with those measured in physical tests.

Once the FE model is validated against experimental data, parametric studies can be confidently conducted on the gastropod shell. Parametric analysis is used in a variety of disciplines to identify the influence of certain parameters on an outcome. In the next steps of our study, parameters such as geometric variables, loading conditions, and natural relationships (e.g., material thickness as a function of position) will be investigated for their effect on the adaptable growth of the shell over time.

The parameters that are discovered to influence overall adaptability can then be compared to factors currently recognized in infrastructure design. For example, shells exhibit an *open layout* and *layer* their materials [25], allowing for unrestrained yet guided growth. By identifying parallel terms, analogous building design concepts can be emphasized to encourage an increasingly adaptable and sustainable infrastructure.

3. Conclusions

This paper discusses how different types of systems can be simplified into elemental models through the use of governing equations. By extrapolating this idea of mathematical characterization to natural systems, we use quantitative biomimicry in an attempt to uncover traits that lead to adaptable design. In the case study described here, we find that spiraled gastropods are able to adaptably and appropriately increase their shell size as the mollusk grows. Further research will use structural engineering tools to examine which parameters allow for its adaptability, and therefore to applications for a more sustainable built environment.

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