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Material ecologies for synthetic biology: Biomineralization and the state space of design

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HIGHLIGHTS

- Synthetic Biology requires understanding physical materials as computational agents.
- Biological materials may not be produced but induced.
- Biological state spaces include cell, and chemical and physical constraints.
- Synthetic Biology represents a new opportunity for material ecologies.

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ABSTRACT

This paper discusses the role that material ecologies might have in the emerging engineering paradigm of Synthetic Biology (hereafter SB). In this paper we suggest that, as a result of the paradigm of SB, a new way of considering the relationship between computation and material forms is needed, where computation is embedded into the material elements themselves through genetic programming. The paper discusses current trends to conceptualize SB in traditional engineering terms and contrast this from design speculations in terms of bottom-up processes of emergence and self-organization. The paper suggests that, to reconcile these positions, it is necessary to think about the design of new material systems derived from engineering living organisms in terms of a state space of production. The paper analyses this state space using the example of biomineralization, with illustrations from simple experiments on bacteria-induced calcium carbonate. The paper suggests a framework involving three interconnected state spaces defined as: cellular (the control of structures within the cell structures within a cell, and specifically DNA and its expression through the process of transcription and translation); chemical (considered to occur outside the cell, but in direct chemical interaction with the interior of the cell itself); physical (which constitutes the physical forces and energy within the environment). We also illustrate, in broad terms, how such spaces are interconnected. Finally the paper will conclude by suggesting how a material ecologies approach might feature in the future development of SB.

1. Introduction

Whereas the latter part of the twentieth century was transformed through information technologies, it is widely predicted that the 21st century world will be radically changed by the emergence of biotechnology. Biological systems exhibit a wide variety of forms and functions, make highly efficient use of energy and other resources, and are capable of processes such as programmed self-assembly and adaptability which are very difficult or, in some cases, impossible to achieve using more traditional human engineered systems. To this end, Synthetic Biology (hereafter SB) has been heralded as an important technological and design paradigm, enabling the development of complex material systems. SB is, however, still regarded as an emerging engineering discipline [1] and has yet to realize its full potential in terms of delivering complex synthetic biological systems.

In this paper we suggest that, as a result of the paradigm of SB, a new way of considering the relationship between computation and material forms is needed, where computation is

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embedded into the material elements themselves through genetic programming. The theme of material ecologies proposes a tight coupling between computational simulation, material properties and the manufacture of material form. Furthermore, it is proposed that design methods developed in the context of material ecologies may find, in a modified form, new applications for the creation of biological materials which are manufactured by living cells.

This paper analyses the relationship between SB, material design and production through first, in Part Two, examining how SB can be approached as an engineering design discipline, and then contrasting this with more speculative discourses in design. This paper will then seek to rationalize these two apparently contradictory approaches by examining the distinction between emergence, self-organization and the state space of material assembly.

Part Three will go on to describe the results of an experiment into biomineralization, the process by which living organisms induce the formation of mineral crystals. The experiment will be used to illustrate complexity in the creation of biological materials by showing the interrelationships between the living organism and its chemical and physical environment. This experiment, which observes the process by which bacterial communities induce biomineralization, will be used to develop a design framework which describes biomineralization as a process of material fabrication and assembly. This framework is illustrated by proposing the design of a synthetic shell by controlling aspects of the state space of material production in the context of a biological system. The outcomes from a further, limited, experiment will be used to demonstrate the effect of such a state space intervention on different scales of material fabrication and assembly.

Finally the paper will conclude by suggesting how a material ecologies approach might feature in the future development of SB.

2. Synthetic biology in engineering and design

While SB is a new discipline (significant citations to the subject first appear in 2003 [2]) there is now a thriving debate on its status as a field of engineering and, more broadly, as a design discipline [1]. There are, however, two contrasting notions of SB which will be the focus here.

2.1. Definitions of synthetic biology in science and engineering

The purpose of SB, according to the Royal Academy of Engineering, is "*to design and engineer biologically based parts, novel devices and systems as well as redesigning existing, natural biological systems*" [3, p. 6]. SB is associated with molecular level manipulation of, often simple, organisms through genetic modification. Since the discovery of the structure of Deoxyribonucleic acid (hereafter DNA) by Watson and Crick in the 1950s, and the associated development of recombinant DNA in the 1970s, the knowledge of the role of DNA in defining the properties of cells, and thus the characteristics of all living organisms, has grown rapidly. Through the scientific discipline of Systems Biology we now have detailed descriptions of the mechanisms through which DNA is transcribed into messenger Ribonucleic acid (hereafter mRNA) to guide the production of protein molecules in protein factories called ribosomes. These proteins act as machines which perform all the functions of living cells. We can now map entire genomes for individual organisms and, increasingly, we are able to make associations between specific DNA expression and the characteristics and behaviors of individual organisms.

While DNA is often described as containing the blueprint of life, the relationship between DNA sequences, the expression of proteins and the characteristics of biological systems are significantly more complex than this analogy implies. While there are instances of isolated gene sequences resulting in clearly defined characteristics in an organism, much of what we understand in terms of the morphology and behavior of biological systems is derived from groups of different genes being expressed through the more complex (compared to the genome) proteome—the entire population of proteins produced by a cell or organism at particular growth stages or in particular environments [4]. This means that Systems Biology is a science of complexity, and reverse-engineering the relationship between gene expression and their function within an organism is very difficult. Where clear relationships between gene expression and protein function are known, however, recombinant DNA techniques can be used to, literally, cut and paste sequences of DNA from one organism into another, and for the new host organism to be modified by the expression of its new genes. A widely publicized example of this is the transplantation of a gene from bioluminescent jellyfish into mouse DNA to highlight the presence of certain proteins in mice bodies [5].

This process of genetic engineering offers a broad definition of SB which is associated with the practices of copying DNA sequences from the genome of organisms and, through recombinant DNA, importing the sequence from one organism to another, so that the host organism exhibits some characteristic of the donor. These practices are now routinely used within molecular biology laboratories and there are already wide applications of genetically modified organisms. There is, however, a stricter definition of SB being proposed, which is based on a more formal conceptualization of genetic modification as an engineering design process. Biological Systems, in this new context, are considered to be akin to electrical systems with biological circuits [6,7].

SB has become subject to wide ranging speculation in many fields of design through initiatives such as the Synthetic Aesthetics project [8,9]. SB has, however, been predominantly developed through collaboration between molecular biology and computer science. A highly influential approach to SB is emerging, which conceptualizes biological systems in terms of the design of more traditional forms of engineering. The emphasis of this approach is to simplify the process of designing biological systems by:

1. Engaging with an engineering design cycle which includes a clear set of requirements, design, implementation, testing, verification and refinement with an emphasis on extensive simulation and modeling throughout the process [6].
2. Describing DNA sequences and their products as standardized, self-contained parts which are interchangeable and can be used to construct genetic circuits for different functions [7].
3. Bypassing complex lab-based practices of recombinant DNA by using synthesized DNA (DNA which has been coded and 'printed out' from a computer).

This framework has shown early successes, notably by enabling a new generation of synthetic biologists to share and build upon each others' work through competitions such as iGEM, and its sister Repository of Standard Biological Parts. As the repository of parts grows, it is suggested that more complex biological systems will be possible through the assembly of many parts [10].

This approach to the design of biological systems is, however, contested. Some suggest that complex biological networks cannot be reduced and partitioned into discrete parts [11] and this leads to informal and often hidden SB practices. O'Malley [12], for example, suggests that '*While engineering certainly contributes to the practices of synthetic biology, (…) it is doing this in more complicated ways than might be envisioned in the "pure" engineering ideal*'. O'Malley goes on to suggest than hidden behind public descriptions of SB are processes which could be characterized as Kludging (i.e. klumsy, lame, ugly, dumb, but also good enough). These practices, she argues, far from being a sign of failure should be seen as a 'highly creative and effective process'.