Abstract
Recent breakthroughs in the area of synthetic biology have invited a speculative design practice concerning a future reality whereby biology can be engineered to evolve material structures through morphogenesis. These potential technologies prompt a discussion on the appropriate design methods to implement a biologically oriented material practice. In this paper, we discuss two seemingly conflicting notions of morphogenesis. Within the frame of biology, morphogenesis is understood as a formal study of mechanisms that allows the formation of increasingly complex patterns in living organisms. Such mechanisms are generally based on chemical and physical interaction which allows the transformation of simple cellular units into complex arrangements. In contrast, digital morphogenesis describes a series of design practices that are largely derived from the development of generative computational tools, and are generally articulated as non-regular variations of geometric abstractions.

The artefacts presented in this paper embody material proxies, a craft-based design strategy which provides a method to bridge the gap between the design discourse on morphogenesis and the actual mechanisms of form generation in biology. Material proxies are assemblages which partly substitute complex biological and chemical mechanisms, managing complexity in order to understand and experiment with basic parameters of biological morphogenesis. We describe the design context and motivations for the artefacts, located in biomineralisation, and provide further examples of the implementation of material proxies as design methodology.

Author Keywords
Synthetic Biology, Morphogenesis, Morphogenetic effectors, Material Ecologies, Self Assembly, Emergence,
Research Imperatives

Recent breakthroughs in the area of synthetic biology have invited a discussion within design and architecture about the possibilities of a future whereby technology can be intertwined with biological life to evolve shape. Cruz and Pike define these design-biological composites as Neoplasmatic, a new stage of materiality that implies a partly designed living material (Cruz & Pike 2008). This concept extends the notion of a designed artefact to include living organisms whose form is a constant process of adaptation and negotiation with the environment (Spiller & Armstrong 2011; Michael Hensel 2006). Such a discourse suggests a fundamentally different material ecology for design, one in which design is not the process of geometrical abstractions realised through material technologies, but one where design is partly embedded in the process of fabrication and assembly.

The prospect of realising material form through living mechanisms brings renewed attention to the concept of morphogenesis, which attempts to identify the mechanisms involved in patterning cells within multicellular organisms. However, the term morphogenesis has been also used in design to encapsulate practices and concepts metaphorically related to biology (M Hensel et al. 2010). Such design practices are largely derived from the development of computational tools in design starting on the 1980s (Roudavski 2009) and can be described as a strategy to create generative variations of geometrical abstractions.

In contrast, morphogenesis is generally understood within biology as a formal study of mechanisms that allows the formation of increasingly complex patterns in living organisms derived from DNA expression within individual cells acting collectively and in relation to their environment.

In The chemical basis of morphogenesis (Turing 1952), considered a foundational text for the current understanding of shape development in organisms, Alan Turing states that the emergence of complexity in biological systems is the result of chemical and physical interactions within tissues, which are commonly initiated by random disturbances in the system. Based on these principles, we propose a method based on craft as means to gain a more direct engagement with the generative potential arising from cellular living matter interacting with their physical and chemical environment. Furthermore we propose a design strategy based on such interactions rather that on a geometric abstraction. We believe that material engagement, combined with computational tools and rapid prototyping technology, affords designers with an unparalleled understanding of the chemical properties which give rise to complexity and variation in biological form.

**Figure 1**
Electron microscopy image showing cell distribution in bacterially induced mineralisation

**Figure 2**
Cell distribution pattern on a modified bioreactor. In this image, crystal formation on threads

**Figure 3.** Electron microscopy image showing calcium carbonate crystals clustering around a bacterial locus. A graphic scale shows the dimension of 100µm
Research Process

The methodology followed in this paper introduces the concept of material proxy. As biological systems pose a significant amount of complexity, we developed a strategy to handle complexity in biologically-oriented design applications. Material proxies are assemblages which simplify certain mechanisms in order to isolate, study and experiment with specific traits of biological shape processes. The series of artefacts presented in this paper are the first design exercise in which craft has been incorporated to develop a material proxy.

Following an initial research, which we conducted to investigate how the macro-geometry of materials resulting from biomineralisation can be influenced by modifying the physical environment at the molecular scale (Dade-Robertson et al. 2013), we began to explore the basic physicochemical interactions to which cell distribution is indexed. We observed that the formation of crystal was tightly linked to the metabolic activity of bacterial organisms. Such organisms form communities, and determine their placement based on the chemical distribution of their immediate environment. In order to explore these dynamics we developed SynthMorph, a form-finding computational tool based on basic morphogenetic principles derived from the theory of Professor Jamie Davies. Davies sustains that all biological structures are articulated by precise morphological permutations (Davies 2008, p.710). SynthMorph was prepared to work around two classes of object: cells and attractors. Cells behave as a system of particles governed by Boid rules, whose distribution around space is determined by disturbances brought about by attractors, conceptualised as centres of physicochemical perturbation.

Using SynthMorph, we conducted a series of experiments that rendered cell distribution as point clouds. Using such point clouds, we implemented an algorithm based on Voroni Tessellation to partition space around cell clusters, thereby simulating material deposition in the fringes of chemical perturbation loci caused by metabolic cellular activity. Results were prototyped using a Selective Laser Sintering machine.

Research outcomes

The artefacts exhibited show two different experiments of cell distribution. Artefact A shows the effect of one attractor in terms of disturbances and cell distribution. Artefact B1, B2 and B3 result from the evolution of a three-attractor system at three sequential stages.
Conceptually, these artefacts provided us with a proxy to understand the interaction of molecular and macro-scale material formation through biological means. The study of biomineralisation suggested that the interactions at the molecular level have an effect on the macro-scale properties of materials. Using this principle as design concept, we worked around the possibility of a material with differentiated graded microstructure, which would render different effects and properties depending on the specific cross section through which we observe it. A useful model to imagine this is to observe the constitution of seashells. Even when the substance of shells is constant throughout their cross section, being constituted of calcium carbonate crystals, their texture and mechanic properties vary in each layer. Whilst the interior is soft and highly reflecting conducive to the development of the mollusc, the exterior is hard and provides protection against the sea environment.

Artefact A embodies what we believe is the simplest instance of a design strategy for a graded microstructure. Placing an attractor in the centre of the structure creates a very dense core which gradually becomes more porous towards the edges. We may imagine a number of design possibilities around this physical property, such as that of creating a material that allows foreign substances to fluid throughout predefined channels. In the case of Artefact A, the flow would be controlled to be especially higher on the periphery. This principle is further elaborated on artefacts labelled as series B, whereby three attractors create a material with three very defined dense cores, and a porous, lighter buffer zone in-between.

The artefacts produced in this research assume a number of mechanisms through which a microscale event, such as cell distribution, affects macroscale properties. Electron microscopy imagery shown as evidence of the biomineralisation experiments constitutes a magnification that we could understand in design terms as being of 1000:1 scale. The artefacts on the other hand operate at a design possibility of potentially 1:1000 scale. Results presented in this paper must therefore be understood in the context of material proxies for a biologically-oriented production of architecture, allowing us to develop design methods around cross-scale interactions.

References