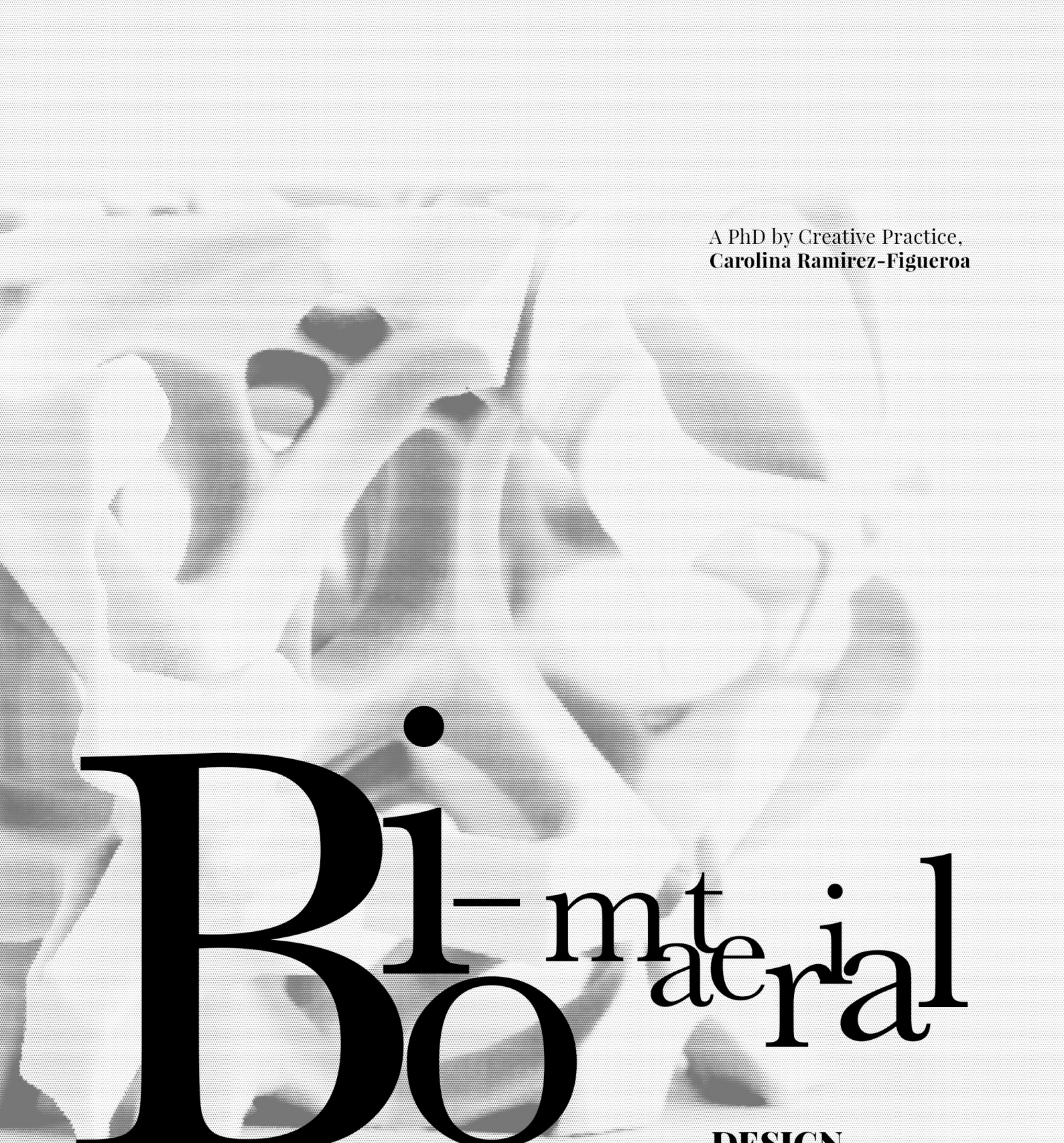

A PhD by Creative Practice,
Carolina Ramirez-Figueroa

Bio-material Probes

DESIGN ENGAGEMENTS WITH LIVING SYSTEMS

B I O - M A T E R I A L P R O B E

Design engagements with living systems

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ABSTRACT

The last decade has seen the emergence of *biotechnical architecture*, a discourse inspired by contemporary developments in biotechnologies and that imagines the possibility and consequences of integrating living systems into the processes of design and fabrication of architecture. In this thesis, I argue that one of the major challenges facing *biotechnical architecture* is in exploring the design possibilities of living systems; given the complexities associated in direct engagement, designers often approach them indirectly by falling back on tools, techniques, and frameworks of existing technologies. The process results in a lack of appreciation of the way living systems constitute potentially revolutionary technologies that can redefine our conception of design and architecture. In this thesis, I propose a creative exploration methodology which affords a direct engagement with living systems, and generates the context to explore their design possibilities.

The thesis is divided in two parts. The first builds the theoretical groundwork and argues that there is tension between two *biotechnical imaginations*: one that operates within *biotechnical architecture*; and the other that defines the narrative of contemporary *biotechnologies*. I argue that the tension raises two research questions: *are there any alternative ways and contexts for working with living systems that take elements from both discourses?* And *what methods and ways of exploration do we need to engage directly with living systems to find the design possibilities?* To explore the research questions, I propose the methodology of *bio-material probe*: design situations that provide the context to explore the design possibilities of biological systems, but that suspend the requirement for a practical design outcome at the outset. Four *bio-material probes* are mobilised in the second part of the thesis to define different approaches to designing form with living systems, starting with parametrics and evolving to an approach that considers non-human agency and assemblages.

To ***L H***

ACKNOWLEDGEMENTS

It is but a mere convention that I sign this work. Katie King reminds us that behind each text there are economies of humans and non-humans that participate in the author inscribing words in the page, and in the reader picking up the text and assembling meaning out of it. The same is true of this thesis — behind it there is a dense mesh of non-humans that have participated in their creation; some of them have left a clear imprint in the work, such as the numerous bacteria that feature in the second part. But there is also an equally significant number of humans and institutions that have supported me in creating this thesis — and since they don't sign this work alongside me, it is only fair that I acknowledge them here.

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INTRODUCTION

Enough of the machine (...) I want to build limbs of Nature
El Lissitzky

INTRODUCTION

On 7 February 2014, a few months into my PhD and already working on *SynthMorph* (Chapter Four), I received an email from my supervisor. I know this because I keep a hard copy on my desk. The subject read 'Of interest?', and the body of the text forwarded the call to *Making Life*, a series of workshops organised by the *Finnish Society of Bioart*. I put together my CV and portfolio as best I could, wrote a short biography of fewer than 1,500 characters (about the length of a tweet), and did the same for the section *'Why would you like to take part? Why should you be selected?'* I sent my application two days later and then almost forgot about it. It didn't escape my notice, however, that there was something poetic and almost sibylline in the coincidence. In *SynthMorph* I was trying to create a computer simulation that was, at its most basic, replicating life to understand how biological form was created. And here was an event called *Making Life*, which was questioning the contemporary drive to tame and manufacture life.

Two months later, I received another email — this one telling me that my application had been successful. There was no way I could know then, but that moment was the unofficial genesis of this thesis. I had been working with synthetic biology (in the widest sense of the term) for a few months, and I had hoped that my boundless excitement would make up for my naivety and beginner's knowledge in the field. For any wide-eyed designer wanting to work with biotechnologies, the first hurdle is access to the tools, spaces, people and knowledge required to work with biology. With varying degrees of creativity, we somehow manage to get inside a lab, talk to a scientist or turn our kitchens into improvised DIY labs (my own tale is partly recounted in Chapter Six). Working with biology from a design standpoint supposes a weird conundrum: designers, and especially architects, often do not specialise in specific fields. We are, to use the description of Phillip Beesley, *dilettantes*. We dip into different topics and disciplines, and learn just about enough to design something around them, before leaving for the next. However, there is a fundamental difference with biological systems – they are alive, and they have their own tendencies and capacities that need

to be negotiated by the designer. In addition, the wealth of knowledge is so vast and dense with technical terms and abstractions that it is often not clear where the entry point is. Orkan Tellhan describes this problem succinctly: '*It requires some knowledge of biology to know what is possible, and some knowledge of what is possible to begin the process of designing*' (Telhan 2016, p.126).

In addition to the problems of access, biotechnical architecture faces the problem of the *horseless carriage*. Biotechnologies represent, as Rachel Armstrong (2015) suggests, potentially revolutionary technologies that can redefine our conception of design and architecture. Yet, we often try to understand them using the tools and frameworks of our current technologies. The process of working with biological systems in design is often preceded by the selection of an organism and a context of operation. For example, we define that we are going to work with a specific form of bacteria that is known to promote biomineralisation. We try to find a domain within architecture in which the process is already relevant, such as the production of bricks. We then define to work with bacteria to produce environmentally friendly bricks. The problem with this process is that when you make the leap of faith — when you select a context for the organism based on current technologies and practices — you collapse the multidimensionality inherent in the organism. At the outset, the notion of 'organism' as 'technology' involves a multitude of dimensions: we can think of them as a potentially infinite number of possible technologies. However, when we impose a context, we collapse the multidimensionality — the organism can only be one thing: this particular bacterium is a technology to fabricate bricks.

Three months after that initial email, I was on a plane to Helsinki to take part in the first of three *Making Life* events. Each event took place over the course of a week and was packed with practical lectures, debates and hands-on workshops. They gave me access to the practical knowledge I sought, and also to *Biofilia* — Base of Biological Arts, a laboratory with the rare combination of state-of-the-art equipment – alongside a group of creative practitioners with whom any intervention was possible. In addition, the workshops taught me how to make my own instruments, ranging from microscopes hacked from a webcam, to incubators made by punching holes

in cheap, plastic boxes. Yet, the most important thing I learnt at *Making Life* was the differences between the artistic approach and the approach of design and architecture. Art practices often involve immersing oneself in the tools and context before defining a specific line of enquiry. In design and architecture, by contrast, explorations tend to start from a specific context; there is a requirement for a practical outcome that needs to be defined at the outset. The contrast between these two approaches would go on to inspire the *bio-material probe,* a methodology I propose in this thesis to navigate the potential of a radically new technology, and which is defined by an open-ended design process that leads to non-deterministic outcomes.

AIMS AND STRUCTURE OF THIS RESEARCH

In this thesis, I respond to some of the challenges faced by biotechnical architecture, a contemporary discourse inspired by advances in biotechnologies; I propose a methodology to engage with living systems, and to explore their design potential without defining a context of use at the outset. To achieve this, the thesis is divided in two parts. The first builds the theoretical groundwork and argues that there is tension between two *biotechnical imaginations*: one that operates within *biotechnical architecture*; and the other that defines the narrative of contemporary *biotechnologies*. I argue that the tension raises two research questions: *are there any alternative ways and contexts for working with living systems that take elements from both discourses?* And *what methods and ways of exploration do we need to engage directly with living systems to find the design possibilities?*

The first part of the thesis is articulated in three chapters: *Biotechnical Imagination in Architecture; Biotechnical Imagination in Biotechnologies;* and *Bio-material Probes.* To explore the research questions, I propose the methodology of *bio-material probes*: design situations that provide the context to explore the design possibilities of biological systems, and that generate non-deterministic, open-ended design outcomes. *Bio-material probes* are used in the second part of the thesis to define different approaches to designing form with living systems, starting with parametrics and evolving to an approach that considers non-human agency and assemblages. This part

is structured in three further chapters: *Digital Parametrics; The State Space of Design;* and *Design Assemblages.*

PART I – BIOTECHNICAL IMAGINATIONS

The *bio-material probe* tries to tackle one of the fundamental issues generated by the tension inherent in what I call *biotechnical imaginations. Biotechnical architecture*, a current discourse inspired by recent advances in biotechnology, can be divided into two main approaches. The first approach I identify, the *speculative biotechnical,* engages with biological systems through technical speculations, and operates using preconceptions of nature, organic form and aesthetics. Moreover, it is often motivated by creating a critical discourse, and shaping public opinions about the implications of biological systems as technology. To do so, however, often requires shortcuts to practical outcomes, often without any direct engagement or knowledge of the tools and processes involved in biological work. The second approach, the *literal biotechnical,* aspires to have a real engagement with biological systems by integrating them as materials and applications. The practical ethos, however, constrains explorations and innovation and results in pragmatic design solutions.

Although both discourses are different in their methods and outcomes, they converge in an altered view of the design process, which is governed by ideas of emergence, complexity and ecology. These principles and aspirations can be detected in discourse but are not necessarily present in their outcomes. I call the combination of both approaches the *biotechnical imagination* in architecture, and define it as an overall aspiration of bottom-up design, as opposed to a top-down, hierarchical approach. *Biotechnical imagination* in architecture involves a lack of control in biology, stressing the existence of emergence, ecologies and complexities that are outside the designeŕ s control.

In addition to the *biotechnical imagination* in architecture, I suggest there is a similar form of *imagination* within biotechnologies. Contemporary discourse in biotechnologies, led by synthetic biology, emphasises the reduction of complexity and randomness of living systems through control, sys-

tematisation, standardisation and clearly defined outcomes and objectives. Broadly speaking, there is an idea of reducibility that engenders a new way of doing biology, which is connected to parts, systems and wholes that are related to the modification of existing organisms or the creation of entirely new ones. Although this approach in biotechnologies has been a productive way of thinking, and has led to tangible results and outcomes, there are several tensions between discourse and practice. Several authors have pointed to the fact that biology doesn't conform neatly to the mechanistic model implied in the discourse. More importantly, from a design perspective the approach misses out on the potential for new ideas, as it requires the definition of every outcome in advance of its process. It could be argued that the approach in synthetic biology entails a return to notions of design, which may now be outdated, as many sub-disciplines have moved past notions based on systematisation, and which requires delineating clear objectives for a design process.

There is a tension between both sets of *biotechnical imagination* that can be described by saying that biotechnologies suffer from short-sightedness, while biotechnical architecture is long-sighted. The approaches in biotechnical architecture expand the horizons of the ways in which biology can be manipulated. They are long-sighted in the sense that they focus so much on distant and ambitious design contexts, that projects often cannot be realised immediately. On the other hand, the *biotechnical imagination* in biotechnologies promises a framework that would eventually lead to standard parts that can be interchanged. The domains of application often described by biotechnologies are, however, short-sighted, as they tend to be so close to the realities of current techniques and tools that it is difficult to find design contexts that are wider.

PART II – BIO-MATERIAL PROBES

In light of the tension between both types of *biotechnical imagination*, this thesis will ask if *there are any alternative ways and contexts for working with living systems that take elements from both discourses.* Moreover, *what methods and ways of exploration do we need to engage directly with living systems to find the design possibilities?* To do so, it explores alternative ways of working with

living systems, and will suggest the methodology of *bio-material probes*. The guiding principle of the *bio-material probe* is its open-ended nature, which involves an exploration that uses design tools and practices, but which is not oriented towards a deterministic outcome—an artefact that solves a specific problem or design situation. In addition, *bio-material probes* are intended to manage and reduce the complexity inherent in working with living systems, while also acknowledging that complexity. This objective is achieved by creating an exploration context that enables direct engagement with a living system, but in a way that does not require a high level of expertise at the outset. *Bio-material probes* can therefore take the form of, for example, a computer simulation based on a biological model, collaboration with a scientist partner or projects that involve working directly in a biology lab.

Generally, *bio-material probes* are intended to provide the setting in which it is possible to engage with biological systems from a design perspective. In this sense, it is a strategy of governing and giving purpose to an activity. They give designers a reason to explore biological systems, and to engage with the context, activities and economies involved in the work with biological systems. A good analogy to describe the *bio-material probe* is to characterise it as a recipe for how cakes are made. It facilitates an understanding of the context, materials, technology and other assemblages, which enable the cake to be made. It doesn't, however, provide a prescriptive recipe for making a specific cake. Rather, it enables a practitioner to locate him/herself in the context of biological work and, as a methodology, provides purposefulness without being tied to a specific design outcome.

I identify four characteristics that define *bio-material probes*. First, they enable open-ended, non-deterministic design outcomes. Inspired by the approach used in art practices, *bio-material probes* operate by using design tools, spaces of practice and methods, but are not oriented towards the production of an artefact or space that solves a specific problem. Instead, they produce a context wherein the exploration of living systems is possible that leads to non-deterministic outcomes. Second, they operate with restricted domains and objectives. The explorations enabled by *bio-material probes* are designed to engage with a set of organisms, and often with one of its behaviours or characteristics. The strategy enables a reduction of the complexity,

rendering more manageable the potential contingencies that appear during exploration. Third, they are articulated by direct engagements with living systems. *Bio-material probes* are intended to create the context wherein design possibilities are derived from the direct experience of living systems and, as a result, need to be designed in such a way that there is always a direct link with the realities of working with living systems. Fourth, they operate as material thoughts. Following contemporary philosophical schools, *bio-material probes* use engagements with matter as a strategy to develop theoretical arguments. They are not used as a way of *illustrating* a theoretical argument, but to derive new knowledge.

Four *bio-material* probes are mobilised in the thesis: *SynthMorph* is designed as a computer simulation that draws on models of morphogenetic processes, *Bacterial Crystals* is based on biomineralisation, and *Bacterial Morphologies* and *Bacterial Assemblages* use bacterial branching as their design context. The sequence represents an evolution in design thinking. It starts with a parametric approach that stays close to the philosophical frameworks, tools, and techniques of biotechnical architecture. Each *bio-material probe* reveals different aspects of working with biological systems, and interrogate and surprise this initial approach, evolving it gradually to a framework based on notions of non-human agency and assemblages. The exploration afforded by the *bio-material probes* argues that designing with biological systems involves *caring* for the deep networks of actants connected to them, and that range from chemical agents, to equipment, to human actors, to spaces, to epistemologies, to institutions.

THESIS STRUCTURE

Chapter One, *Biotechnical Imagination in Architecture*, reviews the historical relationship between architecture and living systems, stretching back to classical antiquity, and including movements of biomimicry and biomimetics in the nineteenth and twentieth centuries, which were influenced by the work of Haeckel and Goethe, among others. I define *biotechnical architecture*, a term that borrows from the work of Pia Ednie-Brown, and propose two branches: *speculative biotechnical*; and *literal biotechnical*. I describe both streams, and review different projects that best illustrate the

methodologies, discourses and tools of each branch. I argue that, although different in terms of methods and tools, both branches converge in an altered view of the design process, which I call the *biotechnical imagination*, and make reference to an aspiration of bottom-up design that mobilises ideas of emergence, complexity and ecology. The chapter comes to a close by suggesting that the tension between imagination and actuality raises the following research question: *Can architectural designers engage with living systems in a way that doesn't prefigure design outcomes but which enables innovative engagements with biology as material?*

In Chapter Two, *Biotechnical Imagination in Biotechnologies,* I extend the notion of the *biotechnical imagination* to the discourse of contemporary biotechnologies, and propose that it is articulated by the engineering design principles of abstraction, standardisation and modularity. I trace these principles back to a nineteenth-century philosophical project of mechanism, which explains living systems by drawing analogies to the interaction of material components in machines. I describe the work of Jacques Loeb, who was instrumental in introducing a mechanistic approach to biology and is often identified as a precursor to contemporary synthetic biology. I also review the work of Stephane Leduc, who coined the term 'synthetic biology' and developed an alternative approach to understanding life. I review the work of contemporary authors who are critical of the use of engineering design principles in synthetic biology, such as Calvert, Bensaude, Danchin and O'Malley, and expand the analysis by comparing the *biotechnical imagination* in biotechnologies with *design methods* and *sciences of design,* postwar design movements that attempted to generate a universal methodology that could be formulated to solve them. I highlight the tension between both *biotechnical imaginations* and propose the following research question: *Are there are any alternative ways and contexts for working with living systems that take elements from both discourses?*

Chapter Three, *Bio-material Probe,* proposes the methodology of *bio-material probes*. I define *bio-material probes* as enablers: situations that provide the context to generate new ideas and questions around the possibility of designing with biological systems. I explain how the term makes reference to the work of Bill Gaver in *cultural probes* and, more closely, to *dérives*, a

technique used by the *Situationist International* movement. *Bio-material probes* are intended to *throw* designers into the economies, spaces and practices involved in biological work. I discuss how the methodology constitutes a departure from the prevalent techniques in the field of research through design, referencing the work of Cross, Frayling and Schön. I propose that, given its focus on the process of design and not on its artefacts, the *bio-material probe* is closer to a notion of design as a form of hermeneutics, as suggested by Snodgrass and Coyne, and I use it in this thesis to explore further the argument laid down by Rachel Armstrong regarding the transformative effect of biotechnologies in design.

The second part of the thesis begins in Chapter Four, *Digital Parametrics,* which describes the first *bio-material probe*, *SynthMorph*, intended to operate as an early exercise to understanding general principles of form-generation in biology, and developed as a computer simulation that draws on the theory of morphogenetic effectors, proposed by Jamie Davies. The design of *SynthMorph* involves drawing upon the work of Christopher Alexander, and takes a parametric approach to interpreting morphogenetic effectors. I analyse the philosophical tension generated by using a rational design approach, and morphogenetic effectors, which are connected to embryology and organicism. Analysing *SynthMorph* as a *bio-material probe* I discuss a number of themes: the tension between design intent and liveness of the particles; the non-linear, emergent properties produced in the simulation; and the way in which the software constitutes a form of mediating artefact, a tool to document and represent form through a precise permutation of behaviours.

Chapter Five, *State-space of Design*, uses two *bio-material probes*, *Bacterial Crystals* and *Bacterial Morphologies,* to explore how a parametric approach can be applied directly to a biological context. The chapter is structured in four parts. The first establishes the conceptual framework by introducing the notion of the *state-space of design* and reflecting on the strategy of black-boxing by referring to the work of Bruno Latour. I propose to interpret the model of *state-space* parametrically, and to draw upon the work of Christopher Alexander in order to develop a diagrammatic strategy to decompose state-spaces. The second part discusses *Bacterial Crystals,* which uses bi-

omineralisation as a design context, and focuses on manipulating the physical state-space. Part three of the chapter reflects on *Bacterial Morphologies*, which uses bacterial branching as the design context and manipulates the chemical state-space in parallel to the physical. I use the experience of both *bio-material probes* to reflect on a number of themes: the existence of contingent state-spaces; the shortcomings of blackboxing; and the volatile nature of the parametric system. The fourth part discusses the adequacy of a parametric approach to designing with living systems. I argue that it is impossible to produce a standard set of parameters, and that the term 'parameter' is imprecise, as living systems cannot be quantified and described in equations.

Chapter Six, *Design Assemblages,* presents an alternative approach to designing with biological systems, and proposes a framework based on assemblages. The chapter is also structured in four parts. Part one addresses the philosophical context, drawing on the work of Bruno Latour, Donna Haraway, Jane Bennett, Katie Lloyd-Thomas and Barbara Bolt to define a design approach based on non-human agency and assemblages. Part two of the chapter documents the design of the *bio-material probe* of *Bacterial Assemblages*, and discusses the key implications of the approach based on assemblages: the impossibility of quantifying actants; the decentring of the human designer as sole creative actor; and the requirement for an experiential approach. I propose interpreting the model of state-space as an initial strategy to navigate the assemblage of bacteria and their context. Part three reflects on *Bacterial Assemblages* and structures the discussion according to three contingent state-spaces: *spaces of practice*; the *culture of crafting;* and *social interaction*. The chapter comes to a close in part four, which argues that the exploration escalates the notion of the biological system, as it shifts the assumption that the object of design is within the membrane of a cellular system, and redraws the boundary to include the design of spaces of practices and instruments used in interacting with biological systems.

The thesis comes to a close in the *Conclusion*, where I discuss the different implications of the creative exploration, developing the notion of *care* associated to assemblages. I draw on the work of Jeremy Till to argue that the exploration of contingencies have a wider implication for architecture, and

that using biological systems in the process of design *buffets* it *from within*, contributing to suspend the fiction of order at the core of the discipline. I follow the discussion with a *Coda*, where I analyse the implications of the thesis in my own practice and review a design exploration that ran parallel to the thesis, which also initiated with *Making Life,* and deals with larger assemblages of organisms, people, practices, epistemologies and institutions.

PUBLICATIONS AND COLLABORATIONS

The design work included in this thesis has been published in a number of venues. *SynthMorph*, discussed in Chapter Four, has been analysed in *Adaptive Morphologies: Toward a Morphogenesis of Material Construction* (Ramirez-Figueroa & Dade-Robertson 2013), included in the 2013 proceedings of ACADIA. It is also used in the discussion of *Synthetic Biology as Material Design Practice* (Ramirez-Figueroa C, Dade-Robertson M 2013), prepared for the Research Through Design conference. Images and references to the work developed in *Bacterial Assemblages*, discussed in Chapter Six, are also included in *Radical Vernacular: Bacterial Architecture on Mars* (M Dade-Robertson et al. 2015) and in *Bio-Materialism: Experiments in Biological Material Computation* (Dade-Robertson et al. 2017). The notion of the state-space of design, upon which I expand in Chapters Five and Six, was originally published in *Material ecologies for synthetic biology: Biomineralization and the state space of design* (Martyn Dade-Robertson et al. 2015). The work included in *Bacterial Crystals* is also documented in *Proto-materials: Material Practices in Architecture at Molecular and Cellular Scales.* Images and references to the work developed in *Bacterial Morphologies* are included in *Bio-Materialism: Experiments in Biological Material Computation* (Dade-Robertson et al. 2017).

I also thank our Stage 6 students in the MArch programme at Newcastle University who contributed to the design work analysed in Chapter Five: John Beattie, Alexander Lyon, Markus Ryden, Malcolm Welford, Gabriella Smith, Jonathan Beeby, and Omer Faruk Alp.

I

1

BIOTECHNICAL IMAGINATION IN ARCHITECTURE

1

CHAPTER 1

BIOTECHNICAL IMAGINATION IN ARCHITECTURE

1 INTRODUCTION

A contemporary discourse, *biotechnical architecture*, can be defined by its interest in recent advances in biotechnologies and, more generally, in living systems. There are two poles to its discourse. One pole, which I propose as *speculative biotechnical*, engages with living systems through technical speculations, and is broadly interested in developing critical discourses, shaping public opinions about the implications of living systems as technology and describing possible futures enabled by biotechnologies. To achieve these objectives, *speculative biotechnical*, draws on methodologies characterised by shortcuts, which enable the extension of observed or known properties of living systems to fit different design scenarios. As a result, it often operates on preconceived notions of biological systems, with limited engagement or knowledge of the tools and processes involved in biological work.

The second pole, *literal biotechnical*, is characterised by an aspiration to integrate biological systems as materials and technological applications. Its methodologies often involve constant, direct engagement with real biological systems and strive to minimise practical shortcuts. Although this strand offers a counterpoint to the speculative strand, the requirement for direct engagement often constrains exploration, leading to pragmatic designs whose only purpose is to accommodate existing techniques, tools and methods of working with living systems. Moreover, the approach hinders an understanding of the unique opportunities that biological systems offer to design.

The classification system proposed is not rigorous. The poles, speculative and literal, are imaginary ends of a spectrum. Biotechnical architecture projects develop discourses and practices that can be located somewhere within the spectrum, closer to one or the other end. The categories are useful, however, in recognising the way in which biotechnical discourses converge in an altered view of the design process, which I refer to as *biotechnical imagination*. I define the concept as an overall aspiration of bottom-up design, contrasting traditional, top-down and hierarchical approaches to design, and which mobilises notions of emergence, complexity and ecology. The disconnect between discourse, method and formal outcomes raises two research questions, which this thesis attempts to answer. First, *can architectural designers engage with living systems in a way that doesn't prefigure design s but which enables innovative engagements with biology as material?* And second, *is it possible to design by engaging exclusively with living systems and their immediate context?*

2 BIOTECHNICAL ARCHITECTURE

The last decade has seen a growing body of theoretical and creative work in architecture, a *biotechnical discourse*, which operates on the premise of using living systems as part of the design and fabrication of buildings. Although sharing some principles with a preceding, long-standing tradition of biological thought in architecture, the biotechnical discourse is distinct in that it not only aspires to imitate nature but it is also interested in the direct use of biological systems as design resources.

Elements of the biotechnical architecture discourse are prefaced by the tradition of biological thought in architecture. Caroline Van Eck (1994) suggests there is a continuous theme of imitation of nature that, she proposes, can be described as an alchemist's quest: a desire to transmute the products of technology — dead matter — into living beings. During classical antiquity and the Renaissance, living systems were considered to be the source of eternal principles of beauty and order. Pillars modelled to the canoni-

cal Doric and composite orders, for instance, integrated acanthus leaves in their capitals. Moreover, Vitruvius' theory of *venustas* proposed that a timeless understanding of beauty could be achieved by studying all things natural, which had developed following universal laws of proportion and symmetry. In describing Greek buildings, Vitruvius refers to the proportion of the human body:

> Since nature has designed the human body so that its members are duly proportioned to the frame as a whole, it appears that the ancients had good reason for their rule, that in perfect buildings the different members must be in exact symmetrical relations to the whole general scheme (Vitrivius 1914, p.73).

Ideas about nature, it could be argued, are crucial to contemporary understandings of architecture as discipline. In describing nature as the source of eternal laws of beauty, and as a model of efficiency, the work of Vitruvius looked to establish architecture as a liberal art, a dramatic change from its then traditional status as mechanical craft. By doing so, the discipline assumed a widespread tradition of imitation of nature. Vitruvius' *venustas* draws from the work of Aristotle, Cicero and Quintilianus, among other classical authors, who developed rhetorical principles based on nature as a model of harmony and persuasion. Quintilianus advises: '*Fix your eyes on nature and follow her. All eloquence is concerned with the activities of life... and the mind is always readiest to accept what it recognises to be true to nature* (Quintilianus, cited by Van Eck 1994, p. 43).

Interest in nature, however, is not limited to classical antiquity, and is a recurrent theme throughout architectural history, as suggested by McDonough (2012). In the nineteenth century, for instance, notions of nature and living systems helped shape the romantic movement, with its central thesis that there are truths hidden in nature that are unknowable to reason. Nature as the ideal of mystical, eternal truths motivated Goethe's studies on morphology, such as his *Metamorphosis of plants*. Goethe's work, in turn, influenced and coincided with a burgeoning interest in nature during the nineteenth century, exemplified in scientific works such as Ernst Haeckel's study on the symmetry and spatial organisation of jellies and microorganisms, and in the formal mimicry of art nouveau in the late nineteenth cen-

tury. The interest in studying nature as a source of inspiration remained a constant and influenced *On Growth and Form*, in which D'Arcy Thompson drew bridges between biological form, physics and mechanics, suggesting that natural systems often strive towards material efficiency. The work of D'Arcy Thompson would prove influential and stirred the emergence of *biomimetics* and *biomimicry* in the twentieth and twenty-first centuries. It also proved influential in the development of proto and modernist architecture in the work of Mies Van Der Rohe, Alvar Aalto and Frank Lloyd Wright. Design principles such as the integration of indoor and outdoor spaces, the use of vernacular materials, the understanding of the architectural building as an organism and the expression of load-bearing structures are thought to have been influenced by the development of biological theories (Mertins 2007; Mertins 2004). Similarly, the Metabolist movement of post-war Japan often referred to the life cycle of biological systems in articulating their built and theoretical megastructures. For them, the city and buildings themselves operated on principles governed by cycles, not unlike processes of birth, death and metabolism (Pardalos 2014, p.83).

Nonetheless, the biotechnical discourse stands apart in its aspiration to use biological systems directly as part of the design and fabrication of buildings. This discourse is inherited from the long-standing tradition in architecture that is described above, but it is distinct in the sense that it draws from recent advances in biotechnologies. Specifically, it is inspired by the possibilities offered by synthetic biology to consider the direct manipulation of living matter as a deliberate design strategy. Often, this involves some level of genetic manipulation, aimed at reconfiguring and optimising natural behaviour to accomplish a specific design task. Ednie-Brown has proposed the term '*biotechnical architecture'* to describe a contemporary discourse in architecture in which '*architects are exploring biotechnologies to engage directly with biological or living materials*' (Ednie-Brown 2013, p. 86). In this thesis, I propose that there are two different approaches that can be detected within the discourse of biotechnical architecture. The first, s*peculative biotechnical*, is characterised by methodologies that aim to construct critical discourses around the use of biotechnologies, or to present possible futures potentially enabled by them. The second approach, *literal biotechnical*, is characterised by an aspiration to integrate biological systems in design

processes and technologies, and follows methodologies that involve direct engagement with the realities of biological manipulation and work.

2.1
SPECULATIVE BIOTECHNICAL

The *speculative biotechnical* pole is defined by its engagement with living systems through technical speculations. It is broadly interested in developing critical discourses, shaping public opinions about the implications of living systems as technology, and describing possible futures enabled by biotechnologies. Moreover, speculative biotechnical often draws on methodologies characterised by the use of shortcuts, which enable the extension of observed or known properties of biological systems to fit different design scenarios. There is a tendency to shortcut to a result — to imagine how biotechnologies might impact processes of design in the future. This is often implemented by drawing inspiration from materials, forms and shapes from an existing lineage of preconceptions about biological systems, with limited engagement or knowledge of the tools and processes involved in biological work.

2.1.1
CRITICAL DISCOURSES AND POSSIBLE FUTURES

Projects closer to the speculative biotechnical pole are often tailored to trigger public debate around the use of biological systems as technology, and to shape public opinion. A good example is *Contaminant,* an installation aimed at making evident the '*colorful embroidery of life in the built environment*' (Myers 2012b, p. 226). In it, Steve Pike collaborates with microbiologist Conrad Millineaux and mycologist Richard Strange to suspend bacteria in gelatinous media, placed in transparent vessels and mounted inside Holborn underground station in London (see Figure 1). The project is intended to raise awareness of the way microorganisms are tightly interwoven with human activity:

> Contaminant is a screen-like architectural installation that displays the growth and colonization of microfungi and dust that were unwillingly

> introduced by patrons of London's Holborn Station during the course of the sampling phase of the project. As people travel through and occupy various locales, they pick up microorganisms and particulate matter, unintentionally transporting them from one place to the next. (ibid)

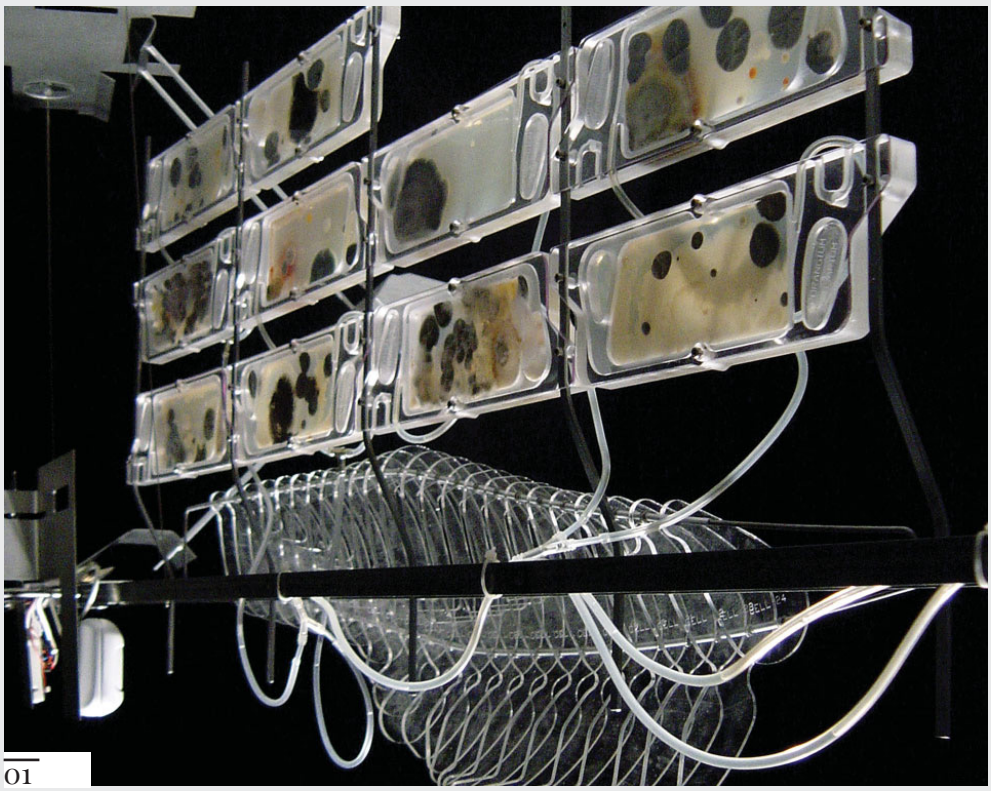
With Contaminant, Pike intends to display an '*architecture of contamination*', and to produce a critical discourse around recurring themes of colonisation and control. Pike is especially interested in using the installation to interrogate an emerging discourse of programmatic control of living systems in architectural design.

The speculative discourse is also used to depict possible futures enabled by the use of living technologies, often contextualising them as a solution for pressing contemporary challenges. One project close to this narrative is *Genetic Barcelona*, in which Alberto Estévez presents genetic modification as a potential tool to reduce cities' dependence on fossil fuels. The project is described as a '*reassessment of how we illuminate urban areas and a search for alternative approaches*' (McDonough 2012, p. 68). Estévez proposes the introduction of the gene for luminescent protein production found in the jellyfish *Aequorea Victoria* into the DNA of plants and trees that would be used to line streets, operating as an alternative form of urban lighting (see Figure 2). In contextualising the project, the author stresses the way in which it might provide a solution to contemporary cities' ecologically problematic reliance on fossil resources.

01 Contaminant installation produced by Steve Pike in collaboration with Conrad Millineau

02 Genetic Barcelona Project by Alberto Estévez

A similar outlook is used in the work of Magnus Larsson in *Dune*. The project speculates on the use of *Bacillus pasteurii* to turn sand dunes in the Sahara Desert into sandstone, producing inhabitable structures. Larsson intends to show biotechnologies as a revolutionary technology, with the potential to solve some of the most pressing environmental and social problems. He proposes injecting bacteria into Sahara Desert dunes to induce the solidification of sand into large porous structures (see Figure 3). The project is contextualised in the Green Wall Sahara initiative, a proposal by the African Union to create a vegetation barrier across the southern limit of the Saha-



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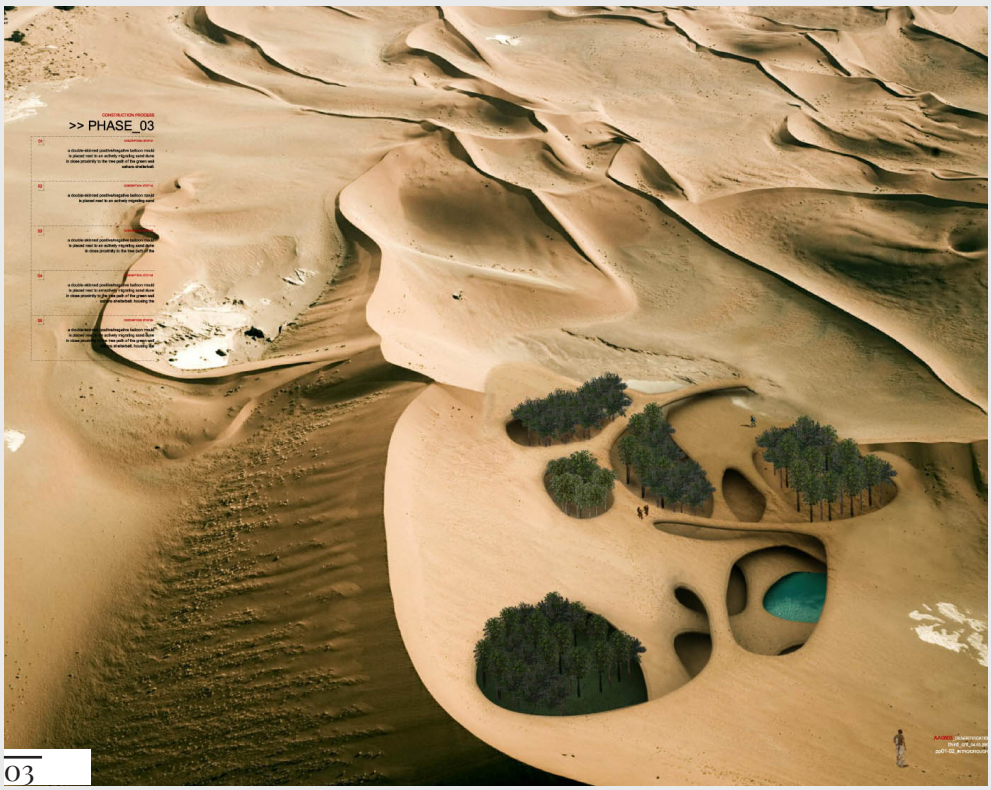

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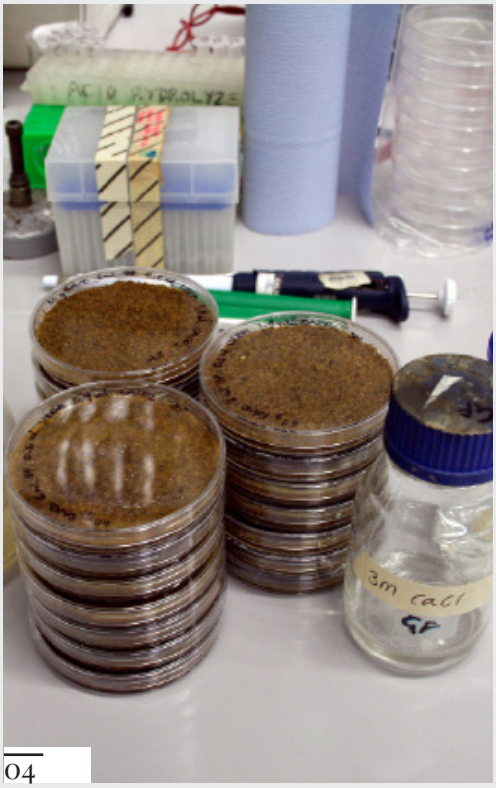

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ra Desert, stretching from Mauritania to Djibouti, and intended to protect the savanna region of the Sahel Belt. Larsson proposes that complementing the Green Sahara Project with bacterially aggregated dunes would contribute to agricultural activities, such as water harvesting, as well as creating micro-climates that are appropriate to different vegetation and inhabitable thermal comfort zones (Larsson & Kaiser 2003; Larsson 2008).

2.1.2
METHODOLOGY AND SHORTCUTS

Given their often ambitious design contexts, projects close to the speculative pole tend to take practical shortcuts that enable them to project observable properties of biological systems onto imagined, sophisticated behaviours. This is the case with *Dune*, in which the author extrapolates the performance of *Bacillus pasteurii* in calcite precipitation to fit as a viable unit of large-scale consolidation in a desert environment. Larsson draws inspiration from the work of Jason De Jong at the Soils Interaction Laboratory, the University of California, and spent time in the laboratory performing experiments on microbially induced calcite precipitation. The protocol set out to perform experiments in small petri dishes, which are then projected onto a large-scale, on-site construction process:

03 *Dune project by Magnus Larsson*

04 *Magnus Larsson performing experiments on microbially induced calcite at the Soils Interaction Laboratory , University of California*

> Bacteria, water, urea and calcium chloride would be injected into the sandscape and would — via a process called microbial-induced calcite precipitation — produce calcite, a natural cement, that would cause the sand to solidify within 24 hours. By choosing where to apply the microorganism, the architect would have a degree of control over the process, but the final form would be heavily influenced by the environment (Myers 2012c, p. 62).

The project's description demonstrates an understanding of the basic principles of calcite precipitation, which is used in proposing a construction process that depends on injecting urea, calcium chloride and bacteria onto sand. There is also, however, a noticeable shortcut: there is no evidence

of exploration into how a protocol designed to operate with the scale and controlled conditions of a petri dish holds up when scaled up and used in site conditions. The shortcut enables Larsson to contextualise bacteria as technology, and to produce a project that talks of its potential to solve large-scale environmental challenges (see Figure 4).

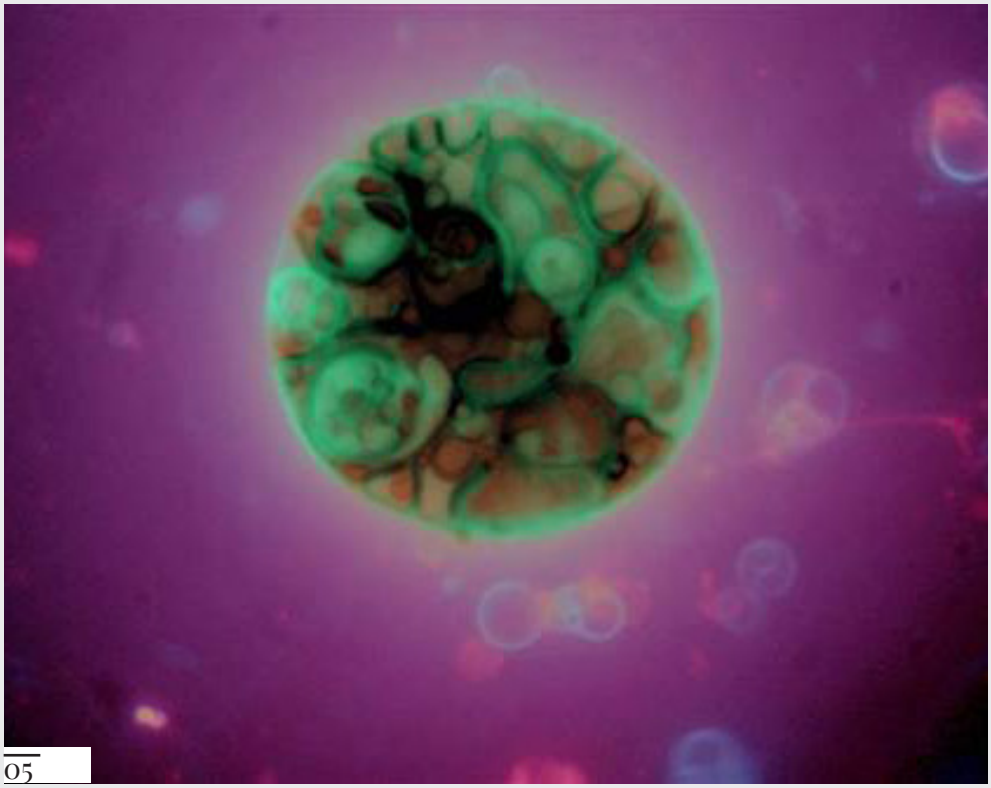
A similar process is followed in the work of Rachel Armstrong on protocells. Protocells are chemical units exhibiting life-like behaviours, and have been used to demonstrate the possibility of creating synthetic cells, with structures similar to living cells such as membranes and an intracellular matrix (see Figure 5). Protocells were initially devised to understand the chemical interaction that gave way to life in the early stages of the universe. It has been proposed that a correct balance of chemicals and environmental conditions might recreate the processes that allowed life to emerge from non-living elements. It is expected that development in this area might lead to the generation of synthetic protocells, incorporating motility, selective membrane and genetic components (Hanczyc 2009).

05 Protocell image by Martin Hanczyc

06 Future Venice project by Rachel Armstrong

In *Future Venice*, Rachel Armstrong proposes protocells that would be chemically programmed to move away from the sunlight and cluster around wooden foundations. Once there, they combine with dissolved carbon dioxide to precipitate carbonate crystals, which accrue into a limestone-like substance that attaches to submerged woodpiles, materially reinforcing foundations and improving their structural performance (see Figure 6). The notion of the protocell as a programmable construction agent enables Armstrong to propose the notion of *living architecture*, in which buildings are thought of as organisms in the way they grow and adapt to the environment. Armstrong reflects:

> An ideal architecture is one that you can plant as a seed, having programmed it with all the information it needs to grow itself in an environment where it can organically seek out and connect with resources that it needs. Through its lifetime it would remain responsive to its surroundings and adjust according to the demands and needs of its human



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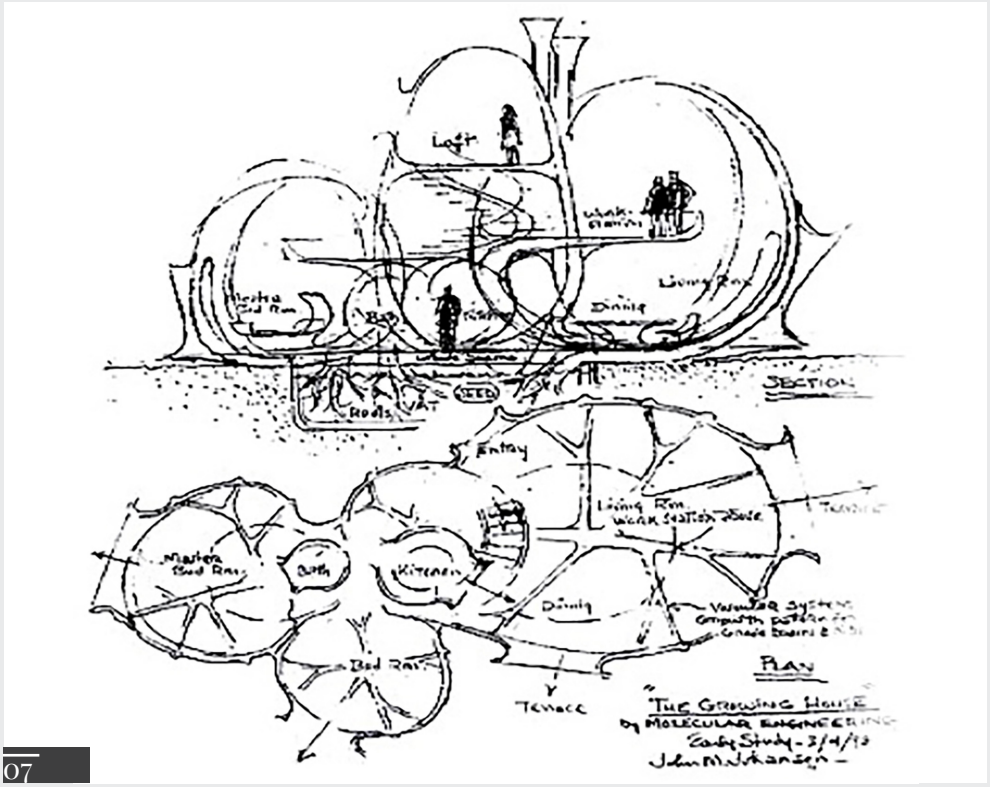
Light
Dining
SECTION
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SEED
Entry
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Master Bed Rm
Bath
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"THE GROWING HOUSE"
by MOLECULAR ENGINEERING
Early Study - 3/4/93
John M. Johansen

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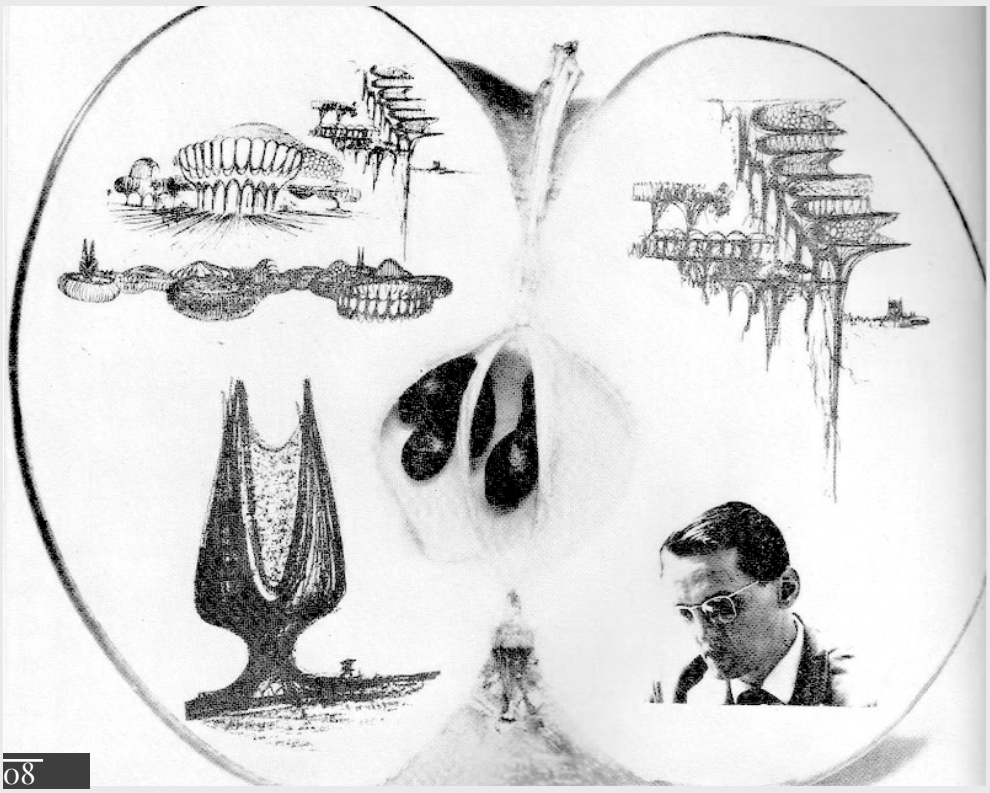

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> habitants. The architecture would be able to reproduce by cloning itself using a germ line structure that offers humans an opportunity to make any necessary genetic adjustments (Armstrong 2008, p. 83).

As with *Dune*, *Future Venice* makes some leaps between observable features of protocells and how they are imagined in a design context. Armstrong collaborated with Martin Hanczyc, who is currently developing research in protocells, to understand the principle of chemical programmability. For instance, one of the protocell models used by Hanczyc involves the use of highly alkaline droplets, which are released in a fat-rich environment. Imbalances between the alkaline and fat component of the system cause protocells to move following chemical gradients, a process that enables droplets to maintain their interface boundary and shape (Spiller & Armstrong 2011, p. 26). This principle is used by Armstrong to speculate on chemical droplets, which are fine-tuned to the conditions of the Venetian lagoon, and chemically configured to swim away from the sun and towards wood foundations, where they would contribute to the calcification of compromised pillars.

2.1.3
PRECONCEPTIONS

In taking shortcuts, speculative narratives often rely on preconceived notions of biological systems. In the context of this thesis, the term 'preconceptions' refers to models of living systems that have developed through an assortment of traditions, ranging from the literary, to the fictional, to obsolete biological theories. In some cases, living and semi-living systems are understood in fundamentally botanical terms: as a form of seed that can be programmed and sown on-site to grow architectural structures. In the quote above, for example, Armstrong defines an ideal architecture as one that can be programmed and planted. Elsewhere, she argues that the ideal of an *architectural seed* can be traced back to the speculative project of Molecular House. In it, John Johansen (2002; 2011) speculates on the possibility of chemically designed materials that

07 Molecular Engineered House 2200 project by John Johansen

08 William Katavolos illustration of his notion on organic architecture that was contributed to the 1963 January issue of Harper's Bazaar

respond to changing conditions in the environment and operate by sprouting on-site (see Figure 7). This notion is used in *Molecular Engineered House 2200*, where Johansen imagines the construction diary of a house, which is derived from a code '*developed from an architect's designs and then engineered and molecularly modeled'* (Johansen 2011). The narrative is intended to follow the possibility of different systems and structures in the house interacting with one another and sprawling in coordination.

09 Fab Tree House project by Mitchell Joachim

10 Mitchell Joachim diagram of pleaching, an ancient process of tree shaping

The notion of an architectural seed, Cruz (2014) suggests, also draws on notions of *chemical architecture* developed by William Katavolos. Often identified as the precursor to current discourses around smart materials, Katavolos built his manifesto *Organics* (1961) around the notion of a chemical fabrication technology, which used polymers to grow built forms. Katavolos wrote against the backdrop of a period of rapid technological development in polymers, which he believed invited a reconceptualisation of architecture: '*Man must stop making and manipulating, and instead allow architecture to happen.*' Central to Katavolos' vision was the possibility of molecular programmability, whereby materials could be chemically codified to follow specific shapes or to fulfil certain functions:

> New discoveries in chemistry have led to the production of powdered and liquid materials which, when suitably treated with certain activating agents, expand to [a] great size and then catalyse and become rigid. We are rapidly gaining the necessary knowledge of the molecular structure of these chemicals, together with the necessary techniques that will lead to the production of materials that will have a specific program of behaviour built into them while still in the sub-microscopic stage. Accordingly, it will be possible to take minute quantities of powder and make them expand into predetermined shapes, such as spheres, tubes and toruses (Katavolos 2013, p. 149).

Katavolos illustrates his notion of organic architecture in an illustration that was contributed to the 1963 January issue of *Harper's Bazaar* (Avedon 1963). Figure 8 shows buildings in a constant process of growth and recon-

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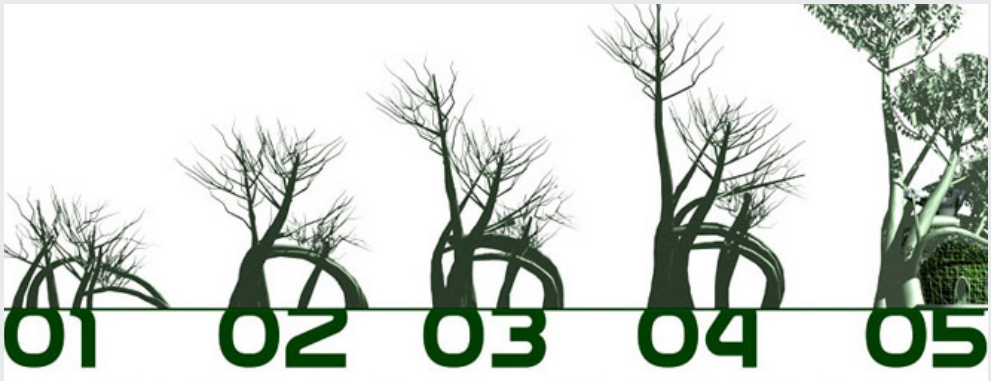

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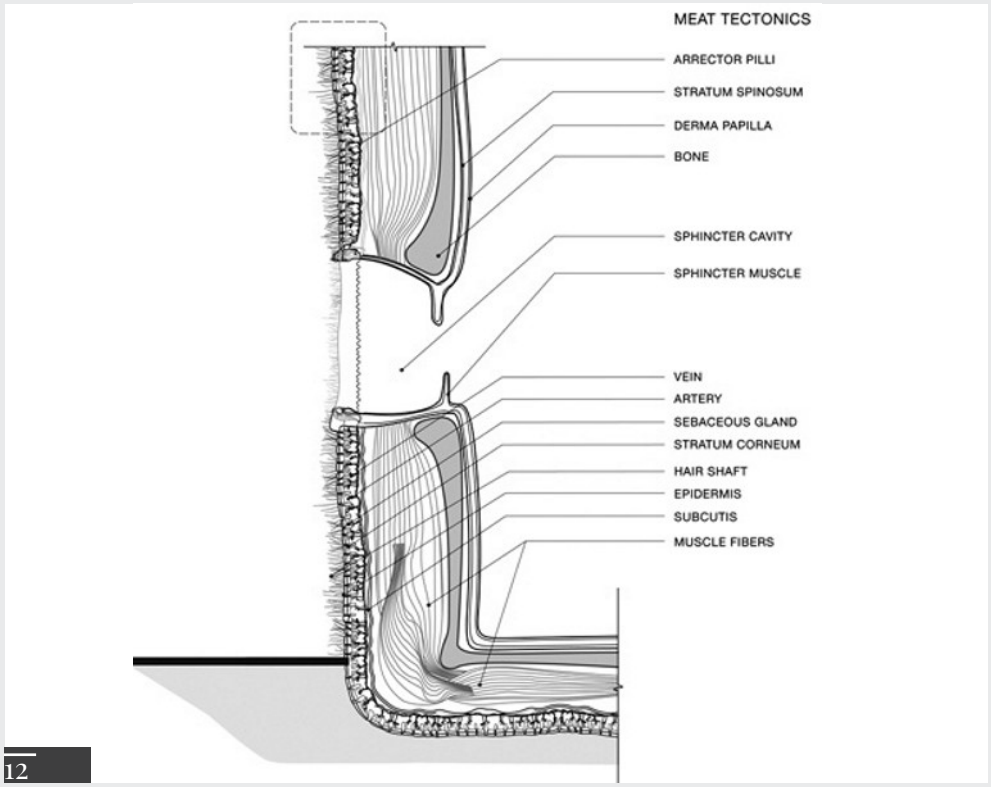

MEAT TECTONICS
ARRECTOR PILLI
STRATUM SPINOSUM
DERMA PAPILLA
BONE
SPHINCTER CAVITY
SPHINCTER MUSCLE
VEIN
ARTERY
SEBACEOUS GLAND
STRATUM CORNEUM
HAIR SHAFT
EPIDERMIS
SUBCUTIS
MUSCLE FIBERS

12

figuration. The collage is framed by the outline of a cut apple, showing its seed in the centre of the image. Its caption includes '*Katavolos and some of his drawings envisioning an organic architecture that the discoveries of modern chemistry make credible*'.

Botanical understandings of biological systems are explored, for instance, in *Fab Tree House,* in which Mitchell Joachim proposes the use of *pleaching*, an ancient process of tree shaping that uses branches to weave different structures (see Figures 9 and 10). The author imagines the process as a method that enables '*growing residential accommodation from native trees that remain living and integrated with the ecosystem'* (McDonough 2012, p. 58). Joaquim proposes the use of manufactured scaffolds, which are grafted onto the tree to programme and control its growth. The project can be read as a close parallel to the same author's *Meat House* (see Figure 11). In collaboration with Nina Tandon, the project speculates on the use of tissue engineering techniques to explore animal cells as material for architectural structures. Epithelial cells are imagined as seeds that grow and differentiate to form different building elements: fatty cells as insulation layers, for example, or sphincter muscles as openings for walls and doors (see Figure 12) (Tandon & Joachim 2014).

Preconceptions of biological systems as seeds also tap into principles of programmability connected to the digital paradigm in architecture. In *Dune* and *Living Venice*, living and semi-living systems are understood as highly intelligent, programmable construction agents, a notion connected with contemporary discourses on the synthesis of digital form generation and fabrication. The notion of programmability in architecture can be traced back to the introduction of digital computers as generative tools for design. The digital paradigm in architecture is characterised by the use of digital tools, which enables the exploration of '*dynamic, open-ended and unpredictable but consistent transformations of three-dimensional structures*' (Kolarevic 2003, p. 2). Its discourse, however, makes strong use of biological referents. It is suggested that the design and construction processes afforded by computers

11 Meat house project by Mitchell Joachim in collaboration with Nina Tandon

12 Section of the Meat house project where Epithelial cells are imagined as seeds that grow and differentiate to form different building elements

are fundamentally different from traditional forms of design and fabrication. In this context, biological references are particularly important, as they provide a framework to understand how computation changes notions of design and its methods. In *Digital Morphogenesis,* for instance, Hensel and Menges speculate on the possibility of considering buildings as living organisms. They argue that the integration of digital technologies, from form-finding techniques to robotic manufacturing, might provide the basis to create semi-living architectures (Hensel et al. 2006). The prospect will, they expect, blur the current division between natural and manufactured, as the logic of forms is directly connected and gradually becomes the same as that of the machines used to construct them (Hensel et al. 2004; Weinstock 2006).

One of the aspirations of the digital paradigm is the synthesis of computation, fabrication and material performance into a single, intelligent unit. Neri Oxman, for instance, has proposed *Material-Based Design Computation*, a framework intended to provide:

> ...a set of computational strategies supporting the integration of form, material and structure by incorporating physical form-finding strategies with digital analysis and fabrication. In this approach, material precedes shape, and it is the structuring of material properties as a function of structural and environmental performance that generates [the] design form (Oxman 2010, p. 3).

Central to Oxman's work is the definition of minimal units, which combine computation and material performance and can be programmed with specific behaviours. In reflecting on the work of Armstrong, and speculating on the potential of protocells in architecture, Oxman suggests parallels between the intelligent units imagined by digital discourses and protocells:

> Parallel to, and inspired by, the contemporary discourse in synthetic biology, a bottom-up approach to design is indeed one of the key characteristics of design inspired by performance. In this approach, a units-based strategy is commonly devised and encrypted in order to correlate between form's material properties and its environmental milieu (...)

> material properties are considered intermediary agents mediating environmental impetus with material response, such that inanimate matter might contain the information for its behaviour and evolution, not unlike protocells. This method assumes complete synergy between geometry, physical matter and energy (Oxman 2011, p. 102).

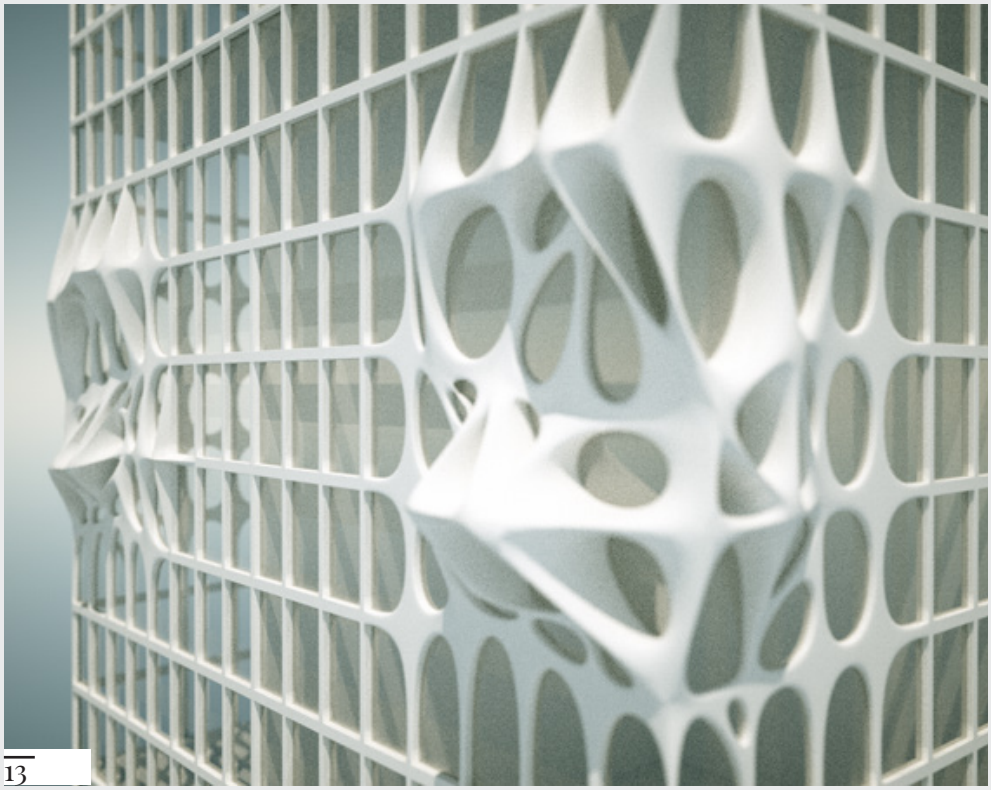
The *Protocell Tower* illustrates how preconceptions of living systems, developed in the digital paradigm, are often used in speculative biotechnical projects. Preissner describes the project as a '*typological prototype for the protocell*' (Preissner 2011). It involves façade panels that are fabricated by solidifying limestone using protocells (see Figures 13 and 14). Preissner suggests that, although revolutionary, protocells can be understood using concepts and tools that are already familiar to digital design. He writes:

> The reality of this biochemical science is oddly a bit behind some of the formal thinking that has taken place within architecture (…) Another way to put it is that we have been waiting for this for a while and have already figured out how to deal with its looks (and a number of us architects have decided we like it!), because we have been goofing around in software fortuitously replicating the shape and fashion of this new tiny life in anticipation of its eventual arrival (Preissner 2011, p. 108).

The quote illustrates the sometimes seamless translation of digital concepts to the biotechnical discourse. For Preissner, the formal possibilities of the protocells are important in as much they realise a decade-long exploration of computational tools. This process conditions the way in which living systems are understood in design terms. Drawing upon digital preconceptions, living systems are seen as computational agents that can be programmed with design intent. The speculation, however, is not necessarily connected to the realities of biological work.

2.2
LITERAL BIOTECHNICAL

A second pole, the *literal biotechnical*, is characterised by an emphasis on the development of actual technological application in design. Projects closer to this narrrative share some elements with the speculative discourse. Some,



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for instance, are often described by inserting them in wider narratives of environmental challenges. Similarly, there are some practical shortcuts that enable designers to imagine living systems in a context that goes beyond what is immediately achievable. However, shortcuts and discourse are minimised and contingent upon an aspiration to direct engagement, which leads to immediate integration to a design context.

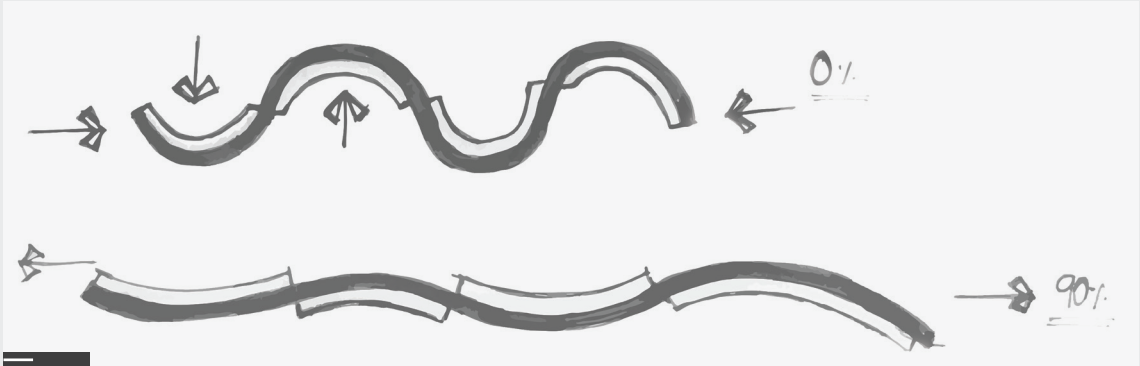
2.2.1
DIRECT ENGAGEMENT WITH THE MATERIAL

One of my own projects, *Bacterial Hygromorphs,* is located closer to *literal biotechnical*. *Bacterial Hygromorphs* explores the use of bacterial spores as hygromorphic materials for architecture. Bacterial spores correspond to a dormant and resistant stage that enables a bacterium to preserve its biological integrity and genetic material to survive adverse environmental conditions (temperature, starvation, chemical changes). They can also expand or shrink in response to relative humidity, as the function, composition and organisation of their components enable them to expand and contract as they absorb water or dry out (see Figure 15). The project develops a design protocol to use bacterial spores, *from the mutated strain of Bacillus subtilis cotE gerE* as an active hygromorphic layer which, when attached to a passive, flexible substrate, generates a highly sensitive material that responds to humidity fluctuations (see Figures 16 to 18). In its initial stage, *Bacterial Hygromorphs* is developed through a thematic, stage 3 studio, which asks students to develop façade panels integrating spore-coated elastomers to produce apertures that regulate internal atmospheres in response to humidity differentials with the exterior (see Figure 20) (Ramirez-Figueroa et al. 2016).

13 Perspective of the Protocell tower by Paul Preissner

14 Frontal image of the Protocell tower by Paul Preissner

As suggested above, one key element of the *literal biotechnical* discourse is the emphasis on direct engagement with the material, which enables the development of concrete technological applications. In *Bacterial Hygromorphs,* students were introduced to the process of spore coating during a two-day laboratory session, in which they were taught basic laboratory techniques, such as pipette handling, and to prepare the spore-based



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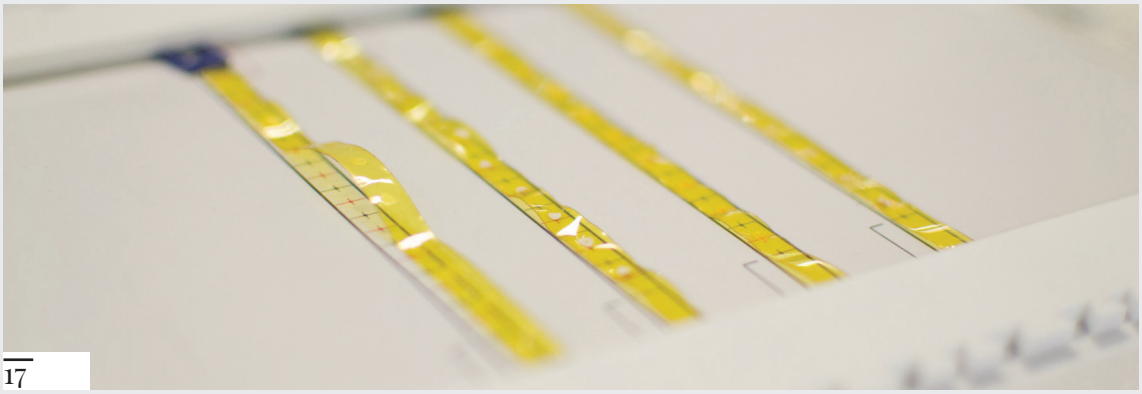

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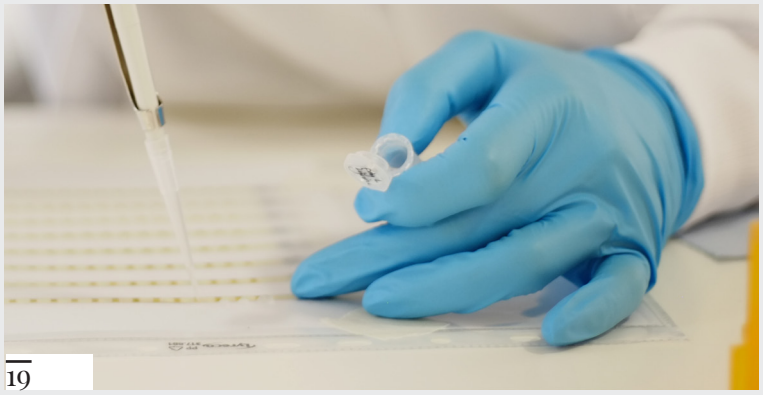

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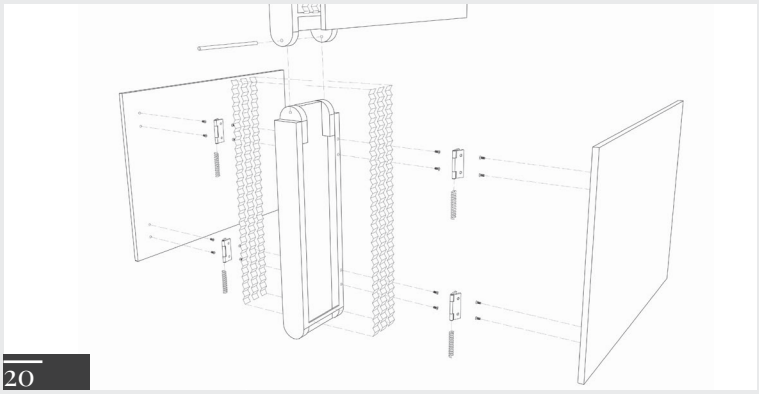

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15 *Bacterial spores expand and contract in response to humidity fluctuations in the environment*

16, 17, 18 *Images show the protocol used in the Bacterial hygromorphs project. Bacterial spores are attached to a passive, flexible substrate, which produces a highly sensitive material that responds to humidity fluctuations.*

19 *Student diagram of a façade panel that integrates the spore-coated elastomers*

20 *The image shows a student using a pipette to coat a series of elastomers with bacteria spores during a two-day laboratory session*

coating (see Figure 19). Current bio-security regulations, however, restrict working with biologically modified organisms outside a laboratory setting. As the project was based in the School of Architecture, students did not have readily available access to a laboratory throughout the different stages of their project development. To maintain a tight link with the material, two strategies were implemented. One was to ask students to design a number of experimental protocols, which represented the design principles of their projects, and to test them in the laboratory. The second strategy was the use of *material proxies* (Ramirez-Figuera & Dade-Robertson 2013), a design strategy that advocates the use of material analogues that mimic some of the behaviours of a target material. In this case, shape-memory alloys were used to keep a constant reference of the force and scale of operation of actual bacterial hygromorphs. It is also important to highlight that the project took some practical shortcuts. As described above, limited access to laboratory facilities meant that students could not produce working models with actual spore-coated elastomers. However, experimental protocols and material-proxy strategies helped to minimise the distance between the actual and projected behaviour of bacterial spores.

21 Images showing wood laminates produce as part of the work of Achim Menges

2.2.2
PRAGMATIC DESIGN CONTEXTS

Connected to the commitment to direct engagement, projects closer to the *literal biotechnical* pole are often oriented to pragmatic design solutions, in which living systems are inscribed in existing design contexts and applications. Their pragmatic orientation often enables projects to develop working prototypes and demonstrators, in which one or several principles are demonstrated through working living systems. *Bacterial Hygromorphs*, for instance, involves the development of experiments and proof-of-concept prototypes, which demonstrate the feasibility of the design proposal. A downside of the methodology, however, is the limited exploration of the unique design opportunities that biological systems offer as technology. Instead, it operates by matching known properties of biological systems to existing design techniques and technologies. *Bacterial Hygromorphs*, for instance, employs bacterial spores as a type of low-energy actuator for kinet-

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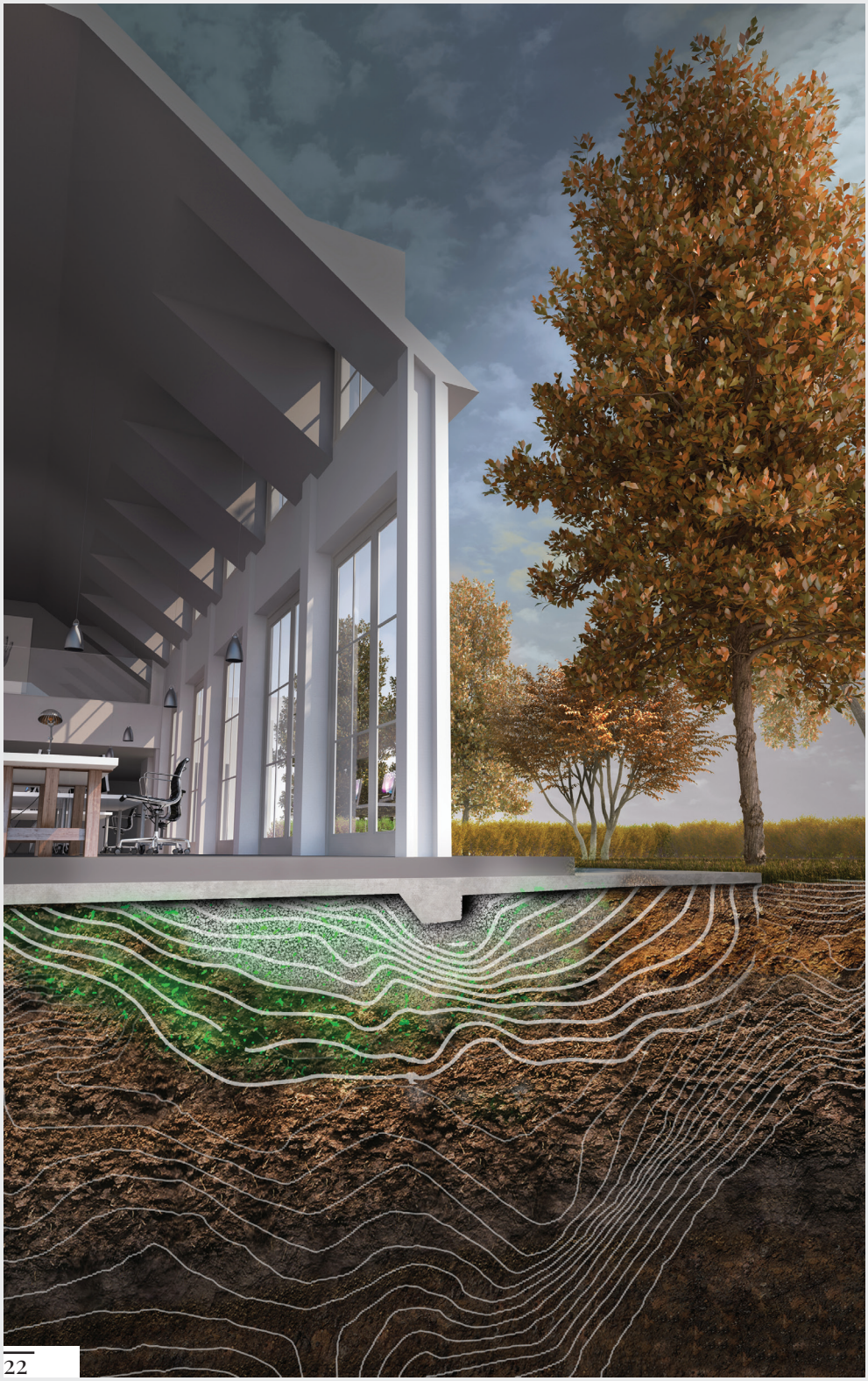

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ic façade systems. The strategy follows existing projects, such as the work of Menges (2015) and others (Holstov et al. 2015), who have explored how non-biological hygroscopic materials, such as wood laminates, can be used as façade components (see Figure 21). The design domain of existing hygroscopic materials offers an ideal match for the observed properties of bacterial spores: it involves a system that reacts to humidity fluctuations in building atmospheres and produces a meaningful response. Similarly, the existing scientific literature harvests spore behaviours to produce evaporation engines, in which moisture is actively controlled to operate moving mechanisms. Although productive, the approach comes at the cost of engaging in more fundamental explorations of how bacterial spores might be integrated in design contexts, other than in existing models of kinetic facades.

Other projects develop similar strategies, in which living systems are placed in existing design contexts, which create the closest match to the conditions they operate in laboratory settings. For example *Thinking soils*, a research project led by Martyn Dade-Robertson (2016), involves using biological systems to develop an intelligent material synthesis system aimed at reinforcing existing building foundations (see Figure 22*)*. It modifies *Escherichia coli*, a bacterial species commonly found in the human digestive tract, to regulate the expression of genes responsible for pressure sensitivity and to respond by synthesising material that, when embedded in a soil matrix, contributes to improving load-bearing capacity. As with *Bacterial Hygromorphs*, *Thinking soils* operates by mapping biological systems to pragmatic design scenarios and applications. In this case an engineered bacteria strand, which is capable of sensing pressure, is projected to building foundations, a context in which pressure and material synthesis are already relevant. The authors write:

22 Thinking soils project led by Martyn Dade-Robertson involves using pressure sensitive bacteria to solidify soil

> *Our starting point is to consider a design scenario where a heavy load is placed on a weak soil. We imagine an engineered bacteria, living in the soil, that is capable of sensing pore pressure changes within the soil and responding by producing material to solidify the soil matrix. Such a system would*

> *create a synthetic foundation beneath the structure* (Dade-Robertson et al. 2016).

Mapping to a pragmatic design solution is emphasised by highlighting the advantages that biological systems represent in the projected scenario, such as in deployment, which '*could be implemented without the need for soil excavations since the bacteria could be seeded and would grow throughout the soil matrix'* (ibid).

Other design domains involve existing construction technologies, such as masonry bricks. In *BioMASON*, for instance, Ginger Krieg Dosier builds on DIY bio-techniques of microbial-induced calcite precipitation to produce masonry bricks (see Figure 23). The process involves the use of *Sporosarcina pasteurii*, a strand of bacteria that precipitates calcite that can glue sand grains together. Bricks are produced by mixing cultured bacteria with urea and calcium chloride, which solidifies after a week (Ednie-Brown 2013). The development of *BioMASON* has triggered the evolution of VergeLabs from experimental design practice to a commercial venture, and has been awarded the US Patent '*Methods for Making Construction Material Using Enzyme Producing Bacteria'* (Dosier 2011). David Benjamin's work in *Hi-Fy* also maps biological systems to the form-factor of bricks. The project, a pavilion commissioned by the Museum of Modern Art in New York, consists of three towers constructed with bricks produced using a mixture of corn stalks, hemp and *mycelium*, a filamentous structure that is developed by fungus to absorb nutrients from its environment (see Figure 24) (Frearson 2014). Similar work has been done by Phillip Ross, who has developed a method to produce bricks based on dried mycelium (see Figure 25). Ross has used these to produce a number of structures, such as arches and small walls, as well as chairs and stools (Boyer 2014).

23 BioMASON project led by Ginger Krieg that focuses on using microbial-induced calcite precipitation to produce masonry bricks

24 The image shows David Benjamin's work in Hi-Fy, a pavilion consisting of three towers constructed with bricks produced using a mixture of corn stalks, hemp and mycelium

Biologically induced mineralisation processes have also been used to enhance other, existing technologies. For instance, Henk Jonkers from Delft

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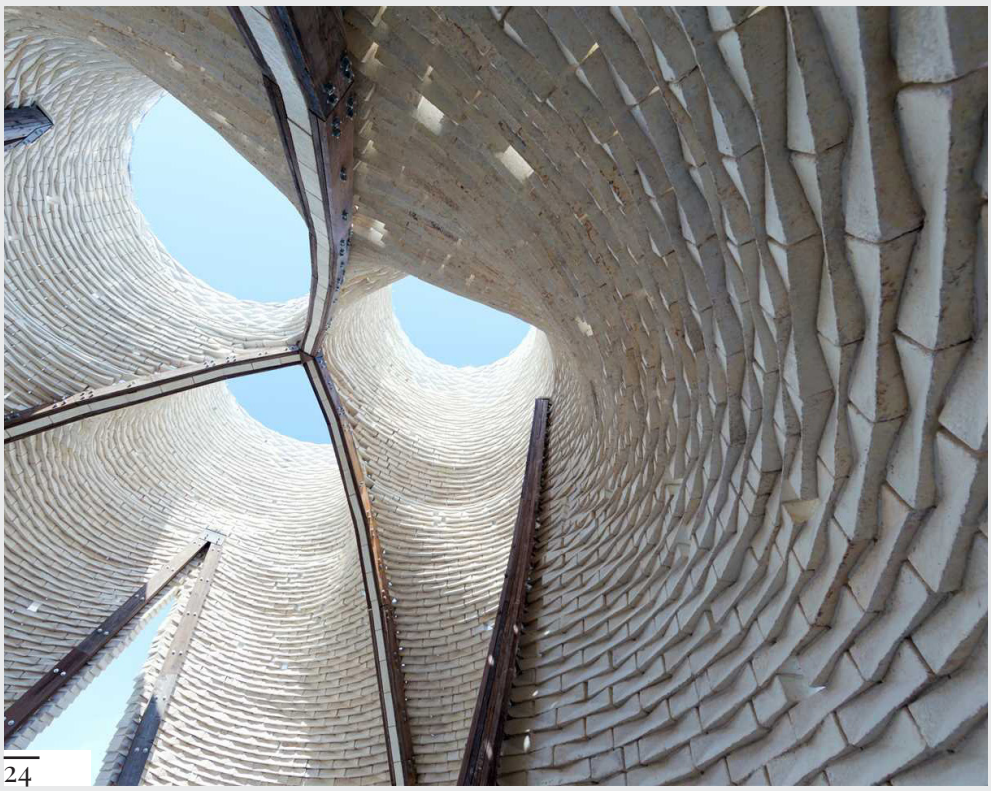

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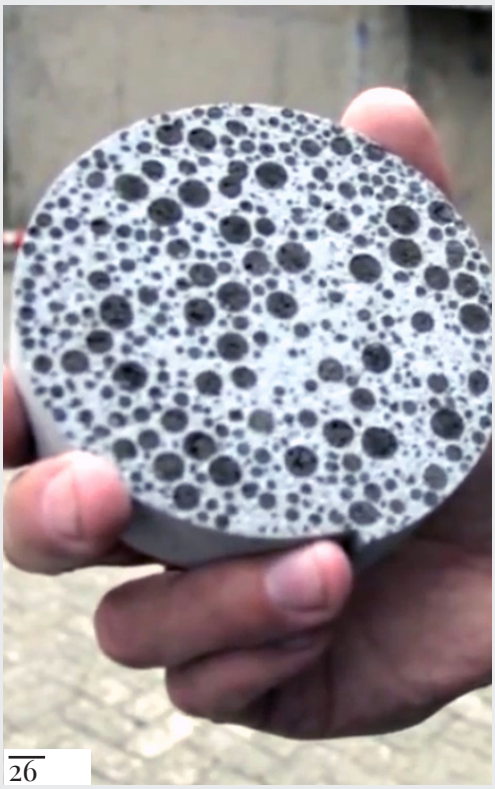

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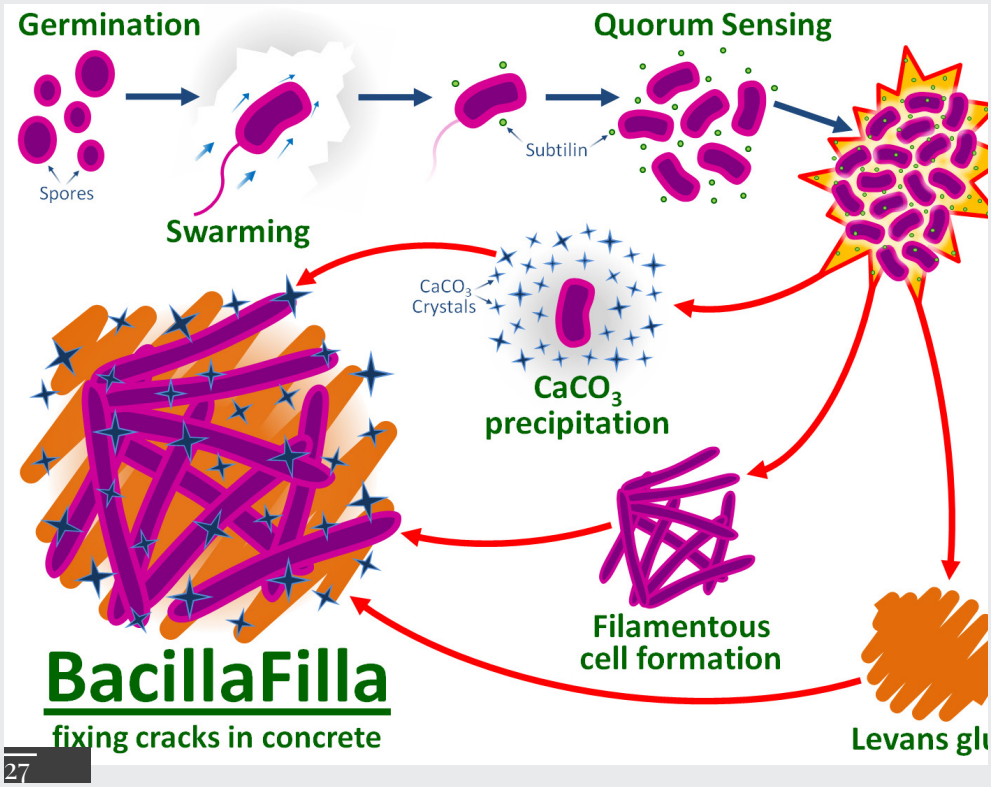

Germination
Quorum Sensing
Spores
Swarming
Subtilin
$CaCO_3$ Crystals
$CaCO_3$ precipitation
Filamentous cell formation
Levans gl
BacillaFilla
fixing cracks in concrete

27

University uses bacteria to generate a form of self-healing concrete, which is capable of filling cracks without external intervention (see Figure 26). The process involves the use of *Bacillus pseudofirmus* and *Bacillus cohnii,* two bacterial strands that precipitate the formation of calcium carbonate through the release of urease in their environment. Bacteria are mixed with cement in liquid state and allowed to cure. When cracks begin to appear, bacteria contribute to the creation of filling material in the form of calcium carbonate, promoting a seal (Jonkers et al. 2010). In a similar strategy, a group of Newcastle University students proposed *BacillaFilla* as the winning 2010 iGEM entry (see Figure 27). *BacillaFilla* is proposed as a modification of *Bacillus Subtilis*, and is designed to fill the gaps in cracks by producing a mixture of calcium carbonate, Levans Glue and filamentous cells as a hardening agent (Threats et al. 2011).

Other projects close to the literal biotechnical pole involve the development of additives and coatings, similar to existing chemical products. A good example of this is the *Bioreceptive concrete façade* by Marcos Cruz*,* which consists of a wall panel system that uses a special concrete mixture with controlled levels of PH, porosity and water retention (see Figure 28). The material is intended to provide a rich substrate for the development of photosynthetic systems, which contribute to carbon sequestering. A similar methodology is followed in *Algae Cellunoi*, an external ornamental wall designed to host different species of algae (see Figure 29). The wall is milled in foam and features a cavernous pattern composed of a number of ridges. Each ridge is designed to receive a custom-made container, which is prepared with nutrients and different algae species. Interaction with the different algae species triggers different colour patterns in the substrate, in addition to generating a protection varnish (Cruz et al. 2013).

25 The image shows a series of bricks produced using dried mycelium a technique developed by Phillip Ross

26 The image shows Henk Jonkers' self-healing concrete

27 The image shows a diagram of the BacillaFilla project. The project was developed by students of Newcastle University for 2010 iGEM entry

The *literal biotechnical* discourse also contextualises living systems as building components, and aims to improve performance and energy production. Algae, for instance, has been explored as part of electricity-generating

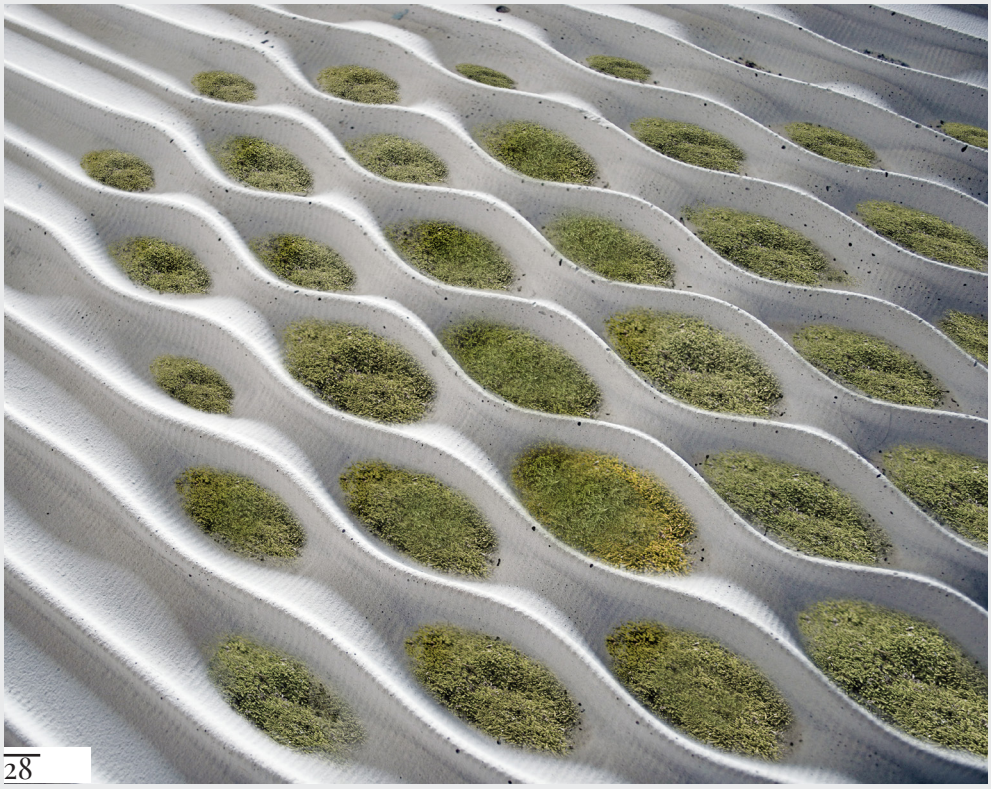
components in the *BIQ Algae House* (see Figure 30). The project consists of a façade that uses a series of panels to house micro-algae grown in aqueous media and supplied with nutrients to promote photosynthesis, which helps in reducing carbon dioxide. Once they have reached a certain size, algae are harvested and transported to the building's energy management centre, where they are processed into a thick pulp and fermented to produce biogas. The gas is then used to produce hot water for the building (Splitterwek & ARUP 2014). A similar model can be found in *Living Architecture* (LIAR), an early-stage research project led by Rachel Armstrong, which involves the development of *modular bioreactor walls*, building blocks based on the principles of microbial fuel cells, and uses ecologies of microbial organisms to produce energy (see Figure 31). Microbial fuel cells refer to controlled systems where biological systems are grown to produce electricity as a by-product of their metabolism. Although in its early stages, the project aspires to embed bioreactors in different building components, such as wall partitions, retrofitting the existing infrastructure:

> The researchers hope that by bringing together different kinds of creatures they could create 'metabolic apps' or programmable soils to make different kinds of products that could be useful in the home or to society. The technology could – in the long-term – be incorporated into building blocks for construction, which could be used in new buildings or for retrofitting old ones (Massy-Beresford 2016).

Other design domains also include computational form-finding methods. In *BioProcessing*, David Benjamin develops a project around the computational properties of Xylem cells, generally found in the vascular tissue of plants, where they create a network of conduits for nutrient transport between soil, stems and leaves, and which are thought to be efficient in their material distribution and mechanical properties (see Figure 32). The project involves collaborating with plant biologist Fernan Federici, which enables the creation of data sets using actual Xylem cells, which are then translated into a digital format that can be used to derive material distribution patterns. By doing this, cells are effec-

28 The image shows the Bioreceptive concrete façade by Marcos Cruz

29 The image shows Marco Cruz Algae Cellunoi, an ornamental wall designed to host different species of algae



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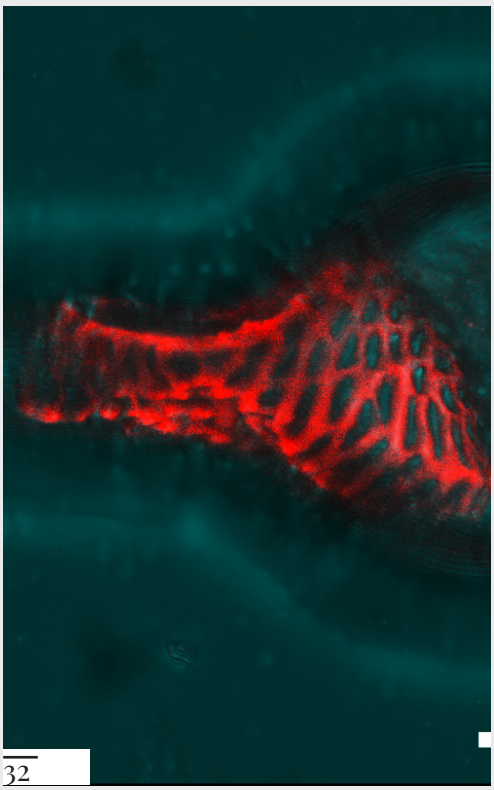

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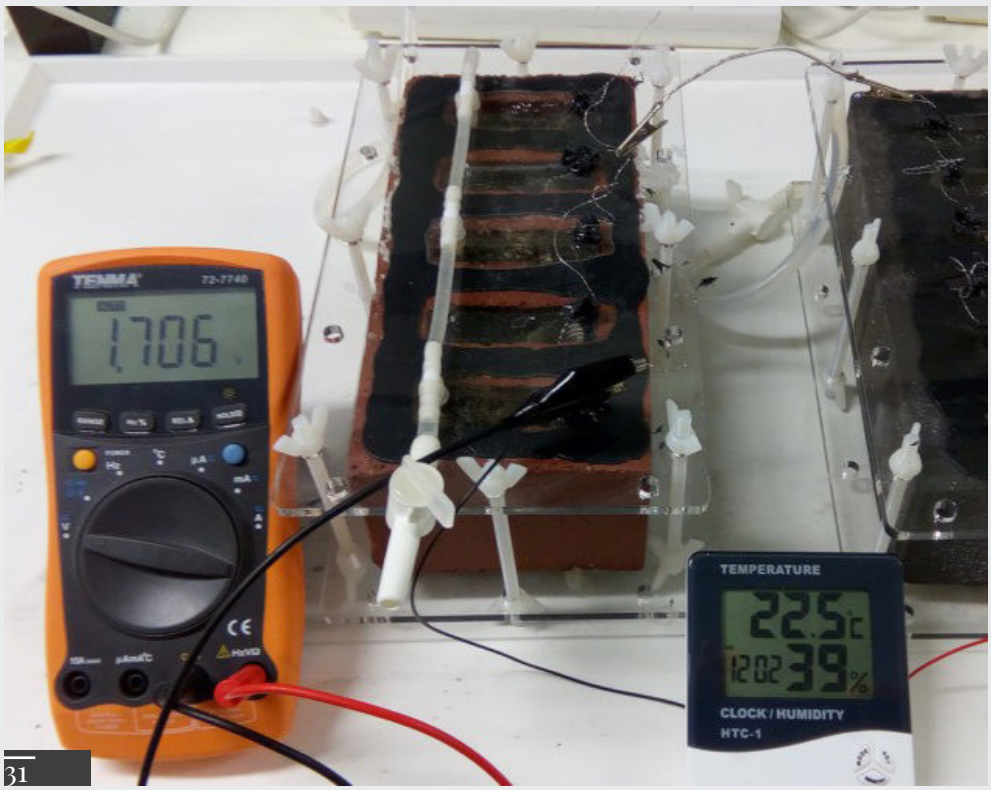
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tively conceptualised as highly sophisticated algorithms to produce optimal material distributions, which are appropriated and translated into architectural structures (Benjamin 2016).

In this section, I have discussed projects located closer to the *literal* end of the biotechnical spectrum. I have proposed that their defining characteristic is an ambition to create actual technological applications in design. I have reviewed the project *Bacterial Hygromorphs* to describe how the commitment to real applications is tied to methodologies centred on direct engagement with biological systems. In *Hygromorphs*, several methodologies are used to maintain proximity to the realities and operation of bacterial spores, including laboratory workshops and *material proxies*, materials whose properties and operation closely mimic those of the biological system, and which offer a more accessible way of developing applications when access to biological lab settings is limited. I have also argued that commitment to a direct engagement with the material, and the ambition to develop real applications, are often connected to the use of pragmatic design solutions. By pragmatic solutions I refer to strategies by which literal biotechnical projects match the known properties of biological systems to existing technologies and techniques. For instance, *Hygromorphs* takes how the hygroscopic properties of spores are used in other fields to power evaporation engines, and matches them to kinetic facades, an existing model that uses naturally hygroscopic materials, and where the humidity differential has already been mapped to an architecturally relevant behaviour.

30 *The image shows two façade panels from the BIQ Algae House. The panels house micro-algae that promotes photosynthesis to help reducing carbon dioxide*

31 *The image shows an early prototype of modular bioreactors from the Living Architecture project (LIAR)*

32 *Microscopic image of Xylem cells which are commonly found in the vascular tissue of plants*

I have described other projects that follow similar strategies, balancing the complexities of developing real applications with pragmatic design solutions. I have reviewed *Thinking soils,* for instance, which maps pressure sensitivity in bacterial cells to foundations, where material synthesis and pressure is already relevant. I have also suggested that *literal biological* projects target a number of other design domains. *BioMASON*, for instance, uses bacteria to modify the traditional process of producing masonry bricks.

Similarly, *Hi-Fy* produces bricks through the metabolic activity of mycelium. Other projects target the composition of materials, such as *self-healing concrete*, which uses the ability of some organisms to trigger mineralisation to produce an enhanced concrete mix. *Bioreceptive concrete façade* and *Algae Cellunoi* use biological systems as alternatives to existing chemical coatings to modify trigger changes in existing building materials. *Bi2 Algae House* and *LIAR* use organisms to produce active components, which are destined to change the way in which energy is produced and handled in buildings. Finally, *BioProcessing* conceptualises biological systems as sophisticated forms of form-finding algorithms, which deliver efficient material-distribution patterns.

The selection of projects included in this and the previous section, however, is not exhaustive. Rather, it is intended to provide an overview of biotechnical projects with clear links to architecture, and which illustrate the *literal biotechnical* approach. In addition to these, there are a number of initiatives that have shown bio-led projects in design practice. Some of them include *Synthetic Aesthetics* (Ginsberg et al. 2014), a research project aimed at pairing scientists with designers to think through the possibilities of biotechnologies in design. *BioProcessing*, reviewed in this section, was produced under the auspices of *Synthetic Aesthetics*. There are also competitions and events that have endeavoured to foster design thinking around biotechnologies. Some of them include *iGEM* and the *BioDesign Competition*. IGEM refers to the International Engineered Machine competition, developed initially by the MIT, which brings together researchers and first-year undergraduate students to develop concept projects that seek to expand the application domain of synthetic biology. The *BioDesign competition* ran for two weeks and invited proposals of new architectural typologies that conflate physical, digital and biological technologies. Also of relevance are *BioArt* (Myers 2015) and *BioDesign* (Myers 2012a), a pair of books that have contributed significantly to formalising and compiling the work that has been done in the intersection of biology, biotechnologies and art and design.

It is also important to mention projects that aim at democratising the means to do biological work, making laboratory and genetic tools available to the design community and promoting grounded speculations in the biotechni-

cal discourse. In *Microbial Design Studio (MDS)*, Orkan Telhan aims to generate a design tool which:

> ...minimizes the learning curve to work with biology to create sufficiently complex applications in food, material, fashion, graphic design, or architecture. The studio functions as a portable wetlab that automates the design and prototyping process of working with microorganisms such as yeast and E. coli. Designers can grow these organisms to synthesize new chemicals and use the chemicals or the organisms directly as part of sensing and remediation applications (Telhan 2016, p.35).

The MDS is rooted in a discourse that is close to the argument of this work. Telhan analyses how biological design faces several challenges. One of them is the considerable amount of complexities involved in acquiring biological knowledge. He observes how scientists, although well versed in technical knowledge, lack the understanding of design thinking, as well as the appropriate methodologies to understand the full possibilities of biotechnologies. Conversely, designers need to engage directly with the tools and techniques involved in biological work to develop an understanding of their design possibilities, in the same way that they build a repertoire of material possibilities by experimenting with wood, ceramics and metals. Telhan writes:

> Today, there is a disparity between the growing demand to use biology and access to the resources to practice it safely outside academic institutions. Biological materials and knowledge are becoming increasingly available at informal learning centers—makerspaces, science museums, or community labs — but even at those places designers have to invest significant time and energy to learn biology and gain the skills to be able to do the simplest experiments. Designers are often expected to become capable amateur biologists before applying biology. Learning biology in this way is a daunting task, particularly when design possibilities are unavoidably vague at the outset; it requires some knowledge of biology to know what is possible, and some knowledge of what is possible to begin the process of designing (...) Designers also need to see biology in form and action — as materials or applications — that can sketched, prototyped, tested in iterations (ibid).

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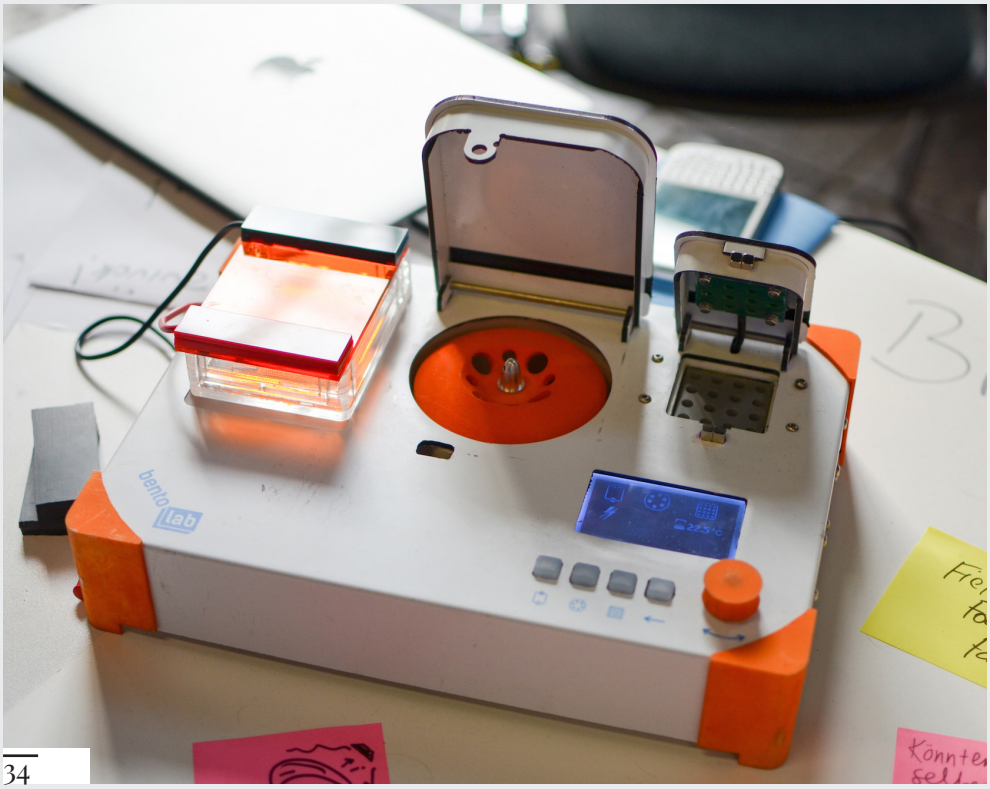

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The Microbial Design Studio aims to solve the challenge of designers' knowledge acquisition by bringing the laboratory tools into the context of the design studio, direct engagement with the processes of genetic modification (see Figure 33). Other efforts have been made to democratise the tools required for biological work, such as the *Bento Lab* (see Figure 34), a start-up project developed by Philipp Boeing and Bethan Wolfenden, which involves a portable, low-cost PCR machine developed with the artistic, design and DIY community in mind (Bancroft 2016).

33 Image of the Microbial Design Studio a project led by Orkan Telhan that aims to bring the laboratory tools into the design studio

34 Image of the Bento Lab a start-up project developed by Philipp Boeing and Bethan Wolfenden

3 BIOTECHNICAL IMAGINATION: AN ALTERED VIEW OF DESIGN

Despite the fundamental differences between the *speculative biotechnical* and *literal biotechnical* poles, it can be argued that they coincide in an altered view of design. In the textual accounts I have analysed, recurring themes of ecologies, emergence and complexity can be detected. These concepts construct what I call in this work *biotechnical imagination*, defined as an altered view of design that argues that biotechnologies constitute an unprecedented, fundamental change to our current understanding of design and its practices.

3.1 EMERGENCE

One recurring notion of the *biotechnical imagination* is *emergence*, broadly understood as a phenomenon where global behaviours arise from the undirected, local interaction between constituent parts of a whole. The notion is often contrasted with centralised forms of organisation, where behaviours are defined centrally and then enacted by providing precise instruction to different parts (De Wolf & Holvoet 2005). In the context of design, the notion of emergence is often used to describe design processes where decisions do not emerge from a single actor, the designer, and then imposed onto a shape. Instead, emergent design is described as arising from the interaction

between building and context, often outside the direct control of the human designer. A general notion of emergence is often used to describe changes to the design process brought about by biotechnologies. For example, in describing *Thinking soils*, their authors write:

> We propose a new design process based on systems in which both modelling and manufacture are combined into an engineered biological system. In this case, the designer does not define the material form, but rather designs a system where the material is synthesised in direct response to an environmental context (Dade-Robertson et al. 2016, p.461).

The notion of emergence is also used to refer to design processes in which the material form is not contingent upon a designer, but is the result of a complex process. For instance, *BioProcessing* is constructed around the notion that exoskeletons generated by Xylem cells are inherently efficient, as they develop through processes that are tightly connected to a complex interaction between cell and environment:

> While there may be numerous examples of identifying and using the form of nature in design and architecture, the team seeks to identify and utilize the logic of nature (...) the team studied the physical constraints of a cell in order to see how its exoskeleton might offer material distribution solutions for architectural forms (McDonough 2012, p. 83).

Notions of emergence are also used in projects placed closed to the speculative pole. *Future Venice,* for example, operates on emergent principles. The project proposes the use of protocells as building blocks, which are programmed with simple rules that enable them to swim away from the sun and towards the foundation pylons. When released in the water, the cumulative effects of individual protocells would produce an overall effect of increased microbial cementation, reinforcing the city foundations. Principles of emergence are reiterated in the narrative that is built around the project:

> The architect's vision is a response to the fact that building technology has remained largely unchanged for hundreds of years — relying on blueprints, industrial manufacture, and teams of workers to create an

> inert object that is ecologically isolated and unsound (McDonough 2012, p. 73).

The discourse on emergence, architectural technologies and infrastructure is central to the work of Armstrong, and has become the backbone of *LIAR*, the ongoing biotechnical project that looks at how buildings can operate as organisms, with components that are able to respond to conditions in their environment.

3.2
ECOLOGIES

Descriptions of *Future Venice* and *LIAR*, however, are also connected to notions of ecologies. In this context, the notion of ecology makes reference to the scientific field of study that deals with the interaction between organisms and with their environment. In architecture, the concept has been used to speculate on design techniques and construction technologies that enable buildings to respond to their environment, by adapting either their built form or their operation. For instance, *Bacterial Hygromorphs* uses a rhetoric that emphasises the potential of spore-coated materials to develop intelligent architectural skins, which employ low-energy strategies to respond dynamically to their environment:

> Hygroscopic materials can be used to produce low complexity actuators, which are operated by changes in moisture content in the air – converting, for example, the energy held within evaporating water into mechanical work. These have been of particular interest in architecture, as they are integrated in the research and development of intelligent skins and dynamic envelopes, which aim to produce sophisticated assemblies that respond dynamically to their environment (...) Spore-coated elastomers constitute a potentially powerful technology to produce highly programmable architectural hygromorphic materials (Ramirez-Figueroa et al. 2016, p.245).

The project of *Fab Tree House* also deals in notions of ecologies. The project is presented as a response to traditional design and building technologies,

which are perceived as being at odds with their environment. The project proposes a methodology in which the form of the house is indexed to its context:

> The concept suggests an alternative to the sterile, stand-alone homes that are at odds with their immediate environment. It offers a method for growing residential accommodation from native trees that remain living and integrated with the ecosystem (McDonough 2012, p. 58).

The same principle is in use in the analogue project of *Meat House*, which explores how mammal cells can grow and adapt to perform different functions required in a dwelling, thus becoming, for instance, sphincters and epithelial tissue.

Notions of ecology are used not only to conceptualise the material configuration and operation of buildings, but also to understand them in wider networks. The façade in *BIQ Algae House* is described as a form of ecology itself, in which organisms are integrated into a carefully orchestrated sequence of processes, thus enabling it to regulate sunlight and produce biomass through its exchanges with the atmosphere:

> The project is a multi-storey residential building that employs a prototypical method of producing energy and regulating light and sun-shading. At close range, the façades – oscillating from afar through the constantly growing algae – start to move; bubbles forming through the supply of carbon dioxide and nitrogen, as well as the permanently essential circulation of water containing aerosol-like microalgae, seem to suggest that biomass production could be a solar-powered art installation, steadily bubbling along (Splitterwek & ARUP 2014).

The production of biomass is dependent on a wider, economic ecology. Biomass stuck to the glass panels is scrubbed manually, culled and mashed into a biofuel mass, which is burnt in a local generator to produce electricity and heating. Excess biomass is expected to be sold to other buildings and local industries to produce food supplements or methane.

BioMASON similarly constructs a narrative around the ecological perspective of bacterially enhanced manufacturing processes. Producing masonry bricks involves burning agricultural soils in coal kilns, which produces large quantities of CO_2. By contrast, the process developed by Dosier involves mixing bacteria, urea, sand and calcium chloride, which is thought to release fewer amounts of harmful by-products to the atmosphere. In addition, the project is often presented through a narrative of '*critical regionalism*', in which the process is fine-tuned to incorporate local resources in producing the required chemistries. Ednie Brown writes about the project:

> Conversations with various individuals who contacted her about the project led Krieg Dosier to explore the use of waste products, such as urea from the swine industry, mine tailings as a source of aggregate, waste egg shells from the poultry industry as a calcium source, and brewer waste yeast extract as a nutrient for the organism. This approach to the sourcing of materials acts to locate the brick product in what Krieg Dosier talks about as a kind of 'critical regionalism': 'the bio-brick material that I make here in the UAE is slightly different to the one that I would make in North Carolina because the different nutrients and waste resources slightly change the characteristics of the resulting material (Ednie-Brown 2013, p. 89).

BioMASON, it is described, participates at different ecological levels. It contributes to improving the exchanges between building technologies and the atmospheres, but also participates in wider ecologies of local resources and industries.

3.3
COMPLEXITY

Notions of emergence and ecologies are often used in the biotechnical discourse in framing a response to a perceived material crisis: a notion that contemporary environmental concerns require a revaluation of the methods through which buildings are produced. In prefacing his book *BioDesign*, Myers writes:

> Designers face an unprecedented urgency to alter their methods and reprioritize their goals to address the accelerating degradation of the environment. This new pressure — intellectual, ethical, and regulatory — demands recognition of the fragility of nature and our responsibility to preserve it for future generations. Under such shifting and intensifying constraints, designers are beginning to go beyond emulation to harness processes observed in the living world, where systems achieve perfect economies of energy and materials (Myers 2012b, p. 10).

I have described above how, for instance, the work of Armstrong is constructed around an urgency to find alternative methods of design, which challenge frameworks that are perceived as inadequate to respond to environmental challenges. *Dune* is described along similar lines. The calcite-forming process is imagined as an interaction between environment and organism, contributing to a notion of architectural structure as a living system. In addition, the narrative constructed around the project suggests that the design and construction methods afforded by biotechnologies are uniquely placed to solve contemporary environmental challenges:

> The urgency of the problem that this project attempts to address cannot be overstated. A United Nations study (Adeel et al., 2007) concludes that 'Desertification had emerged as an environmental crisis of global proportions, currently affecting an estimated 100 to 200 million people, and threatening the lives and livelihood of a much larger number.' The displacement of communities that is often generated by the spread of the desert regularly aggravates political instability in several of the affected countries, such as Sudan, Chad, and Nigeria (McDonough 2012, p. 62).

In addition to issues of material complexity and environmental challenges, *biotechnical imaginations* are also motivated by aesthetic considerations, with a notion that biological systems tend to derive spatial arrangements that are compelling as a result of their intricacy, and by how much they depart from human-made structures. For instance, in *BioProcessing,* David Benjamin, extrapolates Xylem cell patterns to produce new, complex architectural 'exoskeletons'. Myers describes the process as follows: '*An equation for Xylem cell formation is derived by analysing data relating to the distances,*

thickness and angles of the natural cell. This equation is then used to calculate how the natural system might create exoskeletons in more complex shapes' (McDonough 2012, p. 84). A similar approach is taken by Preissner, who uses the Protocell tower project to muse on the aesthetic possibilities of protocells. He argues that the 'looks' of structures grown through protocells have been long anticipated, and now feel old and boring. Instead, he proposes that the untapped potential of protocells is in generating structures that break formulaic contemporary forms, potentially creating cities that look more 'fun'. Preissner writes:

> By growing patches and parts, and amending existing work organically but differently, maybe we can make cities feel more novel, more light, more gun, and use this organic, mutable material to continually reform what we already see through alterations to existing buildings, to create the newness we haven't yet come to expect from technology interfering with the city (Preissner 2011, p. 111).

Biological systems, Preissner suggests, are a source of newness and fun amid what he perceives to be a creative crisis, characterised by endless repetition of computer-generated forms, which already look organic, and therefore boring.

4 BIOTECHNICAL IMAGINATION AND ITS ACTUALITY

A disconnect can be detected between the artefacts produced and the set of principles and aspirations laid down in the *biotechnical imagination*. In this chapter, I have proposed a spectrum of biotechnical architecture projects with two poles, the *speculative* and *literal biotechnical*. I suggested that each is motivated by a different set of goals and objectives, which result in different methodologies of engagement with living systems that involve different shortcomings. Given the breadth and ambition of projects closer to the *speculative biotechnical* end, it is often necessary to rely on preconceptions of what biological systems are and how they operate. Although preconceptions are productive in

assembling possible futures and critical discourses, it is inadequate to explore in detail the implications for design methodologies and technologies. *Literal biotechnical* projects also have limitations in the way that they engage biological systems. By focusing on real, immediate applications, they often project organisms to close matches in existing technologies and techniques. The combination of both does not necessarily contribute to actualising the altered vision of design, based on notions of ecology, emergence and complexity. Despite the discourse on emergence and ecologies, *BioMASON*, for example uses bacteria to produce a well-established building component that relies on existing construction technologies. Despite being contextualised as a potential solution for a pressing environmental crisis, *Dune* does not explore the implications of releasing an organism in the desert dune, or of the feasibility of controlling a process involving precise proportions of chemistries in large, on-site scales.

The gap between imagination and actuality leaves unanswered two critical questions. The fist, *Can architectural designers engage with living systems in a way that doesn't prefigure design outcomes but which enables innovative engagements with biology as material?*, is connected to notions of emergence, which generally suggests that biological systems enable a fundamentally different form of design where material form and building operation are the result of the interaction of parts, and not of a prescriptive definition. *Speculative biotechnical* projects often engage in imagined long-term implications of this, but not in how the realities of biological work affect the methodologies of design; rather, they rely on preconceptions. A good example of this is the quote by Preissner, suggesting that the formal possibilities of protocells had long been anticipated by the digital paradigm in architecture. On the other hand, the pragmatic approach of *literal biotechnical* projects enables engagement with the immediate realities of working with biological systems, developing methodologies that maintain direct engagement with the material. The productivity of the approach is, however, in the limitation of a more fundamental exploration of which possibilities biological systems offer to design and, instead, falling back on existing technological models. Both approaches, the literal and the speculative, fulfil different objectives and have been productive in establishing a biotechnical discourse in architecture. As a result of the limitations in their methodologies, however,

they are ill-equipped to answer the extent to which it is possible to engage creatively with biological systems, and to fundamentally alter the definition of the discipline of design itself by not prefiguring formal outcomes. The possibility is connected to the second question: *is it possible to design by engaging exclusively with living systems and their immediate context?*

2

BIOTECHNICAL IMAGINATION IN BIOTECHNOLOGIES

The things we call 'technologies' are ways of building order in our world
Winner, 1986

CHAPTER 2

BIOTECHNICAL IMAGINATION IN IOTECHNOLOGIES

1 INTRODUCTION

The contemporary discourse in biotechnologies, led by synthetic biology, emphasises the reduction of complexity and randomness of living systems. It proposes principles of abstraction, standardisation and modularity, which result in a design approach led by clearly defined outcomes and objectives. At its core, there is an idea of reducibility that engenders a new way of doing biology, and which is connected to parts, systems and wholes that are related to modifying existing organisms, or to creating entirely new ones. However, there is tension between declared design principles, and the reality of their practices. The dissonance can be described as a second form of *biotechnical imagination*: an altered view of design that is extensively used in contemporary biotechnologies, and which does not correspond to the realities of its outcomes.

The *biotechnical imagination* in biotechnologies has a number of advantages and drawbacks. On the one hand, it is a very productive way of thinking. It involves very direct engagement with the organisms, and a very clear design framework. While it has several limitations, a mechanistic model of biology — one that suggests there are parts that can be reassembled, and that there are minimal units that can be manipulated — leads very quickly to outcomes. Nonetheless, biology doesn't comply to this framework and, from a design perspective, the approach misses out on the potential for new ideas, as it requires defining every outcome in advance of its process which, in contemporary design terms, it is counterintuitive as experimentation is

thought to reveal possibilities for new things. On the other hand, the imagination in contemporary biotechnologies entails a return to anachronistic, design notions. Many fields of design have moved past notions of design tied to systematisation and parts, and has evolved away from approach that requires delineating clear objectives as part of the design process.

In light of the tension between *biotechnical imagination* in architecture and biotechnologies, this thesis asks if *there are any alternative ways and contexts for working with living systems that take elements from both discourses?* To do so, it explores alternative ways of working with biological systems, and suggests that designing with living systems requires a methodology to constrain and reduce complexity while also acknowledging it.

2 BIOTECHNICAL IMAGINATION IN BIOTECHNOLOGIES

The term *imagination* highlights a dissonance between the discourse of biotechnical architecture, and its outcomes and practices. There is a similar tension in biotechnologies, in which declared design principles do not correspond to the reality of their practices. The dissonance constitutes a second *biotechnical imagination*: an altered view of design that operates within biotechnologies.

Broadly speaking, biotechnologies aspire to a reduction in complexity and randomness of living systems through control, systematisation, standardisation and clearly defined outcomes and objectives. In the last 10 to 15 years (Schyfter et al. 2013), synthetic biology has been instrumental in advancing the agenda of biotechnologies, incorporating notions of reducibility that engenders a new way of doing biology, based on an operational hierarchy of parts, systems and wholes. One of the widely used definitions says that synthetic biology concerns *'the design and construction of new biological parts, devices, and systems'*, as well as *'the re-design of existing, natural biological systems for useful purposes'* (Schyfter et al. 2013, p. 1).

Synthetic biology is often defined in opposition both to biology, which is

perceived as oriented only to discovery, and to previous biotechnologies, which are considered too messy. Tom Knight, an early proponent of synthetic biology, contrasts the approach of synthetic biology, oriented to action and driven by pragmatism, with that of traditional biology, which he perceives as being oriented to discovery.

> The biologist goes into the lab in the morning, does an experiment, discovers that the system she's looking at is twice as complicated as she thought it was, and says 'Great, I get to write a paper'. The engineer goes into the laboratory, does the same experiment, gets the same result, and says 'Darn! How do I get rid of that?' (Frow & Calvert 2013, p.43)

A similar discourse is used to contrast synthetic biology with genetic engineering, often considered their immediate precedent in biotechnologies. As pointed out by Frow and Calvert (ibid), proponents of synthetic biology often argue that the term 'genetic engineering' is a misnomer, as its methods are often closer to artisanal craft than to an engineering discipline. In stressing the contrast between both disciplines, Paul Freemont, founder of the EPSRC Centre for Synthetic Biology and Innovation, quotes comedian Simon Munnery when saying:

> What genetic engineers do [today] isn't really engineering. The engineering equivalent of what genetic engineers do is to throw a load of steel and concrete into a river, and then if someone manages to walk across it, call it a bridge (Munnery, quoted by Bland 2011, para. 4).

Similarly, Rob Carlson, also a prominent and influential synthetic biologist, writes in a letter to the *New York Times*:

> Genetic engineering techniques are abysmally primitive, akin to swapping random parts between random cars to produce a better car. Yet our ignorance will fade; biological engineering will become a reality relatively soon (Carlson, quoted by Group 2007, p. 3).

The main point of the contrast between older forms of biotechnologies and synthetic biology, it is argued, is the application of engineering design

principles to biology, which are thought to provide elements of predictability, control and intentionality. Schyfter proposes that the central thesis of synthetic biology is premised on the possibility of creating an *engineerable* nature: '*Biology is to serve as a substrate for engineering much as inanimate materials provide the base stuff for civil, mechanical, and electrical engineering*' (Schyfter 2011, p. 201). The author goes on to propose three engineering design principles that are central to the approach of synthetic biology: the abstraction of complexity (Endy 2005; Way et al. 2014), the standardisation of design components (Arkin 2008; Silver 2009; Benner et al. 2005; Andrianantoandro et al. 2006; Heinemann & Panke 2006) and modularity and decoupling of operational elements (Hartwell et al. 1999; Endy 2005; Sauro 2008; Way et al. 2014).

2.1
ENGINEERING DESIGN PRINCIPLES

The abstraction of complexity enables the description of biological functions in hierarchical categories, and the separation of these descriptions from the physical substrate to which they refer. The principle is often explained by drawing analogies to the way in which computer engineering isolates hardware (the substrate that enables computation) from software (the set of instructions that describe calculations, and how these should be interpreted). This strategy has been highly productive for software engineering, as it enables workflows in which it is possible to design and build software with limited or virtually no knowledge of hardware. Similarly, synthetic biology proposes the use of systems that enable the representation of genetic material and biological functions in the form of *devices*, understood as functional modules that can be manipulated to assemble complex systems with little or no biological knowledge.

Connected to the ideal of abstraction is a requirement for standardisation, which involves the creation of readily available, interchangeable parts, whose properties are clearly described and well documented. The notion of standards is also well disseminated in engineering disciplines. It is used, for instance, in the design of screws and nuts, which are produced to set dimensions and forms. Screws produced by one manufacturer can be in-

terchanged with those produced by a second manufacturer, and paired with nuts provided by a third in order to build more complex systems. In the context of synthetic biology, standardisation is enacted in the form of components called *BioBricks,*™ defined as sequences of genetic code characterised by specific starting and end points. In principle, well-defined BioBricks could be easily assembled to produce more sophisticated, larger 'devices' and systems. In this category of systems, *parts* are thought to characterise basic biological functions, and *devices* represent combinations of *parts* that perform more sophisticated functions, and which can be assembled to produce *systems* (Endy 2005). Also of importance is the *Registry of Biological Parts*, based at the MIT and which operates as an open-source repository of BioBricks. The importance of the registry is evidenced by its central role in the iGEM, short for the *International Genetic Engineering Machine Competition*. The iGEM is a competition, initially organised by the MIT, which brings together synthetic biologists and first-year undergraduate students, with the goal of '*trying to design and build biological systems using standardized genetic sequences*' (Frow & Calvert 2013, p. 42). Students are provided with a sample of BioBricks to produce their design, and are required to submit at least a new BioBrick to the registry.

Another important aspect in enacting the ideal of standardisation is modularity. Frow and Calvert review how the discourse of synthetic biology is predicated on interchangeable biological parts, which can be used '*as one might assemble Lego® bricks',* which enable the creation of *'biological devices that perform specific functions'* (idem p. 43). An important requirement in order to achieve this is *modularity*. Sauro (2008, p. 1) describes a module as a '*functional unit that is capable of maintaining its intrinsic properties irrespective of what it is connected to'*. He goes on to explain that the notion of modularity is crucial in design, as it enables working with components that lead to predictable outcomes, thereby reducing costs and facilitating the design process.

The combination of abstraction, standardisation and modularity enables the design strategy of decoupling, which in synthetic biology is enacted in two forms. First, there is a general principle of breaking down complex systems into smaller, easier-to-understand components. Once these compo-

nents have been characterised in isolation, knowledge can be aggregated to understand and modify the system as a whole. The second form of decoupling refers to the separation of design and fabrication of biological systems. In the early years of synthetic biology, Endy described the decoupling of design and fabrication in terms of the separation of activities, enabled by recent advances that render the DNA sequence both faster and cheaper. He writes:

> The decoupling of design and fabrication in biological engineering is being driven by recent and ongoing improvements in the process of DNA synthesis (…) Given gene and genome synthesis technology, some individuals can and should focus on designing useful pieces of DNA, while other individuals focus on building DNA; each group need only be expert in their respective tasks (Endy 2005, p. 451).

The possibility of separating tasks, Endy explains, enables a more efficient approach to the design of biological systems. Highly specialised individuals concentrate on one aspect of the process, while the use of standards means that their efforts can be combined in producing highly sophisticated biological systems.

2.2
PHILOSOPHICAL MECHANISM

As described in the previous section, a focus on standardisation, decoupling and abstraction is often contextualised as part of an effort to import the engineering model into biology. However, these principles also participate in a wider, historical project aimed at transforming the discipline from a so-called *soft* to a *hard* science. In describing the work of her research group in advancing synthetic biology, Silver reflects:

> Our progress in understanding life, particularly the detailed molecular biology of cells, coupled with new technologies and computing power, is starting to transform biology from a 'soft' science focused on description to a 'hard' science focused on quantifying, predicting and controlling its properties (Silver 2009, p. 283).

The reference to a tier system to classify scientific disciplines dates back to philosophical mechanism, a school of thought that was influential in the development of science during the late nineteenth century and the first half of the twentieth century. It also proved central to developments in virtually every area of biology, Allen proposes, ranging from physiology to cell biology and evolutionary biology (Allen 2005). More importantly, philosophical mechanism influenced a view of science that favoured control over nature, and prized the ability to predict its behaviour. In this context, nascent nineteenth-century biology was regarded as an unruly discipline, and efforts were proposed to align it with physics, then considered the ideal of scientific knowledge.

Philosophical mechanism likens the operation of organisms to the interaction of material components in a machine. In biological thought, philosophical mechanism is often associated with reductionist epistemologies, which advance the notion that the best approach to understanding living systems is the analytical method: taking apart individual components to determine their properties in a set of controlled conditions. Knowing the characteristic of parts, it is proposed, reveals their relationship with other parts, as well as enabling an understanding of the whole. Moreover, philosophical mechanism is concerned with the ultimate goal of controlling and predicting nature for human purposes (Allen 2005). In the evolution of biological thinking, it has been suggested that Jacques Loeb is a foundational figure in the mechanistic approach (Pauly 1987; Porcar & Peretó 2014; Allen 2005). Loeb's work also prefigures the discourse of contemporary biotechnologies, Catts and Zurr (2014) argue, in that it represents the first moment in history in which biology shifted from the descriptive and speculative to the intentional and prescriptive. Phrased in the terms used in the quote by Silver above, Loeb was the first to push for a transformation of biology from a 'soft' to a 'hard' science.

A Prussian scientist, Loeb came to prominence thanks to his work on artificial parthogenesis, which refers to the process by which embryological development is triggered by non-organic chemicals, without fertilisation. The term was coined by Loeb, who happened upon an experimental technique that made possible '*the artificial production of normal larvae (plutei)*

from the unfertilised eggs of the sea urchin' (Pauly 1987). The discovery would provide Loeb with a platform to pursue a radical shift in the outlook of biology, from understanding to manipulating living systems. In his early work, *The dynamics of living matter* (1906), for instance, Loeb would identify two key challenges for biology: transforming common matter into living matter; and the possibility of transmuting one species into another. Then in *The mechanistic conception of life* (1912), he proposed a set of core physicochemical principles of life, which he thought constituted the basis for producing artificial living matter. In a letter to Ernst Mach, Loeb writes: '*The idea is now hovering before me that man himself can act as creator, even in living nature, forming it eventually according to his will. Man can at least succeed in a technology of living substance*' (Landecker 2009, p. 1).

Loeb's prominence as a historical figure responds to the way in which he participated and drew from mechanistic approaches in other disciplines. One of his early inspirations includes Virchow's essay on *Mechanistic Conception of Life,* which advanced a novel model of cells, proposing that they did not constitute independent forms of life, but rather that they were component parts of a systematic unit. Lenoir analyses how Virchow:

> Conceives the complex living organism as composed of multitudes of living individual cells, which remain united because they are interrelated to one another just as members of the same state (Lenoir 2012, p. 224).

Lenoir goes on to analyse the political undertones in the mechanistic discourse. Notions of how natural phenomena operated were often connected to a wider view, which linked to notions of society. The author writes:

> In language heavily laden with then-current political imagery the mechanists stood convinced by advocating a liberal bourgeois conception of biological organization in which the march of technology breaks a truly organic society into factions and ultimately atomic individuals with no connection to one another or the organic whole which is the only source of meaningful existence (ibid).

Loeb was also inspired by other biologists who had attempted experimental

approaches with a mechanistic mindset. Hugo de Vries, for instance, founded the *Carnegie Institution Station for Experimental Evolution*, a centre with laboratory and garden facilities, with the specific aim of developing large-scale breeding in a variety of animal species (Kohler 2002). The centre was intended to provide the basis from which to control evolutionary change for the benefit of humanity. The report of a contemporary newspaper describes it thus: *'Man – long content with his part as caretaker and subjugator of living species – is now learning the new role of creator'* (Campos 2009, p. 7). The effort ties in well with de Vries' own theory of mutations, which postulated that evolution is driven by the appearance of discontinuous variation in individuals, which is propagated to the species via heredity (de Vries 1909). The theory of mutation is expanded through the work carried out at the station, where bred species are referred to as synthetic forms of life. It has been proposed that the work of de Vries at the experimental station represents a blurring of the divide between the artificial and the natural (Campos 2009), which prefaces core philosophical implications of contemporary biotechnologies (Schyfter 2011).

In parallel to Loeb, other biologists approached life with similar objectives of manipulation. Stéphane Leduc, for instance, is credited with the first use of the term '*synthetic biology*'. Leduc used the term as the title for a chapter in *The Mechanisms of life* (Leduc 1911). In it Leduc claimed to have assembled artificial cells, which exhibited organs, nucleus, membrane and cytoplasm, as well as metabolism and evolutionary potential. Leduc uses the term to delineate the last stage in the evolution of biological enquiry. Leduc explains:

> The course of development of every branch of natural science has been the same. It begins by the observation and classification of the objects and phenomena of nature. The next step is to decompose the more complex phenomena in order to determine the physical mechanisms underlying them — the science had become analytical. Finally, when the mechanism of a phenomenon is understood, it becomes possible to reproduce it, to repeat it by directing the physical forces which are its cause — the science has now become synthetical (Leduc 1911, p. 114)

The notion of synthesis served to frame his work: chemistry experiments,

especially developed with crystals, that exhibited life-like behaviours and which, he believed, might lead to understanding the basic principles behind the complexity observed in living systems.

Leduc's principle of synthesis operates as a method to understand the basic biological mechanisms by stripping away their complexity. In *La Biologie Synthétique* (1912) Leduc explained that synthetic biology implied understanding biological morphology through experiments conducted outside biological systems. *Chemical gardens* (see Figures 3 and 4), for instance, provided a means of isolating and studying psychochemical processes such as osmosis and diffusion. Once these processes are understood, they need to be interpreted and mapped back to living systems through analogical reasoning, which validates their status as biological knowledge. Leduc explains:

01 *Chicago Daily Tribune, 28 December 1900*

02 *Experiments in cell morphology by Leduc, showing diffusion and membrane behaviour. Membranes are described as 'Fields of force'*

> The results, the facts presented in this book; the reproduction of artificial cells, structures, fabrics, general forms, functions, centripetal and centrifugal movement, karyokinesis, segmentation, tropisms; these experimental results and the experiences themselves are irrelevant, meaningless, if such research were not inspired by the imitation of life. It is in the analogy to what we observe in living beings that these phenomena have any interest. (Leduc 1912)

Work on synthetic, biological methods were also carried out by Alfonso L. Herrera in Mexico. Herrera put forth the notion of *Plasmogenia*, sketched as a scientific discipline whose aim would be to synthesise life in laboratory settings, using inorganic matter as a starting point. Herrera follows similar conceptual underpinnings to Leduc in proposing a continuum of matter rather than absolute and well-defined *organic* and *inorganic categories*. In *Nociones de Biología* (Herrera 1904) he explains:

> Live pseudo-beings and pseudo-organised structures have been made in the laboratory using reagents that are neither mysterious nor divine (...) Indeed, they are so suggestive of analogies between animate

LOEB TELLS OF ARTIFICIAL LIFE.

Describes Experiments at the Convention of the Western Naturalists.

SAYS SALT IS A FACTOR.

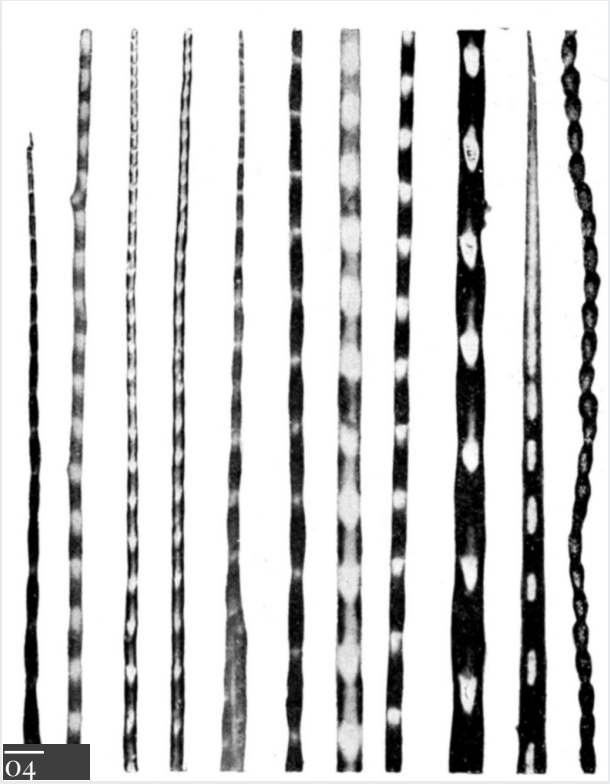
Fish Eggs Developed by the Imparting of a Mild Electric Shock.

MEN OF SCIENCE CONVENE.

01

02

03



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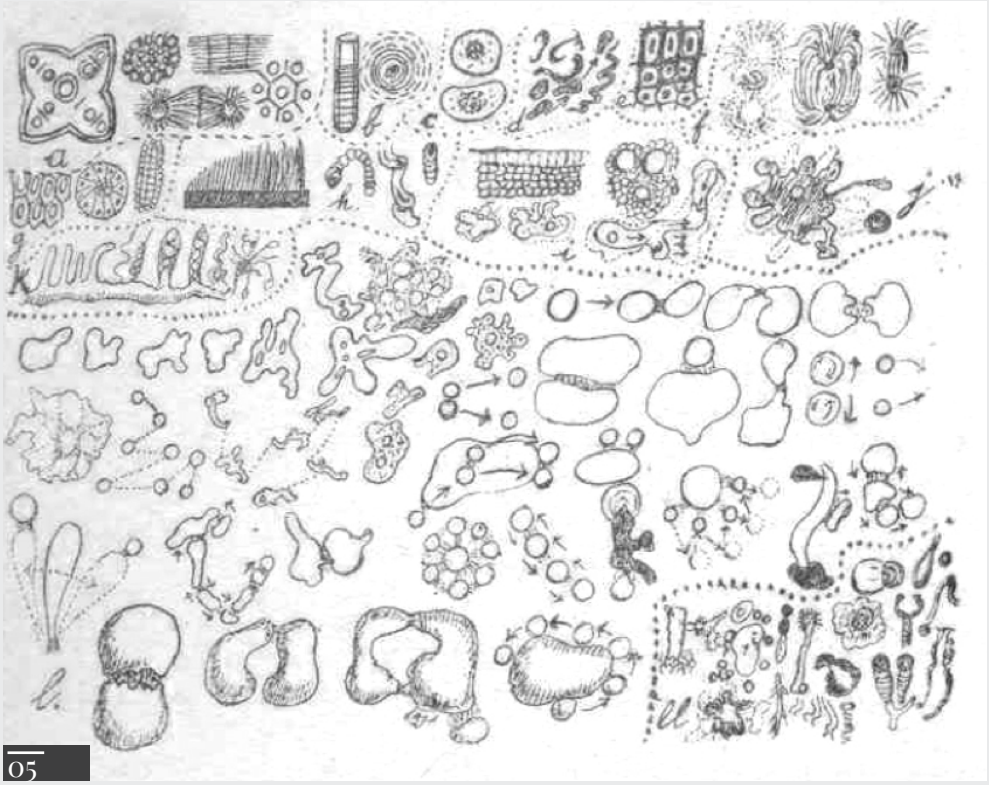


05

> and inanimate matter that the spirit is confused (…) and hesitates before drawing the final and definitive conclusion that there is no separation between living forms and crystallized forms (Herrera, quoted by Porcar & Peretó 2014, p. 17)

The genealogy of contemporary biotechnologies, and of the term *synthetic biology*, is often contested (Campos 2009). The work of Loeb, Leduc and Herrera suggests that principles of control and predictability in contemporary biotechnologies respond not only to a direct influence of engineering design principles, but also to a longer historical process. Synthetic biologists often propose timeline narratives of the discipline that identify digital technologies in the 1990s as the foundational point in contemporary understandings of biotechnologies (Cameron et al. 2014). Others identify the development of recombinatorial DNA techniques in the 1970s as the key moment at which contemporary ideals of standardisation and control were born (Editor 2014). By contrast, Campos (2009) argues for a larger chronology of the idea of synthesis in biological thinking, which starts with the work of Loeb and follows a genealogy of ideas and people similar to the one presented in this section. Regardless of its genealogy, there is a form of *imagination* in biotechnologies: a disconnect between the declared design principles and objectives, and the complexities involved in actual biological work. The next section discusses the *biotechnical imagination*, drawing from different authors who have highlighted the inconsistencies between discourse and actuality in biotechnologies.

03 *Chemical gardens by Leduc, showing osmotic growth produced by a mixture of $CaCl_2$ and $MnCl_2$ in a solution of alkaline carbonate, phosphate and silicate*

04 *Osmotic growths used in Bateson's Problems of Genetics, modelled after that of Leduc. In discussing the figure, Bateson wrote: 'In some respects, perhaps the best models of living organisms yet made are the "osmotic growths" produced by Leduc'*

05 *Illustration from Plasmogenia. The original caption read: 'Assortment of artificial life models. Colpoids'*

3 THE LIMITS OF SYSTEMATISATION: DEALING WITH COMPLEXITY

The approach in biotechnologies, based on principles of abstraction, standardisation and modularity, has several advantages. It is an extremely productive way of thinking that a involves very direct engagement with the organisms, and a very clear design framework. While it has several limitations, a mechanistic model of biology — one that suggests there are parts that can be reassembled, and that there are minimal units that can be manipulated — has led to tangible outcomes, as well as providing a focus in activity and funding. Nonetheless, the realities of working and manipulating biological systems supposes a more complex scenario than the prevailing narrative in biotechnologies. The disconnect between practice and framework suggests the existence of an *imagination* in the discourse of contemporary biotechnologies.

Different authors have highlighted a disconnect between the declared principles of biotechnologies and, more specifically, of synthetic biology, and the realities of its day-to-day practice. Frow and Calvert (2013) suggest that the tension between discourse and actuality is linked to a more general disconnect between idealised and actual design principles in engineering. While declared principles include notions of decoupling, modularisation and standardisation, there are also more 'pragmatic' and less formalised design principles that are often used in engineering, such as *tinkering*, *bricolage* and *kludging*, and which suggest approaches that are contingent upon context. Their analysis is done within the context of the iGEM competition, considered by synthetic biologists to be a test-bed of the design principles of the discipline and its viability. The authors developed a participant-observation and ethnographic study of the competition over four years, as well as being involved in an advisory capacity with the organising committee. In reflecting on the status of the engineering design principles in the practice of synthetic biology, they write:

> At this stage, synthetic biology has not developed the foundational design principles necessary for the reliable design of genetic circuits; much of the work both in the iGEM competition and in synthetic biology more

> broadly is focused on troubleshooting, simple parameter variation, and the generation of data from which more formal design principles might eventually be abstracted (idem, p. 50).

The authors go on to suggest that notions of standardisation, abstraction and decoupling operate as rhetorical devices, used to establish a convincing narrative of the work:

> In practice, engineering rhetoric typically resurfaces as iGEM teams start preparing their project presentations and posters according to the framing of the competition. The messy and often inconclusive laboratory work they engage in over the summer gets re-packaged into a clear story about the engineering of a genetic machine. iGEM presentations at the Jamboree are incredibly slick and professional, and they serve to perform and reinforce the engineering dimensions of the competition (ibid).

While the analysis of Frow and Calvert comes from outside the discipline, practitioners have also reflected on the limitations of engineering design principles in synthetic biology (Bensaude Vincent 2013). Danchin, for instance, has questioned the viability of the principle of abstraction in the design and modification of cells. He analyses how the analogy between cells and computation, central to the implementation of engineering design principles, is misleading. While he recognises how the parallel is useful in recognising the separation of functions between gene expression and the cell machinery, he also highlights how it has contributed to an approach that separates the genetic *programme* from the underlying *hardware*, the chassis of the cell. Danchin writes:

> The present avatar of Synthetic Biology (SB) assumes that we know enough of what life is to allow us to construct life from scratch, or, at least, to modify existing cells and organisms so that they work as cell factories. With this view SB puts together two separate entities, a program (the conceptual extension of the genetic program) and a chassis (the conceptual extension of the living cell). Yet a rapid browsing of publications in the domain indicates that the vast majority of SB-related work

> deals with the program, not the chassis. Most investigators do as if the recipient cell would be nice enough to accommodate entirely artificial constructs and behave as expected, producing the right products, with the right yield, at the right time. Several hard constraints however make this dream difficult, if not impossible to achieve (Danchin 2012, para. 1).

Similar reserves have been expressed regarding the possibility of modularity. Benner questions the possibility of creating interchangeable parts on the grounds of biochemical synthesis. The notion, he explains, hinges on the notion that parts remain stable throughout performance, not changing their expression when they interact with different parts, as suggested by frequently drawn parallels to standardised parts in mechanical engineering or Lego blocks. In reflecting on Benner's lecture, Bansaude summarises the argument thus:

> …making standard interchangeable parts is an ideal far from the actual practices of synthesis. Unlike the parts assembled in mechanical engineering the building blocks of synthesis inevitably interact. Their identity and behaviour is to a certain extent determined by their interactions. In thus emphasizing the gap between the engineering ideals of the Biobricks programme and the principles at work in actual practice, Benner suggests that the delivery of this ambitious and attractive research programme will never be up to the promises. Actually the rare successes of synthetic biology such as the biosynthesis of artemisinin – an anti-malaria drug – were not the result of rational design. In reality they were achieved through more messy and painstaking practices with trials-and-errors and workarounds (Bensaude 2013, p. 27).

O'Mailey also argues that, despite narratives of engineering design principles, the day-to-day reality of working with biological systems is often characterised by workaround, retrofit strategies that can best be described with the colloquial notion of kludge: a clumsy, lame, ugly, dumb but good enough solution to a problem. She writes:

> Synthetic biology's design processes always, so far, end up as iterative rounds of trial, error, and pragmatic solutions—sometimes referred to

> as 'debugging,' 'tweaking,' 'retrofitting,' or 'parameter tuning' — to make systems behavior fit design specifications (...) Kludging, therefore, may be the best way to understand the constructs so far produced within the field. Rather than exemplifying rational, elegant, and efficient design, many devices work because they are kludges (O'Malley 2009, p. 382).

Mechanistic approaches have been scrutinised not only in relation to how well they serve to directly manipulate living systems, but also in terms of how they often involve a limited understanding of its consequences. Working with living systems involves, by necessity, a broader context than the one covered by models of systematisation and control. Jane Calvert has proposed, for instance, that synthetic biologists are *heterogeneous* engineers. The concept was first proposed by Law, who argued that engineering should involve social, political, economic and human factors alongside technical considerations. Law argued that the technological devices produced by engineering are always involved in more complex networks of practices and people:

> Airplanes, electric power plants, the Internet, refrigerators, and playpens are complexes of artifacts together with social arrangements, social practices, social relationships, meanings, and institutions (Johnson and Wetmore, quoted by Calvert 2013, p. 416).

Calvert uses the notion of heterogeneous engineers to reflect on how working with living systems transcends the domain of the organisms themselves, and touches on political, social and economic spheres and, more generally, the building of society. The extent of consequences involved in biological manipulation, she argues, suggests the need to extend the *biotechnical imagination*, from focusing on engineering principles to include methods that enable thinking beyond the immediate microscopic scale.

3.1
BIOTECHNOLOGIES AS DESIGN PRACTICE

The way in which engineering design principles operate as a form of *biotechnical imagination* is also connected to a fundamental limitation of the mechanistic approach. The prevalent narrative in the *biotechnical imagination* entails a return to very old notions of design, which requires establishing clear objectives at the outset. Parallels can be found, for example, in the *design methods* and *science of design*, a pair of post-war design movements that operated under the premise that any design problem could be broken down into functional requirements, and that a universal methodology could be formulated to solve them. Nigel Cross explains how the project to *scientise* design, referring to an aspiration to formulate the design process and its products on principles of objectivity and rationality, has its roots in the avant-garde of the early twentieth century. Theo van Doesburg, one of the main figures behind *De Stijl*, described the art and design in the 1920s as being increasingly hostile to subjectivity and speculation, and was critical of efforts to produce an objective design methodology. Echoes of the hostility to non-rational approaches to design can be found in the discourse of the modernist movement in architecture. Le Corbusier, for instance, sought an objectively designed machine for living:

> The use of the house consists of a regular sequence of definite functions. The regular sequence of these functions is a traffic phenomenon. To render that traffic exact, economical and rapid is the key effort of modern architectural science (Le Corbusier, quoted by Cross 2007, p. 41).

The scientific discourse in design, Cross argues, reached its pinnacle at the *Design Methods* conference, held in London in 1962. The event had the declared objective of exploring the ways in which the design process could be guided by objectivity and rationality. The project was inspired, in part, by the then recent experience of the use of scientific and computational methods during the Second World War, and a conviction that in peacetime these could be used to solve humanity's most pressing concerns. One of the figures to have best captured the spirit of the design methods is Buckminster Fuller. Cross writes:

> The 1960s was heralded as the 'design science decade' by the radical technologist Richard Buckminster Fuller, who called for a 'design science revolution', based on science, technology and rationalism, to overcome the human and environmental problems that he believed could not be solved by politics and economics (Cross 2007, p. 42).

Core to the design methods movement was a shift in the focus of design, from the production of artefacts to a problem-solving activity, and which could be defined in a specific series of steps that could be applied to different situations. These tenets are best articulated in *The Sciences of the Artificial*, a book by Herbert Simon that would prove influential to the project to *scientise* design, or, in the words of DJ Huppatz: '*Design theorists and researchers anxious to establish both a scientific status for design and the most inclusive possible definition for a "designer"*' (Huppatz 2015, p. 29). The work of Simon centred on reforming design pedagogy, formulating clear and rational methods to solve problems. He writes:

> Academic respectability calls for subject matter that is intellectually tough, analytic, formalizable, and teachable. In the past, much, if not most, of what we knew about design and about the artificial sciences was intellectually soft, intuitive, informal, and cookbooky (idem, p. 33)

Huppatz analyses how Simon aspired to align design with optimisation methods, then in vogue in scientific and engineering disciplines, with a view to laying the groundwork for formalising design situations with the clarity of a standard mathematical problem. Mathematical consistency is also attempted by Christopher Alexander in his *Notes on the Synthesis of Form*. Alexander's approach proposes dealing with design complexity by formalising the links between the pattern of a problem, and the physical form that best responds to them. Design, he explained, can be broken down into subsets of functional requirements, which operate following hierarchical relationships. For instance, designing a kettle involves 21 functional requirements, ranging from the possibility of being picked up when hot, to materials that do not corrode, to a form that is easy to fill with water. Once these requirements have been defined, Alexander proposed, they can be grouped into subsystems, which can be dealt with semi-independently, before consider-

ing the integrated object.

Cross reminds us how, despite the optimism behind its discourse, the design methods movement saw a backlash from prominent figures in the 1970s. For instance, Christopher Alexander himself disavowed his own method based on functional requirements, suggesting it had nothing to contribute to design. Christopher Jones, also an early proponent, has also called into question the possibility of describing all aspects of design in logical terms:

> In the 1970s I reacted against design methods. I dislike the machine language, the behaviourism, the continual attempt to fix the whole of life into a logical framework (Cross 2001).

Cross reflects on the backlash of the *design methods* movement, attributing it to the general unsuitability of universal, rational methods to approaching the wide range of problems and complexities often involved in design practices. Rittel and Webber, for instance, suggest that design problems are often *wicked*. In reflecting on the feasibility of importing scientific and engineering methods to planning, they characterise design problems in two categories. They propose that some problems, especially those dealt with by science and engineering, can be well defined and delineated and can be solved with optimal solutions. The problems of other design disciplines, in contrast, are ill-defined. They explain this through a caricature, suggesting the existence of *tame* and *wicked* problems:

> The problems that scientists and engineers have usually focused upon are mostly 'tame' or 'benign' ones. As an example, consider a problem of mathematics, such as solving an equation; or the task of an organic chemist in analysing the structure of some unknown compound (...) For each of the missions is clear. It is clear, in turn, whether or not the problems have been solved. Wicked problems, in contrast, have neither of these clarifying traits (Rittel & Webber 1984, p. 136).

The experience of the design methods movement can be extended to the *biotechnical imagination*. It can be argued that rational design methodologies miss out on the potential for new ideas, as they require the definition

of every outcome in advance of its process. In contemporary design terms, this is counterintuitive, because experimentation is thought to reveal possibilities for new things. Standardised, rational approaches are useful in that they manage complexity, simplifying the process at the outset and enabling clear definitions of a design situation. However, they often prove inadequate at handling design problems where the parts interact in complex, non-linear ways. The definition of Rittel and Webber regarding *wicked* problems encapsulates this, highlighting the impossibility of finding an optimal solution.

4 A METHODOLOGY TO HANDLE COMPLEXITY

Chapter One and Two, suggested the existence of a *biotechnical imagination* at work in architecture and design, as well as within biotechnologies. The term *imagination* highlights a disconnect between prevailing discourses, and the realities of day-to-day practices and material production. The *biotechnical imaginations* are, however, contrasting. While the *imagination* prevalent in architecture and design has revolved around a lack of control and an appeal for complexity, in biotechnologies it has been characterised by a mechanistic approach based on ideals of abstraction, standardisation and modularity. It is important, however, to highlight how both operate as methods to handle complexity. The *imagination* in design and architecture operates through two distinct approaches. The *speculative biotechnical* approach uses speculation to bypass the technical complexity of manipulating biological systems, and instead focuses on thinking through the possibilities and societal consequences of deploying a fundamentally new type of technology. The *literal biotechnical* approach, instead, focuses on the possibilities available in existing techniques and instruments. Both approaches, however, produce a wide array of creative exploration and application domains, expanding the horizons of the ways in which biology can be manipulated. By contrast, the *imagination* in biotechnologies handles complexity by reducing biological systems to parts, which can be characterised individually, designed and then assembled to produce more sophisticated systems.

Moreover, both forms of *imagination* have not been entirely successful at managing complexity, and the results have been modest. Jay Keasling has led a team at the University of California, Berkeley, which has been successful in producing the antimalarial drug *artemisinin* using engineering yeast. Although the project has often been used to promote the broader application of the engineering design principles in biotechnologies (Ro et al. 2006; Khalil & Collins 2010; Editor 2014), Bensaude Vincent argues that the success has been more the result of pragmatic engineering practices such as kludging and tinkering:

> Actually the rare successes of synthetic biology such as the biosynthesis of artemisinin – an anti-malaria drug – were not the result of rational design. In reality they were achieved through more messy and painstaking practices with trials-and-errors and workarounds (Bensaude Vincent 2013, p. 27).

Agapakis also cautions about the limitations of a mechanistic approach to biotechnologies, especially in the way they constrain the understanding of the wider context in which technologies operate. She builds her argument around the arsenic biodetector, developed initially by the 2006 University of Edinburgh iGEM team, and which has attracted funding for further development and deployment. The project aims to produce a low-cost, easy-to-use detector for areas known to be prone to groundwater well pollution in Bangladesh. It involves an arsenate-responsive promoter, which, when inserted in bacteria, enables the expression of genes that change the pH of growth media, providing a colour-coded signalling of arsenic presence. Although the project is a good example of the use of mechanistic approaches to provide elegant solutions to complex, real-world problems, Agapakis reflects:

> The history of arsenic contaminated drinking water in Bangladesh, however, provides an important warning for would-be problem solvers? The shallow, arsenic contaminated tube-wells that provide water for much of the country's inhabitants were dug as part of a humanitarian response to waterborne diseases starting in the 1970s. What was intended as a solution to one problem ended up causing a second public health

> catastrophe. This suggests first of all that inexpensive diagnosis of arsenic contamination will not be able to address the underlying problems of water infrastructure and management in Bangladesh. Second, this history demonstrates that looking at complex problems through a narrow, reductionist lens can lead to harmful designs with dangerous consequences (Agapakis 2014, p. 125).

A good way of describing the limitations in both forms of *imagination* is to say that biotechnologies are short-sighted, in the sense that they tend to concentrate on the immediate complexity of biological work. This methodology has been productive, resulting in demonstrable applications, focus of activity and funding. There are, nonetheless, several limitations, as I have highlighted in this chapter. As analysed by Calvert (2013), the *imagination* in contemporary biotechnologies often overlooks the societal consequences and contexts in which biotechnologies are set to operate. Considered as a design practice, the mechanistic approach of contemporary biotechnologies often results in a limited capacity for innovation or creative exploration. Following the analogy, it could be said that the *biotechnical imagination* in design and architecture is long-sighted. Textual accounts of both speculative and literal biotechnical projects point to an altered view of design, governed by principles of ecologies, complexities and emergence. The material results, nonetheless, are limited as a result of their disconnect from actual biological systems, or their reliance on techniques and instruments developed in other disciplines.

The tension between both types of *imagination* raises the following research question: *Are there any alternative ways and contexts for working with living systems that take elements from both discourses?* As discussed above, both types of *imagination* are useful to different sets of objectives. While one is productive in generating clear application domains, and in leading quickly to tangible outcomes, the other expands the potential design domains, and enables engagement with other aspects beyond the immediacy of organisms and the methods used to modify them. Both, however, often bypass a more fundamental question of what specific design possibilities are open when considering biotechnologies, which are unprecedented when compared to existing forms of technology. These approaches can be described

as the *horseless carriage* stage of biotechnologies.

The phrase 'Horseless carriage' is used to describe a paradigm characterised by the '*shifting perception of a practice as it transforms in relationship to a new technology'* (Chastain et al. 2002, p. 239). It draws a parallel with the early adoption of cars, and is a useful way of describing how new technologies are initially approached using concepts and techniques from their precedents, often resulting in a poor understanding of their true potential. It has been used, for instance, by Chastain, Kalay and Peri (2002) in characterising the early adoption of computers in architectural design. The authors argue that early uses of computers as drafting tools reflected their mapping to existing design practices facilitated by drawing: creating scale representations that prescribed the design intent. This, however, obscured how the *affordances* of the new technology had the potential to transform the discipline of design. The term references the theory of James Gibson to describe the potential of action that is embedded in objects and tools. Computers offer affordances that are fundamentally different to drawing. Digital representation affords, for instance, the codification of a variety of data sets, which would traditionally be distributed in different sources and throughout practice (Chastain et al. 2002). Moreover, digital technologies have an even more profound effect, as they bridge the gap between design and fabrication, a divide established with the introduction of drawing as a technology of representation in the Renaissance (Oxman 2010).

A similar argument can be constructed around biotechnologies. Approaches in both, *biotechnical imagination* in architecture and biotechnologies, often follow a framework of the horseless carriage: they tend to use biological systems as a substitute for existing technologies, or try to fit them into practices developed in response to older technologies. Armstrong (2015) has argued how a contemporary understanding of matter is inadequate to deal with living systems in design contexts and, instead, she proposes approaching living matter as *vibrant*. The concept makes reference to the philosophical project of *Vibrant Matter*, where Jane Bennett (2009) advances the possibility of thinking of matter not as something either living or non-living, but as registers within a gradient of lively intensities: as possessing a range of possibilities to act on one another and to influence humans. The notion

of vibrant matter is built on that of *non-human agency*, which considers the possibility of assigning a potential for action to things that are generally considered non-sentient (Sayes 2013; Johnson 1988). Bennett, in particular, is interested in the political project that results from this understanding of matter. How, for instance, contemporary materialistic culture based on quick cycles of consumerism and waste can be transformed by a new sense of care for matter, forming bonds between human and matter that are more difficult to sever. Armstrong takes up the concept to redraw concepts of matter in design: '*By reframing our expectations of matter, it may be possible to establish principles for an architectural design practice that is not simply environmentally benign, but active, participatory and subversive*' (Armstrong 2015, p. 6).

Another way of explaining how *biotechnical imaginations* often bypass a fundamental exploration of the distinct nature of biological systems as technology is to frame the process in terms of dimensionality. At the outset, the notion of *organism* as *technology* involves a multitude of dimensions: we can think of the organism as an infinite number of possible technologies. However, when we impose a specific context of operation, we collapse the multidimensionality, as the organism can be only one thing. In this thesis, I propose a different approach to biotechnologies that takes inspiration from both sets of *biotechnical imagination*. This avoids starting with a specific form of technology in mind, and instead allows me to interrogate how biological systems constitute a distinct technology, and to suggest a different form of design. In the following chapter, I introduce the notion of the *bio-material probe*, a methodology that aspires to provide a means to explore the design possibilities of biological systems. It draws on elements from the *biotechnical imaginations* that I have analysed in these initial two chapters to handle the complexity involved in direct engagement with living systems. Moreover, it develops non-deterministic and open-ended outcomes that enable exploring the potential multidimensionality of biological systems.

3

BIO-MATERIAL PROBE

CHAPTER 3

BIO-MATERIAL PROBE

1 INTRODUCTION

This chapter discusses the *bio-material probe* as a creative practice methodology, which attempts to answer the research questions that emerged from the tension between *biotechnical imaginations*. In Chapter One, I discussed how biotechnical architecture poses the challenge of exploring the design potential of biological systems without falling back on our preconceptions, and of the possibility of designing completely from the bottom up. In Chapter Two, I discussed notions of control and systematisation present in biotechnologies, and contrasted them with the discourse in architecture and design. The contrast between both suggests a further research question of whether there are alternative ways and contexts that take elements from both discourses.

Bio-material probes, are defined as enablers that provide direct engagement with biological systems, and intended to create situations and contexts that generate new ideas and questions around the possibility of designing with biological systems. The term takes inspiration from the notion of *cultural probes* advanced by Gaver and others (1999), and from *dérives* used by the *Situationist International* movement. I propose four defining characteristics of *bio-material probes*: they generate non-deterministic and open-ended design outcomes, constitute a strategy for direct engagement; use restricted domains and objectives; and operate as material thoughts. *Bio-material probes* draw elements from the two *biotechnical imaginations,* and constitute a departure from prevalent techniques in research through design. Research

through design often uses artefacts as a form or validation of data obtained through scientific methodologies. Instead, the *bio-material probe* uses the situation of design itself as its main mode of enquiry, which positions it closer to a form of hermeneutics, drawing from the work of Snodgrass and Coyne (2013). In this thesis, *bio-material probes* are used to explore the argument developed by Armstrong (2015) regarding how design is transformed and redefined by the use of living systems.

2 BIO-MATERIAL PROBES: DESCRIPTION AND DESIGN

Bio-material probes are intended to provide the setting in which it is possible to engage with biological systems from a design perspective. In this sense, it is a strategy of governing and giving purpose to an activity. The term is inspired by the design-led studies of Gaver, Dunne and Pacenti (1999), who use *cultural probes* in the context of interaction design to provoke responses and engagement in a target audience. The strategy was first deployed in the *Presence* project, which involved working with a number of elderly people from three different countries, consulting them about strategies to improve their relationship with their local communities. Cultural probes consisted of postcards, maps, photo albums and disposable cameras, which were handed to participants to take home and record their thoughts. The authors describe how the probes responded to a design approach to gauge audience perception, and that operates as an alternative to more common methods such as ethnographic studies, interviews or questionnaires. The term points to medical and astronomical probes, which are embedded in phenomena to capture information.

There is a crucial difference between probes as methods in these precedents, and how I propose to use them in this thesis. In the work of Gaver and Dunne, probes are objects designed to gather data about a specific design problem. *Bio-material probes*, in contrast, are situations and contexts that enable the designer to be immersed in a particular domain, and to gather a more nuanced understanding of its challenges and possibilities. The difference in approaches, however, coincides with the original inspiration of the

term. Cultural probes, Gaver and Dunne explain, are inspired by *dérives* in psychogeography, an approach to geography promoted by the Situationist International movement to highlight the influence of the geographical environment, especially urban settings, on the feelings and behaviour of people (Ford 2005; Debord and Knabb 2014). *Dérive*, translated literally as drifting, consists of suspending normal motivations to movement in cities and, instead, allowing themselves to be *attracted* by the terrain, operating as a sort of probe that is influenced by the forces at play in urban environments. In the context of the Situationist movement, *dérive* emerges as a reaction against the average experience of cities, which they perceived as limited. The *dérive* is intended to *throw* people into cities, allowing change to force them into situations they would otherwise rarely encounter (Debord 2006).

Likewise, *bio-material probes* are intended to *throw* designers into the context of biological work. As an active element, they give designers a reason to explore biological systems. They are not oriented to practical applications, but rather to exploring the context, activities and economies involved in the work with biological systems. A good analogy to describe the *bio-material probe* is to characterise it as a recipe for how cakes are made. It facilitates an understanding of the context, materials, technology and other assemblages, which enable the cake to be made. It doesn't, however, provide a prescriptive recipe for doing a specific cake. It enables practitioners to locate themselves within the context of biological work and, as a methodology, provides purposefulness without being tied to a specific design outcome.

Bio-material probes gather inspiration from both sets of *biotechnical imagination* analysed in the previous chapters. More specifically, it appropriates the reductionist approach used in sciences to constrain the domain of design exploration. At the same time, it draws methods and practices from the *biotechnical imagination* in architecture and design, stressing the importance of active engagement with the material. In addition to elements drawn from both *imaginations*, the *bio-material probe* is also inspired by the approach of art practices, and more specifically by my participation in the *Making Life* project. There are four characteristics that define *bio-material probes*. One, they operate as material thoughts. Two, they are articulated by direct engagement with biological systems. Three, they operate on re-

stricted domains and objectives. And, four, they develop non-deterministic, open-ended design outcomes.

2.1
PROBES AS MATERIAL THOUGHTS

Bio-material probes as a research methodology can be described as analogous to thought experiments. They provide a context to think about the material possibilities of biological systems. They don't, however, result in specific applications or well-defined design strategies. Rather, they highlight themes and produce new questions that are relevant to the ways in which the use of biological systems as material transforms the discipline of design.

An important aspect of the *bio-material probe* is the way it uses engagement with matter as a strategy to develop and articulate an argument on the possibilities of design. The process shifts the traditional status of matter in thought, which is often seen as ancillary rather than a driver. A parallel with this occurs in design thinking, wherein matter is seen as the resource to materialise form. Katie Lloyd Thomas (2006) reflects on the way contemporary understandings of design are philosophically rooted in the notion of *hylomorphism*, a tradition initially developed in ancient Greece that privileges form over matter. Hylomorphism is evidenced in contemporary notions of architecture, for example, where matter is generally relegated to the margins of technical specifications. There is a primacy over formal concerns, which are considered to be the mental product of the designer and where material is interchangeable. However, Lloyd-Thomas argues, an increasingly complex relationship with matter has triggered a revaluation of the role of matter in design, in which it is not simply cast in roles that are secondary to matter.

Processes similar to hylomorphism are described by Barbara Bolt (2004, 2007), who analyses the way in which contemporary models of production in creative practices follow an instrumental relationship between practitioner and matter. Artists, for instance, imprint their name in consideration of their mastery over matter — the skilful use of tools allows them to bring about the work of art. Bolt argues for alternative frameworks to understand the relationship between practitioner and matter, pointing to the analysis

of tools in the work of Heidegger (Bolt 2011). In *The question concerning technology* (Heidegger, 1977), he analyses the roots of causality in Aristotle. He starts with a silver chalice as a guiding example to analyse the four types of cause. *Causa materialis*, in this case silver, the material from which the chalice is made; *causa formalis,* the actual geometry or shape the chalice takes; *causa finalis,* the objective for which the chalice is made; and *causa efficiens, 'which brings about the effect that is the finished, actual chalice, in this instance, the silversmith'* (Heidegger 1977, p. 314). The instrumental use of technology, Heidegger goes on to argue, is founded on contemporary thought regarding the *causa efficiens* above the other three types of cause. However, a consideration of all the causes in conjunction, Bolt proposes, provides the basis for a framework of material production that does not involve a relationship of mastery over tools and matter. Rather:

> In the place of an instrumentalist understanding of our tools and material, this mode of thinking suggests that in the artistic process, objects have agency and it is through the establishing conjunctions with other contributing elements in the art that humans are co-responsible for letting art emerge (Bolt 2007, p. 2).

Bolt argues that Heidegger's critique of technology opens the door to considering matter as an agent with a degree of independence from human action. This philosophical project, she reflects, is further developed by Actor Network Theory(ANT) (Latour, 2007), and the work of Donna Haraway (2004), which explores different ways of conceptualising materials and tools as agents in their own right. An example of this is the notion of *creative ensemble*, which involves an understanding of material production as the result of a grouping of agents that contribute in different capacities to the emergence of something new. A good example of ensemble is the *apparatus of literary production* (King, 1988) a postmodernist approach to literary analysis, which offsets the human author and analyses how the intersection of art, business and technology contributes to constructing meaning in literary texts. The *apparatus* allows one to highlight, for instance, the way that language *speaks* through the poem just as eloquently as the human writer does. However, it also allows an extension of the analysis to other *non-human* agents, which are seldom considered. For instance, the paper into which the text is recorded, the mechanical ways used to register it, the binding,

the pencil or typewriter used to inscribe the first drafts, or even the spaces, such as cafes and bars, where the text is written. All these agents, Haraway (2013) suggests, have an effect on the way the text is assigned meaning by a reader, and are often outside the control of the human author.

In this thesis, *bio-material probes* are described as material thought — a strategy that enables a dialogue with biological systems, establishing its material possibilities. It is not preceded by theoretical work, in the sense of illustrating an argument that is already developed. Instead, it operates on the assumption that there are aspects of the material that are only possible to know by engaging with the material itself. In this way, the methodology is intended to highlight important themes and questions that are relevant when working with biological systems as design resources. It operates by establishing a dialogue between designer and matter, placing the practitioner in direct contact with materials and tools. The strategy is expected to develop knowledge of which aspects of the materials are important, of which techniques can be used to engage with it, and to derive the design possibilities of the particular tendencies of each material. A useful parallel to describe this approach is to say it is similar to that of artisans, who work closely with materials in order to understand the specific ways in which they interact with other materials and tools, and how this yields material possibilities. A good description of the dialogue between material and artisan, and the way this operates as a form of thought, is provided by John Protevi:

> We must see that matter-movement carries singularities as 'implicit forms'; in our terms, 'implicit forms' are potentials for material self-ordering with which the artisan negotiates (...) the form must be seen as suggested by the matter rather than as the pure product of the mind of the architect. In other words, forms are not pure but already laden with 'variable intensive affects' and thus tied to 'material traits of expression', that is, actual properties linked with virtual potentials or singularities suggesting ways of working with and transforming the material (Protevi 2001, pp. 7–8).

In the passage, Protevi suggests that matter contains potentialities, what he calls *matter-movements* or *implicit forms*, which can be revealed, *negoti-*

ated, through engagement with matter itself, instead of imposing abstract thought onto them. Similarly, *bio-material probes* as a methodology are intended to provide the context in which these potentialities can be revealed, establishing a dialogue with biological systems to understand their *material traits of expression*.

2.2
DIRECT ENGAGEMENT WITH BIOLOGICAL SYSTEMS

The methodology of the *bio-material probe* also connects with notions of direct engagement, as developed in the *literal biotechnical* approach in architecture and design. In Chapter One, I described how the *literal biotechnical* approach is defined by its orientation to direct engagement with the biological system. Direct engagement is expected to provide the basis for methodologies that reflect the complexities of biological systems, rather than falling back on preconceptions. The *bio-material probe* shares this ethos, and is oriented to creating a design context that enables direct engagement with biological systems. To achieve this, the exploration combines forms of direct engagement used both in biotechnical architecture and within biotechnologies. The first *bio-material probe* draws its methods from biotechnical architecture, and uses computer simulation to explore form-finding processes governed by biological principles of growth and development. The second and third *bio-material probes*, however, use elements of direct engagement inspired by practices used in contemporary biotechnologies. They use biomineralisation and bacterial patterning as their design context, and develop a series of experiments that implement strategies of material manipulation.

The combination of different forms of direct engagement also operates as a strategy to handle complexity. Work with biological systems requires specialised knowledge that is not initially available to designers. In this context, using the computer simulation as the first *bio-material probe* is useful in the sense that it enables the derivation of general insights into the use of biological systems in a design context, but without the need to acquire knowledge of the tools and techniques necessary to materially manipulate organisms. The second *bio-material probe* introduces further aspects of complexity by

working with bacterial cells. Complexity, however, is handled by collaborating with a scientist partner, who implements experiments in the laboratory. The third *bio-material probe* enables the designer to be further immersed in the complexities of biological work. It uses the same design context as the second *bio-material probe*, but implements a strategy in which the designer implements the experiments directly in the laboratory.

It is also worth highlighting the constraints inherent in development of the exploration, and which define the organisms and processes chosen to enable direct engagement. As described in Chapter Two, *the biotechnical imagination* has been inspired by recent developments in biotechnology involving genetic modification. These techniques, however, require resources and specialised knowledge to which I had no access when I began the exploration. To counter these limitations, the exploration in this thesis focuses on modifying aspects *outside* the organism itself. This involves, for example, modifying nutrient concentration, surface hardness or incubation temperature. Modifying their environment is expected to express different traits in their performance. This approach provided a way to engage with the complexities of biological systems, relevant to the *biotechnical imagination*, without access to its direct manipulation.

2.3
RESTRICTED DOMAIN AND OBJECTIVES

The methodology takes inspiration from the *imagination* in biotechnologies in key aspects of their reductionist approach. In Chapter Two, I reviewed how the *biotechnical imagination* in synthetic biology is articulated by notions of abstraction, standardisation of design components, and modularity. I also discussed how these principles converge in a philosophical framework of mechanism, which operates by drawing parallels between the operation of machines and biological systems, and which is often connected to reductionist epistemologies. While I discussed the drawbacks of a mechanistic understanding of biological systems, I also proposed that it is helpful in managing complexity and orienting efforts towards outcomes.

The *bio-material probe* draws from the reductionist epistemology of biotechnologies by restricting the design domain of each exploration, and ori-

enting them to overall objectives. Each *bio-material probe* is described with an initial set of objectives and aims, which respond to questions and aspects that will be explored. This is followed by a definition of a design context, which corresponds to an organism and behaviour used as the design domain.

These reductionist aspects, however, are combined with a design approach to experimentation that involves non-linear, unstructured engagements with the material. Gingsberg (2014), for example, reflected on the differences in the concept of experiment across disciplines. In design, the term is used to refer to open-ended processes that reveal new material possibilities or that highlight important aspects in a design problem. This connects to the description of material thought above, in which unstructured explorations are used to understand the particularities of materials under a range of circumstances. By contrast, scientific experiments, Gingsberg argues, are tools to generate data that validates a hypothesis. This requires a systematic approach, in which repetition provides the context to establish causal links: how one variable is connected to the occurrence of another – '*repeating an experiment and achieving the same results is key to the scientific method'* (idem, 40). *Bio-material probes* attempt to leverage the differences of the experimental approach. They take inspiration from scientific knowledge, especially in establishing its range of action. In addition, they adapt some of the rigour of systematic scientific experimentation, but orient its efforts to understand the consequences of biological systems in design.

2.4
NON-DETERMINISTIC DESIGN OUTCOMES

In discussing the *literal biotechnical* approach, I suggested that a downside to its orientation towards direct engagement is a connection to pragmatic design solutions, which often involve inscribing biological systems in existing design technologies and applications. The *bio-material probe* attempts to bypass this limitation by taking inspiration from artistic practices, thereby enabling an open-ended design process that leads to non-deterministic outcomes.

In Chapter Two, I discussed how the prospect of understanding organisms

as a technology for design is often constrained by the tools and methods already available to us. As a result, design explorations often use biological systems as a substitute to existing technologies, forcing them to operate within familiar boundaries and using existing practices. I used as an example the project of bacterial hygromorphs, in which spores are used as a low-energy, programmable alternative to well-known hygromorphic materials such as wood laminates. The advantage of this approach is that it makes it easier for the architectural community to engage with the project, intuitively grasping some of the potential of a new technology by referring to familiar applications. I discussed that, at the same time, the approach has the disadvantage of constraining the potential of biological systems, as it understands it in terms of a fundamentally different technology. I described the approach as a strategy of a *horseless carriage*, making reference to the way in which new technologies are initially approaches using preceding models. Our imagination of the new is thwarted by our understanding of the existing.

Art practices, however, offer an alternative approach. In the introduction to the thesis I referred to *Making Life*, a series of workshops organised by the BioArt Society and funded by the seventh framework programme of the European Union. The events brought together creative practitioners from different disciplines and backgrounds to '*engage with the socio-cultural, political and ethical complexities of synthetic biology'.* Participating in the workshop proved pivotal, as it immersed me in an alternative approach to understanding biotechnologies, which provided a methodological bridge between the approaches in biotechnologies and design.

I described the role of *Making Life* in shaping this thesis in the introduction. One aspect worth describing here is how the structure of the event inspired the *bio-material probe* as a methodology. *Making Life* was articulated by three work periods, which involved one week-long work session hosted by *Biofilia, Base for Biological Art*s, at Aalto University in Helsinki. Each session combined theoretical and hands-on approaches, including '*workshops, laboratory sessions and field trips, to forums, seminars and lectures*' (Anon 2014, para. 3). The work periods were designed to prepare participants for a final exhibition, which would constitute the group's response to the current state

of synthetic biology. The sequence of events was structured as a gradual immersion in the area. A way of describing them is to say that they started with a phase aimed at direct engagement: gaining basic knowledge about the topic and area, combining theoretical approaches and critical frameworks, as well as laboratory techniques. This phase developed roughly during the first and second sessions. A second phase involved engaging actively in a critical stance towards synthetic biology, declaring areas of interest and finding potential partners to work as a group towards the final exhibition. The second phase occurred at the end of the second session, lasting throughout the interim and up to the beginning of the third. Finally, the third week was used for groups to come together and work on their final pieces, which were exhibited collectively at the *Lasipalatsi Nayttely* gallery in Helsinki.

The work methodology of *Making Life* presented me with an alternative to the practices and cultures I had encountered within biotechnical architecture. It meant engaging directly with the complexities of working with biological systems. By contrast, approaches in architecture often involved collaborating with a scientific partner who would generally be tasked with handling the complexity of biological work. Another important aspect is the way in which the work phases operated, first by providing a context and space for exploration of the milieu, then gearing up gradually to a creative outcome. The approach was in stark contrast to the design projects that I was familiar with, which were often oriented towards a practical outcome from the outset. The approach in *Making Life* represented a way of working without preconceived notions. Being liberated from the task of interpreting a technique or an organism as a specific technology from the outset enabled the exploration of a wider range of possibilities and the acquisition of a more diverse set of possible interpretations and creative responses.

3 BIO-MATERIAL PROBE AS RESEARCH THROUGH DESIGN APPROACH

Non deterministic design outcomes, however, depart from existing research through design methodologies, in which artefacts are often central to the enquiry. The notion of design research stems from efforts, starting in the 1980s, to position design as a third *way of knowing*: a framework to interpret and conceptualise the world, distinct from the more established approaches of science and the humanities (Archer, 1979; Cross, 1982). The argument, initially developed in the context of secondary education, and later extended to research, argues that design provides cognitive styles and tools that are different to those used in natural and social sciences. Cross (2007) proposed the existence of *designerly ways of knowing*, which he defines, using the words of Donal Schön, as '*an epistemology of practice implicit in the artistic, intuitive processes which some practitioners do bring to situations of uncertainty, instability, uniqueness, and value conflict*' (Cross 2001, p. 52)

Design as a distinctive form of enquiry, however, has often been oriented to, or driven by, the production of artefacts. Christopher Frayling, for instance, proposes three modalities of research through design. First, *materials research* refers to explorations of material techniques and methods, which might include '*titanium sputtering or colorization of metal projects*' (Frayling 1994, p. 5). Second, there is *development work*, in which a technology is customised and used in a way that has not been thought of previously. Third, *action research* involves the production of research diaries that inform practical experiments in the studio, alongside their contextualisation in a wider body of work. These modalities coincide in their orientation to produce documentation that contributes to knowledge on material production.

Richard Coyne, in contrast, proposes that the value of design-led research is in providing social sciences with a method of *triangulation*: a way of corroborating data gathered by qualitative and quantitative methods. Coyne proposes three ways in which triangulation is afforded by design. The first is a way in which design is used to produce an artefact that enables the probing of data. In this context, participants are subjected to scenarios outside their immediate experience, embedding a designed object that enables probing

for new data: '*The design approach would be tantamount to the deliberate introduction by an anthropologist of a refrigerator, a mobile phone or a video camera into a community that had never before seen such [a] device, in order to elicit responses, reflections or evidence*' (Coyne 2006, p. 1). In the second strategy, participants are asked to engage in the design itself, which provides a context for them to articulate their thoughts around the subject under study. This might involve, for instance, the organisation of events in which non-designers are invited to engage in design activities related to the subject under study. The activity is proposed to put participants in a privileged, unprecedented position to analyse a familiar situation and articulate their opinions on it. The third strategy involves researchers engaging directly in the process of design, meticulously documenting the process, which is later subjected to critique, and which is often connected to material innovation or production techniques. With the exception of the second strategy, triangulation is predominantly oriented to, or assisted by, a designed artefact.

The *bio-material probe* constitutes an alternative approach, which disassociates research from creative output, instead shifting attention to the creative process itself. The approach has methodological implications, in the sense that the research enquiry is structured around the design process itself, and requires careful reflections on the conditions encountered by the designer as it engages with different materials and situations.

3.1
BIO-MATERIAL PROBE AND INTERPRETATION

The use of *bio-material probes* also has implications for the way in which design thinking is integrated into research. In the previous chapter, I suggested that the approach in biotechnologies was parallel to post-war design movements that aspired to *scientis*ing the discipline. Efforts included the work of Christopher Alexander (1964), who in *Notes on the Synthesis of Form* proposed that any design problem could be broken down into a series of clearly defined, functional requirements. Design involves, he proposes, drawing a set of connections and constraints that determine how these requirements relate to one another, and which in turn define the optimal form of the design.

Snodgrass and Coyne (2013) argue that the approach of Alexander and others can be defined by their scientific discourse, influenced by the positivist tradition developed during the nineteenth and twentieth centuries. The authors argue, however, that these rationalistic models fail to characterise the process of design. Instead, they propose that designing is a *hermeneutical* process, referring to the philosophical notion of interpretation. For Snodgrass and Coyne, design is a continuous process of interpretation, geared towards changing the designer's environment. More importantly, it involves a complex network, in which the designer is also transformed by the material inasmuch as the designer informs the material. The description of the authors of design as a continuous exchange between material and designer is worth quoting:

> Design is interpretative, not least in the play of making. The traditional potter allows the pot to disclose itself in its creation. The pot is not prethought and then made, but made in the making. The potter does not manipulate an object, but becomes one with the materials and the movements involved in its making, and the making continues even after it has left the hands of the potter, and the characteristics of the materials further reveal themselves.
>
> Design can be similarly thought of as a disclosing of the artefact that is being designed. From the insight of hermeneutics design is also an unfolding of self-understanding, since it reveals one's pre-understandings. It uncovers the preconceptions that are constitutive of the design outcome, and at the same time brings to light the prejudices that make up what we are. The design process is thus edification. It builds up the artefact and edifies the designer. To encounter something other or unexpected, we are reminded of what we were anticipating. Next time we might expect something different, or adapt the circumstances to accommodate revised expectations. Our relationships with the world are revised (Snodgrass & Coyne 2013, p. 257).

Similarly, the *bio-material probe* can be described as a methodology that enables the interpretation of how biological systems transform the nature of design. As analysed in the first chapter, the *biotechnical imagination* in architecture is articulated by principles of ecologies, emergence and com-

plexity, which suggest a transformation in the processes of design, in the sense that prescriptive control on outcomes is taken away from the designer. The process, it can be argued, is not a fundamental transformation of design, in the sense that control is still retained by the designer, as principles of emergence and complexity are often indexed to the possibility of programming the behaviour of biological systems to follow specific rules defined by the designer.

However, it has been argued that designing with biological systems has profound consequences, potentially transforming the discipline. I have referenced Rachel Armstrong, who suggests contemporary understandings of matter are inadequate to deal with living systems. She reflects on how architecture traditionally centres around top-down models, wherein design intent is a cognitive outcome of a human designer, who codifies it and imposes it onto matter through mechanisms of practice and technology. Central to this is an understanding of matter as inert: as something that can be shaped at will. Living matter, by contrast, has its own tendencies, which are often independent or contradictory to human intent. As a consequence, Armstrong suggests a shift in architecture's understanding of matter, from raw resource to active co-designer: '*An approach to architectural design that treats matter as possessing technological potential, so that it is no longer a passive subject of design intervention, but becomes an active codesigner of spatial systems*' (Armstrong, 2015). She goes on to propose design as an assemblage of agents, with varying degrees of vibrancy which come together to produce something new. In this context, the designer becomes an actor, charged with orchestrating the ways different elements contribute to an outcome.

The *bio-material probe* is proposed here as a methodology that enables following through the consequences of the argument that biological systems transform the process of designing.

4 OUTLINE OF THE CREATIVE EXPLORATION

In the context of this thesis, *bio-material probes* are used to engage in a creative exploration that looks at how the use of biological systems transforms processes of form-finding and generation in architecture. As suggested in the previous chapters, the exploration is developed in the context of the *biotechnical imagination*: an altered view of design inspired by recent developments in biotechnologies. A crucial aspect of these developments is the discourse generated by synthetic biology, which proposes a number of techniques and practices that streamline genetic manipulation and design.

As described previously, a number of constraints and resource limitations prevented this creative exploration from engaging directly with modifying organisms genetically. Instead, the exploration will shift its focus from designing the genetic make-up of the organism, to influencing the organism by controlling the conditions in its environment. The approach is implemented using the design strategy of parametrics, which has a long tradition in architecture as a method to handle complexity and, as analysed in the previous chapter, parallels contemporary approaches in biotechnologies.
The explorations are documented as a series of exercises, which increase in complexity and escalate the notion of parameter. In the first exploration, parameters are implemented as numerical values that the designer can manipulate, control and dictate to influence the development of spatial patterns. The first probe, *SynthMorph*, is developed as a computer simulation that implements modular behaviours found in mammalian cells and uses them to provide insights into the consequences of integrating principles of biological growth and development in a form-finding exercise. The second and third probes, are intended to escalate the notion of parameter to a physical equivalent. *Bacterial Crystals*, uses the context of biomineralisation, the process through which living organisms produce minerals, and *Bacterial Morphologies* uses the context of branching, spatial patterns developed by bacterial cells in response to changing conditions in their environment. Both explorations involve collaboration with a scientist, who implements the design system in an actual biological context. In the final probe, *Bacterial Assemblages*, the format of the exploration is transformed and, in-

stead of collaborating with a scientist partner, the designer engages directly in the biological work. The experience enables reconceptualisation of the parameters as agents, recognising the limitations inherent in the notion of parameter; and reveals an array of agents, which expands the original categories of parameter and which have variegated degrees of agency over the resulting morphologies.

II

4

DIGITAL PARAMETRICS

CHAPTER 4

DIGITAL PARAMETRICS

1 INTRODUCTION

This chapter discusses the design exploration developed around *SynthMorph*, a *bio-material probe* developed as a computer simulation that draws on notions of morphogenetic effectors, and implements them using a parametric approach. The software is designed as a reflection of the different ways of conceptualising form-generation in design and biology, and the corresponding languages and processes that are used to formalise it. *Morphogenetic effectors* are used by Jamie Davies as the basis for synthetic morphology and refer to the basic behaviours all cells assume in producing complex shapes in tissues and structures. Despite the intricacies involved in the set of behaviours, morphogenetic effectors provide a geometric language to describe form, which can be adapted to design-oriented approaches such as parametrics. There is, however, a philosophical tension by the parametric approach, and the use of morphogenetic effectors. The former corresponds to a rational design approach that follows a similar logic to contemporary biotechnologies. The latter is taken from developmental biology, which is often considered to be the last bastion of *organicism*, a philosophical tradition that argues that biological systems exhibit behaviours that have no direct equivalent in machines, thus invalidating the mechanistic approach that is prevalent in most biological disciplines. Despite this tension, morphogenetic effectors are useful in bridging elements of both sets of *biotechnical imagination*: it combines a reductionist approach that defines a set of basic behaviours through which form can be described; and provides a framework in which form is partly emergent, in the sense that it cannot be entirely reduced to

basic behaviours but results from their interactions.

I propose that *SynthMorph* operates as a bio-material probe in two contexts. First, its design and development involves a number of decisions and strategies, which reveal themes of how biological systems are understood and mapped to design situations. For example, it requires the modification of traditional parametric strategies to include recursion, tightly linking the process to time and iterations. Second, *SynthMorph* operates as a bio-material probe by facilitating a design exploration which highlights a number of themes: it reveals a tension between design intent and the liveness of the system; it produces non-linear, emergent patterns that produce similar but not identical forms; and it constitutes a *mediating artefact*, a tool to document and represent form through a precise permutation of behaviours.

2 OBJECTIVES AND AIMS

In the context of this thesis, *SynthMorph* operates as a bio-material probe by providing a warm-up exercise, which enables an understanding of the general implications of working with biological systems in a design context. It facilitates an understanding of notions of emergence, control and authorship. At the same time, it provides the context, while managing the complexity, of working directly with biological systems, which requires specialised knowledge, tools, techniques and spaces that are challenging to acquire.

Specifically, SynthMorph as a *bio-material probe* enables testing of how the notion of parameter can be applied to the design of biological systems, and interrogating how constraining they are as a design strategy.

2.1 BIOLOGICAL AND DESIGN NOTIONS OF FORM

On a more fundamental level, SynthMorph constitutes an exploration of how form is understood in design and biology. It proceeds from an understanding that there is a fundamental difference in the way form is designed and fabricated in design, and how it is understood and studied in biolo-

gy. In design, form is generally described through geometric abstractions and manipulations, and requires the use of prescriptive mediating artefacts that describe their final state. By contrast, form is understood in biology as the result of a process, which involves a series of chemical interactions. Although a form of 'instructions' are encoded in the genetic material, these instructions are highly dependent on their context, and can produce a wide range of similar but not identical forms.

In his book *Life Unfolding*, Jamie Davies (2014) describes biological morphogenesis by comparing it to human fabrication technologies. He argues that the construction of most human technologies shares common features. Design disciplines, for example, often depend on the use of prescriptive mediating artefacts: instruments that are used to represent and communicate form, which range from '*words, to many kinds of inscriptions and drawings, to full-scale mock-ups*' (Perez-Gómez & Pelletier 2000, p.7). Mediating artefacts are inscribed in a top-down hierarchy that allows communication of the design intent downwards to fabrication. The process relies on a hierarchical structure, which facilitates the convergence of information and energy to make form possible. Materials, for example, do not assemble themselves, and require the energy of an artisan who manipulates them into shape. Moreover, the set of mediating representations seldom include specific instructions on, for example, welding, bolting or bricklaying techniques, which are instead contributed by the artisan.

Davies compares these features to their corresponding biological processes. Biological construction, he explains, does not depend on a mediating artefact holding a description of the final form. Instead, it is based on permutations of events that enact a series of chemical interactions, which allow an organism to be built. These are *inscribed* in a genetic code, in the sense that a sequence of genes conditions the sequence of events. The relationship between *code* and *form*, however, is indirect and complex:

> Unlike engineering projects, biological construction does not involve a blueprint-like representation of the final structure. There is certainly information in a fertilized egg (in genes, in molecular structures, and in spatial variations in the concentrations of particular chemicals), but this

> has no simple relation with how the final built body will look. We know that the information has the effect of controlling the sequence of events that will follow (Davies 2014, p.6).

There are, Davies observes, human technologies that similarly relay design by providing rules and instructions instead of detailed representations. Textile manufacturing, for example, operates by providing knit and purl patterns notated in text, or in punch cards used in Jacquard looms. Food is similarly put together by following recipes, and music is performed by following a notation that instructs the player on the sequence of notes and their duration. There are, however, crucial differences between these and biological systems. In human fabrication, instructions are interpreted by an external intelligent agent; '*The information in an embryo, on the other hand, has to be read and acted upon by that embryo, with no handy external workmen to do the heavy lifting of the heavy thinking'* (idem, p. 7). Moreover, in human engineered systems instructions remain external once fabrication has been completed. In biological systems, by contrast, instructions are part of the system itself.

As the opening *bio-material prob*e in this exploration, *SynthMorph* was designed to reflect on the different conceptualisations of form in design and biology. As suggested by Davies, biological form-generation can be described as a fundamentally different '*technology*' to human design and fabrication. If we follow the argument to its logical conclusion, the main challenge in the *biotechnical imagination* in architecture would be the extent to which contemporary notions of design can accommodate the processes involved in biological form-generation. In this context, SynthMorph provides some initial insights by combining biological models of form-generation with design approaches used in the *biotechnical imagination* in architecture.

3 DESIGN STRATEGY

SynthMorph is a *bio-material probe* in the form of a computer-aided design system, which follows a parametric approach to designing with biological systems. It is important to highlight how the use of computer simulation is consistent with the development of bio-technical architecture. In Chapter One I described how, in engaging with biological systems, the *biotechnical imagination* in architecture has often made use of computational tools and language to describe their design possibilities, and went on to suggest that it can be thought of as an extension of the digital paradigm in architecture. I further discussed that the use of computers constitutes a practical shortcut that is often used to bypass the complexity involved in biological work, providing a platform to speculate on the transformative nature of biological systems in design. The downside of this strategy, I argued, is that it operates on a set of preconceptions, which limit the understanding of actual biological behaviour.

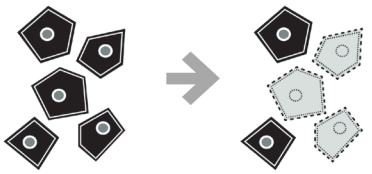
The limitations brought about by computational language, however, are somewhat offset by the use of a biological model that translates morphogenetic processes into a geometrical language. In *SynthMorph*, parameters are defined in terms of *morphogenetic effectors*, a term used in the context of synthetic morphology to describe cell behaviours that are relevant to the generation of biological shape. Synthetic morphology refers to a new discipline proposed by Davies (2008; 2005) that aims to apply the principles and techniques of synthetic and developmental biology to programme '*cells to organize themselves into specific, novel arrangements, structures and tissues*' (Davies 2008, 707).

Davies draws upon the design principles of cybernetics in advancing the notion of morphogenetic effectors. In cybernetics (Wiener 1948), components are divided into three classes: sensory modules, information-processing and effectors. Sensory modules gather information from their context; the processing module uses this information and transforms it into specific actions; and effectors enact these changes. Similarly, morphogenetic effectors are intended to control shape change by regulating cell motility, interaction and replication. Although often critical of how limiting engineering

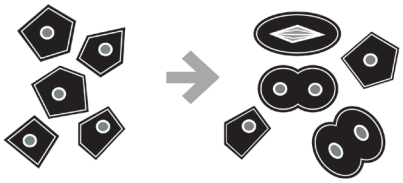
metaphors are in the context of biotechnologies, Davies uses the analogy to cybernetics as a starting point to discuss potential design strategies for biological systems: '*It is intended to provoke discussion about how we might progress to the first, crude, proof-in-principle demonstrations of synthetic morphological systems*' (Davies 2008, 708).

Davies goes on to propose that morphogenetic effectors should mirror naturally occurring morphogenetic behaviours. Reviewing the existing literature in animal development, Davies defines ten basic morphogenetic mechanisms: apoptosis, proliferation, cell fusion, locomotion, chemotaxis/haptotaxis, adhesion, sorting, epithelial-to-mesendnymal transition, folding and MET (Davies 2008). To explain these behaviours briefly, apoptosis refers to cell death that is programmed and regulated for specific morphogenetic purposes. It is used, for instance, to produce the separation of fingers and toes in human embryos. Proliferation is a term used to describe the processes by which the number of cells increases, including cell division, cell loss and cell differentiation. Cell fusion refers to the process in which cells combine to form a single multinuclear cell. Locomotion refers to the capacity of a cell to traverse its medium by various mechanical and chemical devices, which vary according to cell type. Similarly, chemotaxis refers to the movement of cells, which follow the gradient concentration of a chemical substance. Cell adhesion corresponds to processes that enable cells to attach to different surfaces or substrates and is enabled by the interaction of molecules in their surface. Sorting generally refers to a number of processes that enable groups of cells to spatially organise according to intracellular and extracellular properties. Epithelial-to-mesendnymal transition is a process specific to epithelial cells, referring to those constitutive of tissue, and involves the loss of cell adhesion, which facilitates the transition of the cell into mesenchymal stem cells, defined as connective tissue that can differentiate into different types. Mesenchymal-epithelial transition is the reverse process, involving the transition from a mesenchymal stem cell into epithelial cells, which arrange to form tissues (Crosby 2007).

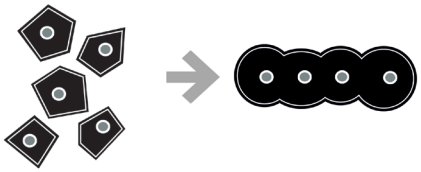
01 *Diagram describing the ten morphogenetic mechanisms used by Davies as a model for his morphogenetic effectors. Redrawn based on Davies' original diagrams, included in Davies (2008: 2005).*



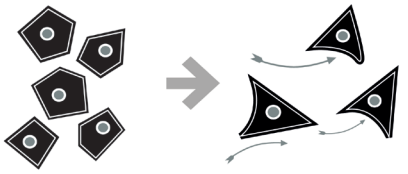
1 *Apoptosis cell*



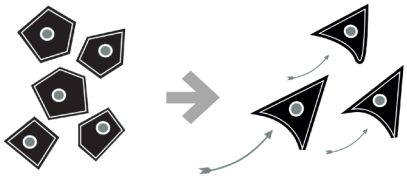
2 *Proliferation*



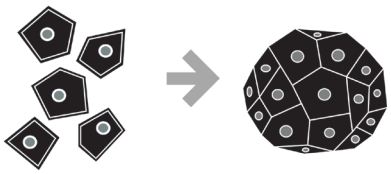
3 *Cell Fusion*



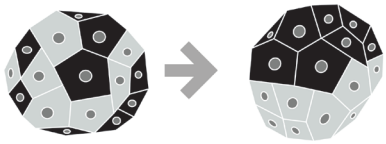
4 *Locomotion*



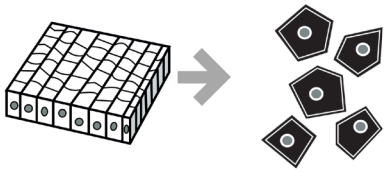
5 *Chemotaxis / Haptotaxis*



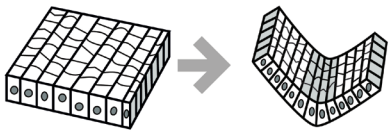
6 *Adhesion / Condensation*



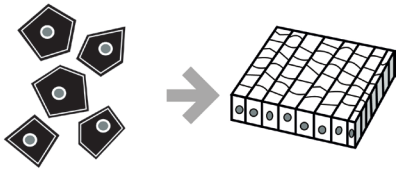
7 *Sorting*



8 *EMT*



9 *Folding*



10 *MET*

Davies argues that all biological structures, ranging from bones to tissues to branching conduits in kidneys, can be described though a sequence of morphogenetic behaviours. For example, renal nephrons, the basic functional units of kidneys, are produced by cells following a sequence of proliferation, condensation, MET, apoptosis, proliferation and folding (Davies & Bard 1998). Although the mechanisms themselves, and their combinations, involve a series of highly specialised processes in cell chemistry, morphogenetic effectors constitute a distinctively geometric language. The diagram in Figure 1 shows a graphic explanation of the ten morphogenetic behaviours described above; it is adapted from the original illustration produced by Davies (2005; 2008). It is important to highlight how Davies enables an understanding of morphogenetic behaviours as a catalogue of spatial arrangement, which form the basis of a modular system to produce sophisticated forms.

The model of morphogenetic effectors proposed by Davies enables a context in which biologically inspired processes can be explored with the aim of developing form. The possibility alludes to the drive to *grow* architecture, a theme that I have suggested is recurrent in the *biotechnical imagination*. However, the way in which morphogenetic effectors are implemented in a computer simulation, as well as the way that the *bio-material probe* operates in the context of this thesis, highlight two themes that I discuss in-depth in the next section. First, the time-dependency involved in morphogenetic effectors requires an alteration of the traditional approaches to parametric design. The second theme involves the tension generated by using a developmental biology model, which is often identified using an organicist approach, in combination with a parametric approach, generally aligned with a reductionist epistemology.

4 DESIGN AND PHILOSOPHICAL CONTEXT

This section discusses the design and philosophical context of *SynthMorph*. The discussion of the design context is driven by the parametric approach itself that, I have discussed, has a long tradition in architecture as a design approach used to handle complexity. I have also referred to parametrics as a parallel to the approach of contemporary biotechnologies, highlighting the limitations inherent in frameworks that require the establishment of clear objectives at the outset. The philosophical discussion is articulated by the decision to use the developmental biology model. Developmental biology is often understood as the last bastion of organicism in biological disciplines, given that the study of morphology is often difficult to approach using a strictly reductionist epistemology. There is a tension generated by models influenced by organicism, and the parametric approach used in SynthMorph; this tension enables a rich discussion of the limitations of both sets of *biotechnical imagination*.

4.1 A PARAMETRIC APPROACH TO LIVING SYSTEMS

As a design framework, parametrics constitutes a useful approach to considering the impact of biological systems in design, as its conceptualisation of form as part of a process is similar to the way in which the biological form emerges and evolves. In the second section of this chapter, I reviewed the work of Davies, who compares morphogenesis to human fabrication technologies. One crucial difference is that, while design disciplines use mediating artefacts to prescriptively communicate design intent, biological form is the result of a series of chemical events that yield similar but not identical structures. Compared to more traditional design approaches, often geometry-oriented, parametrics offers a useful starting point to designing with biological systems.

In the context of this thesis, parametrics is defined as a design methodology that codifies material form through a set of functional requirements and constraints. Traditionally, the design process involves engaging with a

problem and offering a solution in the form of a specific space or artefact. By contrast, parametrics focuses on producing a definition of the problem, which identifies key functional requirements and the way these are interrelated and constrained. One consequence of this approach is that, once a definition has been established, it is possible to produce several variations of spaces and artefacts that answer the design problem. The groundwork of this approach was developed by Alexander in his *Notes on the Synthesis of Form* (Carpo 2016). In it, he aimed to produce a rational design methodology that allowed design problems to be described logically through a combination of functional requirement and approached form as a generative process: '*My main task has been to show that there is a deep and important underlying structural correspondence between the pattern of a problem and the process of designing a physical form which answers that problem'* (Alexander 1964, p.132).

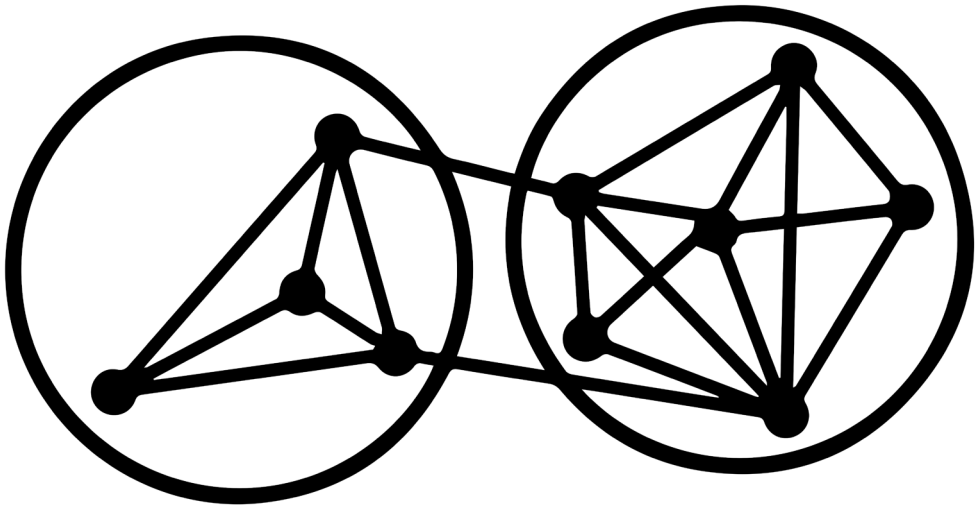
Although Alexander never used the term *parametrics*, his work has proved highly influential in developing the approach. Alexander's aim was to rationalise the process of design by unpicking the complexity of design problems. For him, design is a sort of balancing act, aiming to achieve the best possible fitness between form and context: '*The form is the solution to the problem; the context defines the problem. In other words when we speak of design, the real object of discussion is not the form alone, but the ensemble comprising the form and its context'* (Alexander 1964, pp.15–16). Design problems can therefore be broken down into functional requirements, which are connected by relationships of cooperation or mutual cancellation. Moreover, the system can only achieve an efficient configuration when variables cooperate to solve the design problem. Alexander illustrates this in the diagram in Figure 2, where solid black circles represent functional requirements, with straight lines stating interdependencies. Functional requirements are further grouped into subsets, delineated by circles, and which operate semi-independently: '*We may therefore picture the process of form-making as the action of a series of subsystems, all interlinked, yet sufficiently free of one another to adjust independently in a feasible amount of time'* (Alexander 1964, p.43).

02 *Diagram included in Notes on the Synthesis of Form, used to illustrate the interconnection between functional requirements, and their grouping into semi-independent subsets*

Alexander exemplifies his approach using a kettle. The form of a kettle, Alexander reflects:

> (…) must not be too small. It must not be hard to pick up when it is hot. It must not be easy to let go of by mistake. It must not be hard to store in the kitchen. It must not be hard to get the water out of. It must pour cleanly. It must not let the water in it cool too quickly (…) It must not be too hard to assemble, since this costs man-hours of labor. It must not corrode in steamy kitchens (…) It must not be uneconomical to heat small quantities of water in, when it is not full (…) It must be stable on the stove while it is boiling (Alexander 1964, p.60).

In the original text, Alexander enlists twenty-one requirements. Translated into the diagram below, each would represent individual nodes, grouped into functional categories: '*Kettle's manufacture, its capacity, its safety requirements, the economics of heating water, and its good looks*' (Alexander 1964, p.61). The design approach proposed by Alexander enables the designer to tinker with each subset in relative independence, ultimately bringing them together to produce an optimal form–context fit.



02

In addition to its suitability as a design approach, parametrics also enables drawing from both sets of *biotechnical imagination*. In the previous chapter, I proposed that one of the main objectives of this research was to propose an alternative approach to designing with biological systems, drawing upon elements from both sets of *imagination* reviewed in Chapters One and Two. A parametric model enables, on the one hand, the enactment of aspects of the reductionist approach prevalent in biotechnologies. In Chapter Two, I proposed that the design approach in contemporary biotechnologies can be understood by drawing parallels with the post-war design movements of *design methods* and *science of design, upon* which Alexander's work on *Notes* draws. I analysed how these movements aimed to rationalise the discipline, by generally providing a clear methodology to solve design problems. In this context, the work of Herbert Simon and Christopher Alexander aimed to develop a framework that provided the consistency and clarity of mathematical language to design situations. I suggested that these endeavours are similar to the approach of contemporary biotechnologies, which aim to reduce the complexity and randomness of living systems by introducing rational design principles, which are expected to provide predictability, control and intentionality.

Additionally, parametrics enables the drawing of techniques and tools from biotechnical architecture, especially in its influence from the digital paradigm. In Chapter One I reviewed how the *biotechnical imagination* in architecture often draws upon preconceptions informed by the digital paradigm in architecture. I discussed how the introduction of digital computation to design was often conceptualised through analogies to biological systems, which has contributed to a contemporary understanding of biotechnologies as an extension of digital computers, in what Ednie-Brown has described as a '*blurry bleed between digital and biological paradigms, with metaphorical associations, formal or processual mimicry, and other slippages between the two having a long history*' (Ednie-Brown 2013, p.86).

Contemporary notions of parametrics, often referred to as *digital parametrics*, extend the approach proposed by Alexander, while taking advantage of the computational power afforded by digital technologies to handle large sets of data and produce a potentially infinite number of formal variations (Carpo 2016). Contemporary approaches to digital parametrics have often

emphasised the potential to produce *continuous differentiation* — a constant process of transformation in which the form adapts to the changing conditions in its environment. The concept has often been used to draw parallels between buildings and biological systems. For example, Patrick Schumacher, one of the most vocal contemporary proponents of digital parametrics, uses the approach to define architecture as an autopoetic system. For Schumacher, parametrics enables a bottom-up process in which the designer defines the components of the system and its parameters, and establishes the rules dictating their interaction (Schumacher 2008; 2011). Parametric tools, Schumacher argues, enable thinking of buildings as *autopoetic* systems. The term is loaned from the work of Chilean biologists Maturana and Varela (1980), who used it to describe living systems as self-sufficient. For Schumacher, continuous differentiation will, eventually, enable a design process where the building is capable of constant adaptation, becoming alive in its capacity to adapt to changing conditions in the environment following a genetic code:

> This relationship between the base component and its various instantiations at different points of insertion in the 'environment' is analogous to the way a single geno-type might produce a differentiated population of pheno-types in response to diverse environmental conditions (Schumacher 2008, para. 5)

There are, notwithstanding, several limitations inherent in the notion of parametrics. Coyne (2014) has analysed how parametrics is often better suited to simple design tasks, but is inadequate in dealing with the complexity of under-defined design situations. In designing a chair, for instance, it is possible to define an algorithm that generates variations of a prototypical chair through the manipulation of key parameters: the height of the seat, the back, the length of the armrests. Connecting these parameters requires a set of relationships and *constraints*: provisions on how parameters interact within established limits, and how they adapt to events in which they go off limits: how, for instance, the arms of the chair require an alternative fixing method if the back is eliminated; or the ideal seat heights so that the chair does not topple over or is too high to sit in. This complexity increases when trying to design larger systems, such as buildings, where different parametric systems need to interact with one another. Coyne writes:

> Add to the problem of constraints and combinatorics the ill-defined, 'wicked' and random configuration of constraints imposed by environment, context, people, competing stakeholders, social norms, and cultural practices. There are parametric definitions of crowds, swarms and mobs, but as yet nothing that models human sociability and responses to environments in total — the stuff of architecture (...) With skins, surfaces and sculptural abstractions the constraints and their interdependencies are more amenable to algorithmic control, unencumbered by issues of use, history, culture, politics, and the complexities of human inhabitation (Coyne 2014, para.9).

The problem of digital parametrics, it is argued, is that it is predicated on the possibility of quantifying the unquantifiable. Christopher Jones, for instance, an early proponent of the design methods movement, later reacted against the premise of mathematically capturing design*: 'I dislike the machine language, the behaviourism, the continual attempt to fix the whole of life into a logical framework'* (Jones, quoted by Cross 2001, 2). Cross contextualises the quote in the backlash against the design methods movement following its apogee in the 1960s. It is argued that a more nuanced understanding of design problems is needed. There are problems that can be defined exhaustively; tame problems that can be approached using science and engineering techniques. Others are *wicked* problems, characterised by complex situations, which are impossible to address satisfactorily in their entirety (Rittel & Webber 1973).

Despite the shortcomings delineated above, a parametric approach is a useful starting point for this research. It enables the drawing of elements from both sets of *biotechnical imagination*, in the sense that it implements a reductionist design approach while drawing on the set of preconceptions that are often used in the digital paradigm. In addition, it is flexible enough to interrogate through a series of explorations. The notion of parameter is relatively straightforward to implement in a computer simulation and, as will be explored in detail later, it also provides a linking thread with the explorations in Chapters Five and Six.

4.2
MORPHOGENETIC EFFECTORS AND ORGANICISM

In addition to the points highlighted in the previous section, a parametric approach is useful, as it produces a contrast with the model of morphogenetic effectors. As suggested in the opening of this chapter, the notion of morphogenetic effectors has been developed using a developmental biology approach. Within biological disciplines, developmental biology is often seen as the last bastion of organicism. This section explores how developmental biology subscribes to an organicist understanding of life, in direct opposition to the mechanistic approach used in biotechnologies, which shape their reductionist epistemology.

In Chapter Two I introduced philosophical mechanism, an approach to biology predicated on the notion that organisms can be understood through parallels to the interaction of material components in a machine. The mechanism is connected to a reductionist epistemology, which favours an analytical model wherein complex wholes are separated into their individual components for study. The analytical method operates on the assumption that parts can be characterised in isolation, and that this will shed light on the way that these relate to one another and, ultimately, in understanding the organism as a whole. This is synthesised by Allen as follows:

> In the Mechanistic view the world appears as a mosaic of separate, independent parts. A detailed description of each of these parts and their interactions would produce a complete description of the system (a machine or an organism). From the Mechanistic point of view, the proper way to study any system is to take it apart (the analytical method) and determine the characteristics of the individual, isolated parts under as controlled a set of conditions as possible (Allen 2005, p.265)

I have also discussed how philosophical mechanism was used in the late nineteenth and early twentieth centuries to align biology with physics, considered then to be the standard for scientific enquiry. The historical project is often characterised as making biology a *hard* science, and is actualised in the prevalent discourse of contemporary biotechnologies.

Mechanistic models, however, are well suited only to some sub-disciplines of biology, proving highly constraining for others. Sheldrake highlights how some aspects of molecular biology, such as the study of DNA and the mechanisms of protein synthesis, have benefited greatly from a reductionist epistemology. In addition, reductionism provides firm ground on which to build a model of the cell that accounts for how its molecular processes operate:

> The mechanism of protein synthesis is understood in considerable detail. The structure of many proteins has now been worked out. All enzymes are proteins, and enzymes catalyse the complex chains and cycles of biochemical reactions which constitute the metabolism of an organism. Metabolism is controlled by biochemical 'feedback' and several mechanisms are known by which the rates of activity can be regulated. Proteins and nucleic acids aggregate spontaneously to form structures such as viruses and ribosomes. Given the range of proteins, plus the properties of other physico-chemical systems such as lipid membranes, the properties of living cells can, in principle, be fully explained (Sheldrake 1980, p.126).

An interesting exception to the historical project of mechanism is developmental biology. Developmental biology refers to a sub-discipline within biology that studies the processes by which animals and plants grow and develop. One of the aspects studied by developmental biology includes morphogenesis, generally defined as the study of the biological processes that enable an organism to develop specific shapes, and connected to the spatial distribution of cells. Given the complexity inherent in its study subject, mechanistic approaches have often been considered inadequate for developmental biology. Sheldrake expands:

> There is no doubt that mechanistic biology has been very successful in explaining many of the physical and chemical aspects of living organisms (...) But the form of an organism or the behaviour of an animal are not chemical molecules or physical quantities. The coming-into-being of the form of an organism - its morphogenesis certainly involves numerous chemical and physical changes, and the expenditure of measurable quantities of energy. So does its behaviour. But neither morphogen-

> esis nor behaviour bears the same immediate relation to chemistry as do the molecules studied by biochemists and molecular biologists, or to physics as the physical processes studied by biophysicists and electrophysiologists (Sheldrake 1980, pp.127–128).

In this context, developmental biology is often considered the last stronghold of organicism, a philosophical system described in opposition to mechanism. Organicism operates on the assumption that biological systems exhibit behaviours and properties that have no equivalent in machines. As a result, organisms cannot be understood in terms of machines, rendering inadequate reductionist approaches, which characterise the parts to understand the whole. From an ontological perspective, organicism can be defined as a materialistic philosophy, as it considers the physical universe to be articulated by the interaction of matter and energy. In this, it shares groundwork with reductionism, also a materialistic philosophy propounding that all entities can be entirely explained by the properties of their component parts. However, organicism posits that wholes are always greater than the sum of their parts. Gilbert and Sarkar explain:

> Complex wholes are inherently greater than the sum of their parts in the sense that the properties of each part are dependent upon the context of the part within the whole in which they operate. Thus, when we try to explain how the whole system behaves, we have to talk about the context of the whole and cannot get away [with] talking only about the parts (Gilbert et al. 2000).

Despite operating on diametrically opposed premises, organicist approaches often share methods with reductionism. Allen (2005; 1984) analyses how organicism often uses the analytical method to begin the analysis of a complex whole. The method, however, is always complemented with an understanding of how parts operate within their context. Allen writes:

> The holistic approach does not preclude starting with a reductionist, analytical breakdown of a complex system into its component parts, but it does emphasize that this is not enough. For example, in studying the function of the mammalian kidney holistic materialists might first determine all of the tissue and cell types of which the kidney is composed.

> These might be studied initially in isolation using methods of histology, cytology and cell physiology. However, holistic materialists argue that it would also be necessary to study the whole functioning where its response to variables such as blood pressure, ion concentration and hormones could be revealed. Studying one-by-one the ten or so individual cell types that make up the kidney could not be expected to provide a full picture of how the kidney functions as a whole within the intact organism. The nephron, the main filtration site in the kidney, depends for its function completely on its interaction with cells in different regions of the kidney, from the cortex, where the first major filtration of numerous ions occurs, to the medulla, where much selective reabsorption takes place. Each level of organization within the kidney —cellular, tissue and organ— has its own properties and characteristics that cannot be understood only by examining them separately (Allen 2005, pp.267–268).

Another way of describing the organicist approach is to say that, given the complexity of biological systems, analytical breakdown of their constituent parts offers a starting point to unpick the thick web of relations at play. Harrison, an early twentieth-century anatomist and precursor of tissue engineering, described this entry point as a foothold: '*It is impossible to develop science wholly from the top down or from the bottom up. The investigator enters where he can gain a foothold by whatever means may be available.*'

The model of morphogenetic effectors corresponds to a '*second wave*' in biotechnologies, inspired by organicism and which involves combining engineering design principles with more context-aware approaches. Haseltine and Arnold analyse how context-dependency runs counter to the engineering design principles prevalent in synthetic biology, since it hampers the possibility of standardisation, abstraction and decoupling. They highlight the importance of context in biology:

> The reality (…) is that the function of synthetic components and their assemblies also exhibits this context dependence. A gene circuit does not function outside the cellular context and may behave differently when the context change*s* (Haseltine & Arnold 2007, p.3).

Similarly, Agapakis reflects on the importance of contextual awareness by analysing how even relatively simple genetic circuits, which can be accurately characterised in isolation, are unpredictable as a result of their interaction with cellular environments. She goes on to analyse:

> A growing realization that noise in gene expression and other stochastic processes are fundamental to the robustness of biological systems has also led many to consider a more systems-based approach to informing biological engineering and perhaps a revision of synthetic biology's design principles to enable a 'second wave' of more complex, context-aware engineering (Agapakis 2014, p.125).

Calvert (2008) points to recent efforts within synthetic biology, and in the related area of systems biology, to understand the emergent properties of living systems, and in creating design strategies that integrate them. For Calvert, emergence is *'a concept that complements "reduction" when reduction fails'* (Regenmmortel, quoted by Calvert 2008, 387). Efforts to integrate emergence within the design cycle of synthetic biology, she proposes, keep within the conceptual groundwork of organicism, as developed in developmental biology and embryology, and attempt to shift the constraints inherent in reductionism.

In this context, the model of morphogenetic effectors is useful in exploring a further tension between both sets of *biotechnical imagination*. Morphogenetic effectors enable drawing upon elements of both *imaginations*: on the one hand, the notion of a set of behaviours that can be combined to produce more complex shapes; and, on the other hand, interactions between morphogenetic effectors produce emergent properties, in the sense that the resulting geometries cannot be described entirely through the set of basic rules, but are rather the result of the interaction between them.

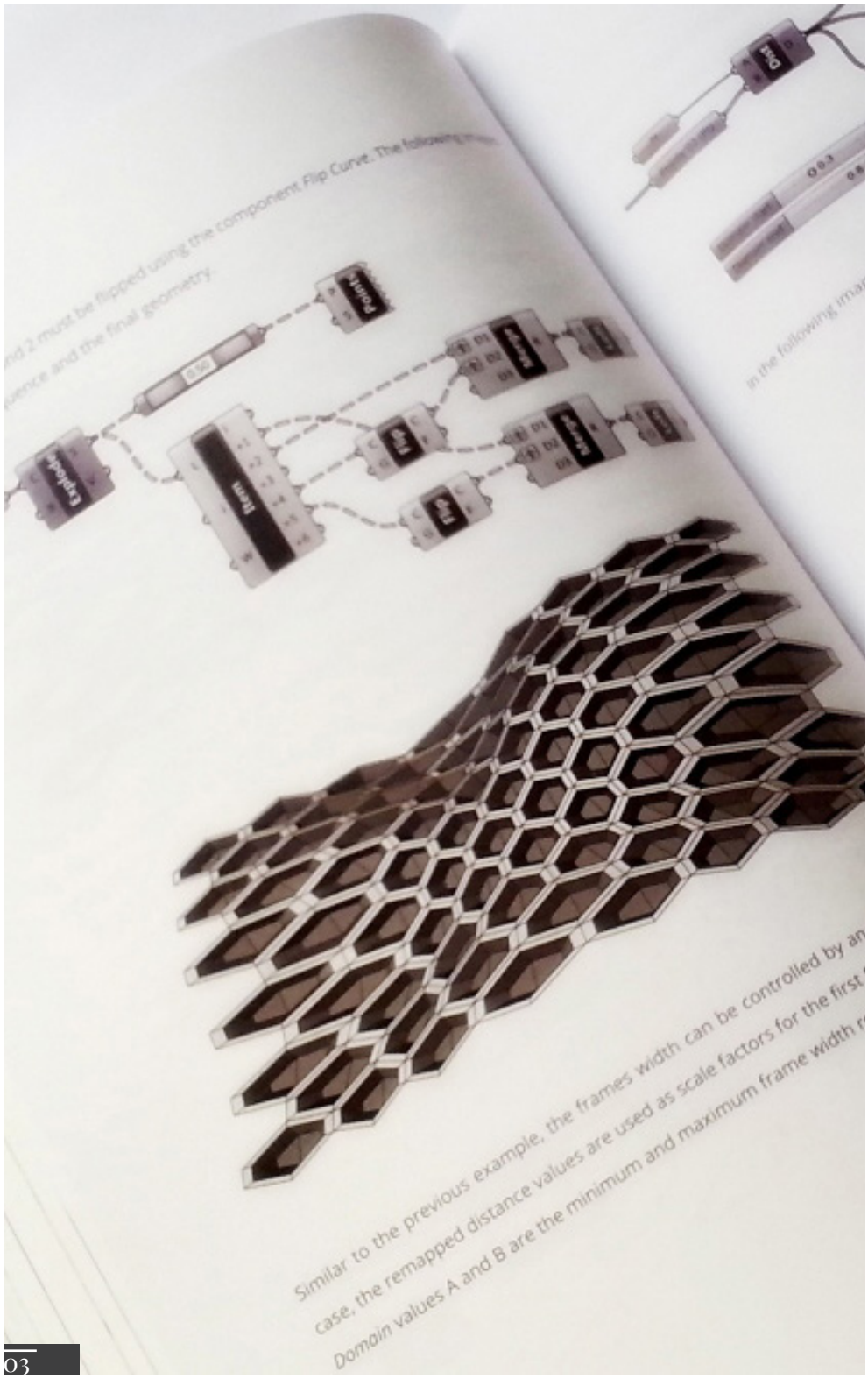
5 SYNTHMORPH AS BIO-MATERIAL PROBE

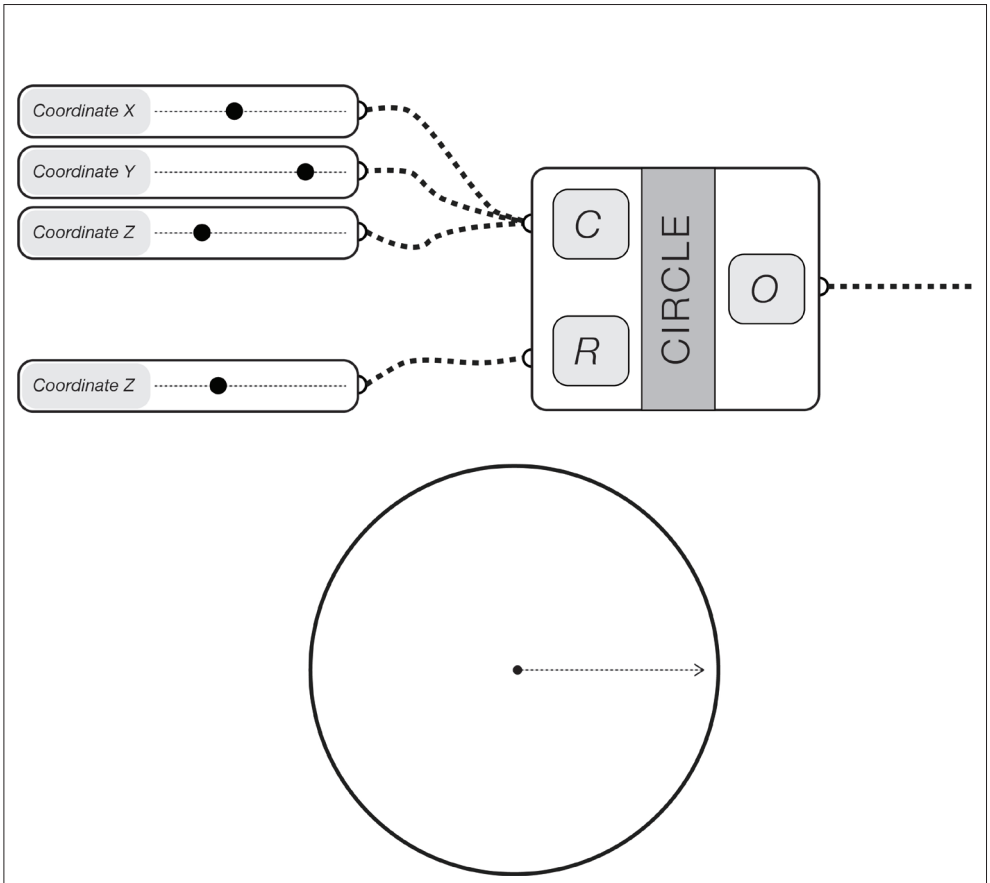
In Chapter Three, I proposed the notion of the *bio-material probe*, defining it as a methodology aimed at exploring a design space without the constraints involved in a practical outcome. I proposed that it did so by generating settings in which it is possible to engage with biological systems from a design perspective. SynthMorph can be said to produce two forms of context. One is in using SynthMorph as a tool for form exploration, deriving general insights into the use of biological systems in design. There is, however, an additional situation that is generated by the development of SynthMorph itself, and that also provides the basis for discussions about the implications of biological systems in design. The following section analyses how the design of SynthMorph operates as a *bio-material probe*, and discusses different design decisions and strategies that reveal themes of how biological systems are understood and mapped to design situations. The second section discusses the use of SynthMorph as a *bio-material probe*, delving into the different themes that come to the surface when the software is used in form-finding experiments.

5.1 PARAMETRICS AND TIME-DEPENDENCY

One aspect worthy of discussion is the way that the time-dependency of morphogenetic processes requires some alterations to traditional models of parametric design. *SynthMorph* takes a parametric approach to implementing morphogenetic effectors, enabling designers to explore form-generation through biological systems. The approach is described as parametric because of the way it defines form in terms of a series of variables, which can be manipulated to produce a potentially infinite number of formal outcomes. The approach of *SynthMorph*, however, is a slight variation in traditional parametric definitions used in digital architecture that incorporate recursion, which enables the production of feedback loops between parameters. The image in Figure 3 is part of *AAD Algorithms-Aided Design* (Tedeschi 2014), a handbook on parametric design strategies using Grasshopper, a plug-in for McNeel's Rhi-

03 *Parametric definition for a facade. Taken from AAD Algorithms-Aided Design (Tedeschi 2014)*


Point
Explode
Item
Similar to the previous example, the frames width can be controlled by an
case, the remapped distance values are used as scale factors for the first
Domain values A and B are the minimum and maximum frame width


Coordinate X
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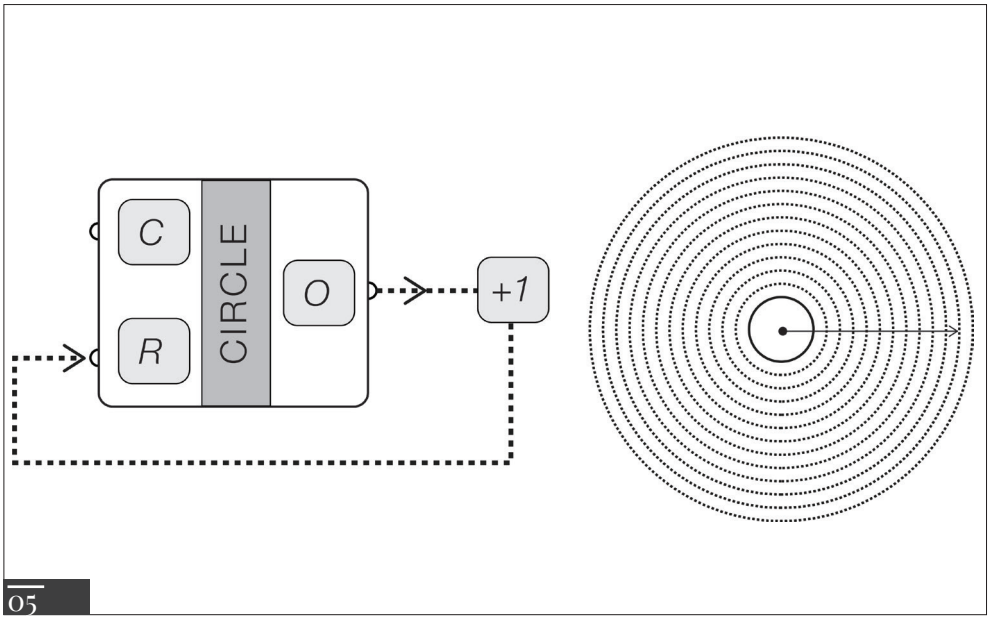
O

04


C
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05

noceros 3D software. Grasshopper is a visual programming tool, which has gained popularity in parametric design. Visual programming, also known as *spaghetti-wiring,* enables designers to create algorithms by manipulating *nodes*, graphic representations of code routines, which can be connected to one another to enable data to be stored and exchanged.

The lower part of the image in Figure 3 shows the design of a façade that has been generated using the *definition* at the top of the figure. The term refers to the collection of nodes that have been wired to achieve a specific result. The definition consists of nodes, identified here by a small label in the centre, and input interfaces, in this case horizontal sliders, which enable designers to input numerical data into the system. Once a definition has been set up, it enables designers to produce form variations by manipulating the input values in the definition.

An important aspect of parametric definitions that should be highlighted is how they are often structured to operate in linear data flows. Nodes are set up to take in numerical values, and to produce a sequence of data manipulations. The output of nodes is not connected to their input, which means that once an input has been transformed, it is carried through to the next node to produce further manipulations. This can be explained using Figure 4, which shows a notional parametric definition for a circle. The definition at the top shows a node that draws the circle using two sets of parameter, one controlling the XY coordinates for its centre, and the other its radius. These parameters are used to produce the circle on the lower section of the image.

04 *Notional parametric definition for a circle*

05 *Notional parametric definition using iteration*

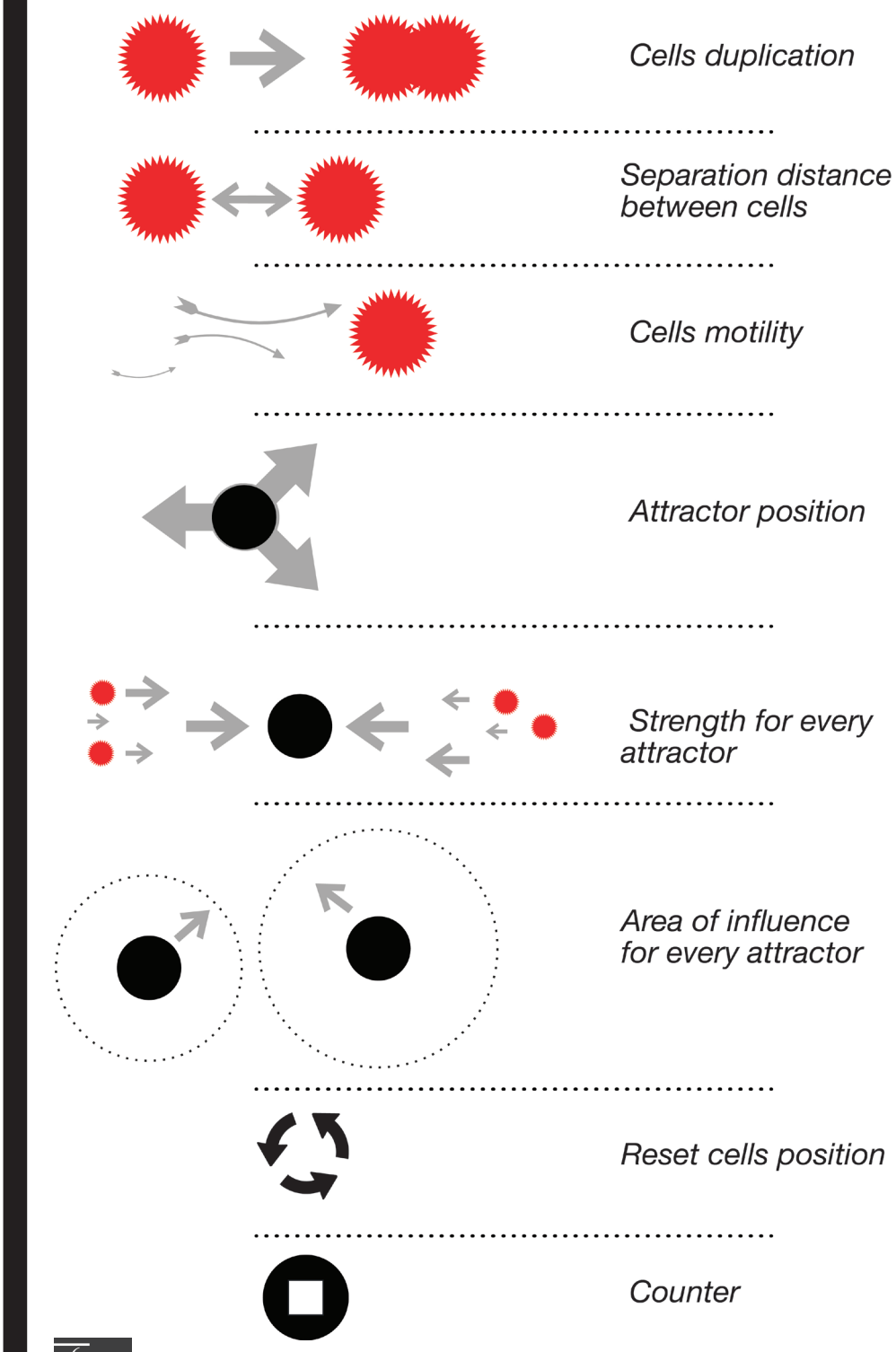
A non-linear data flow involves using the output of nodes as their own input, transforming data again using the same routine. Figure 5 modifies the definition above to introduce iterations. The centre of the circle is fed back into the node, while the radius is transformed by adding one unit in each pass. This results in a potentially infinite array of concentric circles, as shown to the right.

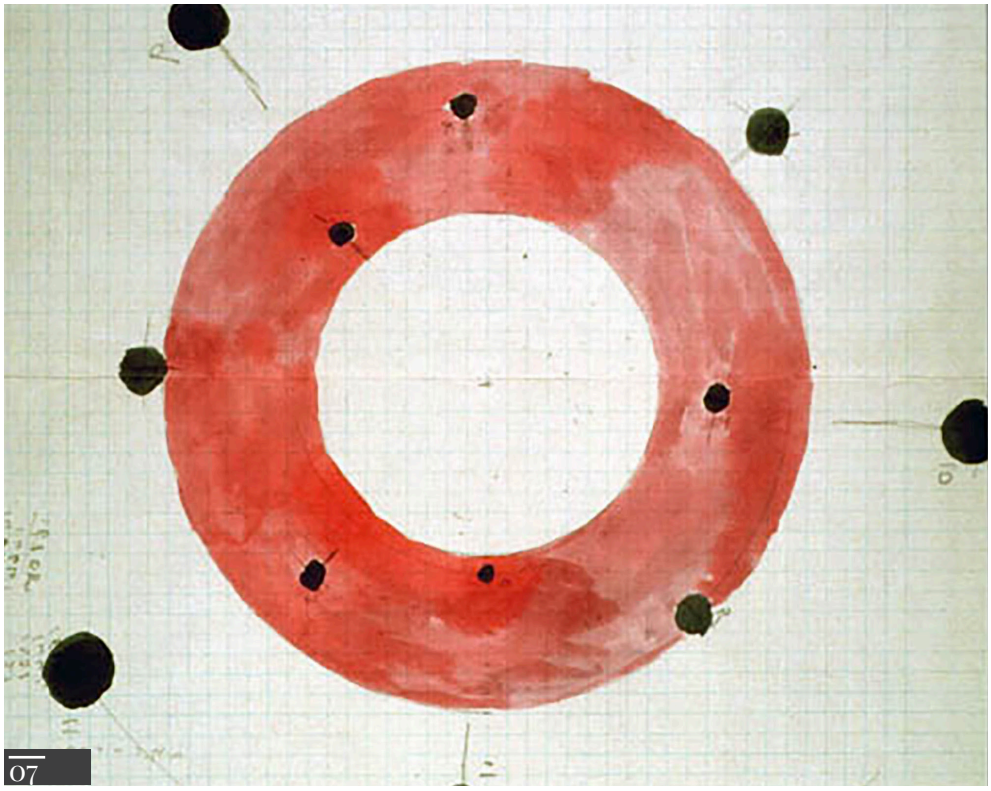
5.2
MAPPING MORPHOGENETIC EFFECTORS TO CODE

Morphogenetic effectors are implemented in SynthMorph through a particle system written in Processing. Processing is a graphics-oriented programming language and development environment derived from Java. It was originally conceived by Casey Reas and Ben Fry as a natural evolution of the work produced by their tutor John Maeda (2001) in *Design by Numbers*. Maeda is one of the pioneers who introduced programming as a medium for creative expression. His intention was to show non-programmers how boring programming can be, using this as a provocation to reimagine what he describes as a '*superior form of programming for the non-mathematically inclined'* (Maeda 2005, p.1). Particle systems refer to an algorithmic technique used to handle large sets of objects, in which simple governing rules are given to autonomous agents, and whose positions are calculated iteratively as a result of local interactions (Pearson 2011). This is achieved by highly efficient mathematical formulae, which describe the transformation that individual particles undergo as the result of interaction with heterogeneous forces in its context. Particle simulation is used widely in programming, and is useful in implementing the notion of continuous transformation and differentiation that is core to parametric design approaches.

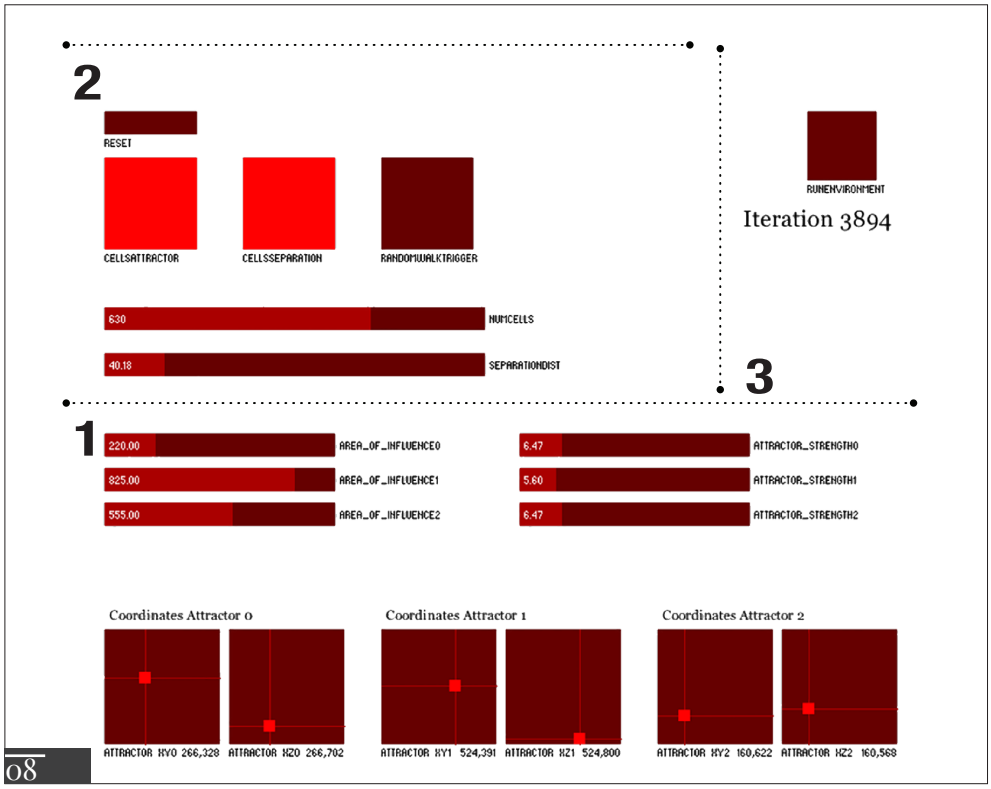
06 *Diagram of morphogenetic effectors codified in SynthMorph*

The simulation integrates four morphogenetic effectors from the original ten proposed by Davies: adhesion, locomotion, apoptosis and proliferation. Figure 6 provides a graphic representation of these effectors. To begin with, adhesion is implemented using Boid rules. Originally devised by Craig Reynolds (1987), Boids are used to describe local interactions between agents in particle systems, such as flocking behaviours. The basic implementation of Boid rules includes a set of three behaviours: (1) separation, the condition to keep separated from other particles; (2) alignment, an average direction based on the state of neighbouring agents; and (3) cohesion, an immediate reaction in position based on neighbours' direction (Pearson 2011, p.109).


Cells duplication
Separation distance between cells
Cells motility
Attractor position
Strength for every attractor
Area of influence for every attractor
Reset cells position
Counter



07


2
RESET
CELLSATTRACTOR
CELLSSEPARATION
RANDOMWALKTRIGGER
630
NUMCELLS
40.18
SEPARATIONDIST
RUNENVIRONMENT
Iteration 3894
3
1
220.00
AREA_OF_INFLUENCE0
825.00
AREA_OF_INFLUENCE1
555.00
AREA_OF_INFLUENCE2
6.47
ATTRACTOR_STRENGTH0
5.60
ATTRACTOR_STRENGTH1
6.47
ATTRACTOR_STRENGTH2
Coordinates Attractor 0
Coordinates Attractor 1
Coordinates Attractor 2
ATTRACTOR XY0 266,328
ATTRACTOR XZ0 266,702
ATTRACTOR XY1 524,391
ATTRACTOR XZ1 524,800
ATTRACTOR XY2 160,622
ATTRACTOR XZ2 160,568

08

Locomotion is implemented as a routine that updates the position of each cell by one unit per iteration, and uses a random function to determine the direction of movement. In addition, locomotion is also driven by a series of attractors, which create a field of influence to bias the locomotion of cells into a particular direction. This strategy is intended to simulate heterogeneous contextual conditions. The development of biological structures is often thought to be connected to non-equilibrium dynamics. Chemical gradients and imbalances are thought to provide cells with the motivation to reorganise into more efficient spatial patterns, which are closer to equilibrium (Pelce & Pocheau 1992; Ben-Jacob 1997). In his seminal work on simulating morphogenesis, for example, Alan Turing reflected on the way that disturbances are key to accounting for the sequence of events that allow pattern-formation in living systems: '*Although it may originally be quite homogeneous, [it] may later develop a pattern or structure due to an instability of the homogeneous equilibrium, which is triggered off by random disturbances*' (Turing et al. 1952, p.37). Turing illustrates this in Figure 7. A cell of a perfect circular shape has no incentive to develop into any other arrangement. Disturbances in its context, however, compel it to deform and trigger a series of events that allow other behaviours to occur, leading to the formation of biological form.

07 *Diagram by Turing explaining context disturbances as the basis of morphogenesis*

08 *SynthMorph graphic interface, showing controllers for area of influence, strength and attractor coordinates*

Apoptosis and proliferation were implemented using a routine involving regular evaluations. Cells were assigned a limited lifespan, and erased from the data structures once they had reached a limit. An additional routine selected certain particles at random, duplicating them instead and creating two new particles next to the position of the parent one. Finally, a control was made available to the designer that allowed manipulation of the count of active cells, invoking the routines of culling and duplication.

An important aspect in the development of *SynthMorph* was defining the way in which designers could interact with the software. The software was designed to be operated through a graphical user interface, which provided a way to manipulate parameters and assemble combinations of morphogenetic effectors. There are two main sections in the interface (see Figure 8). The first section is related to the attractors (labelled 1 in Figure 8), while the

second section deals with cell properties (labelled 2). Attractors are initially positioned randomly in a three-dimensional enclosing space. Users can modify coordinates by manipulating two bi-dimensional sliders for each attractor: the first controls XY coordinates and the second XZ. Additionally, each attractor is provided with a set of sliders, controlling the area of influence and strength values. The area of influence refers to the size of a field of influence that attracts cells within it. Strength determines the acceleration at which cells move when influenced by an attractor.

In addition, cell particles had four types of controller (Section 2 in Figure 8). The first control modified the number of cells in the simulation, thus controlling duplication. This behaviour is codified as an increment in the number of cells, with new cells being placed next to their mother cells. A second control manipulated cell distance to avoid collision. The third control activated the random walk function, which is analogous to the function of motility in real cells. Finally, the fourth control allowed the user to reset the position of all the cells. Globally, the system is controlled using an iteration counter (Section 3 in Figure 8). Given the time-dependency of all biological systems, a time display was implemented in the interface. Designers can know the iteration the simulation is running, and they can programme the system to stop at a particular iteration.

5.3
MATERIAL INTERPRETATION: PHYSICALISING PARTICLE DISTRIBUTION

In addition to the process of interpretation required to map morphogenetic effectors into code sequences, there is also a further layer of interpretation in the way particle distribution is translated into material form. Initially, *SynthMorph* was intended to operate as an enabler of conversations about morphogenesis and form-generation with practitioners from different backgrounds, including designers and scientists. One challenge, however, was that the output generated by the program was difficult to interpret as form, as it consisted of a point cloud that represented particle distribution. I experimented with different ways of representing the data, such as, for example, representing points as spheres so that they would be easier to read (see Figure 9). A second experiment involved using a space tessellation al-

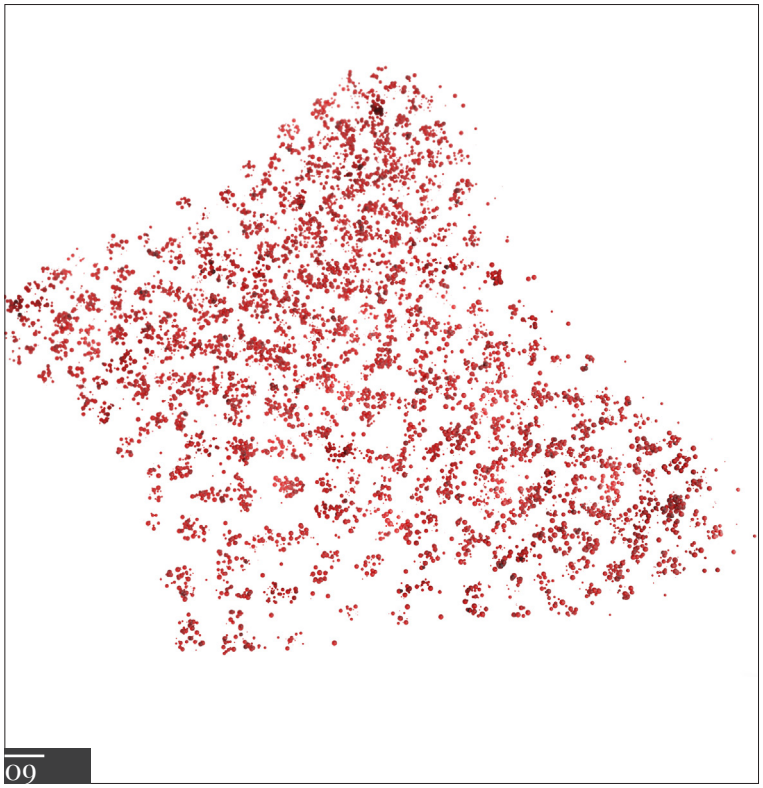
gorithm, which took the pattern distribution and produced a material form that responded to it. To achieve this, a simulation was generated in Grasshopper. The distribution of particles in *SynthMorph* was exported as a list of 3D positions, which was then parsed to produce a spatial pattern based on Voronoi-Delaunay, a space optimisation algorithm that allocates the optimal area around a set of points (see Figure 10). The resulting geometries were fabricated using a selective laser sintering machine (see Figure 11).

The Voronoi tessellation is a popular tool among contemporary architecture and design. It was initially devised to describe crystal formation based on the physicochemical interactions around nucleation sites (Aurenhammer 1991). In architecture, Voronoi gained popularity in the 1990s as part of the digital paradigm and has been adopted as a shorthand for biologically inspired forms and used, for example, as part of biomimetic and biomimicry strategies (Nowak 2015) and as a structural optimisation technique (Gawell & Nowak n.d.). Voronoi is also part of the graphic vocabulary of biotechnical architecture. In Chapter One I reviewed a number of projects that I identified as part of the speculative biotechnical discourse. In one of them, the *Protocell Tower*, Paul Preissner suggests a continuum between tools and techniques developed in the digital paradigm of architecture, and the topological possibilities of biotechnologies. Preissner writes that:

> Another way to put it is that we have been waiting for this for a while and have already figured out how to deal with its looks (and a number of us architects have decided we like it!), because we have been goofing around in software fortuitously replicating the shape and fashion of this new tiny life in anticipation of its eventual arrival (Preissner 2011, p.108).

The status of Voronoi tessellations is problematic in the context of SynthMorph. As described above, the algorithm has become a shorthand to signify biological *intention* in a design context. Using it in the context of SynthMorph, it risks signalling an uncritical use of digital tools for the sake of appearing to be biologically related. There is, however, a counterargument to this in the way that it helps to attract the attention of other designers and architects, operating as the intended enabler of conversations and discussion. The pieces in Figure 11, for example, have been presented in a number of conferences and events. They were part of the submission to the

Research Through Design conference in 2013, and were exhibited as part of the *Ordinary Takeover* held at the AA in 2014 and the *Biological Architecture Lab* series in Edinburgh. In these events, the pieces helped to attract attention, and were the enabler to talk to other designers about alternative approaches to biotechnical design, and to scientists about the role of design in scientific enquiry.



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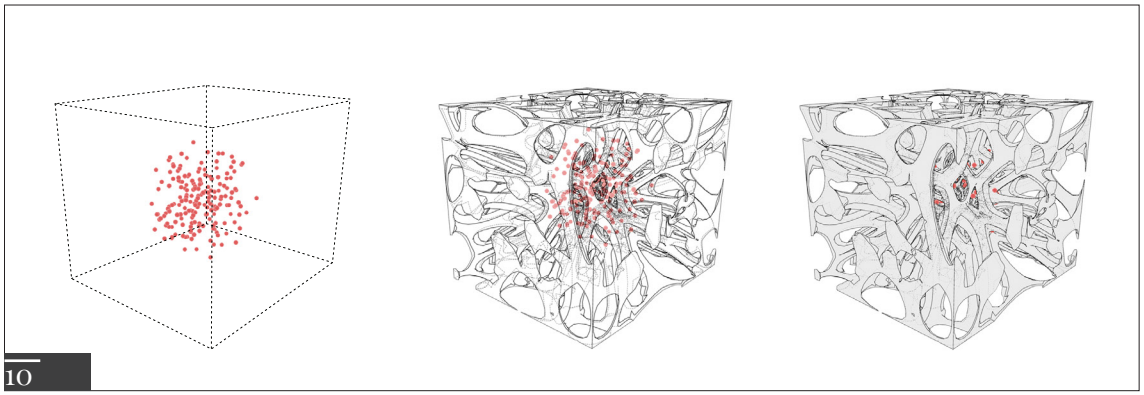

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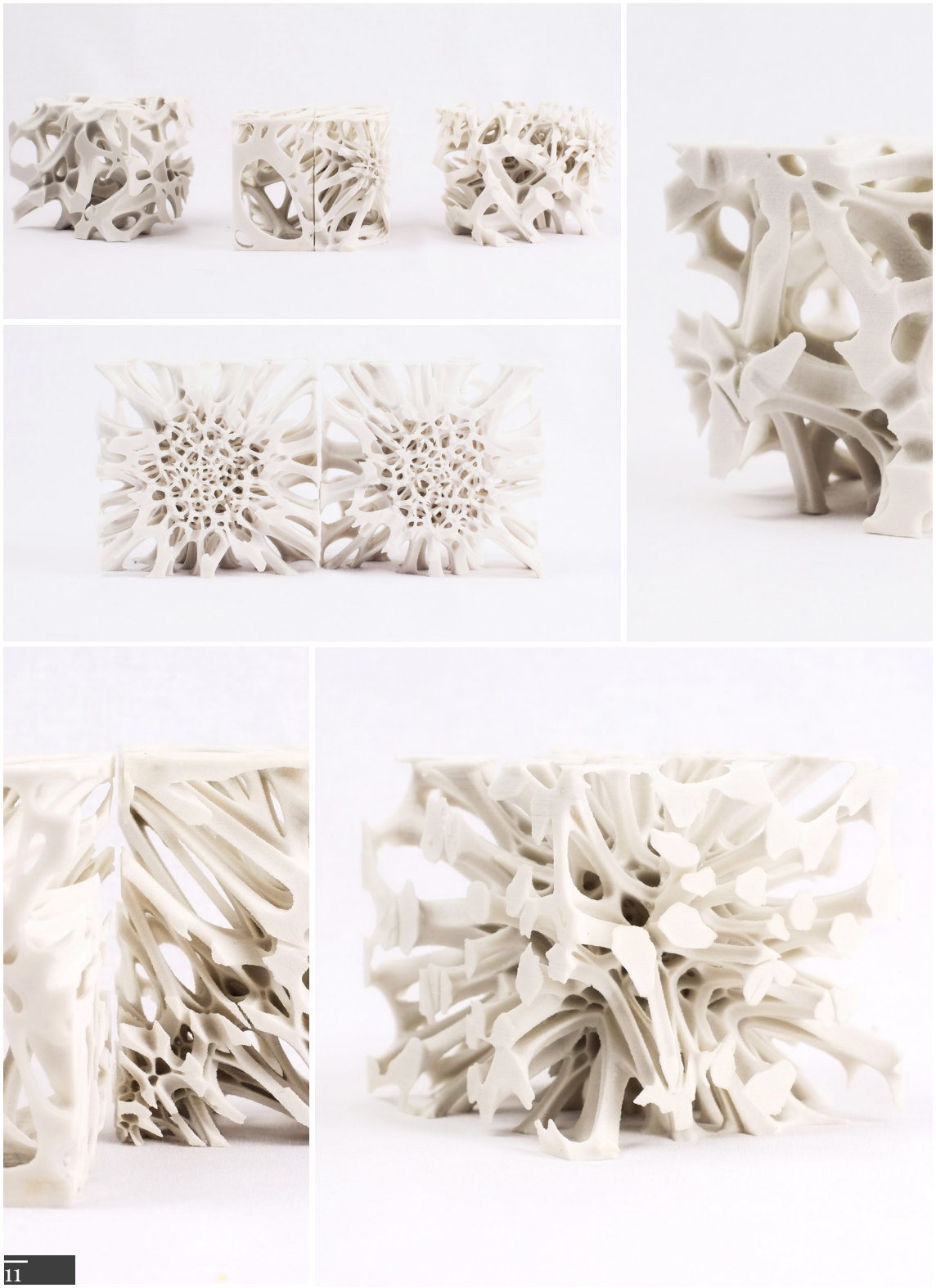
09 *SynthMorph particle distribution represented by red spheres*

10 *The diagram shows the progression, from particle distribution to material formation.The first image at the top indicates the particle distribution developed in SynthMorph. This is exported as comma separated value data, and imported in Grasshopper where it is interpreted as coordinates to recreate the position of particles. This is used as the basis for a Voronoi tessellation routine, which then distributes material around particles*

11 *Images show the physical artefacts fabricated using a selective laser sintering machine*



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5.4
SYNTHMORPH FORM-FINDING AS BIO-MATERIAL PROBE

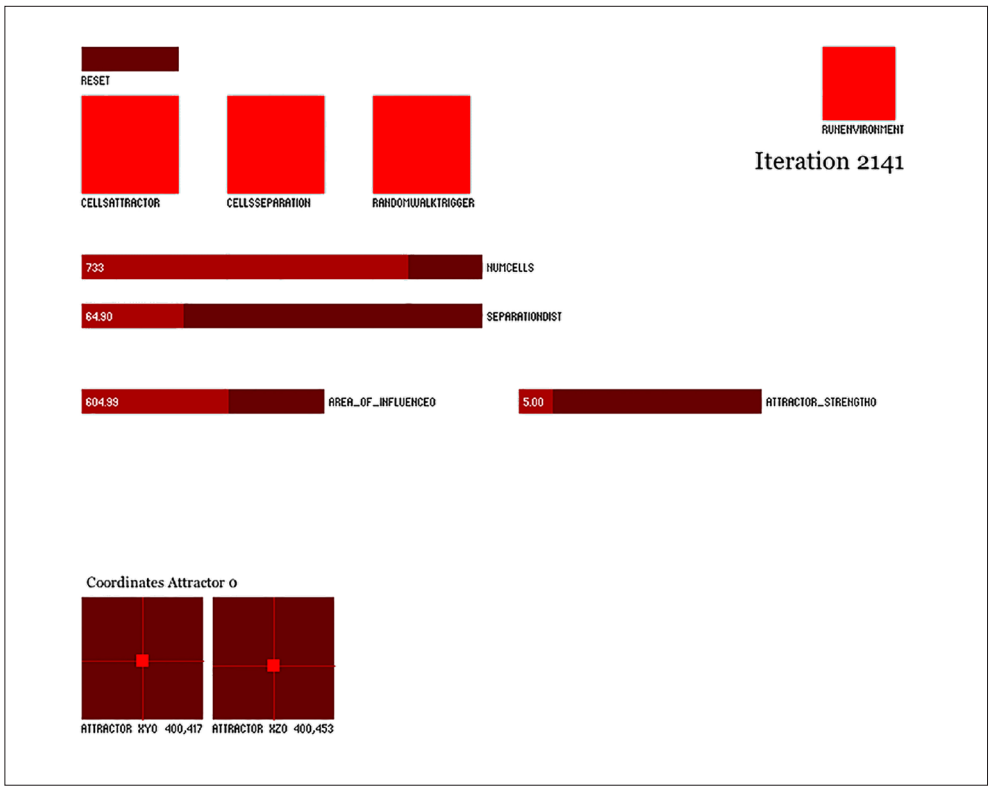
SynthMorph is also relevant as a *bio-material probe*, as it reveals the challenges inherent in shifting prevalent modes of design and fabrication. Specifically, there are three themes that SynthMorph brings into high relief. First, it highlights the tension between design intent and the liveness of the system itself. Second, it brings into contrast the difficulties inherent in interpreting biological behaviour into material form. Third, it reveals the non-linearity between morphogenetic effectors and form, which results in an emergent design process. The following sections delve into these themes by reflecting on the experience of working with SynthMorph.

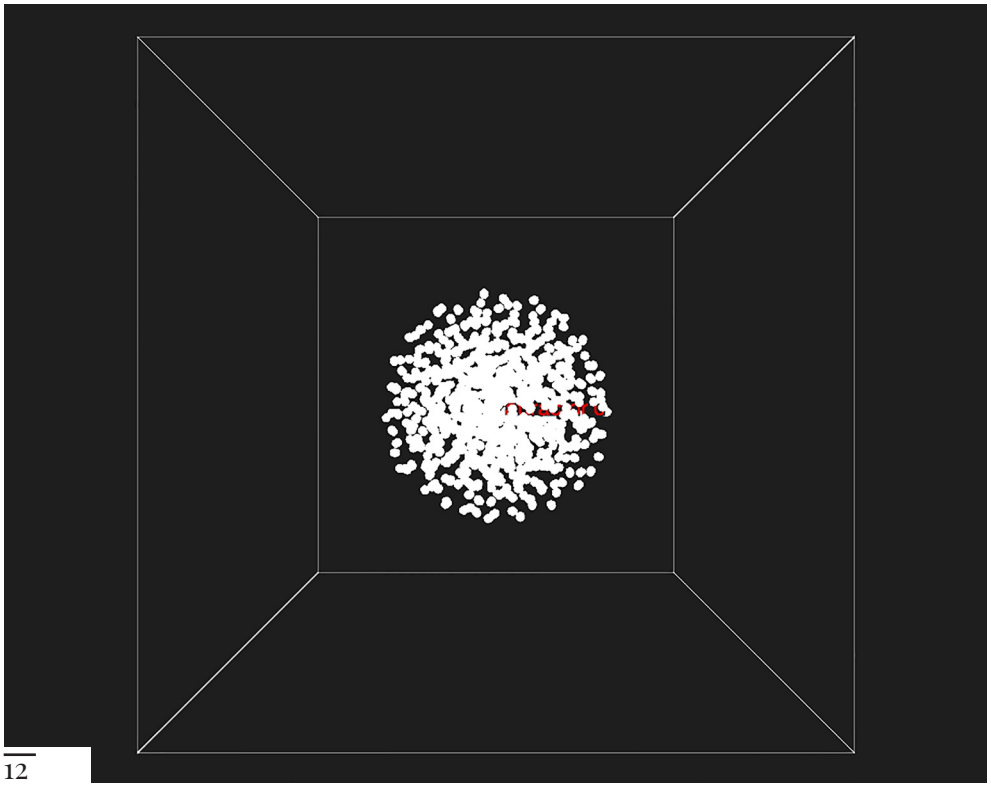
5.4.1
DESIGN INTENT AND LIVENESS OF THE SYSTEM

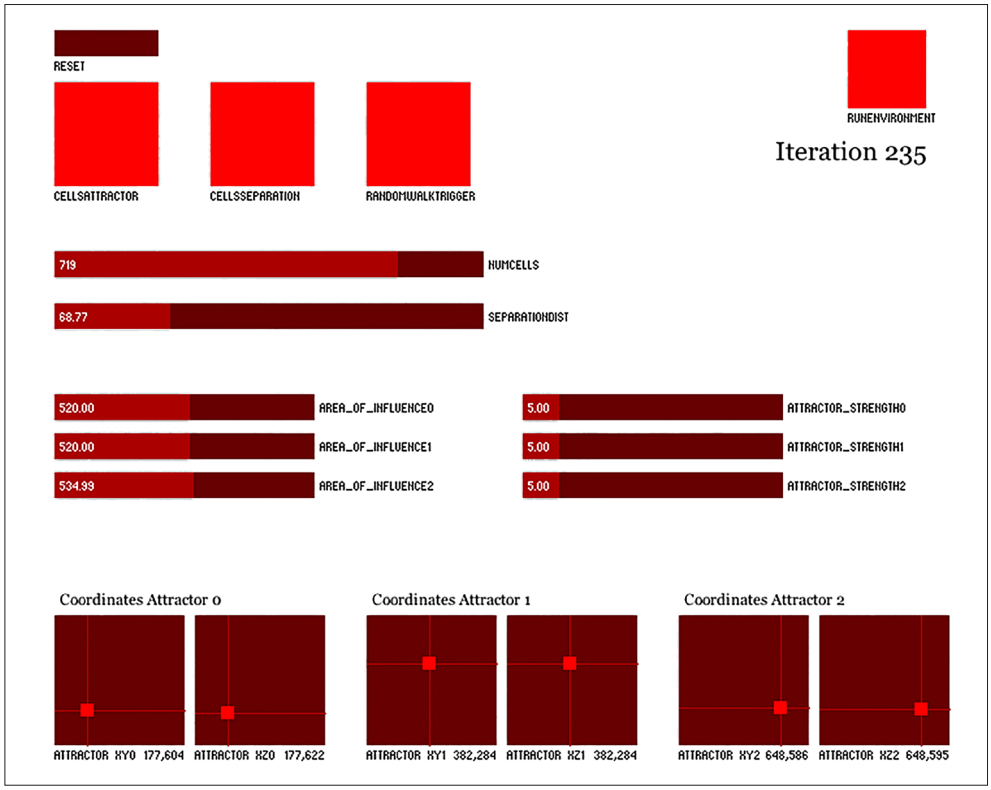
An important aspect of the exploration afforded by SynthMorph is the way in which it evidences the tension between design intent and the liveness of the system itself. On the one hand, design generally involves a mental process, in which formal and functional outcomes are initially imagined by the designer and later translated into material form. The use of SynthMorph, however, involves a process of continuous negotiation between intent and the liveness of the system. For example, Figure 12 illustrates an experiment generated with one single attractor. The spread of cells shows how a single attractor generates an area of influence that approximates the shape of a perfect sphere. The *area of influence* variable determines the radius of the sphere of influence, while the attractor strength determines how fast cells are pulled towards the attractor.

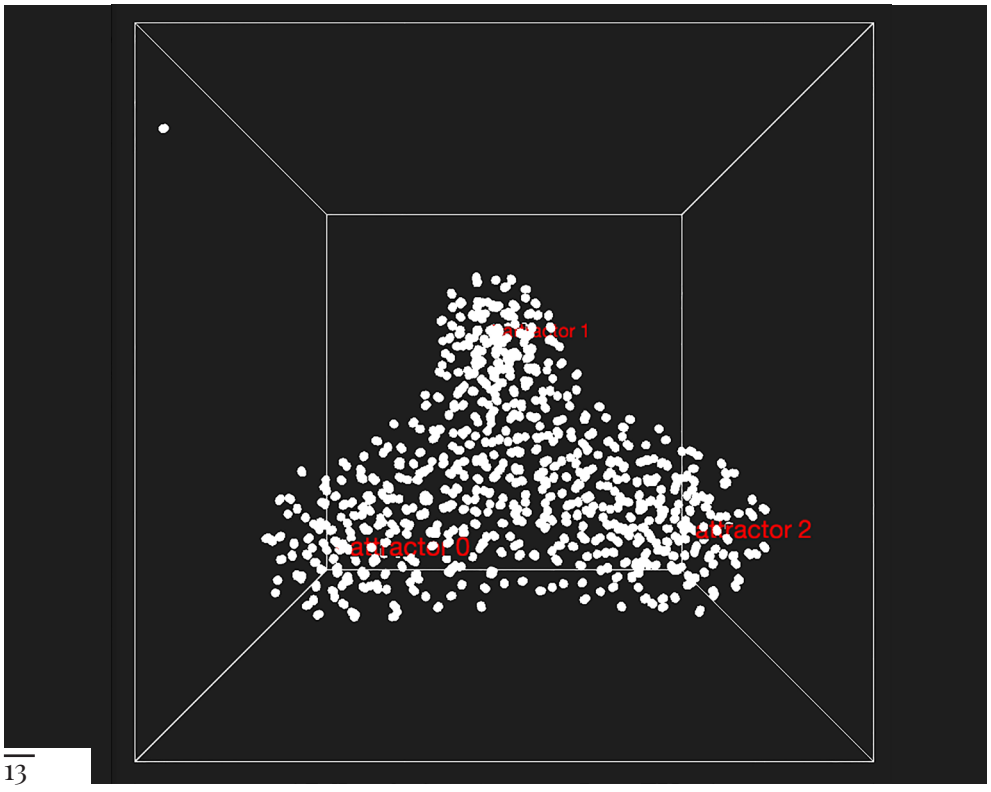
12 *Single attractor system depicting area of influence*

Using *SynthMorph* with a specific form in mind involves shaping the field of influence, and activating the relevant modules, in order to approximate it. Figures 13 to 15 show, for example, form explorations with three and four attractors that were conducted with a formal outcome in mind. Figure 13 was initially intended to produce a triangle; Figure 14 a hyperbolic paraboloid;


RESET
RUNENVIRONMENT
CELLSATTRACTOR
CELLSSEPARATION
RANDOMWALKTRIGGER
Iteration 2141
733
NUMCELLS
64.90
SEPARATIONDIST
604.99
AREA_OF_INFLUENCE0
5.00
ATTRACTOR_STRENGTH0
Coordinates Attractor 0
ATTRACTOR XY0 400,417
ATTRACTOR XZ0 400,453




RESET
CELLSATTRACTOR
CELLSSEPARATION
RANDOMWALKTRIGGER
RUNENVIRONMENT
Iteration 235
719
NUMCELLS
68.77
SEPARATIONDIST
520.00
AREA_OF_INFLUENCE0
520.00
AREA_OF_INFLUENCE1
534.99
AREA_OF_INFLUENCE2
5.00
ATTRACTOR_STRENGTH0
5.00
ATTRACTOR_STRENGTH1
5.00
ATTRACTOR_STRENGTH2
Coordinates Attractor 0
Coordinates Attractor 1
Coordinates Attractor 2
ATTRACTOR XY0 177,604
ATTRACTOR XZ0 177,622
ATTRACTOR XY1 382,284
ATTRACTOR XZ1 382,284
ATTRACTOR XY2 648,586
ATTRACTOR XZ2 648,595


attractor 0
attractor 2

and Figure 14 a pyramid. Achieving each form requires different strategies. Creating a triangle-like distribution involves, for example, configuring both attractor strength and area of influence to the same values. Figure 13 was achieved by setting attractor strength values to 5 and area of influence to 520, which distributes cells in a three-manifold shape. The resulting form, however, deviates from a perfect triangle, instead approximating a manifold-like structure.

Similar dynamics are at play in Figures 14 and 15. Figure 14 uses four attractors, configured to equal values in area of influence and attractor strength parameters, and was intended to produce a hyperbolic paraboloid. As with the experiment in Figure 15, the shape somehow resembles the intended outcome. The distribution, however, is slightly off the intended distribution and tends to be more weighted towards one of the attractors. The mismatch between intended and actual distribution is more latent in Figure 15, in which the resulting shape deviates considerably from a pyramid.

It is important to reflect on how particles constantly resisted the design intent, often going in the wrong direction, despite the fact that they were, only in a limited sense, mimicking biological processes. It is impossible, for instance, to establish a clear parallel between the particles represented in SynthMorph, and a specific biological organism such as a cell or a cellular colony. The connection to biological processes, however, is created by the use of biological models that describe the transformations that cells undergo in morphogenesis. Despite these limitations, particles appear to have a life of their own, which resists the designer's intent.

13 *A three-attractor system featuring an intermediate state between triangle-like and manifold structure*

One potential conclusion is to say that SynthMorph is a bad form-finding tool, as designing with it could be described as constructing geometry with toothpaste — despite the designer's actions, the system goes off on its own. An alternative viewpoint is to say that *SynthMorph* is inadequate for a very specific, and potentially narrow, understanding of design: one in which formal outcomes are always the prerogative of the human designer operating as a single actor. One component of the *biotechnical imagination* in architecture is formal complexity. In Chapter One I discussed how this theme involves a fascination for design systems that are beyond the control of the

designer, and which produce highly sophisticated and complex forms. An underexplored aspect, however, is that the liveness of the biological system also hampers design in a traditional sense, as it requires orchestration of the intent of a human designer with the organisms and other materials.

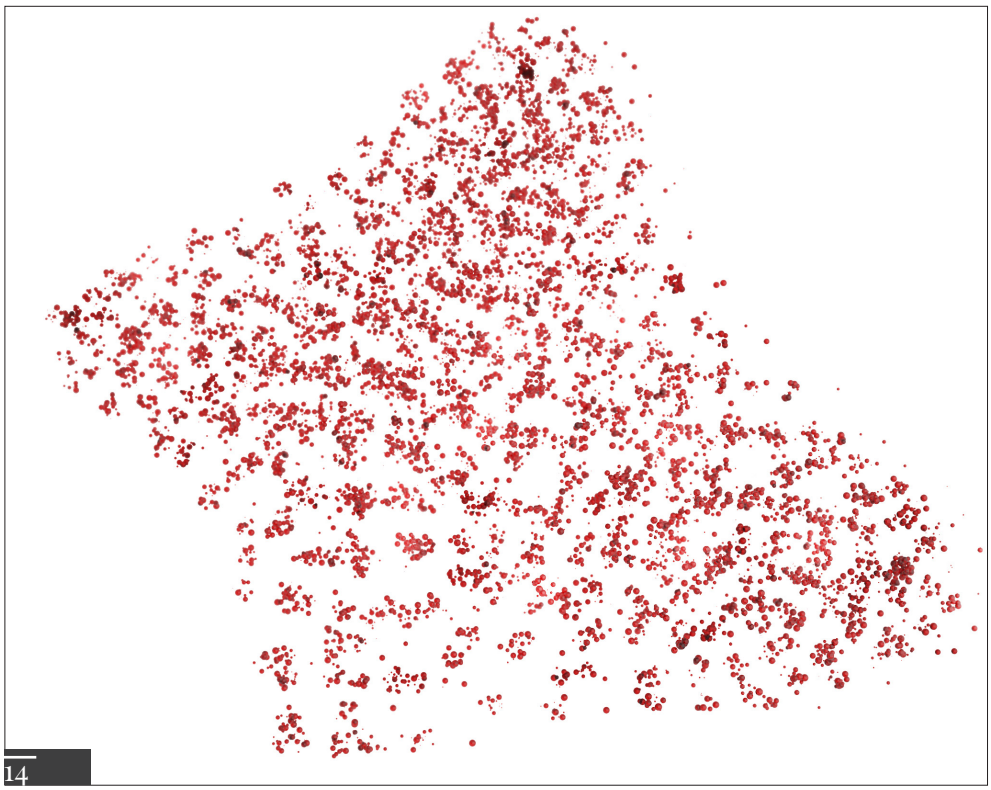
The orchestration of humans and non-humans in design connects to notions of material thinking. In Chapter Three, I reviewed the work of Katie Lloyd-Thomas (2006), who reflects on how contemporary understandings of design are philosophically rooted in *hylomorphism*, which describes the philosophical tradition that privileges form over matter. An increasingly complex relationship with matter, she goes on to argue, demands new understandings of design, which shift this instrumental approach to matter. I also reviewed the work of Barbara Bolt (2004; 2007), who is also critical of the instrumental relationship between practitioner and matter. She offers an alternative in models of co-creation, in which the designer becomes part of a creative assemblage, which provides the conditions necessary for form to emerge. The process of negotiation between parameters, design intent and the system's liveness described above can be understood as a preliminary inkling of the nature of the creative assemblage.

14 *Particle distribution resembling a square surface*

15 *Particle distribution resembling a pyramid*

5.4.2
NON-LINEARITY AND EMERGENCE

One crucial aspect of the tension between intent and liveness is the non-linearity of morphogenetic sequences. At the outset, I explained how morphogenetic effectors constitute basic cellular behaviours that are combined to produce any biological structure and tissue. One way of interpreting this, however, is to say that, given a specific sequence of effectors, it is possible to replicate a specific form. In this case, the dynamics of arranging the position and strength parameters of attractors on SynthMorph would operate as a form of mould: conditions are prepared to ensure that particles follow the pattern established by the field of attractors. The relationship between form and morphogenetic sequence, however, is non-linear. Following the same sequence of morphogenetic effectors will produce similar but not identical shapes. In the case of the structures, the pores will be roughly the



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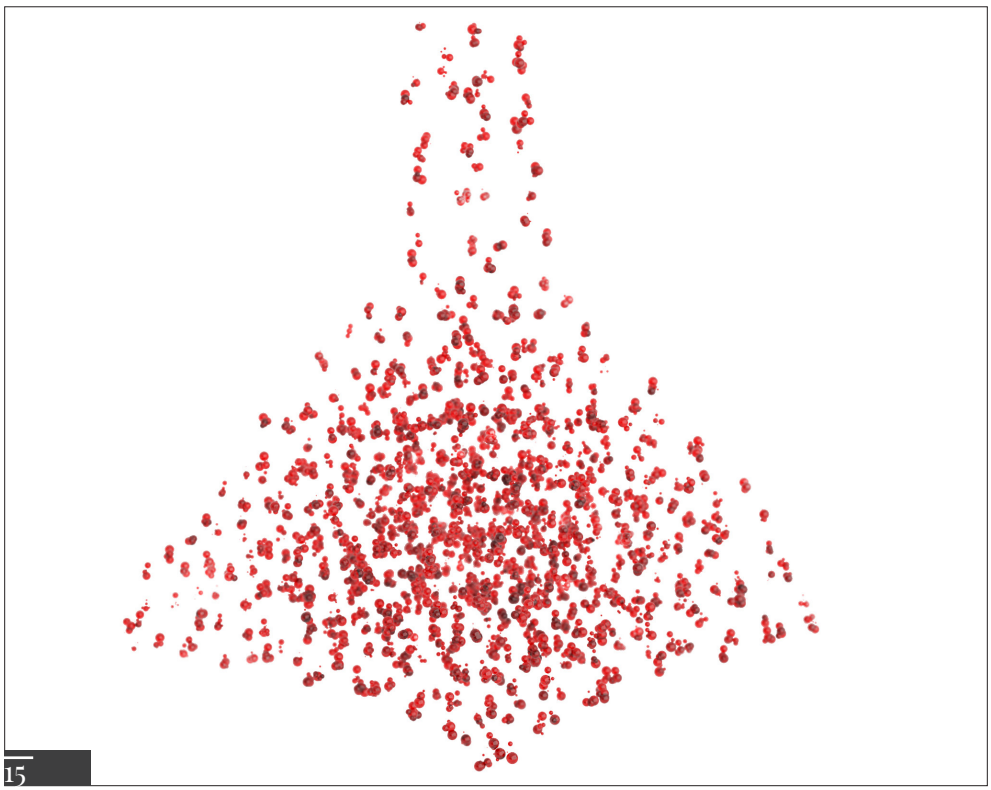

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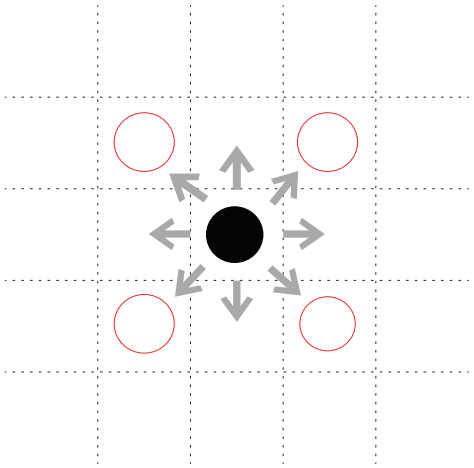
same size and have similar distribution. Put side to side, however, they will reveal different geometries.

One way of explaining the non-linearity of *SynthMorph* is to look at the random walk function used to simulate cell locomotion. Particle systems operate by calculating new positions for each particle in every clock cycle of the processor. The mathematical formulae used to achieve this take into account attractor forces, which weight the movement in a particular direction. This is compounded by an initial state of *random walk*. The notion of random walk in particle simulation is generally implemented in analogy to Brownian motion: a term used to describe the motion of particles suspended in fluids and which result from the collision with other particles and micro-interactions with their context (Pearson 2011; Shiffman 2012). It was named after Robert Brown (1828), who described how particles move inside pollen grains when submerged in water, later extending his observations to organic and non-organic molecules. The phenomenon had previously been described by Ancient Roman philosopher Lucretius (2007), who reflected on how dust particles would seemingly move randomly when revealed in sunbeams.

In *SynthMorph*, the random function creates a new possibility path at every clock cycle. Figure 16 illustrates how a particle moving in 2D has eight potential new positions assuming a random vector of one unit.
If we imagine a particle with an initial position in co-



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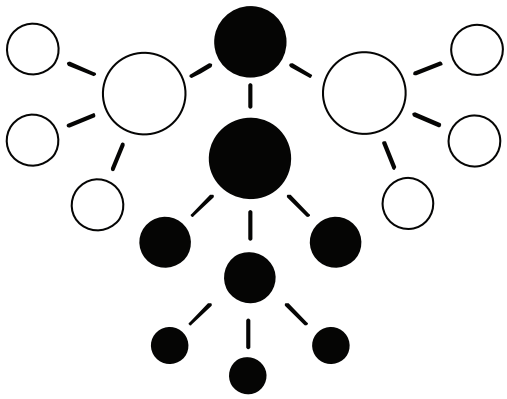
16 *Diagram showing a particle and its eight neighbouring cells as potential new positons*

17 *The diagram shows three potential new positions for an initial particle and extends this over three generations*

ordinates (0,0,0), there are eight potential new positions in iteration 0 of the clock cycle. Each of these represents a new path, which, in iteration 1, will ramify into eight further new possibilities (as illustrated in Figure 17). In the context of *SynthMorph,* this means that the sequence of effectors will never produce the exact same form, as every clock cycle produces a unique state that will influence the next. The process results in geometries that are located within a *state-space* of possibilities, rather than as precise solutions. The same sequence of effectors will produce a number of artefacts like the ones described above, similar in terms of size and general distribution of pores, but not identical. The term of *state-space* is used in mathematics to describe complex systems, and describes the array of values a given process can assume as input. The term is also used in the context of bio-design by Dade-Robertson (2015) to describe the context and time-dependency of morphogenetic processes, and will be expanded upon in the next chapter.



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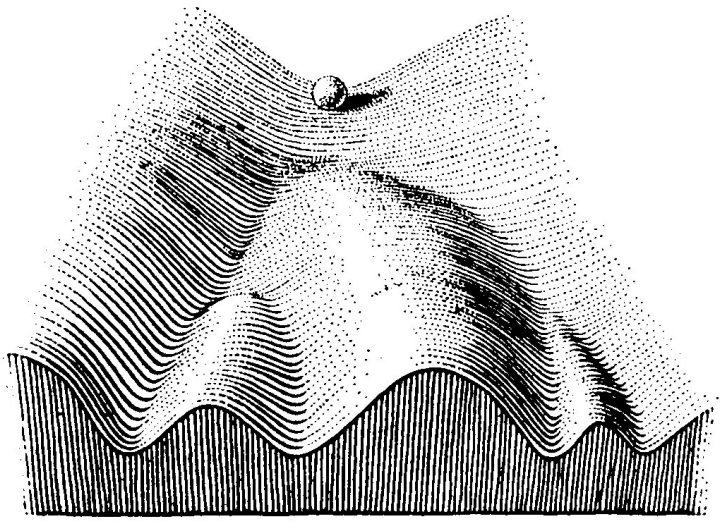
The non-linearity between sequence and form in SynthMorph is reminiscent of the property of adaptive self-organisation in biological morphogenesis. Davies (2014) observes how biological structures are created using the same genetic code. Variations in contextual circumstances, however, produce different geometries. Two tibia bones will never be an exact replica of each other, as they adapt to the different mechanical stresses and contextual chemical conditions. Similarly, bones in different parts of the body will assume different configurations, responding to the specific task and conditions in which they are embedded. One way of summarising this is that the process is emergent, which makes it impossible to infer the morphogenetic process by looking at the final morphology. Conversely, the same morpho-

genetic process will produce a host of morphologies within a state-space. The diagram in Figure 17 is also reminiscent of the work of Conrad Hal Waddington, an embryologist who theorised on epigenetic landscapes (shown in Figure 18). Waddington proposed that every cell can take a number of developmental pathways, which determine the way they differentiate. In developmental biology, differentiation refers to the process by which a cell changes from one type to another, often from a zygote to more specialised cells that make up tissues and structures. To illustrate this process, Waddington produced a graphical description, in which a series of ridges and valleys represent the different pathways open to a cell.

18 *Epigenetic landscape by Conrad Hal Waddington, accounting for the differentiation of cells in development*



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5.4.3
MORPHOGENETIC SEQUENCE

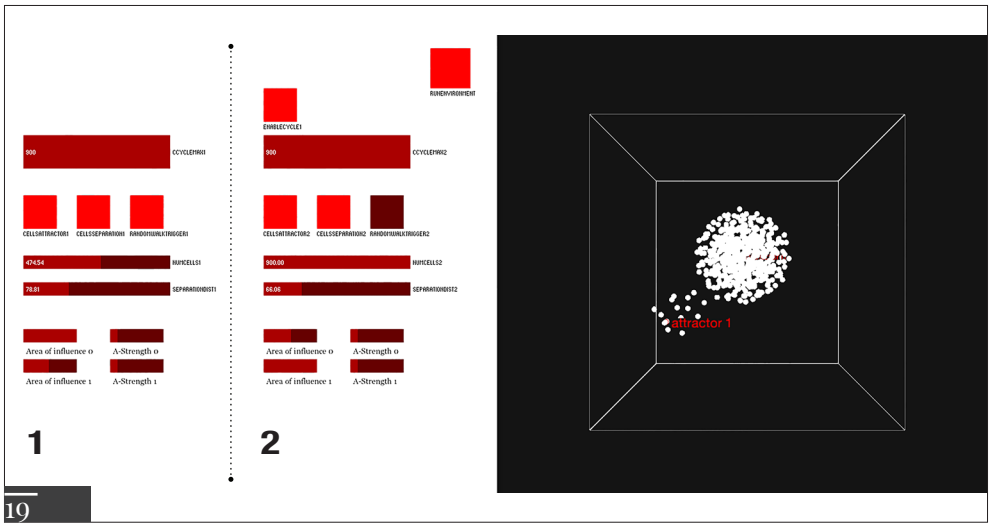
In describing material thinking, Lloyd-Thomas (2010; 2006) refers to the way that hylomorphism is encoded in architectural practice. In order to communicate design intent, architecture makes use of *mediating artefacts*, which produce a prescriptive representation of the final form of the building, using scaled drawings that represent each aspect of its components.

The nature of the creative assemblage described above, however, invites a revaluation of which forms of mediating artefacts are adequate when the design intent shifts from the designer, as single actor, to the collection of materials involved in form-generation. In this context, morphogenetic effectors in SynthMorph operate as a form of non-prescriptive mediating artefacts. Given a specific combination of morphogenetic effectors, a designer could produce a host of forms that are similar to one another. Figure 19 shows, for example, a simple particle distribution that has been generated by a sequence of morphogenetic effectors. These are structured in phases, labelled as 1 and 2 in the diagram, which themselves are defined by a combination of individual effectors. A number of iterations is assigned to each phase, which determines their duration in the overall sequence.

The same morphogenetic sequence is used to produce figure 21, which highlights their time-dependency. Columns represent the simulation at three stages, and rows illustrate how point distributions are transformed in artefacts using the space tessellation routine. Column A1 corresponds to the pattern that results when the sequence is simulated for 70 iterations; A2, 120 iterations; and A3, 180 iterations. The combination of images highlights the dynamic nature of the system when compared horizontally, and assesses the influence of a time-based system in the distribution of material, as seen when read vertically. Moreover, the use of morphogenetic sequences as mediating artefact can be extended to more complex particle distribution. Figure 20 shows the interface of *SynthMorph* extended to a sequence of three morphogenetic phases. As described in the labels, each phase has individual control over the number of iterations, and offers the possibility of activating different morphogenetic effectors, configured by the sliders at the bottom of each phase.

The proposed morphogenetic sequences are described as a form of mediating artefact in the sense that they are used to document and communicate form. They do not, however, share the prescriptive description of final form that is often found in the mediating artefacts used in architecture, such as plan drawings and detailed mock-ups. Instead, each sequence has the potential to produce a number of structures that are similar to one another, but not identical.

The following chapter escalates the notion of parameter, while coming back to, and re-approaching, some of the themes revealed in *SynthMorph*. It takes the notion of parameter, and attempt to map it to a physical equivalent that can be manipulated in actual, biological experiments.



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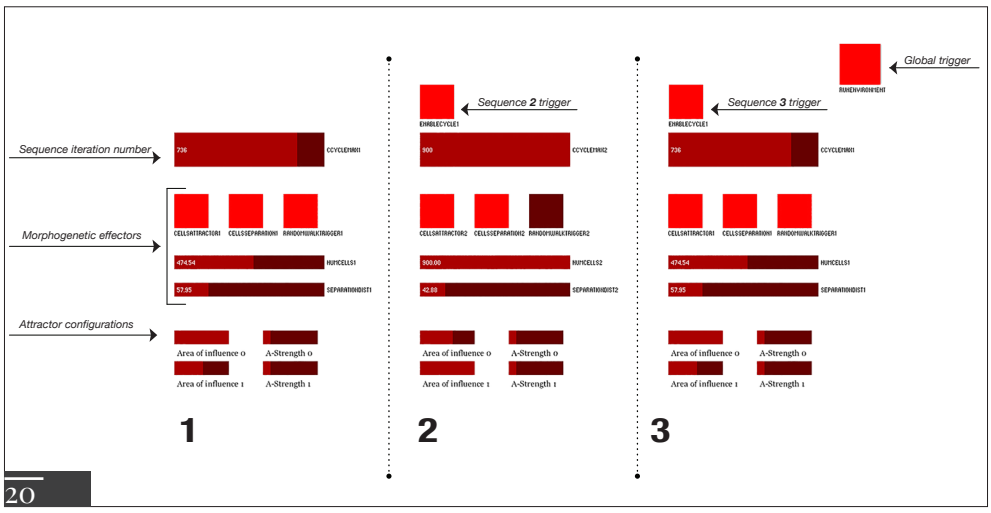

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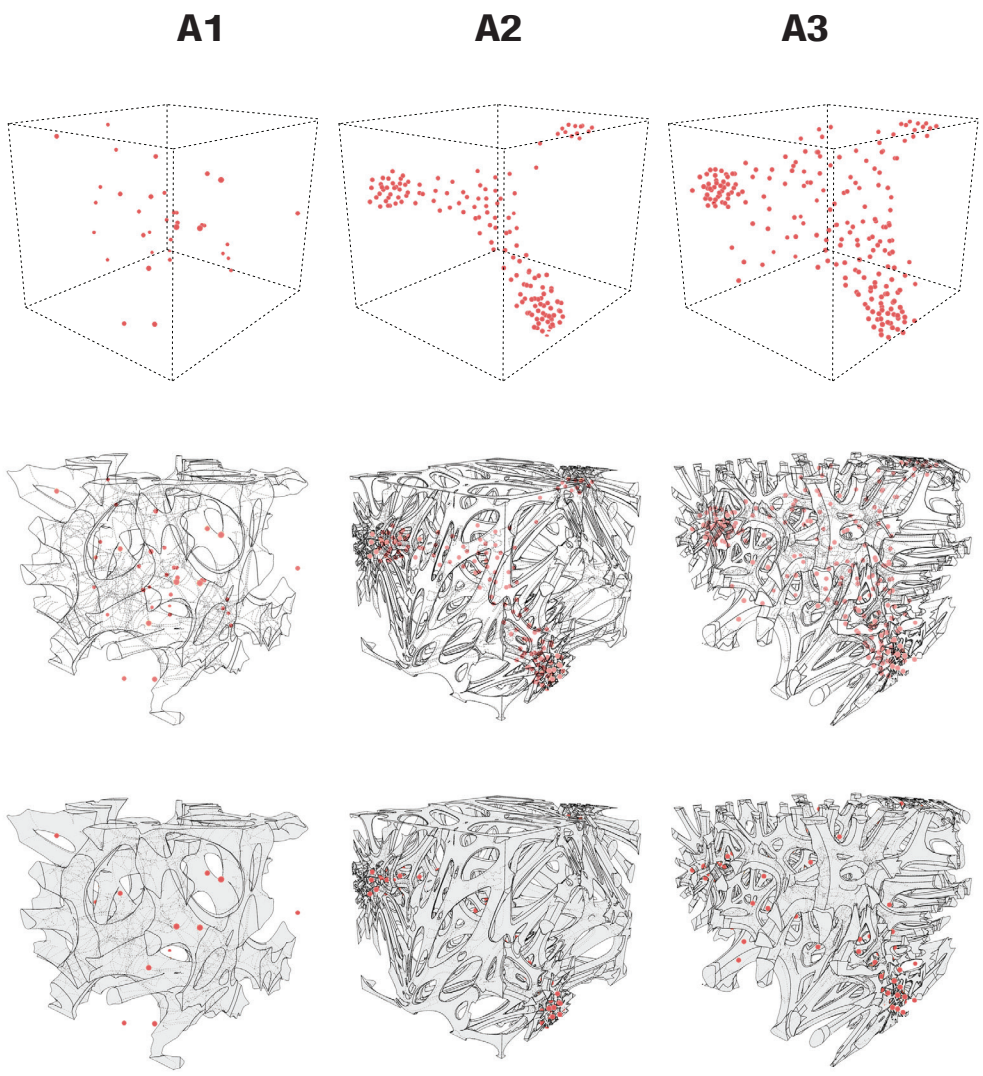
19 *A single attractor system depicting phases of morphogenetic effectors*

20 *SynthMorph graphic interface depicting a sequence of three morphogenetic phases*



21 *Diagram A shows material progression for a three attractor system. A1, A2 and A3 are created with the same morphogenetic sequence, with each representing a different stage. A1 has been produced by allowing the sequence to run for 70 iterations, A2 120 and A3 180. The combination of images enables understanding the dynamic nature of the system where compared horizontally, and assess the influence of a time-based system in the distribution of material, as seen when read vertically*

5

THE STATE-SPACE OF DESIGN

CHAPTER 5

THE STATE-SPACE OF DESIGN

1 INTRODUCTION

The chapter explores parametrics in the context of a biological system, and attempts to find a physical equivalent of parameter. While *SynthMorph* implemented parameters as sliders of numerical data, this chapter looks at how similar concepts can be applied to influence the way that biological systems organise and pattern spatially. The chapter is structured in four parts. The first lays the conceptual groundwork, introducing the *state-space of design*, a model that argues that designing with biological systems involves dealing with cellular, chemical and physical developmental constraints. I propose a number of diagrammatic techniques, inspired by the work of Alexander in *Notes on the Synthesis of Form*, which are intended to formalise the way that state-spaces can be decomposed: articulated in specific parameters that offer a hint of how biological systems can be engaged. The state-space approach is implemented through *blackboxing,* which involves collaboration with a scientist partner who implements the design systems. The strategy is used in two tracks of exploration, both modelled as part of the primer component of Stage 6, themed design studios delivered at the School of Architecture, Newcastle University. The first *bio-material probe*, *Bacterial Crystals,* uses the context of biomineralisation to explore strategies used to manipulate the physical state-space. The second *bio-material probe*, *Bacterial Morphologies,* uses bacterial branching to explore manipulation of both the chemical and physical state-spaces.

Part two of this chapter documents *Bacterial Crystals*. I discuss a number

of themes that are highlighted by the *bio-material probe:* the existence of new, contingent state-spaces that are not captured by the original three, and that correspond to aspects of laboratory and experimental protocol; the limitations of blackboxing, and how it limits the possibility of anticipating contingencies found in the laboratory; and the constant reconfiguration of the state-spaces. Part three covers *Bacterial Morphologies,* and discusses a number of similar highlights and themes: the relevance of contingent state-spaces, which group parameters such as decontamination and pouring sequence; the shortcomings of blackboxing evidenced in complications in enacting some of the prototypes, and which resulted in the introduction of contamination; and *parametric volatility*, a notion that the link between the state-spaces and biological form are non-linear. Part four evaluates the adequacy of a parametric approach when designing with biological systems. I suggest that, although the diagrammatic strategies used in the explorations are helpful in keeping track of the way one parameter affects and reconfigures others, it is not possible to implement these strategies as a way of anticipating the contingencies of the design systems and their outcomes. As a result, I suggest the term *parameter* is inadequate in describing organisms and their context.

2 OBJECTIVES AND AIMS

The first overarching objective of this chapter is to implement a parametric design approach in an actual, biological system. This objective connects with the themes explored in the previous chapter. While *SynthMorph* implemented the model of parametrics computationally, the *bio-material probes* in this chapter explore how a parametric model can be used to approach an actual biological system within a design context.

The second objective corresponds to escalating the notion of parameter. Implementing a parametric approach to biological systems requires interrogation of the notion of parameter. In a computational context, SynthMorph is implemented as a slider, which enables control of numerical data. Actual biological systems, however, require a different definition. The key question here is: *What aspects of biological systems can be mapped as pa-*

rameters? And, ultimately, *is it possible to use the notion of parameter when designing with biological systems?*

3 DESIGN STRATEGY: STATE-SPACE OF DESIGN

In *Material ecologies for synthetic biology* (Dade-Robertson et al. 2015) we propose *state-space of design,* a framework with which to approach biological systems in design contexts. The term was originally used in mathematics to describe the configuration of dynamic systems in terms of key variables, and a set of equations that describe their behaviour and interconnections. A state-space representation consists of a graph whose axes are the key variables, and where the *state*, or the possible configuration of the system at any point in time, can be represented as a vector. In the paper, we argue that biotechnologies enable us to think of organisms as combining computation and material synthesis. This possibility requires new design frameworks that integrate *'computational simulation, material properties and the manufacture of material form'* (idem, p. 29). Designing with biological systems, we argue, involves managing the developmental constraints imposed by organisms and the environment. This is in contrast to prevalent approaches in architecture, where design is communicated through hierarchical, linear patterns of information and decision-making, which culminate in material form. The rules governing the behaviour of individual living systems and their interactions, however, are not directly accessible to the human designer. Rather, they are defined by a long series of transactions by which they have gradually adapted to their environment:

> Biological organisms can (...) be considered to be operating and finding form on the basis of programmed self-assembly where the code is written through an emergent and evolutionary process (idem, p. 31).

In this context, design is redefined as a process that enables dealing with the *state-space*, a term we use in the sense of the potential configurations of a system that are defined by the interaction between the cell and its environment:

> The state space of biological material construction is one of developmental constraints defined by both the organism and its environment. More accurately (...) biological materials are produced through the interaction of a number of different state spaces (ibid.).

There are three state-spaces, we go on to propose, which influence biological form: cellular, chemical and physical. The cellular state-space is defined by the boundaries of the cellular membrane, and it is used to define all the processes that take place within it, including, for example, DNA transcription and translation, as well as protein production. The chemical state-space refers to conditions in the environment, such as pH levels and nutrient concentration, which are thought to trigger specific sections of the genetic code that result in the development of form. Finally, the physical state-space:

> ...constitutes the physical forces and energy within the environment (...) this state space is defined by the physical confines of the agar plate, the temperature of the growth environment, and the physical structure of the agar itself. Again, the physical space is altered by the bacteria and its extra cellular processes (idem, p. 34).

The paper uses abalone shells to illustrate the interaction between the three state-spaces. Abalone shells are an interesting case study in biological material formation: although relatively chemically homogeneous, a cross section of the shell reveals different orientations of crystal, which produce a functionally graded material. On the outside, the shell has a rough and resistant composition, and changes gradually towards its core, where the mother of pearl offers a soft texture. Abalones produce their shells by first laying out soft tissues through morphogenesis processes. The tissue operates as a form of scaffold, which allows the organism to alter the chemical composition of its environment, increasing its alkalinity to precipitate the formation of calcium carbonate crystals. The example is useful, as it highlights the three state-spaces in operation. In the cellular state-space, the genetic make-up of abalone cells determines the patterning of the scaffold. The scaffold participates in the physical state-space, as it provides a specific landscape that determines the sites for crystal nucleation. Finally, metabol-

ic activity of the tissue activates the chemical state-space by manipulating alkalinity, which triggers the reaction that leads to the formation of calcium carbonate crystals.

In this thesis, I intend to expand upon the original use of the model to challenge prevalent notions in biotechnical architecture, which assumes that biological form can be programmed exhaustively by manipulating genetic code. Instead, state-spaces are used to explore how contextual factors play a role in defining biological form. Following the exploration in the previous chapter, the model follows a parametric approach, interpreting state-spaces as measurable factors '*forming one of a set that defines a system, or sets the conditions of its operation*' (Rybczynski 2013). Moreover, state-spaces are connected by a series of rules and transactions that determine the way that altering one affects the other two and, as a consequence, the form of the biological system.

3.1
DECOMPOSABILITY OF STATE-SPACES

Nonetheless, one challenge involved in using the model is the extent to which each state-space is decomposable. In mathematics, decomposability refers to the articulation of graphs, which is expressed in terms of the grouping and clustering of its component elements. For example, the diagram in Figure 1 is intended to represent the way that biological form is contingent upon the interaction of physical, chemical and cellular aspects of the system, as proposed by the model of state-space of design. There are elements that can be easily represented symbolically and captured numerically so that they can be manipulated by the designer. In the design context of biomineralisation used in the paper, the chemical state-space is defined by, among other things, pH levels and nutrient concentration. In biological experiments, nutrient concentration is often defined by the amount of *peptone* that is used to prepare the growth medium. Peptone refers to a soluble protein that is used to provide nutrients to microorganisms in laboratory experiments. Thus, it is relatively straightforward to define nutrient level as a parameter, as it can be captured numerically by referring to the weight of peptone solution that is mixed in the growth media. Moreover, the parameter follows a linear behaviour: a greater weight of peptone solution results

in a higher nutrient concentration, and vice versa. Thus, the chemical state-space can be *decomposed*, or articulated in terms of nutrient concentration and pH levels, as shown in Figure 2. Instead of representing the chemical state-space as a solid node, the diagram articulates it in two further subsidiary nodes, which represent parameters that can be manipulated by the designer.

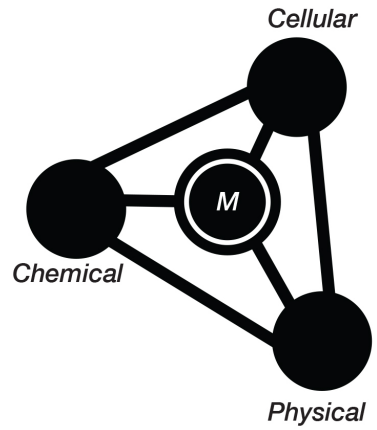
The process of decomposition should be understood as an iterative process, which enables the designer to formalise the way that different components of the system have an effect on one another. The diagram in Figure 2, for instance, can be further articulated to include *surface hardness*. Solid growth media is generally prepared by mixing agar concentrate, which refers to a gelatinous substance derived from *polysaccharide agarose*, a carbohydrate extracted from algae. Agar is combined with distilled water to produce a semi-solid substrate that is commonly used in microbiological experimentation. The texture of agar is ideal for microorganisms to attach to, which enables quick and easy inspection of an organism compared to liquid culturing. As with nutrient concentration, surface hardness can be captured numerically in terms of the weight of agar concentrate that is used to create the growth media mix. Increasing or decreasing the amount of agar concentrate alters the composition of the growing media: higher concentrations of concentrate result in a *harder* growing surface, which delay cellular locomotion. Lower concentrations produce more flexible surfaces, which facilitate cell movement. Nutrient concentration can then be represented as a further node in the diagram, as shown in Figure 3.

01 *Diagram of the state-spaces of design, featuring the physical, chemical and cellular space*

02 *Diagram of the state-spaces of design, featuring the chemical state decomposed into two parameters: nutrient concentration and pH levels*

03 *Diagram of the state-spaces of design, featuring the extra node on surface hardness inside the chemical*

The use of diagrams as a way of exploring and refining a design situation has been explored by Christopher Alexander. In *Notes on the Synthesis of Form* (1964), Alexander argues that design involves a balancing act in which forms are created to provide the best possible fit to their context. Each form is, in turn, defined by a set of *misfit variables*, which need to be manipulated by the designer to *fit* the contextual conditions. A crucial aspect of design, Alexander proposes, is the designer's mental image of which elements are



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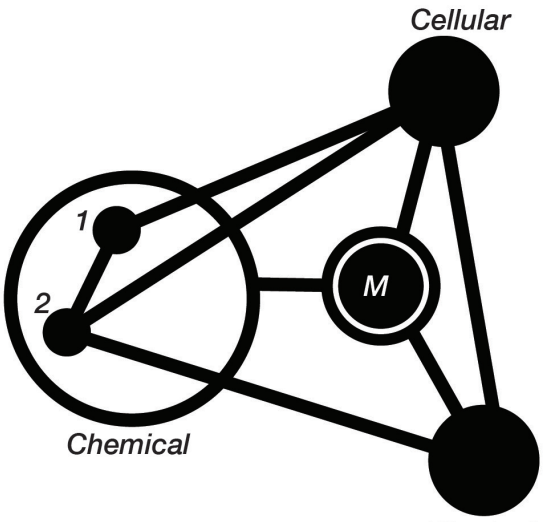
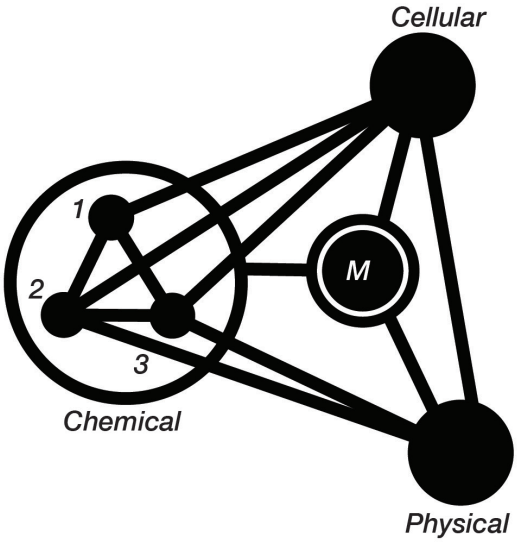


M Morphology

1 Nutrient concentration
2 pH Levels

02



M Morphology

1 Nutrient concentration
2 pH Levels
3 Surface hardness

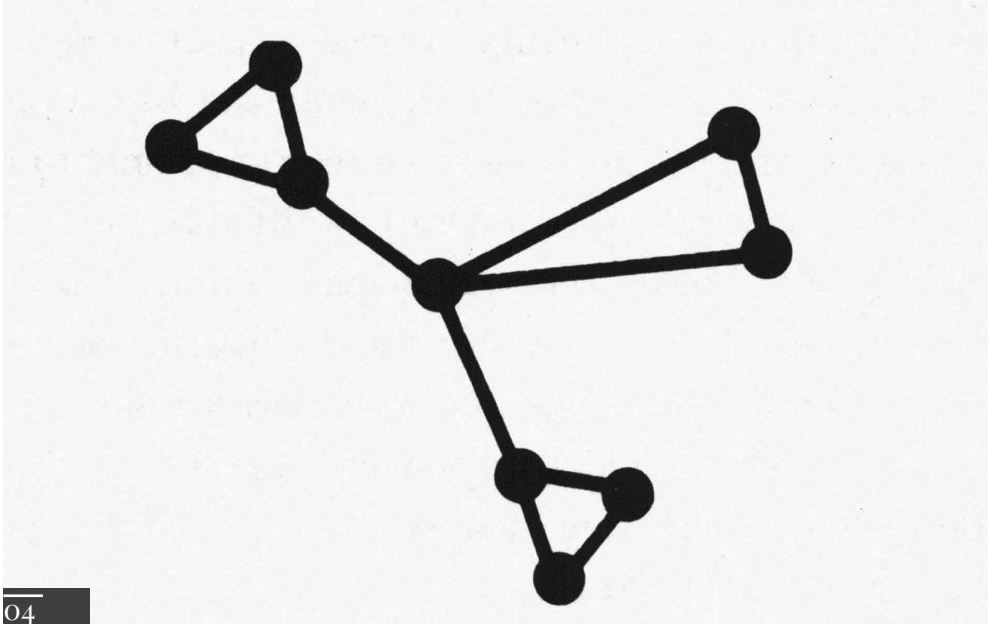
03

relevant, how they connect to one another and the effect they ultimately have on the synthesis of form. He illustrates this mental image in the diagram in Figure 4. Nodes represent *misfit variables:* functional aspects that have an influence on the way the form adapts to its context. The solid lines represent *links* and indicate the way that variables affect or interfere with one another.

In describing Figure 4, Alexander explains:

> Such a graph serves as a picture of a designer's view of some specific problem. It is a fairly good picture, in the sense that its constituents (...) are available to him introspectively without too much trouble; also because it keeps our attention, neatly and abstractly, on the fact that the set of misfits has a structure (idem, pp. 80–81).

Design, Alexander goes on to propose, requires a constant redefinition of this mental image, which enables finding the form that best fits the requirements of the context. The process of refinement involves creating alternative configurations of how each requirement connects to others, or how they can be nested and grouped into different categories, as suggested in Figure 5. Alexander writes:



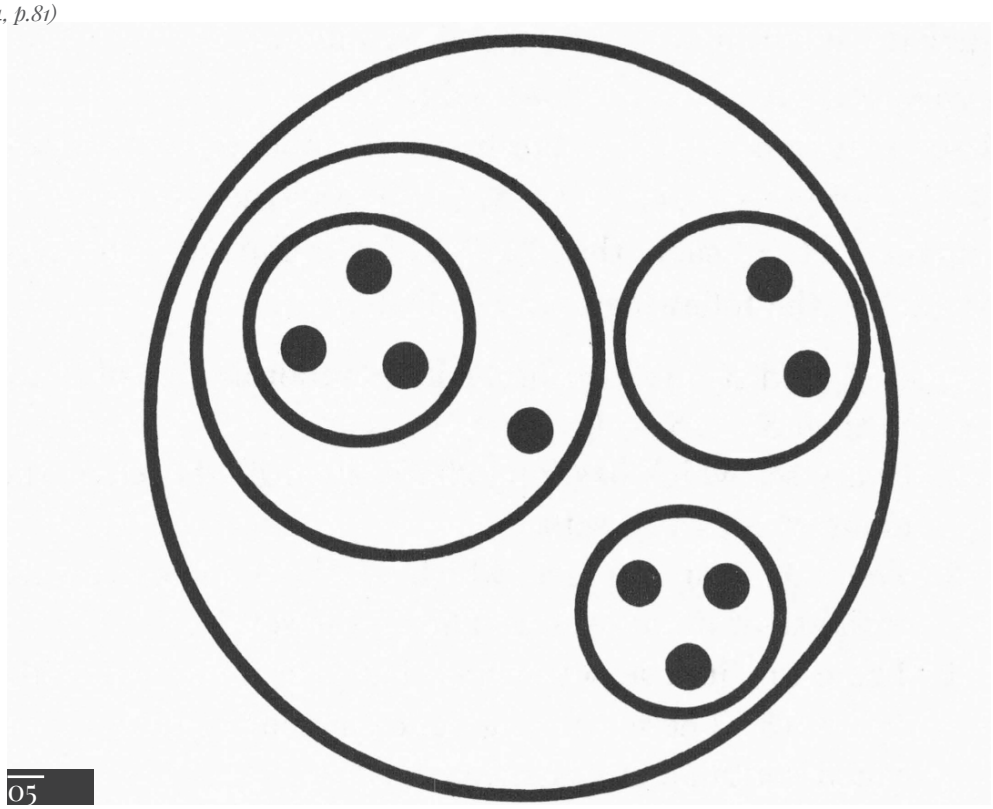
04

> It is very possible, and even likely, that the way the designer initially sees the problem already hinges on a conceptual hierarchy not too much unlike a decomposition in general outline. In trying to show that the links (...) favour a particular decomposition, I shall really be trying to show that for every problem there is one decomposition which is especially proper to it, and that this is usually different from the one in the designer's head (idem, p. 83).

In this chapter, I propose using the state-space of design as a parametric approach to biological systems. Moreover, I intend to use the diagrammatic exercise developed by Alexander to define the decomposition of each *state-space*. There are, however, important differences between how Alexander uses these diagrams, and how I propose to use them in this chapter. For Alexander, these diagrams constitute a tool to define a design problem, and to refine the optimal configuration in which a form

04 *Representing a designer's mental picture of the design situation. Reproduced from Alexander (1964, p.80)*

05 *Diagram representing the different configurations that misfit requirements can assume in a diagram. Reproduced from Alexander (1964, p.81)*



05

adapts to its context. In contrast, I have proposed using *bio-material probes*, which are predicated on an open-ended design process and non-deterministic outcomes. As such, the diagrams are not geared towards producing an optimal form, but rather intended to explore how the notion of parameter can be escalated to an actual biological context. Moreover, the diagrams are intended to assist in the formulation of strategies through which the designer can have some control or influence over the development of biological form. Two instances of biological form are used in this chapter. The first *bio-material probe*, *Bacterial Crystals*, uses the design context of *biomineralisation*, used above to develop the notion of state-space, articulates the physical space. The second, *Bacterial Morphologies*, uses the design context of bacterial branching, and decomposes the physical and chemical spaces, providing a wider context to reflect upon the advantages and limitations offered by the model of state-space of design.

4 PHILOSOPHICAL CONTEXT: BLACKBOXING

In the *bio-material probes* used in this chapter, the state-space framework is implemented through a strategy of *blackboxing*, which keeps the designer separate from the biological system itself. This expression has been used by Bruno Latour as a way of describing how technology is often invisible to its users, who are not required to grapple with its internal complexity. Rather, they are required to understand the system in terms of input and output, without having a detailed understanding of the processes that enable the transformation. Latour defines *blackboxing* as:

> An expression from the sociology of science that refers to the way scientific and technical work is made invisible by its own success. When a machine runs efficiently, when a matter for fact is settled, one need focus only on its inputs and outputs and not in its internal complexity. Thus paradoxically, the more science and technology succeed, the more opaque and obscure they become (Latour 1999).

Latour goes on to explain how blackboxing enables users of technology to understand a component as a single entity, which operates according to predefined parameters.

Although blackboxing is problematic in the sense that it limits the engagement and understanding of the technology, it is helpful in the context of this chapter as a strategy to engage designers without previous biological knowledge. Both *bio-material probes* were designed as primers, part of themed design studios in Stage 6 of the *Masters in Architecture* programme. Primers are short design exercises, lasting five weeks, which are used in the context of the School of Architecture at Newcastle University to engage students in novel themes and technologies that serve as inspirations for their year design projects. Direct engagement with biological systems would require, for example, the provision of workshops to introduce students to health and safety rules, to cover the basic principles of experimentation in a biological lab, and some training in using the tools and techniques required for the specific experiment. The amount of time available in a primer, however, limits the possibility of implementing direct engagement with laboratory work.

Instead, both primers were designed following a blackboxing approach. The exercises involved collaboration with a scientist partner, Dr Meng Zhang from the Department of Applied Sciences in Northumbria University. Exercises were designed to provide students with an initial visit to Dr Zhang's laboratory, in which they would be given a brief talk on the complexities of laboratory work. The visit would be followed by a design tutorial back at the School of Architecture, where they would be introduced formally to the state-space framework, and given instructions on the specific parameters they could manipulate. Students were also asked to develop a format to communicate their design systems as a precise set of laboratory protocols, making specific notes on how each of the proposed parameters were to be implemented. Developing these protocols required them to draw upon their initial visit to the laboratory, thinking about the implications and feasibility of the proposed strategy. At the same time, they stressed the approach of blackboxing, keeping the designer away from the actual implementation of the proposed systems. The collaboration made it possible to run this exer-

cise in the space of a month. Moreover, it enabled the handling of complexity in such a way that students could engage directly in exploring how specific parameters could be manipulated, while specifying the others according to the guidelines provided.

The strategy of blackboxing, however, has several shortcomings. While it is a useful strategy for handling complexity, it is also constraining in the sense that it doesn't provide enough information for designers to identify the parameters that are relevant in each design system. In the previous section, I suggested implementing the model of state-space of design using diagrams to formalise the structure and connections of different parameters. I also reviewed how the strategy, first employed in design by Alexander, involves a reiterative process of redrafting diagrams, which contributes to a refinement of the understanding of the system itself. Refinement, however, is contingent upon an understanding of the system, which is always limited when the designer remains outside the design system.

2

PART TWO

EXPLORATION TRACK ONE: BACTERIAL CRYSTALS

The *bio-material probe* of *Bacterial Crystals* uses biomineralisation as the design context, and explores how the physical state-space can be implemented. As described in Section *3.1*, there are state-spaces that provide more evident cues regarding how they can be articulated. I have used the chemical state-space as an example, describing how aspects such as pH and nutrient concentration are easier to represent as parameters and to capture numerically.

The physical state-space, however, is more challenging to articulate in terms of parameters. In part one of this chapter, I defined the physical state-space broadly as involving the physical forces and energy within the environment of an organism. In the original publication (Dade-Robertson et al. 2015), we suggested temperature of the growth environment, structure of the agar itself and the physical confines of some examples of the different aspects that constitute the physical state-space. Although some of these can be captured numerically, for example, temperature, others are more difficult to quantify and manipulate, such as the physical confines of the dish or the configuration of agar. The exploration analysed in this track focuses on strategies to articulate the physical state-space. The chemical state-space, on the other hand, is kept at constant levels, following early laboratory experiments on biomineralisation. The cellular state-space is manipulated using two species of the *Bacillus* genus, a gram-positive, rod-shaped bacterium commonly found in soils: *Bacillus pasteurii (recently reclassified as Sporosarcina pasteurii)*, and *Bacillus megaterium*.

The design experiments included in this track were previously published as part of the conference proceedings of *Prototyping Architecture 2013* (Dade-Robertson et al. 2013).

1 DESIGN CONTEXT: BIOMINERALISATION

Biomineralisation refers to the process by which living organisms produce minerals (Lowenstam & Weiner 1989; Tong et al. 2004). There is a wide array of processes in which biomineralisation is used. Multicellular organisms, for instance, employ it in the production of bones, teeth and shells. In bacterial biomineralisation, on the other hand, calcium carbonate crystals are precipitated when urease, an enzyme that alters the alkalinity of the extra-cellular matrix, triggers calcium particles to bind with carbon. In addition, bacteria produce extracellular polymeric substances (EPS), which have been shown to control both the morphology and distribution of calcium carbonate crystals (Tong et al. 2004).

In biomineralisation, the configuration and density of crystal formation is connected to the way that cells and bacterial colonies distribute in space. For example, Abalone generates its shell through an indirect process, which involves patterning cells in specific arrangements. Cells are used as soft scaffold in the sense that they manipulate the chemical composition of the environment, triggering a crystallisation process in their vicinity (Tong et al. 2004). This leads to the formation of hard mineral layers, which eventually become the structure of the shell. Moreover, cells are capable of controlling the macro-level properties of the shell. The cross section shows a gradient of compositions and textures, ranging from a hard outer shell to a soft mother of pearl interior. It is generally believed that these macro-level properties are connected to the microscopic configuration of crystals. Crystals on the inner soft layers of the shell are oriented horizontally, while the outer layer is made up of vertical crystals to create an exceptionally strong surface.

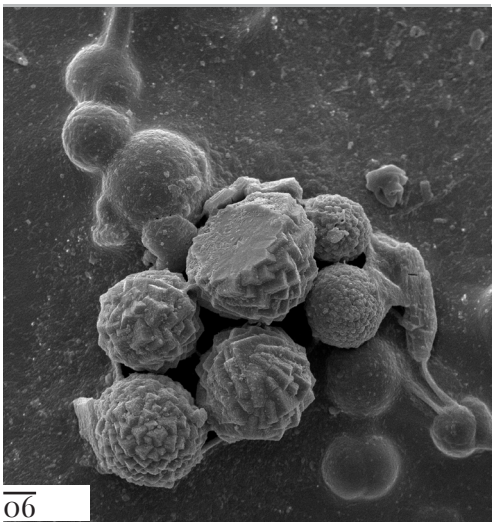
Prior to the design exercise with the students, a number of lab experiments were performed to better understand biomineralisation. Two different bacteria species, *Bacillus pasteurii* and *Bacillus megaterium*, were grown on a series of nutrient-rich plates, which contained calcium chloride, urea and a neutral pH. As described above, the metabolic activity of bacterial colonies have the effect of raising the pH of the growth medium, inducing the formation of crystals in the presence of calcium chloride (Dade-Robertson et

al. 2013; Dade-Robertson et al. 2015). These early experiments show the connection between cellular and chemical state-spaces. Figure 6 shows crystals resulting from the activity of *B. pasteurii*. The texture and geometry of the crystals is contrasted with those of Figure 7, which were created by the metabolic activity of *Bacillus megaterium*, featuring a plate-like structure.

The experiments hint at some of the connections between the cellular state-space and the configuration of crystal structures. It is generally believed that bacteria is capable of changing the chemical composition of its immediate environment, creating a gradient of chemical concentrations across the plate (Wheeler et al. 1981). Extracellular processes change the concentration of xanthan and amino acids, which have a direct effect on the morphology and concentration of crystals. Figures 8 and 9 show some examples of these processes in action. Figure 8 shows crystals that can be seen to be connected through a mesh of what is thought to be organic, tubular structures connecting bacterial colonies. The relationship between bacterial activity and crystal formation is made more evident in Figure 9, which shows uneven density in crystal distribution, which were interpreted as being tied to the concentration of bacterial colonies and their extracellular processes (Dade-Robertson et al. 2015).

2 BACTERIAL CRYSTALS AS BIO-MATERIAL PROBE

The experiments described above were used to define the design context of the *bio-material probe*. Students were asked to produce several prototypes, annotated by a laboratory protocol specifying their implementation. Biomineralisation was explained to students as a process in which bacterial colonies patterned in space and produced the chemical context to create hard mineral structures through crystallisation. Likewise, students were invited to think of the structures they would be producing as providing a further scaffold in the process, which would change the physical context in which the bacteria grew and influence the configuration of mineral formation.



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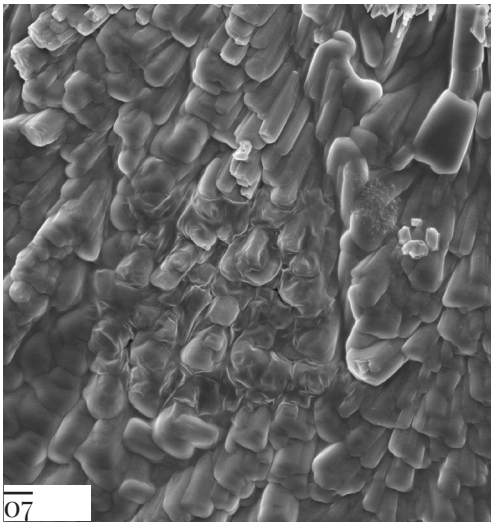

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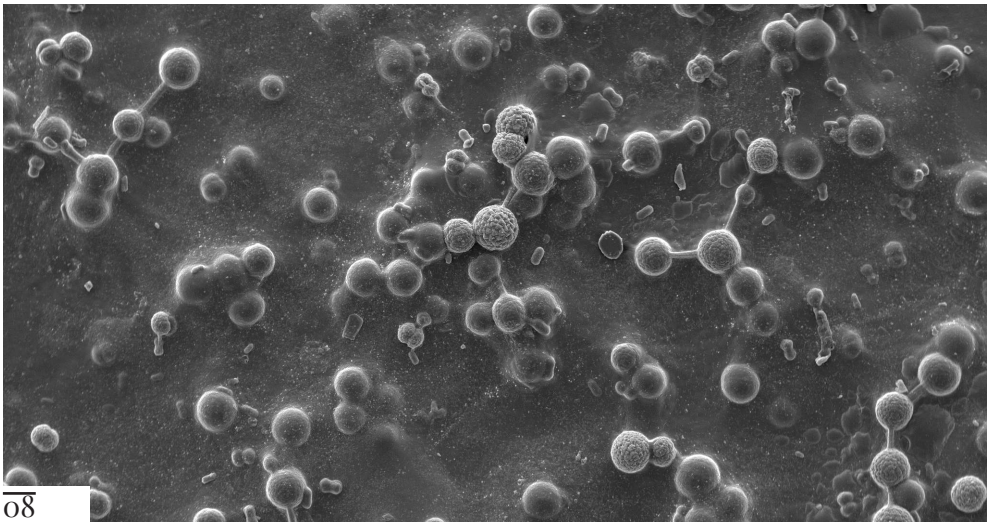

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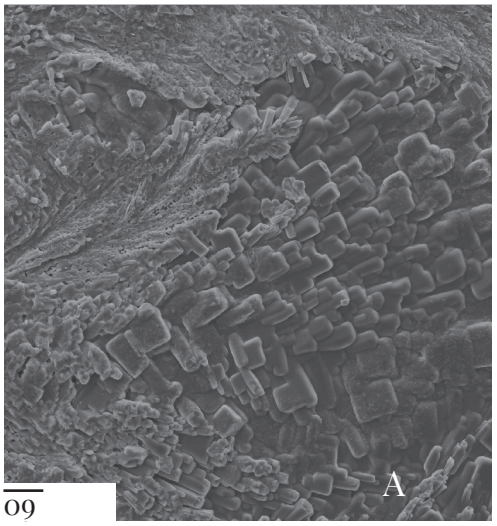

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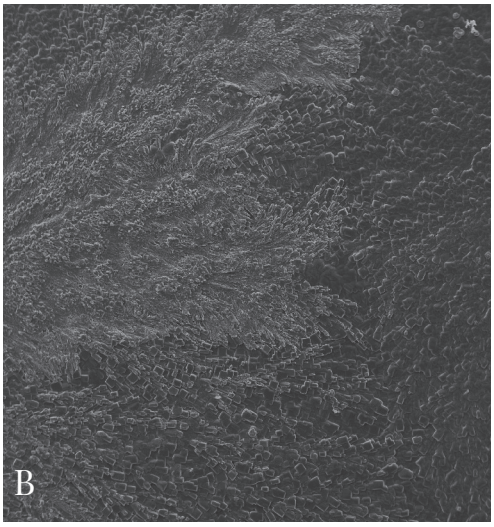

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The following sections reflect on some of the themes that emerged from the prototypes produced by the students, their design decisions and the complexities inherent in implementing their design by the scientist partner. The design exercise is used as a preamble to *Bacterial morphologies*, covered later in this chapter, and which delves deeper by opening all state-spaces to manipulation.

2.1
ARTICULATING THE CHEMICAL AND CELLULAR STATE-SPACE

The design exercise articulated the chemical and cellular state-space minimally. The chemical state-space, for example, was only articulated in one parameter for growth media type. Biological laboratory work often makes use of two growth media. Solid media is produced by mixing an agar solution with peptone, a mixture which remains liquid when heated, but solid at room temperature. Liquid growth media is also used, and is prepared by using powdered beef extract containing peptone, which is dissolved in distilled water. Each growth media offers different advantages. Liquid media, for example, offers a gradient of oxygen concentrations, which provide ideal growing conditions for organisms with oxygen-specific requirements. Furthermore, liquid media offers an environment in which microorganisms can move freely. Solid media, on the other hand, offers a gelatinous surface, which facilitates visual inspection of the cultures. These possibilities can be represented as a single node in the chemical state-space, as shown in Figure 10.

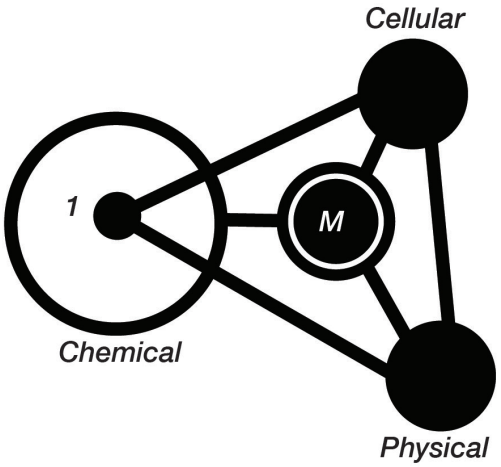
06 *Electron microscope image of calcium carbonate crystals precipitated by Bacillus pasteurii*

07 *Electron microscope image of calcium carbonate crystals precipitated by Bacillus megaterium*

08 *Electron microscope image of calcium carbonate crystals connected through an organic mesh*

09 *Image a and b show electron microscope images of plate-like crystals of calcium carbonate crystals precipitated by Bacillus megaterium.*

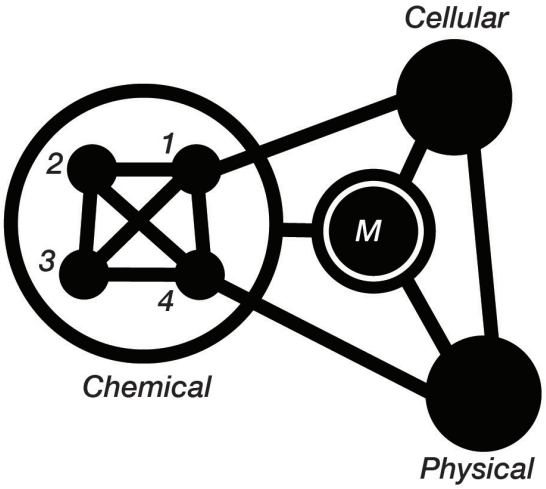
Other chemical parameters are worthy of consideration. To produce the adequate environment for biomineralisation, growth media should be prepared to specific levels of surface hardness (agar percentage), nutrient concentration and pH. These parameters are represented as nodes in Figure 11. The diagram also shows the links between surface hardness and the



M Morphology

1 Growth media type

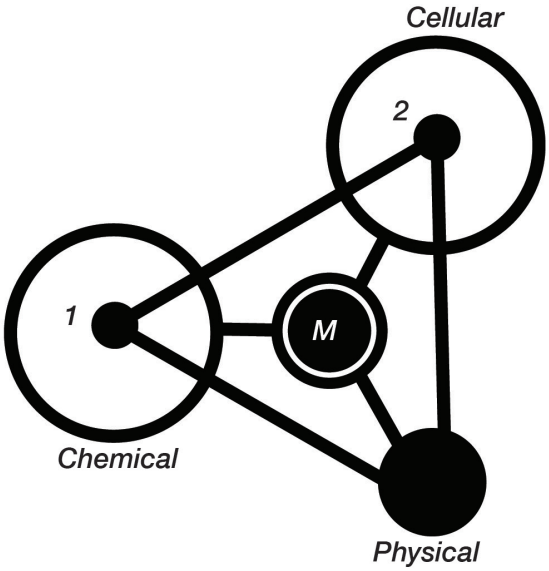
10



M Morphology

1 Growth media type
2 pH Levels
3 Surface Hardness
4 Nutrient concentration

11



M Morphology

1 Growth media type

2 Bacteria species

12

physical state-space, because agar concentration changes the physical configuration of growth media, thus exerting physical forces. Since the design experiments didn't open these parameters to manipulation, the following diagrams collapse them and include a single node for growth media type.

The *bio-material probe* was designed to articulate the cellular state-space using two different bacterial systems: *Bacilus pasteurii* and *Bacilus megaterium*. The existing literature has linked the metabolism of both species with an increase in urease and, as described in the preliminary experiments of biomineralisation above, can be linked to the production of different crystal morphologies. The articulation can be formalised in the diagram as a single node, which represents the bacterial species used, as shown in Figure 12.

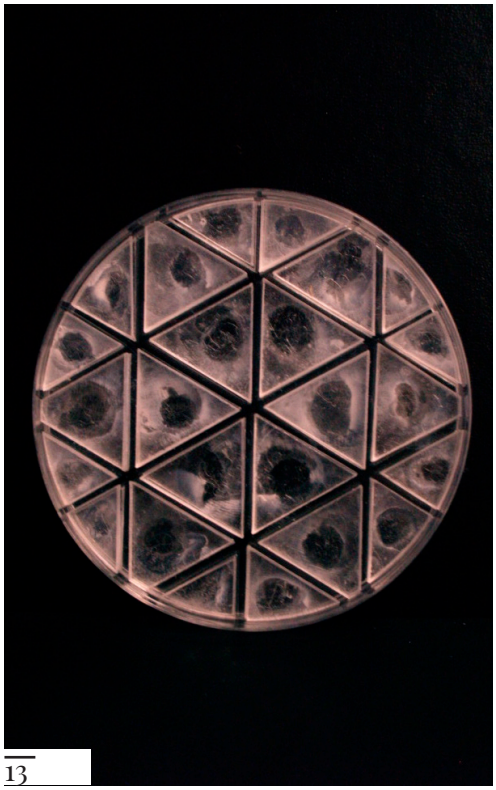
2.2
ARTICULATING THE PHYSICAL STATE-SPACE

The series of prototypes produced provided different strategies to articulate the physical state-space. One initial strategy involved generating insets: plastic pieces designed to sit inside a commercial petri dish. The geometry of these pieces enabled two main strategies. The first is characterised by the creation of narrow channels. Figures 13 to 16 correspond to variants of three dish insets produced in methyl methacrylate plastic. Pieces were initially laser cut in three-millimetre material and then glued together to achieve the depth of commercially available petri dishes. In the documentation handed over with the artefacts, students declared specific aims for experiments running with each of the artefacts. The prototype in Figure 13 was intended to test the growth of bacteria in narrow channels. The assumption behind this design was that the intersection of narrow channels would concentrate bacteria, producing denser crystal formations. The prototype in Figure 14, by contrast, was intended to test the directionality of bacterial growth. Lab protocol for this prototype involved inoculating at a single initial point to test whether the bacteria would follow the path created by the channels. A second strategy involved using narrow

10 *Diagram of the state-spaces of design featuring the growth media type*

11 *Diagram of the state-spaces of design featuring chemical parameters of growth media type, pH levels, surface hardenss and nutrient concentration*

12 *Diagram of the state-spaces of design, featuring the extra node on surface hardness inside the chemical*



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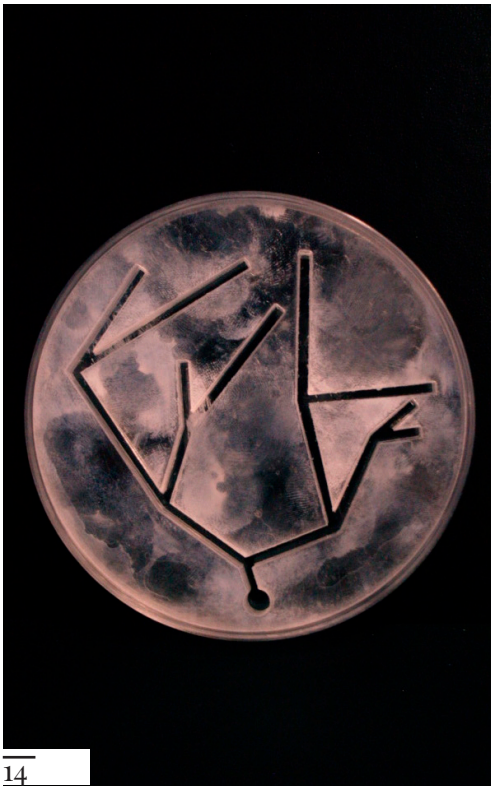

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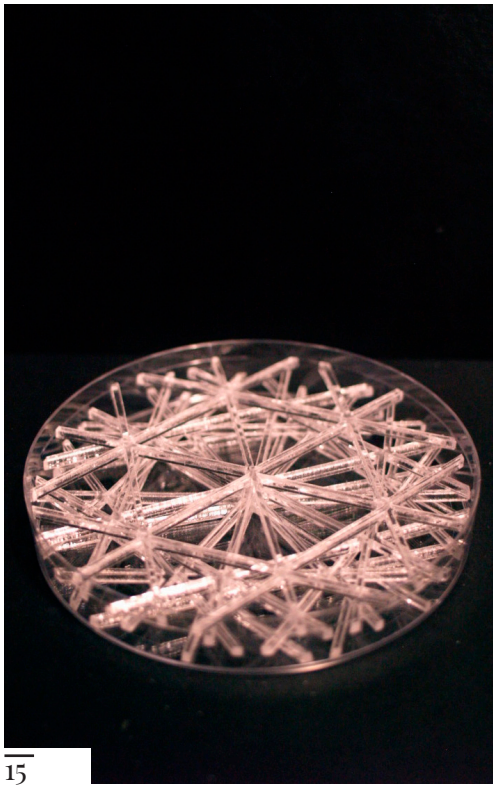

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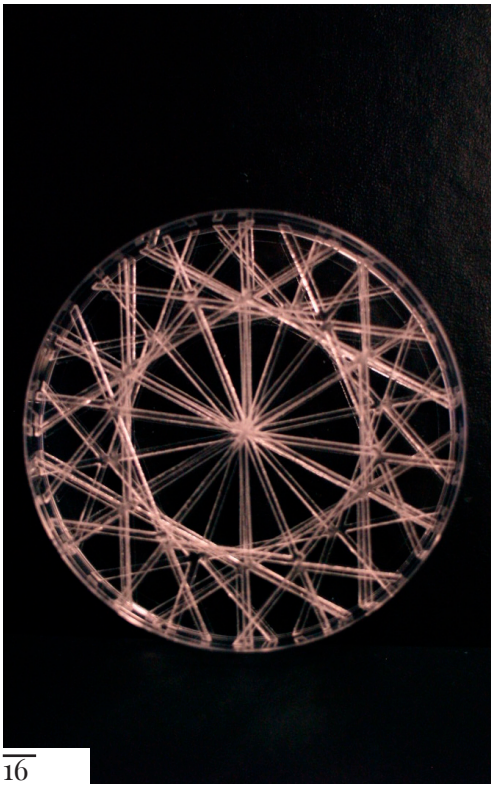

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plastic pieces, intended to create an intricate interior configuration of the growth media. Figures 15 and 16 show an example of this strategy, in which the prototype departed from the two-dimensional configuration of the first two and introduced a structure with complexities across depth. The intent of this was to test how bacteria reacted and behaved in the interstices between plastic layers.

These prototypes suggest an articulation of the physical state-space in terms of geometry, as shown in Figure 17. The different geometries are intended to produce different configurations that exert physical forces on the growing bacteria. One challenge in representing geometry as a parameter is its quantification. Each typology can, in principle, be *parametricised* in terms of specific features such as the number of parallel channels and arms, or the angle at which they intersect, for example. In a more general sense, however, it is difficult to represent each strategy along a sliding gradient of values.

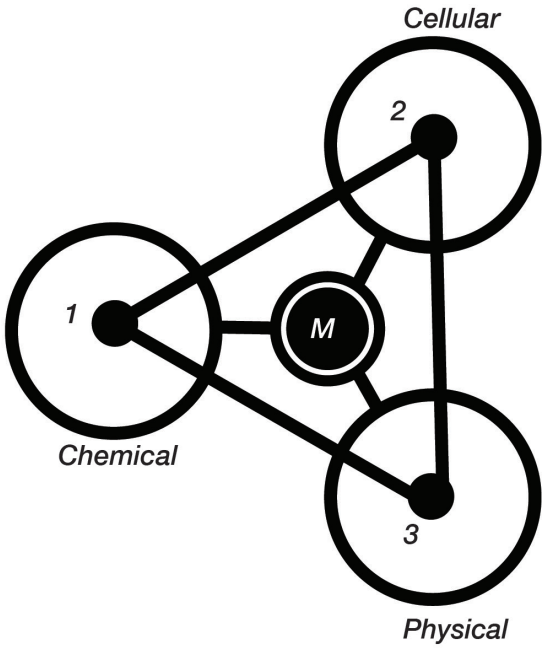
13 *Prototype for insert creating narrow channels*

14 *Prototype for insert creating narrow channels*

15 *Insert prototype creating an intricate interior configuration*

16 *Top view of the prototype produced in Figure 15*

17 *Diagram of the state-spaces of design featuring the chemical parameter of growth media type, the cellular parameter of bacteria species and the physical parameter of geometry*

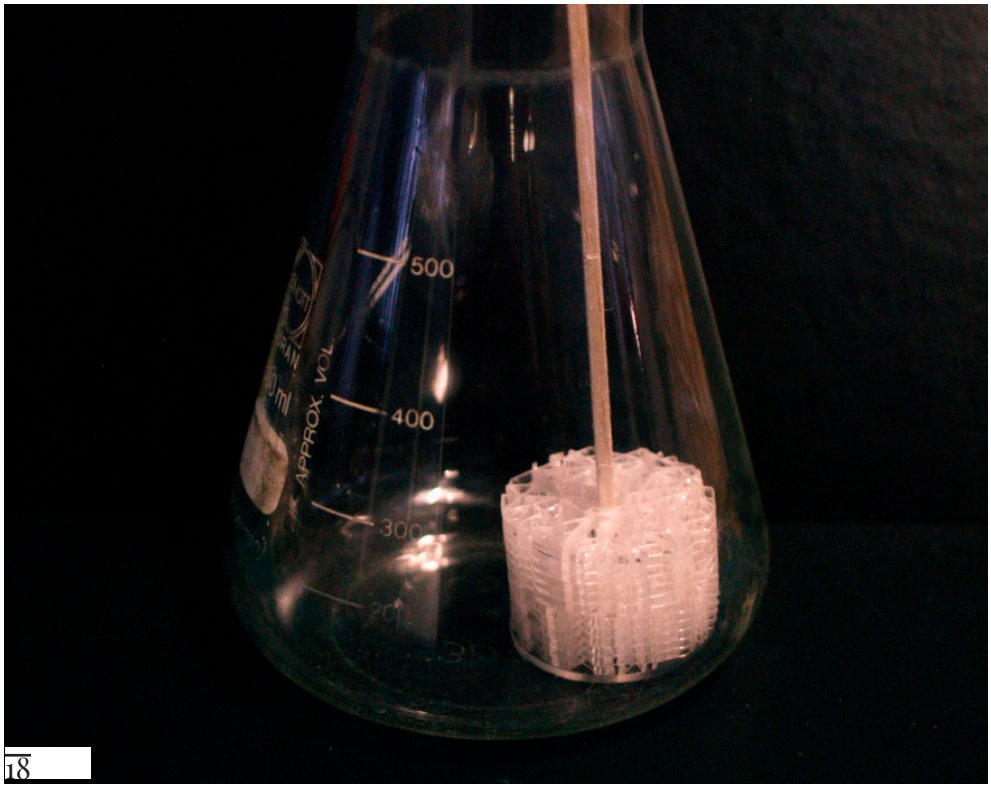


M Morphology

1 Growth media type

2 Bacteria species

3 Geometry



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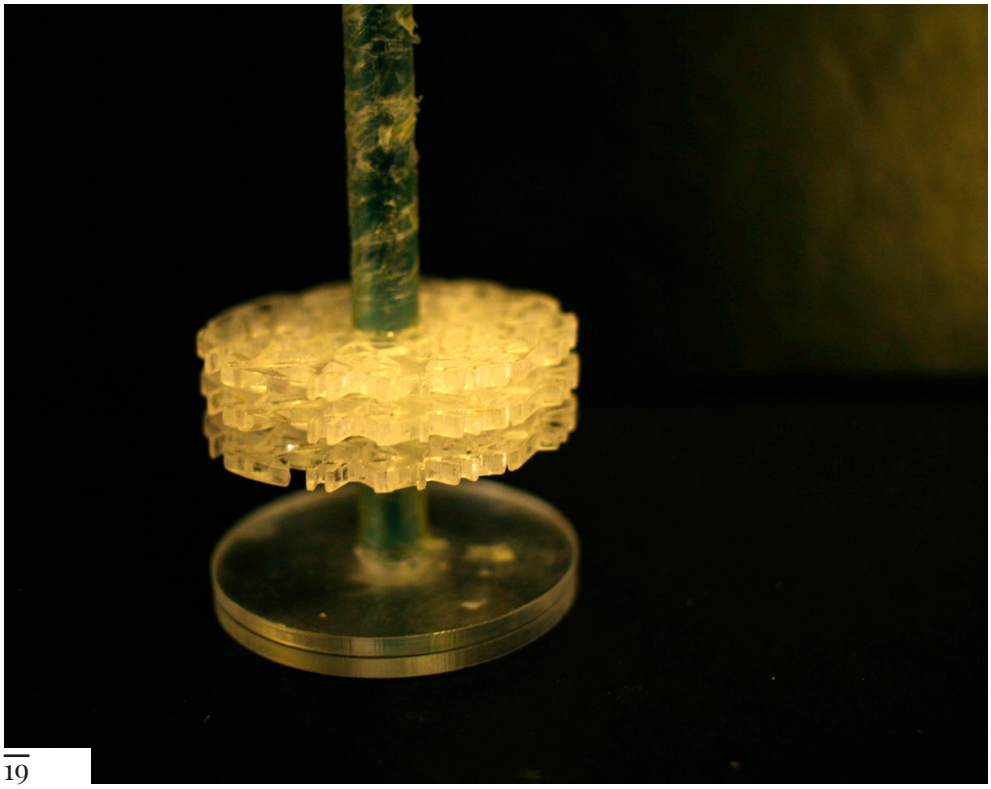

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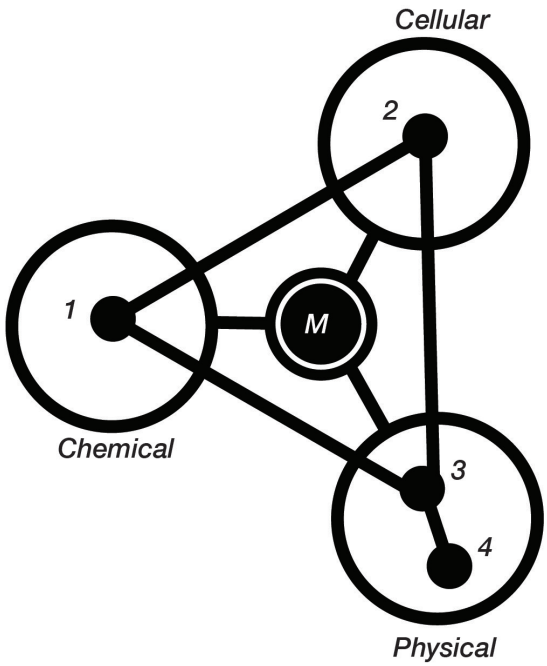
It is also important to highlight the nature of the link between geometry and growth media type. The prototype shown in Figures 18 and 19 was designed to operate in liquid media. It consists of a central rod, which is fitted with discs that are stacked to create layers of hard plastic. Each disc features a serrated outline, which is intended to provide crevices in which bacteria can attach. These design features are not only connected to a specific growth media, but also reflect aspects of laboratory protocol. During their introduction to the lab processes, students were shown how liquid media required the culture to be kept inside a shaker. The shaker available in the laboratory was optimised to take 500 ml conical flasks. As a result, the prototype is configured to fit through the mouth of the conical flask, as shown in Figure 18. The prototype not only illustrates the link between geometry and growth media represented in Figure 17, but also suggests the need for a further node, which includes the incubation protocol. Figure 20 updates the diagram to reflect the addition.

18 *Artefact designed for liquid media*

19 *Detail of artefact in figure 18*

20 *Diagram of the state-spaces of design featuring the chemical parameter of growth media type, the cellular parameter of bacteria species and the physical parameters of geometry and incubation protocol*



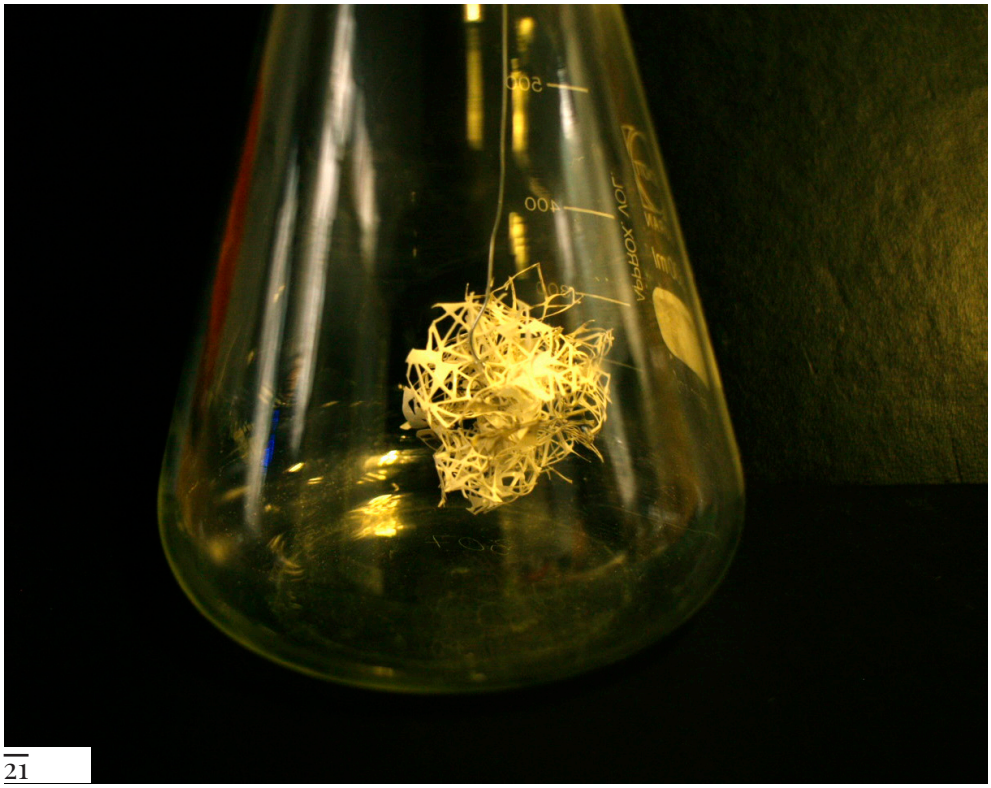
M Morphology

1 Growth media type

2 Bacteria species

3 Geometry
4 Incubation protocol

20



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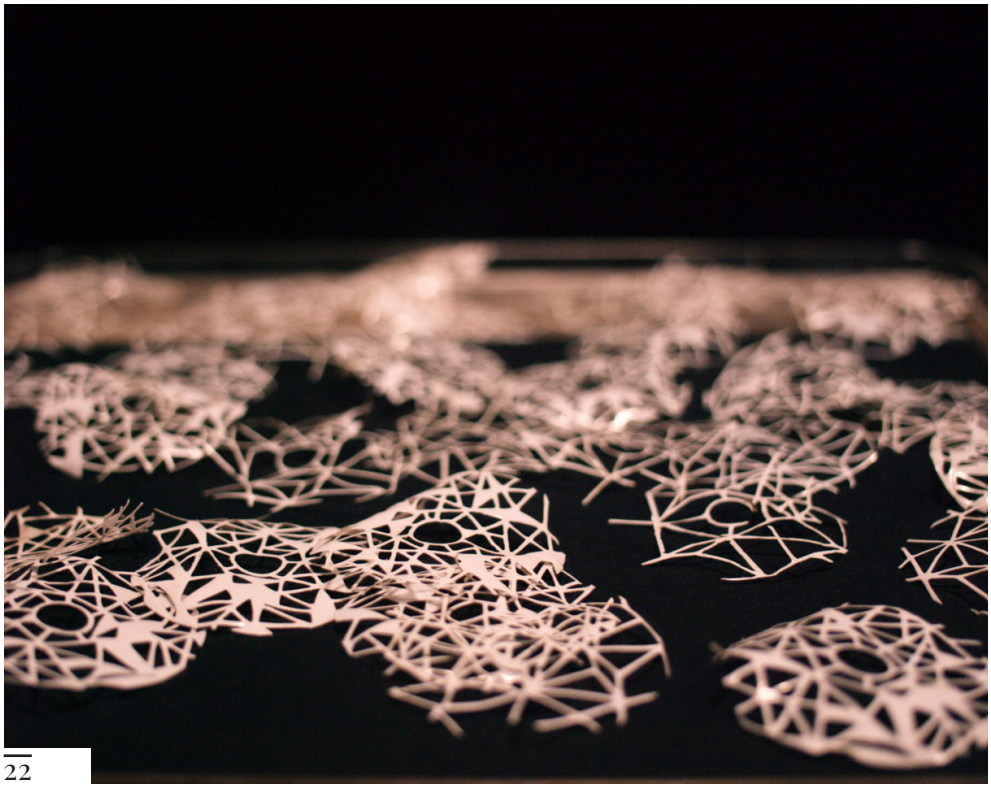
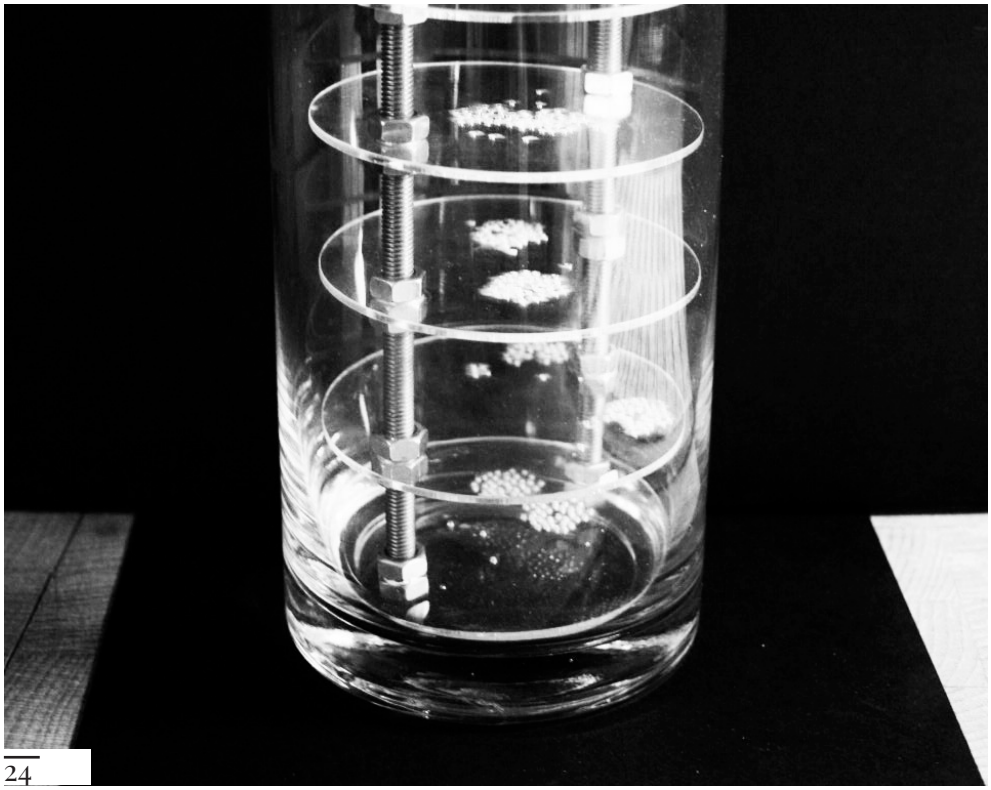


22

A second design strategy suggests a further articulation in material flexibility. Figures 21 and 22 show a prototype fabricated from protective film cutouts from the Perspex pieces used in the previous experiments. Slices were threaded together and shaped into a ball that was to be suspended on a flask containing bacteria in liquid media. The use of soft material was intended to test the possibility of the structure being hardened by the mineralisation process. It was speculated that bacteria might grow and stick to the surface of the structure, precipitating crystals that would harden the material. Conversations with our scientist partner suggested a further articulation of the state-space. One aspect she raised was that the success of mineralising soft structures might be connected to the porosity of the material, as well as its superficial finish. Porous structures might offer a more conducive environment for bacteria to cluster, increasing potential crystallisation. Likewise, a superficial finish might also have a bearing, as it would be easier for bacteria to stick to rough surfaces. Taking these features into consideration, the physical state-space is articulated in three further nodes, representing material flexibility, porosity and superficial finish, as shown in Figure 23. As the diagram suggests, the connections between nodes become complex. Porosity can also be connected to bacterial species, as the size of different species might determine which pore size, for example, might be better for fostering clustering.

21 *Artefact designed for liquid media*

22 *Detail of artefact in figure 18*



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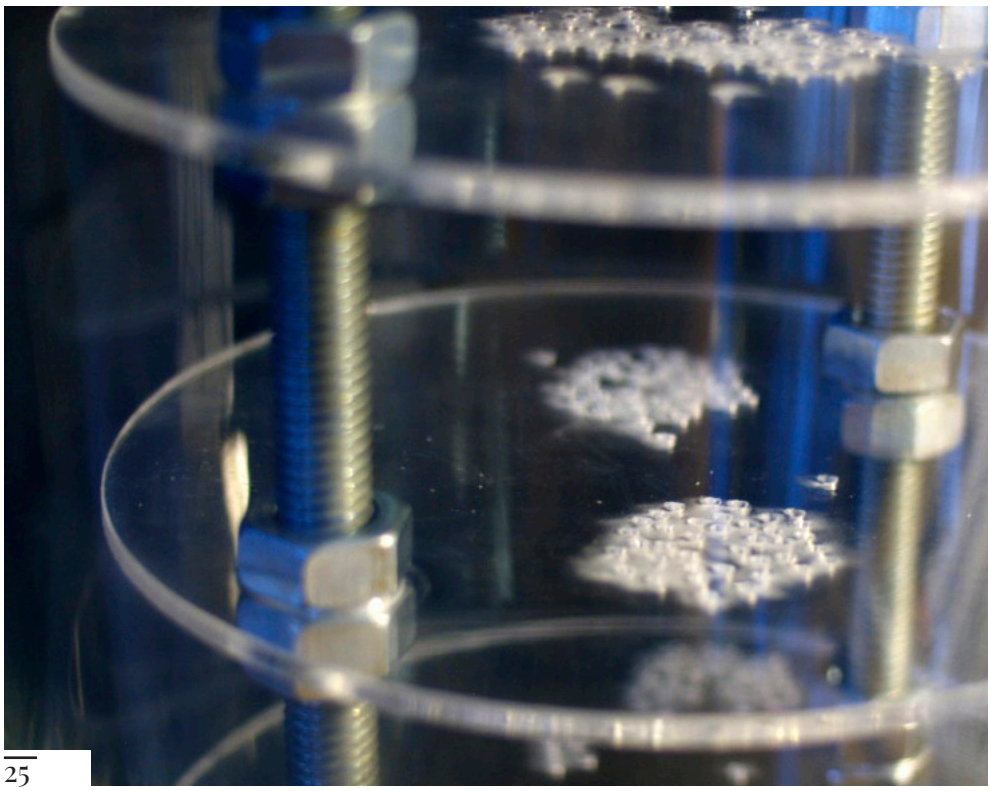

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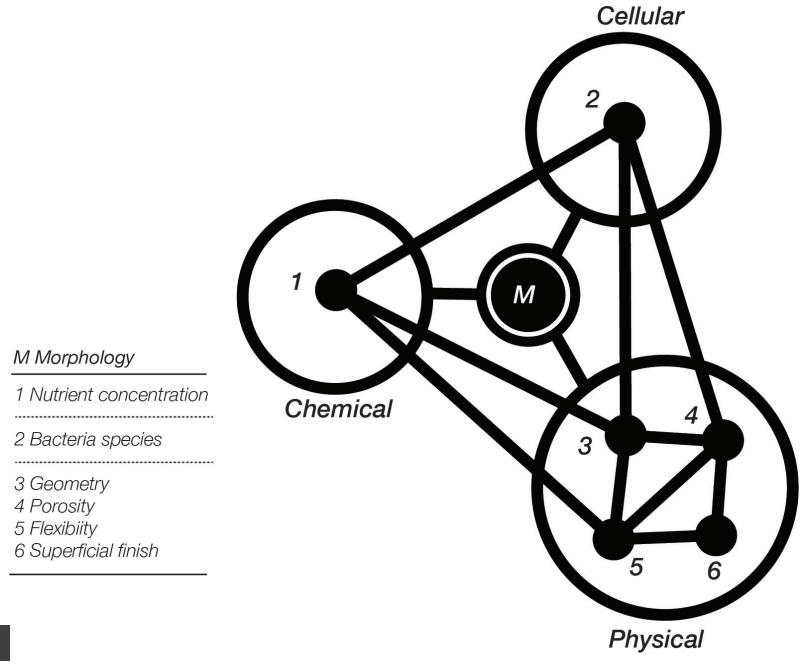


23

Other prototypes suggest there are parameters that cannot be grouped under the existing state-spaces. The artefact in Figures 24 and 25 was designed as a custom-built container, with internal layers of rigid plastic discs. Each disc is etched to create a nylon thread web. Conversations with our scientist partner, however, revealed a number of implementation issues. For one, the container was fabricated in Perspex, with joints that hadn't been bonded to stay watertight. In addition, the amount of liquid media required to fill the volume of the prototype was so great that it required the creation of a special protocol for preparation. Finally, the form-factor of the container made it impossible to fit it into the shaker, as it would be required for any liquid media experiments. These challenges suggest a further articulation of the design system, involving nodes that would represent the incubation procedure, media preparation and decontamination procedure. It is, however, difficult to fit these nodes into any of the existing state-spaces. Although they are connected to the physical state-

23 *Diagram of the state-spaces of design featuring the decompose nodes*

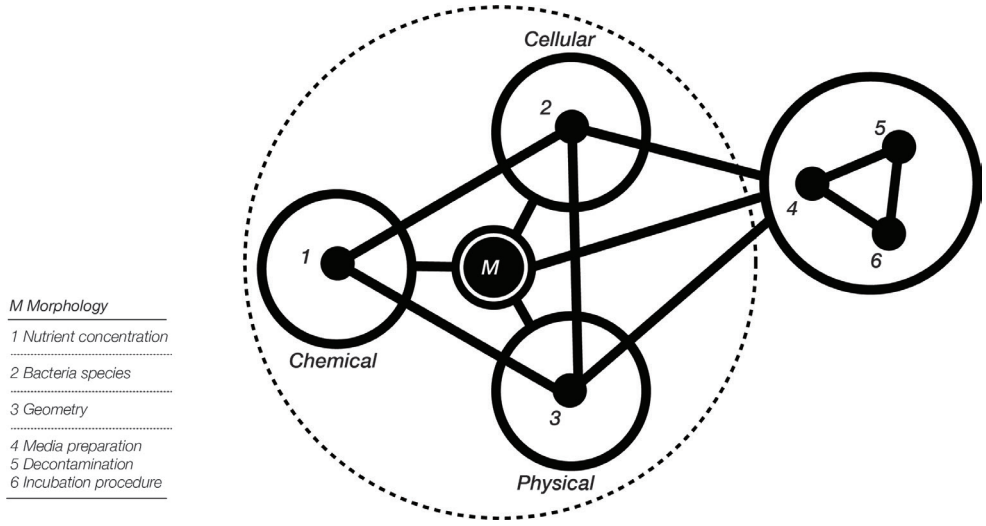
24 *Prototype featuring a custom-built container and a series of discs*

25 *The discs are fitted with holes, designed to thread nylon wire across them*

space, they are also related and contingent upon more complex aspects of laboratory practices. A good example is the alternative protocol suggested by the scientist partner. She suggested using solid agar, using a spatula to smear threads with agar solution before it settled and hardened. Formalising the new nodes in the existing diagram would require locating them in a new state-space outside the original ones, as shown in Figure 26.

26 *Diagram of the state-spaces of design. A new state-space has been included outside the three original ones*

27 *Example of a protocol sheet prepared by the students as documentation for the prototypes. The image hasn't been corrected for typos*



M Morphology

1 Nutrient concentration

2 Bacteria species

3 Geometry

4 Media preparation
5 Decontamination
6 Incubation procedure

26

2.3
SHORTCOMINGS OF BLACKBOXING

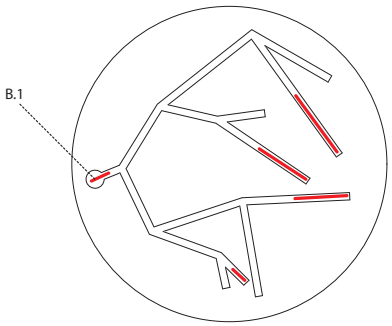
The prototype in Figures 24 and 25 also hint at some of the shortcomings of the blackboxing strategy. As described above, all prototypes were handed over to the scientist partner with a protocol sheet, which detailed the instruments and procedures required to implement the system. Figure 27, for example, shows the protocol sheet prepared for the prototype in Figure 14. The strategy was mainly oriented at engaging students with laboratory

B. Branching pattern (PETRI – AGAR).

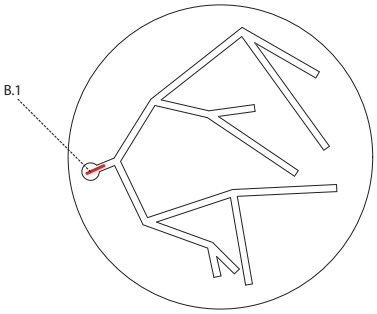
Aim – test whether the growth of calcium carbonate is directional and/or has a range dependant on the mass of available agar.

Procedure:

1. UV sterilise the Perspex mould and place in petri dish.
2. Pour agar into channels of tree network until a suitable depth is reached without flooding the plate.
3. Inoculate with bacteria A at circle location shown below:



or



4. Seal and incubate petri dish.
5. Remove samples from branch junctions for examination.

work, making sure they would take advantage of the collaboration with our scientist partner to ask questions that were relevant to their designs. However, the collaboration is not a substitute for direct engagement and, as the alternative protocol described above suggests, understanding laboratory techniques opens up new design possibilities.

There were further limitations caused by indirect engagement with the design context. Some of the prototypes, for example, proved challenging to implement in the laboratory, or resulted in no crystallisation. The prototypes in Figures 18 and 21, designed for liquid media, produced no clear signs of crystal formation. Conversations with the scientist partner suggested potential reasons for this. One is that the porosity of the material and its surface finish was not ideal for bacterial growth, which might suggest that these parameters can only operate within a tight range of values. Another possibility involves fine-tuning some of the protocols to specific parameter values. For example, the speed used in shaking the liquid experiments would need adjusting to foster growth with the different prototypes. Another aspect that hints at the shortcomings of blackboxing is the way in which protocols were changed by the scientist partner during implementation. Despite the students handing in detailed protocol sheets, a number of laboratory work contingencies required the experiments to be modified. Some of them include, for example, reducing the amount of agar to correspond to the containers used to prepare it. In other cases, the suggested inoculation points were too difficult to reach with the available instruments, and needed to be modified or reduced. The lack of direct knowledge of these instruments and practices reduced the possibility of anticipating these contingencies.

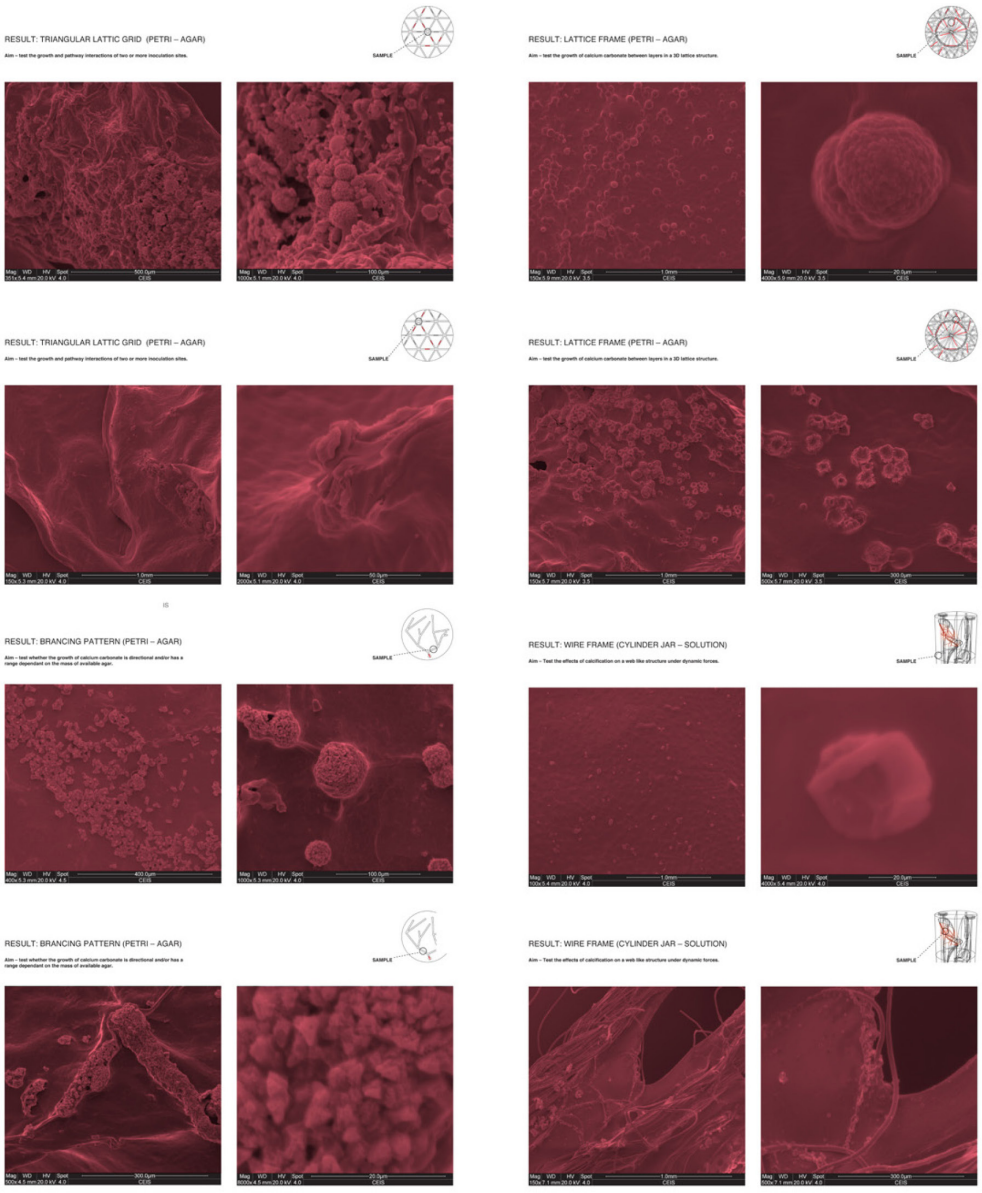
2.4
RECONFIGURATION OF THE STATE-SPACE DIAGRAM

The contingencies analysed in the previous sections suggest a continuous reconfiguration of state-spaces. The series of diagrams analysed in 2.1 suggest that including a new node often required creating another, or reconfiguring a state-space entirely. This is the case in Figure 23, where considerations of material flexibility required considering porosity and superficial

finish. Moreover, it was suggested that porosity is also connected to bacterial species, located in the cellular state-space, as larger or smaller microorganisms might be more or less affected by certain configurations. Another example is the growth media type parameter. Using liquid media required the addition of the flexibility parameter, which in turn precipitated the addition of the porosity and superficial finish nodes. In addition, these parameters are relevant only to very specific configurations of the state-space.

2.5
STATE-SPACES AND FORM

As suggested above, the design exercise was useful in understanding the complexities of implementing a parametric system within an actual biological context. The design decisions suggested interesting articulations of the physical state-space, and hinted at any shortcomings of the model. Although the experiments constituted a small sample from which to draw any conclusions, the results suggest links between the state-spaces and crystal formation (as suggested by the condensed result matrix shown in Figure 28). Generally, it can be speculated that crystal formation is denser inside crevices, especially for *Bacillus pasteurii*. Figures 28A and B, for example, show the result of inoculating *pasteurii* inside narrow channels. The sample used in 28A was taken from one of the central intersections of the prototype, and shows a higher concentration of crystals. By contrast, 28B was taken from an intersection closer to the edges of the prototype, where crystals are found to be more evenly spread, with clusters of only a few spherical crystals. The experiments also provide some evidence of hardening of soft materials. Figures 28F and 28H show samples of thread taken from the custom-built prototype. The images show some evidence of calcium carbonate crystal clustering around the threads. Following the patterns observed in the other scaffolds, clusters appear fragmented and less well defined than, for example, formations in 28A with the triangular lattice grid.



28 *Diagram produced by the students showing electron microscope images from each of the experiments developed with the scaffolds. The image hasn't been corrected for typos*

3

PART THREE

EXPLORATION TRACK TWO: BACTERIAL MORPHOLOGIES

The *bio-material probe* of *Bacterial Morphologies,* uses bacterial branching as the design context. The exercise builds on *Bacterial Crystals*, which worked as a preface to using the state-space of design as a parametric approach. Although the probe was limited to, largely, manipulating the physical state-space, it also provided valuable insights, such as the reconfiguration of state-spaces and the shortcomings of blackboxing.

Bacterial Morphologies implements some of the strategies used in *Bacterial Crystals*, while using them in combination with the chemical state-space. The cellular state-space is kept stable, using *Bacillus subtilis* strain *168,* a gram-positive, rod-shaped bacterium commonly found in soil and the gastrointestinal tract of humans and ruminants, throughout the exercise. As with *Bacterial Crystals*, this probe is designed as part of the primer component of a Stage 6 Design studio. The primer asked students to consider bacterial branching as a parametric, form-finding system that leverages how bacterial colonies organise in sophisticated ways to develop forms that adapt to contextual conditions. In essence, the exercise looked at the possibility of having a catalogue of shapes associated with specific parametric values.

The exercise is also designed around a blackboxing strategy, involving collaboration with our scientist partner, Dr Meng Zhang. Students were charged with creating a series of prototypes, in which parameters would be specified and communicated to Dr Zhang for implementation in the laboratory. To achieve this, they were introduced to the techniques involved in the development of micro-biological experiments. Dr Zhang provided an introductory lecture and demonstration in the laboratory, which covered the basic steps of experiments with bacterial cells, the decontamination of instruments and containers, mixing and handling growing media, as well as the handling of pipettes and inoculation. A second session was organised to enable students to ask Dr Zhang specific questions regarding their designs.

In the following section, I provide an introduction to bacterial branching as a design context. I describe the way that bacterial colonies adapt to the conditions in their environments by developing branches, which are the result of sophisticated strategies of specialisation and coordination. Moreover, I

propose that bacterial branching is often reported in scientific literature in a way that lends itself to a parametric approach, providing a catalogue of forms connected to specific values in nutrient concentration and surface hardness. I then describe how the design exercise was implemented in two phases to account for the added complexity of manipulating both the physical and chemical state-space. These sections provide the groundwork for a discussion on how *Bacterial Morphologies* operates as a *bio-material probe*, expanding on the themes discussed in *Bacterial Crystals*.

1 DESIGN CONTEXT: BACTERIAL BRANCHING

Bacterial branching refers to spatio-temporal patterns that are observed in some bacterial colonies in response to adverse growth conditions. These responses are the result of sophisticated, coordinated efforts of the bacterial colony. Ben-Jacob (2009) describes how, when grown under ideal laboratory conditions, bacteria exhibit few, if any, social or cooperative mechanisms. Studies from the 1990s onwards, however, have revealed highly complex behaviours of bacterial colonies (Golding et al. 1998b; Ben-Jacob 1998b; Ingham et al. 2008; Ben-Jacob et al. 1998). Under sub-optimal growth conditions, bacteria develop in large, complex colonies capable of adapting dynamically to their environment. One adaptation strategy involves branching. Low nutrient levels force bacterial colonies to implement a series of behaviours to organise in optimal spatial patterns, which maximise access to resources with the lowest energy use. The strategy results in the formation of branches, which refer to elongated aggregations of bacterial cells that extend from a dense core, promoting context exploration.

Branching patterns are defined by a set of chemical transactions, which enable bacterial cells to communicate and organise in sophisticated behaviours, such as cell differentiation, the distribution of tasks and the generation of functional subunits (Ben-Jacob et al. 1998; Ben-Jacob 1998a). The process of branching is of particular interest to the generation of biological form, as it is capable of creating complex spatial organisations that adapt

to their environment without explicit genetic programming. Ben-Jacob has stressed the flexibility of bacterial cells, proposing that they operate by dynamically adapting their internal structure and behaviour, which enables colonies to configure into high levels of functional complexity:

> To form such multicellular superorganisms, new functional features appear at every level from the internal cellular gel and genome states to the growth of the colony as a whole, thus facilitating a high level of functional complexity. Bacteria cannot store genetically all the relevant information required for creating colonial patterns. In a new scenario that I propose they need not do so, because the respective units (the individual bacteria) assume newly co-generated traits and faculties that are not explicitly stored in the genetic information of the individuals. The required contextual information is cooperatively generated by using internally stored information, as well as new information extracted from the environment. Thus, these bacteria only require genetically stored information on how to produce perceptive faculties and how these capabilities, along with the guidelines for using them, may be employed to generate new knowledge as required (Ben-Jacob 2009, pp.25–26).

In the quote, Ben-Jacob describes bacterial colonies as a form of multi-cellular superorganism. Although individual bacteria have very limited movement and sensing, they can organise themselves into colonies that provide enhanced traits and faculties. Branching can be described as a self-organising phenomenon, in the sense that mechanisms of signalling allow cells to organise into complex spatial patterns. Chemical signalling enables communal forms of communication and memory, which creates a collective awareness of their context and enables swarm behaviours to forage for the closest nutrient sources (Ben-Jacob 2009).

1.1
A PARAMETRIC READING OF BRANCHING

One relevant aspect of bacterial branching is that the way it is reported in scientific literature is conducive to a parametric reading. Fujikawa and Matsushita (1989; 1990), for example, have studied the way *Bacillus subtilis* develop branching morphologies under different levels of nutrient and sur-

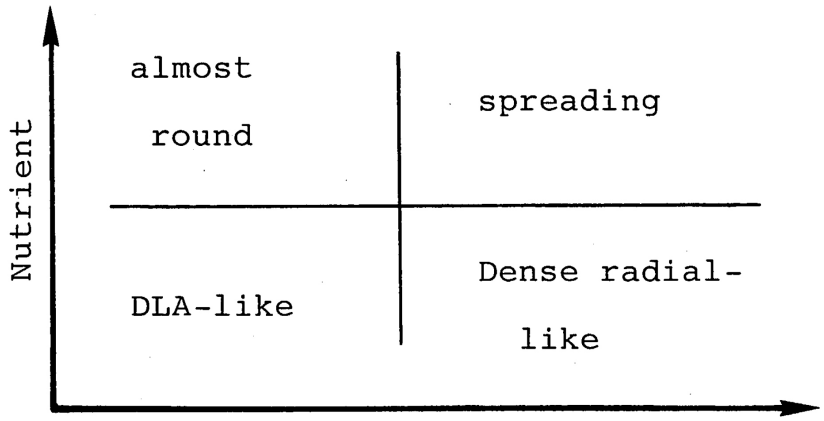
face composition. The chart in Figure 29 shows what can be described as the state-space of the *Bacillus subtilis* branching patterns: it correlates the emergence of morphologies to the levels of nutrients and surface moisture, allowing the state of a dynamic system to be mapped through a combination of both parameters.

Other studies also offer a vast catalogue of bacterial branching connected to nutrient and surface hardness values (Golding et al. 1998b; Ben-Jacob 1998b; Ingham et al. 2008; Ben-Jacob 1997; Ben-Jacob et al. 1998; Ben-Jacob 2009). Ben-Jacob, for instance, has studied how when *Bacillus subtilis* 168 is grown in harsh conditions, characterised by a low concentration of nutrients and a hard growth surface, it grows into complex, radial branches. Conversely, better conditions prompt the emergence of more compact branching. Ben Jacob goes on to propose a computer model, which characterises bacterial cells as random walkers that move within an area defined by a lubricating fluid segregated by the colony. Differential equations are used to calculate the rate at which cells consume nutrients in their environment, and the way these sources deplete and diffuse in the medium. Additional counters keep track of the levels of energy reserve for each cell. If cells are not able to locate and consume nutrients, their energy counter decreases until it reaches a pre-established threshold and they become spores. The term refers to *a dormant form of bacteria with the capacity for life when environmental conditions become favourable* (Ramirez-Figueroa, et al, 2016). Similarly, when a cell fills up in energy reserve, it subdivides. Using the simulation, Ben-Jacob produces the chart in Figure 30, which correlates branching patterns with nutrient levels (plotted in the horizontal axis and labelled P) and surface hardness (vertical axis labelled Nc). The diagram suggests a behaviour where high peptone levels induce a higher concentration of branches. Similarly, lower levels of nutrients create denser cores with few branches. Surface hardness

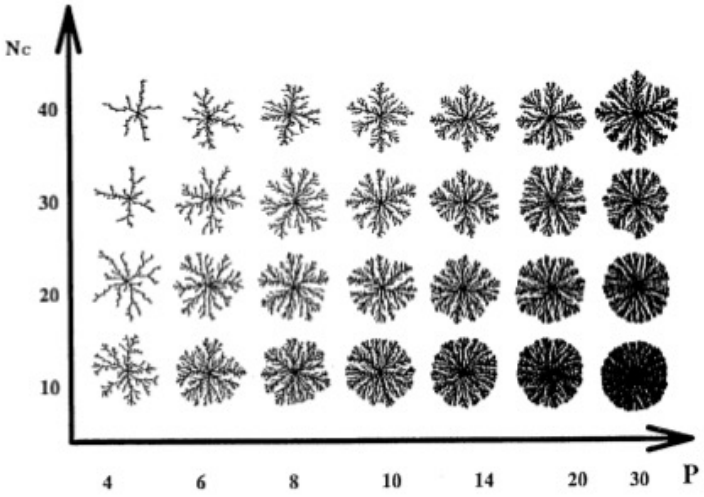
29 *State-space diagram of the branching morphology of Bacillus subtilis, included in (Fujikawa & Matsushita 1989)*

30 *Shape catalogue produced by Ben-Jacob using the communicating walkers model. Branching patterns are positioned in a two-axis matrix, showing their correlation to nutrient and surface hardness growth conditions. Values in P correspond to peptone levels, where, for instance, a value of 10 corresponds to 1 g/L. Similarly, Nc describes the agar concentration, which is responsible for surface hardness. A value of 40 in the chart corresponds to an agar concentration of 4%. Illustration from Eshel Ben-Jacob (1997, p. 217).*

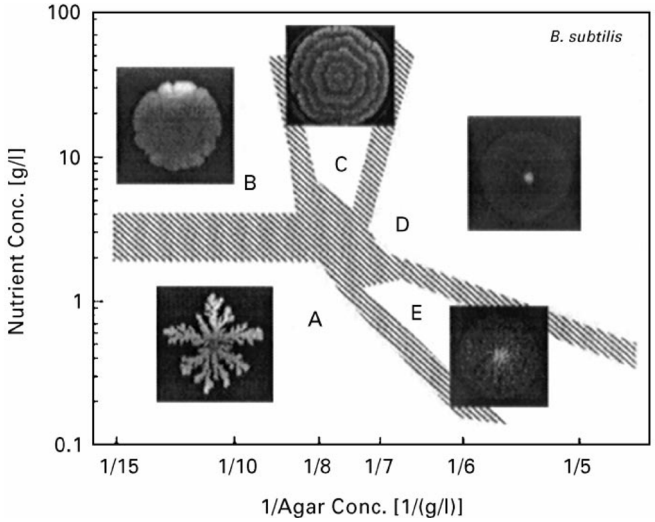
31 *Diagram of Bacillus subtilis OG-01 morphologies linked to agar and peptone concentrations. Produced by Golding et al. in compiling the work of Matsushita*


almost
round
spreading
DLA-like
Dense radial-
like
Nutrient
Surface Moisture

29


Nc
40
30
20
10
4
6
8
10
14
20
30
P

30


B. subtilis
100
10
1
0.1
Nutrient Conc. [g/l]
A
B
C
D
E
1/15
1/10
1/8
1/7
1/6
1/5
1/Agar Conc. [1/(g/l)]

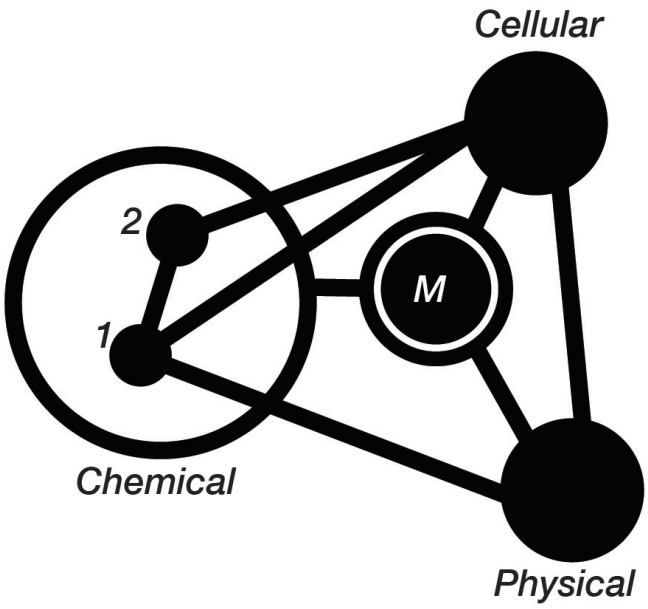
31

has the inverse influence in branching formation. Higher values of surface hardness result in a lower concentration of branches, while softer mediums result in a higher density of branches.

Similarly, Golding et al. (1998a) compiled the work of Matsushita et al. (Fujikawa & Matsushita 1989; Matsushita & Fujikawa 1990; Fujikawa & Matsushita 1991; Matsuyama et al. 1993; Matsuyama & Matsushita 1996) on the branching of *Bacillus subtilis* OG-01, and produced the diagram in Figure 31, also linked to nutrient and agar concentration.

2 DESIGN EXERCISE AND STRATEGIES

Compared to *Bacterial Crystals*, this probe presents the added complexity of manipulating both chemical and physical state-spaces. To assist students, a design lecture was organised to introduce them to some specific design strategies to manipulate each one. The following sections document these and consider how each one articulates its corresponding state-space.



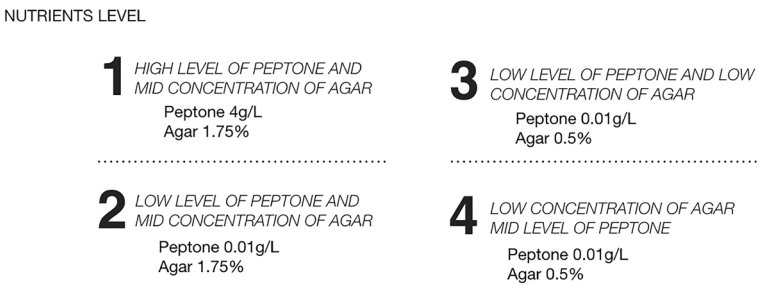
M Morphology

1 Surface Hardness
2 Peptone

32

2.1
CHEMICAL STATE-SPACE STRATEGIES

Strategies to manipulate the chemical state-space focused on nutrient level (peptone) and surface hardness. Based on the existing literature, each parameter was defined with maximum and minimum threshold values. The range for nutrient concentration was set between 4 g/L and 0.01 g/L. Surface hardness was described as the parameter in terms of the agar concentrate ratio in growing media solution, and set between 1.75% and 0.5%. Figure 31 shows the chemical state-space articulated by these parameters. Moreover, the four combinations of peptone and agar concentrations in Figure 33 were also linked to specific branching patterns found in the literature (see Figure 34). Students were encouraged to treat the table as a guide, and to use each combination to reproduce a specific pattern in their experiments.



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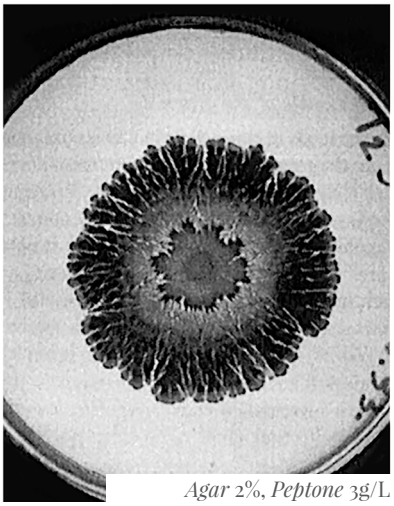
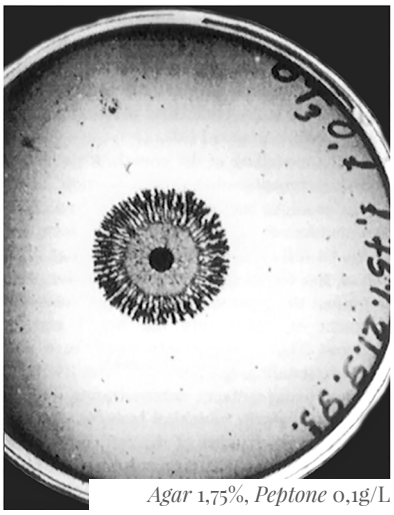
32 *Diagram showing the chemical state-space parameters of: Peptone and surface hardness*

33 *Combinations of nutrient level and surface hardness presented as guidance for the design exercise*

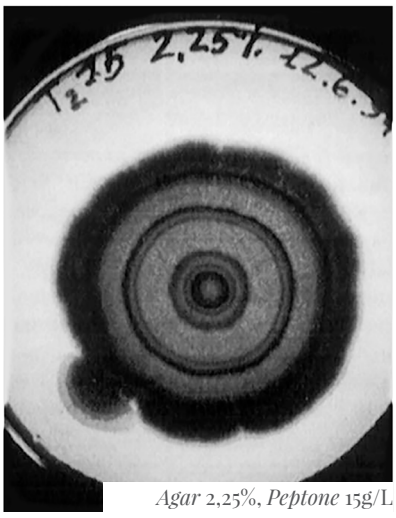


Agar 2%, *Peptone* 3g/L

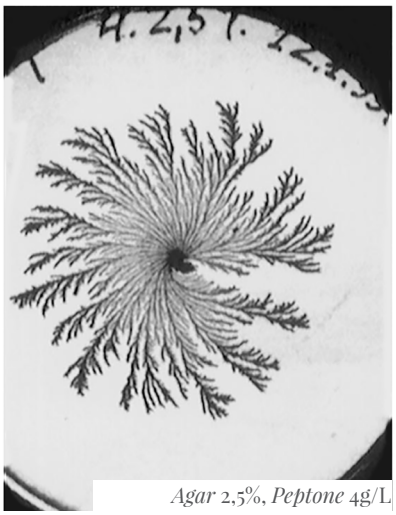
Agar 1,75%, *Peptone* 1g/L



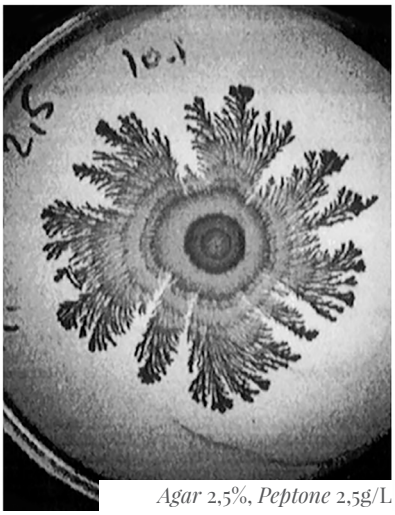
Agar 1,75%, *Peptone* 0,1g/L



Agar 2,25%, *Peptone* 15g/L



Agar 2,5%, *Peptone* 4g/L



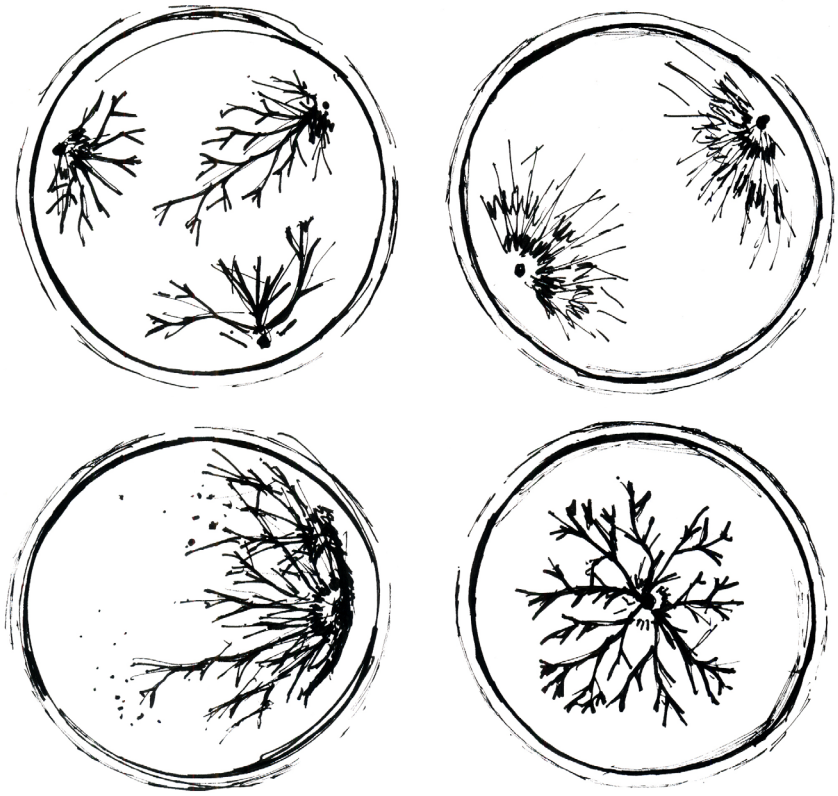
Agar 2,5%, *Peptone* 2,5g/L

2.2
PHYSICAL STATE-SPACE STRATEGIES

Students were also introduced to a number of potential strategies to manipulate the physical state-space. The first involved considering the effect that the initial point of placement has on the development of branching. They were encouraged to speculate on how colonies would interact with the boundaries of the container and within one another. Figure 35, for example, shows how placing the bacterial colony close to the edges of the container might produce branching that moves away from the walls.

34 *Reference morphologies found in the existing literature. Photographs are presented with the combination of nutrient level and surface hardness used to produce them. Images taken from Eshel Ben-Jacob (1997), Eshel Ben-Jacob et al. (1994) and Golding et al. (1998a).*

35 *Diagram showing some of the possible strategies for initial*



35

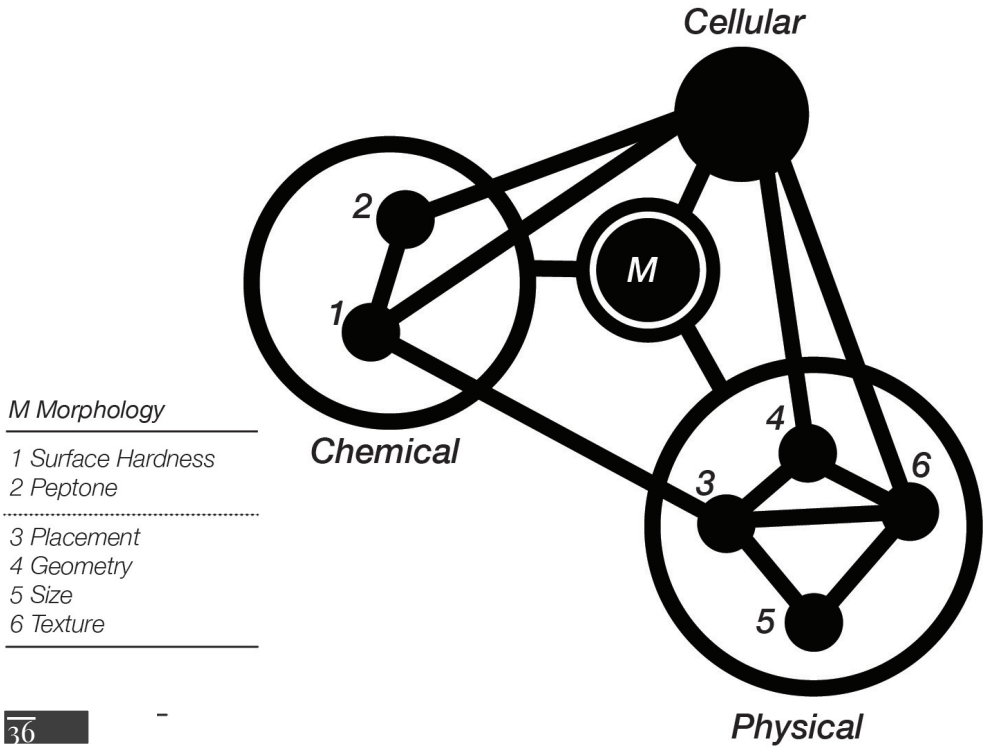
Following up on the strategies developed in *Bacterial Crystals*, students were also encouraged to consider how custom containers and other structures might be used to influence bacterial branching. As pointers, it was suggested that some relevant aspects might include the shape, size and texture of the material. Considered in combination with initial placements, these parameters articulate the physical state-space, as suggested in Figure 36.

A number of specific strategies were suggested, which connected physical and chemical state-spaces. Figure 37, for example, shows a prototype that uses geometry and size to manipulate both physical and chemical state-spaces. The prototype is structured as a series of concentric rings that enable a graded growth medium. The rings would act as a barrier, holding different growth media. A solution of 2% agar with 0.1 g/L peptone concentration, for example, could be poured using the interior ring.

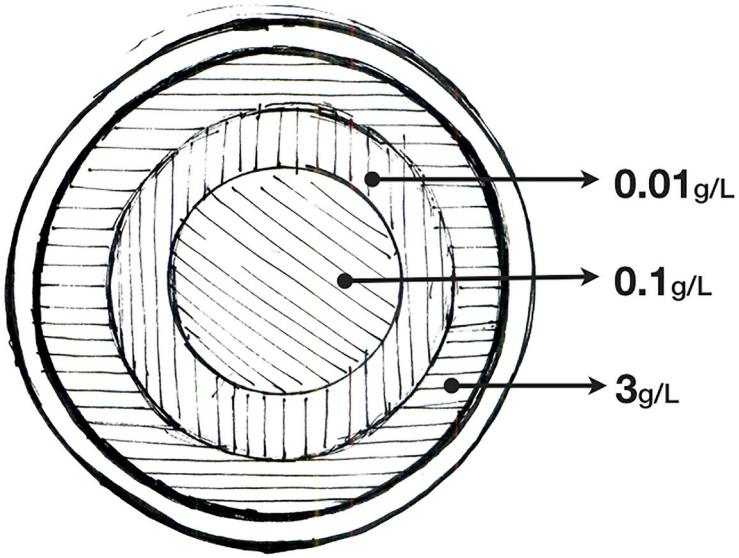
36 *Shows the diagram of state-space design with the physical subunit articulated*

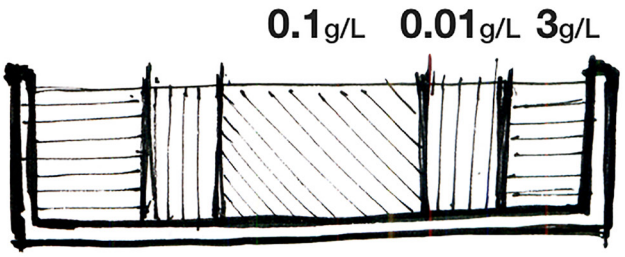
37 *Example of custom container, manipulating surface hardness in different phases across the plate*

38 *Plastic inset designed to produce a gradient in nutrient concentration*

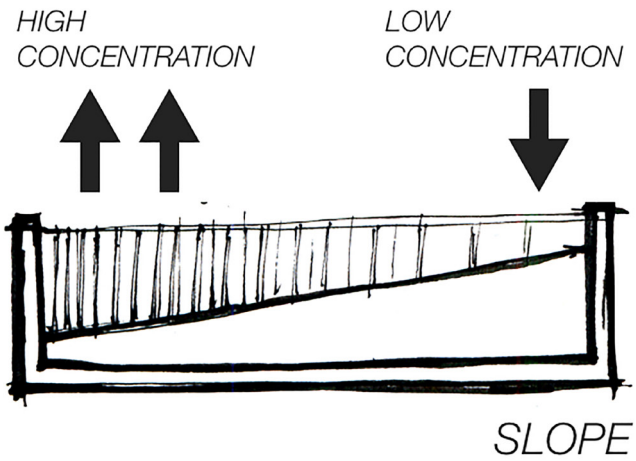


36

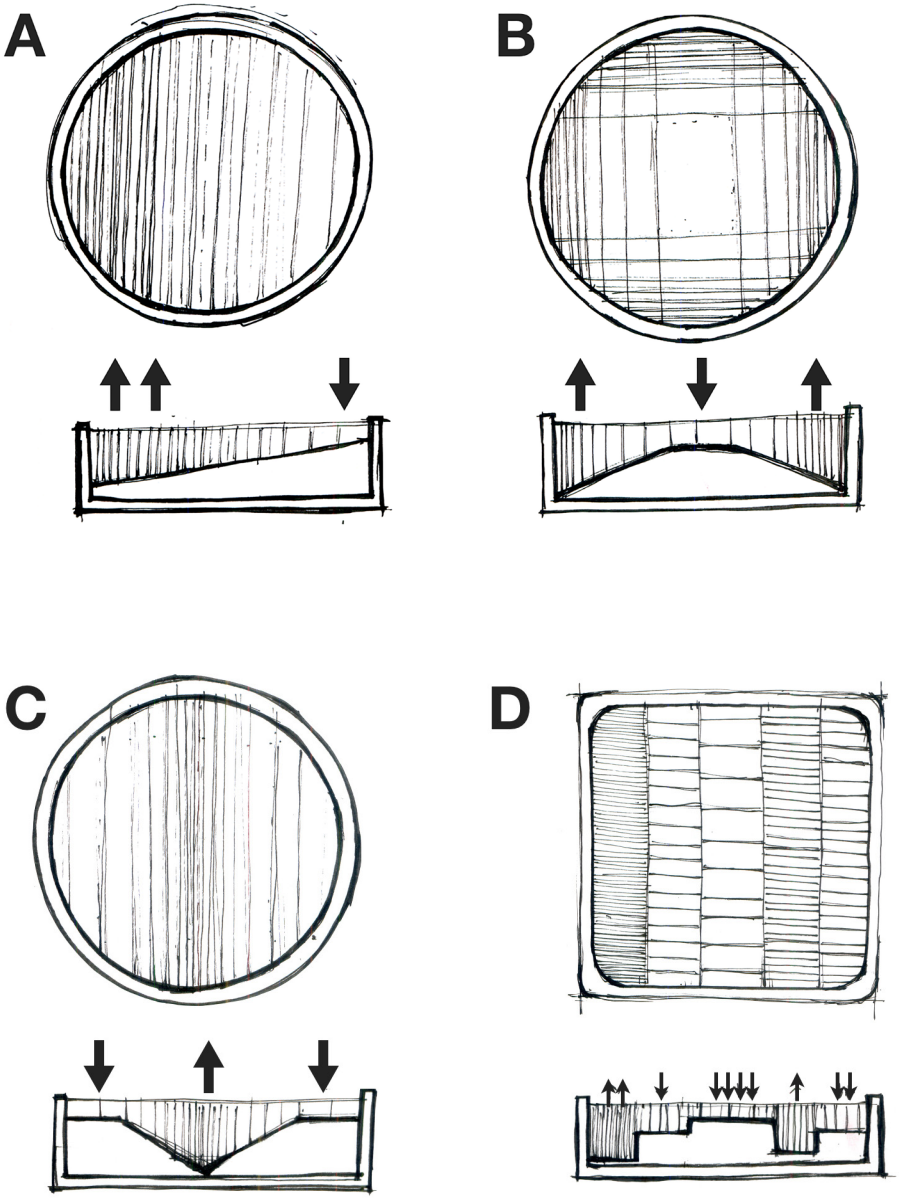

0.01g/L
0.1g/L
3g/L


0.1g/L
0.01g/L
3g/L

37


HIGH
CONCENTRATION
LOW
CONCENTRATION
SLOPE

38


A
B
C
D

A second agar solution could then be poured into the space created by a second ring. A third solution could then be used to fill the remaining space. The prototype results in a graded growth media, with different levels of nutrient concentration and surface hardness.

Another suggested strategy was the use of plastic insets to modify the chemical gradient of the growing medium. Figure 38 shows the design of a plastic inset that sits inside a square dish, creating a slope in its cross section. This affects the depth of agar volume, which was speculated to have an effect on the concentration of nutrients: as the relative concentration of agar diminished, so did the saturation of peptone. This was intended to produce a bias in the branching morphology, as the colony would swim towards the deeper side of the dish, following the nutrient concentration.

Figure 39 shows the design of four plastic inserts, which explore further the same principle. Variants *A* and *B* are intended to produce a gradient of nutrient distribution by producing a gradual slope. In *A*, low saturation is located at the edge of the container, while *B* grades towards the centre. *C* inverts the distribution and creates an area of high concentration of peptone towards the centre of the plate. Variant D is created by merging strips of different heights together, producing a cross section with stark shifts in nutrient distribution.

3 BACTERIAL MORPHOLOGIES AS BIO-MATERIAL PROBE

3.1 CONTINGENT STATE-SPACES

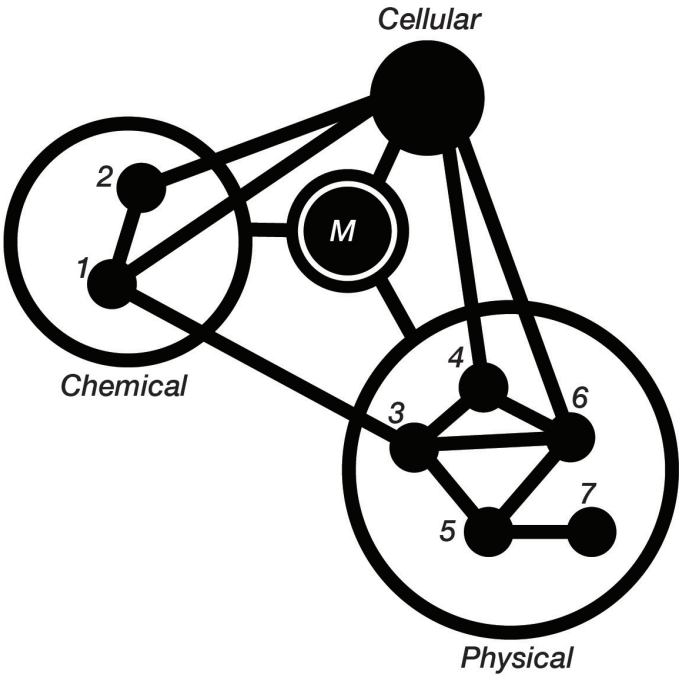
In discussing *Bacterial Crystals*, I suggested there were parameters that could not be grouped under the proposed state-spaces. For example, a prototype, featuring a custom-shape container, revealed the relevance of laboratory techniques, such as decontamination and agar preparation, which needed to be taken into account as parameters. Similarly, *Bacterial Morphologies* revealed parameters that were difficult to position in the existing categories of physical, chemical and cellular state-spaces.

Implementation in the laboratory, for example, revealed new contingent state-spaces. A good example is the use of custom-shaped containers. Traditionally, microbiological experiments are performed in glassware that is decontaminated in an autoclave, a pressure chamber that sterilises equipment and containers by heating them to above boiling point. The combination of heat and steam contributes to killing bacteria, spores and germs, eliminating other microorganisms. Another common practice is the use of plastic petri dishes, often available in circular and square shapes, and which come sterilised from the factory. Part of the strategies proposed by the students involved fabricating a number of containers in a range of plastics, such as acrylic and polyethylene terephthalate (PET). Containers produced with these plastics, however, cannot be sterilised on an autoclave as they have a low heat distortion temperature (HDT), a term that refers to the temperature at which polymers become malleable and deform. Instead they can be decontaminated with ultraviolet light, which requires a constant bath of up to ten hours.

Aspects related to laboratory protocol, such as decontamination techniques, are difficult to classify in the existing model of state-spaces. As shown in Figure 40, one possibility is to place them within the physical state-space, as it is connected to the size parameter. However, the original definition of physical state-space involved the '*physical forces and energy within the environment'.* Another possibility, sketched in Figure 41, would be to group decontamination inside the cellular state-space, as it is intended to control the amount of bacterial species introduced to the growth media. Neither of these two spaces, however, is a clear fit to decontamination, which, instead, relates to other aspects of laboratory protocol that are not captured in the original state-spaces. One way of explaining this is to say that not only does biological form result from the interaction between physical, chemical and cellular elements, but that it is also facilitated or hampered by the laboratory techniques used to enact different parameters of the initial three state-spaces. Figure 42, instead, places decontamination outside the three state-spaces.

40 *Diagram showing decontamination as part of the physical state-space*

41 *Diagram showing decontamination as part of the cellular state-space*

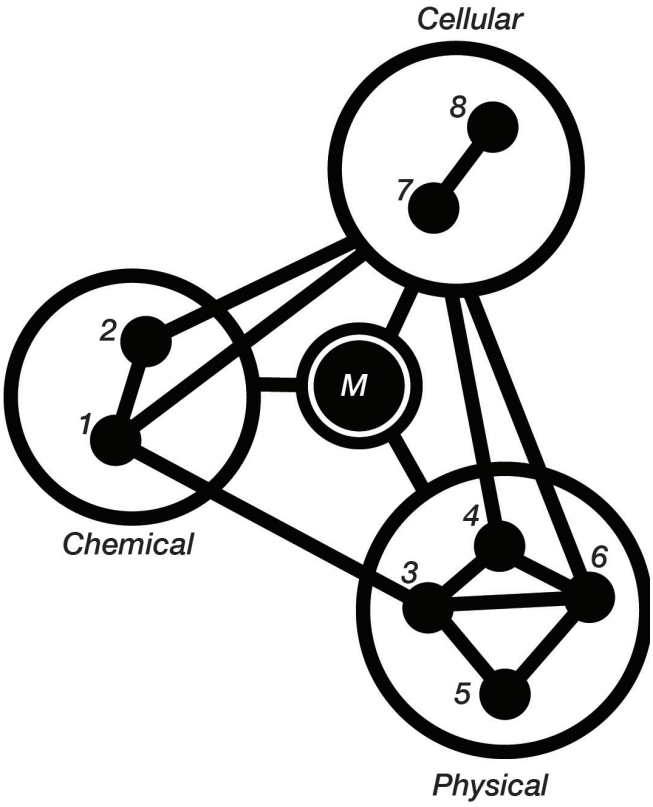


M Morphology

1 Surface Hardness
2 Peptone

3 Placement
4 Geometry
5 Size
6 Texture
7 Decontamination

40



M Morphology

1 Surface Hardness
2 Peptone

3 Placement
4 Geometry
5 Size
6 Texture

7 Species
8 Decontamination

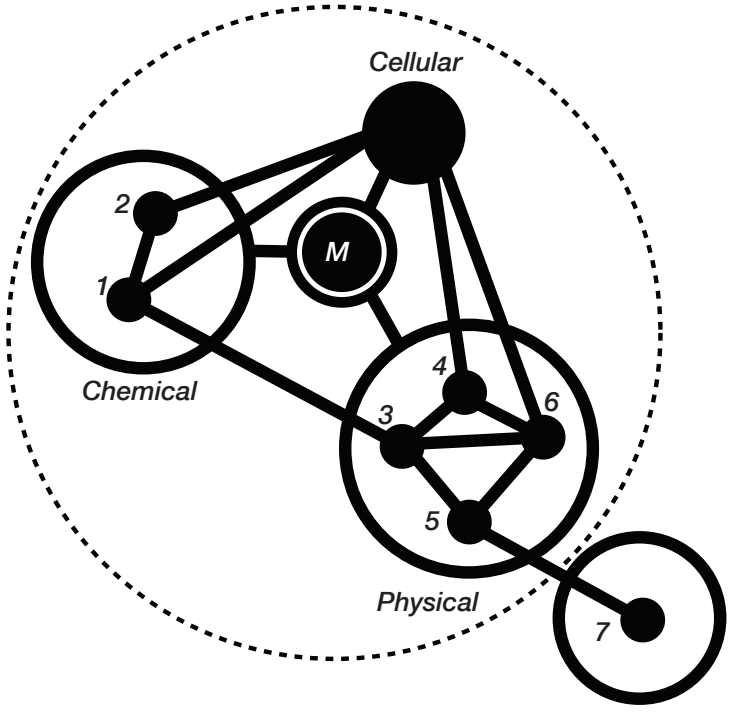
41

The difficulty inherent in classifying parameters connected to laboratory protocol also hints at the shortcomings of blackboxing. In *Bacterial Crystals* section, I reflected on how the strategy of blackboxing, originally intended to handle complexity, also constrains the capacity of the designer to anticipate contingencies. The prototype in Figure 43, for example, involves a commercial, square dish fitted with a series of interlocking barriers that create ten media zones, each with a different level of nutrient concentration and surface hardness. In addition, the central part of the dish is fitted with a number of platforms that produce an uneven container landscape. When the prototype was presented to Dr Zhang, it was deemed impracticable. She described how it would require the preparation of ten small quantities of media, as well as the careful and timed removal of barriers to pour them. In addition, the size of the plastic pieces makes it difficult to remove the barrier in the required time sequence, and increases the probability of introducing contamination. These steps involve the creation of a number of new parameters that, as in the example above, cannot be

42 *Decontamination outside existing state-spaces, but connected to parameters within the physical*

43 *Protocol sheet describing an experiment involving several nested areas of inoculation*

44 *Diagram showing the creation of a new state-space which refers to laboratory protocol*



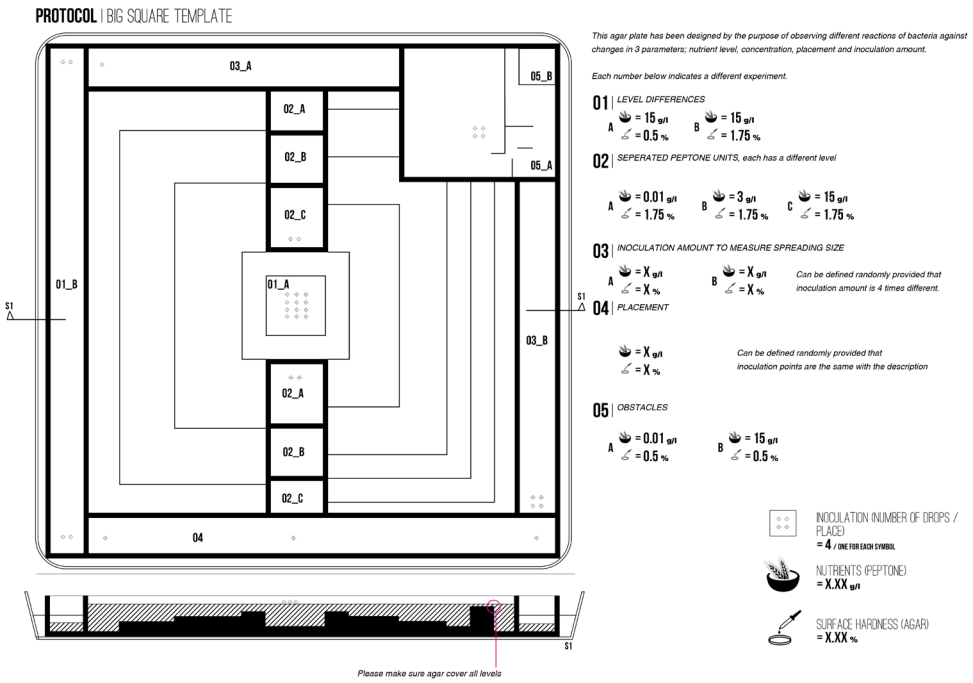
M Morphology

1 Surface Hardness
2 Peptone

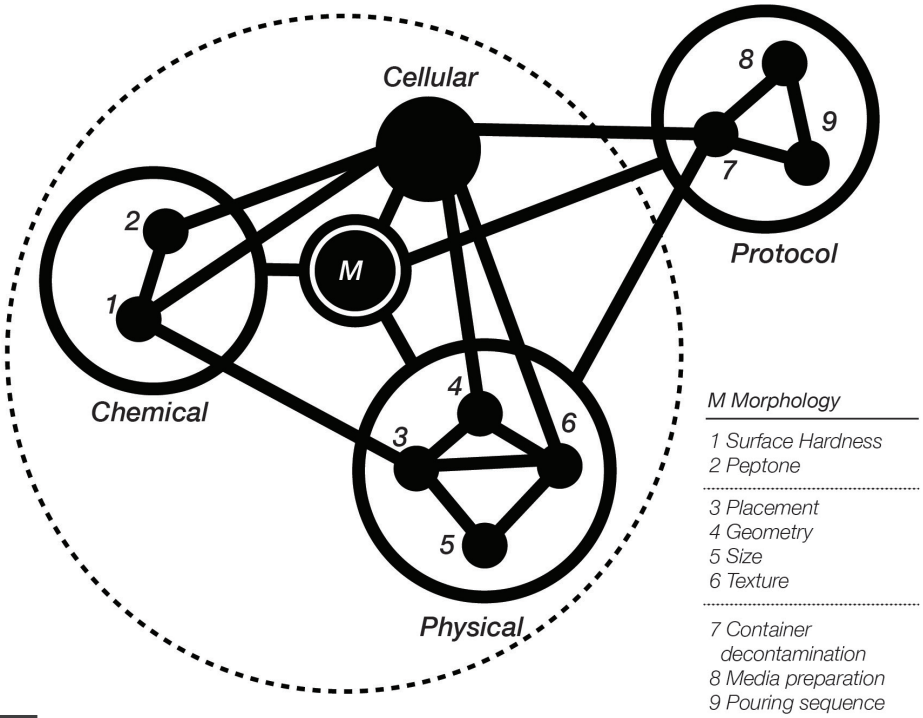
3 Placement
4 Geometry
5 Size
6 Texture

7 Container decontamination

42


PROTOCOL | BIG SQUARE TEMPLATE
03_A
05_B
02_A
02_B
02_C
05_A
01_B
01_A
S1
S1
03_B
02_A
02_B
02_C
04
S1
Please make sure agar cover all levels
This agar plate has been designed by the purpose of observing different reactions of bacteria against changes in 3 parameters; nutrient level, concentration, placement and inoculation amount.
Each number below indicates a different experiment.
01 | LEVEL DIFFERENCES
A = 15 g/l = 0.5 %
B = 15 g/l = 1.75 %
02 | SEPERATED PEPTONE UNITS, each has a different level
A = 0.01 g/l = 1.75 %
B = 3 g/l = 1.75 %
C = 15 g/l = 1.75 %
03 | INOCULATION AMOUNT TO MEASURE SPREADING SIZE
A = X g/l = X %
B = X g/l = X %
Can be defined randomly provided that inoculation amount is 4 times different.
04 | PLACEMENT
= X g/l = X %
Can be defined randomly provided that inoculation points are the same with the description
05 | OBSTACLES
A = 0.01 g/l = 0.5 %
B = 15 g/l = 0.5 %
INOCULATION (NUMBER OF DROPS / PLACE)
= 4 / ONE FOR EACH SYMBOL
NUTRIENTS (PEPTONE)
= X.XX g/l
SURFACE HARDNESS (AGAR)
= X.XX %

43


Cellular
8
9
7
Protocol
2
1
M
Chemical
4
3
6
5
Physical
M Morphology
1 Surface Hardness
2 Peptone
3 Placement
4 Geometry
5 Size
6 Texture
7 Container decontamination
8 Media preparation
9 Pouring sequence

44

classified within the existing state-spaces. Figure 44 suggests the addition of a new state-space, which refers to the laboratory protocol required to implement the original three state-spaces.

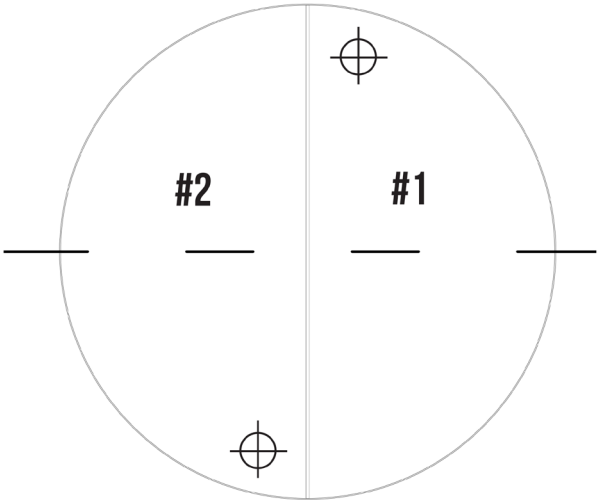
The protocol in Figure 45 suggests another situation in which laboratory protocol should be considered a contingent state-space. The prototype involves placing a temporary barrier that divides the plate, which enables the medium to be poured in two stages. This creates a new node for decontamination, as the plastic barrier needs to be sterilised by a UV light bath. In addition, a medium is first poured into one half and left for a few minutes to partially settle. Before it has achieved its final consistency, the barrier is removed to fill the second half of the plate with a different medium mixture. The timing allows both mediums to bond, while retaining their different nutrient concentrations.

The relevance of laboratory protocol as state-space is further illustrated by the outcomes of the prototype in Figure *46*. Figure 46 shows the resulting bacterial growth after an incubation period of six days, showing a number of microorganisms other than *Bacillus subtilis* 168. Our scientific partner interpreted this experiment as being the result of contamination introduced during the pouring sequence. As shown in the protocol sheet in Figure 45, the prototype required one medium to be poured into one half of the plate, waiting for it to harden and removing the barrier before pouring in the second half. Handling the plastic barrier provides ample opportunity to introduce other microorganisms. One of these can be seen as dense spots (labelled *a* in the image), with a second growing towards the edges of the plate (labelled *b* in the image).

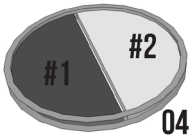
45 *Protocol produced by the students for an experiment involving mixed media. A temporary barrier is placed in a circular petri dish to allow media to be poured in two stages, thereby allowing different nutrient concentrations for either side. The image hasn't been corrected for typos*

PROTOCOL 03 | DIVIDING PLATE

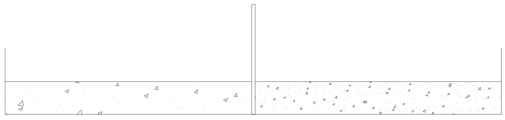
Plan



Diagrams



Section



= Innoculation

Method

01 | Steralise mixtures, petri dish and artefact & decontaminate work area,

02 | Pour #1 agar mixture into one side of the petri dish. leave to set.

03 | Remove artifact. Light bunsen burner to decontaminate the work area.

04 | Pour #2 agar mixture into the other side. leave to set.

05 | Innoculate at points indicated.

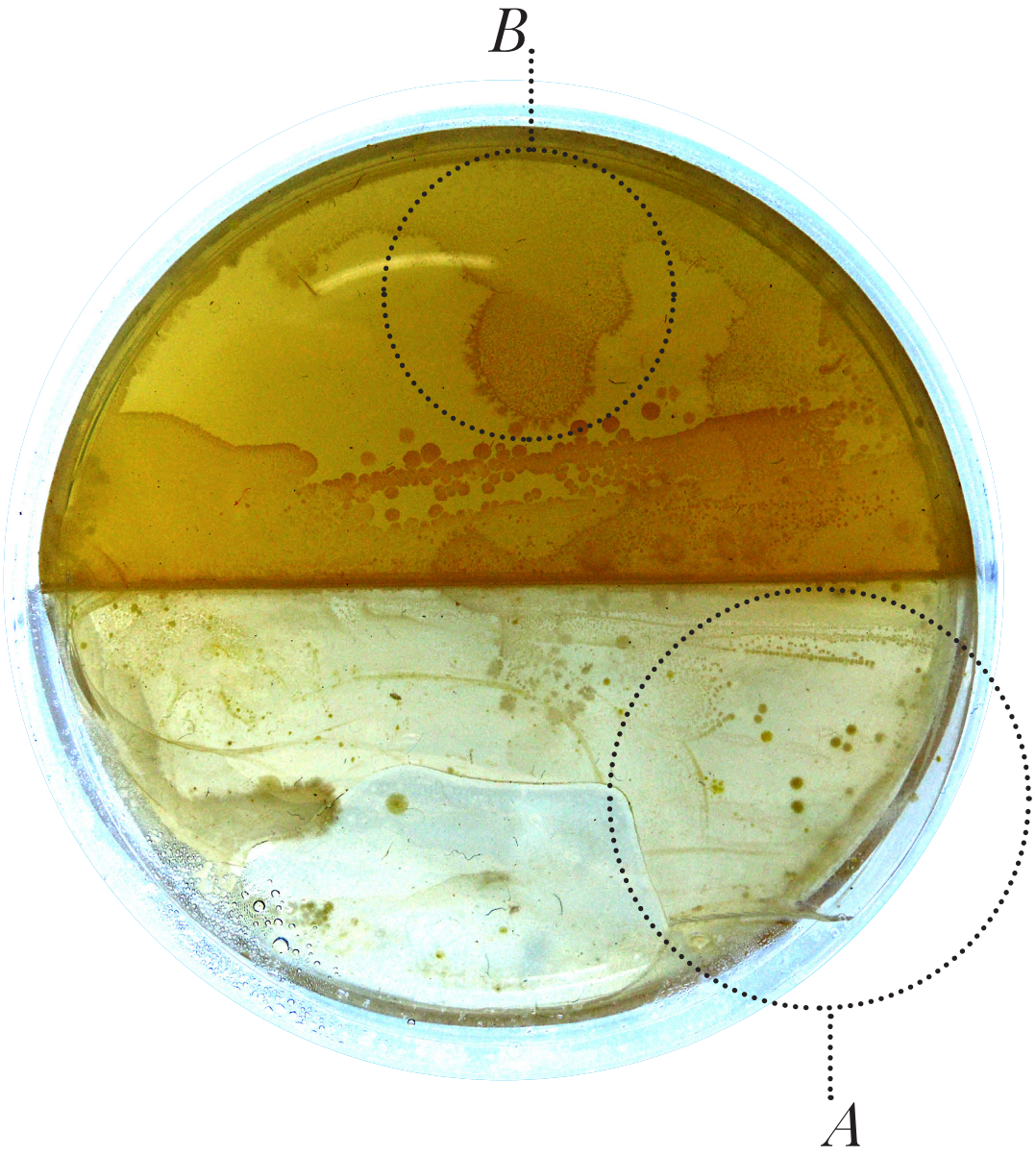
06 | Place the petri dish into the incubator.

Description

A test to observe how the bacteria colonies act when confronted by two agar mixtures within one petri dish. The dividing plate mathod may well create a rift between the two agars which the bacteria can not cross.

NUTRIENTS (PEPTONE)
#1= LOW
#2= HIGH

SURFACE HARDNESS (AGAR)
#1= MEDIUM
#2= HIGH

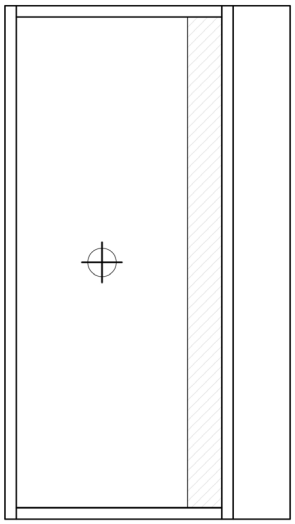


46 *Resulting bacterial growth after a six-day incubation period*

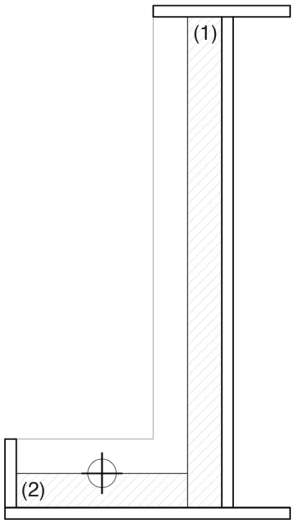
47 *Protocol produced by the students showing a prototype design to test bacterial growth against gravity. The image hasn't been corrected for typos*

PROTOCOL 03 | WALL CLIMBER

Plan



Section



= Innoculation

Method

01 | Lay plate down on long side

02 | Pour agar solution (1)

03 | Allow to set

04 | Stand on shorter side (as pictured)

05 | Pour agar solution (2)

06 | Allow to set

07 | Sterallise

08 | Innoculate in centre of base plate

09 | Store in upright position (as pictured)

Description

The plate is designed to be innoculated in an area with a relatively small amount of space to move. Using a small amount of nutrient & easy to move solution, the bacteria is encouraged to spread onto the vertical plane.

NUTRIENTS (PEPTONE)
= 0.01 g/l

SURFACE HARDNESS (AGAR)
= 1.75 %

3.2
CONFLICTING SCALES

One consequence of blackboxing is the conflicting scales between prototypes and the growth spread of bacteria. Figure 47 shows a prototype that involved hoisting a sheet of agar from a plastic rig, which was intended to test whether a bacterial colony would grow against gravity. Figure 48 shows the resulting growth after a six-day incubation period. One aspect to highlight is the disconnection between the scale of the rig and the spread of the colony. In general, the rig seems to be oversized to the scale of the bacterial colony itself, which spreads to 3 cm at its widest. Bacterial growth seems to suggest the influence of the rig configuration. Branches, for example, seem to grow longer towards the sides of the rig than they do upwards. The effect, however, would be easier to evaluate had the rig been modelled to a smaller size, closer to the reach of the bacteria colony.

48 *Resulting bacterial growth. Colony branches suggest some influence of the rig configuration, as they seem to grow longer towards the sides than upwards.*

3.3
PARAMETRIC VOLATILITY

The examples above attest to the difficulty inherent in anticipating how the addition of a new parameter, or an existing parameter assuming a new value, affects the system as a whole. There is a complex relationship between protocol and parameters, in which changes in one reconfigure the other, thus creating new nodes and redrawing links. In Section *3.1* I described how custom containers require the addition of decontamination as a parameter. In terms of the state-space model, decontamination can't be grouped within either physical or cellular state-spaces, instead requiring the generation of a new state-space altogether. *Bacterial Crystals* suggested similar complexities. In part 2, I described how changing from a solid to a flexible material to fabricate scaffolds required further consideration of porosity and superficial finish. The articulation of the physical space also has consequences for the cellular state-space, as the size of bacterial species determines which pore size is more conducive to growth.

One way of framing the volatility of the parametric approach is to say that the relationship between state-spaces and biological form is non-linear. In this context, a linear relationship suggests that a parameter always has the same effect on the resulting form. At the outset, I assumed a linear relationship between branching patterns and the combination of nutrient and agar concentration. Using the existing literature as a reference, I defined a number of nutrient/agar pairings, and characterised them in terms of the branching patterns they were expected to develop (see Figure 34). This assumption was based on models proposed by Ben-Jacob (1994), who proposed that, generally, lower nutrient concentration results in a higher density and spread of branches. I further suggested that parameters within the physical state-space would influence variations in these patterns. In Figure 35, I speculated upon how the geometry of the container and the initial placement might force the bacterial colony to adapt, driving variations in its branches.

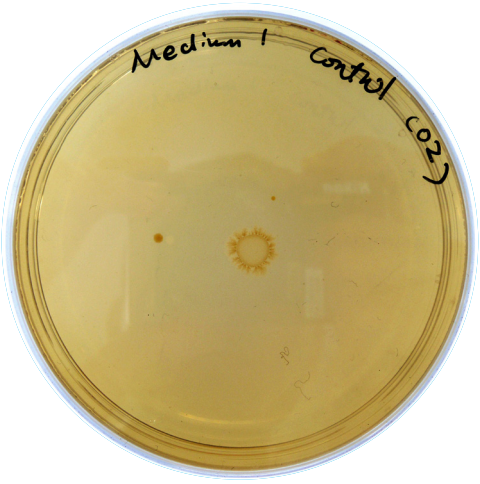
There are, however, parameters and state-spaces that make the relationship between nutrient/agar and branching patterns more complex. A good example of this is incubation humidity and temperature. Different organisms require different conditions of temperature and humidity to grow. In addition, different branching patterns take different amounts of time to develop, even within the same bacterial species. Golding et al. (1998b) analyse the way that different branching patterns in *Bacillus subtilis* grow at different rates:

> The different morphologies correspond to different growth velocities; DLA-like patterns grow in about a month, compact patterns at intermediate concentrations of agar grow in about a week, dense branching patterns and patterns of concentric rings grow in [a] few days, and compact patterns at low concentrations of agar grow in half a day. From this we learn that indeed the growth velocity of the various morphologies is very different (Golding et al. 1998b, p.520).

The difference in incubation time follows a non-linear logic. It is not possible to draw a link that states, for example, that a higher nutrient concentration results in longer incubation times, or that surface hardness has a direct or inverse correlation to incubation time. Instead, different combinations

of nutrient levels and agar concentrate require different times to develop branching forms. Moreover, the complex relation between laboratory protocol, incubation conditions and the original three state-spaces makes it difficult to use the model as a way of anticipating branching patterns. Here it made it difficult to refer to a form catalogue, or indeed to replicate specific patterns by simply reproducing nutrient and agar concentration levels. Instead, the conditions described above constituted contingencies that were not always easy to anticipate, as some would only become relevant in very specific situations. There complexities are further compounded by the way in which laboratory protocol and incubation are reported in scientific literature. For example, Ben-Jacob et al. (1994) specify morphologies based on incubation at 37°C and 30% humidity. Golding et al. (1998a), however, only report their nutrient and surface hardness levels. Fujikawa and Matsushita (1989; 1990) report on incubating their experiments at 35°C inside a humidified box, without any indication of the humidity level. Given these discrepancies, Dr Zhang had to make a decision about the incubation temperature, settling for a common temperature for all experiments. Similar decisions were taken with regards to the time of incubation.

The difference in incubation protocols helps explain the difference in bacterial growth. In Section 6.2, I described how the existing literature was interpreted parametrically, constructing a catalogue of branching patterns connected to specific levels of nutrient and agar concentration. Part of the exercise involved producing *control experiments*, which refer to plates where a basic set of variables are tested. In this case, control experiments were run to corroborate that the combination of peptone and agar produced the patterns suggested in the literature. Figures 49 to 52 show control experiments for the four media combinations used in the experiments, and were photographed after a six-day incubation period. As shown in Figure 33, medium 1 contains 4 g/L peptone in a 1.75% agar solution; medium 2 0.01 g/L on 0.5% agar; medium 3 0.01 g/L on 0.5% agar; and medium 4 0.01 g/L on 0.5% agar. The mosaic shows the difference in bacterial growth connected to medium type. Even when all the experiments were photographed at the same stage of incubation, each shows a different spread. The colony in Figure 49, measured from tip to tip, spreads a total diameter of *1.10 cm*. By contrast, the colony in Figure 50 covers *1.85 cm*; Figure 51, *1.64 cm;* and Figure 52, *1.37 cm*.



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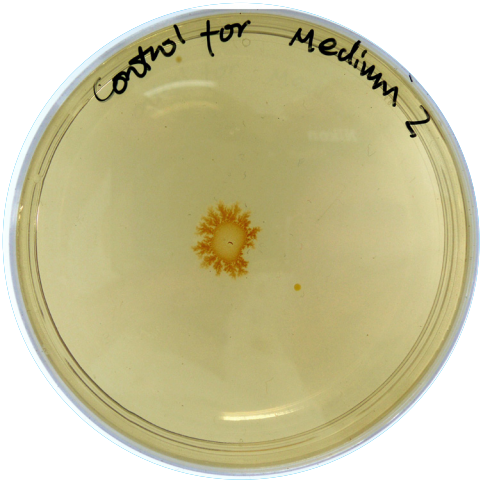

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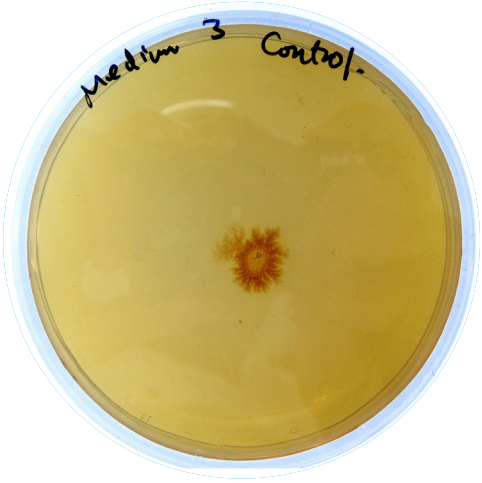
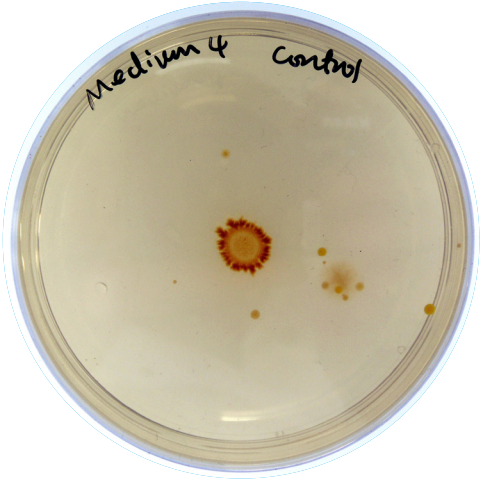


51



52

49–52 *Four control experiments testing each combination of peptone level and agar concentration used.*

4

PART FOUR

DISCUSSION

1 A PARAMETRIC APPROACH TO DESIGNING WITH BIOLOGICAL SYSTEMS?

One important aspect to reflect upon is the extent to which a parametric approach is suitable to designing with a biological system. The process of formalising how state-spaces are articulated results in a useful tool to keep track of changing conditions, being aware of how the change in one parameter affects and reconfigures the rest. To what extent, however, is the approach useful in anticipating the contingencies likely to be found, and to determine which parameters are important to maintain control over?

One way to answer the question is to look back at the work of Alexander in *Notes*. In reflecting on the value of formalising design problems in graphs, he writes:

> We now have a graph (...) which represents the design problem. As we have seen (...) to solve the problem, we shall try to decompose the set *M* in such a way that it gives us a helpful program for design (Alexander 1964, p.116).

For Alexander, the value of articulating a design problem lies in providing the designer with a cognitive aid to understand how the system operates. He is, however, conscious of the difficulties inherent in producing formal definitions that try to account for all the problems that might arise in the context. He argues that:

> It is a common experience that attempts to solve one piece of a problem first, then others, and so on, lead[ing] to endless involutions. You no sooner solve one aspect of a thing than another is put out of joint. And when you go back to correct that one, something else goes wrong. You go round and round in circles, unable ever to produce a form which is thoroughly right, because there is no way of integrating the pieces you have tackled independently (idem, pp. 116–117).

Despite the myriad complexities involved in a design problem, Alexander is convinced that, given enough resolution in articulating diagrams, it is indeed possible to generate a program that accounts for potential eventualities. He goes on to argue:

> If (…) we break the problem apart in such a way that its clusters of variables are as richly connected, internally, as possible, we shall have clues to those physical aspects of the problem which play the most important functional part in the problem and are therefore most likely to furnish handles for the designer's comprehension (idem, p. 122).

However, as the analysis of both *Bacterial Crystals* and *Bacterial Morphologies* shows, diagrammatic definitions do not always provide a means of anticipating contingencies. The state-space of design is useful as a non-decomposable diagram, which defines that biological form results in the interaction between the organism and its physical and chemical context. There is, nonetheless, no standard way of articulating it to define exactly which aspects of the physical and chemical context are to be considered in every situation. As the analysis of both probes suggest, there are contingencies that become relevant only in specific contexts. In terms of a parametric approach, it is difficult to relate, for example, a specific branching pattern to set parameter values. Instead, there is a continuously changing set of contingencies that point to the inadequacies of the initial articulation of the diagram. These probes challenge the notion of parametrics itself as a way of developing a variety of design solutions using the same definition, as there are complex relationships in which changes in one parameter reconfigures the diagram.

Related to the inadequacies of a parametric design approach is the question of how precise the term *parameter* is. The notion has been notoriously ill defined in contemporary discourses of digital parametrics, lending itself as a pretext to conjure up gratuitously complex forms. Witold Rybczynski (2013), for example, criticises the use of the word in describing seemingly *parametric* projects. In describing the Foreign Office Architect's cruise ship terminal in Yokohama, Japan, he observes how a primer on parametric design describes the project as '*complex building forms correlated to a series*

of imagined or perceived parameters could be organized and constructed on a grand scale with dynamic, real-world results' (Rybczynski 2013, para.2). The author challenges the use of parameter in this context as follows: '"*Imagined or perceived parameters" sounds pretty arbitrary. Indeed, the algorithms that underlie parametric modeling are altered seemingly at will, and can rapidly churn out a variety of forms from among which the designer can choose'* (idem, p.3).

Rybczynski turns to the work of Alexander to divine some clarity. The work of Alexander, however, does not directly address what a parameter is, instead making use of the term of *functional requirement* or *misfit variable* in describing aspects that govern the production of form. Italian architect Moretti, however, did use the term directly, defining parametric design as the study of architecture systems geared at '*defining the relationships between the dimensions dependent upon the various parameters'* (Moreti, quoted by Davis, 2013, para. 2). Daniel Davis reminds us how the work of Moreti was firmly cemented in mathematics and, as such, used the term *parametric* to refer to the '*set of equations that express a set of quantities as explicit functions of a number of independent variables, known as "parameters"* '(idem, para. 6).

However even within mathematics, the term parameters is difficult to define. James Kilpatrick describes a '*multi-ambiguous non-specificity*' of the term, and reviews how the use of the term within mathematics has:

> ...no apparent rationale, nor even a hint of reasonable extension of its use in mathematics, *parameter* has been manifestly bastardized, or worse yet, wordnapped into having meanings of consideration, factor, variable, influence, interaction, amount, measurement, quantity, quality, property, cause, effect, modification, alteration, computation etc. (Kilpatrick, referenced by Davis, 2013, op. 4).

Despite the imprecision of the term, Davis goes on to propose two formal criteria to determine a parametric approach:

> A parametric equation expresses 'a set of quantities' with a number of parameters [4].

> The outcomes (the set of quantities) are related to the parameters through 'explicit functions' [5]. This is an important point of contention in later definitions, since some contemporary architects suggest that correlations constitute parametric relationships (idem, para. 7).

Is it possible therefore to articulate state-spaces into parameters? One notable point of both exercises is the difficulty inherent in articulating the physical state-space. I have proposed that there are elements of the chemical state-space that are relatively easy to characterise as a *parameter,* in the sense that they can be quantified, and the relationships between them can be described in terms of equations. For example, *nutrient levels* can be described in terms of mass dissolved in units of volume, and *surface hardness* can be defined by the amount of agar concentrate that is dissolved in a volume of water. Moreover, Ben-Jacob has proposed mathematical models that account for how these relate to branching patterns. Moreover, aspects of parameters of contingent state-spaces, such as those analysed in Sections *3.3.1* and *3.2.2*, can be defined as a boolean-like variable that takes one of two states, such as decontamination methods, for example. Others, nonetheless, simply can't be quantified. In part three, I reflected on the difficulties of numerically capturing parameters such as the material used in producing a container, or its geometry. Although it is possible to parametricise specific geometries, it is impossible to represent numerically all the possible geometries a container might take. The same holds true for parameters of contingent state-spaces, such as pouring sequence.

The framework of the parameter, thus, seems to be imprecise to describe the different aspects that become relevant when designing with biological systems. As described above, some are simply impossible to quantify, therefore failing the first formal criterion proposed by Davis. In addition, it is important to highlight how the second criterion, the possibility of formalising their relationships, is also limiting when working with biological systems. One way of explaining this is that the notion of parameter requires quantifying and defining behaviours at the outset at the system, and relies on the assumption that these remain constant throughout the operation of the system. However, *Bacterial Crystals* and *Bacterial Morphologies* suggest that biological systems are often volatile, and tend to change their behaviour and

invoke new state-spaces when one aspect of their context changes. In Section 3, I argued the notion of *parametric volatility*, making reference to how when one parameter assumed specific values, it triggered the appearance of new parameters and, more generally, the sudden reconfiguration of the state-spaces. One question, therefore, that is carried to the next chapter is: *If a parametric approach is not helpful in designing with a biological system, what alternative frameworks and approaches can be used in engaging with them?*

DESIGN ASSEMBLAGES

6

CHAPTER 6

DESIGN ASSEMBLAGES

1 INTRODUCTION

This chapter presents an alternative design approach to biological systems that draws on notions of non-human agency and assemblages. In the previous chapter I concluded that biological systems and their context cannot be described in terms of parameters. Here I propose conceptualising them as having *agency,* and that they coalesce in assemblages in which agencies align, cooperate or block one another. The chapter is structured in four parts. The first describes the philosophical context covering non-human agency, and the way the concept is used in Actor Network Theory, and within feminist critiques of scientific epistemology. I draw on the work of Jane Bennet to define assemblages as a conglomeration of non-humans that come together to form complex systems that are in a constant process of change and negotiation. I also review the work of Katie Lloyd Thomas in defining *material thinking* as a project to revaluate contemporary engagement with matter in design; and the methodology of *tissue of making* proposed by Barbara Bolt, and which involves an experiential approach to design that sees the designer as a craftsman who engages in a dialogue with tools and matter.

The second part of the chapter documents the design of the *bio-material probe* of *Bacterial Assemblages*. I propose there are three key implications in taking an approach based on assemblages: biological systems cannot be described exhaustively or quantified; the role of the designer as sole creative actor is decentred; and a requirement of an experiential approach that enables reading the assemblage. The third part reflects on *Bacterial Assem-*

blages, discussing the way the exploration revealed how different agencies aligned, cooperated and blocked one another in the assemblage. I follow the structure of state-spaces, and begin by describing how actants within the cellular, physical and chemical state-spaces interacted and had specific effects on the generation of branches. I then reflect on *contingent* state-spaces, which cover aspects of protocol and implementation: *spaces of practice, cultures of crafting* and *social interaction.* The chapter comes to a close in *part four*, where I draw on the observations developed in *Bacterial Assemblages* and throughout the thesis to reflect on general implications for approaching biological systems as assemblages.

1

PART ONE
CONTEXT

1.1
AIMS AND OBJECTIVES

In general terms, this chapter responds to the exploration of Chapter Five, and attempts to carry on its exploration and discussion, finding ways of furthering the understanding of biological systems where a parametric framework is limited.

The chapter sets out to explore alternatives to a parametric approach to dealing with biological systems within a design context. The creative exploration in this chapter will attempt to build a model for an experiential approach to biological systems, which involves prioritising direct engagement with the tools and practices of laboratory work, and one that draws not only on technical knowledge, but also on intuitive and non-rational dimensions.

1.2
PHILOSOPHICAL CONTEXT

The previous chapter explored how the framework of parametrics constituted a model to understand how biological form resulted from the interaction between the organism and its context. I argued, however, that one shortcoming of the approach is the requirement for *invariability*: the notion that parameters retain their essential attributes in any portion in time. In the context of bacterial branching, a parametric approach involves defining the way in which elements of the state-spaces define features of branching patterns. How, for example, lower nutrient concentration results in a higher number of branches. The tracks of exploration, nonetheless, suggested that biological systems behave differently depending on the configuration of their context. I described how change in some parameters would reconfigure the state-spaces, introducing new parameters or requiring the elimination of others. As a result, there was no standard way of decomposing, or articulating, each state-space: the configuration of parameters was contingent upon the status of other state-spaces, and in the laboratory practices required to implement the system.

In this chapter, I will draw on contemporary design thinking to suggest that an alternative way to frame biological systems is to say that they constitute

an *assemblage*. The word is derived from the French *agencement* (Phillips 2006), and has been popularised by the work of Deleuze and Guatari (1980), who use it as an analytical tool that highlights the way heterogeneous elements come together in loose, reversible associations. One main difference in understanding a design system as an assemblage is that its constituent elements are described as actants that, as I will explain in detail in the next section, cannot be exhaustively quantified and described in equations. As a result, working with assemblages requires different strategies to navigate them, and to identify the way in which different *agencies* align to produce specific outcomes.

1.2.1
NON-HUMAN AGENCY

Agency can be broadly defined as the capacity to affect change in the world and, in the context of assemblages, is connected to the notion of non-human. Both concepts are used in *Actor Network Theory* (hereafter ANT), a methodology developed in the field of science studies, which is intended to '*signal dissatisfaction with the philosophical tradition in which an object is automatically placed opposite a subject, and the two are treated as radically different*' (Sayes 2013, p. 3). Bruno Latour proposes that human actions are delegated to *non-humans*, inanimate objects and materials, who assume *agency* through this process. A door-closer, for example, performs a function, keeping a door closed, which would otherwise be needed to be performed by a human (Johnson 1988). In this, the artefact has agency, as it is designed to replace human action, but also potentially to shape the actions of other humans (Latour, 1992). A good example of how *agency* and *non-human* are used in ANT is the way in which Latour (1993) accounts for the rise of germ theory, proposed by Louis Pasteur and which triggered a scientific and medical revolution in the nineteenth century. Latour challenges prevalent narratives, which tend to explain its success by pointing to its scientifically sound underpinnings. Instead, he proposes that its rise is the result of a number of humans and non-humans *negotiating* and *aligning* their agencies, ranging from military and civilian doctors to hygienists, laboratories, farms, sheep and microbes.

Microbes, for example, had to be isolated from their original settings in breweries and farms, and analysed in the laboratory. Evidence of their existence enabled scientists to link them to the development of diseases. Scientific validity, however, was not sufficient for the theory to gain acceptance, and required further associations. For example, hygienists accepted it because it helped them to improve public health using strategies they were already familiar with. General practitioners, on the other hand, were reticent to adopt it, as it presented little financial gain. They changed their opinion, however, with the development of anti-toxins, which they could administer and charge for in their private practices (Latour 1993). These interactions between humans and non-humans, Latour proposes, help to highlight the way that each has an independent agency: they are capable of effecting change on one another. More importantly, these *actants* and *agents* cannot be reduced or subsumed entirely by others. The theory succeeded once humans, such as general practitioners, aligned with non-humans, such as anti-toxins and microbes.

In addition to its use in science studies, the concept of non-human agency has proved influential across different disciplines. It has been instrumental, for example, in feminist critiques of scientific epistemology. Haraway (2013) proposes that scientific enquiry is based on a narrative of *mastery*, in which the natural world is objectified as null matter whose only relevance is in becoming the subject of study of humans. However, she argues, scientific knowledge does not suppose mastery, and instead proposes *situated knowledge*, an approach in which the object of study is conceptualised as an agent. Moreover, situated knowledge involves admitting that nature is a *trickster,* or a figure that refuses to be mastered or reduced:

> Acknowledging the agency of the world in knowledge makes room for some unsettling possibilities, including a sense of the world's independent sense of humour (....) Perhaps the world resists being reduced to mere resource because it is — not mother/matter/mutter — but coyote, a figure for the always problematic, always potent tie of meaning and bodies (...) Perhaps our hopes for accountability, for politics, for ecofeminism, turn on revisioning the world as coding trickster with whom we must learn to converse (Haraway 2013b, p.199).

Notions of agency and non-humans are also used in political science discourses, which seek to reassess the status of matter in contemporary society. This is the case with *vibrant materialism*, in which Bennett argues against the '*partition of the sensible*' (Bennett 2009, p. vii), which refers to the artificial separation between intelligent life and inanimate matter. This partition lies at the core of consumerist society, Bennett argues, and constructs an asymmetrical power relationship. In doing this, it renders matter a resource to be used freely by humans, who are granted a higher status. Instead, vibrant materialism proposes that all matter, sentient or otherwise, has a degree of agency, or *vibrancy*, and should be assigned the same importance.

Central to vibrant materialism is the notion of *assemblages*, which describes complex systems composed of elements whose functions are not always aligned and synchronised. They are defined as '*living, throbbing confederations that are able to function despite the persistent presence of energies that confound them from within*' (Bennett 2009, pp. 23–24). Bennett describes assemblages as being characterised by the diversity of their members, which creates an uneven distribution of power and energy in its interior. As a result, no member in the assemblage can consistently influence or steer the behaviour of the whole. Instead, members interact in diverse ways, and the assemblage is constantly changing and reconfiguring. Bennett writes:

> Each member and proto-member of the assemblage has a certain vital force, but there is also an effectivity proper to the grouping as such: an agency of the assemblage. And precisely because each member actant maintains an energetic pulse slightly 'off' from that of the assemblage, an assemblage is never a solid block but an open-ended collective (Bennett 2009, p. 24).

The efficacy of actants to act and influence the assemblage, Bennett goes on to argue, is dependent upon the sum of forces at play, as other actants might cooperate, resonate or interfere with their own trajectories. As a consequence, agency fluctuates in the assemblage, as it is constantly shifting according to the association of bodies.

1.2.2
AGENCY AND ASSEMBLAGE IN DESIGN

The notion of assemblage has been influential in contemporary design discourses, used to propose new, material-oriented methodologies. One of these is the framework of *material thinking*, which challenges understandings of matter as passive and raw. Instead, it proposes that matter possesses agency of its own, and that humans do not define the creative process, but act rather as co-creators (Bolt 2004; 2007; Thomas 2006). Barbara Bolt (2007), for instance, proposes the methodology of the *tissue of making*, in which the human is intertwined with the non-human in a non-hierarchical, material conversation: '*In this encounter, the human is no longer outside of the assemblage directing the proceedings*' (Bolt 2007, p. 2). In doing this, design is described as a practice of creating the conditions for certain agencies to exist and express:

> This focus on the acting ensemble rather than the artist as the locus of art enables us to come closer to an understanding of the dynamism of material practice and to the radicality offered by the notion of material thinking. In this dynamism, the outcome cannot be known in advance. Thus although we may have some awareness of the potential of a tool or a piece of wood — for example, through previous dealings with wood and tools — every new situation brings about a different constellation of forces and speeds (Bolt 2007, p. 3).

Central to the tissue of making is the impossibility to prescribe the outcome, which recasts the role of the designer. Instead of being the central node from which design emanates, the designer becomes an interpreter of the assemblage, tuning the relationships to enhance or supress some of the agencies at play. In the quote above, Bolt explains how the behaviour of materials and tools can be anticipated to a degree, drawing on knowledge gained in previous encounters. There are, however, contingencies that make every situation different. In these cases, the practitioner relies on bodily awareness to *listen* to the material, and understands the possibilities that are being created by the new situation. Bolt explains:

> In the act or event of painting, sensory and other bodily responses are fully focused on the demands of the unpredictable and uncontrollable materiality of paint interacting with the environment (...) stimuli arise in the heat of the moment to which the creative gesture becomes a reaction that is released from conceptual ways of thinking (...) In this experience, painting may be seen as a response to what happens in the interaction between paint, oil, turps, canvas, gravity, sun, heat, the occasional live beast and the human body. In this process, the body, the materiality of the paint and the environment are implicated and mutually dependent (Bolt 2004).

In addition to the experiential approach described by Bolt, another crucial difference in understanding a design system as an assemblage, as opposed to using a parametric approach, is connected to causality. Bennett (2009) proposed that the multiple agencies at play imply that traditional models of linear causation are insufficient to account for the way in which assemblages operate. Causality is traditionally understood as following a billiard ball model, where action is transmitted in one way through direct contact, creating a chain of cause and effect. When agency is distributed, it is more difficult to connect elements linearly. Rather, causality becomes emergent and fractal in nature, mirroring the articulation of scales within assemblages. Connolly (2004) uses the term 'emergent causality' to explain how political events are produced through interactions between individuals, social groups and institutions. In this context, causality is emergent, as it connects things across scales. Events in smaller scales, for example, the individual, define effects on the larger scale, such as institutions. Moreover, the connections run in both directions: the system generates feedback loops through which events on the larger scale connect to the smaller, creating conditions of stability. In these conditions, it is impossible to locate a single point where an effect starts, its cause. Rather, cause is entangled in the relationships between agents.

2

PART TWO

DESIGN OF THE BIO-MATERIAL PROBE

2.1
DESIGN CONTEXT AND STRATEGIES

As described in the sections above, the notion of assemblage suggests an alternative mode of engagement with biological systems, which is fundamentally different to the parametric approaches used in previous explorations. There are three key aspects in which they differ.

One, the notion of assemblage assumes that all its constituent elements have a degree of agency. In the previous section, I described how different authors describe assemblages as confederations of variegated bodies, which, to use the words of Latour, interact through trials of strength. The implication is that it is impossible to describe them in terms of parameters, in the sense that constituent parts cannot be exhaustively quantified, and their behaviour cannot be expressed in equations. There is a degree to which the behaviour of actants can be anticipated, but they will behave in unexpected ways when the configuration of the assemblage shifts.

Two, non-human agency decentres humans as sole creative actors. I have reviewed the work of Bennett, and the way she describes the outcome of assemblage as being the result of different agencies aligning, cooperating, resonating or interfering with one another. As a result, the role of designers is recast, and they are required to *read* the assemblage, understanding the way its actants align.

Three, in order to *read*, designers need to engage directly with the assemblage. I have described this engagement as a *conversation*. One model for the engagement is the *tissue of making*, a methodology proposed by Barbara Bolt, which draws on sensory and bodily responses to deal with unpredictable and uncontrollable materiality. This experiential approach prioritises direct acquaintance with the materials and tools of design, in a way that draws on intuitive and non-rational dimensions, as well as a technical understanding of them.

In this chapter, I will use the *bio-material probe* of *Bacterial Assemblages* to explore the implications of understanding biological systems as assemblag-

es. Furthermore, I propose to use the state-space of design as an initial strategy to navigate and negotiate the assemblage of bacteria and their context. As such, it is used as a guide to plan explorations, and to provide an entry point to explore the interaction of different agents in laboratory work. In the following sections, I will document the initial strategies I used to engage with each state-space.

2.2
CELLULAR STATE-SPACE STRATEGIES

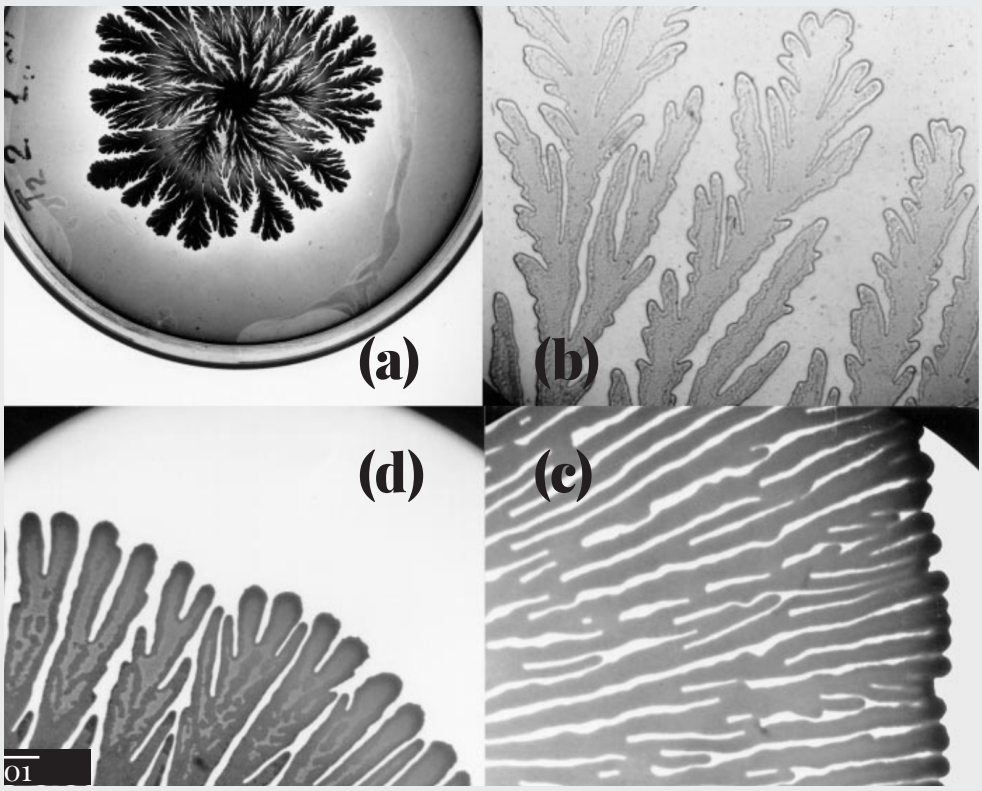
Chapter Five introduced the model of the state-space of design, and defined the cellular state-space as being '*defined by the boundaries of the cellular membrane, and it is used to define all the processes which take place within it and that include, for example, DNA transcription and translation, as well as protein production*'. One possible strategy to manipulate the cellular state-space, I proposed, was to use recombinant and synthetic DNA approaches, which modify the behaviour of existing cells. Given that I do not have access to these techniques, I decided to vary the cellular state-space by using different cellular species, which provides a contrast of genetic make-ups.

The previous chapter used *Bacillus subtilis* 168 as part of *Bacterial Crystals*. In *Bacterial Assemblages*, I use the same specie, in addition to three new ones: *Paenibacillus dendritiformis C* morphotype (see Figure 2), *Paenibacillus vortex* (see Figure 3), and *Paenibacillus dendritiformis T* morphotype (see Figure 1). One of the main differences between *B. subtilis* 168 and the new organisms is locomotion. In Chapter Five I explained how *B. subtilis* 168 uses locomotion strategies that involve deforming their membrane in order to crawl. By contrast, the *Paenibacillus vortex*, a bacterial species isolated by Ben-Jacob and Gutnick (1998), secretes lubricant chemicals, and possesses a flagella, which enables it to slide easily on hard surfaces.

Species within the *Paenibacillus* genus also differ from *B. subtilis* 168 by their colony cooperation and signalling behaviours. The *T* morphotype, for example, gets its name from a tendency for tip-splitting

01 P. dendritiformis T morphotype. Image taken from Ben-Jacob et al. (1998, p. 784)

02 P. dendritiformis C morphotype. Image taken from Ben-Jacob et al. (1998, p. 786). The original caption reads: 'The C morphotype. (a) burst of bacteria belonging to the C morphotype from colony of the T morphotype; (b and c) examples of chiral patterns exhibited by Paenibacillus dendritiformis var. chiralis' (ibid).



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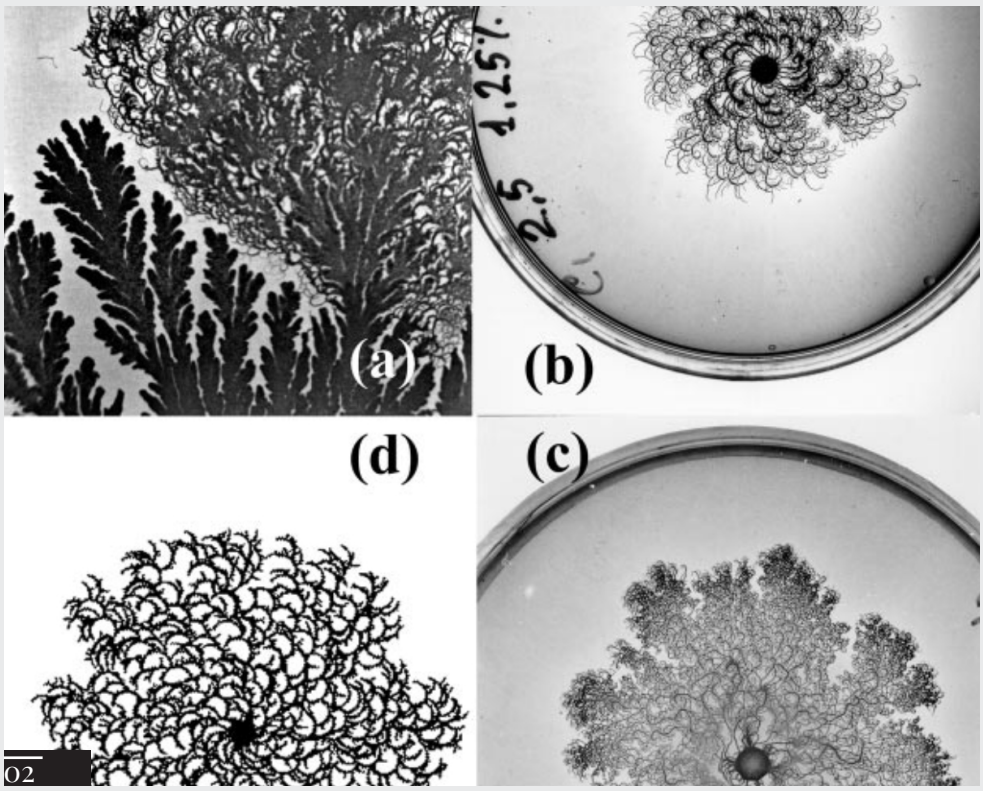

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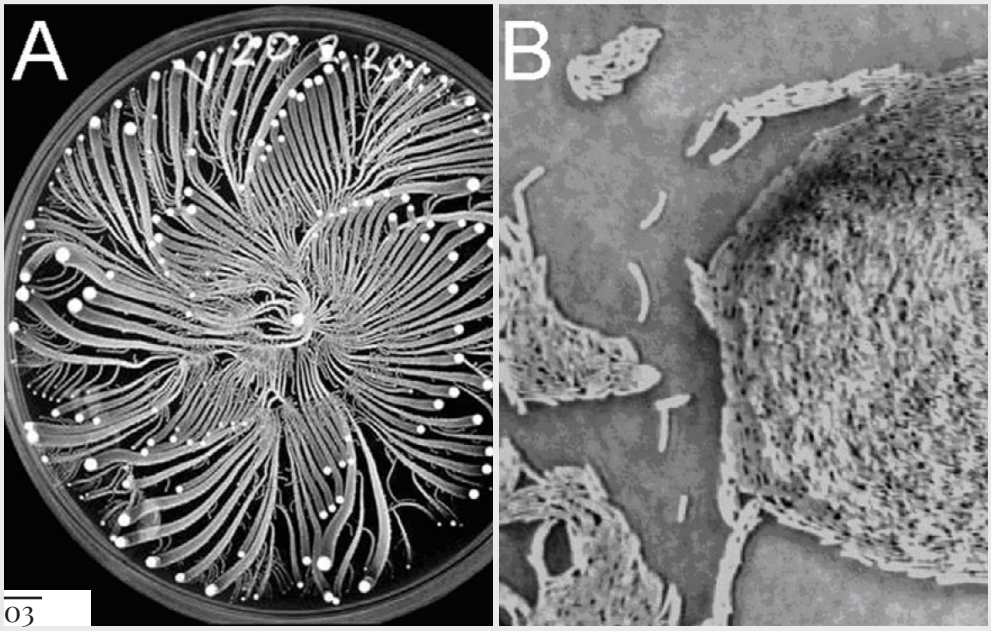
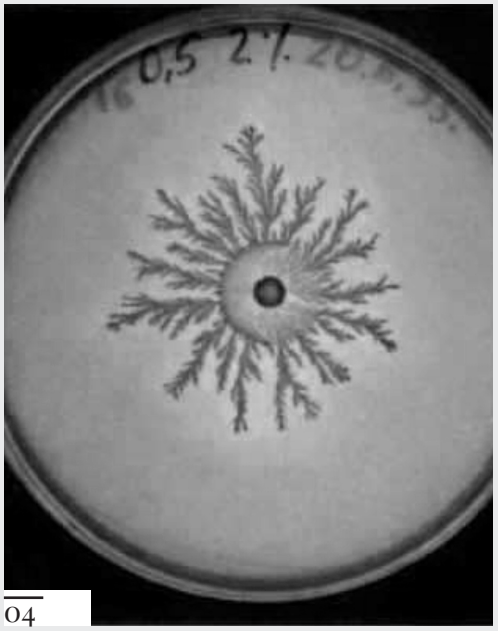


03

03 Paenibacillus vortex. Image taken from (Ingham et al. 2008, p. 3). The original caption reads: 'A typical colonial pattern generated by P. vortex when grown on 2.25% (w/v) agar with 2% (w/v) peptone in a 9 cm Petri dish. A. Whole colony view. Each vortex (the condensed group of bacteria – the bright dots) is composed of many cells that swarm collectively around their common center at about 10 µm/s. B. An individual vortex – the diameter of the vortex is 75 µm. Both clockwise and anticlockwise rotating vortices are observed, although the majority have the same handedness' (ibid).



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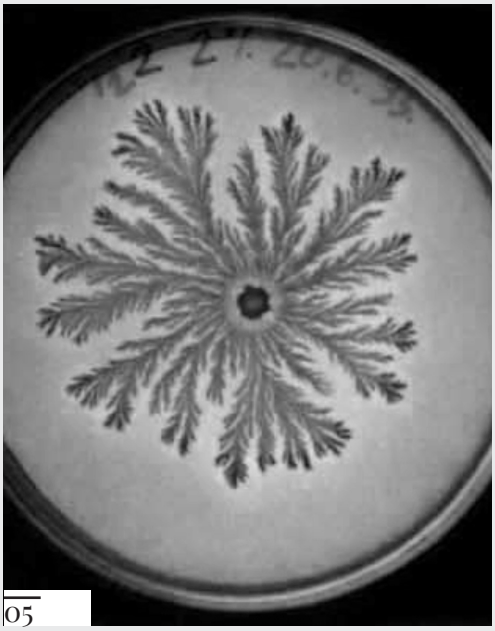


05

(Ben-Jacob 1997), referring to the process in which branches subdivide into thin arms, as seen in Figure 1D. The behaviour is thought to be connected to *repulsive chemotaxis* (Ben-Jacob et al. 1998), which describes a process by which bacteria are thought to secrete a repulsive chemical agent at low nutrient levels. The *repulsive chemotactic behaviour* is also hypothesised to operate across *Paenibacillus* sibling colonies (colonies taken from the same mother colony), preventing them from growing too close (Ben-Jacob 2009). In addition, *P. dendritiformis* morphotypes are thought to induce the death of cells that get close to the border (Be'er et al. 2009). The *C* morphotype and *P. vortex* are also named after their branching behaviours. The *C* morphotype, short for chirality, develops branches that grow into a twisting pattern (as seen in Figure 2). Similarly, *P. vortex* is characterised by tip vortices, which are linked to the clustering of hundreds of millions of cells that circle around a common centre. The behaviour enables colonies to organise according to cooperative tasks, with individual bacteria rotating either clockwise or anticlockwise (Ben-Jacob et al. 1998). As seen in Figure 3, *P. vortex* tips appear as dense circles at the tip of each branch.

Another difference between species is their appearance to the naked eye. *Paenibacillus* cells grow into highly translucent patterns, which are difficult to inspect visually. Standard protocol in working with these organisms involves dying, generally with a blue solution, to contrast them against the background of agar. A staining solution is poured into the dishes and then removed after a couple of minutes. Then, a de-staining solution is poured and left to act for a few hours. This process works by binding a colouring agent to specific proteins present in the bacteria, with the caveat of killing the organism in the process. For this reason, documenting growth also results in halting development altogether, making it impossible to document the growth of colonies across different stages in time.

04 (left) Bacillus subtilis 168 grown under 0.5g/L peptone and 2% agar. Image from Ben-Jacob et al. (1994, p. 46)

05 (right) B. subtilis 168 grown under 2g/L peptone and 2% agar. Image from (ibid)

2.3
CHEMICAL STATE-SPACE STRATEGIES

Bacterial Assemblages uses the same chemical strategies as those introduced in Chapter Five, namely, the modification of nutrient levels and of agar extract concentrate, which controls the surface hardness of the growing medium. Initially, five combinations of nutrient and agar were defined for *B. subtilis* 168 (see Table 1), drawing on those used in the literature. Medium 1 is reported by Ben-Jacob et al. (1994), and is associated with branching patterns reminiscent of diffuse limited aggregation simulations (as shown in Figure 4). Medium 2, also reported by Ben-Jacob et al. (ibid), is associated with patterns reminiscent of electrochemical deposition (see Figure 5). Medium 3 (Figure 6) is reported by Ben-Jacob (1997) and Golding (1998a), and is associated with a higher density of branches than in medium 2, and an overall longer reach. Medium 4 (Figure 8) constitutes the highest agar ratio combination. It is documented to produce highly dense, thin branches with an overall symmetrical distribution. Medium 5 is not documented in the literature and was established to offer a midpoint between the range of peptone levels used in mediums one to four, and a lower agar concentration.

06 (left). P. dendritiformis T under peptone levels of 1 g/L and agar concentration of 1.75%. Image taken from Ben-Jacob (1997)

07 (right). P. dendritiformis T under peptone levels of 1 g/L and 1.75% agar concentration. Image from Golding et al. (1998b)

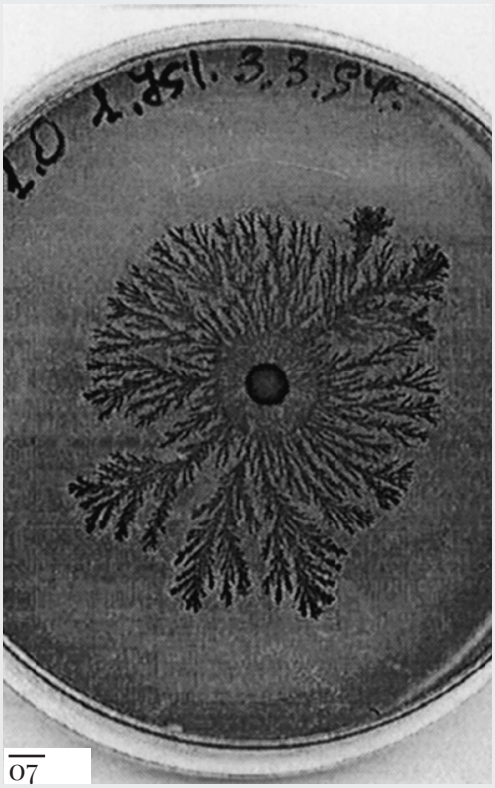
08 P. dendritiformis T under peptone levels of 4g/L and agar concentration of 2.5%. Image taken from Ben-Jacob (1997)

Medium	Peptone (g/L)	Agar (%)
1	0.5	2%
2	2	2%
3	1	1.75%
4	4	2.5%
5	3	7.5%

Table 1. Configuration of agar medium

Samples of *Paenibacillus vortex* and *dendritiformis T* and *C* morphotypes were generously supplied by the research group of Dr Ben-Jacob, who are credited with isolating and classifying the species. Along with the shipment, Dr Alin Finkelshtein sent a set of protocols (included in Figure 9), which

06



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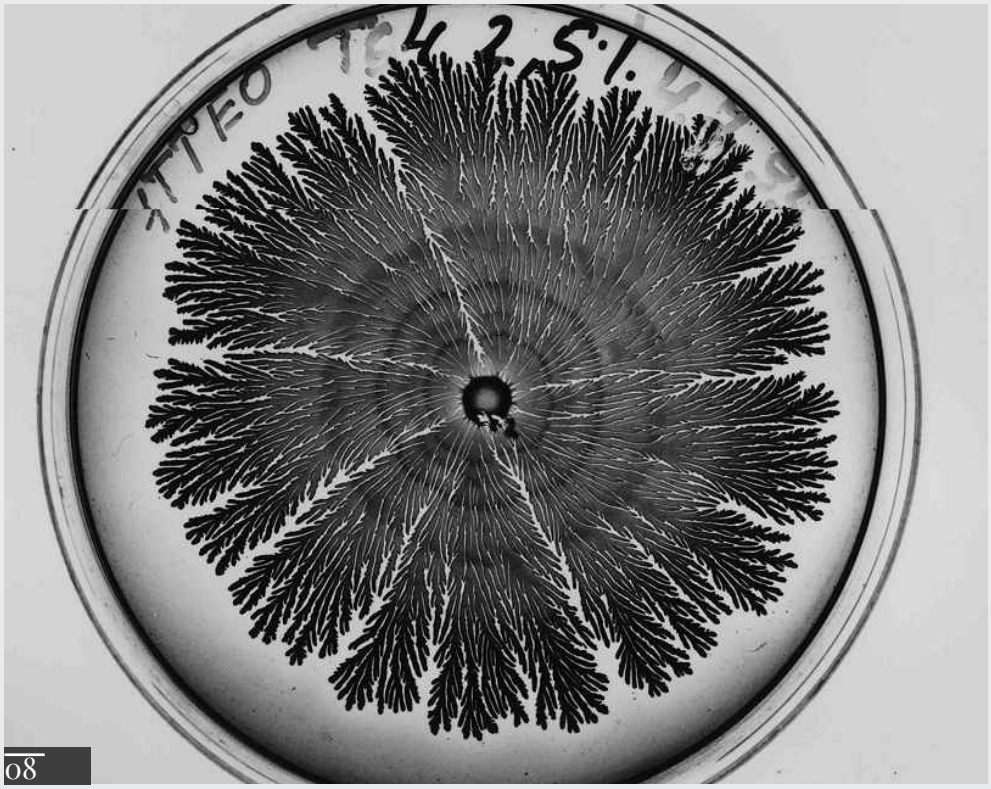


08

stated the recommended values for nutrient and agar concentration. The combinations are shown in Table 2, which shows the original value suggested for each morphotype, alongside variations that were introduced in some experiments.

Strain	Peptone (g/L)	Agar (%)
P. Vortex	15	2.25%
P. denditriformis T	2	1.5%
P. denditrifomis C	2	0.9%

Table 2. Best medium for each morphotype

a Protocols for growing the Paenibacillus.st:

Peptone plates - medium for plates (Page 2). This is the best medium for growing the beautiful shapes you have seen on the Internet and publications.

The best mediums for the strains are

P.vortex - 15gr/lit peptone 2.25% agar

P. dendritiformis T - 2gr/lit peptone 1.5% agar

P. dendritiformis C - 2gr/lit peptone 0.9% agar

Notice that changing the agar percentage will greatly effect the colony shape.

Staining protocol (Page 3) - will fix the bacterial growth on plates and allow you to see them clearly (gives a contrast) and to preserve them for a long time (years). If you are interested in colorful staining you can use any material colors instead of Briliant blue.

In general you keep the microbes in Glyserol stock (25% glycerol) in deep freeze (-80) or liquid nitrogen. Refresh once in a week on LB plate (37 Celsius degrees). The growth in liquid is also in LB 37 Celsius degrees O.N. Then you plate 5-10ul on the peptone plate and grow it at 30 Celsius degrees. If you want to see interaction (mainly repulsion) you can plate in two parallel lines with 2 cm in between them or several points (or any shape you want). The microbes will grow a bit and stop when close to each other (Be'er.A et.al 2008; Be'er.A et.al 2009).

Let me know if there is anything else I can help you with.

Staining protocol

Stain solution				Destain solution		
Brilliant Blue	0.1%	1gr				
Methanol	50%	500ml		Methanol	30%	300ml
Acetic acid	10%	100ml		Acetic acid	10%	100ml
DDW	40%	400ml		DDW	60%	600ml

Pour a stain solution on the plate until all plate is covered.

Incubate in room temperature for 2 min.

Discard the stain solution and replace it with destain (until all plate is covered)

Incubate in room temperature for 2 hours.

Dry the plate upside down until all liquids evaporate.

Peptone plates :

	1 liter	500 ml	250 ml	100 ml	50 ml
NaCl	5 gr	2.5 gr	1.25 gr	0.5 gr	0.25 gr
K2HPO4	5 gr	2.5 gr	1.25 gr	0.5 gr	0.25 gr

AGAR	1 liter	500 ml	250 ml	100 ml	50 ml
0.5%	5 gr	2.5 gr	1.25 gr	0.5 gr	0.25 gr
0.9%	9 gr	4.5 gr	2.25 gr	0.9 gr	0.45 gr
1%	10 gr	5 gr	2.5 gr	1 gr	0.5 gr
1.25%	12.5 gr	6.25 gr	3.12 gr	1.25 gr	0.63 gr
1.5%	15 gr	7.5 gr	3.75 gr	1.5 gr	0.75 gr
1.75%	17.5 gr	8.75 gr	4.37 gr	1.75 gr	0.87 gr
2%	20 gr	10 gr	5 gr	2 gr	1 gr
2.25%	22.5 gr	11.25 gr	5.67 gr	2.25 gr	1.13 gr
2.5%	25 gr	12.5 gr	6.25 gr	2.5 gr	1.25 gr

PEPTONE	1 liter	500 ml	250 ml	100 ml	50 ml
0.5	0.5	0.25	0.125	0.05	0.02
1	1	0.5	0.25	0.1	0.05
2	2	1	0.5	0.2	0.1
3	3	1.5	0.75	0.3	0.15
4	4	2	1	0.4	0.2
5	5	2.5	1.25	0.5	0.25
6	6	3	1.5	0.6	0.3
7	7	3.5	1.75	0.7	0.35
8	8	4	2	0.8	0.4
9	9	4.5	2.25	0.9	0.45
10	10	5	2.5	1	0.5
15	15	7.5	3.75	1.5	0.75
20	20	10	5	2	1

09

2.4
PHYSICAL STATE-SPACE STRATEGIES

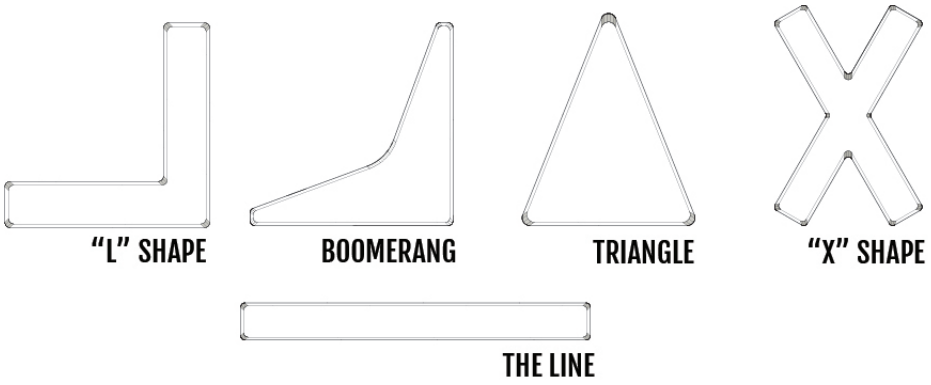
Three physical strategies are used: fabrication of plastic containers in custom shapes; the production of inserts, understood as pieces that fit inside commercially available dishes and intended to change the configuration of agar volume; and variation of inoculation techniques and patterns.

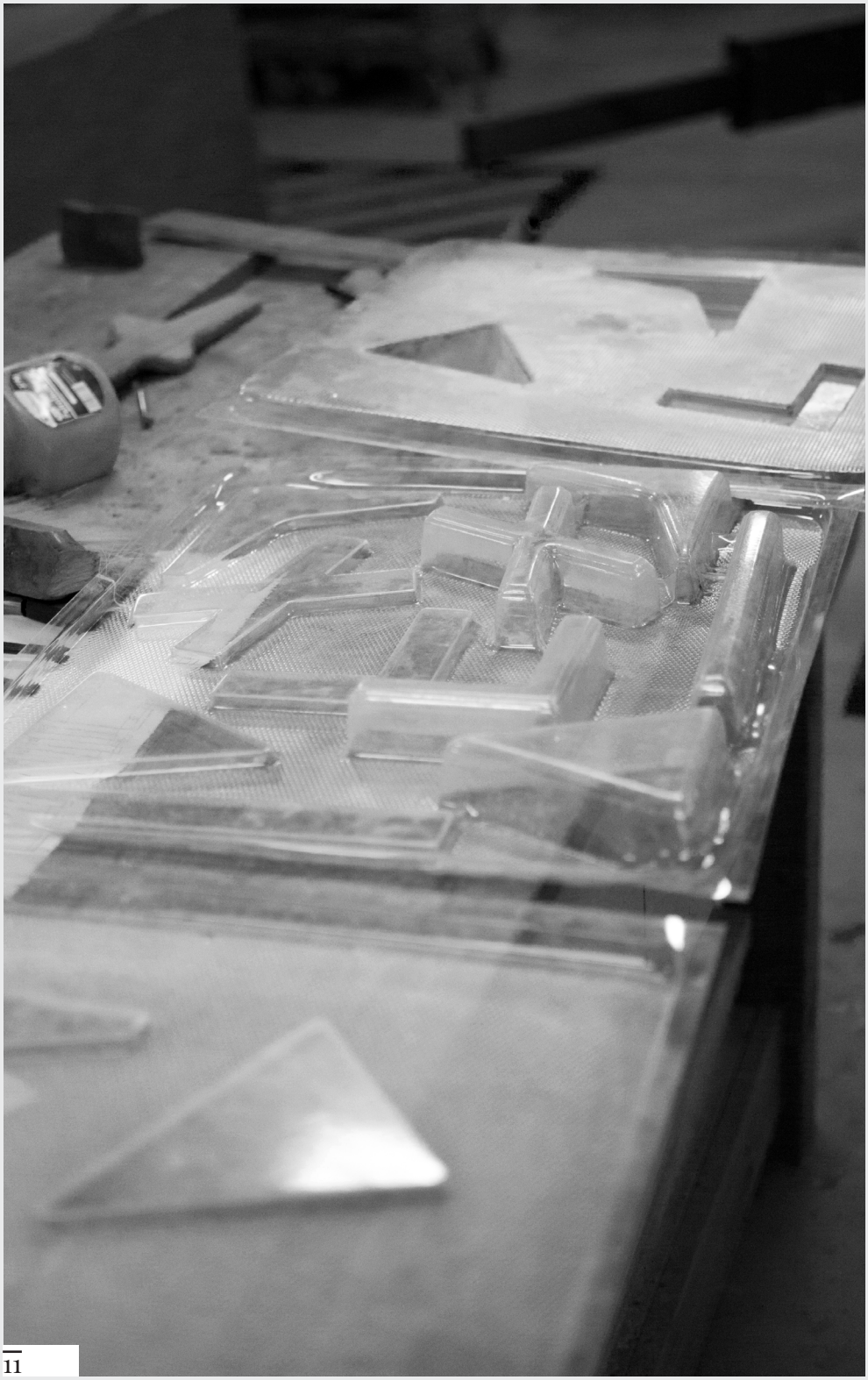
2.4.1
CUSTOM-MADE CONTAINERS

The use of custom containers is intended to explore how different geometries change the profile of physical forces in the agar volume. Containers were modelled in five custom shapes: L-shaped, line, triangle, boomerang and x-shape (Figure 10), and thermoformed in PET-G (Figure 11). The fabrication techniques, materials and spaces used to produce the containers are relevant in the analysis of the assemblage, and will be discussed in detail in the third part of this chapter.

09 *Copy of the protocol sent by Dr Alin Finkelshtein*

10 *Custom-made containers*





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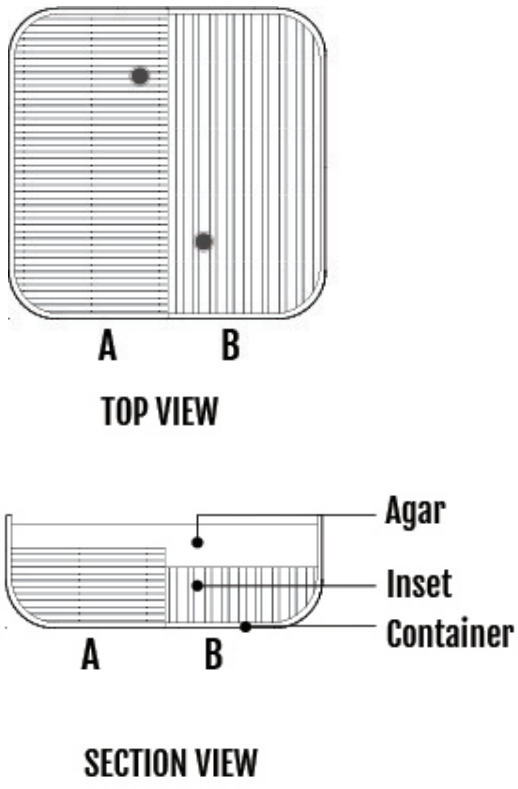
2.4.2
INSERTS

Inserts refers to plastic pieces designed to fit inside commercial dishes, and intended to modify the configuration of the agar volume by introducing volume changes. An example of this is shown in Figure 12, which changes agar depth across the dish section. The design works on the assumption that bacterial colonies would respond to the changing composition of agar by developing branches towards areas of richer concentration of nutrients. The insert is composed of two main bodies, labelled A and B in the top view. The section view shows how agar poured over body A has a lower thickness than body B, which results in a drastic change in nutrient levels. Inserts were generally fabricated using 3 mm Perspex layers, which were stacked together and glued. Figured 13A to G show images of some of the prototypes that were fabricated.

11 Fabrication of the custom-made containers

12 Diagram showing basic design of inset



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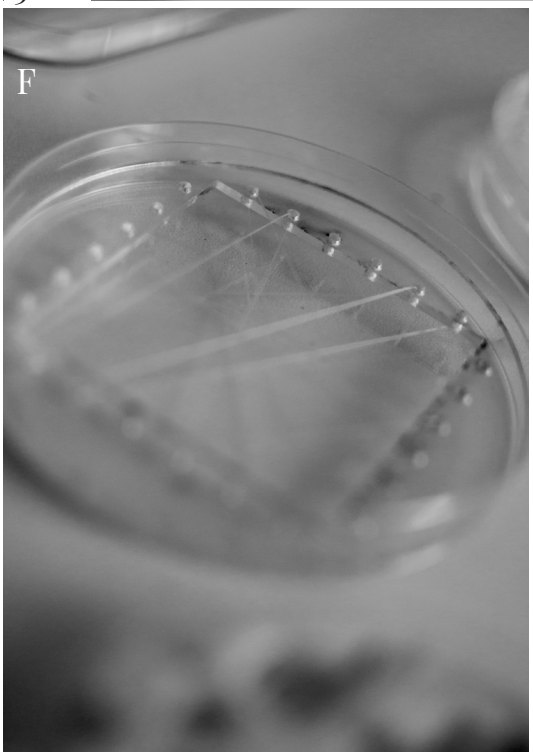
A

B

C

D

E


F

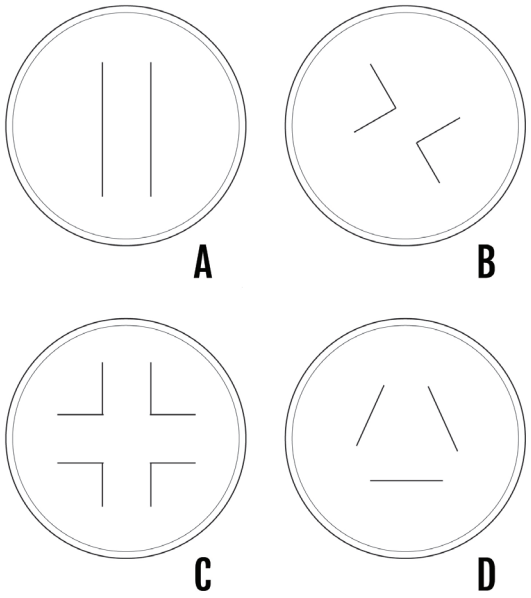
G

2.4.3
INOCULATION TECHNIQUES

Another strategy designed to manipulate the physical state-space is the use of different inoculation techniques. Two techniques are used. Pipetting involves placing a small volume of bacteria colonies, 5 *microliters*, using a tool known as a pipette, which is an instrument that uses a partial vacuum holder to control the suction and release of liquids. As a result, pipetting affords a high level of accuracy in placing bacteria in concentrated drops. By contrast, streaking makes use of the smear loop, which consists of a metal rod ending in a small loop of approximately 5 mm in diameter, which is used to transfer bacterial colonies onto plates by streaking them over the surface of the agar, resulting in broader area placements. Figure 14 shows a diagram of streaking patterns used in explorations with *Paenibacillus*.

13 13A to 13G. Inserts fabricated in Perspex and inserted in commercial dishes

14 Streaking diagram



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3

PART THREE

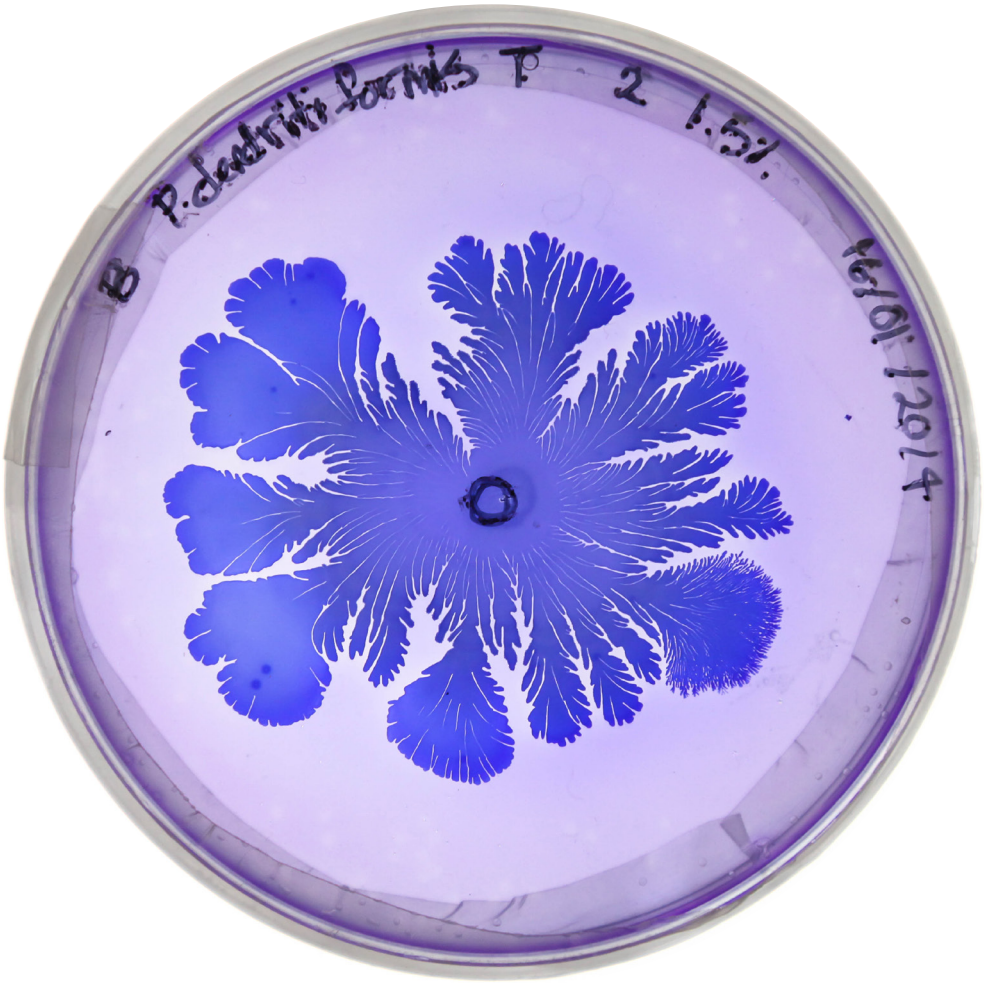
BIO-MATERIAL PROBE: BACTERIAL ASSEMBLAGES

This part of the chapter documents how the creative exploration revealed different aspects of the assemblage, suggesting how actants aligned, cooperated and blocked one another. As suggested in part two, *Bacterial Assemblages* takes the model of the state-space of design as a strategy to find an entry point into the assemblage, and to navigate the complexities of its constituent parts interacting with one another.

Chapter Five suggested that, in addition to the original state-spaces, there were also contingent ones, which grouped aspects of protocol and implementation, interacted with the originals, and became relevant in specific configurations of the design system. In *Bacterial Assemblages*, I use the approach of assemblages to explore the notion further. I expand the original notion and propose three contingent state spaces: *spaces of practice, cultures of crafting* and *social interactions. Spaces of practice* refer to the way that the spatial configuration of workspaces and tools conditions the development of activities, in the way they embody a specific script that refers to different frameworks of knowledge. *Cultures of crafting* concentrate on the frameworks and techniques that enable things to be done within disciplinary boundaries. *Social interactions* refer to the governance of spaces that enable certain things to happen, and which depend on exchanges between individuals.

3.1
PHYSICAL, CHEMICAL AND CELLULAR STATE-SPACES

Earlier I explained how species within the *Paenibacillus* genus are characterised by distinct cooperation behaviours, an example of which can be observed in Figure 15, which shows an experiment with *P. dendritiformis T* morphotype grown under peptone levels of 2 g/L and agar concentration of 1.5%. Branching is characterised by tip splitting, with branches subdividing into smaller arms. I also explained how the *Paenibacillus* genus are characterised by repulsive chemotactic behaviours across sibling colonies. Figure 16 shows an experiment with the *T* morphotype and the same conditions as Figure 15. The plate is inoculated with two sibling bacterial colonies placed 2 cm away from each other, and that grow to leave a clear gap.



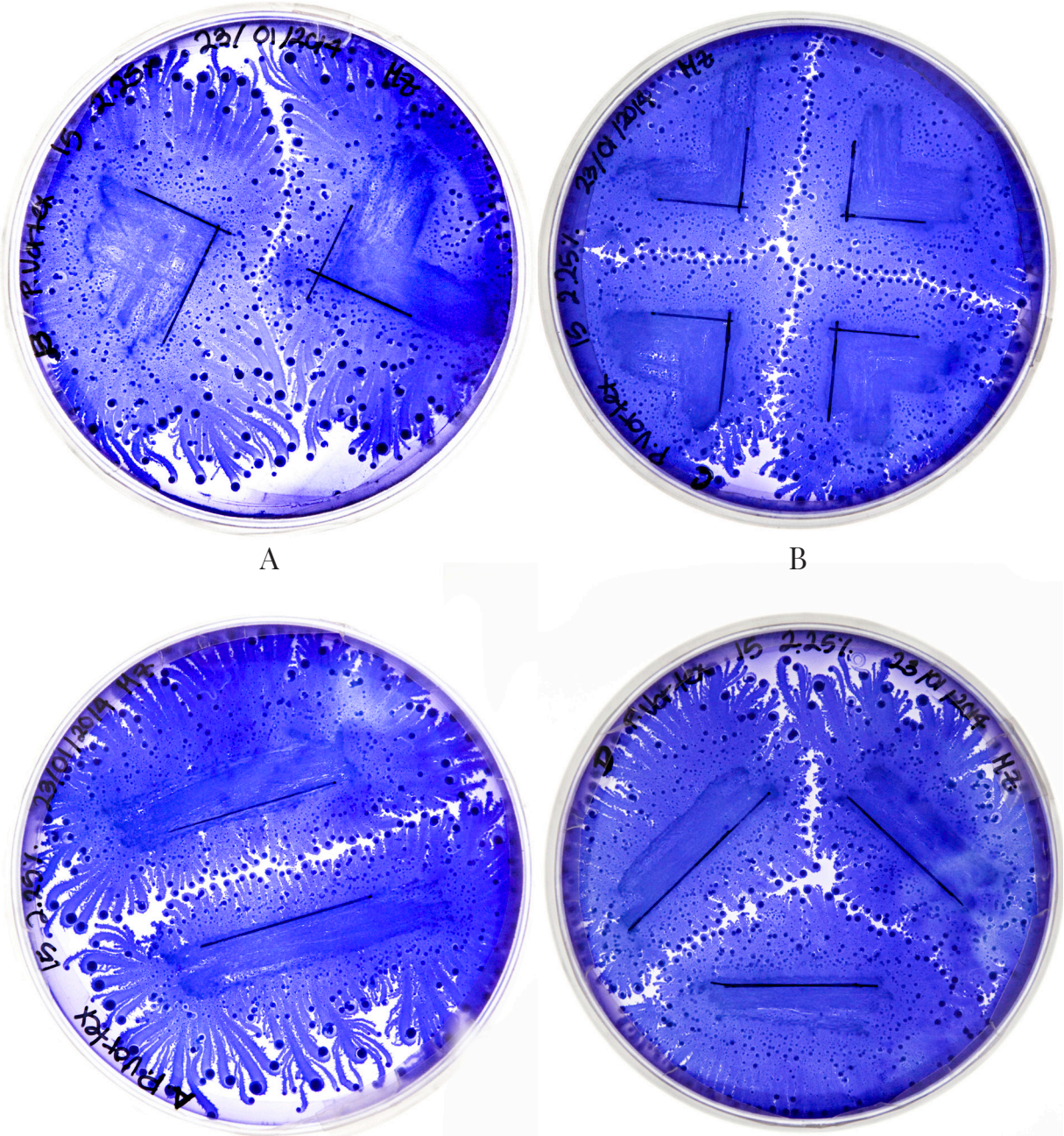
15 P. dendritiformis T morphotype grown under peptone levels of 2g/L and agar concentration of 1.5%

16 Two sibling colonies of P. dendritiformis T grown under peptone levels of 2g/L and agar concentration of 1.5%. The colonies where inoculated 2cm away from each other

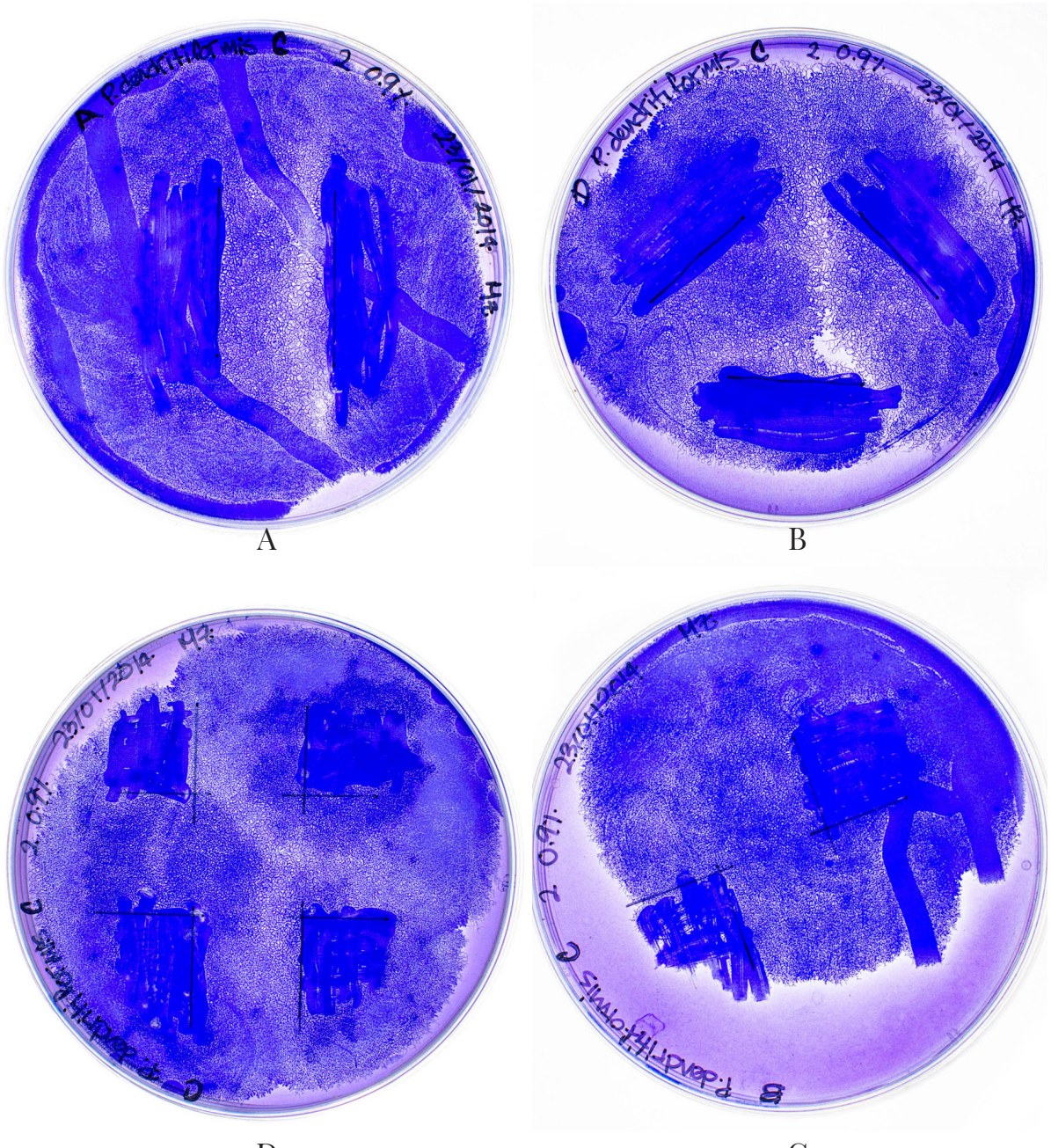
Figures 17 and 18 show some behaviours that are characteristic of *P. dendritiformis C* morphotype and *P. vortex*. Each plate uses a different streaking pattern, which activate repulsive behaviours. In 17A the cleft between sibling colonies follows a sinuous line, which results in the relative angle at which inoculation areas are located. Similarly, clefts in 17B to 17D follow straight lines, which mirror the relative angles between streaking patterns.

Chemotactic repulsive behaviours combine with attraction in *P. dendritiformis C* morphotype. Figure 18A shows a faint cleft running parallel to the inoculation line to the right, which diffuses into attraction at the top and bottom sections of the plate. This is similar to the pattern in 18B, which develops repulsion gaps intersecting at angles similar to those of the initial inoculation streaks. The effect of repulsion is more difficult to perceive in 18C, where the repulsion gaps are less pronounced but follow a spatial configuration connected to the four streaking areas. Repulsion patterns diffuse to the edges into attraction, suggesting that portions of each colony fuse into one general colony for the overall dish. Also of interest is the texture of the area surrounding the overall growth spread. 18B and 18D show a transparent edge in the agar composition, which might suggest the effect of the lubricating fluid generated by the colony to facilitate locomotion.

The experiments in Figures 17 and 18 make use of different streaking patterns, a strategy that influences the physical state-space, as well as being specific to different species. I have also suggested two further physical strategies: custom-shaped containers, and inserts. Figures 19 and 20 show experiments developed with *B. subtilis* 168 using custom-made containers. In both cases, the medium is prepared with peptone levels of 4g/L and agar concentration of 2% . The images show an incubation period spanning four weeks, with each photograph representing the state of the experiment at one-week intervals. In Figure 19, the long-shaped plate is prepared with three points of inoculation and shows how colonies tend to develop branches that run parallel to the walls of the container. During the first two weeks, documented in 19A and 19B, colonies grow into radial, evenly distributed patterns. 18C shows how, as branches reach the boundary, they swerve and develop into elongated branches parallel to the wall. Similar effects are seen in Figure 20, in which branches grow to avoid the boundary starting in week three. Colonies on the right arm of the container grow their branches along



17 *17A to 17D, from top-left clockwise. P. vortex inoculated in four different streaking patterns. The colonies were grown under peptone levels of 15g/L and agar concentration of 2.25%.*



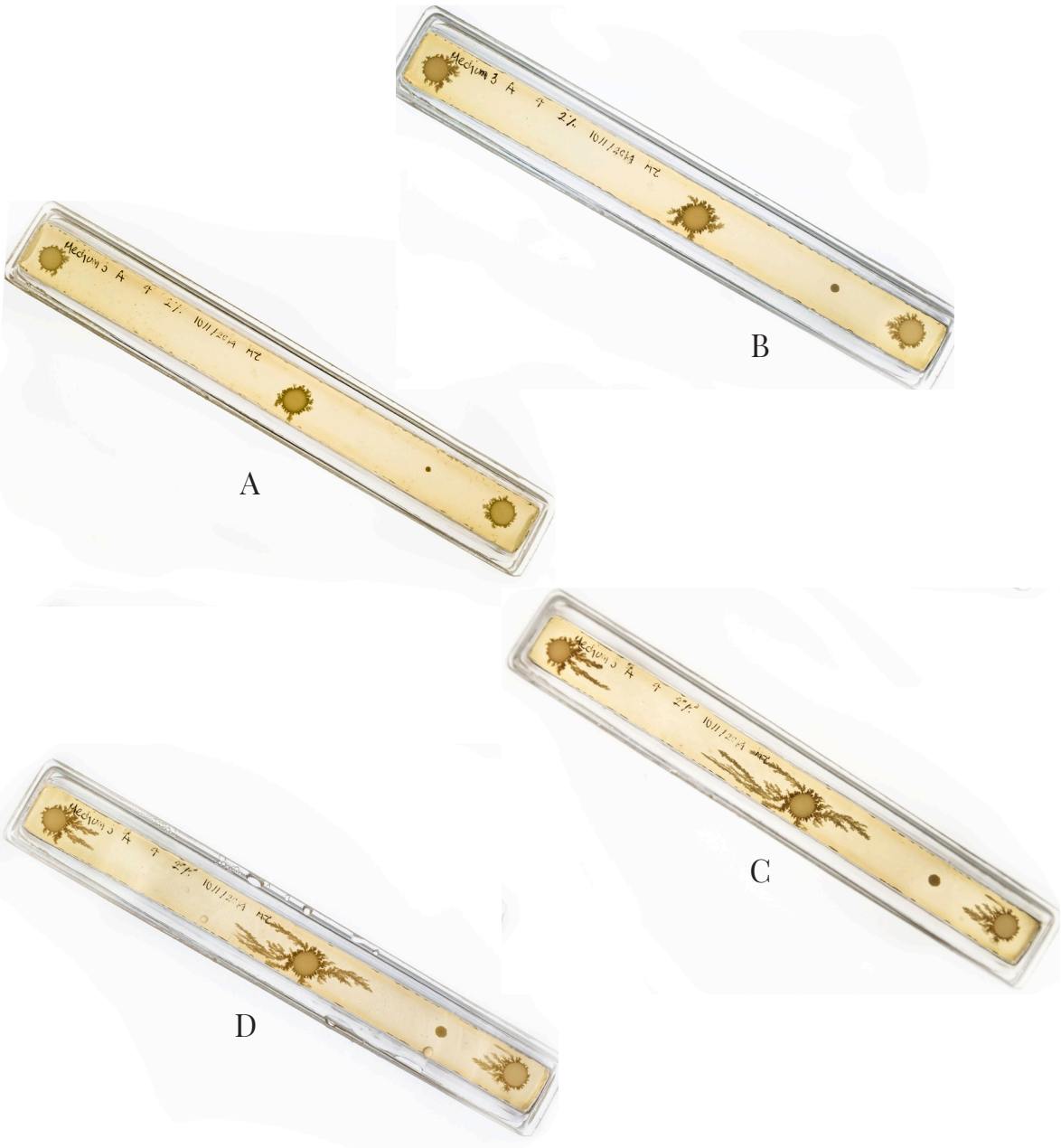
A B D C

18 18A to 18D, top-left clockwise. P. dendritiformis C under peptone levels of 2g/L and agar concentration of 0.9%. The plates were inoculated using four different streaking patterns

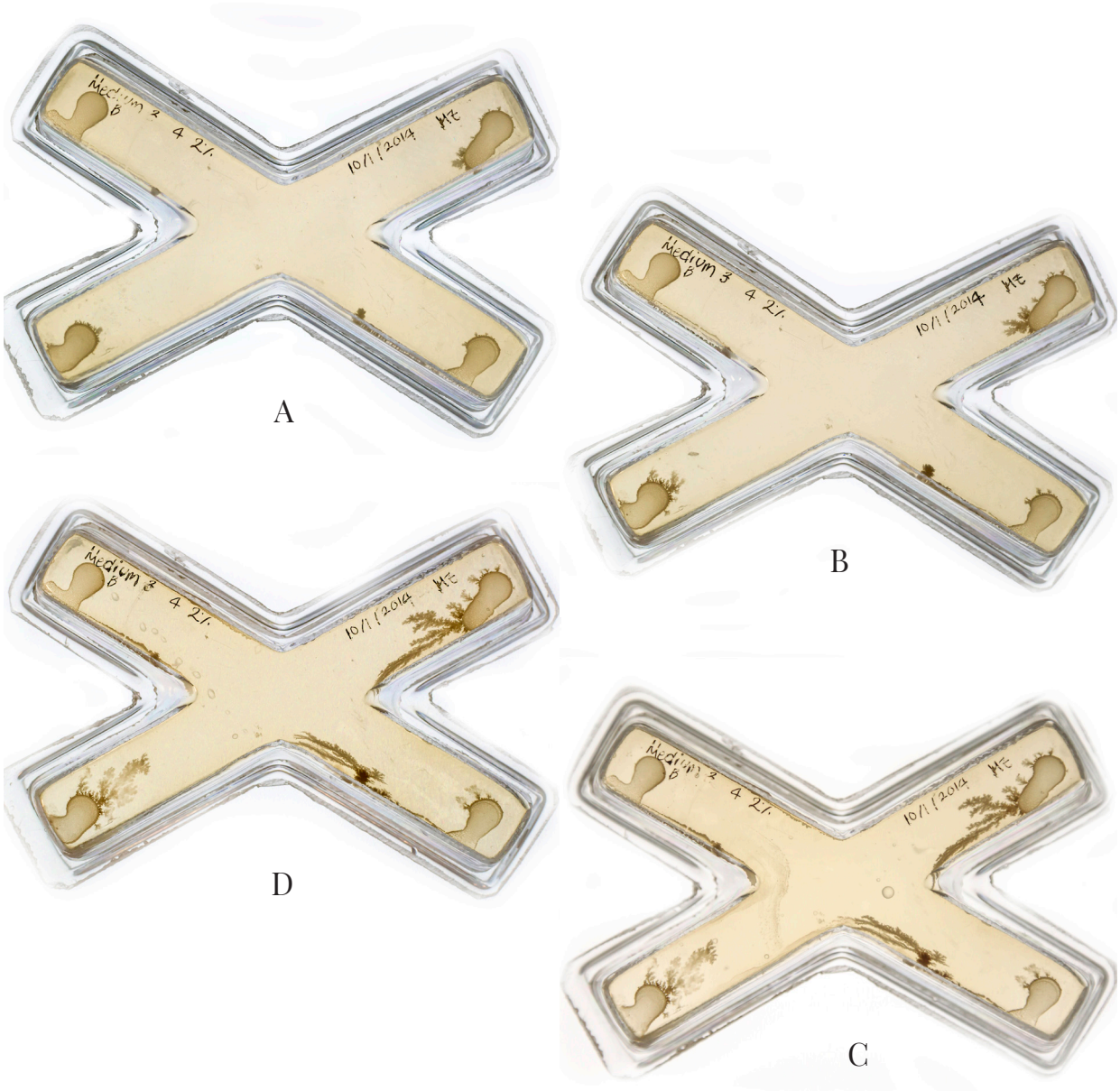
the edge of the container, while the colony on the lower left arm develops its branches at a distance from the walls. Moreover, the colony growing from the upper right arm shapes the tip of its branches, following the sharp corner where the arms of the containers meet.

Figure 21 shows experiments performed with custom containers and *P. dendritiformis C* morphotype. The composite shows four experiments with agar concentration of 0,9% and peptone of 2g/L . Branching morphologies develop to adapt to the shape of the container, exhibiting similar strategies to *B. subtilis* 168 in running parallel to the walls of the container.

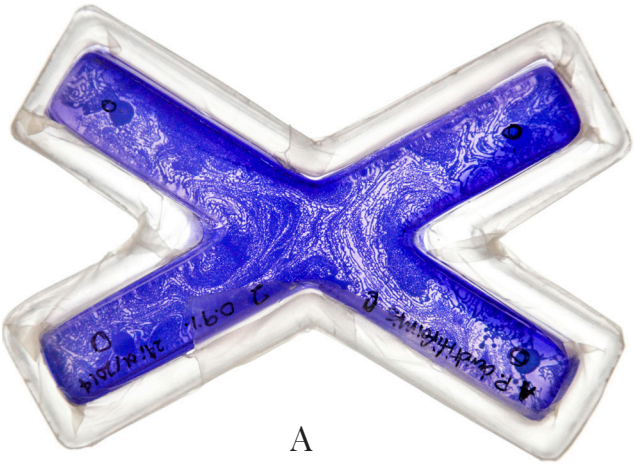
Another strategy to influence the physical state-space was to introduce inserts into commercially available dishes. Figure 22 shows an experiment using *P. vortex* inoculated in media prepared with a 2.25% agar concentration and peptone levels of 15 g/L. The dish is prepared by inserting Perspex pieces, which creates agar channels. Three colonies are inoculated close to the boundaries, forcing them to grow along the edges and to branch out away towards the centre of the channels. This is combined with repulsive behaviours, leaving a gap with the nearby colonies. A similar behaviour can be seen in Figure 23, that shows an experiment with *P. dendritiformis C* grown under peptone levels of 2 g/L and 0.9% agar. The dish integrates a similar configuration of Perspex inserts. Three colonies are inoculated close to corners generated by the insert, which forces morphologies to grow along the edges and away towards the centre. Clefts between colonies are less noticeable than in the *P. vortex*, reducing to a faint gap at the middle of the channel and merging towards the periphery.



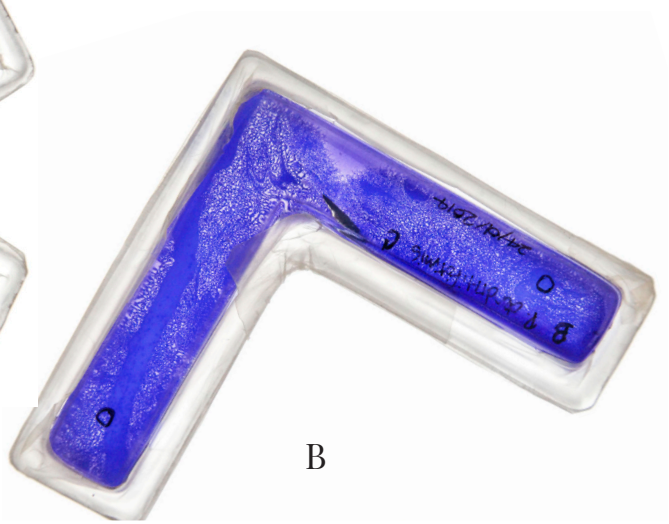
19 *19A to 19D, left to right, clockwise. Time lapse showing Bacillus subtilis 168 under peptone levels of 4g/L and agar concentration of 2%. The experiments were carried out using an l-shaped container*



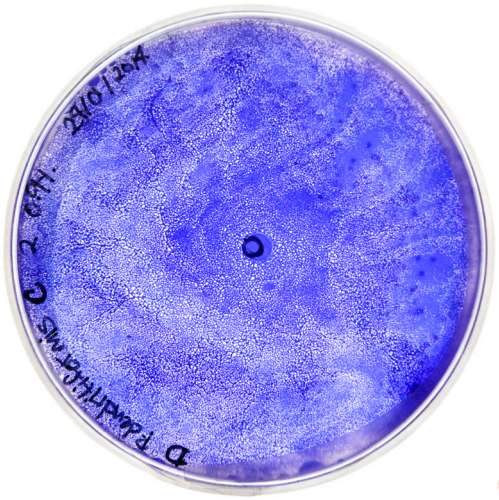
20 20A to 20D, left to right clockwise. Time lapse showing Bacillus subtilis 168 under peptone levels of 4g/L and agar concentration of 2%. The experiments were carried out using an x-shaped container



A



B



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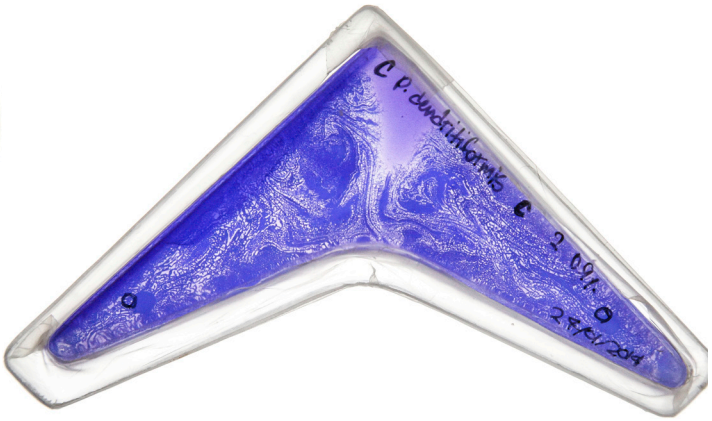
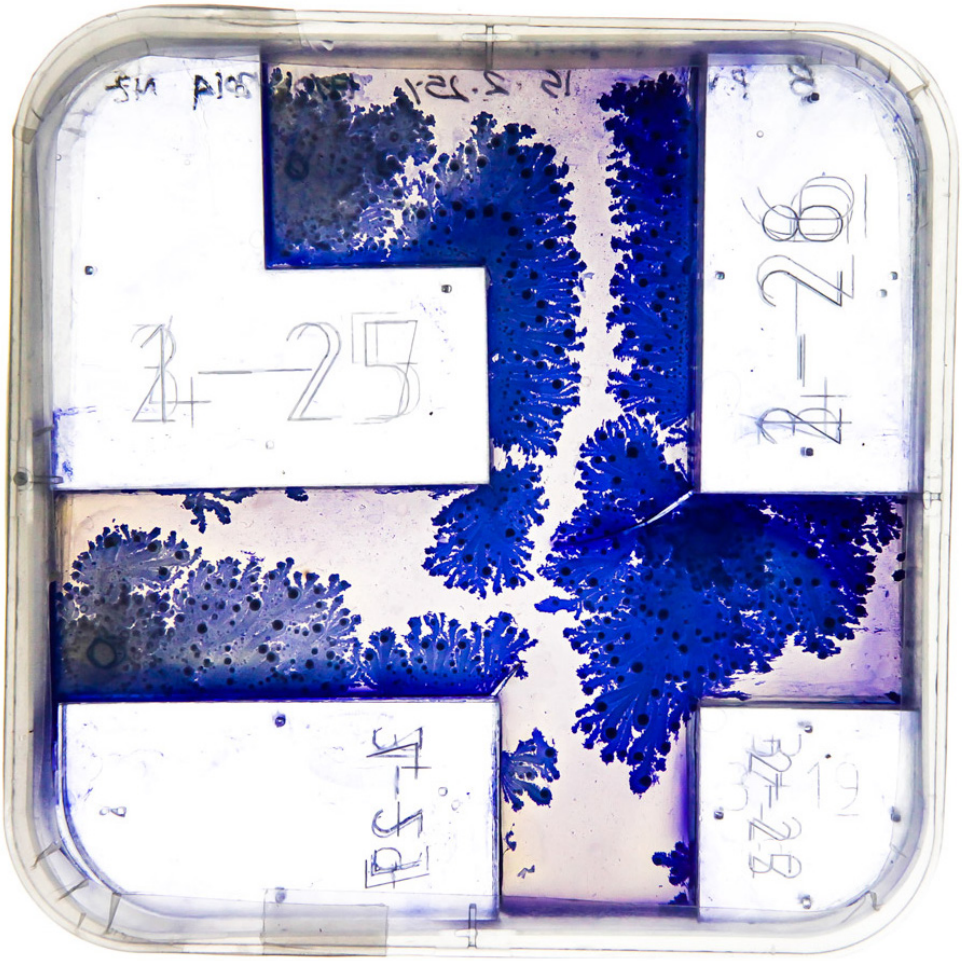


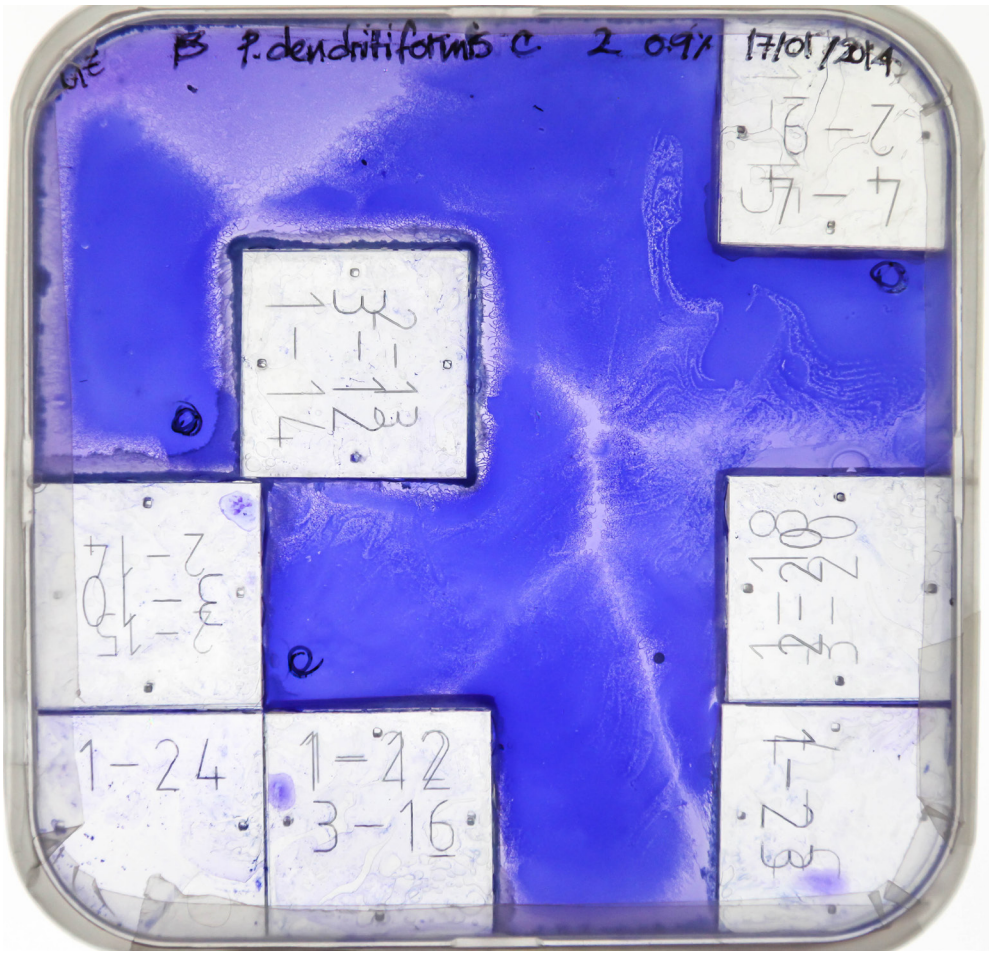
C

21 21A to 21D, from top-left clockwise. Experiments with P. dendritiformis C morphotype under peptone levels of 2g/L and agar concentration of 0.9% The experiments were carried out using four different containers and with multiple inoculation points

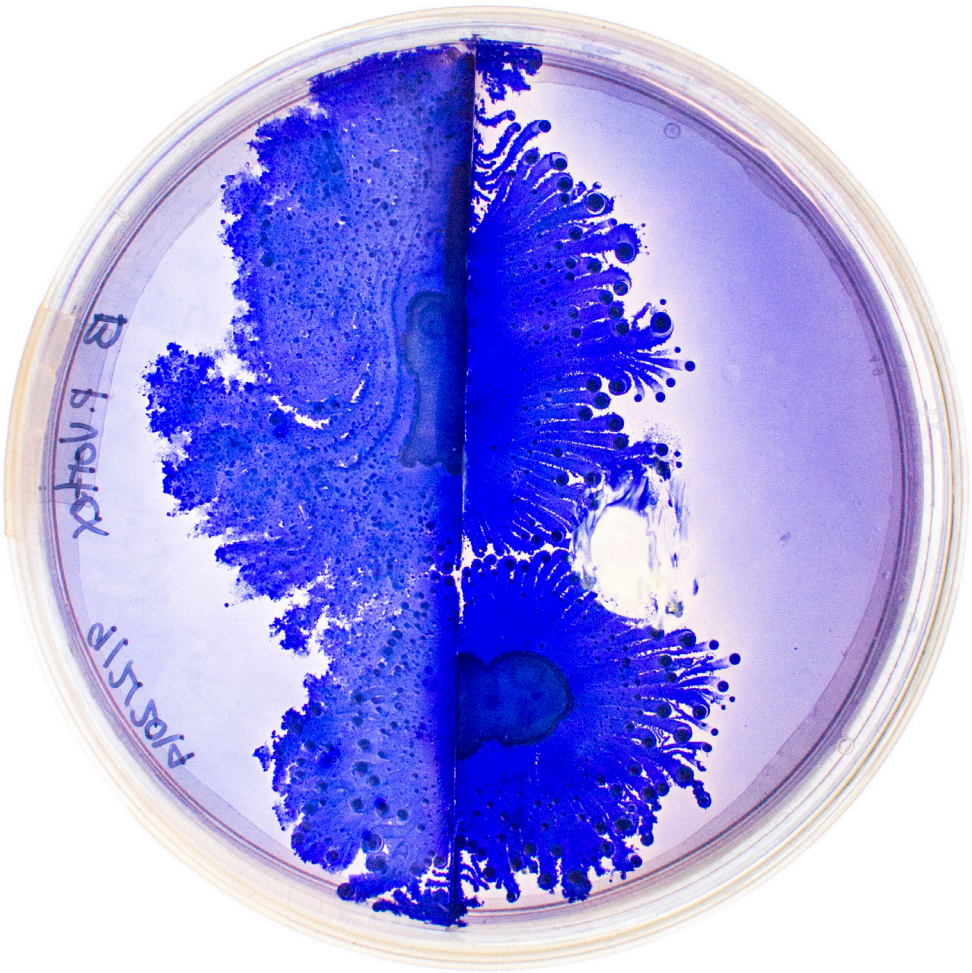
The experiments above explain how different strategies within the physical and cellular state-space were implemented and are connected to different concentrations in agar and nutrient level. Another strategy used to influence the chemical state-space was the creation of plates with two different media, produced by placing a plastic barrier that holds one half of agar concentrate, which partially settles before pouring a second media with a different composition. Figure 24 shows an experiment using this strategy. The medium on the left uses a 15g/L nutrient concentrate, and a surface hardness of 2.25% agar. The one on the right is prepared with 7g/L peptone and 2.25% agar concentration. The plate is inoculated in two spots with colonies of *P. vortex*, which, as the image shows, create markedly different branching patterns in both sides. The branches on the left, for example, exhibit denser tips than the one on the right, with clearly defined branches. The same set-up is used in the experiment shown in Figure 25, resulting in similar patterns.



22 P. vortex on labyrinth-shaped plate grown under peptone levels of 15g/L and agar concentration of 2.25%



23 P. dendritiformis C grown under peptone levels of 2g/L and agar concentration of 0.9%. The experiment was done using a labyrinth-like inset



24 Image showing a plate with two halves of media with different compositions. P. vortex grown under peptone levels of 15g/L and agar concentration of 2.25%

25 Image showing a plate with the same set-up as Figure 24

3.2
SPACES OF PRACTICE

The implementation of the experiments analysed above requires two physically separated spaces: a microbiology laboratory located in Northumbria University, and a fabrication workshop located in Newcastle University's School of Architecture, Planning and Landscape. Each of these *spaces of practice* is designed under different *scripts*, following the term used by Madeleine Akrich to refer to the way artefacts and spaces encapsulate a vision of the world. She proposes that:

> By defining the characteristics of his object, the conceiver puts forward a number of hypotheses concerning the elements making up the world into which the object is intended to fit. He proposes a 'script'.,. a 'scenario', intended as a predetermination of the settings which users are called upon to imagine starting from the technical device and its accompanying prescriptions. (Akrich 1992, p. 208)

Latour has also analysed the way that scripts operate in laboratories, pointing at how furniture and space arrangement is configured according to models of knowledge acquisition. In *Circulating Reference,* Latour proposes that, in order to bridge the gap between reality and its representation, science often relies on non-humans. These non-humans, he goes on to explain, are often physically configured to reflect the structure of scientific knowledge itself, facilitating the translation between the natural world and scientific theory. He describes how following a group of pedologists and botanists in fieldwork in the Amazonas reveals these non-humans at different scales, ranging from tags attached to trees to surveying instruments, which superimpose a grid of Cartesian coordinates onto the jungle. These non-humans, Latour proposes, transform the jungle into a laboratory:

26 Photograph showing a classification shelf in Manau Botanical Institute, and referred to by Latour as Figure 2.5. Image from (Latour 1999)

> I thought I was deep in the forest, but the implication of this sign, '234', is that we are *in a laboratory*, albeit a minimalist one, traced by the grid of coordinates. The forest, divided into squares, has already lent itself to

26

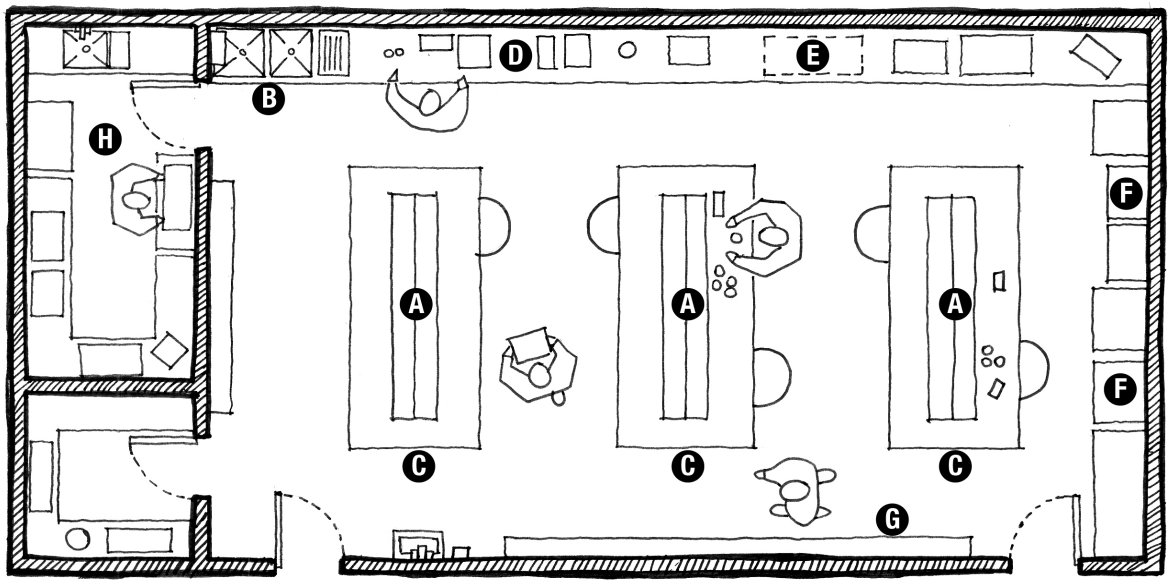
> the collection of information on paper that likewise takes a quadrilateral form (Latour 1999, p.32).

The analysis extends to the way in which specimens collected in the jungle are organised for later reference. For example, the storing cabinets in the laboratory are also configured to follow the same logic of quadrants and Cartesian grids. Latour writes:

> What will happen to these plants? They will be transported further, placed in a collection, a library, a museum (...) In Figure 2.5 [Figure 26] we are in a botanical institute, quite far from the forest, in Manaus. A cabinet with three ranks of shelves constitutes a workspace crisscrossed in columns and rows, x- and y-axes. Each compartment shown in this photograph is used as much for classification as for tagging and preservation. This piece of furniture is a theory (...) capable of organising this office, a perfect intermediary between hardware (since it shelters) and software (since it classifies), between a box and the tree of knowledge (idem, p. 36).

A similar analysis can be made of the spaces of practice, laboratory and workshop, which codify scripts that afford specific forms of exploration. The laboratory, for instance, codifies the script of reductionist epistemology. The microbiology laboratory used in this exploration is part of the School of Applied Sciences in Northumbria University (see Figure 27), and hosts the research spaces of postgraduate and postdoctoral researchers in the area of microbiology and biotechnologies. A plan drawing of the space is included in Figure 28, and an isometric in Figure 29. The space is organised as a series of large parallel benches (labelled A), subdivided into four areas, which are assigned to individual researchers. High shelves are attached to each bench space, which provide storage space for frequently used chemicals and instruments. Bench surfaces are made of plastic with a polished finish, which facilitates cleaning and hygiene inspection. Along the long sides of the room are additional benches, which contain instruments for communal use, such as electronic scales (label D), fridges (label F) and a drying oven (label E). A water distiller and two sinks are located at the left end of the bench (label

27 Panoramic image showing the laboratory used at Northumbria University



A Working bench

B Sinks & water distiller

C Chemical cupboard
The chemicals are organised by alpahetical order.

D Electronic scales

E Drying oven
Tips and dishes are kept inside to keep them sterile.

F Fridges

G Lab consumables

H Incubation area
Incubators at different temperatures for the diferent samples.

28 Plan drawing of the main microbiology laboratory used in the exploration

B), where instruments and non-disposable containers are washed for future use. Shelf G is used to store lab consumables, such as petri dishes, gloves and protection masks. Chemicals are stored in cupboards beneath bench ends (label C in Figure 11, see also Figure 30), organised alphabetically and stored at both ends. Adjacent to the main area is H, a smaller room, separated by a communicating door and which houses a number of incubators (such as the one shown in Figure 31) and chambers.

The layout of the space is designed around the programme of the scientific experiment, in which the validity of the experimental protocol is tied to the control of variables. The arrangement of furniture and equipment in space is designed to provide the conditions required to develop experimental protocols that guarantee substrates free of foreign organisms. Figure 29 shows, for example, how the bench arrangement provides researchers with individual, designated workspaces, which limits the amount and size of experiments. This also constrains the use of custom-made instruments to support the experiments, or indeed the size and shape of the containers that can be used to perform experiments. The social ties and dynamics elicited by the space also contribute and reflect a scientific epistemology. The fact that researchers depend on shared instruments and facilities means, for example, that experimental processes have to adhere to standards of use. Likewise, a shared work environment facilitates a diffuse control of standards: senior researchers can call off bad practices from PhD students, for instance. The combination of these events and practices are intended, ultimately, to produce models of causality that connect one variable to a specific effect.

The fabrication workshop, on the other hand, codifies a script of experiment as understood in design and craft traditions. In this context, experimentation is an open-ended process that enables the understanding of a material, or exploring potential design solutions through the fabrication of prototypes. Here, the focus is not on the production of sterile conditions, but on the availability of different tools that enable the manipulation of an array of materials. Agapakis has reflected on the different meanings of *experiment* across design and biology:

> In art and design, I use the 'experiment' as an open-ended process to open up and reveal potential ideas; in science, the 'experiment' is a

DISTILLER

Most procedures are carried out using distilled water

WET AREA

Glass dishes, bottles and containers are washed in this area

PREP AREA

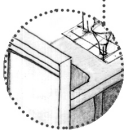
The area is used to prepare compounds and mixtures. It is equipped with electronic scales and centrifugues

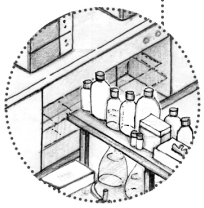
HEATED CUPBOARD

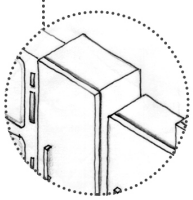
The heated cupboard is used to control internal moisture. Petri dishes are placed inside for a few minutes to dry the agar surface

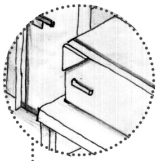
FRIDGES

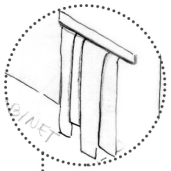
Small fridges are used in the lab to, for example, preserve a bacterial culture for the day experiment. Bacteria strains are preserved in -80c freezers, located in another laboratory

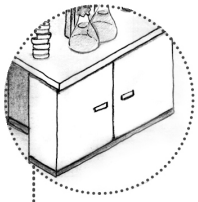


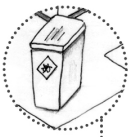












INCUBATOR

The incubator is located in an adjacent room to the main laboratory and is a common resource. Experiments have to be brockered, as the incubator has a global temperature control.

LABCOAT RACK

The 'ritual' of working in the lab begins just after crossing the door, where the researcher leaves their personal belongings and puts on the labcoat to reduce contamination.

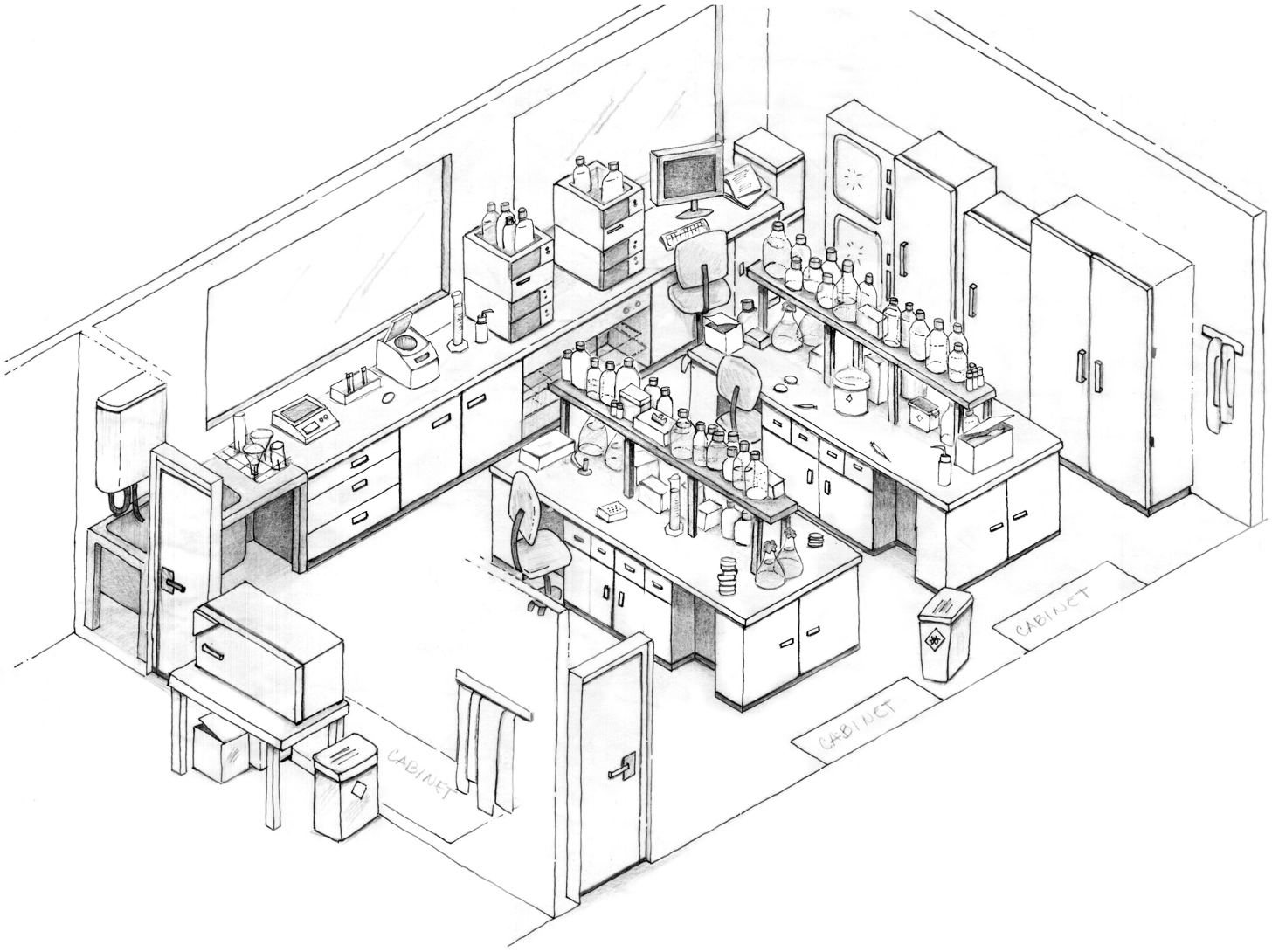
CHEMICALS CUPBOARD

Chemicals and powder compounds are sorted alphabetically and stored under the work benches

'WASTE' DISPOSAL

Strict protocols are in place to make sure that any piece of equipment that has been in contact with biological systems are decontaminated or disposed of. Yellow 'biological waste' bins are scattered throughout the lab

29 *Isometric diagram of the main lab. The drawing shows the main lab used in the exploration. Key areas and pieces of equipment are highlighted, referring back to themes that are discussed in the main text.*


CABINET
CABINET
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> tool to generate data to test a hypothesis. Repeating an experiment and achieving the same results is key to the scientific method, whereas the experimental process in art often seeks out the exceptional or unique. Artifacts may emerge from experiments. In science, the 'artifact' is an outlying bit of data — an erroneous, often human-induced thing that can be ignored, like the distortion caused by the curvature of a lens. Conversely, for the artist or designer, the artifact is the focus of our attention: We are actively making things (Agapakis 2014, p. 122).

The differences in frameworks of experimentation are manifested in the spaces of each discipline. The fabrication workshop used in this exploration is organised into two different sections. One is a traditional workshop, articulated around work tables, with machines and tools organised in the periphery. Workshop users can take up a space at the tables, moving to use each machine for specific interventions, such as creating straight and curvilinear cuts or sanding, and assembling prototypes at the table. The second space is organised around digital fabrication technologies, which involve laser-cutting machines, 3D printers and CNC routers.

Introducing custom containers, fabricated in different materials and shaped to non-standard geometries, involves bringing a new agent into the assemblage of the laboratory. Microbiological experiments are generally conducted in petri dishes: shallow, cylindrical plates, which, combined with a lid, provide a standard environment for growth and observation. The configuration of these plates is itself an interesting process of negotiation of humans and non-humans. Petri dishes are part of an array of equipment developed by the team of bacteriologist Robert Koch in the nineteenth century to improve the techniques of a then incipient bacteriology. Koch was particularly interested in demonstrating the link between different species of microorganism, and the role they played in the development of diseases. This required isolating microorganisms in a controlled environment that enabled visual inspection. By 1870, common laboratory techniques involved growing bacteria in liquid media, which presented several issues, especially as bacteria move easily in fluid. Moreover, it was difficult to isolate single species of bacteria in liquid culture (Blevins & Bronze 2010).

30 Cupboard underneath workbench, storing assorted chemicals

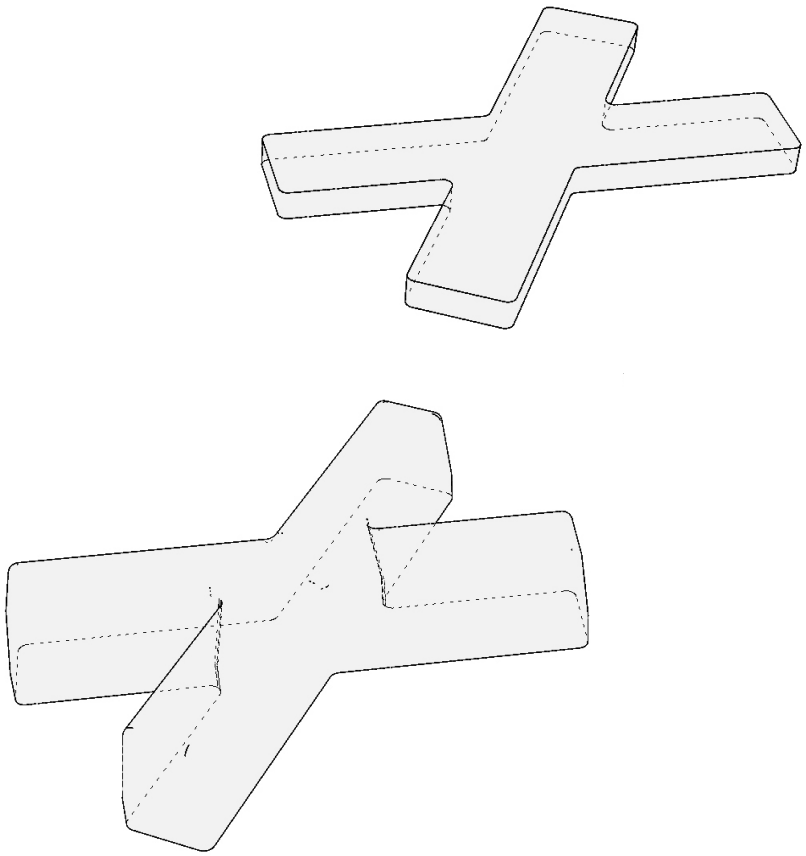
31 The incubator used in the experiments, located in the room adjacent to the main laboratory

Koch realised that fungal organisms would grow 'pure' on a slice of potato, without mixing them with other colonies and species. This prompted his team to experiment with growing substrates and eventually settle for gelatine, which could be dissolved in hot water and poured as liquid into containers. When it cooled down, the media solidified into a smooth, translucent medium that enabled isolation and ease of inspection. Later, Fannie Hesse, the wife of one of Koch's postdoctoral researchers, suggested using agar, a seaweed extract that had a similar texture to gelatine but with a higher melting point, thereby improving the consistency of the substrate at room temperature (ibid). To avoid contamination, plates were covered with bell jars that minimised contact with other microorganisms, air and human breath. Bell jars, however, presented another problem, as they made it difficult to inspect growth, often forcing researchers to remove the bell jar to collect data, introducing contamination. One of Koch's laboratory assistants, Julius Petri, devised a flat lid, slightly larger than the plates, which protected the experiments from contamination and improved visual inspection. Koch presented the pure plate technique and Petri lid to Pasteur, which helped to make the technique widespread in bacteriological and, later, microbiological work.

Introducing custom-shaped plates involves finding ways in which agencies can align, in both the workshop and laboratory. Custom-made containers need to maintain some of the features of Koch's pure method, such as ease of visual inspection and aseptic conditions. As a result, containers need to be watertight; to be produced in materials amenable to sterilisation; and to possess high optical qualities. Furthermore, the manufacturing process should provide the versatility to produce relatively smooth shapes, while offering quick reproduction. The workshop, however, was predominantly configured for woodwork, and the best fit to produce the containers was thermoforming, a technique that uses a mould, often referred to as a plug. The process involves heating up a plastic sheet to achieve a plastic state, and using a vacuum machine to force the sheet to take the shape of the plug. The technique allows for relatively inexpensive and quick reproduction of prototypes using the same mould. Moulds were created by developing a digital 3D model (see Figure 32), which was used to derive slices that were laser cut in MDF. Layers were glued together and sanded by hand to produce a

smooth surface. The influence of space on practices is evidenced in Figure 33, which shows the production of custom-made containers and which involves the creation of moulds in MDF; the preparation of the moulds by coating them in talc; the arrangement of moulds in a vacuum-former; and the production of containers in plastic.

32 Image of the 3D model created for the X-shaped container



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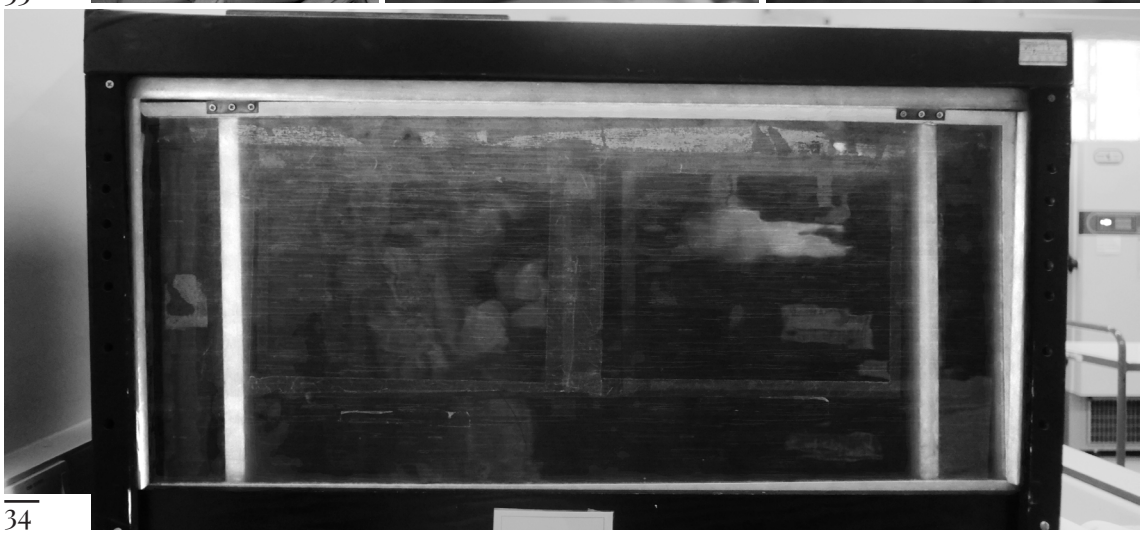

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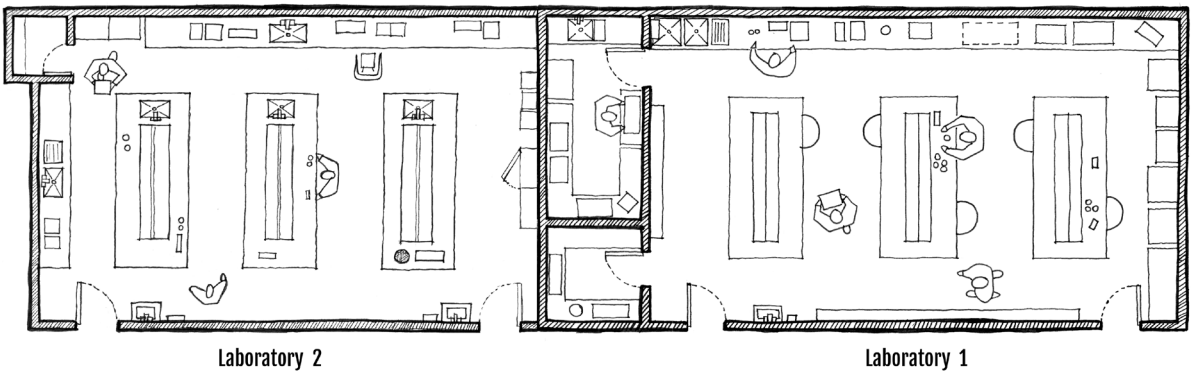
3.2.1
SPACE AND CONTAMINATION

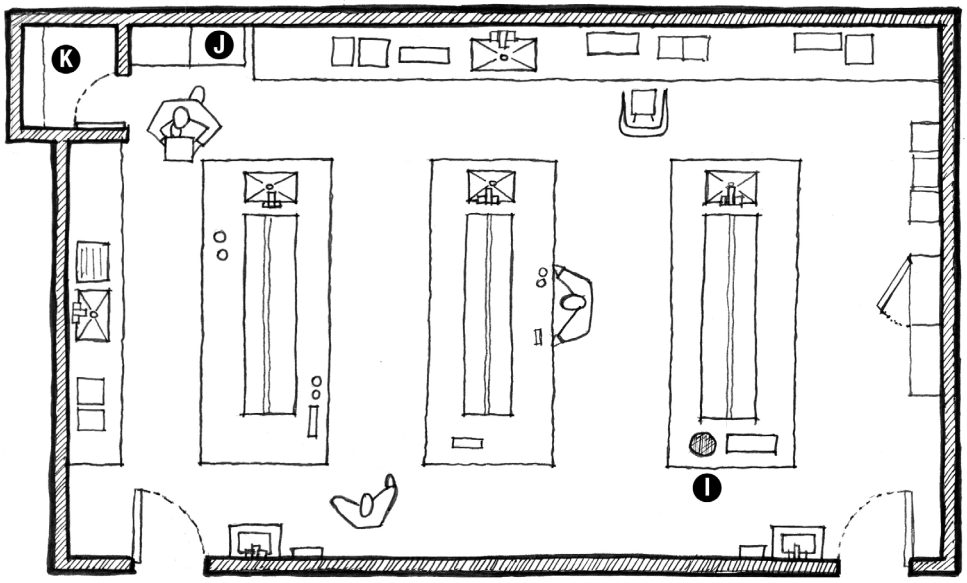
The physical space influences branching via contamination. Implementing the physical state-space involved fabricating containers in the workshop and decontaminating them before introduction to the laboratory. There are two possible procedures to sterilise containers. One is to place them in the autoclave, which raises their temperature above 100 °C for one hour, killing microorganisms. However, the plastics used in the containers, initially polystyrene and later PET, have a low heat distortion temperature, which makes them unsuitable for temperature-based decontamination. The alternative is to use a UVC bath, in which containers are placed in a UV light chamber for several hours prior to the experiment (see Figure 34). Each decontamination procedure involves different sequences in the use of spaces. Researchers in laboratory 1 depend on other laboratories to access additional pieces of equipment (see Figure 35). For example, Figure 36 shows the location of the autoclave (label I), -80 °C freezer (label J), and walk-in fridge (label K), which are located in laboratory 2. Additionally, the UV decontamination chamber (see Figure 37, label C) is located in a third laboratory, located elsewhere in the building. Using the autoclave involves carrying containers from the bench (label A in Figure 37) across the laboratory, opening the door, walking through the corridor, opening the door of the next laboratory and placing the container in the autoclave (label B). Using the UV light bath involved a similar procedure, but with a longer walk through the corridor.

33 *Sequence showing the production of custom-made containers in the workshop*

34 *Photo of the UV light chamber*

The spatial sequence involved in using the UV ray bath makes contamination more likely as a result of the longer distance. The risk is reduced when the autoclave in the adjacent laboratory is used. The effect of these spatial sequences in morphology can be seen in Figures 38A and 38B. The image composite shows the evolution of an experiment, performed in an x-shaped container, with *B. subtilis* 168 inoculated in five points. Two white spots are seen in the lower right arm of the container, which indicate the presence of another microorganism, possibly a fungus. Contamination constrains the development of nearby colonies, which develop away from the other organism.



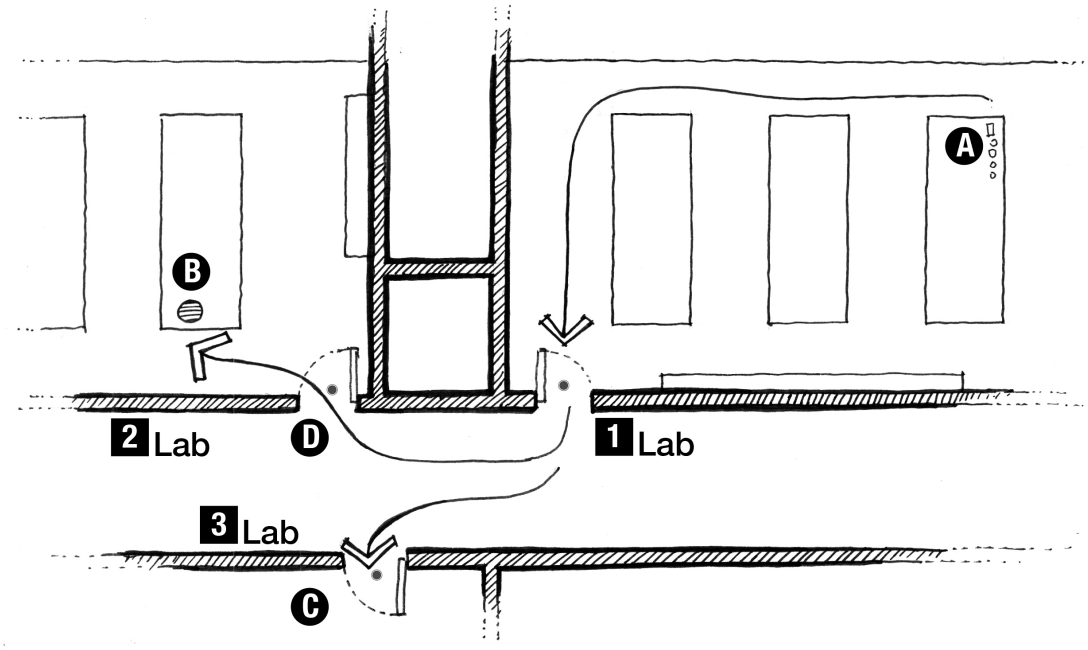


I Autoclave machine

J Freezer to -80 ºC
Here are keep all the samples of organisms availables in the lab.

K Walk-in fridge

35, 36 Figure 35 drawing showing the location of laboratory 1 and 2. Figure 36 drawing showing the location of equipment in laboratory 2



A Working bench

B Autoclave machine
Chemicals are sterilse for there use

C UV light chamber
For instruments that cannot be sterilse at higher temperatures

D RFID access control

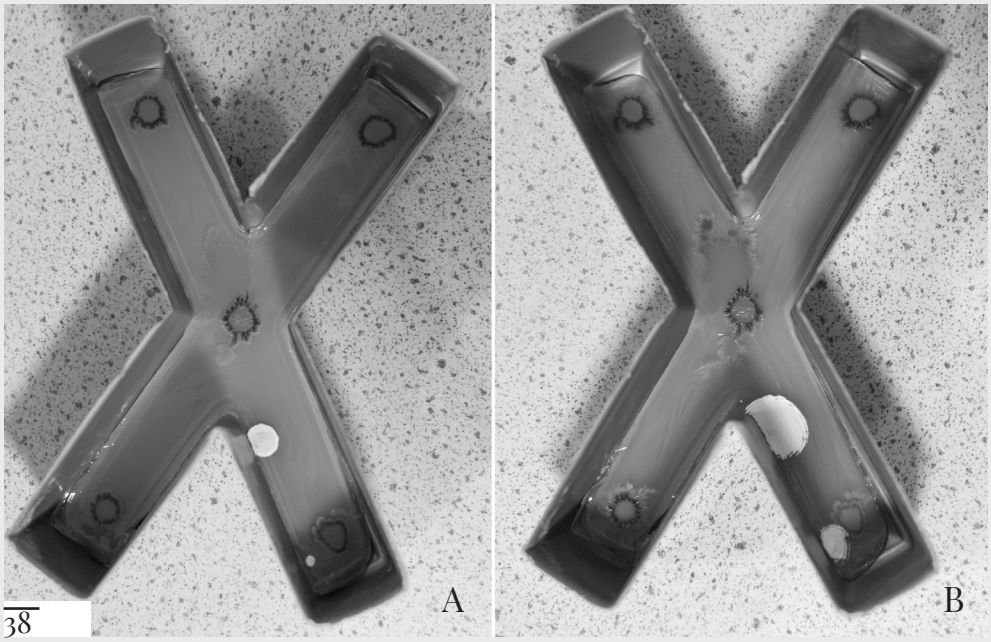
3.2.2
THE MICRO-SCALE OF THE BENCH

Interaction between the physical space and morphologies is also seen in the smaller scale of the bench, in which a number of protocols are implemented to reduce the possibility of contamination. A good example of this are the protocols for dish preparation and inoculation. Both processes require the precise articulation of the bench space, which is organised around a heat bubble generated by the Bunsen burner, and which contributes to generating a sterile volume around it, as visualised in Figure 39.

Preparing petri dishes with agar requires a number of actions to be carried out in two stages, the latter of which involves careful articulation of the bench space. The first stage involves a careful choreography around the physical space of the laboratory. Agar is available in a fine powder that is dissolved in water to achieve different consistencies in the solidified volume. The process contributes to controlling the physical conditions of the experiments by constraining or facilitating cellular locomotion, as a harder surface will prove more difficult for microorganisms to move in. Agar concentration is generally expressed in percentage. A 2% agar solution, for example, contains 2 mass units of agar concentrate per 100 units of water volume. Preparing agar involves calculating the approximate combined volume needed for a number of dishes, determining the corresponding agar extract weight and water volume required. In the space, the procedure involves gathering glassware in the bench space (step 1 in Figure 40), locating and retrieving the agar and peptone extract containers from the cupboards (step 2), weighing the concentrates in the electronic scales using a small plastic dish (step 3), and transferring to a glass container . Distilled water is drawn from the dispenser (step 4) using a graduated cylinder and poured into the glass container with the solid concentrates. The container is then placed on top of a magnetic stirrer (step 5). A magnetised stir bar is thrown inside the container, rotating as a consequence of the magnet and stirring the contents. Once the solution is homogenous, the container is closed with a lid and sealed with autoclave tape, which chang-

38 38A and B. Experiments performed in an x-shaped container, which show evidence of contamination

39 showing convection lines representing the heat 'bubble' generated around the Bunsen burner, which provides a sterilised atmosphere to work in



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39

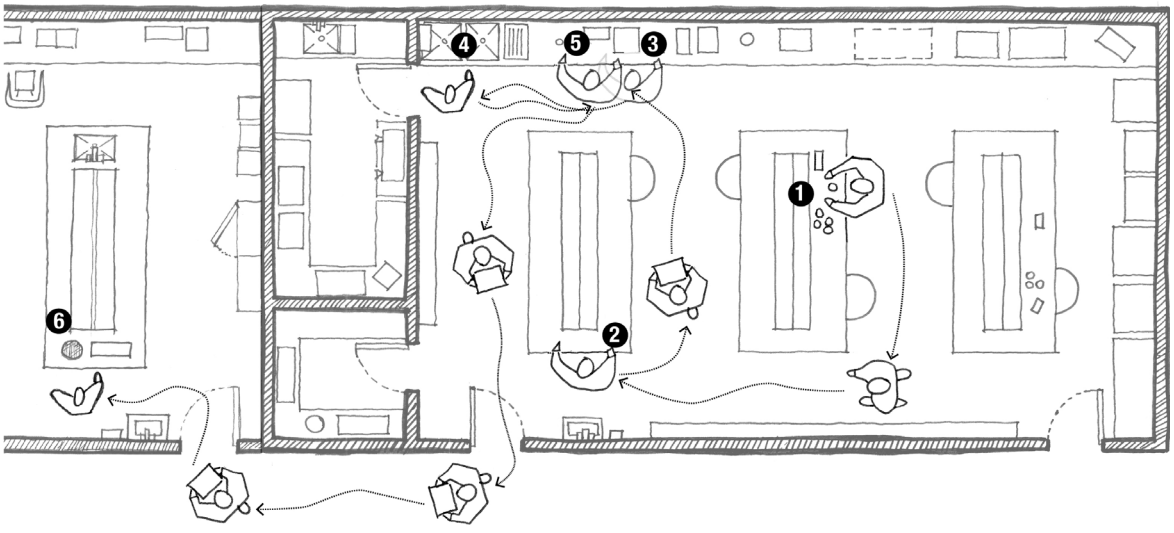
es colour from green to black as an indication that the contents have been sterilised. Sterilisation involves placing the container in an autoclave machine (step 6), which consists of a pressure vessel containing an amount of water and a grid basket. Instruments and containers are placed inside the basket, which is placed above water level. Water is boiled, producing steam, which builds up in the chamber. This conserves the contents at high temperatures, generally around 120°C, for an amount of time, approximately 30 minutes. Figure 41 shows a photographic description of these actions, and Figures 42 and 43 show the interior of the autoclave.

40 Series of steps involve in preparing growth media

41 Sequence showing the process of preparing growth medium, starting from locating the chemicals through to placing the solution in the autoclave

42 Autoclave used in the exploration

43 43A and B, showing the interior of the autoclave, and its controls



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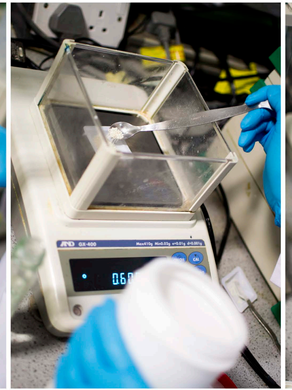

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A

B

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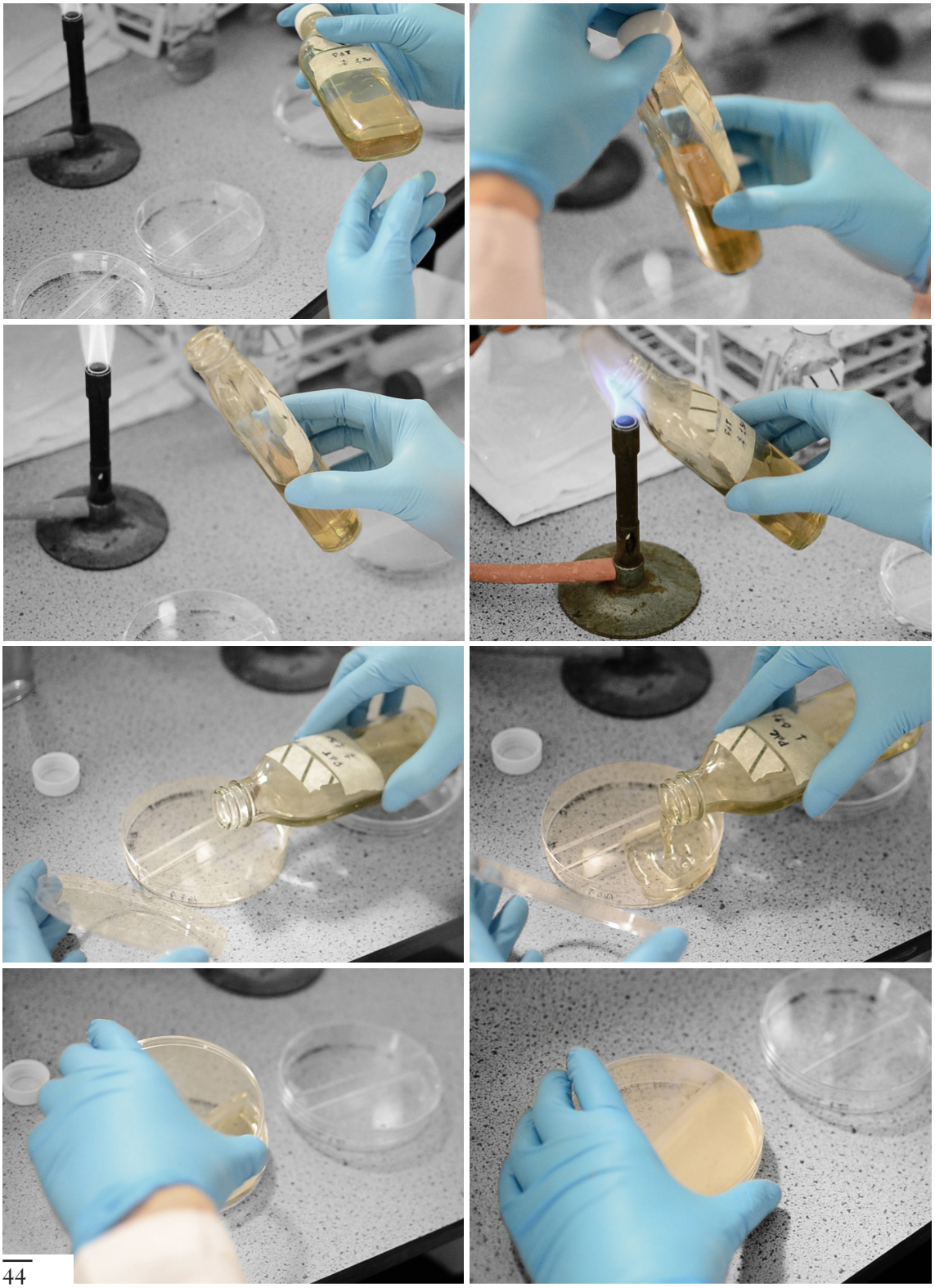
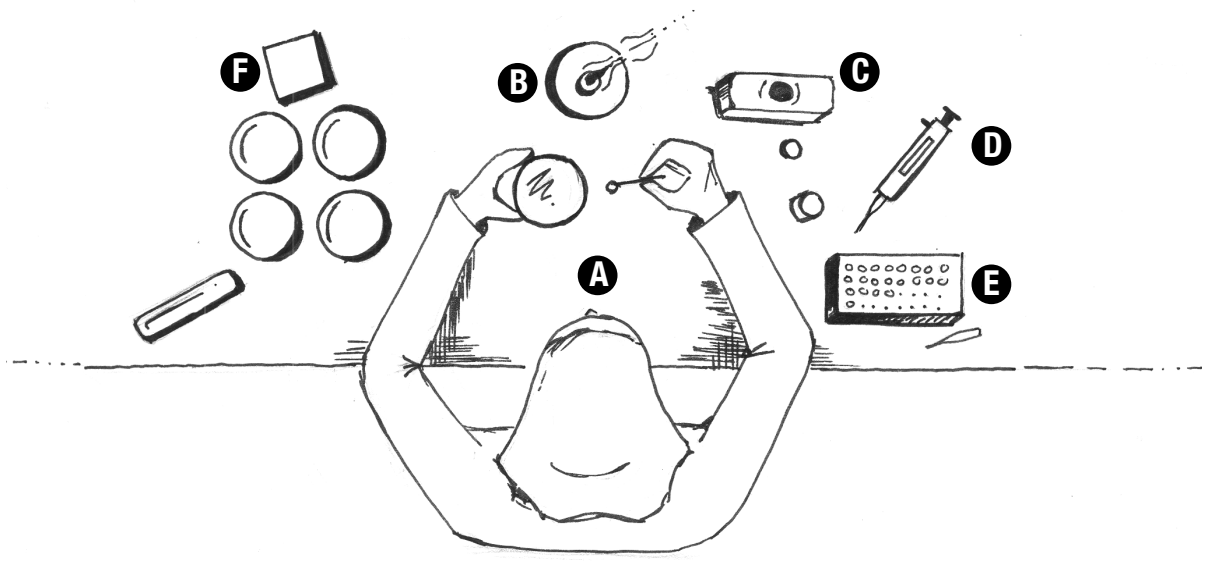


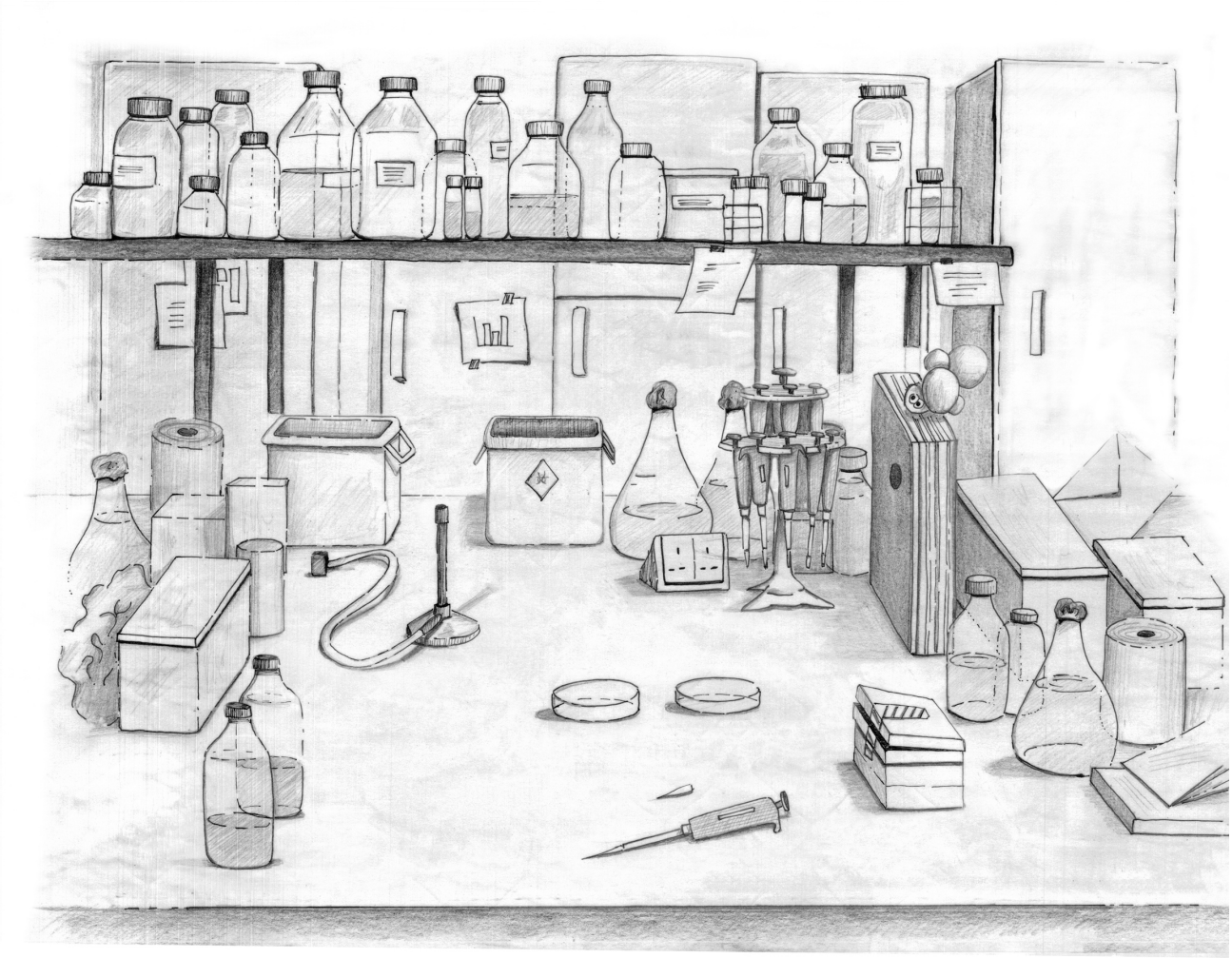
The second stage, pouring agar on containers, requires careful organisation of the bench space, which is articulated around a *heat bubble* produced by the Bunsen burner (shown in Figure 39). The bubble provides an aseptic volume: high temperatures kill any foreign organism that might have remained in surfaces and tools, and those carried in the air. The organisation of instruments and dishes on the bench affords a quick succession of actions, involving opening the container with sterilised agar, exposing its neck to the flame for a few seconds, removing the lid of sterilised plates at an angle, pouring the agar, and replacing the lid quickly to minimise exposure to foreign organisms. The process involves the careful choreography of hand movements, illustrated in Figures 44 and 45, starting with taking the container with the right hand and removing the lid with the left. Containers should initially be positioned close to the burner, in such a way that the right hand travels as little as possible to bring the container's neck to the flame. The lid is placed on the bench upside down to avoid contamination. The left hand is then used to replace and hold the plate's lid at an angle. The right hand brings the agar container to the dish and pours its contents to fill the plate. The left hand quickly closes the dish, and either reaches for the next plate for preparation or replaces the lid on the agar container. Figure 46 shows the ideal bench arrangement to make this choreography possible. The burner is labelled 'B'. Actions take place in the closest area to the burner (A), with tools and instruments arranged outwards. Label C represents the bottle with sterilised agar, which is only opened in A. Plates are held in F and transported to A to pour the agar, where their lid is replaced. Figure 46 also shows a sketch of the bench station. The sequence of layers in the tracing paper shows the different components and the way they are arranged in space according to their relevance.

44 *Sequence showing the process of pouring agar onto the dishes*

45 *Photographic study of the hand choreographies involved in pouring agar into a plate*

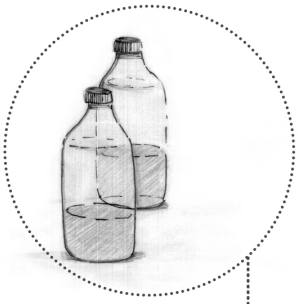


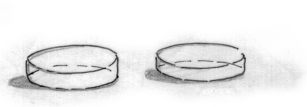
46 Bench arrangement



47 The micro-space of the bench. The diagram shows how the space of a bench is articulated. Each layer in tracing paper shows different elements that are carefully placed around the main working area, and that correspond to the choreography of body movements associated with different techniques and procedures in the lab.

05 *Experiment*
The final pieces of equipment depend on the specific experiment. The diagram represents the process of poruing agar.





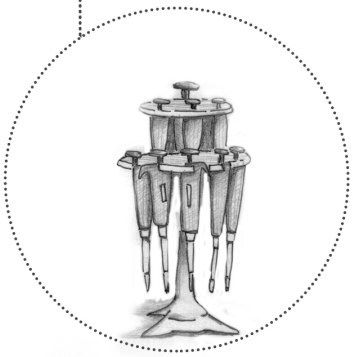
LIQUID AGAR

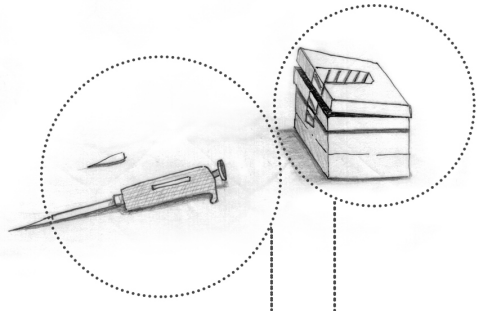
Equipment and tools specific to each experiment are often the last elements that delineate the micro-space of the bench. In this case, bottles of liquid agar are placed close to the spot where the dishes are poured

04 *Pipettes*
Pippettes are carefully placed in the bench, corresponding to the body movements required for different operations

PIPETTE RACK

The rack is designed to store pipettes vertically, making sure the suction mechanism isn't damaged. The position of the rack within the bench needs to be carefully considered, as it responds to the path of the arm as it moves the pipette to load a tip, obtain more culture, release and dipose of the tip.





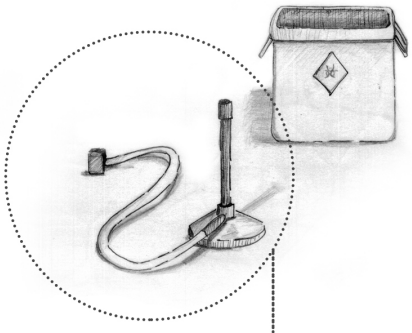
PIPETTE

Pipettes should be handled with care. They can be placed horizontally, but never when liquid is contained in their tips — the liquid might seep through the suction mechanism damaging it.

DISPOSABLE TIPS

Disposable pipette tips are stored in this plastic box. The design allows to open the lid with one hand, and to bring the pipette to slide into a new, disposable tip.

03 Heat bubble.
The Bunsen burner is used to generate an invisible, sterile space — a heat bubble— to manipulate experiments



BUNSEN BURNER

The Bunser Burner is the main piece of equipment that delineates the workspace. As explained in a separate diagram, the burner generates a bubble of heat which creates a sterile zone to manipulate experiments.

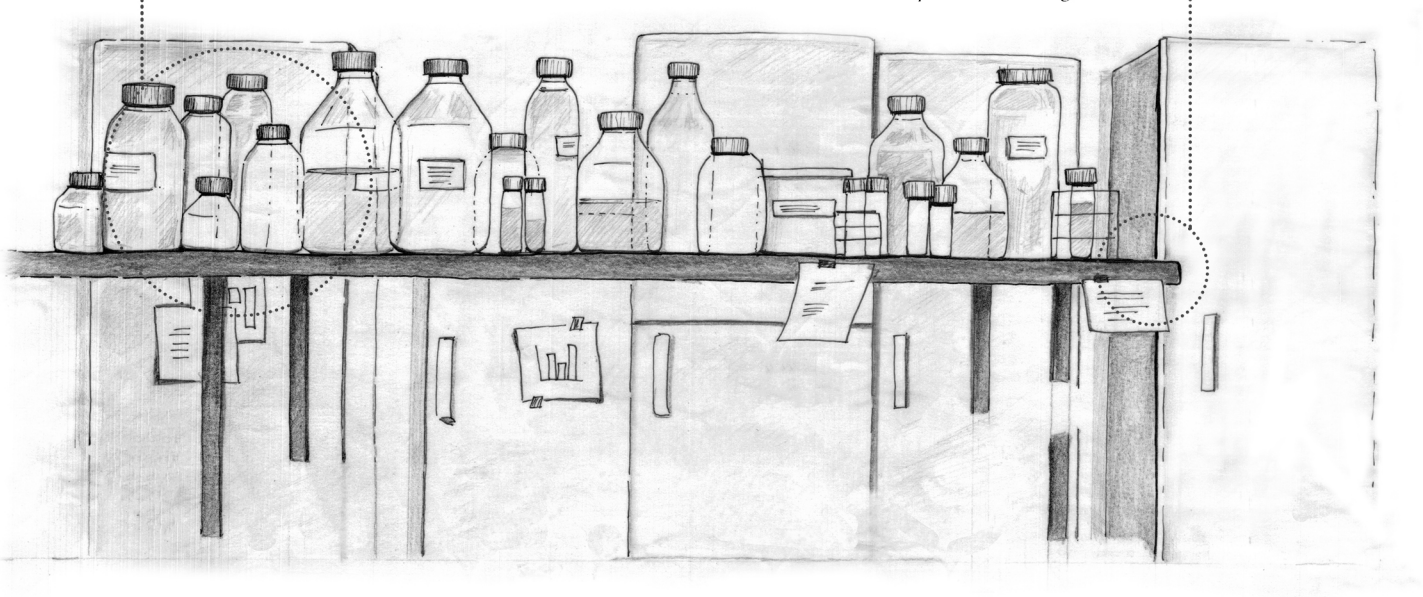
O1 *Base layer. Contains the basic pieces of furniture and equipment that roughly delineate the working areas*

BOTTLES & CONTAINERS

Generally used to store frequently used chemicals and compounds. They are also a way of patterning personal space—other people in the lab know who is working in each bench by looking at the containers and their labels.

OVERHEAD SHELVES

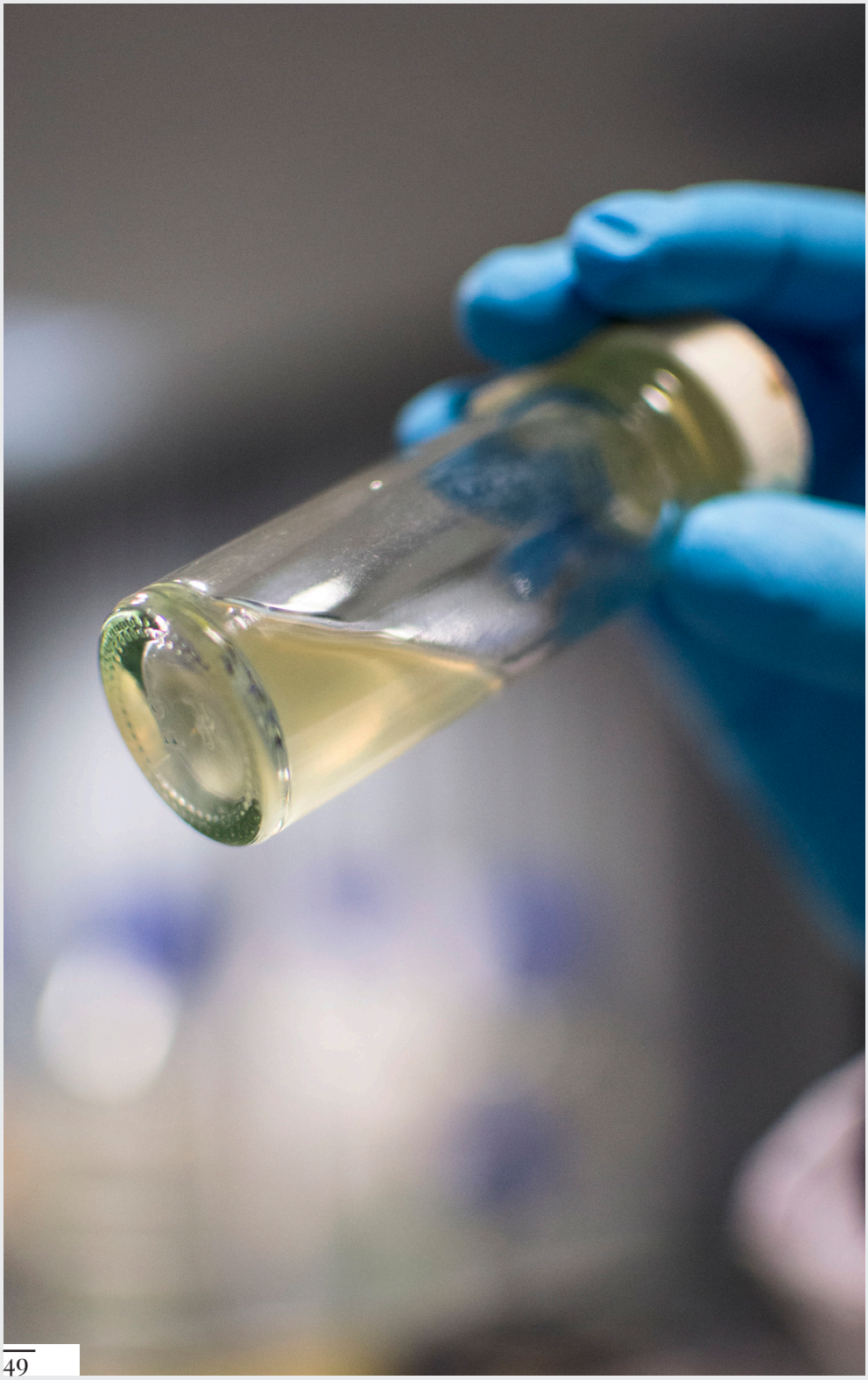
The overhead shelf provides storage space for containers and equipment. It also operates as a visual barrier between researchers working at either side of the bench. It is also often used to place notes used as reminders, but also as a way of communicating with others



A similar configuration of space is used in inoculation, which refers to the placement of organisms to agar plates. As with agar and plate preparation, the process involves a choreography that demands a careful control of hand movements. Cellular organisms are generally stored in a liquid, nutrient-rich medium in small, screw-capped bottles that provide sterilised containment (see Figure 49). When inoculating by pipette, the choreography starts with configuring the pipette to the required volume by turning a series of revolving dials on its side. The pipette is then prepared with a disposable plastic tip, which is stored in a rigid plastic box (shown in Figure 47). The researcher opens the box with the left hand. The right hand brings the pipette to the box, and clicks one of the disposable tips into place. The box is then closed, and the left hand then grabs the bacterial culture, removes the cap, and brings the container to the flame to decontaminate its neck. The tip of the pipette is then brought inside the culture, without touching the walls of the bottle, and activated with the thumb to suction the liquid. The bottle is then brought back on the table and closed quickly to minimise risk of contamination. The left hand then moves the petri dish close to the Bunsen burner, and removes its lid. The pipette is then brought to the agar surface, and activated again to release the liquid. The plate is closed quickly after, and the pipette is brought into the yellow disposable bin to release the disposable tip. The choreography is documented in the photographic sequence in Figure 48. Once dishes are inoculated, they are stored upside down to avoid condensation, as droplets might carry organisms from one spot of the plate to another, distorting observations of their locomotion. Plates are then transported to an incubator, where they are kept in high temperatures to promote growth.

48 Photographic study of the hand choreographies involved in inoculation ia

49 Bottle containing bacteria



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The spatial configuration of the bench influences the development of morphologies through the form-factor of the containers. As suggested by Figures 39 and 45, the Bunsen burner generates an aseptic bubble where instruments and containers are kept during preparation and inoculation. Figure 46 describes the articulation of space around the burner, where A represents the working area available to the researcher to manipulate containers within sterile conditions. Indirectly, this also restricts the size of the containers. Larger containers are difficult to organise within the sterile bubble (see Figures 50 and 51). The irregular shape and size made them difficult to manipulate with one hand, as required in preparation and inoculation. Coincidently, the size proved too large to have a significant impact on the development of morphologies. Figure 52 shows an experiment developed in an early configuration of the line-shaped container. The dish was inoculated in three points, at either tip and centre of the container, resulting in radial growth with fractal branches towards the edges. Colony reach, however, extends to less than 2 cm, developing well within the boundaries of the container. In practical terms, this means that physical forces introduced by the container's shape are spread too widely to influence the morphology of *B. subtilis* 168. Containers fabricated for subsequent experiments were sized down to fit better within the heat bubble, and to respond to the size of bacterial morphologies.

50 First batch of custom-made containers arranged on the bench space

51 First batch of custom-made containers after inoculation. The image contrasts the efficiency of regular dishes (shown at the back), which can easily be stacked and transported to the incubator, with the difficulty inherent in stacking the custom ones.

52 Experiments performed in line-shaped container

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3.3
CULTURES OF CRAFTING

The practices described above signal the importance of the experiential approach suggested at the outset of this part of the chapter, and how it connects to an awareness of body movements within the laboratory. Developing lab experiments requires researchers to finely tune their actions to minimise parasite movements: hands need to move precisely to reach for the pipettes, switching between opening bottles, manipulating containers and replacing lids. These procedures are part of a number of techniques and practices that are generally not communicated in the literature and, instead, constitute a form of crafting, which is communicated from scientist to scientist in the context of lab practice. Scientific publications generally include a section on methods and tools in which protocols are explained in some detail (see, for example, Figure 9, which shows the protocol for work with the *Paenibacillus* genus). There are, however, parts of the procedure that are not codified formally, and which can be described as *situated knowledge*, in the sense that it is acquired by continuous practice and social interaction in a specific context.

53 Stack of petri dishes seconds after pouring agar, and showing the formation of droplets on the lids

54 Enlargement of the image in 53, showing the condensation of droplets

55 Heated cabinet used in the experiments

56 Placing poured petri dishes to control humidity

A good example of these craft practices is the control of moisture in petri dishes. Temperature differentials between the interior and exterior of plates cause condensation on the internal walls of the lid and container. This condensation can result in fogging and, over time, the formation of water droplets. Figure 53, for example, show a stack of petri dishes seconds after agar has been poured. Figure 54 shows an enlargement of the image, which shows the formation of droplets on the plate's lid. These droplets can precipitate back into the surface of the culture, transporting with them bacteria across the agar surface, producing migration (Finer & Finer 2007). Generally, moisture control is difficult to resolve, as it is contingent upon a number of temperature-control mechanisms, both of the general space of the lab but also of the cabinets, work surfaces and incubators. Moreover, it has been suggested that moisture accumulation is also connected to

the polymer used in the fabrication of the dishes, which can vary slightly from manufacturer to manufacturer (Finer & Finer 2007). For this reason, it is difficult to anticipate a strategy that will work for all environments, and moisture control tends to be developed and implemented specific to local laboratory conditions. In the laboratory where this exploration took place, the craft practice to control moisture involved leaving dishes to dry in a heated cabinet (see Figures 55 and 56) for ten minutes prior to inoculation, which minimises condensation in the later stages.

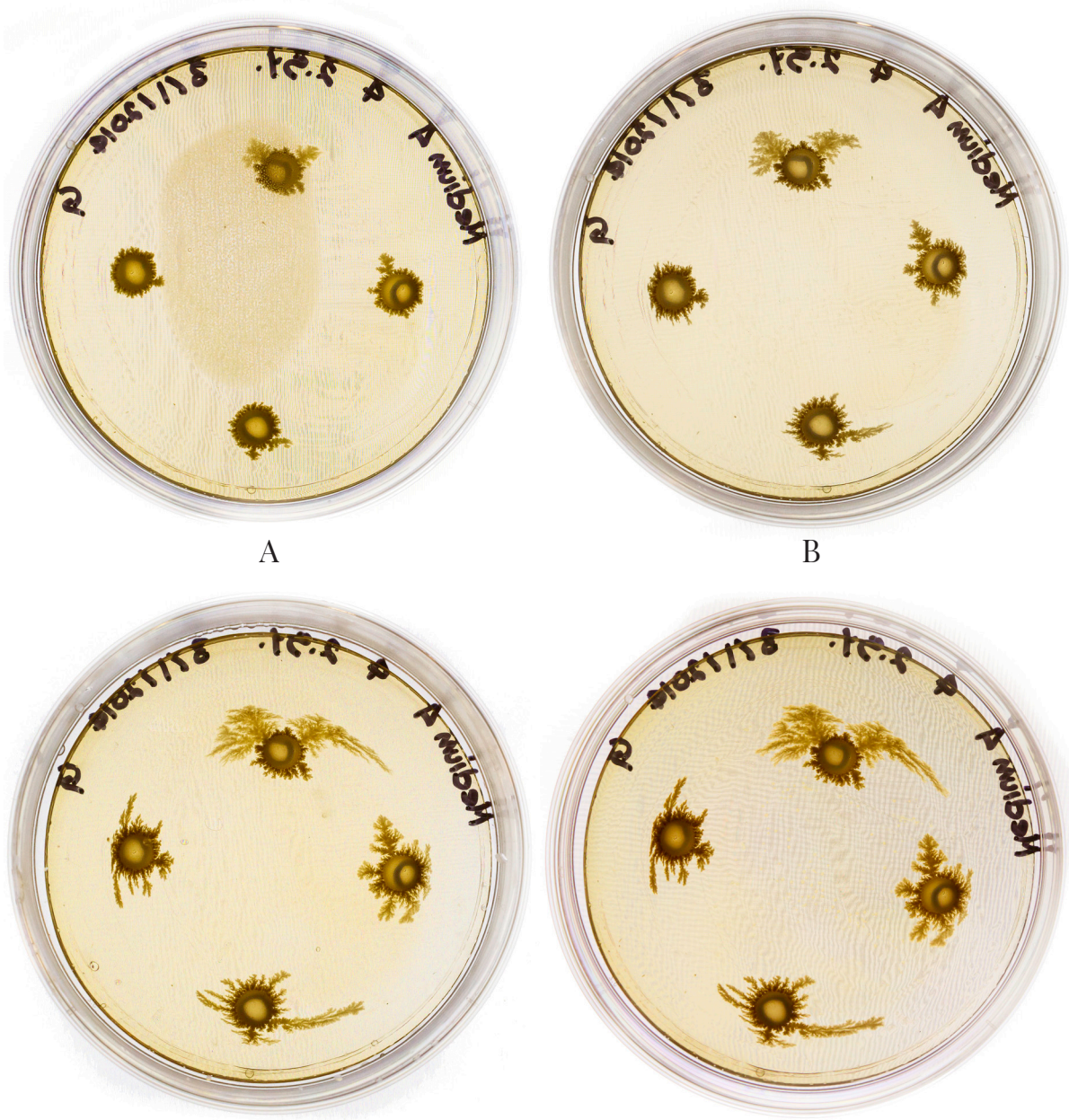
The control of moisture has a direct effect on the development of morphologies. Figure *57* shows an experiment with *B. subtilis* 168 prepared with 2.5% agar and 4g/L peptone concentration. An initial colony is inoculated in the centre of the plate using a pipette. Although identical conditions are used in the experiments in Figures *58* and *59*, there is a noticeable difference in reach. The branching in Figure *57* stretches as much as 10 cm at its widest. By contrast, in Figure *58* the branching reaches a maximum of 4 cm wide, and just under 3 cm in Figure *59*. The difference in reach is likely to be connected to trapped humidity, which softens the growing surface. Generally, agar is used to provide a hard substrate, which facilitates visual inspection compared to aqueous media, where bacteria diffuse evenly. Water trapped in the dish, however, tends to generate a wet surface on top of the agar, in which bacteria diffuses. In the experiment in Figure *57*, this results in the morphology developing a lighter core, which delineates the spread of the water surface. At the edges of this, the colony becomes denser and starts to develop into branches, indicating their locomotion strategy to forage the agar's surface.

57 Bacillus subtilis 168 grown in 4g/L peptone and 2.5% agar and with a central point of inoculation

58 58A to 58D, top-left corner clockwise. Time lapse of Bacillus subtilis 168 grown under 4g/L peptone and 2.5% agar

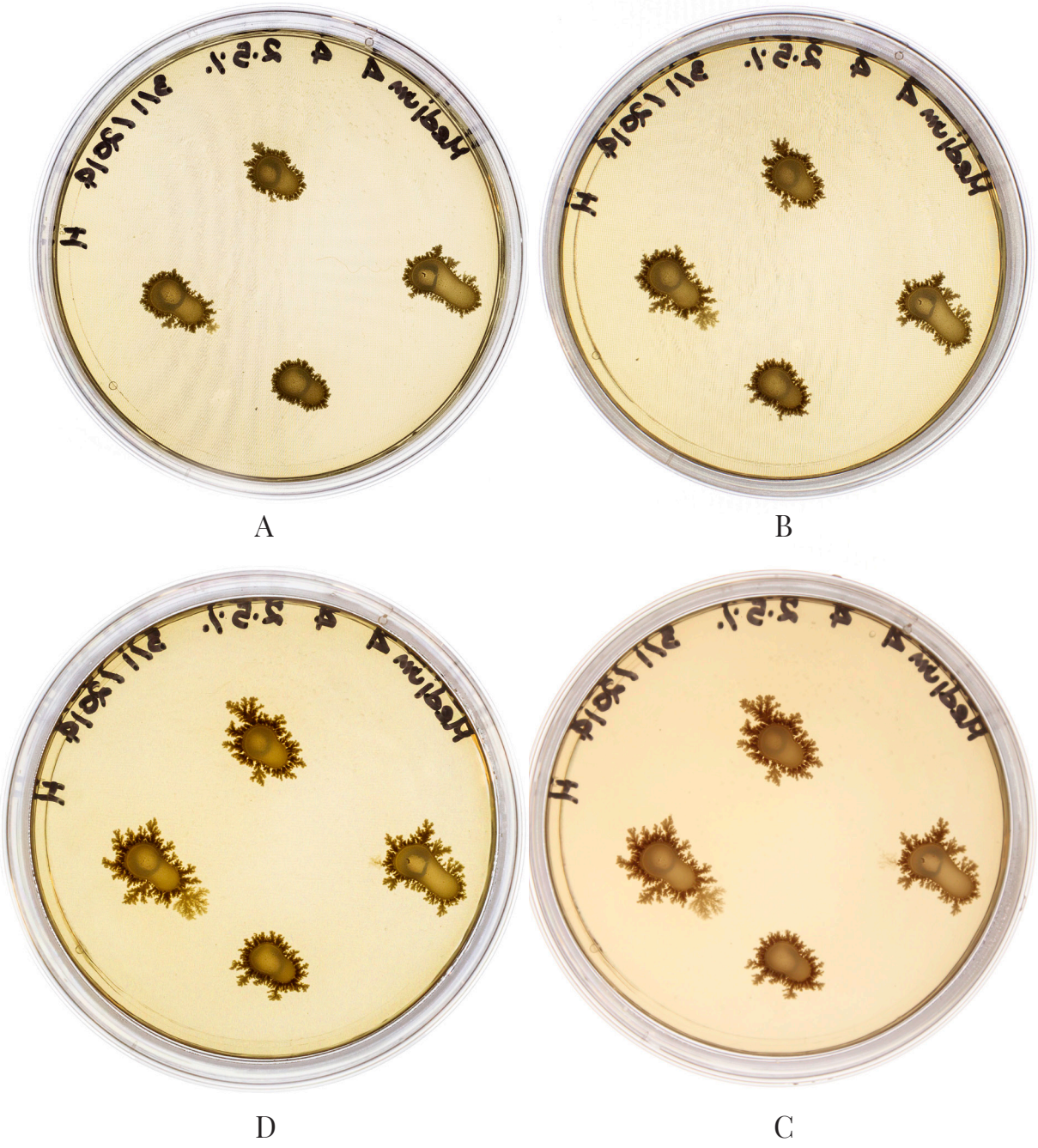
59 59A to 59D, top-left corner clockwise. Time lapse of Bacillus subtilis 168 grown under 4g/L peptone and 2.5% agar

There are also effects in the branching connected to a lack of moisture. Figure *60* shows an experiment with *B. subtilis* 168 prepared with agar at 2.5% concentration and peptone levels of 4 g/L. Four colonies are inoculated at independent points. Each image was captured at one-week intervals, recording the development of the morphology across a one-month period. Identical conditions are used in Figure *61*. There is a noticeable difference, however, between both morphologies, in that Figure *60* grew to develop branches that extend away from their inoculation point, and in a general pattern that seem to follow concentric lines. By contrast, each colony in Figure *61* grew radially away from its inoculation point. Growth in Figure *60* corresponds to a general shrinkage of the agar medium, which can be observed by comparing the gap between the edge of the plate and that of the agar. In Figure *60A*, there is no noticeable gap, with a small gap appearing in *60B* and growing consistently in *60C* and *60D*. Shrinkage in agar volume forces colonies to develop along the stress lines generated by the physical change, and is caused by dry conditions inside the incubator. A technique to counter this effect involves wrapping dishes in layers of wet towels, which contributes to maintaining sufficient moisture in the environment, thereby avoiding internal dryness. The decision to implement the wet wrap is taken by researchers when they start noticing shrinkage, for instance, in the first week of development, as shown in Figure *60B*.



A B D C

60 60A to 60D, top-left corner clockwise. Time lapse of four sibling colonies of Bacillus subtilis 168 grown under 4g/L peptone and 2.5% agar



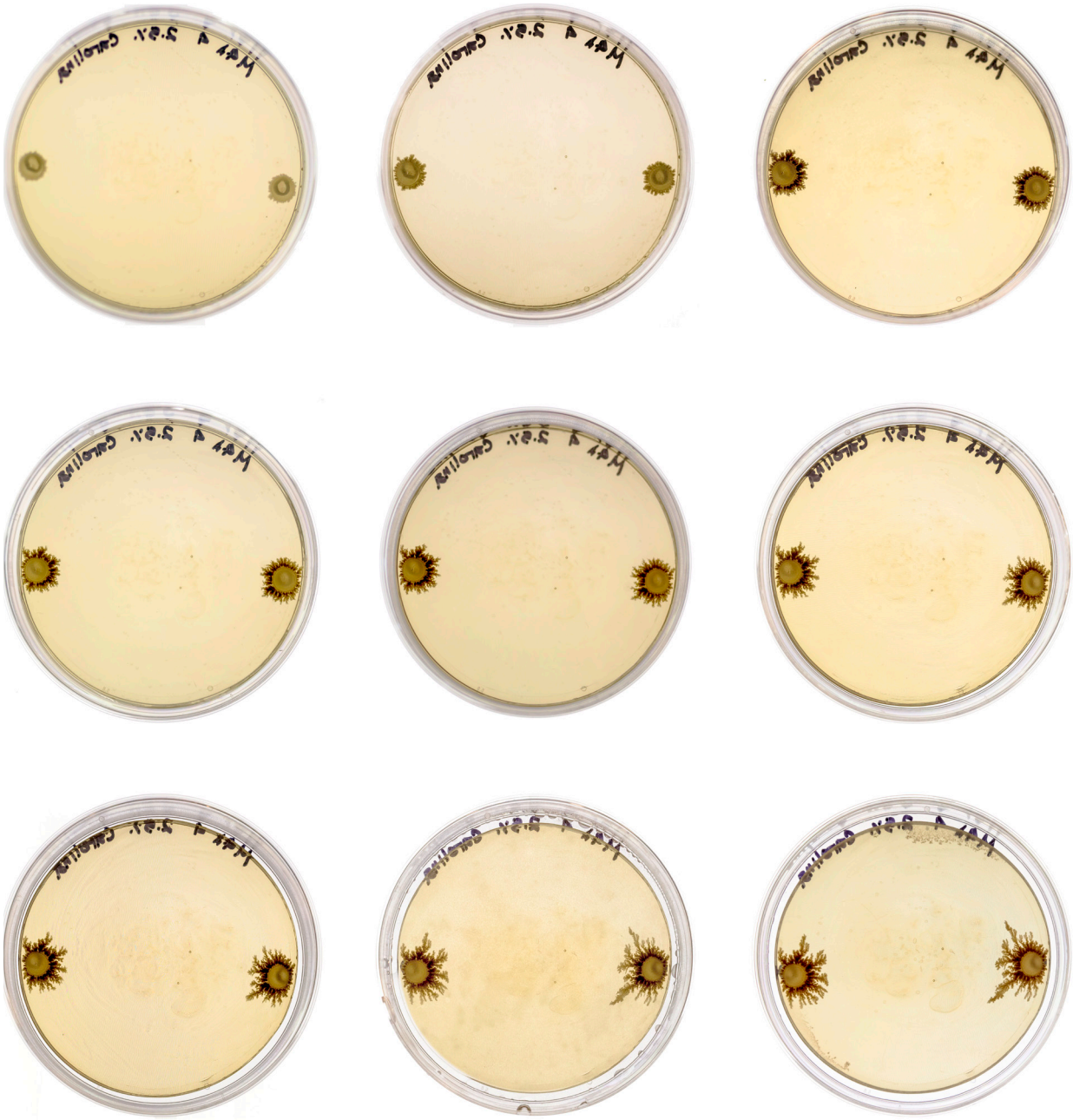
61 61A to 61D, top-left corner clockwise. Time lapse of four sibling colonies of Bacillus subtilis 168 grown under 4g/L and 2.5% agar

3.4
SOCIAL INTERACTION

There are also links between the social space and morphologies, often intersecting with the crafting and physical spaces in the assemblage. In this context, social space is used to describe the interactions between people that enable things to happen, and often relate to the governance of physical spaces. A good example of this is the negotiation of resources in the laboratory, which is often contingent upon social practices and perceptions of hierarchies. A good example is the negotiation to use the incubator at the required temperature. The existing literature documents incubation at 37 ºC and 30% humidity (Ben-Jacob et al. 1998; Ben-Jacob et al. 1994). In the laboratory used in this experimentation, incubators (see Figure 62) were booked by principal researchers, who did so on behalf of postdocs and PhD researchers working in their research groups and projects. At the time of developing this exploration, all incubators were booked and, in most cases, used to their full capacity. In addition, they were all set to incubate at 27ºC. To perform the experiments, I had to broker some space in the incubators, but had to adapt the experiments to the lower temperature.

The impact of a lower incubation temperature is seen in Figures 63 and 64, corresponding to experiments developed with *B. subtilis* 168, using a 2.5% agar concentration and 4 g/L peptone levels. Figure 63 shows two inoculation points placed at opposite sides of the plate. Figure 64 has a single inoculation point, placed in the centre of the plate. Each figure presents a series of nine images, spanning to a total incubation of four weeks. In Figure *63* colonies grow to reach 1 cm. Similarly, the dense core of the colony in Figure *64* grows to reach 3 cm and develops a secondary, lighter branch extending a further 1.5 cm. The stark difference in growth can be attributed to the lower incubation temperature. In general, a lower temperature might impact experiments by slowing or hampering bacterial growth.

62 *Incubator shown in Figure 47, with the door closed*



63 Grid of images showing a time lapse over a period of four weeks. Bacillus subtilis 168 inoculated in two points and grown under 4g/L and 2.5% agar

64 Grid of images showing a time lapse over a period of four weeks. Bacillus subtilis 168 grown under 4g/L and 2.5% agar

3.4.1
THE POLITICS OF COLLABORATION

Other aspects of social interaction contribute to the difference in branching size. There are, for example, issues with the age of the bacteria culture used in the experiments, which also intersect with space governance and social interactions. I will always be immensely grateful to Dr Meng Zhang, who was very generous in giving access to her lab to a wide-eyed designer who wanted to do '*things with bacteria*' (as I recall saying the first time I had a chat with her and 'casually' asked to gain access to the lab). One downside was that I had no official funding for the research, so access could only be brokered informally. Consequently, I had no key card, and could only work in laboratory 1 (see Figures 28 and 37), which Dr Zhang would very kindly and patiently open for me every day.

Albena Yaneva has analysed the way technologies of access, such as doors, locks and key systems, make manifest and renew the repertoire of social ties: a mediator that enables specific social ties to occur. In analysing how a door with a mechanical code operates within an institutional assemblage, Yaneva writes:

> The making of this lock implies a particular way of regulating and maintaining the social. Made so as to allow only colleague fellows to access the research group resources and to impede others from using them, this simple mechanical door lock divides and congregates university fellows in a particular way (...) the lock regroups university users and reconnects them differently. That is, design functions socially; the social is not outside it, at a cosmic distance from its objects. It is *in* the objects' world. Design allows this door lock to take on the conflicting wishes and needs of many university colleagues (Yaneva 2009, p. 278).

The passage is an interesting analysis of the way in which non-humans wield their agency to create and reconfigure social ties. It also offers a way of understanding what the lack of an access card represents in the context of *Bacterial Assemblage*. In the previous sections, I tracked how my presence in a laboratory setting reconfigures the existing assemblage, as I bring with me and my practice other assemblages connected to my familiar spaces of

practice, epistemologies and specific interests in microorganisms. The key card highlights the effects of the assemblage being reconfigured. However, as institutional boundaries have rarely stopped designers, I had to navigate my access into the assemblage by creating other social ties.

One implication of the strategy, nonetheless, is that I had no access to shared facilities in laboratories 2 and 3 and, as a result, could not retrieve 'fresh' culture samples. Generally, libraries of microorganisms are kept for long term storage in freezers at 80°C below zero (see Figures 65 to 67). When a specific strain is required, it is retrieved from the library and regrown in liquid medium containing nutrients. The culture is left inside an incubator for approximately eight hours, in which bacteria restarts from its dormant state and is ready for experiments. The high costs associated with equipment and the maintenance of freezer facilities mean that these are shared by research groups. In the laboratory used in the exploration, freezer facilities were located in *laboratory 2* (see Figure 65). To make the bacterial strains available, Dr Zhang carried out the process beforehand. This, however, was done days in advance of the beginning of the experiments. After reflecting about the results with her, it was deemed that the age of the culture might have had an effect on motility and metabolic activity, referring to the amount of time between retrieval from freezer to experiment.

65 Two of the freezers at -80°C used to store microorganisms located in laboratory 2

66 Two of the freezers -80°C used to store bacterial colonies

67 Freezer interior showing the libraries of microorganisms

68 The freezers in Figures 65 and 66 are at the back

There are other aspects, such as media preparation, in which the politics of access and resources are made manifest. Experiments performed by Matsushita and Fujikawa (1990) are described to prepare the nutrient solution by mixing 5g of sodium chloride and 5g of *potassium phosphate dibasic* with *bactopeptone*. In the laboratory however, only *potassium phosphate tribasic* was available. The small chemical difference, an additional molecule of *hydrogen* and one less of *potassium* in *potassium phosphate dibasic,* has a number of effects in the microorganisms. One of them can be seen in the amount of agar/nutrient concentrations used in the experiments. In the second part of this chapter, I described a total of five combinations that were taken from

Thermo
ELECTRON CORPORATION
Chris Blackwell 5890
or
Steve Reed 7044
Thermo
SCIENTIFIC
DO NOT OPEN
UNLESS THE
TEMPERATURE
IS BELOW -75°C
Chris Blackwell 5890
or
Steve Reed 7044

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Thermo
SCIENTIFIC
DO NOT OPEN
UNLESS THE
TEMPERATURE
IS BELOW -75°C

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68

the literature to use with *B. subtilis* 168. The initial experiments, however, showed that only one combination, medium 4 (4g/L peptone levels and 2.5% agar concentration), would foster considerable growth. As a result, most of the experiments analysed in the previous sections were performed using this combination.

3.4.2
DOCUMENTATION AND RECORDING

Other aspects of social ties and space governance also had an effect on *Bacterial Assemblage* A good example of this is the process documentation and recording of experiments. Taking the pictures used in the previous sections involved using a DSLR camera and a small backlight (improvised using an iPad, as shown in Figure 69), which had to be brought into the lab each day, as no storage space was available at the time. On one of the first days of the exploration, I met a postdoc researcher in the laboratory, who called off the process on the grounds that bringing and taking equipment out of the lab every day increased the risk of contamination. This, he argued, was a particular concern, as other researchers might be working with bacterial strains more hazardous than the ones used in the exploration. After explaining the exploration and its background, he suggested using a re-sealable bag, which could be left permanently in the lab and used to wrap the camera and backlight.

69 Improvised backlight used to take the pictures shown in this chapter

3.4.3
SOCIABILITY WITH THE NON-HUMAN

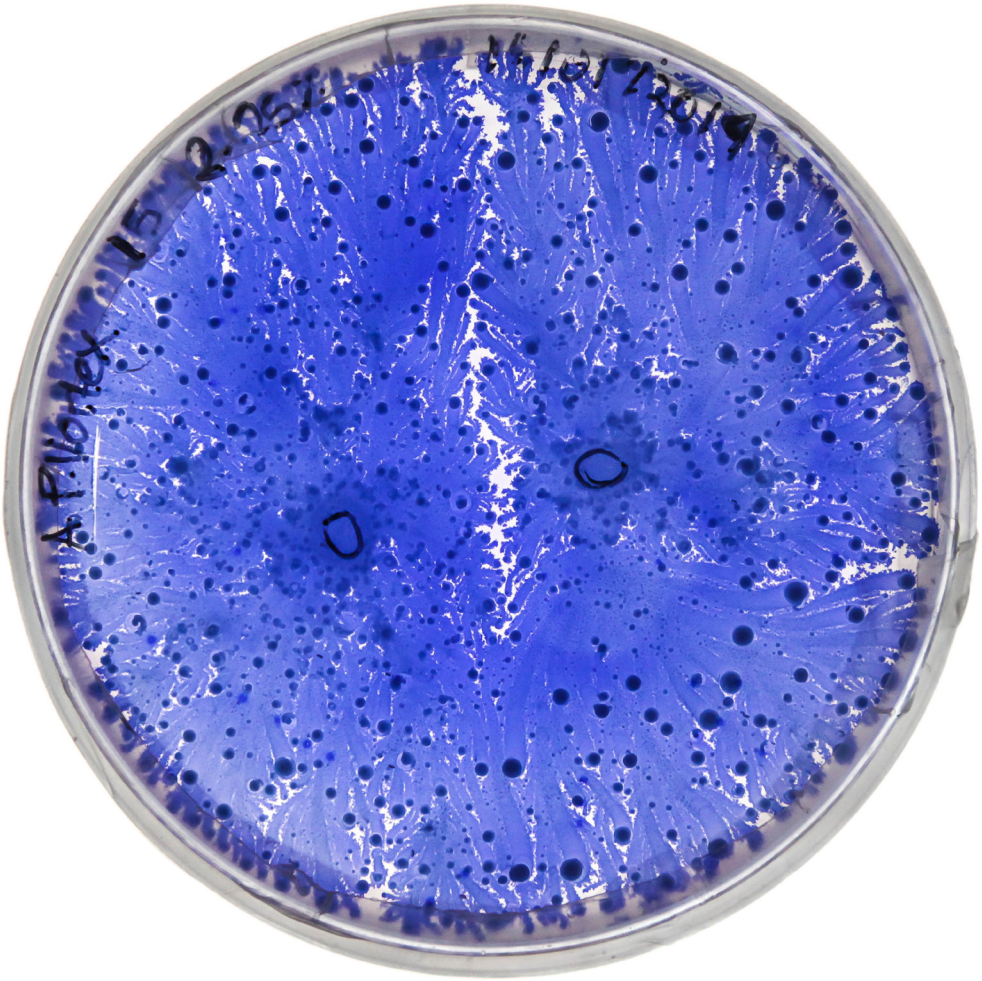
The notion of social, often understood as relating to the relationships between people, can be extended to include the ties between humans and non-humans. Latour has described how social can be taken to signify 'a trail of associations between heterogeneous elements'. He expands:

> The latin socius denotes a companion, an associate. From the different languages, the historical genealogy of the word 'social' is constructed first as following someone, then enrolling and allying, and lastly, having something in common (...) Because of [a] constant shrinking of mean-

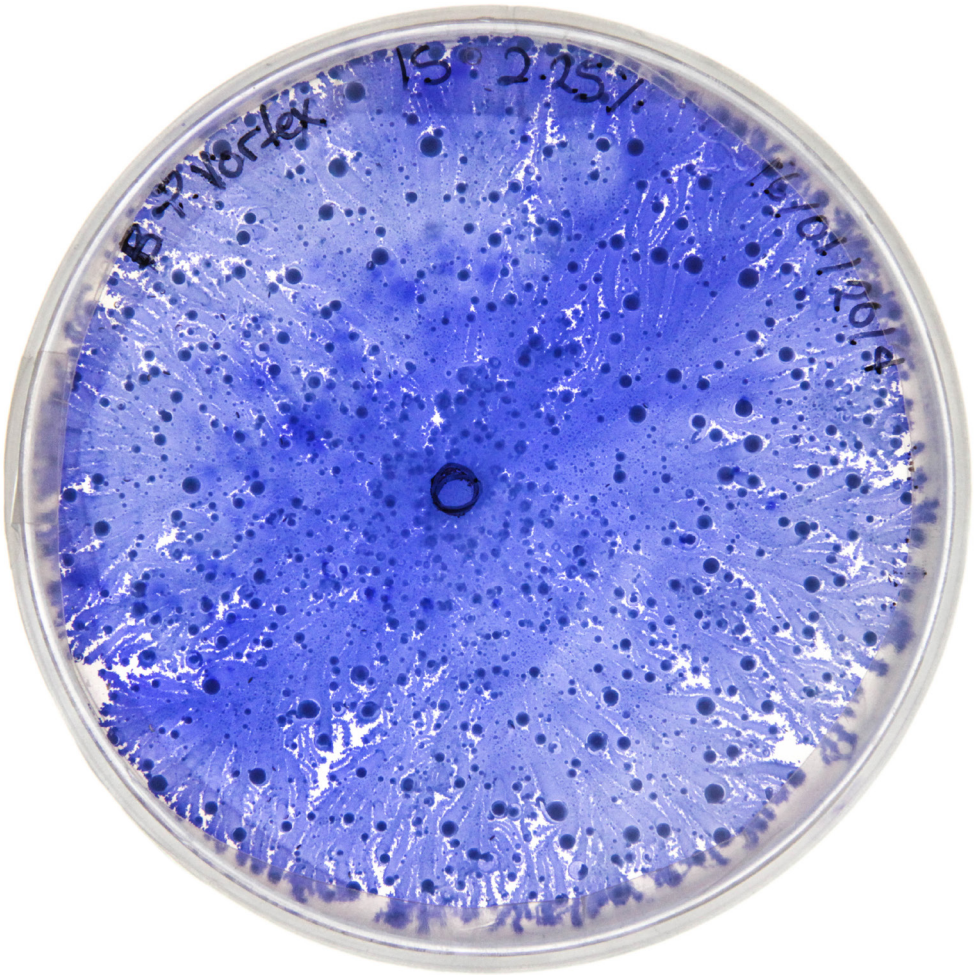
> ing (social contract, social question, social workers), we tend to limit the social to humans and modern societies, forgetting that the domain of the social is much more extensive than that. De Candolle was the first person to create scientometrics — the use of statistics to measure the activity of science — and, like his father, a plant sociologist (Candolle 1873/ 1987). For him corals, baboons, trees, bees, ants and whales are also social (Latour 2007, pp. 5–6).

Work in laboratory settings involves a constant process of sociability with microorganisms, partly manifested in the way that researchers often synchronise to different cycles. Most biological experiments are dependent on sequential processes, ranging from simple sterilisation to inoculation, to incubation, which require researchers to develop precise spatial and temporal choreographs around them. Some of these sequences are, for example, connected to the use of common resources. To ensure that the autoclave resource was readily available for everyone, a protocol was put in place whereby instruments and containers to sterilise were placed on a tray close to the autoclave. Once enough material had been collected to fill the autoclave to its maximum capacity, it would be placed in the autoclave and put through the sterilisation cycle of 50 minutes. The time it takes for the autoclave cycle to finish is generally used to prepare instruments for use in the next part of the experiments. If a researcher needs to review protocols or make notes, he or she needs to set an alarm, walk downstairs to the shared workspace in level 1, and come back once the process has completed.

The regulation of work cycles also extends to the circadian *clocks* of the organisms being used in experiments. The term circadian refers to the temporal rhythms specific to biological organisms, which vary from species to species. Different bacteria perform activities such as metabolism in longer or shorter cycles, which modify the time required to complete the experiments. In the context of this exploration, *B. subtilis* 168 would take periods of time spanning weeks to develop branching morphologies of sizes larger than 3 cm. By contrast, *P. vortex* develops in similar sizes in days. Figures 70 and 71 show initial experiments conducted with *P. vortex* using a 2.25% agar concentration and 15 g/L peptone levels. The images correspond to photographs taken after eleven days of incubation, at which point the colony had



70 P. vortex colony after an incubation period of eleven days. The colony was grown under peptone levels of 15g/L and agar concentration of 2.25%.



71 *P. vortex colonies after an incubation period of eleven days. The colonies were grown under peptone levels of 15g/L and agar concentration of 2.25%.*

extended to cover the dish completely.

The social aspect of working with microorganisms is also manifested differently in the way that researchers talk about them. After a few weeks in the laboratory, I realised I had assigned *names* to the colonies growing in different plates. The one in Figure 57 was called '*Champion*', based on the speed at which it developed its branches. The one in Figure 15, on the other hand, was '*Philomena*', as it was the first colony of *P. vortex,* which I had incubated and grown into the characteristic, tentacle-like branches of the *C* morphotype. Similarly, it is not uncommon to find organisms represented in some way in the lab. Figure 72 shows *Staph*, a soft-toy bacterium I found in one of the neighbouring bench spaces. Although it is easy to discard these practices as idiosyncratic, it is also possible to read them as a form of social tie to the organism, which alludes to the notion of *care* I introduced in part 2. Feminist theories, and specifically situated knowledge, suggest that the relationship between the scientist and the object of study can transcend instrumentality. Similarly, Bolt (2007) argues that contemporary creative practices are characterised by an instrumental understanding of matter and tools, justifying the artist and designer *signing* the work. She, however, proposes that there are other modes of engagement, or *caring,* which presume different ethics other than the ethics of mastery. Assigning proper names to organisms might suggest a degree of caring, which is already part of the practices of laboratory work.

72 Soft-toy bacterium found in the laboratory produced by Giant Microbes and representing Staphylococcus Aureus. The tag in the background shows the name of the bacterium as 'Staph'.

staph

4

PART FOUR

DISCUSSION

Bacterial Assemblage stands in contrast to *Bacterial Crystals* and *Bacterial Morphologies*. They all use the same model, the state-space of design, to conceptualise how biological form results from the interaction between organism and context. While *Bacterial Crystals* and *Bacterial Morphologies*, however, interpreted this as a parametric model, *Bacterial Assemblage* took a different approach, using the model of *assemblages* to conceptualise the way interactions operate. Each approach, parametric and assemblages, enables different readings of contingent state-spaces.

In a parametric reading, contingencies constitute a set of potential challenges that need to be accounted for in advance. In Chapter Five, I proposed a diagrammatic exercise, which involved articulating state-spaces, a process that was expected to yield a standard decomposition that might be used as a tool to anticipate contingencies prior to implementing the design process. Once in place, this would need to be confronted with the elements of the design system, which would be understood as a series of restrictions that impose limits on the values different state-spaces might take, for instance, in choreographing the experiments around UV decontamination, or adjusting the size of custom containers. There are, however, imponderables. Parametric models are useful when planning a design assemblage involving living systems, but they cannot be used to prescribe the objects of design work. It is technically possible to create models that enable anticipation of the effect of different contingencies. For example, a model could be constructed to describe the physical forces induced by the drying up of agar plates. However, since these contingencies are specific to the assemblage, they can only be defined when the designer is embedded in the context.

Interpreting the model through the framework of assemblages, on the other hand, shifts the conceptualisation of biological systems and their context. Instead of understanding them as parameters, which can be anticipated and defined numerically, they are framed as agents, in which some aspects of their behaviour remain impossible to anticipate. In this interpretation, living systems are understood as actants that organise in complex, non-linear assemblages. The approach also calls for an experiential approach. In this chapter, I have analysed how, in the context of material thinking, the complexity of matter is approached by enabling a sort of conversation be-

tween designer and material, in which '*sensory and other bodily responses are fully focused on the demands of the unpredictable and uncontrollable materiality of paint interacting with the environment'*(Bolt 2004). Similarly, work with biological systems always requires a degree of response in the context, in a way similar to descriptions of how the craftsman *listens* to the material and responds to its changing demands and conditions. One way of describing biological systems as agents is, to paraphrase Donna Haraway (2004), to say that they are *shape-shifters.*

The set of contingencies discussed also point to a redefinition of the boundary implied in the notion of the *biological system*. Throughout this thesis, I have used the term to refer to the organisms used in the different explorations, and proposed that form results from the interaction between biological system and context. The notion, however, implies delineating a boundary, which defines what counts as a biological system, and what is part of its context. In Chapters One and Two, I have introduced the biotechnical imaginations in architecture and within biotechnologies themselves. I suggested that in architecture this is articulated by notions of ecologies, complexities and emergence. The discourse within biotechnologies, I went on to propose, is organised around principles of standardisation, control and systematisation. Moreover, both imaginations tend to assume that the boundary that defines the biological systems is, generally, the membrane of cellular systems themselves.

One consequence of the implicit boundary is that biotechnical architecture tends to identify the interior of the biological system as its object of design. In Chapter Two I discussed how biotechnical architecture tends to focus on the possibility of *programming* organisms with design intent by manipulating their genetic make-up, operating in this as an extension of the discourse, techniques and tools of the digital paradigm. The set of contingencies in the context of manipulating living systems, nonetheless, suggests an escalation of the boundaries, to include the set of epistemologies, spaces, practices and economies that sustain the operation of the organisms themselves. As such, designing with biological systems involves *caring* for the design of the spaces of practices, and of the instruments used in the process. In order to maintain aseptic conditions of experiments, for instance, an incubator could

be designed to include a camera inside the chamber, minimising the risk of contamination. Awareness of these extended state-spaces also involves the design of the physical space itself, suggesting the need for a wet-lab, which sustains the sort of unstructured exploration associated with design disciplines. This would include, for example, the succession of equipment and zones arranged to facilitate a more fluid transition between prototyping, decontamination and the use of purpose-built instruments and containers.

Strategies to engage with the assemblages of biological systems, what *caring* for them implies, is a subject of exploration by a number of designers involved in the biotechnical discourse. A good example is the work of Orkan Telhan in the *Microbial Design Studio*, a project aimed at engaging with the design of the biological system by designing the context of the tools and instruments needed to interact with them. Telhan describes how one of the main challenges facing biotechnical design and architecture is the acquisition of specialised knowledge. He writes:

> Designers are often expected to become capable amateur biologists before applying biological principles and processes. Learning biology in this way is a daunting task, particularly when design possibilities are unavoidably vague at the outset; it requires some knowledge of biology to know what is possible, and some knowledge of what is possible to begin the process of designing (Telhan 2016, p. 126).

One solution to the problems faced by designers, Telhan proposes, is to bring the laboratory into the studio:

> While it is important for designers to engage with biology in a lab and to understand the labor intensive culture of working with living organisms, it is also true that design almost always happens [in] studios where computers, software, and various prototyping tools — laser cutters, plotters, 3D printers — work next to each other. These tools help us quickly test ideas in various forms, get feedback, and more importantly connect to the larger work of resources — images, fonts, code, 3D models, circuit designs — that are created by others and can quickly be incorporated into our designs (ibid).

The combination of both spaces, laboratory and workshop, is similar to the larger boundaries of the biological system suggested above. An understanding of biological systems and their context as assemblage involves understanding the interaction of agencies, and engaging with them by understanding the object of design beyond the genetic level.

Another important highlight of *Bacterial Assemblage* is the decentring of humans as sole creative actor. In the first part of this chapter, I described how an approach based on assemblages is predicated on notions of non-human agency, and imply the impossibility of prescriptive control. As a result, the work of Barbara Bolt, for example, explores how frameworks of material thinking imply that the designer is no longer outside the design system, directing the proceedings, but is instead immersed and invested in the material fabric. The contingencies explored in the previous section suggest a similar conclusion, in the sense that designing with biological systems is a process of understanding how different agencies align with one another. Extrapolating this observation invokes a redefinition of design itself: instead of the process of specifying a design solution to its minutest detail, it involves a humbler approach that requires attuning to biological systems and, more generally, to the materials and tools used in interacting with them.

Another way of framing the decentring of humans as sole creative actor is to look at the work of Rachel Armstrong, who discussed the possibility of understanding biological systems as being capable of *creative* expression. By reflecting on explorations with *Physarum polycephalum*, commonly known as slime mould, Armstrong argues that creativity '*can be observed in nature as the deliberate (but not rational) interactions between chemical processes (agents) and is the outcome of the restless condition that is innate to matter*' (Adamatzky et al. 2013, pp. 1–2). Admitting the possibility of creativity in non-rational entities, the authors argue, assumes the possibility of non-human actants to '*make choices and potentially express "creativity" in their actions, in ways that are not accounted for by conventional Western schools of philosophical thought' (*idem, p. 1*).* The authors go on to propose that understanding the potential of biological systems requires non-anthropocentric frameworks that concentrate on understanding the organism, its environment and chemical artefacts as a design assemblage. They write:

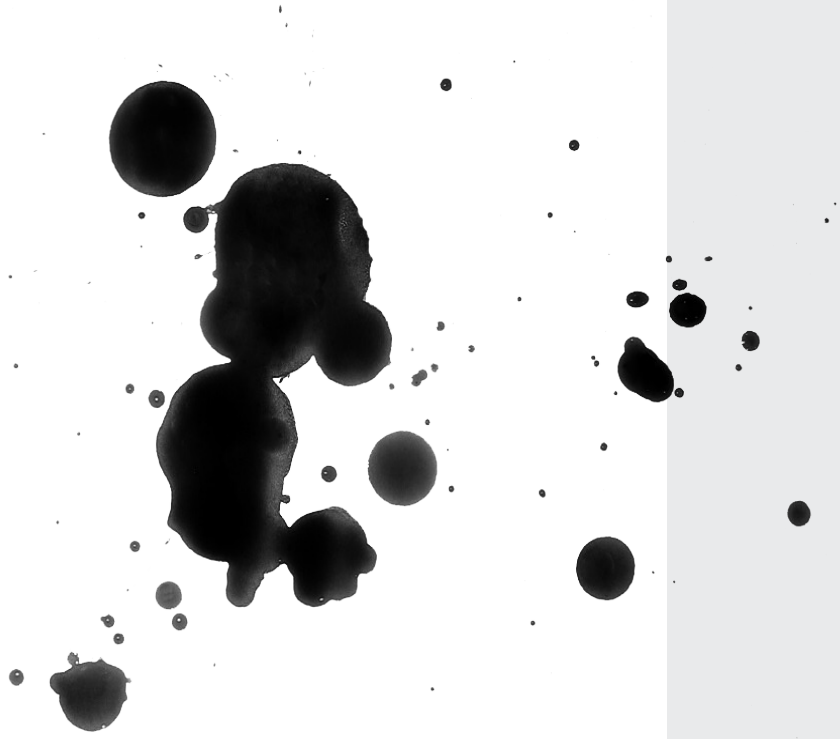
> The plasmodium expresses itself via morphology of its body and its protoplasmic network (…) while we traditionally deal with 'creativity' as being something internally generated (like logic) to consider an environmental role [that] requires the attribution of 'meaning' to context, which can be explored by the agent, or organism (…), the term 'meaning' could be used to describe the contingent entanglements of qualities and forces that compel 'actants' (or organisms) to keep on existing (Adamatzky et al. 2013, p. 3).

One question that remains is the extent to which the redefinition of design is specific to the work with biological systems, and how much it extrapolates to design and architecture more generally. One way of probing a potential connection between both scales is to look at the notion of contingency itself, and to the antipathy to contamination. In the previous section, I described how many of the spaces, practices and economies around laboratory work are aimed at preventing contamination. The relevance of control in this context alludes to the work of Jeremy Till, and the way he suggested that architecture is a *contingent discipline*. Yet, the architectural discourse has, since classical antiquity, constructed a fiction of the discipline as the guarantor of order and cleanliness. Till writes:

> …architecture is through and through a contingent discipline, but that architects have to a large extent attempted to deny this contingency through a retreat to notions of order, beauty and cleanliness. This stance can be traced from the first principles of Vitruvius, with his simplistic, but pervasive call for coherence, through to Le Corbusier, with his cry for architecture to be rid of contingent presences (…) the denial of contingency is not simply an issue of aesthetics and visual order, but a much wider one of social control and cultural cleansing. Whilst architects might acknowledge the former, they are less good at dealing with the latter (Till 2007, p. 120).

One potential conclusion is to say that work with biological systems has the potential to supersede the fiction of order. The other possibility is to say that *caring* for biological systems in a design context is, in essence, doing architecture.

CONCLUSION



When I tell my colleagues that I am writing a thesis on architecture and biotechnologies, I am invariably greeted by incredulous faces and the following question: *What do biotechnologies have to do with architecture? Can we then grow a building?* We tend to think about the relationship between living systems, biotechnologies and architecture in terms of how microorganisms can produce a building, and the immediate response is, 'Well, we would have to begin by scaling it up.'

The assumption is recurrent. When I was working on an early draft of this thesis in 2015, I was invited to a series of talks and workshops at the University of Edinburgh under the general theme of *Biological Architecture Lab*. The events were intended to bring together scientists and designers who were, generally speaking, interested in biology and design. In one of the events we were asked to form a group from a mixture of scientists and designers, and to determine the crucial hurdles to be overcome before collaborating across disciplines. The discussion in my group developed around scales. On a flipchart, one of the designers drew a line, crossed it with ten vertical marks and said — 'Right, so at what scale do you work?' Some worked with proteomics, which went at the left end of the scale with the nanometres. Others worked directly in microbiology, which was right on the middle of the scale, between the micrometres and the millimetres. The product designer in the group was mapped in the last but one notch, and the architects at the end of the scale. When we had our reference chart, another designer asked — So, how can we build bridges across the scales? The conversation stopped at that point, with blank faces around the table and with some minutes still to go on the clock.

I also started work on this thesis assuming that my biggest challenge was scale — How do I connect what I'm seeing under the microscope with the scale that I can touch and interact with? In *SynthMorph,* I initially tried to understand connections across these scales. The experience of using it, however, quickly revealed the rift between design intent and the liveness of the system. The simulation was only indirectly related to biological systems,

in the sense that it was mimicking behaviours found in biological systems in a very loose way. Even so, the system had a liveness, tendencies and capacities of its own that had to be negotiated — wrestled with in the first instance — in order to influence its formal outcome. However, the philosophical underpinning was inadequate to engage with its liveness. *SynthMorph* supposed a parametric framework with an instrumental understanding of the biological system; organisms were a means to an end and, as such, needed to be described in terms of what inputs and outputs they would take. In this sense, it followed the *biotechnical imagination* in architecture, which often sees biological systems as the logical continuation of the cybernetic model used by the digital turn in architecture and understood as intelligent agents that can be programmed to enact design intent.

Mobilising the following three *bio-material probes* surprised and challenged the parametric approach. *Bacterial Crystals* and *Bacterial Morphologies* showed what Donna Haraway calls nature's '*independent sense of humour*' (Haraway, 2004, p. 199). Organisms don't like being instrumentalised and understood in terms of parameters and equations; they are constantly fighting back, changing shape and becoming other as their context changes. The framework shifted to admit a new understanding of the biological system; it is not a parameter, but rather an actant. It has independent agency that cannot simply be described in terms of equations. This new understanding opened up a different possibility. The challenge was not in understanding how the different scales connected; but in admitting a different form of design, one in which the designer is not the sole creative actor but part of an assemblage of creativity. Rachel Armstrong has suggested that living organisms are capable of *creativity,* in the sense that they express themselves via morphological meaning: deliberate interactions between organism and chemical context that '*is the outcome of the restless condition that is innate to matter*' (Adamatzky et al., 2013, p. 2). If creativity in design is not the preserve of humans, the designer then needs a different form of engaging with the dense networks of organisms, chemistries and people coming together to produce form – a form of engagement that does not involve making living systems do what we want, as that would take away their liveness. It is, instead, a form of engagement that enables human and non-human agencies to be aligned.

My approach, based on the concept of assemblage, suggests that designers should develop a form of *care*. *Care* involves drawing on non-rational and intuitive dimensions of knowledge in addition to the technical understanding of the organisms and their behaviour. This form of engagement is developed through, I've suggested in *Design Assemblages*, synchronising body movements and actions to the circadian rhythms of organisms. It is also manifested in the forms of representation that we create to deal with them, such as the names I used when referring to specific bacterial colonies. A culture of *Bacillus subtilis 168* that grew larger than the others became my *Champion;* the first culture of *Panebacillus* that I saw became *Philomena*. *Care* is also evident in the way that scientists with whom I have worked talk about their own research, and the time they spend with different organisms in the lab. I've been told, for example, that mammalian cells are *picky* — they won't grow unless you make sure to keep them at a specific temperature; or that *Bacillus subtilis* is *fussy* — you have to keep them *comfy* and *happy* so they grow. Care is, as Evelyn Fox Keller would phrase it when discussing the work of Barbara McClintock, having a '*feeling for the organism*'. A '*capacity for intimate unity (...) fidelity to experience [that] includes the intuitive and the non-rational dimensions (...) direct acquaintance with her object of study and oneness with it*' (Hein, 1984, p. 9).

HYPERCOMPLEX DESIGN

Engaging then with biological systems from a design perspective requires a form of engagement – of *care* – that challenges and upends instrumentality. The notion suggests not only a more thoughtful approach when integrating living systems in the process of design — it suggest an entirely different form of design. I *proposed the bio-material probe* as an instrument to explore such wider consequences. To do so, the methodology takes the form of conversation starters, cartographic instruments and, overall, an iterative process that enables an ethical engagement of *care* for the living that conceptualises them as *hyperobjects.* The term has been coined by Timothy Morton to refer to '*things that are massively distributed in time and space relative to humans'* (Morton, 2013, p.1). I have proposed that one consequence *of bio-material probes* is the expansion of the commonly assumed boundaries of the living system. Biotechnical architecture often assumes that designing with

organisms involves a design space that is delimited by the membrane of cellular systems. The assumption quickly leads to ideals of microorganisms as highly intelligent construction agents, and has often resulted in speculations of designing architecture by manipulating their DNA. I suggested, however, that designing with living systems involves engaging with a thick mesh of non-humans that go beyond the organism itself, and that extends to a number of encounters between the designer and materials, physical spaces, institutions and other researchers. The extended set of interactions involved in designing with living systems suggests that the boundary of the design space — the things a designer needs to engage with in working with living systems — expands exponentially. The living system, and the mesh constituted by the design assemblage, are hyperobjects that the designer needs to engage with.

Designing in a *hypercomplex* environment involves doing so without a clear idea of the outcome in advance. In this situation, there is a need for instruments that perform a cartographic function, in that they assist to navigate through an unknown design space. The *bio-material probe* performs this function. They constitute maps which are in constant change, drawing and redrawing their boundaries as the exploration progresses and providing a way of reading into an unreadable situation. At the same time, *bio-material probes* represent conversation starters — a way of developing a language to engage with non-humans. They highlight the need for an ethical understanding of organisms in biotechnical architecture. I use the term of *ethics* less as a definition of what is right and what is wrong, and more aligned to the work of Pia Ednie-Brown, who suggests it is *'a careful openness to the trouble that the collective, ecological nature of life brings with it'* (2017). Ednie-Brown suggests that creative practice research requires a form of ethical know-how, in which the practitioner *'prior to ethical deliberation – that we draw upon amidst the spontaneous unfolding of events'* (Ednie-Brown, 2017). The *bio-material probe* can be said to provide the means to develop an ethical know-how to deal with living systems. Designing with living systems requires inbuilt notions of responsibility and mutuality, which call for an underlying ethics — an ethical know-how in the terms of Ednie-Brown — and which I have raised in the thesis through the notion of *care* for and attunement to the living system.

The thesis also contributes to the field of architectural design, and more broadly, to design research by defining an approach that is non-deterministic and which, in opposition to scientific methods of enquiry, uses experiments as an open-ended, continuous form of exploration. By working within the purview of biology, a crucial aspect of this research has been defining what the character of a design exploration in contrast to science. More importantly, there has been a need to define how the experiments performed for this exploration are different to those done with a scientific epistemology, even when they might be conducted in the same laboratory, and sharing some techniques and methodologies. The difference is not in the level of detail or rigour in the experiments themselves, but in admitting the possibility of surprise. By doing so, the experiments assume a probabilistic rather than a deterministic role. They have a rigour and they emerge from a set of principles that are testing. However, while scientific enquiry supposes the use of experiments to prove or disprove a hypothesis, their role in this research is that of expanding the boundaries of the exploration while the experiment is being conducted.

A TOOLSET OF BIO-MATERIAL PROBES

More specifically, each bio-material probe in this thesis takes different forms, and provides different lessons of designing with living systems.

SYNTHMORPH

In *SynthMorph*, the *bio-material probe* takes the form of a computer simulation, which validates its link to living systems by integrating morphogenetic effectors. The software enables an open-ended exploration which highlights a rift between deterministic approaches to design, and the agency of living systems. Traditionally, Computer Aided Design system enable designers to describe forms that have been previously conceived, and that are represented in a way that is convenient to communicate as part of the process of making it material. *SynthMorp*h complicates this process. By using morphogenetic effectors as its basis, it makes it difficult for the designer to approach the design process with a form in mind — for instance, trying to use the system to reproduce a cube or a sphere. Therefore, there is a rift be-

tween what the designer expects of the design process, and the tendencies of the particles as they follow the morphogenetic effectors. The dissonance is somewhat resolved by a continuous process of negotiation between designer and simulation, which makes it a conversation starter between the non-human, a digital simulation of a biological system, and the human designer.

SynthMorph is also a conversation starter between designers and other practitioners about the difficulties of understanding biological form. The simulation is supplemented by a series of artefacts that are produced by interpreting patterns produced by the particles using strategies that include information visualisation, and physicalisation of patterns in the form of 3D printed artefacts. The process supposes a jump between the known properties behaviour of cells, and involves a series of decisions that are dissected in the text. These decisions have been central in the conversations that the artefacts have started with other designers, but also with scientists.

BACTERIAL CRYSTALS AND BACTERIAL MORPHOLOGIES

As *bio-material probes*, *Bacterial Crystals* and *Bacterial Morphologies* perform a cartographic function, mapping a design space that is being understood through the design exploration itself. A key component of the exercise is the development of node diagrams that are continuously redrawn to reflect connections between physical parameters that are continuously redrawn as different branching patterns emerge. The exploration starts with three notional state-spaces—chemical, physical and cellular—which are meant to encompass the parameters that are documented in scientific literature to take a part in the development of branching patterns. However, as the exploration gets underway the cartographic process highlights the changing relationship between these initial state-spaces, and detect the emergence of contingent parameters that have a bearing in the way that branches develop, but that are difficult to capture numerically.

Bacterial Crystals and *Bacterial Morphologies* also probe the conceptual background used in understanding biological systems. The emergence of contingent parameters suggests that there are situations in which biolog-

ical systems behave unexpectedly, thus requiring a more flexible way of understanding them. A different framework, however, requires a different engagement. *Bacterial Crystals* and *Bacterial Morphologies* were performed in association with a scientific partner, who executed the explorations in the laboratory. But describing organisms and other non-humans as having agency requires a direct engagement of the designer to enable a constant revaluation of uncertain trajectories.

BACTERIAL ASSEMBLAGES

The fourth *bio-material probe* in the thesis, *Bacterial Assemblages*, take on an ethical role. *Bacterial Assemblages* carries on the exploration started in *Bacterial Morphologies*, but re-approaches bacterial branching by considering the non-human as agent rather than parameter. The re-conceptualisation involves a different engagement with biological and other matter in the form of *care* that calls on non-rational, intuitive understanding. The approach enables a re–categorisation of contingent parameters as spaces of practice, cultures of crafting, and social interaction. *Bacterial Assemblages* also assumes a cartographic function in the sense that it describes in detail the way that spaces, practices, people, institutions and epistemologies have a bearing on the bacterial branches that develop in the petri dish. The map delineated by *Bacterial Assemblages* is also relevant to the field of biotechnologies in general. It suggests that the limits of the design space are not within the membrane of the cellular system, as the influence of Synthetic Biology often implies. Instead, designing with living systems expands the contours of the design space to the assemblage of non-humans connected to the biological system.

THE OTHER ARCHITECTURAL IMAGINATION

The notion of *care* has consequences beyond the immediate concern of biotechnical architecture. It invites us to re-examine wider concepts of design and architecture. When I was preparing to develop *Bacterial Assemblages,* I had to go through a number of flash health and safety courses to, among other things, make sure that I kept my working spaces to the standard of

cleanliness that was expected of a microbiology laboratory. Although the practices themselves were new to me, the basic idea — order and cleanliness enacted through a general aversion to contamination — was not. Cleanliness and order had been part of my training as an architect. Jeremy Till proposes that, despite the fact that architecture is a *contingent* discipline, shaped by external forces, architects often retreat to notions of order, beauty and cleanliness. There is a fiction of the discipline, a form of *imagination* to follow the term I introduced, which is articulated by notions of beauty, cleanliness and order, and which has been constructed by architects despite a multitude of contingencies: external forces that '*are, to a greater or lesser extent, beyond the control of the architect'* (Till, 2013, p. 1). Despite its *imagination*, architecture is defined by contingencies. Till writes:

> Architecture is (...) shaped more by external conditions than by the internal processes of the architect. Architecture is defined by its very contingency, by its very uncertainty in the face of these outside forces (Till, 2013).

For Till, the triumvirate of beauty, cleanliness and order can be traced back to the work of Vitruvius who, in comparing buildings to bodies, instituted a form of architecture that is understood in terms of coherence and order and finds its pinnacle in modern architecture. In an echo of Vitruvius, Le Corbusier would famously suggest that '*to create architecture is to put into order'.* The result, Till suggests, is a fiction of architecture, which is a '*closed, homogeneous, monumental, centred and symmetrical system*' (Stallybrass and White, quoted by Till, 2007, p. 123).

The *imagination* of architecture has at its core forms of representation that enable it to maintain '*a professionally required distance from, and thus anxiety about, material*' (Hughes, 2014, p. x). Katie Lloyd Thomas has analysed how Cartesian geometry enables the distance between the practice of design and the realities of material. She writes:

> I sit alone at my drawing board, trying to design a building. There are memories of smells, the echoes between walls, textures in my fingertips; raised voices arguing their case, quiet gestures of resistance, faces lit in anticipation of possibilities. But my pencil can only draw the lines of

> habit. Lines, more lines, on white until the configuration resembles other drawings of buildings I have seen. It is ready to be built, but all I see are the omissions — no history, no location, no corporeality, no contestation — between the geometries. Can there be another place to begin? (Lloyd-Thomas, 2001, p. 57).

Francesca Hughes (Hughes, 2014) has similarly analysed how the possibilities afforded by computational technologies have served to reinforce and amplify the *imagination*. Decreasing the margins of redundant precision, she argues, widens the chasm that separates material from design.

In describing the difficult negotiations of the architectural *imagination* and material reality, Till writes that '*architecture at every stage of its existence — from design through construction to occupation — is buffeted by external forces. Other people, circumstances, and events intervene to upset the architect's best-laid plans'* (Till, 2013). The quote suggests a core where the fiction of order, beauty and cleanliness exists, placed on top a motte and fortified by ditches and palisades of Cartesian geometry and computational precision. From outside comes the attack of material reality, intent on buffeting the castle. To extend the analogy, bringing living systems into this carefully assembled fiction of architecture, however, buffets the discipline *from within*.

In analysing the consequences of situated knowledge and, more generally, of feminist studies to the production of scientific knowledge, Donna Haraway has proposed that:

> Acknowledging the agency of the world in knowledge makes room for some unsettling possibilities, including a sense of the world's independent sense of humour. Richly evocative figures exist for feminist visualizations of the world as witty agent. We need not lapse into an appeal to a primal mother resisting becoming resource. The Coyote or Trickster, embodied in American Southwest Indian accounts, suggests our situation when we give up mastery but keep searching for fidelity, knowing all the while we will be hoodwinked (Haraway, 2004, p. 199).

This quote is relevant here, as it helps to think of a biological system as a shape-shifter, a trickster that upends and buffets from within. If we accept

that organisms are tricksters, we can then admit the possibility that biological systems are anything but control and efficiency. They are contingency and mess — a shape-shifter. It is the trickster that brings matter right into the process of design itself — with the urgency of the smell on entering a lab where *E.Coli* has been growing, a kick right to the pit of the stomach; it is a visceral shape-shifter. And in this context, biological systems are relevant to architecture in the way that they amplify the argument of *material thinking,* challenging, as Lloyd-Thomas (2006) has, the prevalent philosophical tradition of hylomorphism, which tends to suppose that form is imposed on matter. Or in opening up the possibility of a design engagement that is not focused on the instrumental use of tools and materials to produce form, as Barbara Bolt (2007) has suggested. Biological systems are loud and articulate in expressing the wills of their agency.

Let us go back to the question — *can we then grow a building?* The answer is that we can't really know. Not until we make peace with the imprecision, messiness and general lack of control that is brought about by living systems. And one possibility that needs to be countenanced is that, by adopting an engagement of *care* to living and non-living matter, we are no longer doing *design* and *architecture* in their strictest definitions. Perhaps we don't yet have the language to refer to engagements with matter that are not predicated on the instrumental, but all the same suppose an association that *produces* something that wasn't there before. It is a design with no author. Or a design with a multitude of authors. *A-design*, *non-design*, *quorum-design*.

NEXT STEPS

There are a number of limitations that future work would need to address. The most salient is that, while the notion of biotechnical imagination references synthetic biology, the *bio-material probes* in this thesis do not engage directly with its tools and practices. One strategy I used in Chapters Five and Six to engage with the cellular state-space, which references techniques such as recombinant and synthetic DNA, is instead to use different microorganisms, which provide a contrast to genetic material and behaviours. In terms of assemblages, there are distinct tools, spaces and social interactions connected to synthetic biology, which have not been explored

in this thesis and which would undoubtedly change the themes that have been highlighted in Chapter Six.

It is also important to analyse how the philosophical frameworks used in this thesis constrain at the same time as they facilitate action. The sequence of *bio-material probes* develops a transition that starts with the framework of parametrics, and transitions into approaches that consider non-human agency and assemblages. In doing so, I drew heavily on Actor Network Theory, and on feminist critiques of scientific epistemology, which enable me to reframe and interpret my own relationship to biological matter. These influences also helped me to take an auto-ethnographic approach to laboratory work in Chapter Six. In *Laboratory life* (2013), Latour and Woolgar introduced the notion of anthropological strangeness, which involves studying scientists and their work in laboratories as part of a tribe that is foreign to the social researcher. The methodology involves *bracketing* previous knowledge of what scientists do, and of how scientific knowledge is generated, which leads to a gradual process of refinement and observation. The influence of ANT enabled me to generate the analysis in Chapter Six, in which I attuned to the different transactions that were involved in the experiments that I was conducting, and tried to convey the strangeness of getting inside a laboratory without formal training in sciences.

There are other frameworks, however, that would also have been helpful in framing this research. One of them is the notion of *Informed Materials*, a term that has been introduced in the context of chemical R&D and the development of new drugs. In *Pharmaceutical matters*, Andrew Barry described how the term, first introduced by Bensaude-Vincent and Stengers (1996), makes reference to the fact that '*molecules should not be viewed as discrete objects, but as constituted in their relations to complex informational and material environments'* (Barry, 2005, p. 56). Barry is interested in the way that chemistry deals with the contingencies of compounds and molecules behaving differently in different contexts. He writes:

> For chemists, the fact that molecules have changing properties depending on their associations is an everyday reality. The molecule that is isolated and purified in the laboratory will not have the same properties as it has in the field, the city street or the body (...) The challenge, for the

> chemist, is to multiply the relations between different forms of existence of a molecule both inside and outside the laboratory (idem, p. 57).

There are some parallels in Chapters Five and Six, in the sense that different associations of organisms and context produced results that were difficult to anticipate. Barry draws upon the philosophy of A.N. Whitehead to suggest that chemical molecules are *historical* events, instead of immutable entities that are simply *discovered* by scientists. They are *informed* materials. Barry writes:

> The molecules produced in the contemporary pharmaceutical laboratory certainly are more or less purified as chemicals, but they are also enriched in new ways. They are part of increasingly dense, spatially extended and changing informational and material environments formed not just through laboratory syntheses and tests, but through virtual libraries, computational models and databases. The notion of 'informed materials', introduced by Bensaude-Vincent and Stengers, describes such novel entities very well (idem, pp. 64–65).

The notion of informed materials might be equally useful in describing the way that biological systems behave differently according to context and are informed by dense networks of information, materialities and economies. Similarly, there are other philosophical approaches that might add flexibility when dealing with the contingent nature of biological systems. The work of Simondon, for example, might also offer an interesting framework with which to approach biotechnologies – one that enables concentrating on the interactions between organisms and their context through the notion of *associated milieu* (Mitchell, 2012).

CODA

I began the thesis by referring to *Making Life*, the series of workshops that provided me with the tools and knowledge to understand better how creative practice could engage with biotechnologies. The work I did in *Making Life* ran parallel to the exploration of this thesis, and also constitutes an example of the next step after *Bacterial Assemblages.* The three-event structure was intended to provide a critical and skill base, and to build up to a series of collaborative pieces that would be exhibited at the end of the third event. I worked with six other practitioners, each based in different countries and from a wide range of backgrounds: Pei Ying Lin, who has a degree in life sciences and art; Charli Clark, who was studying the environmental art MA at Aalto University; Helena Shiomar, who was pursuing her PhD in synthetic biology; Johanna Rotko, a visual artist and photographer based in Helsinki and who was also enrolled in the new media MA in Aalto University; and Luis Hernan, who was also completing his PhD in creative practice. The group was collaborating with Martin Hanczyz, a researcher heading up the Laboratory for Artificial Biology at the University of Trent, who specialises in interfacial dynamics, complex chemistries and artificial life. Martin was an invited speaker at the second event of *Making Life,* where he presented his research on artificial life and ran a workshop on creating *protocells*.

Protocells can be described as '*chemical models of living cells that possess some of their properties, such as metabolism, movement, replication, information, and evolution, but are not necessarily alive'* (Hanczyc, 2011, p. 27). In his workshop, Martin presented the model proposed by Otto Butschli, who was interested in producing an artificial amoeba with pseudopodia that mimicked some of the behaviours of living protists (Armstrong and Hanczyc, 2013). The Butschli protocol involves adding a few droplets of potash to olive oil. The process triggers a saponification reaction, in which the molecules of

triglycerides are split and produce fatty acid salts and glycerol, making the droplets react by migrating through the olive oil and, eventually, breaking up into smaller droplets.

In the project, we were interested in experimenting with the Butschli method. The original protocol involved creating potash by soaking wood ashes in rainwater. The mixture is left for a week, which promotes the transfer of potassium contained in the ashes and creates a solution that is rich in potassium hydroxide. By the time we started working on the project, I had been working on an early draft of Chapter Six and was interested in Jane Bennett's notion of vitality and the way she described a gradient of potencies that all entities, human and non-human, possess — of a vibrant materiality that runs alongside humans. Her words kept resonating in my mind about how things '*act as quasi agents or forces with trajectories, propensities, or tendencies of their own*' (Bennett, 2009, p. vii). When I put the idea to the group, the concept of the project evolved, and we started to understand protocells as agents that would enable us to *amplify* the gradient of vitalities. We started thinking of the reactions that lead to the creation of protocells as a fluctuation — a split second in which vitality spikes up to stabilise and become soap. As a result of this new direction, we began to focus our experiments on looking at how different sources of fats and ashes might result in different vitalities – how drawing ashes not only from wood, but also from paper, bananas, cigarettes or hair would result in more or less *lively* behaviours. But also how combining ashes with different fats — olive oil, beeswax, poppy oil, lard, goose fat — would magnify the different vitalities. The project then took on an official name: *Living Ashes*.

Living Ashes expands the networks of materials, people, disciplines and epistemologies that I have analysed in the thesis. The project involves negotiating the agencies of humans and non-humans across different scales. It starts with the immediate scale of the chemistries, understanding which ashes produced strong enough potash, and which worked best with different fats. Working with these chemistries was a process of negotiation with the non-human, in the same way that I wrestled with the liveness of *SynthMorph* in Chapter Four or negotiated with bacteria and its complex engagements with *potassium phosphate tribasic* in Chapter Six.

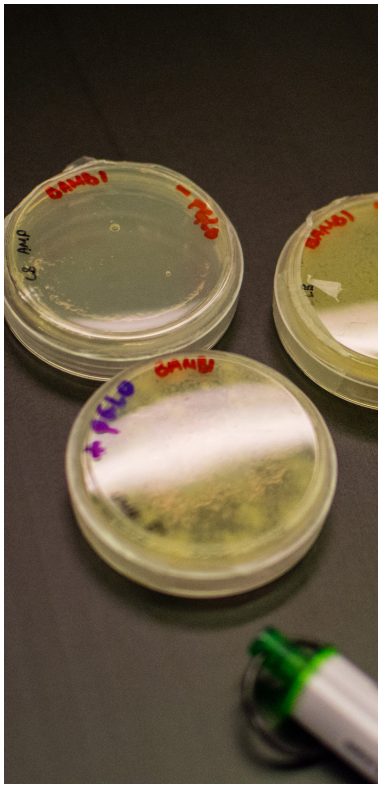
But the boundary of the assemblage scales upwards. Just as it was challenging to align the agencies of non-humans to produce saponification, the agencies of humans were also difficult to navigate. We began production of the project following the second edition of *Making Life*, and we created a blog to communicate with one another about our explorations once we had returned home. We dutifully photographed, filmed, sketched and blogged on our individual experiments, drying banana husks, rendering lard, burning Taiwanese paper money and collecting honey. By the time we landed back in Helsinki for the third event we probably all felt that the project was well on track, and that only a few wrinkles needed ironing out before we launched into the final production week. And then we realised how difficult it was to agree. Discussions quickly flared up over small things, such as which combinations of ash and fats should be pursued and what each represented. And then the big arguments appeared. Should we produce a video? Maybe this was not really so important? Maybe the concept was not about vitality? Were we exploring soap?

Living Ashes also involved several contingencies. Martin Hanczyc, who acted as our scientific partner and adviser, cancelled his participation in the last event at the last minute, so we had to communicate with him through email and Skype. And, as in Chapter Six, the contingencies had to be negotiated by creating new assemblages, often put together through informal social ties. The deficits in expertise were filled in by Helena and Pei, who had a background in science and were more adept at interpreting the chemistries that Martin was sending via email. But the assemblage also drew upon institutional structures. As I mentioned previously, Making Life was hosted by *Biofilia Base for biological arts,* a laboratory operated by an art school, which seeks to provide the context for creative practitioners to get directly involved in biological work. Crucial to achieving this objective was Marika Hellman, who works as lab manager, overseeing the laboratory logistics and making sure that instruments and compounds were ready when different experiments took place. However, she was also instrumental in creating the context for practitioners to follow their own line of work and enquiry. Given the fact that most of the people who use the laboratory don't have a formal biological background, Marika often fills in and supports by explaining how to use the instruments, or by providing chemical and biological knowledge.

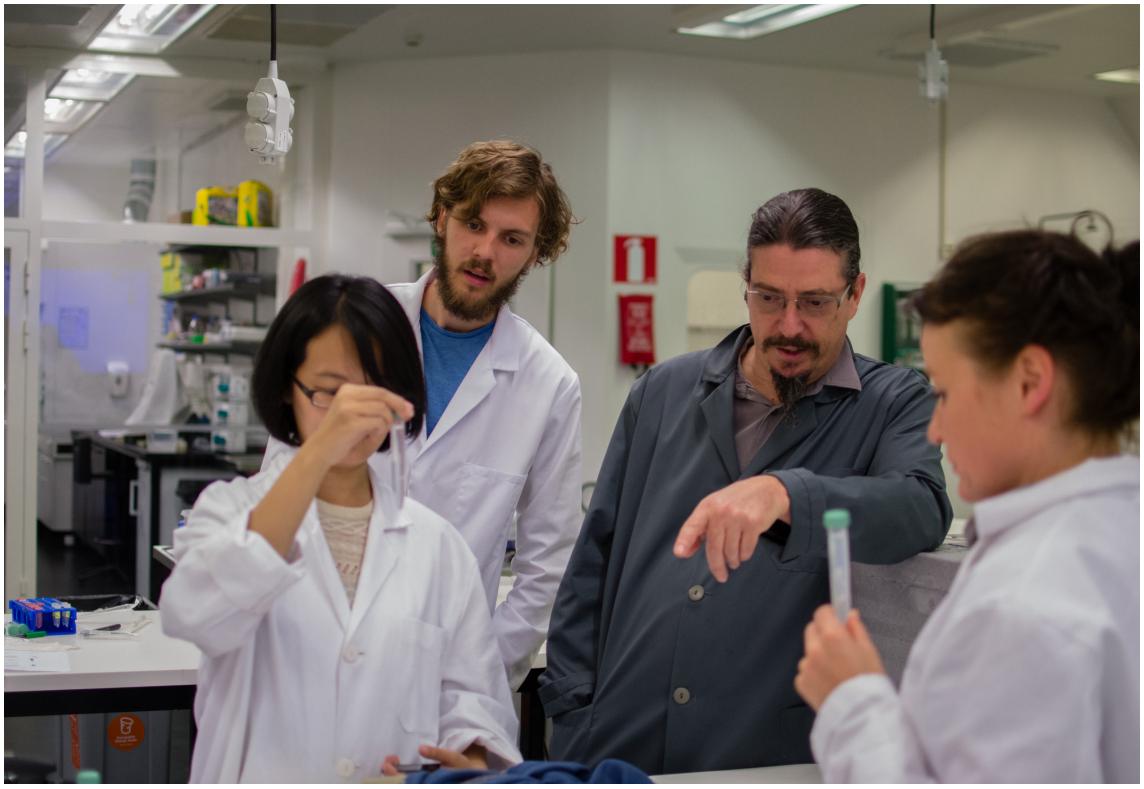
More importantly, she makes sure that critical protocol is followed, such as, for example, contamination control or limiting the movement of organisms outside the lab. Part of the assemblage that enabled us to negotiate the contingencies involved the kind support of Marika, who often helped us in finding techniques to draw fatty acids from different sources, or in explaining how to use specific pieces of equipment.

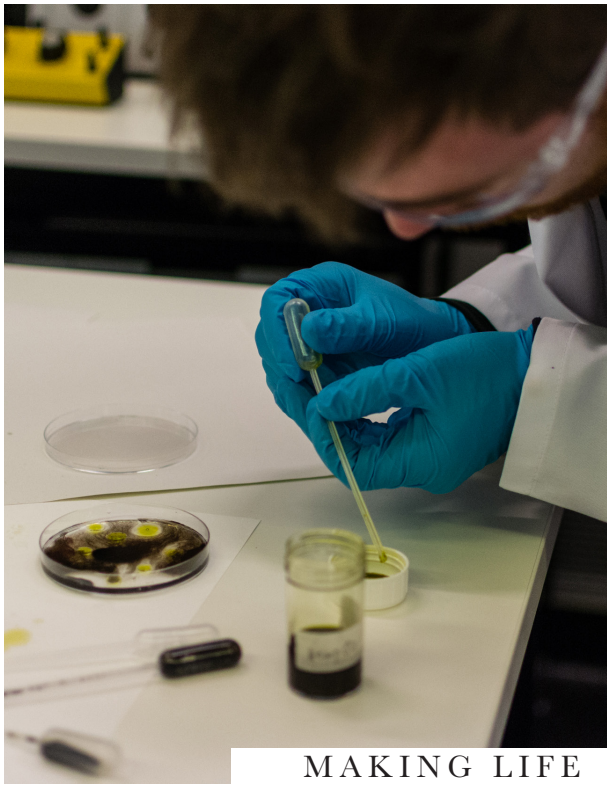
Living Ashes can be read as an extension of the work that I have done in this thesis. In order to influence specific characteristics in a semi-living system, the project involves engaging with an assemblage that extends outwards from the immediate context of the water droplet and its immediate context, expanding wide to engage people, organisations, epistemologies and also spaces. The project, however, also suggests that entering assemblages with living and semi-living systems involves a condition of *fluidity*. A good example of the fluid exchange between semi-living systems, actants and designers is evident in the way that the exploration in *Making Life* and *Living Ashes* influenced the notion of the *bio-material probe*. In order to engage with living systems, epistemologies and practices had to be transformed to enable a different configuration of the assemblage. In doing so, the notion of design exploration is bent, accommodating an open-ended process that leads to non-deterministic outcomes. And in the context of Living Ashes, engaging with protocells to explore their vitality required a different form of transformation to the one permitted by the context of Making Life.

Exploring the vitality in the first edition of Living Ashes involved tracing back the *chain of materiality* of protocells: looking at how the different chemistries were rendered. To highlight these connections, we developed a series of videos that showed the process we went through to obtain four different combinations of ashes and fats, and finished with a microscopic video of the different behaviours of the protocells resulting from each combination. The videos were synchronised and shown in parallel on four monitors in the exhibition, enabling the audience to compare how the different combinations resulted in different levels of vitality. We felt, however, that the medium was not able to communicate fully the tactility of the process, deciding therefore that the exploration required a different format.



MAKING LIFE





MAKING LIFE

In *Living Ashes II,* I collaborated with two of the original members, Pei and Luis, to explore how the assemblage had to be reconfigured to amplify the vitality and fluctuations of the process. The project was accepted to the *Click Festival,* an annual art, science and technology festival. The festival takes place in *KulturVerftet*, a cultural centre located in the former shipyard of Helsingør in Denmark. The format of the event enabled us to explore the concept in a live performance. We set up a small chemistry laboratory on stage and created six 'stations' in which specific parts of the process of drawing chemistries took place. The set-up included a number of directional microphones, which helped us to pick up and amplify the sounds as we hacked, tore apart, burnt, soaked and decanted. The final stage of the performance involved combining the chemistries and placing them under a digital microscope that was connected to a projector, enabling the audience to see how protocells emerged.

The fluidity of the assemblage is highlighted by the transition between *Living Ashes I* and *II.* Engaging with the protocells, and amplifying their vitality and material transactions, involves understanding how different actants needed to be transformed, and resulted in a reconfiguration of the designers involved, of the geographical and institutional context, and of the format of exploration itself. The nature of these negotiations has broader consequences for the definition of design. For example, it can be said that forcing the living to do what you want them to do somehow takes away their liveness. As a result, notions of design as a discipline that enables the exertion of control over matter are impossible when dealing with living systems, as they are unpredictable and difficult to instrumentalise. The argument resonates with the work of Rachel Armstrong (2015), who has suggested that engagement with living and semi-living systems requires a re-definition of design disciplines. It also resonates with the discourse of *material thinking* (Thomas 2006; Bolt 2007), which suggests alternative design engagements in which form is not imposed on matter, but is the result of the tendencies inherent in matter. Living systems can be said to *amplify* the argument, bringing into sharp relief the nature of how different forms of matter interact and affect other aspects of the design process. Design requires a degree of humbleness.

The fluid nature of living assemblages also has consequences for the argument I used to describe *bio-material probes*. I suggested that imposing a design context on living systems results in a process of a horseless carriage, as it flattens its potentially infinite potential. To use one of my projects, *Bacterial hygromorphs,* as an example, deciding that bacterial spores are a technology for kinetic façade panels constrains possibilities: spores can only be thought of in terms of a panel. We can reformulate this argument to attend to the fluidity of living assemblages. When a practical context is imposed, both living system and context become fluid. In thinking about how the spores can be used in a façade panel, the notion of the panel itself is interrogated and transformed as it tries to accommodate the realities of the living system. The process results in a design outcome that is not a panel in the traditional sense but an entirely new category. It has become part of the living assemblage, and it has become *other* — it is no longer just a panel, but rather a new category of design element that admits the new possibilities of living systems.

LIVING ASHES I

LIVING ASHES II

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