8 ‘Hylozoic Ground’

> *A soil is not a pile of dirt. It is a transformer, a body that organises raw materials into tissues. These are the tissues that become mother to all organic life.* (Logan, 2007, p.181)

8.1 Overview

An opportunity to investigate the applications of vibrant matter in an architectural context arose from an invitation to collaborate on the Hylozoic Ground installation by Philip Beesley. This chapter, therefore, examines the conditions in which vibrant matter and different species of ELT such as the Bütschli system can be applied and orchestrated, using morphological computing approaches within an architectural design setting. General design principles were developed for the installation with potential applications for broader architectural design contexts. A series of design experiments were also conducted to establish an approach towards developing appropriate infrastructures that may enable and prolong the lively action of vibrant matter.

8.2 An Exploration of Vibrant Matter in an Architectural Design Context

Hylozoic Ground is an architectural installation that was conceived and designed by architect Philip Beesley as Canada’s entry to the 2010 Venice Architecture Biennale (see Fig. 8.1). Hylozoic Ground is a version of Beesley’s ongoing series of installations (Armstrong and Beesley, 2011), which reflects his extensive engagement with responsive and distributed architectural environments and interactive systems. Beesley’s practice is particularly concerned with design integrated with Nature, lifelike systems and their materiality.

My involvement with Hylozoic Ground began as a series of conversations with Beesley when we met at the ‘Plectic Systems Architecture’ conference held by Neil Spiller’s AVATAR (Advanced Virtual and Technological Architectural Research) group in 2009. I had co-organized the event to bring together scientists working with emerging technologies and architects. The event consisted of a series of public presentations and a moderated workshop that aimed to explore and forge new possibilities for a 21st century practice of architecture in a multidisciplinary, collaborative environment (Armstrong, 2010b). A series of exploratory exchanges between Beesley and myself ensued, which reflected on the practical opportunities for directly integrating vibrant matter, ELT and morphological computing techniques into cybernetic frameworks (see Fig. 8.2).

Figure 8.1: Hylozoic Ground installation, Canadian pavilion, Venice is a cybernetic matrix that integrates a range of different 'organ' and 'tissue' types such as swallowing tubes (tapered cylindrical structures to the right of the photograph) and sound organs (clustered leaf-like structures in the centre of the photograph). The challenge was to design a set of dynamic chemistries that would aesthetically and functionally complement the soft mechanical systems. A centrally placed (yellow) chemical organ can be seen in centre field. Photograph, courtesy Philip Beesley, August 2010.

Figure 8.2: Some of the dynamic chemistries designed for the Hylozoic Ground installation resonated aesthetically with some of the soft, mechanical, feathery actuators within the cybernetic matrix. Photograph, Rachel Armstrong, July 2010.

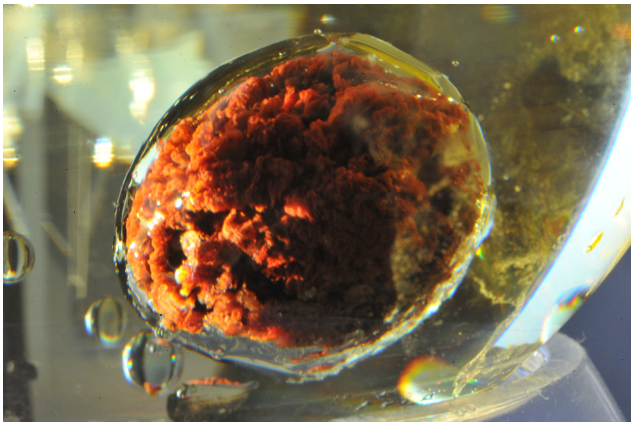

Figure 8.3.: Chemical experiments performed at the University of Waterloo with Philip Beesley, explored some of the properties of self-organizing systems so that they could potentially be coupled within a large, soft mechanical cybernetic framework. In this experiment, a copper II sulphate crystal was added to a weak potassium ferrocyanate solution in a flask, which produced a strong, undulating brown precipitate. Photograph, Rachel Armstrong, September 2009.

A variety of chemical systems, namely dynamic droplets (Hanczyc et al, 2007; Toyota et al, 2009), Traube cells (Traube, 1867) and Liesegang rings (Liesegang, 1869) were of interest to Beesley as the basis for a series of experiments that could be incorporated into his installation work. The suitability for each of these systems to be explored in a design context was established through a series of experiments at the laboratory at the Center for Fundamental Living Technology (FLinT) at the University of Southern Denmark, courtesy of the centre's director Steen Rasmussen and chemist Martin Hanczyc. Having worked closely with Beesley on these lifelike technologies and materials, a set of designs were developed and systems constructed that could be integrated into Hylozoic Ground, and installed in Venice in July 2010.

8.3 Hylozoic Ground at the Canadian Pavilion, Venice

Hylozoic Ground was situated in the Canadian pavilion at the Giardini on the island of Venice. The unique gallery space was designed by the Milan-based architecture firm BBPR (Gian Luigi Banfi, Ludovico Barbiano di Belgiojoso, Enrico Peressutti and Ernesto Nathan Rogers) (Di Martino, 2007) and inspired by the Nautilus shell. At the heart of the gallery was a thriving oak tree enclosed by glass panels that led to a skylight through which the foliage hung over the roof of the building (see Fig. 8.4).

The Hylozoic Ground installation itself is a complex, cybernetic system of interacting synthetic organs that are connected across interstitial spaces. The matrix is forged by a series of 'mycelium-like', delicate plastic fronds that are integrated with

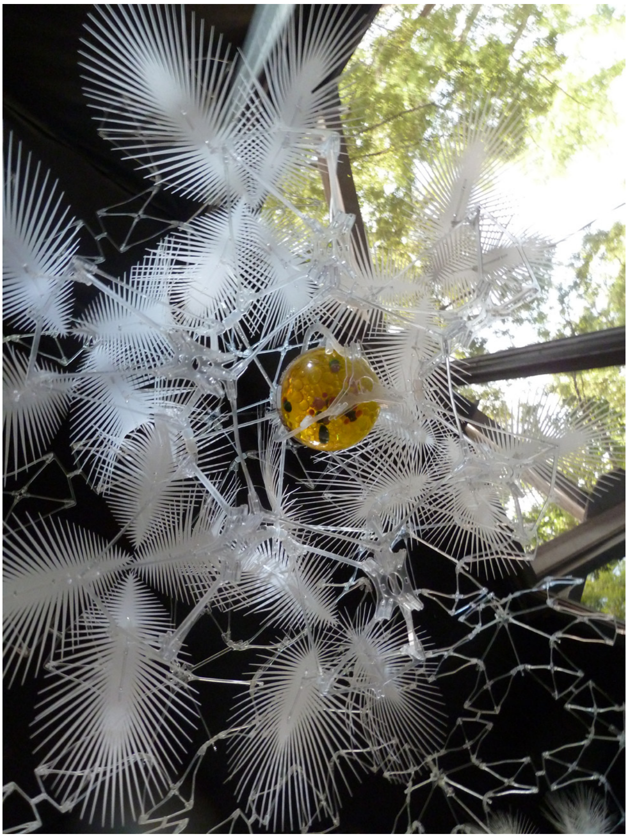

Figure 8.4: Hylozoic Ground chemistries were nested within the cybernetic matrix of the installation and could also be seen against the natural oak canopy, which rose from the centre of the Canadian pavilion. Photograph, Rachel Armstrong, July 2012.

a neural network, which activates a variety of sensors and effectors. The cybernetic components of the installation respond to disturbances in the matrix by episodically discharging volleys of light, shaking the geotextile canopy like the wind through leaves and prompting feathery columns to greet visitors with sweeping salutations. The various species of systems that collectively make up the installation can be thought of as a web of physical, chemical and environmental connections through which a range of actants may participate. The installation may be likened to a soil, which is not formless, but has a specific architecture and an evolving body that is shaped by its responsive, material ecologies. The vibrant community of assemblages and robust centres of organization within Hylozoic Ground create a set of fertile conditions in which further lifelike events may occur. Conjecturally, given enough time, perhaps a sufficiently life-promoting environment could provoke an event that might be considered formally ‘alive’[43] should it become possible to set up uninterrupted generations of droplet ‘bodies’ within the system.[44]

8.4 Hylozoic Ground Dynamic Chemistries

The dynamic cybernetic matrix of the Hylozoic Ground installation provided an active site that invited collaborative explorations with the non-linear outputs of its actuators, which were intrinsically coupled to the conditions of its site. The complexity of this environment required systems that could respond to unpredictable events and contribute creatively to the complex spatial programs continually shaped by the many participating actants, which could be considered as an ‘ecology of design’.[45] A range of species of vibrant matter was therefore an obvious candidate for incorporation into the cybernetic system. The ‘metabolism first’ model of organization and the Chemoton (Gánti, 2003) criteria for ‘life’ were applied to develop a fundamental set of conditions around which ideas about creating a fertile material field could be developed, in which increasingly complex phenomena could potentially be observed. The responsive infrastructures of the cybernetic system, the neural network, the movement of people around the space, the flow of air and the material conditions within the gallery (gases, water vapour, dust) provided a rich landscape and infrastructure, which could be considered as participating agents within an ecological system of abiotic assemblages.

Chemistries were selected for incorporation into the cybernetic system on the basis they demonstrated some recognizable lifelike qualities, such as movement, sensitivity and the ability to adapt to changing environmental conditions (Armstrong, 2010a). Four different dynamic chemical species were developed into arrangements that complemented the hylozoic, or life-bearing, ambitions of the installation. They were positioned within the cybernetic matrix as a cohesive web of materialities that invited the participation of other actants. The striking lifelike characteristics of the Bütschli system (water in oil) (Armstrong and Hanczyc, 2013) warranted further

43 There is no universally accepted definition of life, although the working definition applied in the case of the ‘lifelike’ chemistries relates to the Chemoton model, which specifies that life needs a container, metabolism and information (Gánti, 2003). Although the conditions for the Chemoton model were not met, these principles provided a guide for considering the kind of chemical conditions that might increase the material ‘fertility’ of the site.
44 Continual flow of nutrients and removal of waste can prolong the activity of self-organizing systems (Hsu, Mou and Lee, 1994).
45 Stengers’ notion of ‘an ecology of practices’ has many resonances with Hylozoic Ground, which is a non-hierarchical collaboration between many heterogeneous agents that may ‘dream along with’ each other to generate novel events (Stengers, 2000).

architectural exploration as well as developing a comparative reverse phase system (oil in water droplet technology), which provided an ‘open’ aqueous system through which a flow[46] of resources could be delivered to support the droplets’ metabolic activities. The self-organizing properties of Liesegang rings (Liesegang, 1869) that result from chemical precipitation and diffusion of minerals through a reactive gel were also selected to augment the hylozoic potential of the site. Islands of hygroscopic materials within semi-permeable, latex envelopes encouraged airborne water movement through the installation, enriching the potency of the space to support living processes. Notionally, the Hygroscopic Islands functioned as an inorganic lymphatic system and speculatively provided a vehicle for the potential transfer of minerals in solution, or particles throughout the hylozoic matrix. These various chemical systems worked as an assemblage of chemical actants that orchestrated the movement of elemental systems and mineral resources through a cybernetic matrix, to establish fertile conditions that increased the probability of synthetic events occurring within the cybernetic field. These species included:

— Incubator Flasks: Modified Bütschli system
— Carbon Eater Flasks: Carbon-fixing oil droplets
— Liesegang ring plates: Vertical diffusion–precipitation fields
— Hygroscopic Islands: Assemblages of hygroscopic materials

8.4.1 Incubator Flasks: Modified Bütschli System

With the advent of synthetic biology (the design and engineering of living things) (Armstrong, 2013c; Armstrong, 2013d) and morphological computing (Armstrong, in press) it is possible to design with fully alive and lifelike processes using chemical building blocks. This scientific practice is relatively new and it is still unclear exactly what kinds of challenges the technology of ‘life’ is best placed to address. It is also uncertain how it may be possible to design with lifelike technologies in everyday situations. Synthetic biology and morphological computing are normally carried out on a very small scale, often in sterile laboratories; therefore, establishing a design practice based on vibrant matter, different species of ELT and morphological computing techniques within an architectural installation poses a number of design challenges:

— Is it possible to work with vibrant matter, ELT and morphological computing at a human scale?
— What design principles apply to materials that are lively?
— What infrastructures enable vibrant matter, ELT and morphological computing to be accessible for architectural design practice?

46 Continual flow of nutrients and removal of waste can prolong the activity of self-organizing systems (Hsu, Mou and Lee, 1994).

These questions were approached by working like Nature does, starting with the chemical principles that underpin living building blocks and aiming to 'grow' an architectural technology. The outcome was not specified at the start of the experiment, which was in keeping with design principles consistent with emergence, but left 'open' to explore the limits of the system. Chemistry is a parallel programming language and hardware, which can respond to changing circumstances and opportunities, just like natural systems do – although lifelike chemistry is not instructed by DNA. The participating chemical agents were regarded as codesigners of the cybernetic system that would establish their own relevance to and connection with the installation's actants by acting as ELT. This is a very different approach to architectural design conventions, which operate according to predetermined outcomes.

The lifelike qualities of the Bütschli system constituted a powerful platform and chemical operating system through which ELT could be developed. The dynamic chemistry was installed within a glass vessel, which comprised a design unit called an 'incubator'. The terminology reflected an ambition to design with living processes and to explore the conditions of chemical fertility in which other systems could thrive. Potentially, a fertile material matrix colonized by vibrant matter and different species of ELT increased the probability of hylozoism, where new kinds of lifelike chemical systems might emerge. To develop the technological potential of the Bütschli system as ELT required modification of the system so that it could orchestrate material events. Bütschli droplets spontaneously assemble when a drop of alkali is added to a dish of olive oil, where the aqueous phase spreads out and breaks up into tiny droplets that are about a millimetre in diameter and are just visible to the naked eye. At this scale, they are difficult to individually manipulate and even more difficult to see with the naked eye, especially in a challenging gallery context. When Bütschli droplets are examined under a light microscope they exhibit a striking range of lifelike behaviours. Each droplet possesses a unique personality and explores an individual trajectory. As Bütschli droplets push through the oil field they leave trails of soap crystals behind them, some of which are rather biological in appearance.

The first attempts to scale up this fascinating miniature world from the petri dish into a public space explored the possibility of using chemical attractants to induce population-scale activity within a droplet colony. Bütschli droplets respond vigorously to ethanol (alcohol), butanol and acetone (nail polish remover) and form droplet swarms in the oil medium. However, even using large amounts of droplets and chemoattractant did not produce an aesthetically appealing result, as aggregated Bütschli droplets simply looked like milky streaks over an oil field at the human scale (see Fig. 8.5).

Unmodified Bütschli droplets are not easily visible from any distance with the naked eye, since they are denser than their medium and sink to the bottom of the flask as they are formed. Although it was intended that visitors would view the chemistry from underneath, the droplets tended to clump together on the base of the petri dish in which they were prepared where it was not easy to see them clearly. A layer of

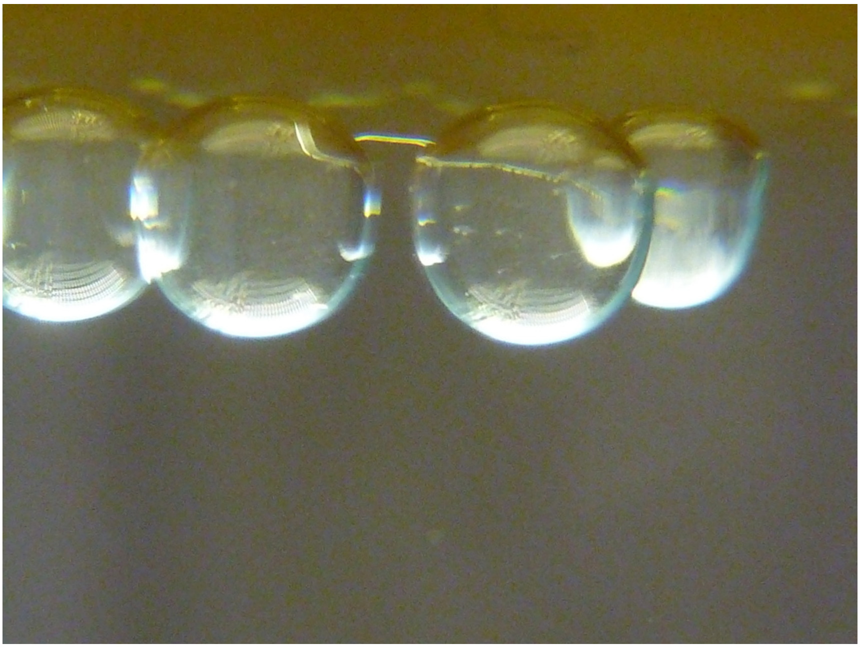

Figure 8.5: Unmodified Bütschli droplets are not readily visible to the naked eye and require a contrasting interface if they are to be easily seen within a gallery setting. Photograph, Rachel Armstrong, February 2010.

diethyl phenyl phthalate (DEPP),[47] which is clear oil with a specific gravity of 1.12 g/cm^3 at 20°C, was added into the petri dish to form an interface with the olive oil. DEPP is denser than olive oil, with a specific gravity of 0.9150–0.9180 g/cm^3 at 15.5°C (Olive Oil Source, 1998–2013) and it is also denser than water, with a specific gravity of 1.0 g/cm^3 at 20°C. So, with a layer of DEPP at the bottom of the container, a clear interface could be developed against which the droplets could be clearly seen, by carefully layering olive oil over it so that the oils did not mix (see Fig. 8.6). A 250 ml round-bottomed flask was clamped in a retort stand and 100 ml of DEPP was added, before carefully pipetting 100 ml of olive oil by hand down the side of the flask over the DEPP to create an interface and avoid mechanical mixing.

An inhibitor was added to the 3 M sodium hydroxide aqueous phase to increase the size and visibility of the Bütschli droplets, which was prepared by agitating 20 ml olive oil and 20 ml 3 M sodium hydroxide in a 50 ml screw-cap disposable test tube, for 2 min. The emulsion was then spun down in a centrifuge at 10,000 rpm for 30 s and the milky precipitate that had settled at the interface by hand was extracted

47 DEPP is commercially used as a plasticizer, a perfume diluent, emollient and as a fixing agent in gas chromatography.

Figure 8.6: Modified Bütschli droplets self-assemble at the interface between green olive oil (above) and yellow-tinged DEPP (below) and are clearly visible in a gallery setting. Photograph, Rachel Armstrong, April 2011.

with a 2 ml disposable pipette. 1 ml of extracted surfactant (precipitate) was added to each 10 ml of 3 M sodium hydroxide in the preparation of the Bütschli system, which produced greatly enlarged droplets with diameters of 1–2 cm. These modified droplets self-assembled into evenly spaced formations and produced a clearly visible layer that settled at the interface between the two oils (see Fig. 8.7).

Under these conditions, the Bütschli droplets produced milky, soapy deposits at the oil/water interface and could also be built up carefully by hand to a few centimetres in diameter. Additional metabolisms of brightly coloured 1 M inorganic salts that included copper II sulphate, iron II chloride, iron III chloride, cobalt II chloride and nickel II sulphate, in amounts of 1–2 ml, were pipetted by hand into the flask (see Fig. 8.8).

The reagents are summarized in Table 8.1.

These droplets fused on contact with the enlarged Bütschli droplets to create insoluble, brightly coloured precipitates within the alkaline environment of the Bütschli system, which promoted crystal growth (Spanos and Koutsoukos, 1998). Modified droplets could be clearly seen against the oil layers within the flasks and formed miniature, suspended crystal gardens and shell-like structures that were remarkably stable in the gallery conditions and survived for the entire duration of the installation. However, since the Bütschli droplets had been greatly slowed down

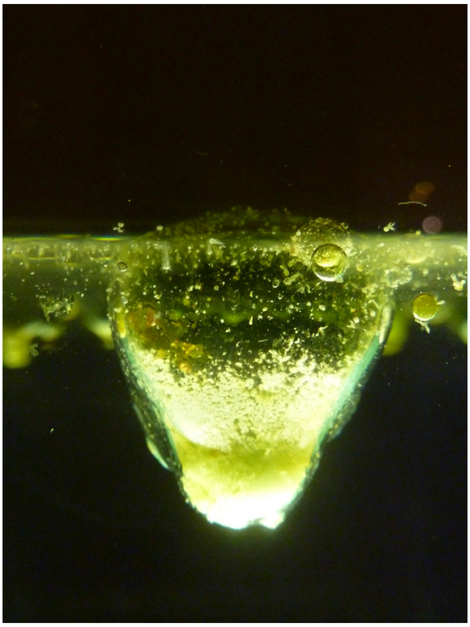

Figure 8.7: Modified Bütschli droplets will enlarge from the millimetre to the centimetre scale by introducing a small quantity at 1% v/v of the system’s soap-like product into the 3 M sodium hydroxide solution. This can be seen accumulating at the bottom of the droplets under the influence of gravity as a highly reflective sheen, which is produced by the soap crystals. Photograph, Rachel Armstrong, April 2011.

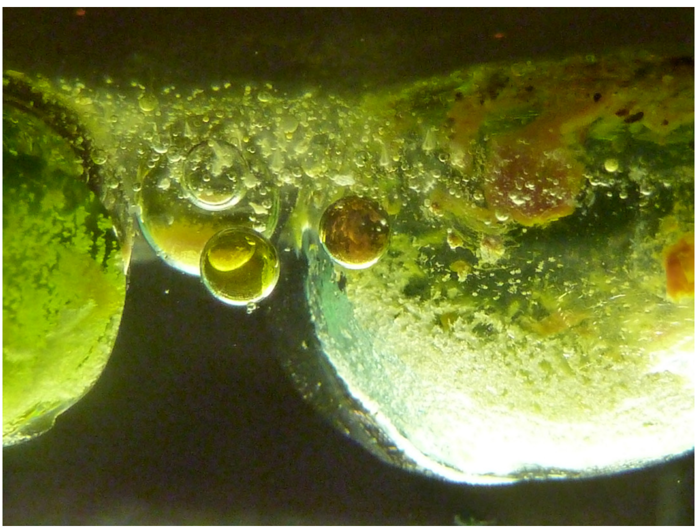

Figure 8.8: With the addition of 1 M mineral solutions, modified Bütschli droplets produce insoluble carbonate crystals, whose growth is facilitated in the alkaline droplet interior. Photograph, Rachel Armstrong, April 2011.

by the surfactant inhibitor, they did not exhibit the same kind of striking lifelike behaviour of the original recipe. Yet, they were not inert and produced a different kind of morphological computation where the droplets self-organized into periodically spaced clusters (see Fig. 8.9).

Table 8.1: Incubator Flask preparation for a 250 ml flask

Chemical	Strength	Amount
Diethyl phthalate	n/a	100 ml
Extra virgin olive oil	n/a	100 ml
Sodium hydroxide	3 M	40 ml
Iron II chloride	1 M	10 ml
Iron III chloride	2 M	10 ml
Nickel II sulphate	1 M	10 ml
Copper II sulphate	1 M	10 ml
Cobalt II chloride	1 M	10 ml
Calcium chloride	1 M	10 ml

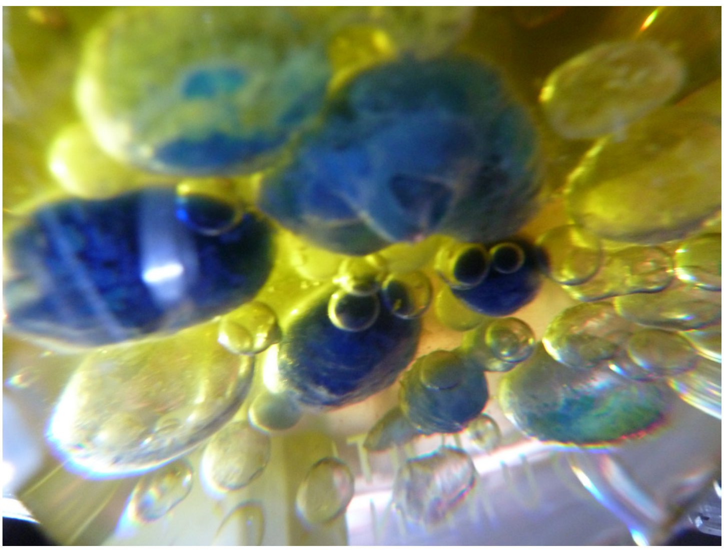

Figure 8.9: Droplet clusters are spontaneously produced through morphological computing interactions than can be shaped by adding mineral solutions to the flasks, which convert dissolved carbon dioxide into structural carbonate precipitates. Photograph, Rachel Armstrong, April 2011.

These formations were considered to behave as a slowly mineralizing artificial tissue system within the cybernetic installation as in Fig. 8.10.[48] The modified Bütschli droplets responded to physical changes in the environment through subtle changes in the speed of crystal growth that were influenced by movement and heat produced by the mechanical cybernetic matrix.

The Incubator Flasks were prepared for the Hylozoic Ground installation by hand as a series of 20 round-bottomed flasks, each of which housed an individually modified version of the Bütschli system. They were suspended in specially designed holders within the Hylozoic Ground matrix by Beesley’s team (see Fig. 8.11).

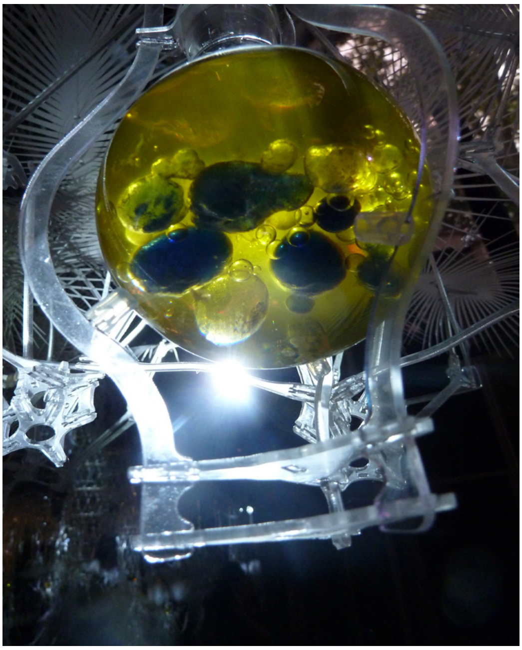

Figure 8.10: Modified Bütschli droplets respond to environmental conditions in flasks that are open to the air. Incubator Flasks were suspended in the Hylozoic Ground matrix and positioned over LEDs to capture heat and light emitted by the activated cybernetic matrix. Photograph, Rachel Armstrong, April 2011.

Other collaborators included chemist Martin Hanczyc from the University of Southern

48 Vesicle-based, artificial tissue systems have been described in Gabriel Villar’s work on printing with microscale abiotic vesicles (University of Oxford, 2013).

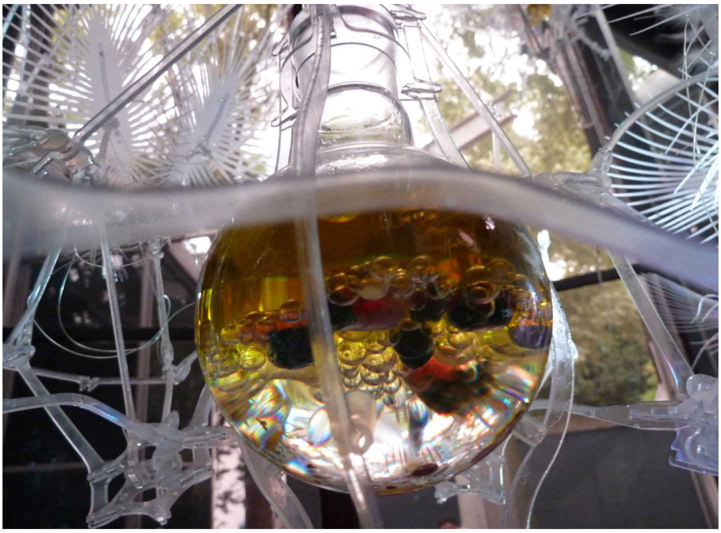

Figure 8.11: The selection of a range of mineral solutions, such as soluble nickel and iron salts, may cause a range of brightly coloured precipitates to be formed. Modified Bütschli droplets with mineral metabolisms gradually produce internal crystalline structures at the oil/water interface, as miniature crystal gardens (Glauber, 1651). Photograph, Rachel Armstrong, April 2011.

Denmark, who was consulted on the chemical design of the Incubator Flasks, and Explora Biotech, who maintained the chemistry for the installation duration. The Incubator Flasks were integrated into the cybernetic matrix by their positioning over LEDs, which were activated by the mechanical sensors of the cybernetic matrix. Summated activation of the sensory network also produced periodic bursts of movement within the Hylozoic Ground matrix that accelerated and shaped crystal formation within the Bütschli droplets. During the three months of the exhibition, the crystals became more visible within the incubators and their striking appearance drew visitors into the depth of the cybernetic matrix, which activated proximity sensors that were most active when the gallery was busy.

Visitor activity also provoked volleys of movement in the feathery appendages throughout the cybernetic matrix, which stirred up the air in the gallery and circulated the carbon dioxide around the space, which fed the metabolism of the 'Carbon Eater' Flasks. The entangled chemical, mechanical and human actants created a positive feed-forward loop of activity that attracted more visitors into the cybernetic matrix, which further stimulated the behaviour of actants and fed the Hylozoic Ground's metabolism.

8.4.2 ‘Carbon Eater’ Flasks with Carbon-fixing Oil Droplets or ‘Protopearls’

The ‘Carbon Eater’ Flasks were designed to produce artificial shell-like structures that could be built from resources in their immediate environment such as dissolved carbon dioxide and minerals (see Fig. 8.12).

An oil droplet within an aqueous phase was chosen to keep the system materially open so that, as a universal solvent, it could continue to harvest water-soluble resources. Oil droplets in aqueous media have been demonstrated as an effective distribution platform for a metabolism and under the right conditions they may also exhibit lifelike properties such as self-propulsion and chemotaxis (Hanczyc et al, 2007; Toyota et al, 2009). An oil droplet system was considered a suitable technology that would detect and respond to changes in the gallery environment such as carbon dioxide concentrations. This respiratory gas is of particular architectural and cultural importance as it is an indicator of life, being exhaled by gallery visitors, and is also of global and environmental significance as a ‘greenhouse gas’ (GHG), which is released into the atmosphere from other sources, such as the burning of fossil fuels within the city. Venice lagoon water was chosen as the aqueous medium for the oil droplets,

Figure 8.12: This protopearl flask is suspended in the Hylozoic Ground matrix, where airflow is augmented through the system by feathery actuators. As the flasks are open to the air, a profuse copper carbonate precipitate is produced, which has formed a green ring-like structure at the base of the flask. Photograph, Rachel Armstrong, July 2010.

which is extremely poor quality and highly saline (3.5%) so it is rich with substances that could be used by the metabolizing droplet technology. The lagoon's water quality is affected by many factors, such as high population density, reduced exchanges with the sea, accumulation of nutrients from its drainage basin, exploitation of its natural resources (Facca et al, 2011) and effluent. Indeed, Venice has never maintained a main sewage system and the urban effluent, run-off from agriculture and industry discharges feed into the lagoon (Fletcher, da Mosto and Spencer, 2005). DEPP was chosen as the oil carrier system for the Carbon Eater metabolism, which is not vigorous or lifelike in the way that other oil/water systems are (Hanczyc et al, 2007; Toyota et al, 2009) but possess dynamic physical properties that provide a lively gallery performance. DEPP is heavier than water with a specific gravity of 1.1 that is temperature sensitive, so it exhibits a range of behaviours in aqueous environments. Below 25°C, the droplets sink in the flasks and form spheres, while at higher temperatures DEPP droplets rise to the surface and spread out like plates.

Magnesium and calcium (Anthoni, 2006) were used as metabolic agents as they reflected the natural preponderance of mineral species in the Venetian lagoon water, which form white precipitates in the presence of dissolved carbon dioxide (see Fig. 8.13).

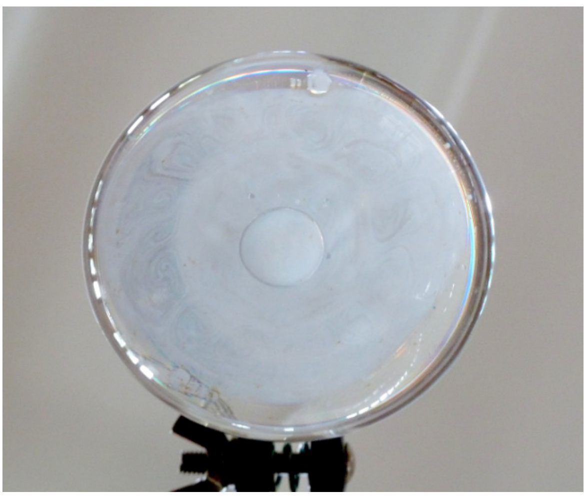

Figure 8.13: Calcium carbonate-producing protopearls can be seen at the bottom of the round-bottomed flask. Photograph, Rachel Armstrong, July 2010.

Two different species of DEPP droplets were prepared – one with calcium chloride, to produce a white precipitate, and the other with copper II sulphate, which would produce a green precipitate. Since inorganic salts are insoluble in oil, they were manually ground into the DEPP to form a paste. Six 250 ml 'Carbon Eater' Flasks were filled with 200 ml of Venice water. 0.5 g of calcium chloride and 0.5 g of copper II sulphate were separately crushed into a paste of 6 ml of DEPP using a metal spatula. A hand-held pipette was used to draw up 2 ml of the oil mixture at a time, which was dropped into the flask. The droplets sank to the apex of the bulb and within a few minutes precipitation could be seen.

These white and green crystal-coated oil droplets, or protopearls, provided a site for crystal growth throughout the duration of the installation, when minerals in the DEPP droplets and dissolved carbon dioxide from the Venice water reacted to produce insoluble precipitates. The carbonate-coated droplets were extremely robust and would re-form after even vigorous shaking. The oily 'pearl' droplets became opaque at high levels of carbon dioxide and with time, as carbon dioxide from the surrounding atmospheric air dissolved into the flasks. In the same way that the Incubator Flasks were nested within the cybernetic matrix to connect with the activity in the body of the installation, the Carbon Eater Flasks were positioned so that LEDs situated at the bottom of the flasks generated a small amount of heat, which nominally speeded up mineralizing activity within the flask.

The Carbon Eater Flasks were hung using specially designed holders created by Beesley's team, adopting the same approach as for the Incubator Flasks and leaving the vessels open to the air, so that carbon dioxide could diffuse into the Venice water to replete the carbon dioxide necessary for carbonate precipitation. The formation of carbonate could be speeded up by adding 0.02 g of 1,1-dicarbonyl imidazole to the DEPP droplets, which rapidly hydrolysed on contact with water to produce a local concentration of carbon dioxide. High concentrations of local carbon dioxide speeded up the formation of carbonates at the oil/water droplet interface and promoted carbon dioxide uptake in the Venice water. Additionally, very small amounts of soluble copper and calcium ions (0.1 g) added could also speed up carbonate precipitation. These chemical modifications provided a set of technological approaches that enabled Beesley and his team to optimize the performance of the Carbon Eater Flasks as a spontaneous construction process. During the three-month installation the abundance of materials from the air and in solution was reflected in the vigorous production of precipitate. Explora Biotech therefore provided a fresh supply of ingredients on a weekly basis. The ingredients are summarized in Table 8.2.

Carbon Eater droplets could be regarded as ELT that enables designers to begin to influence the carbon cycle (TED blog, 2010) by directing mineral formations in an environmentally responsive manner. However, Carbon Eater droplets do not propose to be a geoengineering-scale intervention that can address the current global crisis of rising levels of the greenhouse gas but suggest that more site-specific and local interventions are possible in an architectural context. Although the quantitative value

Table 8.2: Carbon Eater preparation for a 250 ml flask

Chemistry	Strength	Amount
Diethyl phthalate	n/a	1 ml
Copper sulphate	Powder	0.5 g
Calcium chloride	Powder	0.5 g
Venetian water	n/a	200 ml

of the possible carbon fixation of the DEPP droplet system was very small (Webster, 2011), the results are qualitatively significant. These models suggest that it may be possible to go beyond the carbon-neutral ideals for the production of architecture and strive for environmentally remedial or synthetic outcomes (Armstrong, 2011c).

The open flow of resources through the Carbon Eater Flasks, which is mediated through Venetian lagoon water, increases the probability of an emergent, self-propagating or even self-regulating material event. Yet, these potential hylozoic activities are not random, nor left to chance, but are midwifed using ELT. To augment the likelihood of hylozoism, the assistance of mechanical apparatuses could be incorporated, which, for example, would act as a 'birthing unit' for the automatic release of metabolic DEPP droplets into the system in response to mechanically sensed parameters, such as light density or carbon dioxide concentrations. Future versions of this installation may be designed to work in concert with human surveillance, such as Explora Biotech's diligent vigilance of the performance of the chemical systems, to develop an assemblage of interacting agents that nurture the site's potency. Resource abundance within Hylozoic Ground was most open and richest where blooms of intense light notionally stimulated the mineralization processes within the Incubator Flasks (see Fig. 8.14).

Also, small plumes of air movement provided a matrix for abundant exchanges of vaporized solutes and particles that were directed around the flasks, which were provoked by gallery visitors moving close to the Incubator and Carbon Eater Flasks and by the vigorous, periodic volleys of the canopy. The shifting of resources around the site through air-cooling, metabolic exchanges (via carbon dioxide and humidity-rich transpired and respired air) and heat (via the LED lights) were designed to provoke mineralization of the Carbon Eater droplets. Indeed, inducing division and fusion in various droplet species (Caschera, Rasmussen and Hanczyc, 2013) may speculatively provoke hylozoic activity. It is also anticipated that the integration of different ELT species with mechanical systems may provide new opportunities to increase the possibility of autopoietic systems in future versions of the Hylozoic Ground installation. Although the organic/mechanical interface is notoriously difficult to design, the potential for notional bidirectional exchange is ever more likely. One of the major challenges in developing biohybrid robots is in creating an interface that

Figure 8.14: An aqueous infrastructure is required for the effective carbon-fixing action of protopearls, which is provided by the open environment of the round-bottomed flasks. Photograph, Rachel Armstrong, July 2010.

allows effective communication between the biological and electronic components. This is inherently difficult because of the ontological differences between the systems, and because the vast majority of cellular signals do not easily translate into digital codes. Conversely, cellular processes usually produce signals that travel too slowly for electrical circuits, and electrical fields have negative effects on many cells, which can lead to cell death (Lee, 2006).

Currently, the engineering practice of microfluidics, which works with the properties of liquids at very small scales, mediates exchanges between mechanical and organic systems. However, since they are shaped by physical principles that are unique to the microscale such as surface tension, energy dissipation and fluidic resistance, these systems are scale-specific. Recently, cells have been genetically engineered to behave in ways by producing digital signals by genetically modifying them to produce modified proteins that release nitrous oxide in response to light (Yarkoni, Donlon and Frankel, 2012). This research suggests that developments in bio/electronic interfaces may present opportunities to increase the material complexity and fertility of future versions of the Hylozoic Ground installation by integrating living and mechanical systems through substrate independent modes of operation that involve the coupling of actants into functional assemblages and point towards possible further developments for the collaboration.

8.4.3 Liesegang Ring Plates: Vertical Diffusion–Precipitation Fields

The ‘Liesegang ring’ plates consisted of a gel-based chemical ‘clock’ that produced brightly coloured mineral patterns with the passage of time. They represented a chemical archive of material change within the installation over the duration of the exhibition and exhibited the qualities of vibrant matter (slowness, porosity, inorganic sympathy) (Bennett, 2011). The diffusion of the salts through the active alkaline gel constitute slowness, as the reaction takes place under the actions of gravity and propagate at a rate of about a millimetre per day. Porosity occurs in the fluctuations in the states of the metal ions descending in the gels between precipitate and solution, and inorganic sympathy takes place when the system reaches equilibrium as the banding patterns reach the lower portion of the plates, where there is no further active gel substrate to encourage the oscillations between solid and liquid forms. The Liesegang ring plates provide a counterpoint to the rapid vigorous, sporadic behaviour of the mechanical, cybernetic system and work along a similar timescale to geological processes, with similarities to the processes that produce banding structures in the mineral agate. The evolving traces in the plates marked a baseline indicator of the dynamic chemical and physical forces at work in the installation, which gradually decay towards equilibrium as – unlike the Carbon Eater Flasks – they are sealed and not replenished.

The Liesegang ring plates were designed as a modification of a self-organizing chemical process that produces periodic precipitates in an active gel medium. Liesegang first described this phenomenon when he was preparing photographic plates using silver nitrate and potassium dichromate and documented the spontaneous formation of ring-like patterns (Liesegang, 1869). Rather than simply creating a light-sensitive field, these salts had produced their own patterning system in the absence of light. Liesegang and Runge (Runge, 1850) further characterized the phenomenon as occurring when interacting ion species that produce density fluctuations in weakly soluble salts are separated through a matrix. The principles of pattern formation are based on the interactions between different types of salt as they exchange ion species and periodically form precipitates (sparingly soluble salts) and solutions (strongly soluble salts). Liesegang rings also form naturally in various rock types (Heaney and Davis, 1995) when minerals diffuse through gel-like mud, or fossilizing flesh, and are shaped by geological forces. They can be induced in a laboratory setting by impregnating a watery gel with a soluble salt species and diffusing another salt species into an alkaline matrix to produce slowly forming precipitates that (re)dissolve in keeping with the periodic fluctuations of chemical species in the system. Under the influence of gravity and diffusion, the spatial distribution of the resultant weakly and strongly soluble salt species appears as rhythmic bands or rings (see Fig. 8.15).

The Liesegang ring plates constructed for Hylozoic Ground were formed from a series of two sets of leaf-shaped perspex plates that were mounted in floret formation. Each unit consisted of two parallel plates that were fixed with a polymer at a uniform distance of 0.5 cm. The apex of the plate was left open for the introduction of solutions. Eight units were prepared in total, and were left to dry thoroughly before the addition of the active gel matrix. This was prepared using 400 ml of agarose gel made up to a concentration of 2% by weight and stirred over a hot plate at 70°C in a fume cupboard in Explora Biotech's laboratory in Marghera, in an industrial park just north of Venice

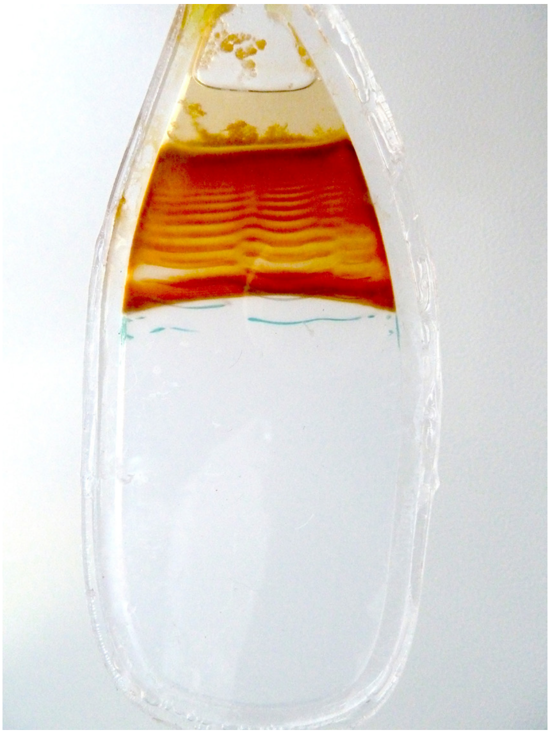

Figure 8.15: Liesegang ring plates were constructed from two perspex plates separated by a 0.5 cm gap sealed with silicone. Alkalinised agarose at 2% v/v was introduced into an apical gap in the plate system and allowed to cool for an hour. A solution of iron II, iron III and copper II salts was introduced into the apical reservoir. Within a few hours, precipitates could be seen moving through the plates, and produced striking banding patterns that continued to evolve over the duration of the three-month installation. Photograph, Rachel Armstrong, July 2010.

on the mainland. 20 ml of 1 M ammonium hydroxide was added and vigorously stirred into the gel so that the salt was evenly mixed. This solution was then carefully pipetted by hand into the gap between the fixed perspex plate pairs at 50 ml aliquots.

Great care was taken to avoid bubble formation in the matrix of the rapidly cooling gel and a space for 10 ml of fluid was left at the top each plate. The prepared plates were then carefully transported back to the Canadian pavilion. In the gallery, holders created by Beesley's team secured the plates vertically, in floret formation. When the plates were secured, 4 ml of 1 M copper II sulphate solution, 2 ml of 1 M iron II chloride solution and 2 ml of 2 M iron III chloride solution were added to the 10 ml reservoir at the apex of the units. The preparation is summarized in Table 8.3.

These solutions provided a supply of competing ion species that diffused through the gel under the influence of gravity. The plates were permanently sealed to avoid contamination or spillage. Over the course of the installation, the Liesegang ring plates produced clearly visible, brightly coloured, unique, evolving banding

Table 8.3: Liesegang ring plates: Evolving diffusion–precipitation reactions

Chemistry	Strength	Amount (per component)
Agarose gel	2%	50 ml
Copper II sulphate	1 M	4 ml
Ammonium hydroxide	1 M	10 ml
Iron II chloride	1 M	2 ml
Iron III chloride	2 M	2 ml

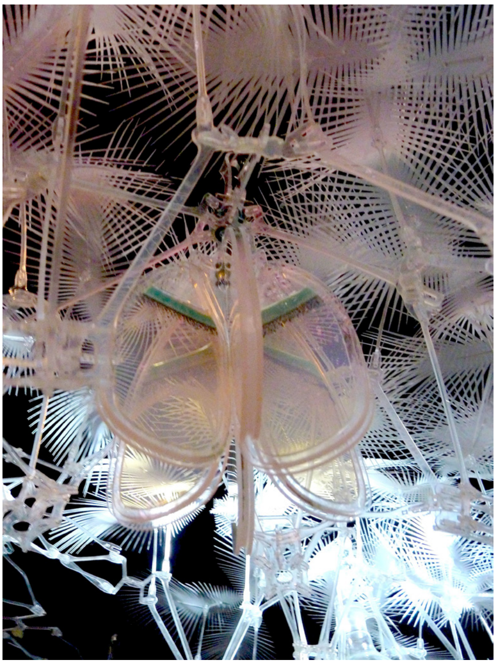

Figure 8.16: Clusters of vertically mounted Liesegang ring plates were introduced as a time-based chemical system in the Hylozoic Ground matrix, like the bark of a tree. Photograph, Rachel Armstrong, July 2010.

patterns that continued to develop and separate for the duration of the exhibition (see Figs. 8.16 and 8.17).

Owing to the robust integrity of the sealant, only a few of the plates started to dry out in the last week of the Biennale. None of the plates succumbed to bacterial or fungal colonization and they required no maintenance. Yet, the Liesegang ring plates had reached equilibrium by the close of the Biennale.

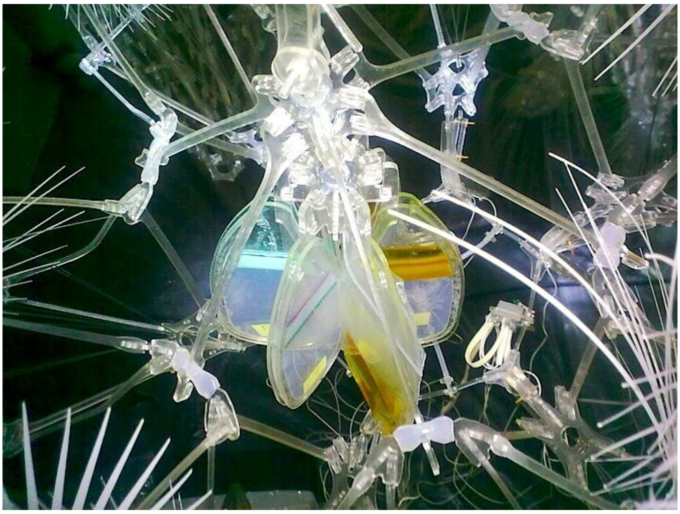

Figure 8.17: Liesegang ring plates are entangled in the Hylozoic Ground matrix as a sealed time-based organ system. Photograph, Rachel Armstrong, July 2010.

8.4.4 Hygroscopic Islands

The ‘Hygroscopic Islands’ were an arrangement of thousands of semi-permeable, latex vessels that contained hygroscopic salts (such as calcium chloride), desiccated organic matter (like dried lavender and herbs) and concentrated salt solutions (such as soy), and exhibited the qualities of vibrant matter (slowness, porosity, inorganic sympathy) (Bennett, 2011) (see Fig. 8.18).

As attractors, the hygroscopic materials worked slowly, since they relied on diffusion and the active stirring of water vapour in the gallery by the action of visitors and the mechanical volleys of the matrix. Their interactions with water were loose and, therefore, showed porosity as they associated and disassociated with water molecules as the humidity and temperature of the gallery changed. They did not reach equilibrium, as their affinity with water is entirely reversible and so they were continually able to make associations and disassociation with water molecules depending on the ambient humidity. Hygroscopic Islands exhibited strong inorganic sympathy (Bennett, 2011), as their actions in forming associations with water were weak, but when viewed as an assemblage of thousands of hygroscopic bodies, this lively force could be regarded as being much stronger. The hygroscopic materials were suspended from the cybernetic canopy in bunches, which hung low into the matrix of the gallery space. Hygroscopic Islands were strategically positioned to act as water-organizing systems that facilitated the movement and distribution of fluid between the chemically active flasks (see Fig. 8.19).

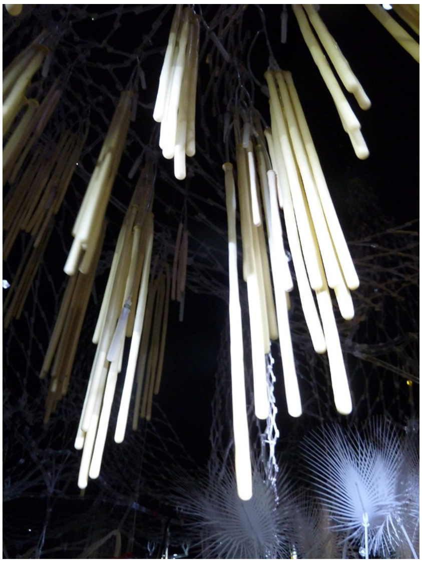

Figure 8.18: Hygroscopic Islands attract water vapour into their substance through their porous latex container and invite the presence of a primitive circulatory system within the gallery space. They may be notionally likened to a lymphatic organ that distributes nutrients throughout living tissues. Photograph, Rachel Armstrong, July 2010.

Figure 8.19: The combined weak water-transferring interactions of Hygroscopic Islands are amplified through assemblage formation. They provide a 'wet' infrastructure through which material transfer between sites may be possible. Photograph, Rachel Armstrong, July 2010.

These formations propose that active, diffusively distributed, material operations could meaningfully facilitate flow and resource exchanges within a technologically mediated site and are consistent with the conception of a cybernetic ‘soil’. Further research and development of these ideas based on interacting assemblages of chemical systems may lead to a greater understanding of how self-regulatory, potentially hylozoic systems could deal with notions of resource abundance, material transformation and autopoiesis within architectural design practice through the construction of synthetic soils.

8.5 Modifications of the Hylozoic Ground Chemistries

The Hylozoic Ground chemistries established design principles for ways of working with lively substrates as sets of actants and assemblages in an architectural design context that were transferable to other contexts. Two particular modifications of interest are the ‘hygroscopic preparation’ and the ‘BIO-FICTION installation’, since they establish additional properties of chemical technologies that demonstrate their innate flexibility and are relevant to architectural design.

8.5.1 Hygroscopic Preparation

The modified Bütschli system led to requests from architectural students to repeat the formula in different settings, such as the Gallatin School NYU, School of Architecture at the University of Nottingham, and the Bartlett at UCL. Other events such as Secret Cinema,[49] the ArtScience Prize themed on synthetic biology at the Silk Mill, Derby (UK ArtScience Prize, 2013) and Glenfiddich Pioneers (Future Laboratory, 2010)[50] requested demonstrations of the self-organizing principles of the Bütschli system. Owing to the difficulty of sourcing some of the chemicals without the assistance of a chemistry department, alternative preparations were developed to embody the dynamic qualities of the system and develop ideas that explored the principles associated with living systems.

49 “I would like to acknowledge Liam Young and Kate Davies in connecting me with the Secret Cinema event that presented Ridley Scott’s Prometheus in Euston, London, throughout June 2012, transforming a vast abandoned warehouse into the Brave New Ventures/Weyland Industries embarkation terminal and spacecraft, which was staffed by actors (Secret Cinema, 2012). Within the makeshift spacecraft, rooms were dressed as science laboratories and briefed to conduct experiments that searched for unusual life forms. I was invited to demonstrate my work in this context, participating with the general public and demonstrating the living qualities of chemistry, for which I used a hygroscopic preparation.
50 This event enabled participants to produce ‘self-evolving’ 3D paintings using olive oil, glycerine and food dyes as a visual counterpoint to the art and science of mixology.

The hygroscopic preparation of a species of ELT was prepared to visualize the dynamic properties of water and the materials that are invigorated by it. Hygroscopic materials exhibit a powerful affinity for water and their dynamics operate on a much faster timescale than the modified Bütschli system in the Incubator Flasks. Although this system was unsuitable for a three-month installation, as it reaches equilibrium quickly, it is a lively demonstration formula (see Figs. 8.20 and 8.21).

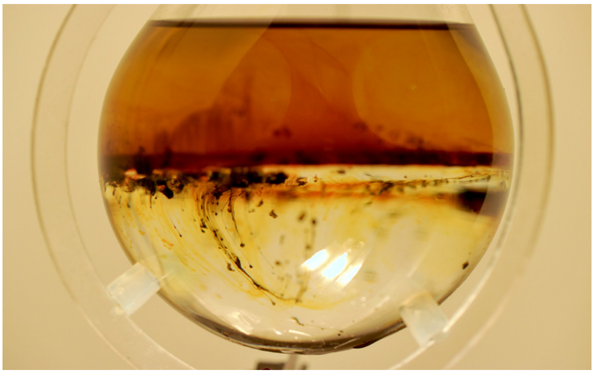

Figure 8.20: This chemistry demonstrator shows how some matter seeks out water – even when it is not 'alive'. This system was originally designed for Philip Beesley in Mexico City as part of the Hylozoic Ground chemistry series. Photograph, Philip Beesley Architect, March 2010.

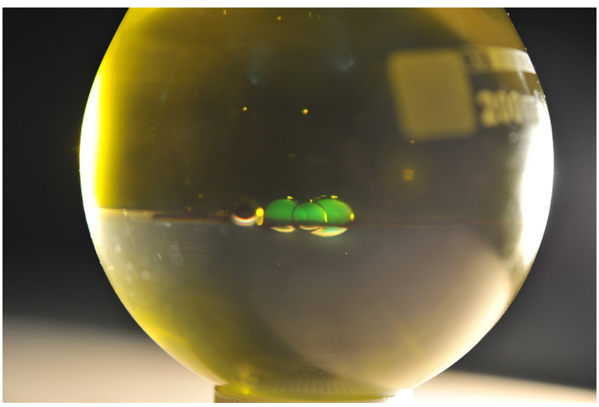

Figure 8.21: Droplets of strong salt solutions are pulled down into hygroscopic glycerol leaving a trail of solutes behind. This graphically portrays the 'battle' for water between different chemistries. Photograph, Philip Beesley Architect, March 2010.

The hygroscopic metabolism was designed to work safely with readily available household ingredients that may be purchased from grocery stores, local pharmacies and supermarkets. Hygroscopic materials may be prepared in an unpatterned 250 ml tumbler, with a base layer of glycerol, which is a viscous, hygroscopic, clear liquid. It has three hydroxyl groups that are responsible for its solubility in water and its hygroscopic nature. It is popularly used as a base for cough medicines and also as a laxative. 100 ml glycerol was poured into the tumbler to the halfway mark and 100 ml of olive oil was then layered carefully on top using a disposable pipette. Careful addition of the oil could also be achieved by pouring it over the back of a tablespoon and running the olive oil down the side of the glass to avoid mixing of the fluids which, once combined, cannot be separated. The droplets were prepared by using the central well of a saucer to contain 2–4 ml of different food colourants. Rock salt, which is weakly hygroscopic (from the traces of other minerals contained in the salt, such as magnesium chloride), was stirred and crushed into the liquid until the mixture was thick and super-saturated. 0.5 ml aliquots of the mixture were then added to the tumbler where they formed droplets at the glycerol/oil interface. The hydrophobic olive oil repels water, so that only aqueous solutions can move downwards in this preparation (see Figs. 8.22–8.25).

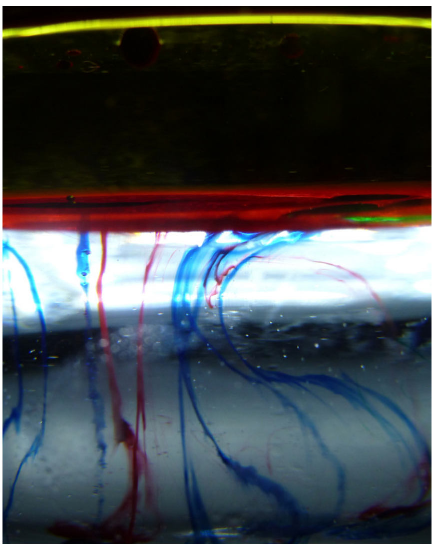

Figure 8.22: This hygroscopic demonstration was prepared for Liam Young’s ‘Contamination’ event for the launch of Ridley Scott’s film *Prometheus* at a premiere event organized by Secret Cinema in London. Photograph, Rachel Armstrong, June 2012.

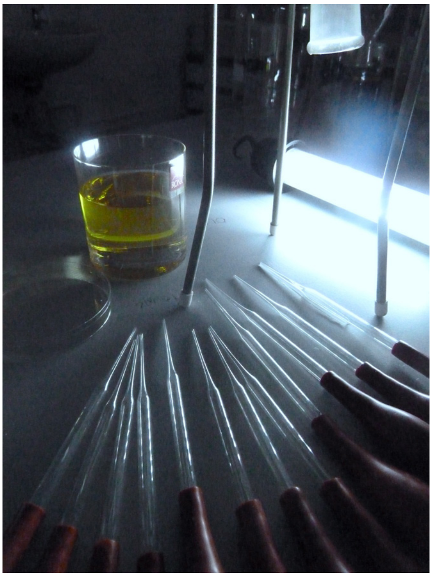

Figure 8.23: Laboratory bench equipment needed to prepare a hygroscopic demonstration of dynamic chemistries. Photograph, Rachel Armstrong, June 2012.

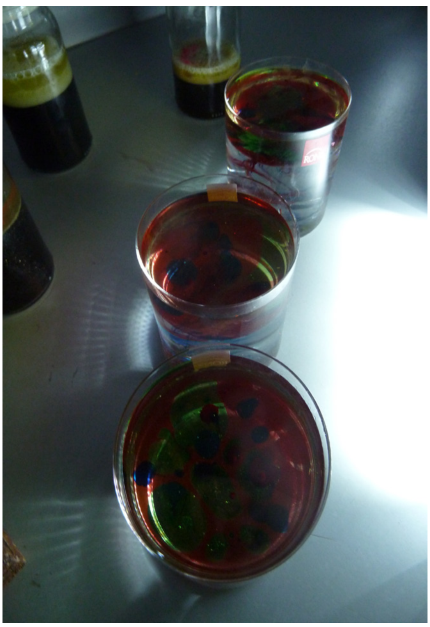

Figure 8.24: Tumblers used by participants to set up their own hygroscopic chemistry preparation. Photograph, Rachel Armstrong, June 2012.

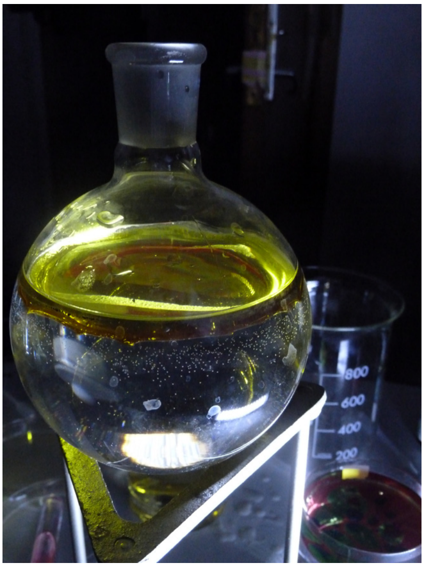

Figure 8.25: Round-bottomed flask set up to demonstrate a hygroscopic chemistry preparation. Photograph, Rachel Armstrong, June 2012.

The ingredients are summarized in Table 8.4.

Table 8.4: Hygroscopic preparation for a 250 ml tumbler

Chemical	Strength	Volume
Glycerine	n/a	100 ml
Olive oil	n/a	100 ml
Food colouring	n/a	1–5 ml of each colour
Table salt	Crystals	2–5 g

A physical/chemical ‘tug of war’ for water ensued between the salty food dye and the glycerol. The more vigorously hygroscopic glycerol associates with the water in the droplets and, when this tipping point is reached, descending, firework-like trails of colour can be seen exploding into the glycerol, as in Fig. 8.26.

This may take between several seconds to several minutes to be reached and this dynamic process can be used to make ‘three-dimensional’, self-evolving ‘paintings’, which speak of the importance of water as an organizing force in material systems and as a necessary precondition for life.

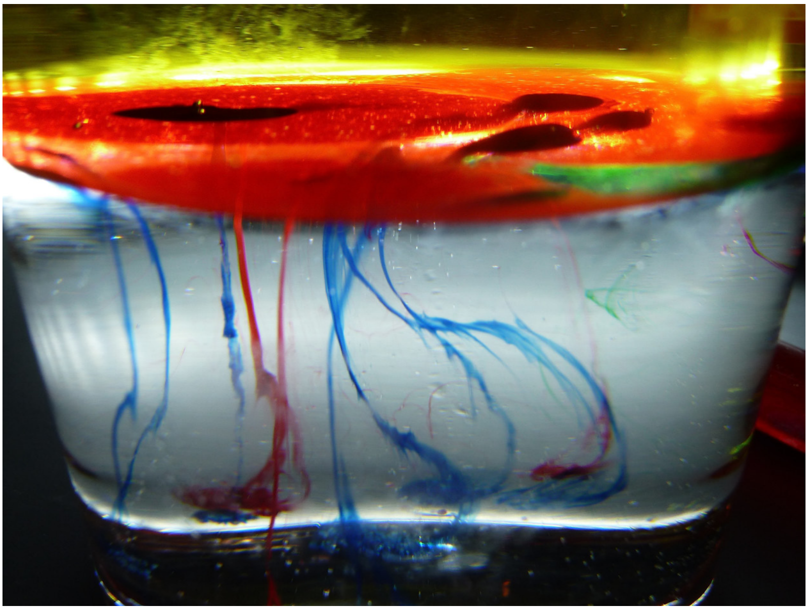

Figure 8.26: Tumbler details showing solute traces in the glycerol base layer. Photograph, Rachel Armstrong, June 2012.

8.5.2 BIO·FICTION Installation

A further modification of the Bütschli system was designed for the Synth-ethic art group show for the BIO·FICTION event at the Natural History Museum, Vienna, May 2011 (Synth-ethic, 2011). The chemical principles were identical to the modified version of the Bütschli system for the Incubator Flasks in the Hylozoic Ground installation. An important modification was made to this system in restricting the space in which self-organization of the droplets could take place. This was limited to a 2 cm gap in the walls between two tanks (one constructed inside the other) and approximates to the average diameter of a modified Bütschli droplet. A lower layer of 20 l of DEPP and an upper layer of 20 l of extra virgin olive oil were carefully constructed so that the two oils did not mix. 200 ml of 3 M sodium hydroxide was then pipetted evenly around the tank in 2 ml aliquots where droplets spontaneously formed at the interface. An additional total of 100 ml of salt solutions were added into the tanks as 2 ml aliquots, which included 1 M solutions of nickel sulphate, copper II sulphate, iron II chloride, cobalt II chloride, calcium chloride and 2 M iron III chloride (see Fig. 8.27).

The recipes are summarized in Table 8.5.

The Bütschli droplets and salt solutions began to reorganize over the course of several hours to produce distinct, banded patterns (see Figs. 8.28 and 8.29). The spatial constraints created the conditions for the production of undulating chemical

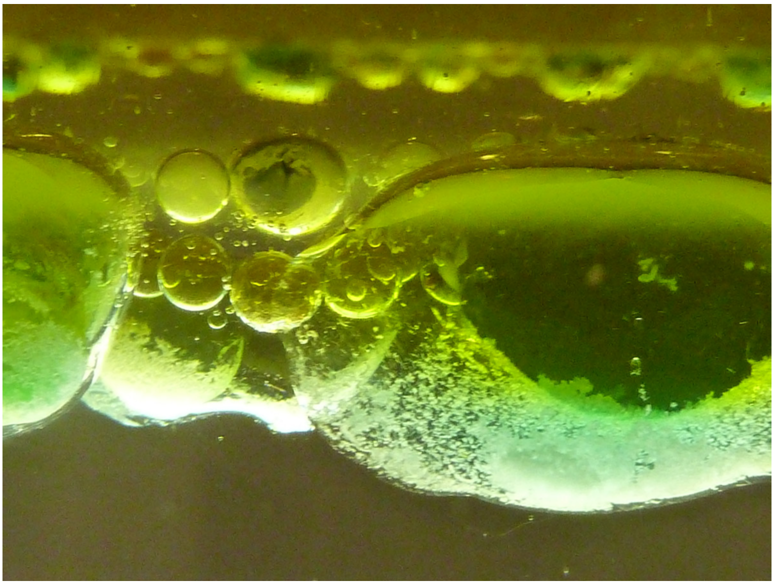

Figure 8.27: Self-organizing modified Bütschli droplets settle at a DEPP/olive oil interface and begin to respond to the introduction of simple salt solutions such as copper II sulphate. The actants are constrained within a narrow space, which reveals their propensity to produce sinusoidal Turing bands. Photograph, Rachel Armstrong, April 2012.

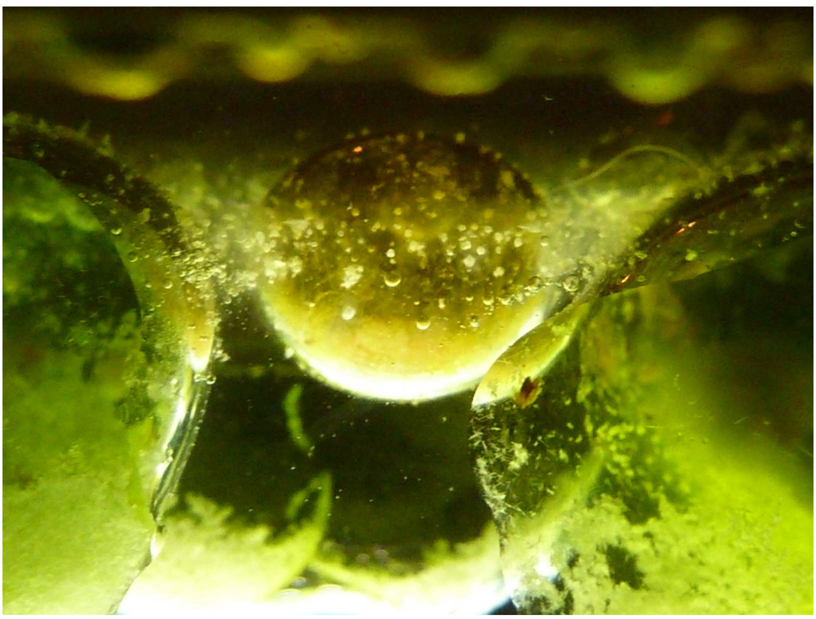

Figure 8.28: Modified Bütschli droplets self-organize within a 2 cm space to produce undulating Turing bands. Photograph, Rachel Armstrong, April 2012.

Figure 8.29: Modified Bütschli droplets self-organize within a 2 cm space to produce undulating Turing bands. Photograph, Rachel Armstrong, April 2012.

Table 8.5: BIO-FICTION installation preparation for a 45,000 ml tank

Chemical	Strength	Amount
Diethyl phthalate	n/a	20,000 ml
Extra virgin olive oil	n/a	20,000 ml
Sodium hydroxide	3 M	200 ml
Iron II chloride	1 M	10 ml
Iron III chloride	2 M	10 ml
Nickel II sulphate	1 M	10 ml
Copper II sulphate	1 M	50 ml
Cobalt II chloride	1 M	10 ml
Calcium chloride	1 M	10 ml

waves as expressions of reaction-diffusion bands. Turing (1952) proposed that such structures could account for patterning in animals, specifically ‘dappling’.[51]

8.6 Design Principles

> *… architecture does not exist without a program, and its presence changes with the differing nature of the programs.* (Tschumi, 2012, p.22)

The modern industrial age is characterized by its use of inert materials that are insensitive to their context or any change in their surroundings. Contemporary architecture also seeks dryness and the conditions in which materials are imagined and designed are optimized for anhydrous environments, yet living systems require water to function and thrive. The various explorations of vibrant matter and different species of ELT within the Hylozoic Ground installation established a set of design principles by which materials that were not compatible with natural systems through a shared chemical language could thrive in aqueous conditions. They demonstrated a series of transferable properties that enabled them to be entangled with other non-equilibrium outputs from different systems, such as airflow in the environment or heat from a light source, and to respond to these new couplings through self-modification and adaptation. In an architectural context, vibrant matter and different species of ELT suggest that it may be possible to design architectures that are able to grow or adapt to their environment. Although traditional techniques can achieve this, such as ivy being trained over frameworks to grow arches, or trees being pleached to build fences, biotechnological advances now enable the modification of living processes at such small scales and with such precision that living systems may be considered as a set of technological species. For example, it is possible to introduce jellyfish genes into pets such as mice, fish and cats so they express a protein that glows under ultraviolet light (Chalfie at al, 1994). Matter has never been so strange or creative. Yet, designers are habituated to working with living systems in such a limited set of circumstances, such as gardening and agriculture, that design practice is mostly imagined through applications of inert materials with predictable properties.

Different species of ELT increase the range of possibilities for a more environmentally contextualized, dynamic design practice by bringing materials which share some of the qualities of living things but do not have the status of being truly ‘alive’ into everyday manufacturing practices and social spaces. Indeed, these kinds of materials

51 Animal markings are explained today in terms of differential expression of genes that are modified by cellular signals and although the process is more complex than Turing reaction-diffusion bands, the principles of organization are still relevant to the pattern-generating process.

are beginning to influence the way cities are imagined and designed. Henk Jonkers at the University of Delft is developing concrete impregnated with bacteria that can survive in alkaline conditions (Jonkers, 2007, pp.195–204) and Elizabeth Demaray paints lichen on to the walls of buildings (Reutgers, 2011), which may help to regulate their temperature; while the engineering company Sustainable Now Technologies is developing an algae bioreactor that houses 1,000 gallons of algae, which can be kept in a garden shed and produce enough biofuel to keep a family car topped up – without needing to visit a fuel station (Sustainable Now Technologies, 2012). Working with vibrant matter and different species of ELT informs a set of principles that could be applied to a whole range of lifelike materials, which may be smart chemistries but they may also be of animal, plant or bacterial origin. These kinds of materials could be used in a range of systems from desalination plants (Bland, 2009) to domestic lighting units (Cha, 2011). Such lifelike systems can be designed from a top-down perspective by modifying an existing system so that it works slightly differently, such as using goats' milk that contains spider protein (National Science Foundation, 2010), while an alternative approach is design from the bottom up and using chemical self-organization to give rise to lifelike phenomena. This method is consistent with Stéphane Leduc's notion of synthetic biology, which he regarded as being an extension of synthetic chemistry (Leduc, 1911, pp.113–121).

Despite 150 years experimenting to produce life in the laboratory, nobody has been able to synthesize life from chemical ingredients (Hanczyc, 2011a). From a technological perspective, being able to work directly with the dynamic processes embodied in living systems is a creative opportunity for designers. Vibrant matter and ELT constitute a non-equilibrium platform in which the variables in dynamic chemical systems can be explored, and require very different approaches to designing a static object that is optimized for equilibrium states. To carefully characterize the system and select the right ingredients it is essential to clearly understand the reason for selecting vibrant matter and the kinds of outcomes that may be anticipated. Although different kinds of ELT present unique sets of challenges in different circumstances, there are general technical considerations to address when working with vibrant matter:

- Born not made (Kelly, 2010): Vibrant matter is a fundamental quality that exists as a function of the primordial laws of the universe and cannot be built into a system or acquired.
- Scale: Vibrant matter works across different scales simultaneously. Materials are more lively and further from equilibrium at the nanoscale owing to the effects of quantum physics. The scale at which design decisions are made influences the choice of materials, tools, contexts and infrastructures to shape the interactions of vibrant matter. Working at the nanoscale is very different to engineering a building (Haldane, 1926; Thompson, 1917, pp.22–77).
- Equilibrium: Vibrant matter exists at far from equilibrium states and resists the decay towards equilibrium (Schrödinger, 1944). This is different to designing with classical materials, which are designed to operate at equilibrium states.

- Metabolism: Vibrant matter evades reaching entropic equilibrium by coupling with other systems to form mutually reinforcing assemblages. The horizontal chemical couplings between assemblages that resist energetic decay may be thought of as 'metabolism'. Principles for designing with metabolisms have not been formalized, although Kauffman's notion of autocatalytic sets where groups of chemistries form closed-loop interactions (Kauffman, 2008, p.55) begin to speak of possible criteria for self-supporting assemblage formation, which might be applied within a design context.
- Simultaneity: Vibrant matter exists both as an object and as a process. It is therefore simultaneously soft (porous) and hard (impermeable) as well as being wet (flow) and dry (static). The intensity between these states and how we perceive them is dependent on time, scale and the nature of the participating assemblages.
- Program: Vibrant matter does not produce straight lines (Hundertwasser, not dated), or exist as expressions of Euclidean geometries. It does not snap to a grid nor respond to an 'undo' function. Instead, vibrant matter exists as creative, constantly forming fields of interactivity that can be combined with one another and cyclically and unevenly bloom and collapse, until they reach entropic equilibrium. These entanglements are capable of acts of radical novelty and may perform completely differently to their original constituents and their interactions may vary spatially and with the passage of time.
- Sustenance: Vibrant matter seeks food and energy sources to resist entropic imperatives and delay reaching equilibrium. The requirements change with time and, as the system develops and grows, so infrastructural concerns are of vital importance for vibrant matter to thrive.
- Mass: Vibrant matter possesses mass and therefore works more slowly than digital computing, which relies on the flow of nearly massless subatomic particles called electrons. However, possessing mass enables vibrant matter to make more interactions simultaneously and it can, therefore, perform parallel computing functions.
- Vectors: Since the chemical functions of vibrant matter are embodied they possess directionality and are ultimately polarized.
- Unpredictability: Complex, embodied materials can surprise designers and may require flexible strategic approaches. Vibrant matter may exert unusual effects that may be observed at the human scale; according to the laws of quantum physics, for example, it may vibrate and not vibrate simultaneously (TED.com, 2011).
- Rhythm: Vibrant matter works possesses a unique periodicity, which depends on its molecular and macroscale interactions. It therefore may perform its operations faster, or slower than natural systems.
- Control: Vibrant matter does not come with a push button and responds to soft (facilitative continual nurturing) rather than hard control systems (energy-

intensive command). It also possesses a chemical 'will' of its own and influences the performance of material systems by acting as a codesigning agency that makes claims within material territories, which challenge past events and resist the limits imposed by other codesigners in the system.

— The Inevitable: Designers need to consider what to do when vibrant matter and different species of ELT reach equilibrium. It is also important to consider what kinds of removal or recycling systems are appropriate for their disposal.

Working with vibrant matter and different species of ELT poses many design challenges so that each system requires special consideration. However, the investment made in using vibrant matter as a design solution enables architects to work directly with the kinds of material transformation that characterize natural systems, so that they can innovate organically. Indeed, ELT suggests that it may be possible to transform our resource-consuming industrial processes into potentially life-giving ecological ones. Further exploration of vibrant matter and its associated technologies and infrastructures in many different contexts may establish parameters for new kinds of design thinking. However, potential applications are more than an academic proposition to make a transition from mechanical to ecological approaches but establish the technological, material and infrastructural conditions that move towards this possibility.

8.7 The importance of Infrastructure

> *… buildings, and even whole cities, have become infrastructural technologies.* (Easterling, 2012)

William Bryant Logan notes that for living systems to dwell on land they had first to develop bodies that 'learned to contain the sea' (Logan, 2007, p.11). The inner seas of organisms are those cellular infrastructures have enabled creatures to develop chemical systems and metabolisms that sustain them in arid conditions. If vibrant architecture is also to thrive, and not only anticipate our physiological challenges but also find ways of working with fluid spatial programs, then buildings may also need to contain the sea. Although water is a significant organizing matrix, other elemental systems such as air, earth and heat may also provide a flow of resources and support for increasingly lifelike material systems (Armstrong, 2012b). The unique role of infrastructures in facilitating new performance standards in vibrant matter and different species of ELT, such as creating new aesthetics and generating diverse material solutions, has been evidenced in the fossil record. For example, rainforest plants blossomed when they were able to solve a water-supply problem that also increased their ability to fix carbon (see Fig. 8.30). This surge of resources enabled non-flowering plants (gymnosperms) to develop into flowering ones (angiosperms) (Field et al, 2011).

Figure 8.30: Water droplets on the narrow, waxy leaves of a pine tree (gymnosperm) after a rainfall in Monte Verita, Switzerland echo the evolutionary transitions of ancestral plants that were able to transport water more effectively, fix carbon and develop sufficient organic complexity to develop flowering reproductive systems. Photograph, Rachel Armstrong, July 2013.

The explorations of vibrant matter and different species of ELT in the Hylozoic Ground installation raise questions about how elemental forces that support lifelike systems may be harnessed in an architectural context. They form an alternative technical system that enables architects to exploit the interstitial condition between the elements that a system is composed of. ELT can process space, events, movement and metabolism and offer a rich, dynamic palette for programmatic and spatial devices. While we may regard the sun, wind, rain and earth as powerful agents that shape our lives in ways that are mostly beyond our control, we have also found ways of manipulating them using infrastructures that convert these unruly forces into a kind of geoengineering-scale[52] form of technology. For example, the construction of canals and irrigation systems have used the power of water to transform the fertility of landscapes and even brought water into our homes (see Fig. 8.31).

52 The Royal Society defines geoengineering as 'the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change' and divides methods into two types: carbon dioxide removal from the atmosphere, and solar radiation management (The Royal Society, 2009).

Figure 8.31: Canal construction was essential to the development of Venice's infrastructure as a means of enabling its communities to populate previously uninhabitable land. Photograph, Rachel Armstrong, August 2012.

While we are not the 'gods' that Stewart Brand suggests,[53] neither are we hapless victims of circumstance. In the Anthropocene, our complex and difficult relationship with the natural world may be strategically managed through the use of technologies that harness elemental systems such as wind, waves and solar energy. Indeed, as we fail to cut emissions, industrial nations are increasingly turning to geoengineering (Hamilton, 2013a) to remedy environmental impacts such as that of China (Hamilton, 2013b). While most geoengineering-scale projects, by definition, have a global-scale impact that stems from top-down centralized strategies, renewable energy systems also draw from the same principles but at the scale of cities. Exactly when a renewable energy solution, such as the massive solar array in Morocco (Hickman, 2011), becomes a geoengineering technology is yet to be established and is indeed a desirable outcome for the solar power industry. Similarly, environmentally responsive vibrant

53 The 1968 Whole Earth Catalog began with the words 'We are as gods and might as well get good at it'. Yet, in his publication 'Whole Earth Discipline' (Brand, 2009), Brand stresses the urgency to get involved with ecosystems engineering despite likely opposition by the environmental movement (Edge, 2009).

matter and different species of ELT may be regarded as manipulating environmental impacts in technologically similar ways to harnessing renewables and reducing carbon dioxide emissions, but take place between the microscale and the human scale. Rather than using centralized forms of technology, their systems are distributed and organized using bottom-up approaches. Through the horizontal coupling of sufficiently expansive assemblages, forged from microscale interactions between dynamic systems and ELTs, environmentally remedial effects may be achieved. While geoengineering practices are defined by their global-scale impacts, the manipulation of elemental infrastructures to shape interactions between assemblages offers a non-equilibrium platform for architects that may help them develop spatial programs that enable transformations in material systems (see Fig. 8.32).

Yet, elemental infrastructures in these systems are not obedient carriers of chemical information, but a context or technology that contributes to structuring systems that interact with environmental conditions, which revises how we may deal with architectural concerns. For example, carbon dioxide may be extracted from the environment using bioprocesses and used to shape the production of microscale crystals in a self-healing system (Jonkers, 2007). Additionally, elemental infrastructures possess multiple properties and therefore offer a range of spatial programs and tactics that can operate within non-equilibrium conditions such as the natural environment. When elemental infrastructures are challenged by complex environmental changes, they can undergo a range of responses that can be witnessed

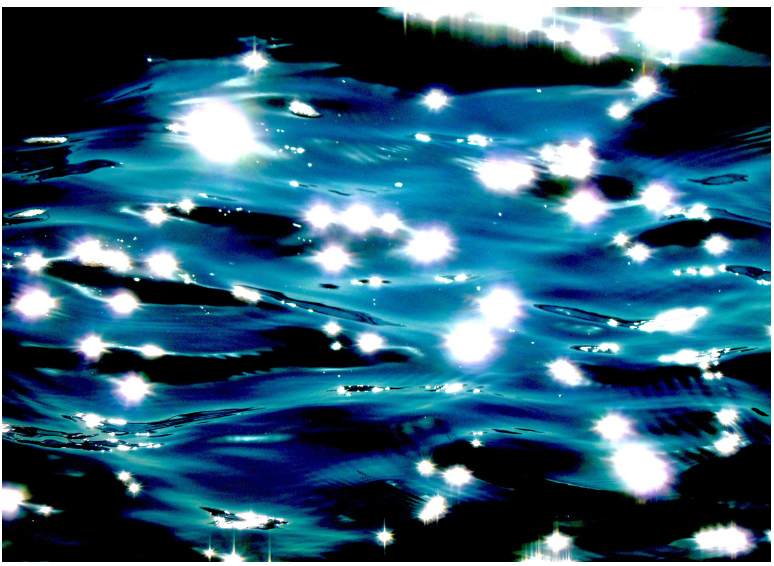

Figure 8.32: Light, carbon dioxide and water provide rich elemental infrastructures in the Venetian lagoon that are transformed into biomass for the rapid seasonal growth of algae blooms. Photograph, Rachel Armstrong, August 2012.

by observing complex events in their matrix, such as collapse, robust adaptation, or phase shifts in their performance. Examples of these have been demonstrated earlier in the Bütschli system where alterations in the chemistry of an olive oil field are brought about by the action of dynamic droplets, which give rise to phase changes in behaviour and morphology (see Fig. 8.33).

These produce local changes that induce an as yet uncharacterized, chemical feedback system, which prompts radical reorganization of droplet behaviour. The points of transition are known as 'tipping points' and are provoked by their contingency so, although they may be anticipated, they cannot be accurately predicted. It is challenging to incorporate these kinds of complex behaviours into conventional architectural design, since vibrant matter and different species of

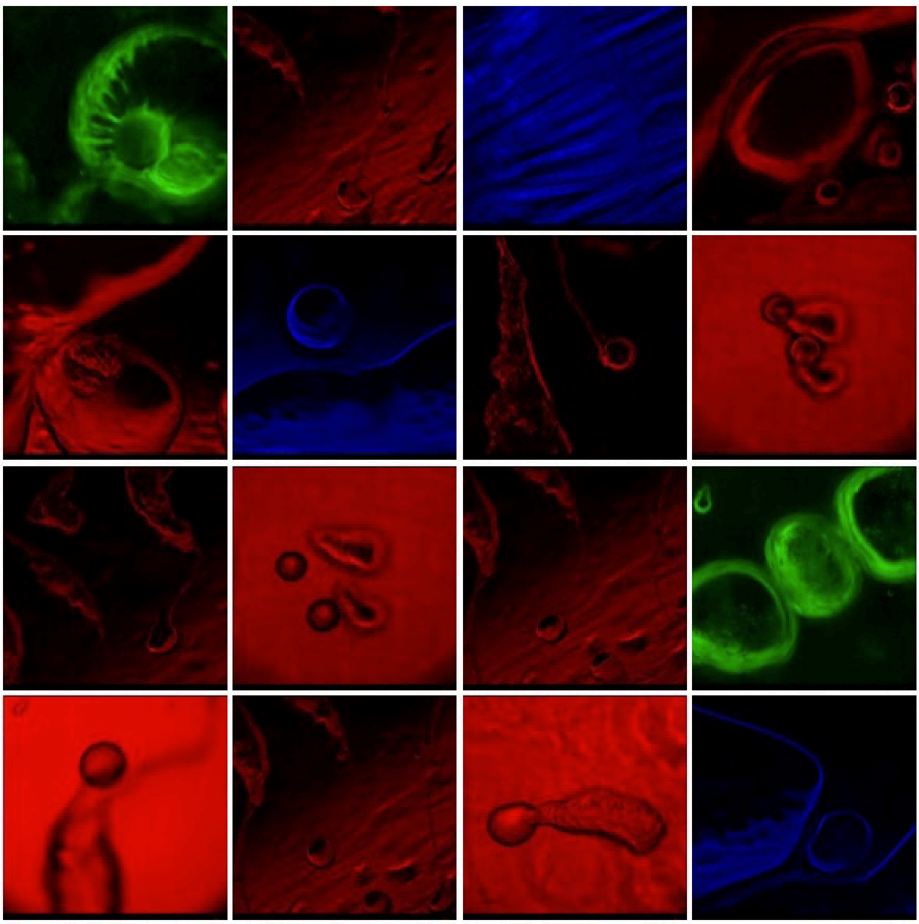

Figure 8.33: Bütschli droplets produce a variety of different outcomes, particularly when they reach a tipping point. Micrographs and collage, magnification 4×, Rachel Armstrong, February 2009.

ELT not only behave according to the laws of complex systems but also operate at multiple scales of order, and the processes that give rise to these transitions have not yet been resolved. Yet the kinds of strategies needed to work with ELT are familiar ones, as they deal with complex, dynamic environments. Gardening and agriculture already enable us to work with complexity and deal with probability. In horticultural practices, agents operate within limits (e.g. crops cannot be guaranteed to produce a certain yield) which are defined by the properties of the agents (e.g. plant species) and their elemental infrastructures (e.g. soil, weather). However, these restraints provoke creativity within the system rather than supress it (e.g. plants may grow shorter, or bloom earlier during drought). It is critical to understand where sites of abundance exist within elemental landscapes as 'life' may thrive in difficult circumstances by finding richness in their surroundings as in the case of troglodytes, hydrothermal vent ecologies and extremophile bacteria. Based on the Bütschli experiments, this quality also appears to be characteristic of lifelike systems where subtle changes in the composition of environment and infrastructure shape their performance. Identifying these subtle cues could provide the opportunity to develop spatial programs and tactics that enable architects to design systems that can provoke or transform events within systems, as well as maintain them. Yet, complex systems are largely conservative despite their revolutionary potential. Philip Ball describes the ordering systems that conserve the behaviour of complex systems, which stem from their elemental infrastructures or Nature's tapestry. He describes these forces in terms of 'shapes' (the subdivision of space) (Ball, 2009c), 'flow' (movement) (Ball, 2009b) and 'branches' (connectivity) (Ball, 2009a), which establish the general behaviour of the systems and may be disrupted when conditions are changed (see Fig. 8.34).

For example, saturated copper II sulphate salt solution will form diamond-shaped crystals under cool, clean conditions (Searle, 2008). However, if the system is encouraged to make new material connections, such as introducing dust into the crystallizing solution, then behaviour occurs that exists within a spectrum of possibility (scientific experiments indicate that the crystal lattice will be disordered under a variety of conditions), yet it is not possible to exactly predict all the variations (Giulietti et al, 1996). So, when a complex system is perturbed in different ways, its apparent 'simple' logic shatters and new patterns burst forth, which sometimes surprise us. Perhaps, then, rather than establishing formal rule sets to govern generalizations in performance, non-linear systems may perhaps be most effectively titrated by adjusting their infrastructures. Indeed, Keller Easterling observes the importance of infrastructure and how this shapes our experiences of architecture:

> *We do not build cities by accumulating singular masterpiece buildings. The constant flow of spatial projects and urban formulas is more infrastructural. Architecture is making the occasional stone in the water. The world is making the water.* (Easterling, 2012)

If the world is making water, then elemental infrastructures quite literally provide a means through which the traditional boundary between landscape and building may

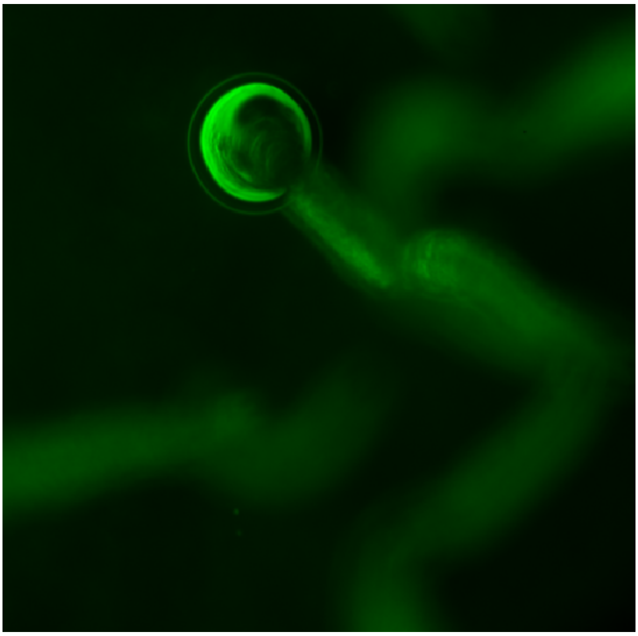

Figure 8.34: Osmotic skin produced by a Bütschli droplet exhibits branching structures that are primordial homologues of 'nature's tapestry' (Ball, 2009a). Micrograph, magnification 4×, Rachel Armstrong, February 2009.

be eroded and shaped by new spatial programs. Elemental infrastructures may serve as a transport medium for substances that permeate the barrier fabric of buildings and open up the possibility of designing in new and surprising places. Rather than buildings being cleaved from their surroundings by brute matter, the spatial programs that shape the non-equilibrium properties of vibrant materials through morphological computing literally bring living processes into building fabrics so they breathe, feel, grow and change with time (see Fig. 8.35).

To enable vibrant matter to thrive in modern buildings, elemental infrastructures will need to be incorporated into their mechanical shells and façades. This is likely to be challenging, as vibrant matter behaves non-linearly and undergoes spontaneous phase transitions (Ulissi, Strano and Braatz, 2013). Yet, the architectural challenge at hand is not for a designer to become an expert physicist, engineer or materials scientist but to set new goals when developing design tactics and spatial programs. Designers may need to consider the sequences of spaces and sequences of events between the participating actants, which may become totally interdependent on each other and fully condition each other's existence. While some interactions may be mutually reinforcing, others may result in conflict when spaces contradict each other's internal logic (Tschumi, 2012, pp.62–63).

Figure 8.35: Reflection of a building in a Venetian canal graphically displays the multiple, complex overlapping spatial programmes of a site, which living systems may respond to. Photograph, Rachel Armstrong, August 2012.

Such possibilities require an inventive use of matter so materials no longer obstruct events but become porous to them. Hundertwasser proposes that buildings are made of windows rather than walls. His ‘Forest Spiral’ (2000) features an uneven grid of more than a thousand windows, none of which are exactly the same (Dannies, not dated:b). This enables ‘porosity’ through self-expression, as well as the permeability of space, where a person can ‘lean out of his window and scrape off the masonry within arm’s reach … [or] … take a long brush and paint everything outside within arm’s reach’ (Hundertwasser, not dated). Infrastructures that facilitate the creative passage of elements, like a brush delivering continual paint strokes of lively matter, may similarly give rise to architectural events that are associated with a material form of creativity and self-expression. For example, spongy material offers a substrate for mineralization as inorganic salts pass through its body, as in Mother Shipton’s cave (Mother Shipton, not dated), where groundwater filtering through limestone-rich bedrock becomes highly saturated with minerals. As the minerals come into contact with dissolved carbon dioxide, they precipitate and produce solid matter within the substance of soft, porous objects, such as John Wayne’s hat and teddy bears (see Fig. 8.36).

These materials not only fix carbon into a solid form and soften the drinking water but also offer a form of construction through an accretion process, which may be translated to architectural practice. Yet the opportunities to manipulate

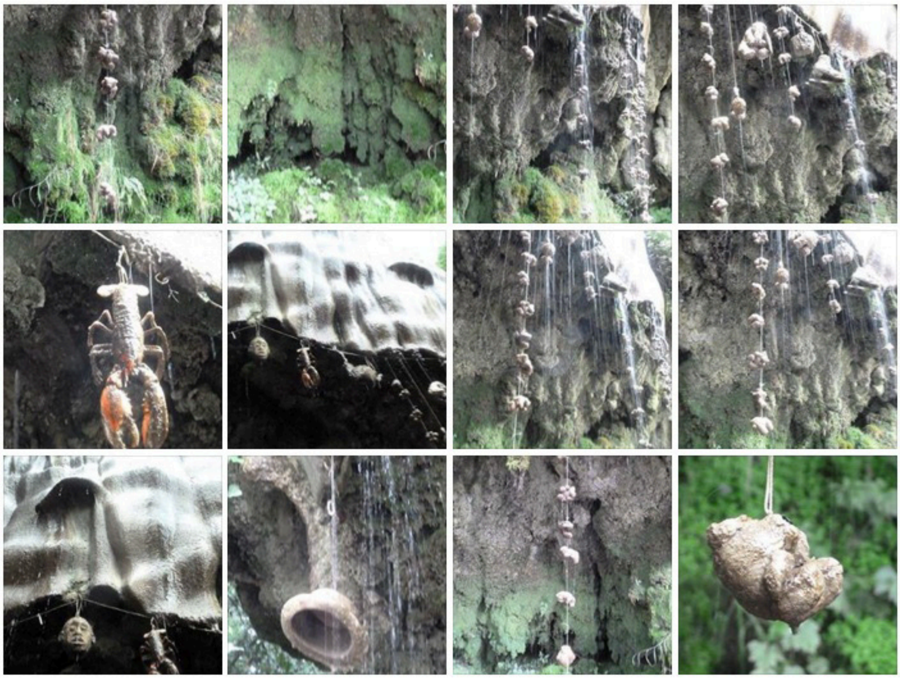

Figure 8.36: Soft objects suspended in the heavily mineralized waters of Mother Shipton's cave in Yorkshire produce a limestone-like crust and become petrified within three to four weeks. Photographs and collage, Rachel Armstrong, July 2012.

elemental infrastructures and a flow of materials through a system in naturalistic ways are limited by the site conditions, infrastructures and technologies that feed and orchestrate these processes. Indeed, if an architectural design practice that incorporates vibrant matter is to be realized, then combined computing and 'printing' platforms that integrate chemical, biological and mechanical systems are a fundamental requirement (University of Southampton, not dated; WETFab, 2011; Armstrong, 2012g; Adams, 2012; Villar, Graham and Bayley, 2013; TED.com, 2013b).

8.8 Infrastructure Experiments

Design-led experiments were conducted to further explore the importance of infrastructure in vibrant matter by applying the Hylozoic Ground chemistries in contents where the flow of material could be facilitated beyond the closed constraints of glassware with restricted access to environmental actants. Potentially, developing a system where semi-permeable materials with leaky, open interfaces, such as gels, paper or foams, could be used, would keep the supply of nutrients flowing. Increasing the porosity of the Hylozoic Ground installation could potentially construct programs for agile architectures that could respond and adapt to changing conditions through processes such as accretion, proliferation, reabsorption and remodelling. Although, for financial and practical reasons, such systems could not be incorporated into the installation in Venice, several experiments were conducted at the FLinT laboratory in Denmark, using self-organizing chemistries. The reaction time of the chemical systems was modified by using porous materials such as gels and tissue paper, which were supported on rigid scaffolding like wire and wood. The permeable materials were selected so that they would change the way that non-equilibrium chemistries interacted with their surroundings so that it might be possible to establish how their dynamic behaviour could be sustained, shaped and manipulated in a design context.

Two preparations were distributed using hand-held syringes over a scaffold framework:

- Liesegang scaffolding preparation: A framework to support an alkali-activated gel was fashioned and reactive salt solutions added to produce bands of precipitating crystals.
- Traube scaffolding preparation: Modified Traube cell chemistry where 1 M copper II sulphate solution was added to 0.1 M potassium hexacyanoferrate in 5% agar.

8.8.1 Liesegang Scaffolding Preparation

A frame was fashioned from wooden sticks with cotton tips, which was fastened using cotton thread to provide a makeshift porous framework to accommodate the gel and solutions.

An agar gel base impregnated with alkali was prepared as a medium for the Liesegang ring reaction by adding 10 ml of a 1 M solution of ammonium hydroxide to 50 ml of a 5% agar gel solution. The wooden–cotton framework was then saturated with the gel using a hand-held syringe. Using a hand-held pipette, solutions of iron (II and III) and copper II salts were carefully dropped on to the agar and the reaction observed over the course of an hour (see Fig. 8.37). The preparation is summarized in Table 8.6.

The makeshift framework attenuated the movement of the agar medium, although insufficiently long enough for the structure to become saturated with the reactive base. Addition of the iron (II and III) and copper II salts therefore produced bright patterns in the gel, although mostly on the base of the structure.

8.8.2 Traube Scaffolding Preparation

Moritz Traube first described the production of ‘artificial plant’ cells in 1867 (Traube, 1867), which were formed by inorganic substances. A Traube cell is an artificial, inorganic model of a cell that is produced by adding a violet-blue, typically diamond-

Table 8.6: Liesegang scaffolding preparation

Chemistry	Strength	Amount (total)
Agar gel	5%	50 ml
Ammonium hydroxide	1 M	10 ml added to agar
Iron II chloride	1 M	2 ml
Iron III chloride	2 M	2 ml
Copper II sulphate	1 M	4 ml

Table 8.7: Traube scaffolding preparation

Chemistry	Strength	Amount (total)
Agar gel	10%	50 ml
Copper II sulphate	1 M	40 ml
Potassium hexacyanoferrate	0.1 M	10 ml

Figure 8.37: Makeshift, porous wood and cotton scaffoldings were constructed and coated with alkaline agar base. Iron (II and III) and copper II salt solutions were dropped on to the gel infrastructure by hand using a disposable pipette. Reactive, brightly coloured patterns within the gel over the course of an hour at the base of the structure, although the distinctive Liesegang bands were not observed in this preparation. Photographs and collage, Rachel Armstrong, February 2010.

shaped crystal of copper II sulphate into a weak (0.08–0.1 M) pale yellow solution of potassium hexacyanoferrate. The ingredients are summarized in Table 8.7.

As the crystal dissolves into the surrounding solution, it produces a brown, semi-permeable membrane of copper hexacyanoferrate. This allows water to enter but not leave the vicinity of the dissolving crystal. The osmotic pressure inside the crystal rapidly builds up and creates a force that ruptures the copper hexacyanoferrate membrane. As the membrane splits, the copper sulphate and potassium hexacyanoferrate solutions mix, forming a new membrane as they come into contact with each other. More water can now enter the repaired interface and the structure swells and extends, until the osmotic force builds up and ruptures it again, transforming the geometric, blue crystal into a sprawling, membranous, seaweed-like mass as shown in Fig. 8.38. This membrane growth and repair process is iteratively repeated and can be seen with the naked eye as jerky growth spurts of the membrane, which can be observed in Movie 8.1 and continue to occur at the microscale (Fig. 8.39) until all the copper ions have been depleted. Typically, a 0.5 cm diameter copper II sulphate crystal may grow up to 4–8 cm within 30 min, after adding it to a field of potassium hexacyanoferrate,

The Traube cell preparation was modified to create conditions in which the osmotic growth phase could be delayed by attenuating the movement of water molecules and copper ions, by adding water-seeking biopolymers. Potassium hexacyanoferrate was added to the agar to make up a 10% solution to provide additional structural integrity for the Traube membrane. The biopolymer would also confer it with an extended osmotic physiology where water movement would take place more slowly. These combined effects were thought to amplify the growth of the chemical cell, as well as enable it to exhibit water-seeking, hydrophilic tendencies. The agar impregnated with potassium hexacyanoferrate was applied using a hand-held syringe on to wire scaffolding and was titrated to produce brown, membranous structures by the addition of 1 M copper II sulphate solution. As the two substances mixed, fibres of gel-expanded membranes self-formed and with care, they could be extended to up to 60 cm under the force of gravity, which can be seen in Fig. 8.40. Gradually, the elongating structures began to dry out owing to evaporation of the water over the large surface area-to-volume ratio of the expanding structures, which made them fragile and prone to fracture.

Simple tests were conducted to further alter the performance of the modified Traube cell preparation by adding cotton thread and fibrous tissue paper to assist in weight bearing as the growing membranes elongated. A wire frame was constructed from materials available in the laboratory and the solutions were added by hand to the framework. The most interesting results were produced when the gel matrix was laid down first, as it attenuated the passage of solutions and changed the temporal and spatial programs of the system, as in the Liesegang ring scaffold experiments. The results of this test can be seen in Fig. 8.41.

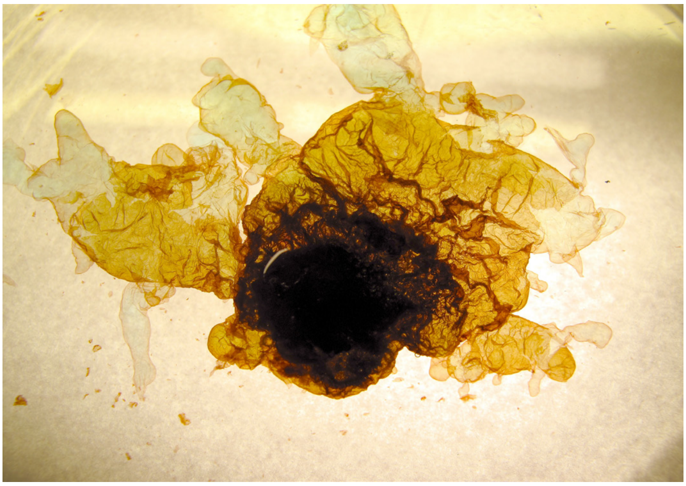

Figure 8.38: ATraube cell membrane is produced when a crystal of blue copper II sulphate is added to a weak solution of potassium hexacyanoferrate. Photograph, courtesy Philip Beesley Architect, February 2010.

Figure 8.39: Osmotic forces rupture the Traube cell membranes that form around the copper II sulphate crystal and immediately heal as the salt solutions come into contact with each other. Micrograph, magnification 40×, Rachel Armstrong, February 2009.

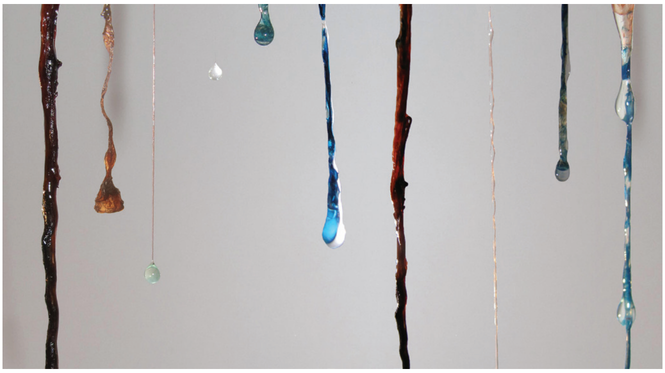

Figure 8.40: Modified Traube cell preparation produces elongated cell membranes that are extended by self-organizing chemical processes working in combination with gravity. Photograph, courtesy Philip Beesley Architect, February 2010.

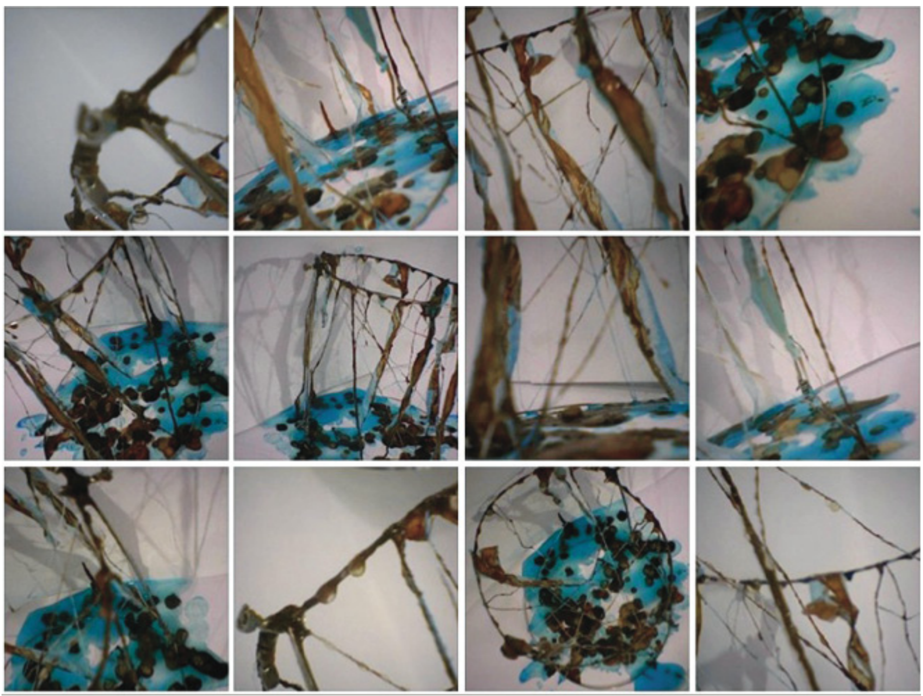

Figure 8.41: Wire and cotton scaffolding draped with porous paper supports a potassium hexacyanoferrate-impregnated gel that responds to copper II sulphate droplets by producing a profuse brown membrane. Photographs and collage, Rachel Armstrong, February 2010.

8.8.3 Scaffold Experiment Observations

These experiments, which were conducted using hand-held distribution systems, reactive chemistries and porous materials (wood, cotton, fibrous tissue paper and agar gel) revealed a number of practical design challenges, namely:

- Lack of readily available infrastructures and tools to assist in dextrously manipulating the outputs of dynamic chemical systems.
- Poor structural integrity of soft, wet systems that required the used of mixed materials and scaffolding for support.
- Inefficient use of materials, since at least one reagent is required in abundance for the system to proliferate.
- Limited precision with available tools.
- Disruption of event sequences through environmental changes, e.g. drying out of elongating structures. However, these experiments were exploratory and suggested modifications could be made to improve the responsiveness and performance of the participating chemistries.
- More rigid biological scaffolding materials could be applied, such as Zbigniew Oksiuta's gelatine 'biospheres' (Oksiuta, 2006). This may further attenuate the passage of solutions through the structure and increase structural integrity. For example, it may be possible to run the experiments for longer and observe the formation of Liesegang bands, which usually begin to appear within an hour, and may continue for many years under the right conditions.
- Humidifying the environment may prevent gels from drying out.
- Development of more specific, robust infrastructures (macrofluidics, porous clays) and computer-aided tools, which may diversify possible design methods.

Complex heterogeneous infrastructures, like soils, may best optimize the performance of dynamic chemistries by engaging with material, parallel programs to produce integrated, heterogeneous fabrics that can simultaneously deal with rigid, semi-rigid, soft and solid materials and systems (Armstrong, 2013a). As Tschumi notes, 'not all architecture is linear, nor is it all made of spatial additions, of detachable parts and clearly defined entities' (Tschumi, 2013, p.63). A fluid system shaped by a non-linear matter and technological physiology creates the conditions for probabilistic spaces that may form and re-form through endless acts of creation and subtraction, such as Darwin's wormstones.[54] Consequently, buildings may be able to respond to the activities of human and non-human inhabitants through growth, extrusions,

54 In his essay on vegetable matter, Charles Darwin noted that the downward movement of rocks was produced by more than the effects of gravity but by the concerted subtractive and additive processes mediated by earthworms who removed soil from under the boulders and transferred it to the surface as worm casts (Darwin, 2007).

reabsorption, fixing carbon or recycling water. These ceaseless material exchanges may ultimately empower inhabitants to sculpt their surroundings as acts of self-expression and according to their needs.

8.9 Hylozoic Ground and the Architectural Transferability of ELT-informed Design Principles

> *… an aesthetic shift must be appreciated: where mechanical joints squeak, molecular chains hum.* (Khan, 2011, p.59)

The Hylozoic Ground chemistries embody an emerging platform whose material and technological systems are intimately coupled, since matter can respond to and act at the molecular scale. They operate as sensitive, responsive membranes that oscillate between cybernetic framework, environment and visitors. These chemistries could simultaneously produce microstructures and formal traces, which documented events within the installation and operated across many scales with a high degree of specificity and environmental sensitivity.

The principles explored in designing the Hylozoic Ground chemistries could be further developed beyond the gallery setting through the production of simple scaffolding systems that opened up the interfaces available for chemical and environmental exchanges. This flexibility and adaptability in the platform suggests that it may be possible to develop more dynamic, ecologically contextualized forms of architectural design practice. Such approaches may work in parallel at multiple scales of operation by deploying unconventional means of constructing space, such as material depositions and metabolisms. Moreover, Hylozoic Ground chemistries are more than materials for the production of an installation but operate as codesigners of systems. Their outputs may be engaged and shaped through unconventional computing techniques that engage with spatial programs and notions of soft control.

As such, the Hylozoic Ground chemistries are not deterministic agents, but exhibit a degree of unpredictability that can be defined within site- and context-specific limits. Although playful and ephemeral, the chemical experiments embodied within Hylozoic Ground were not developed in isolation as purely aesthetic practice, but engaged with essential contemporary architectural debates – embodying a way of working, rather than a style (Gage, 2012). Importantly, they decentralize the production of architecture by proposing new ways of making and prototyping (Armstrong, 2012g; Adams, 2012; Graham and Bayley, 2013; TED.com, 2013b), where materials themselves contribute directly to the production process in concert with digital manufacturing platforms – being codesigners, and not simply passive substrates on which to be acted. Yet, vibrant matter possesses different qualities to classical architectural substrates and is optimized for non-equilibrium conditions, so vibrant bodies are soft, fluid and malleable rather than rigid and tensile. Indeed, Nicholas Negroponte proposed that radical responsive architectures[55] needed to be soft (to deform and transform) and cyclic (undergoing continual cycles of construction and deconstruction over their lifetimes) (Negroponte, 1975). Yet, the Bütschli system – and by implication other forms of vibrant matter – are more than soft bodies, but 'wet' technologies that carry their own operational infrastructures (or sea) (Logan, 2007, p.11). Indeed, the Bütschli system can orchestrate detailed interactions within complex, overlapping material systems and fluid programs (see Fig. 8.42), which not only embody material responsiveness but also constitute a material (rather than digital) sensory system.

A new kind of architectural 'body' arises from the interactions between dynamic infrastructures and technologies to facilitate new associations between space and the events within it, by harnessing the lifelike qualities of non-linear, material systems. Such corpulence is not a digital puppet awaiting the translation of commands through multiple software layers, but can directly sense and respond to environmental changes in real time. Such dynamism and responsiveness requires the construction of new kinds of spatial and temporal programs to shape the potency – rather than performance – of vibrant material systems.

Figure 8.42: When a modified preparation of Bütschli droplets is observed within a constrained space and enabled through a fluid infrastructure, the production of Turing bands can be observed. Photographs and collage, Rachel Armstrong, February 2010.

55 Negroponte's notion of 'radical', in this case, is an architecture that can respond to disruptions which are greater than the everyday disturbances in its native system.

In the most basic sense of the word, the Hylozoic Ground chemistries begin to indicate that materials, which might conventionally be regarded as inert, may actually be 'living'.

8.10 Ontological and Epistemological Questions Raised by the Hylozoic Ground Chemistries

> *And all this material is being put through a reduction process that brings it down to the essential, condensed, miniaturised minimum, a process whose limits have yet to be established; just as all existing and possible images are being filed in minute spools of microfilm, while microscopic bobbins of magnetic tape hold all sounds that have ever been and ever can be recorded. What we are planning to build is a centralised archive of humankind, and we are attempting to store it in the smallest possible space, along the lines of the individual memories in our brains.* (Calvino, 2009, p.366)

The ontological and epistemological issues raised by Hylozoic Ground chemistries are shared by the Bütschli droplet system since their outputs are ontologically non-deterministic and therefore exist within a spectrum of degrees of freedom, which poses epistemological challenges for classical pedagogies. This section takes an applied view of using non-classical frameworks to observe the potency of dynamic chemistries, with the intention of providing architects with alternative portfolios of design possibilities that do not constrain the expectations of dynamic chemistries within the lexicon of miniature 'wet' machines.

However, such perspectives pose significant challenges to design and engineering portfolios, as it requires an alternative way of thinking about 'control' where influence in producing outcomes is shared between participating actants. This viewpoint challenges our classical expectations of the material and even natural world, whose identities have been constrained by object definitions within hierarchical orders or existence. For example, a human is considered more 'evolved' than a bacterium, which in turn is considered more sophisticated than a crystal. Indeed, modern anthropocentrism and biocentricity[56] is problematic for the appreciation of lively matter that is not fully 'alive' as it is not recognized by a formal classification system.

In the current age of scientific 'omes'[57] perhaps there is a need to bring forth a 'ge-ome'[58] so that it may be possible to apprehend the character of lively inorganic

56 By 'modern biocentricity' I am referring to the western late 20th century focus on the 'gene' in neo-Darwinism, as the primary organizing agent of the natural world – a viewpoint that is not shared by Linnæus (1735), Vernadsky (2007) and Gould (1994) where the role of environment is emphasised.
57 This expression refers to refers to the capacities of chemical systems to act in the course of biological development, such as the genome (genes) and proteome (proteins).
58 Geo, as in 'geological', or possibly mineral-ome.

substances and how they give rise to lifelike structures and behaviours. Yet, 'omes' may be too deterministic and restrictive a concept for dealing with the flexibility of lively systems. For example, there is a significant linguistic challenge in characterizing genes using terms that do not provide an intuitive feel for the character, function or spatiality of the systems or their domains. Although the Human Genome (HUGO) Gene Nomenclature Committee (HGNC) proposes a system for naming unique gene symbols and names – with links to genomic, proteomic and phenotypic information, as well as dedicated gene family pages – the language is aimed at specialists (HGNC, not dated).

For example, the gene for carnitine O-acetyltransferase, situated at location 9q34.1, is represented by its approved symbol 'CRAT'. This does not have any metaphorical connection with other words in the English language and therefore does not convey the character of the substance encoded by the gene, which is an enzyme involved in amino acid (protein) synthesis. Nor does CRAT indicate its 'gene ontology' – 'has no children' (AMiGO, not dated).[59] In dealing with complex, emergent and probabilistic agents it is essential to communicate their potential in meaningful ways. Indeed, to further complexify matters, Eva Jablonka and Marion Lamb propose that evolution is characterized by four dimensions (genetic, epigenetic, behavioural and symbolic) (Jablonka and Lamb, 2006, p.1), which introduces further complexity into the relationships between lively structures, their expression and their trajectories. These multidimensional relationships also challenge classical models of a centralized hierarchy of command proposed by neo-Darwinism (Dawkins, 1979). Kauffman embraces the incalculable nature of matter (Kauffman, 2008, p.126), referring to the potent, emergent space into which substances may bloom by virtue of their own agency as the 'adjacent possible' (Kauffman, 2008, p.100). Perhaps, then, the ontological and epistemological frameworks that deal with probability need not to be closed down with rigid definitions, but remain open so they may couple horizontally with other concepts (see Fig. 8.43).

Yet, without a formal language it becomes impossible to convey the nature of vibrant matter. New forms of classifying probabilistic events will help designers navigate the opportunities implicit in convergent, advanced combined technological platforms in which vibrant matter plays a part. These notations may indicate synergies and connections, rather than differences, and designers may iteratively work between classical and non-classical systems to develop tactics that enable them to navigate

59 'Having no children' in genetic terms implies that there are no other genes that are derived from the particular sequence of interest. 'Children', used metaphorically in this case, is informative and conveys relationships better than the name actually ascribed to the gene sequence itself. Additionally, gene ontologies come with graphical representations of the relationships of the gene of interest to biological process, cellular component and molecular function. Although inventive, these ontologies are difficult for non-experts to understand and navigate the concepts.

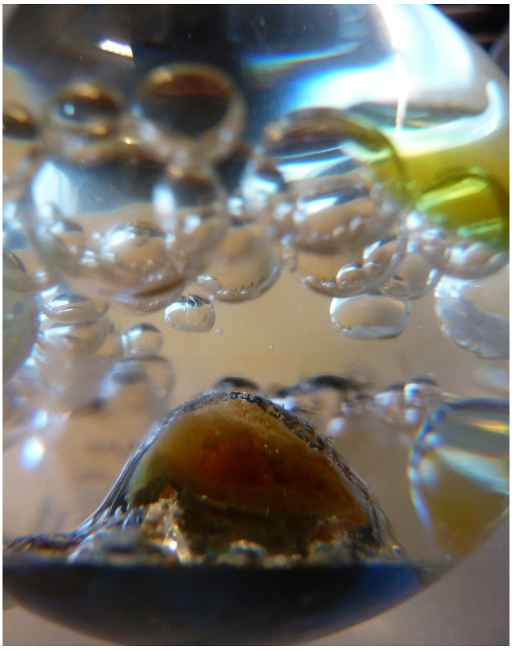

Figure 8.43: Photograph, Rachel Armstrong. August 2012. Since dynamic chemistries are contingent on their environment and are continually processing information, they are challenging to classify on account of their temporal nature and oceanic ontology.

previously unchartered territories. They may, for example, infer synthetic periodic tables of materials with repeating elements or characters, such as Luigi Serafini’s *Codex Serafinianus*, which constructs a whole new set of material taxonomies in a mysterious language reminiscent of alchemical codes (Davis, 1996–2013). Indeed, the practice of alchemy may offer tactics for developing new forms of classification. For example, Spiller describes ‘protocells’ as ‘surrealist technologies of softness, growth, swarm and scaffold’ (Spiller, 2011, p.65) whose various stages and transformations produce ‘taxonomies of form’ (Spiller, 2011, p.65). He proposes that such groupings may be considered as a form of architectural alchemy where one substance is transmuted into another, and becomes an invitation to ‘the architectural observer to read, explore and use’ (Spiller, 2011).

8.11 Summary

The Hylozoic Ground installation collaboration offered a rich and creative engagement with the material possibilities of vibrant matter that went beyond the formalist constraints of mechanical paradigms and bucolic expectations of naturalism. Working with a range of ELT species, it was possible to explore model systems that

could operate differentially within a definable range of variables using morphological computing techniques. Using a range of dynamic chemistries, it was experimentally demonstrated that vibrant matter:
- Possesses agency
- Is programmable using morphological computing techniques
- Exhibits co-authorship in our environments
- Coherently operates across many scales that include the architectural realm

These observations go beyond what was possible to demonstrate in a laboratory setting by providing the additional challenges of context and scale to the various model systems used. These dynamic chemistries forcibly inserted the passage of time as a source of creativity into these systems by working with the idea of material bodies at non-equilibrium states (Prigogine, 1997). When sufficiently supported by open and resource-rich infrastructures, ELT provides new species of materials, tools and approaches, in which vibrant matter may codesign outcomes. The Carbon Eater Flasks, Incubator Flasks, Liesegang ring plates and Hygroscopic Islands exemplify these creative relationships and possibilities.

The multiple activities and relationships embodied in the Hylozoic Ground chemistries created a context within a site that, owing to their innate parallel programming abilities, could provoke multiple juxtapositions, which gave rise to a series of interactions and events, which, in themselves, were contingent on their circumstances and context. Changing the chemical programs within these systems – for example, when carbon dioxide is made available by dissolving into solutions – resulted in the transformation of processes and materials, which were also environmentally responsive. The multiple overlapping of languages, programs and events produced complex fields of interaction, which continually fed back to each other through countless parallel interactions, such as in the continual association and disassociations of water with hygroscopic materials.

These networks could reach tipping points that produced significant structural events, or architectures, which could also be (re)assimilated back into the system; for example, through the production of stripy precipitates in Liesegang ring plates as Turing bands or osmotic structures. Within these probabilistic fields of multi-scalar activity, engaging lively matter as the codesigners of programmatic concepts may shape the production of events. The outputs of these systems reveal new understandings of events through human and non-human agencies. They also question the content of experience, examine the structure of space and explore our intimate relationship with the parallel ecologies in which we are immersed.

Vibrant matter offers a new set of principles for designers that may be transferable to other architectural contexts. However, these exciting investigations need to be characterized in more detail through further experiments, models, prototypes and installations. Yet, the Hylozoic Ground chemistries establish a benchmark that may help to develop further applications of non-linear material programs in a design context, and strongly indicate the possibility of convergent tools and techniques where a range of technological types could potentially be meaningfully entangled in the material realm (WETFab, 2011; Armstrong, 2012g; Adams, 2012; Villar, Graham and Bayley, 2013; TED.com, 2013b). The agency of these assemblages may be shaped by architectural tactics at the human scale to produce post-natural landscapes (Armstrong, 2011a) using soft control systems, which enable architects to influence and suggest effects through creating fertile fabrics that perform probabilistically, rather than command them using deterministic styles and hard control mechanisms. Indeed, our full participation is needed in elevating the status of the material world (Bennett, 2010, p.13) if we are to develop a portfolio of approaches that may establish a different kind of relationship between human development and many different kinds of ecologies.

Kevin Kelly notes that even when it is possible to see the perfect outlines of how an emerging technology such as ELT may be realized, we tend to overestimate how soon it will become available to practitioners. He attributes this delay to the need for other invisible ecologies of co-technologies to exist concurrently. In other words, design possibilities with vibrant matter may only be realized when they are supported by the appropriate infrastructures. In the case of Hylozoic Ground, rich water infrastructures were necessary for the chemistries to blossom, in a similar way to how flowering plants suddenly evolved when they solved a water infrastructure challenge (Field et al, 2011). However, when these technological ecologies finally converge, advances seem to suddenly appear in our lives as if from nowhere, and are received with much surprise and applause for the ‘unexpected’ development (Kelly, 2010). Observing dynamic chemistries through non-classical frameworks opens up the frontier of transformation as being a tangible design strategy where architects may intuitively work with the probabilities within a site without having to be able to fully predict all the possible outcomes. It also requires designers to think differently about how participating agencies in a site may be orchestrated, rather than controlled and to be surprised by unanticipated events provoked by their codesigners. This kind of approach is most appropriate when sites possess many complex, dynamic variables and are likely to face unpredictable challenges, such as intercoastal regions that oscillate between being dried out and flooded.

In the following chapters I will explore how these materials, infrastructures and technologies may be applied in project work, in specific sites, where the application of such interventions may be ecologically and architecturally pertinent.