Part IV

MAKING
LIQUID TECHNOLOGY

This section examines the capacities of liquids to produce work at the cellular and human scale in ways that differ from machines. A range of materials and techniques are discussed that may form a ‘soft’ technological palette and portfolio of effects, which speak to the principles of liquid life.
Engineering Water

My house … is diaphanous, but it is not of glass. It is more of the nature of vapour. Its walls contract and expand as I desire. At times, I draw them close about me like protective armour … But at others, I let the walls of my house blossom out in their own space, which is infinitely extensible. (Bachelard 1992, 51)

Liquids have long been known to possess structure and character, from the turbulent currents that shape the hunting grounds for fishermen, to arched fountain sprays, the bottomless valley of Charybdis and raindrops that bleed onto window panes. As we are not in control of these configurations, we must constantly negotiate our relationship with them.

Since ancient times, we have sought to better understand the elusive, yet mighty forces of the fluid realm. In his treatise Meteorologica, Aristotle describes the principles of hydrologic cycle, where water evaporates by the action of the Sun and forms vapour that condenses as clouds (Koutsoyiannis and Angelakis 2003). From the third century BCE, the invention of hydraulic engineering enabled the dynamics of fluid forces within closed bodies of water to be understood and harnessed. Leonardo da Vinci, who considered water as the driving force of all nature, established the central narratives of modern hydrology that began to reveal the organisational principles through which it could potentially be commanded.

The whole mass of water, in its breadth, depth, and height, is full of innumerable varieties of movements, as is shown on the surface of currents with a moderate degree of turbulence, in which one sees continually gurglings and eddies with various swirls formed by the more turbid water from the bottom as it rises to the surface. (Ball 2009, 10–11)
Da Vinci had witnessed the terrible force of the Arno River ‘devouring’ people, animals, plants, and the ground itself, when its banks burst on 12 January 1466, and again in 1478. Setting out to know his ‘enemy’ through drawings, he showed how the structure of water flowed faster and more linearly in the centre of rivers than around the shallow sides of their banks (Ball 2009, 11), then he designed mechanical systems to control and constrain these forces. Studying the hydra-headed rivulets that writhed through deltas and curling vortices within rivers, he applied this knowledge to link Florence with the sea through a navigable canal. This involved cutting a series of giant steps with locks and siphons to enable ships to sail up into the hills. He also worked on a system of locks and paddlewheels to wash the streets of Milan and even invented a way of cleansing the disease-carrying marshes of the Val di Chiana.

Rather than working through the innate properties of liquids, da Vinci constrained and channelled them through apparatuses, rendering their forces compatible with the logic of machines, through which they could be subordinated to perform simple tasks like turning switches, screws, and gates. This highly effective approach continued to be developed throughout the Enlightenment.
Living Water

Were water actually what hydrologists deem it to be — a chemically inert substance — then a long time ago there would already have been no water and no life on this Earth. I regard water as the blood of the Earth. Its internal process, while not identical to that of our blood, is nonetheless very similar. It is this process that gives water its movement. (Bartholomew 2003, 110)

Viktor Schauberger, like da Vinci before him, observed the way that water moved, as he was interested in better understanding how, through continual movement, water became uniquely lively. Regarding water as a living organism that was conceived deep under the ground in the cool, dark cradle of forests, he imagined its life-giving potency was conferred through the stages of its natural lifecycle. Rising slowly from the aquifers as a juvenile form of pure ground water, it was enriched with mineral impurities and spurted to the surface as a spring. Tumbling through streams and rivers, this ‘living’ water became even more complex and mature, until it eventually joined the sea. Through its various forms — blood, sap, plasma — Schauberger believed that ‘living’ water, was Earth’s lifeblood. Schauberger was particularly interested in the way that ‘living’ water self-regulated its character through lively, corkscrewing, hyperbolic spirals.

With the right lighting, it is possible to see the path of levitational currents as an empty tube within the veil of a waterfall. It is similar to the tunnel in the middle of a circulating vortex of water plunging down a drain, which brings up a gurgling sound. This downwardly-directed whirlpool drags everything with increasing suction with it into the depths. If you can imagine this whirlpool or water cyclone operating vertically, you get the picture of how the levitational current works and you can see how
Believing that the energy and vigour of these dissipative structures could also be weakened by pollution and stasis, Schaubeger produced a number of inventions that sought to counteract the effect of industrial catastrophes on the rivers. Pioneering a scientifically verifiable framework for a study of natural processes, he used simple but effective physical interventions, which were informed by his deep knowledge of the forest and its systems to produce natural turbulence; for example, adding a large boulder strategically in the middle of a river. Technologies like the ‘vortex-generator’ and ‘river generator’ were naturally energetic structures that produced and propagated ‘living’ water anew. These revitalising systems could also perform useful work such as driving propellers and rapidly transporting logs downstream.

Although Schau berger dedicated his entire life to demonstrating how working along with the natural technology of the living world could be applied to everyday challenges, he failed to persuade ‘techno-academic’ scientists that their rationalist approach to natural phenomena, and their domination of them, would result in environmental devastation. Consequently, the principles of ‘living’ water are no longer applied to bodies of water as a revitalising system, or alternative technology. We may wish to revisit these principles and explore more fully their potential.
Rainmaking

Working with water is more than manipulating a material; it requires engagement with all phases of the water cycle, each of which is essential for the farming practices that feed our cities. Summoning the rains is an ancient practice whereby cultures channelled rainfall through rituals, like rain dances. These were succeeded by agrarian technologies that used the formation of artificial waterways, irrigation systems, and aqueducts to help divert the flow of streams and rivers to arable lands. In the modern era, we have learned how to build instruments that can hold back tides, like the MOSE project in Venice (United Nations Office for Disaster Risk Reduction 2012), and even induce strategic downpours. The challenge remains in our expectations of control over them.

The first devices that suggested rain could be ‘made’ were particle detectors. In 1911, Charles Wilson developed a cloud chamber using a sealed container filled with supersaturated water vapour. As cosmic rays moved through the space, they produced paths of ionised matter, around which water droplets condensed, with the appearance of tiny contrails. The droplet-making principles of this apparatus were applied in 2010 as the Teramobile, which is a laser that fires short pulses of infrared laser light into the atmosphere and represents an eco-friendly form of cloud seeding, compared with its chemical forerunners (Teramobile 2008; Harris et al. 2017).

An electromagnetic device to make rainfall was developed by Juan Baigorri Velar in 1938. While the internal workings were kept a secret, it was known that circuit ‘A’ could produce slight drizzles, while circuit ‘B’ generated downpours. Although Velar received international offers to buy his machine, he refused, insisting that the device was designed to serve Argentina’s driest regions. Today, nothing remains of the mysterious machine (Vintini 2013).

The first breakthrough in the technology of chemical cloud seeding took place in 1946 at a General Electric facility in Schen-
nectady, New York, where three researchers, Vincent Schafer, Irving Langmuir and Bernard Vonnegut, established a productive basis for the use of chemicals to initiate chain reactions that crystallised naturally forming ice in the clouds. The dispersants, which originally included silver iodide, potassium iodide, and dry ice, could therefore increase or alter the distribution of natural rainfall. Their work led to the development of further chemical agents that could produce similar strengths of precipitation, such as liquid propane and hygroscopic materials like table salt.

‘Rainmaking’ or weather control can be as powerful a war weapon as the atom bomb, a Nobel prize winning physicist said today Dr. Irving Langmuir, pioneer in ‘rainmaking,’ said the government should seize on the phenomenon of weather control as it did on atomic energy when Albert Einstein told the late President Roosevelt in 1939 of the potential power of an atom-splitting weapon. ‘In the amount of energy liberated, the effect of 30 milligrams of silver iodide under optimum conditions equals that of one atomic bomb …’ (Novak 2011)

With growing interest in weather-manipulating technologies, Wilhelm Reich was asked to intervene in a drought in 1953. Adopting a typically controversial approach, he asserted that drought was the result of build-up of orgone radiation in the atmosphere—a hypothetical, omnipresent libidinal life force, which Reich claimed was responsible for gravity, weather patterns, emotions, and health. His rainmaking device therefore set out to automatically remove excess orgone. This ‘cloudbuster’ was formed from a set of hollow metal tubes that were connected at the back end to a series of flexible metal hoses and placed in water, a medium that would supposedly draw orgone energy to the ground like a lightning rod. The instrument was then aimed into areas of the sky to disperse orgone accumulations. Seemingly, Reich’s apparatus worked and he continued developing orgone accumulators, which attracted the attention of the US Food and Drug Administration (FDA). After one of his
associates violated an injunction to stop him shipping them out of Maine, Reich was sentenced to two years in prison, where he died from a heart attack (Atlas Obscura 2013).

Representing a newfound freedom from nature, rainmaking technologies demonstrated that humans could command the weather and unleash the fury of the tempest. Artificial rainfall was also of interest to military forces as a delivery system for chemical and biological warfare. However, rainmaking technologies cannot be controlled with the precision of machines. Even the most plausible cloud-seeding devices are unreliable, as they are severely challenged by the highly nuanced and unpredictable nature of weather. In fact, the statistical ‘noise’ naturally produced by weather greatly overwhelms the possibility of success of any interventions that are possible with anthropogenic agents. For starters, the stratiform clouds targeted by these technologies are fragile structures, with a poor capacity for precipitation on demand, and most droplets evaporate again before they reach the ground. Importantly, the effects of cloud seeding are contingent upon environmental conditions. For example, hilly terrain that bounds mountainous regions can cause reliable rainfall patterns, while flat agricultural lands are much more mixed in their responses and carry the additional risk of precipitating thunderstorms. Misplaced doses of cloud-seeding chemicals, poorly judged sites of delivery and changing contexts are also likely to result in failure to produce rain. To compound these difficulties, it is currently impossible to digitally model the appropriate parameters for effective micro-casting forecasts. Evaluation difficulties also arise, as existing cloud formations are the targets for the production of rain and it is not possible to distinguish between how much rain would have fallen naturally, or has been induced (Langewiesche 2008). The very nature of rainfall currently exceeds the capacity for modern technologies to constrain it, but in the process of these experiments and explorations, our engagement with hypercomplex systems is improving — but we are certainly not ‘there’ yet.
We conclude that the initiation of large-scale operational weather modification programs would be premature. Many fundamental problems must be answered first … We believe that the patient investigation of atmospheric processes coupled with an exploration of the technical applications may eventually lead to useful weather modification, but we emphasize that the time-scale required for success may be measured in decades. (Novak 2011).
Sonifying Liquid

... molecular evidence linking hippos and whales overwhelms dissenting fossil evidence to the contrary... The biggest problem with thinking of hippos as close relatives of whales is that the oldest hippos are only about twenty million years old, nearly thirty million years younger than the oldest whales, and that body-wise, the similarities are very limited. The long ghost lineage of hippos, between forty-nine and twenty million years ago, implies... that the ancestors of hippos were so unlike modern hippos that we do not recognise them... (Thewissen 2014, 159)

Whales and hippopotamuses not only share a surprising ancestry (Thewissen et al. 2007), they are also peculiarly adapted to aquatic life by using sound to communicate through water. The sounds of baleen whales originate in folds in the larynx, whose vibrations are then transmitted through the ventral grooves before being finally emitted into the water. In toothed whales, the movement of thick membranes called phonic lips is triggered by air that enters the nasal tract. This causes the surrounding tissues to vibrate and produces a sound that passes through the skull to reach the melon, a fatty sound box in the forehead, which modulates and focuses the sound beam in the water. They also listen to their watery world through special structures in their jawbones (National Geographic 2011). In contrast, hippopotamuses can communicate through both air and water, responding to signals in these separate media at the same time. Hippos bellow and grunt, in a manner not dissimilar to whales, where their voices travel through the air and across a fatty layer around their neck into the water. Like other terrestrial mammals that can clearly detect air vibrations, hippos have ears but also use their jaws, like whales, to transmit sounds in the water through their body. These aquatic vibrations travel through their bones and into the middle ear, where they are translated into auditory signals. Hippos, therefore, are immersed within a dual auditory...
realm weaving together the liquid language of their evolutionary ancestors with the rarefied vibrations of the gaseous realm.

We, without listening jaws,\(^1\) may also experience the auditory landscapes of hippos and whales using hydrophones to capture the intensified effects of sound in liquid environments. Packets of sound travel much faster and over longer distances in water than through air, as molecules are much more closely packed together. It is also possible to feel the physical presence of sonic vibrations, which produce a spectrum of real, potentially usable, physical effects.

Although sound waves are influenced by many factors such as salinity, temperature, and pressure, they can be used passively to gather information about an underwater landscape. Listening-only technologies, such as SOund Navigation And Ranging (sonar), detect waves that are travelling through the water and use them to gather spatial information about the environment, which can be used to generate images.

Active processes like echolocation can also be used where shock waves are applied to achieve specific effects. Changes between an emitted and received signal provide directional information about obstacles; or, at higher energies, may even be used to generate forceful impacts. Pulse waves will travel through a medium without causing too much harm until there is a density discontinuity — then, they act like an explosion, ripping matter apart.

Technologies that lock aquatic sound into highly repetitive patterns, perhaps something like cymatics (Jenny 2001, 8), are also possible. These structures are produced by the periodic organisation of standing waves, which can mobilise loosely associated particles — from sand to ferrofluids.

Since the various aspects of these phenomena are due to vibration, we are confronted with a spectrum which reveals a patterned, figurative formation at one pole and kinetic-

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1 Bone conductivity is used to directly stimulate the cochlea using electronic implants in people with sensorineural hearing loss.
dynamic processes at the other, the whole being generated and sustained by its essential periodicity. (Jenny 2001, 11)

‘Bodies’ produced by the oscillations of actively colliding fields set the scene for lifelike events by establishing energy gradients, generating density currents and producing katabatic flows, creating vortices. They may even result in ‘organs [that] are not homogeneous masses, but tissues of the utmost delicacy which go on developing and repeating themselves indefinitely’ (Jenny 2001, 18). Such liquid bodies maintain their structure through the constant flow of energy through their particle systems, which enable them to adapt fluidly with alternations in their environment; namely, the frequency and intensity of vibration. As long as these vibrational energies are sustained, the resultant bodies possess agency and may even be regarded as possessing a ‘life’ of their own. In highly constrained environments, such as the abyss, continuous flow systems may arise as fields of infernal heat from geothermal systems are rapidly cooled in the pressurised, freezing ocean and recursively heated again as they fall. These hypercycles (cyclically linked, self-replicating, metabolic reactions) (Eigen and Schuster 1979) are rich in organic building blocks such as hydrogen, carbon dioxide, and sulfur (Martin and Russell 2007) and are considered as possible sites and apparatuses for the initiating sequence of ‘life’ — through the onset of (liquid) biogenesis.
Glassmaking

A glass-blower, remember, breathes life into a vessel, giving it shape and form and sometimes beauty; but he can, with that same breath, shatter and destroy it. (DuMaurier 2004, 11)

A frozen supercooled liquid, glass is a fluid that has never set, where covalently bonded silica crystals do not take back their original form after melting, but become an amorphous solid. Possessing some of the order of solids, as well as the randomness of a liquid, it remains pliant, and can be shaped by a variety of approaches.

The first forms of glass were naturally sourced as obsidian, which forms during volcanic eruptions when silica in granite or sand becomes molten and which also spontaneously formed in the New Mexico desert sand following the detonation of an atomic bomb prototype in 1945. Glass may have originally been manufactured as a by-product of metalworking, or through developing glazes in ceramic practices. Glazes used for coating stone beads have been discovered that date back to 4000 BCE, and sand casting (pouring molten glass into moulds), may have appeared around 1500 BCE (British Glass Foundation 2013). Glass blowing (using air to expand a ‘gob’ of glass wrapped around an open pipe that is turned to form a range of complex formations) appeared from around the first century BCE, when glass engraving (using tools to mark the surface) also became increasingly common. During the fourteenth to sixteenth centuries CE, glass-cutting techniques were developed to give dazzling finishes to the material and float glass techniques (where molten glass is floated into sheets upon molten metal to produce sheets of glass) were developed in the mid-nineteenth century, which made the industrial manufacturing of glass possible.

Glass became a versatile and inspirational building material for early modernists such as Bruno Taut, who thought it could re-tune Geist (the spirit) and Volk (the mass of humanity). Having already made incredible use of coloured glass, mosaics, glass
paintings, glass bricks, and floors to construct the Glass House pavilion for the German glass industry for the Werkbund (the German Work Federation) exhibition in Cologne in 1914, Taut was inspired to design a new city. Using glass building materials to embody his vision of an intellectual socialist revolution, he positioned a crystalline beacon at its centre to unify people through transcendent notions of the collective good.

The cathedral was the container of all the souls that prayed in this way; and it always remains empty and pure — it is ‘dead’. The ultimate task of architecture is to be quite and absolutely turned away from all daily rituals for all times (Taut 1919, 53–54).

Today, additive manufacturing techniques use cartridges that are heated to 1000°C to develop glassware, which is built up from cooling liquid layers (Temperton 2015). The properties of glass can be altered by a range of additives and finishes, which have been refined during its long history in artisan and industrial practices, which determine the strength, malleability, colour, and physical properties that, in recent times, can now react to light and temperature, conduct electricity, and transmit information (British Glass Foundation 2013).

While glass is well-known for these unique and malleable properties, water can also behave as an amorphous solid although its potential has not been fully explored. Glassy water, or amorphous ice\(^2\), behaves somewhere between (disordered) water and (crystalline) ice. While they do not naturally form on Earth, they constitute the dominant form of water in the universe, occurring most frequently on interstellar dust, comets, Kuiper Belt objects, icy moons (e.g., Europa and Ganymede) and other cosmic structures like Saturn’s rings (Loerting et al. 2015).

\(^2\) Different forms of amorphous ice are distinguished by their densities.
We know a lot about glasses that form from ordinary silicates, sugars and metals … They’re making golf clubs out of glassy metals these days. But how important is the glassy state of water. And what can it tell us about ordinary water, which is such an anomalous liquid? … [Glassy water suggests] a different sort of thermodynamics in water than … in any of these other molecular glass-forming liquids. (Phys.org 2008)

The strangeness of glassy bodies resonates with the peculiar nature of cosmic matter, which becomes complicit with Earth’s laws as soon as it approaches terrestrial environments. Our understanding of what appears to be ordinary matter, like water or glass, may not be at all ‘usual’ within the cosmos but highly localised within the cosmos, where worlds with dynamic liquid infrastructures are extremely different from our own. Owing to our familiarity with the chemistry of our own world, it is generally assumed that only ‘Goldilocks’ planets are capable of bearing life, however alternative life-generating environments may be possible.

The gas giant HD 189733b is 63 light years from Earth. It has a ‘blue marble’ appearance that is thought to be due to its molten glass rain. Since only one side of the planet permanently faces the star, daytime temperatures soar to 930°C and it is rapidly bleeding its atmosphere into the cosmos at a rate of 100–600 million kilograms per second (Poppenhaeger, Schmitt and Wolk 2013).

… the nightmare world of HD 189733b is the killer you never see coming. To the human eye, this far-off planet looks bright blue. But any space traveler confusing it with the friendly skies of Earth would be badly mistaken. The weather on this world is deadly. Its winds blow up to 5,400 mph (2 km/s) at seven times the speed of sound, whipping all would-be travelers in a sickening spiral around the planet. And getting caught in the rain on this planet is more than an inconvenience; it’s death by a thousand cuts. This
scorching alien world possibly rains glass—sideways—in its howling winds. The cobalt blue color comes not from the reflection of a tropical ocean, as on Earth, but rather a hazy, blow-torched atmosphere containing high clouds laced with silicate particles. (Loff 2017)

While the conditions in this world are completely hostile to our carbon-based chemistry, in a liquid world where glass rains from the skies, it might be possible that alien silicon-based chemistry organises in ways that prompt tenacious dissipative structures. Although we are unlikely to test this in any meaningful way soon, this strange planet draws attention to our presumptions about life on Earth that deeply shape our expectations, not just about life on other worlds, but what conditions that are necessary for ‘life’ on our own planet. This will not be life as we know it — but other kinds of infrastructures capable of producing dynamic, persistent liquid bodies.
Liquid Apparatuses

We already have digital computers to process information. Our goal is not to compete with electronic computers or to operate word processors … Our goal is to build a completely new class of computers that can precisely control and manipulate physical matter. Imagine if when you run a set of computations that not only information is processed but physical matter is algorithmically manipulated as well. We have just made this possible at the mesoscale.³ (Katsikis, Cybulski and Prakash 2015; Carey 2015)

To negotiate with the liquid domain, we need to establish how fluids may not only be screens for projecting ideas, substrates to work upon or bodies that can power machines, but also become operational as liquid technology and substrate for analogue computing. Vladimir Lukyanov’s 1936 ‘water computer’ could solve (partial) differential equations to address calculations in geology, thermal physics, metallurgy, and rocket engineering. The computation was performed by translating physical properties into (real) numbers, then titrating fluid displacements within a series of interconnected, water-filled glass tubes and then levelling the parameters through the equalising flow of water under gravity. This hydraulic integrator was used until the 1980s, when personal computing became cheap, configurable, and powerful enough to run complex equations.

Water bodies have also been programmed to generate large-scale spectacles in public spaces such as the Palace of Versailles, the Villa da Pratolino, the Tivoli gardens and the hydraulic gardens of the brothers Salomon and Isaac de Caus. These mechanically enlivened liquid systems deploy the same kind of tactics as da Vinci, where the power of water movement is controlled

³ The experiment explores the capability of synchronous logic-based droplet control to enable algorithmic manipulation of materials at the intersection of computer science and fabrication.
through hydraulically operated circuitry to produce largely pre-
determined effects. These spectacular gardens may also be re-
garded as architectural-scale water computers, whose spectacu-
lar water features demonstrate the dominance of machines over
the natural realm and whose potential for an alternative kind
of liquid technology and performance, remains only partially
explored (Pruned 2012).
Soft Robots

It lumbered slobberingly into sight and gropingly squeezed its gelatinous green immensity through the black doorway into the tainted outside air of that poison city of madness. … The Thing cannot be described—there is no language for such abyssms of shrieking and immemorial lunacy, such eldritch contradictions of all matter, force, and cosmic order. (Lovecraft 2002, 167)

Typically, robotic systems are considered animated machines, where the ‘brute’ mechanical body, often made of steel, or aluminium, is provided with an external energy source. Algorithms that encode pre-programmed motion patterns instruct its tasks from the inside-out, which may be informed by feedback from inbuilt mechanical sensors. By contrast, the responsiveness of living systems comes from the outside-in as embodied intelligence, where soft, elastic, and flexible materials like soft skin, hairs, elastic muscles, tendons, and various fluctuant organs direct the movement of rigid mechanical components. Operations are governed by local reflexes that are modulated by a central ‘brain’.

Two types of applications of liquid technologies are relevant to the emerging field of soft robotics: those systems that are actuated by external liquid pneumatic or hydraulic forces, which engage with the dynamics of non-linear materials, and those whose soft bodies are internally agentised and receptive to external conditions.

Externally powered ‘soft robots’ are actuated by ‘liquid’ forces that work with the plasticity of soft structures, which can adapt and endure complex unstructured environments. Challenges are ‘solved’ both centrally and locally, using the responsive apparatuses of non-linear ‘sensing’ materials, where intelligence is embodied in the structural systems that fine-tune pre-formulated external programs. Delegating task-solving to the periphery of the operational program makes it easier for robots to perform
complex tasks (Iida and Laschi 2011). For example, fabricated transparent, hydrogel-based robots can perform a number of fast, forceful tasks, including kicking a ball underwater, and grabbing and releasing a live fish. Actuated through an assembly of hollow, hydrogel structures that are connected to rubbery tubes, these robots can be inflated into different orientations by the rapid inward movement of water, which enables it to curl up or stretch out (Chu 2017).

Soft bodied robots without internal actuators such as ‘walking’ gels and dynamic droplets (see section 08.13 and chapter 09) are both activated and modulated by their contexts, which enables degrees of ‘soft’ control. The chemical ‘inchworm’ created at the Shuli Hashimoto Applied Physics Laboratory at Waseda University, Tokyo is a colour-changing, ‘walking’ gel. Actuated by a periodic, oscillating Belousov-Zhabotinsky reaction, where the concentration of reagents periodically increases and decreases (Belousov 1959; Zhabotinsky 1964) the polymers in the gel shrink or grow in response to cyclical variations in the presence of ruthenium bipyridine ions. Traction for this movement is gained on a notched surface, so the entire ‘self-organising’ chemical system generates its own control and mechanical signals from within its body operating within environmental constraints (Maeda et al. 2007; Simonite 2009). Modulating the performance of such agentised soft robots can involve fine-tuning environmental conditions. At Brandeis University, researchers have created a gel from a solution of bovine protein tubes and bacterial motor proteins that is capable of spontaneous movement. The gel is activated by mixing it with energy-rich adenosine triphosphate (ATP), which enables the individual tubes and proteins to slide past each other to form patterns or bundles that grow and eventually fall apart in a cyclic fashion. The movement and formation rate of these patterns can be modulated by altering the concentration of ATP while the character of motion is adjusted by changing the number of tubes in the original solution (Yirka 2012).

The control of autonomously agentised systems, or liquid technologies, requires a more detailed engagement with the en-
vironmental design than mechanically operated systems. Life is the ultimate embodied computer where, through various forms of molecular memory (DNA, brain, tissue receptivity), agents can make informed decisions about how to act by comparing internal models of ‘self’ with the actual external conditions.
The future is unknowable, though not unimaginable. Future knowledge cannot be had now, but it can cast its shadow ahead. In each mind, however, the shadow assumes a different shape, hence the divergence of expectations. The formation of expectations is an act of our mind by means of which we try to catch a glimpse of the unknown. Each one of us catches a different glimpse. The wider the range of divergence the greater the possibility that somebody's expectation will turn out to be right. (Lachmann 1977, 59).

Computation is a mode of thinking and practice that enables the world to be sorted, ordered, and valued, so that new knowledge may be acquired. In this book ‘computing’ is considered a way of interrogating the processual building blocks of ‘decision-making’ proposed by Descartes’ ‘rational thought’ — a thing that doubts, understands, affirms, denies, is willing, is unwilling, and also imagines and has sense perceptions. Implementing models of the world, the computing process can be iteratively tested and altered through the recognition of different ‘states’, or stored information/inputs (memory). In particular, computing within the material realm is considered, as it is very different to the symbolic exchanges of digital computers that are encoded into patterns of ones and zeroes (‘bits’).

In a digital computer, binary information (0,1) is grouped into ‘bytes’ (usually eight digits) and moved around into different physical storage areas according to a set of instructions, or algorithm, where they are etched into electronic components, and can collectively perform specific ‘applications’, or ‘apps’ (Epstein 2016). Since massless electrons carry digital information, the speed of calculation is limited by the hardware, and not by information travel speed.

In contrast, natural computing (Denning 2007; Zenil 2013) places matter at the heart of its computational processes and operates through ‘actual’ material paradigms, which explore the
computational strategies and parallel processing abilities of living and dynamic physical systems. This is only possible when matter is at far-from-equilibrium states, where the atomic realm is capable of making decisions and therefore, exerting effects in the world, which are shaped in relation to external events.

The internal agency of atoms (Dyson 1979, 249) responsible for this ‘decision-making’ resides in their structure where, for example, chemical bonds spontaneously associate through weak and strong molecular forces to produce different kinds of molecules. John Dalton symbolically represented the mass of atoms, calculated from the averages of large sample numbers, so they could be theoretically and practically combined in ways to make new substances, or compounds. The computational capacity of the molecular realm reached a new threshold with the advent of supramolecular chemistry, or chemistry ‘beyond the atom’, which is concerned with the use of weak intermolecular interactions to produce different configurations of molecules. Donald J. Cram, Jean-Marie Lehn and Charles J. Pedersen were awarded the 1987 Nobel Prize in this field for developing structural and functional building blocks that could be used to build up larger molecular architectures, so materials could be synthesised, which had not previously existed in the history of the universe (Steed and Atwood 2009).

Alan Turing was interested in how the combinatorial processes that occurred within the natural realm (chemical, physical, developmental, adaptive, evolutionary) could produce morphogenetic forms (Turing 1952). While Turing’s inquiry was mathematically symbolic, he inspired the field of natural computing that is interpreted according to respective interests and existing knowledge sets within a range of overlapping disciplines, and has given rise to a range of derivative practices. For example, morphological computing arises from the field of robotics and engineering, which exploits the physical dynamics of non-linear material systems to perform a computational task (Füchslin et al. 2013); ‘collective computing’ observes how adaptive biological systems solve problems (Sokol 2017a); while unconventional computing aims to enrich, or go beyond, the
standard models of computing such as the Turing machine and von Neumann architectures, which have dominated computer science for more than half a century (Adamatzky et al. 2007). Collectively, these emerging practices are generating new computing systems, which are producing new insights into the nature of the world such as soft robotics (Shepherd et al. 2013), slime mould computing (Adamatzky et al. 2013) and reaction diffusion computing (Adamatzky and De Lacy Costello 2003). Although digital computing plays a critical role in all fields of computing, the analogue modes of advanced computation raise questions about number theory, hardware systems, and appropriate programming languages for working directly with matter. For example, when slime mould ‘computes’, it does not use our number systems.

... biological systems ... are collective ... They are all made up of interacting components with only partly overlapping interests, who are noisy information processors dealing with noisy signals. (Sokol 2017a)

In living systems, material iterations, or oscillations, perform the role of numbers. They are not symbolic gestures but actual: an orbital pathway around the Earth, a pulse, a blink, a footstep, a bowel contraction, the tide, and rain. These iterative, persistent occurrences are not exact, self-similar, regular, or universal, and constitute nature’s ‘beats’. These numerical-equivalent systems are nothing like numbers at all. As Henri Lefebvre notes, the departure point for this history of space is not to be found in the geographical descriptions of natural space, but rather in the study of natural rhythms, and of the modification of those rhythms and their inscription in space by means of human actions, especially work-related actions. It begins, then, with the spatio-temporal rhythms of nature as transformed by a social practice. (Lefebvre 1991, 117)
Simultaneously fields and particles, atoms, and molecules are in constant oscillation at the atomic scale as their active fronts collide, interdigitate, collapse, or persist long enough to shape the course of proximate events. The next level of organisation involves the generation of hubs and ‘attractors’ that shape and characterise spaces and environments across many scales, like the Belousov–Zhabotinsky reaction, which produces colourful, fractal-like patterns (Belousov 1959; Zhabotinsky 1964). Within these potent fields of activity, excitable molecules can then make decisions about their configuration and spatial distribution in relationship to other atoms. Material expressions arise from molecular ‘discourses’ that take place through agile molecular fields of potential and even quantum states. While these events may provide a basis for prediction, since they arise from probabilistic systems, they are not absolute indicators of events. However, they create the conditions for shaping outcomes that can be clearly observed at the macroscale in systems like the pulsatile connecting tubes of slime mould colonies (Adamatzky and Schubert 2014). While repetitions within lively systems create bifurcations that demand molecules make choices and ultimately, result in irreversible events; such agentised matter is not ‘alive’.
Dissipative Structures

Life then is a vortex, more or less rapid, more or less complicated, the direction of which is invariable, and which always carries along molecules of similar kinds, but into which individual molecules are continually entering, and from which they are continually departing; so that the form of a living body is more essential to it than its matter. As long as this motion subsists, the body in which it takes place is living — it lives. When it finally ceases, it dies. After death, the elements which compose it, abandoned to the ordinary chemical affinities, soon separate, from which, more or less quickly, results the dissolution of the once living body. It was then by the vital motion that its dissolution was arrested, and its elements were held in a temporary union. All living bodies die after a certain period, whose extreme limit is fixed for each species, and death appears to be a necessary consequence of life, which, by its own action, insensibly alters the structure of the body, so as to render its continuance impossible. (Cuvier 2006, 6)

Dissipative systems are paradoxical structures like tornadoes and whirlpools that form spontaneously when reactive energy/matter fields overlap. Characteristically, they resist Newton’s law of increasing disorder (or entropy) to produce dynamic, yet persistent, material systems with recognisable forms of organisation. While dissipative gravitational fields are likely to give rise to celestial bodies such as planets and galaxies, everyday examples include convection currents, turbulent flow, cyclones, hurricanes, and living organisms, which are ‘the most stable and complexly differentiated dissipative structures in existence’ (Nicholson 2018, 8). Less commonly encountered dissipative systems are ones that can be constructed, or produced, such as lasers, the Belousov–Zhabotinsky reaction and Rayleigh–Bénard (convection) cells, which are formed when a layer of liq-
uid is heated from below, so that hexagonal convection cells are formed in the layer of liquid.

Dissipative structures challenge our expectations of objects, as they are simultaneously structures and also processes that produce lifelike patterns, which cannot be distilled into any discrete phenomena, but perform a range of recognisable activities with many variations. While no two twisters are exactly the same, their unique qualities are instantly recognisable. Characteristic to all life is the extension of their influence beyond their apparent boundaries, semi-permeability and deep entanglement with context—not as an afterthought, but as a primary condition of existence. Dissipative structures are coupled to an as yet unspecified, but mathematically proven, internal reorganisation and reordering process, which becomes more efficient at remaining stable over time by diffusing energy into its surroundings. This extends way beyond the apparent object boundary and also impacts on its environment. Think of a cyclone that can influence extensive landscapes through the winds it sets up, long before a storm chaser reaches the eye of the storm. Consequently, in possessing a dynamic energy cloud, dissipative structures are not blind automata, but demonstrate a kind of primitive subjectivity that is not only extruded into, and responsive to its environment. Such agentised expansion constitutes an active and hyperlocal decision-making system that operates through auras, fields, and fuzzy zones. Dissipative structures may also assimilate passive objects into their bodies, slingshotting them into higher levels of thermodynamic order, unless the objects themselves obstruct the flow of exchange. Imagine Dorothy’s house as it becomes loosely coupled with the tornado in which it is swept up and carried to the Land of Oz, where it is eventually dumped along with the energy that the tornado is trying to shed.

Dissipative systems are important infrastructures in the evolutionary story of life, whose flows of material and energetic exchange constitute the webs of life and death. Although their ultimate destiny is to collapse back into nothingness, their very presence alters the probability of further lifelike events. Over
time, the collective actions of dissipative networks may even become organised enough to function as oscillators, which can compute and pattern their surroundings. Such dissipative chains of events have already persisted on Earth long enough to support the transformations arising from energetic and material exchanges between organisms over the course of 3.5 billion years and constitute the fundamental infrastructures for life.
While any given change in shape for a dissipative system is mostly random, the most durable and irreversible of these shifts in configuration occur when the system happens to be momentarily better at absorbing and dissipating work. With the passage of time, the ‘memory’ of these less erasable changes accumulates preferentially, and the system increasingly adopts shapes that resemble those in its history where dissipation occurred. Looking backward at the likely history of a product of this non-equilibrium process, the structure will appear to us like it has self-organized into a state that is ‘well adapted’ to the environmental conditions. This is the phenomenon of dissipative adaptation. (England 2015, 922)

As systems dissipate energy they become increasingly ordered over time, so that their complexity and stability increases, without the need for organising codes. In the late 1990s, Gavin Crooks and Chris Jarzynski showed that a small open system driven by an external source of energy could irreversibly take up a new configuration, as long as it shed energy into its surroundings. The ‘memory’ of these changes preferentially accumulated within the body of the dissipative structure and increasingly adopted configurations that were ‘well adapted’ to their environmental context (Eck 2016).

This means clumps of atoms surrounded by a bath at some temperature, like the atmosphere or the ocean, should tend over time to arrange themselves to resonate better and better with the sources of mechanical, electromagnetic, or chemical work in their environments … (Wolchover 2014)

‘Dissipative adaptation’ proposes that matter rearranges to channel the flow of energy through its structure increasingly more effectively. It accounts for how molecules can remain stable and
even become more effectively organised by dumping excess energy into their surroundings. It is a mode of analogue computation that increases the organisation of lively matter without recourse to central organising systems like biological code, such as RNA or DNA. This process does not just reference the past states of dissipative structures, but also creates a platform for alternative ways of designing and engineering with lively materials.
Is Dissipation Enough?

It is obvious that organisms differ from flames, whirlpools and other dissipative structure in a number of ways. For a start, organisms exhibit a far greater degree of stability, being able to maintain themselves for much longer periods of time. The key to their extraordinary stability lies in their ability to store energy, which enable them to manage their metabolic needs without having to rely on a constant supply of experimental energy, like other dissipative structures. In addition, organisms are distinctive in that they are demarcated by a physical boundary — a semi-permeable membrane — which helps regulate the intake and outtake of materials flowing through them … Organisms … derived from previous organisms, and their structure reflects the gradual consolidation, through the eons of evolution, of an intricate higher-order self-organizing dynamic among component self-organizing processes. (Nicholson 2018, 16)

Dissipative structures that spontaneously occur in nature do not completely describe all those characteristics that we recognise as ‘life’ (Moreno and Mossio 2015, 18). While they do not provide literal accounts of biogenesis, they exhibit principles of organisation that enable further exploration of how matter becomes lively. Given that the Modern Synthesis assumes the fundamental building blocks of life are inert, dissipative systems generate experimental apparatuses to rethink our assumptions of living processes through lively matter, and enable different kinds of questions regarding the nature of life to be explored. They also help us (re)consider the trajectory from non-living to living matter in ways that are consistent with the principles of liquid life.
Making Liquid Life

Liquid life offers a metaphorical and physical way of developing the character of living things through the perspective of fluid substance that were banished like the soul, from the \textit{bête machine} and Modern Synthesis.

Finding ways to convert the principles of liquid life into a toolset of materials, apparatuses, and prototypes that enable these ideas to be further explored in testable and observable ways, is akin to ‘nailing jellies to walls’. To date, testing the liquid nature of life in practice has been an observational pursuit (a natural philosophy) without meaningful ways to explore its actuality an experimental capacity. With advances in our understanding of matter at far-from-equilibrium states (spectroscopy, particle tracking), dissipative structures (characterisation of dissipative adaptation), natural computing (reaction/diffusion waves) and biotechnology (difference analysis, microarrays), it becomes possible to develop a design-led exploration of liquid life, which is situated within a realm of constant flux and instability, whose outcomes are contextual and contingent and therefore, seeks to raise possibilities rather than predict outcomes. Unlike the classical worldview, where the relationships between things is abstracted and simple, the fragility, incidental nature, and unpredictability of lively systems requires a different way of producing effects.

Shaped by curiosity and provoked by odd juxtapositions, design-led experiments begin with sculpting questions using spatial, material, and temporal ‘liquid’ tactics. Establishing terrains of rebellion, soft systems, and resistance against entropy, which are coerced and seduced towards desired states and encounters, they reveal and make familiar a realisable framework for ‘liquid life’.
... a computer of such infinite and subtle complexity that organic life itself shall form part of its operational matrix. (Adams 2009, 158)

A range of dynamic droplet systems exist that exhibit strikingly lifelike properties. The most commonly observed model of self-organising non-linear systems is the Rayleigh–Bénard convection cells, which are hexagonal structures that are caused by convection currents when a thin layer of fluid is open to air and submitted to a vertical temperature gradient (Bénard 1900). They operate by way of a gravity-driven positive feedback system, where molecules in liquid states continually move through colder fields as they rise and results in instabilities that produce the characteristic, morphologically stable ‘structure’, which resembles biological cells (Rayleigh 1916).

David Deamer has observed hydrocarbons in amoeboid bodies splitting into daughter cells (Wolchover 2017c), while Manu Prakash observes water and propylene glycol-based droplets as mimicking the behaviours of living cells (Abate 2015; Cira 2015) and Martin Hanczyc and colleagues have also designed droplets that can be induced to go through cycles of fusion and division (Caschera, Rasmussen and Hanczyc 2013).

Arguably, the most lifelike droplet system was first discovered by Otto Bütschli (Bütschli 1892), whose spectrum of body morphology and behaviour is much more diverse than the previous examples. By adding a drop of strong alkali (potash) into a field of olive oil (oleic acid) at room temperature, Bütschli created a recipe for life whereby the drop transformed into a complex structure with strikingly lifelike behaviours. Extruding proto-

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4 In contrast to Rayleigh–Bénard cells, the Bütschli system’s metabolism produces varied structures that may facilitate the transition from apparent order to lifelike behaviour
plasmic-like tentacles into its surroundings, he likened it to a simple, single-celled organism (or protist) such as an amoeba.

In 2009, this system was observed for the first time in a modern laboratory at low power (×10) under a light microscope with a backlit stage, which enabled the droplets to be seen more easily. Each alkali droplet broke down into stable but mobile structures around 1 mm in diameter, which produced soapy deposits (sodium oleate) that recorded their movements like automatic drawings. Iterations of the experiment produced various trajectories that shared common characteristics. Droplets could move around their environment, sense it, and respond to each other through coordinated population-scale events. Such extraordinary lifelike behaviour may be a consequence of the relative abundance of the ‘food source’ in which the beads of alkali are immersed, which provides unlimited energy for the structure-producing exchanges. Through the principles of dissipative adaptation, these lifelike characteristics persist long enough to result in increasingly organised agents and complex behaviours (Armstrong 2015). While the Bütschli system is not ‘alive’, it can be practically applied to construct an apparatus that explores how primordial (liquid) agents produce diverse and persistent structures. This constitutes both a visualisation tool and native experimental platform for directly observing and exploring questions pertaining to liquid life (Armstrong 2015).