This chapter highlights the fluidic, mutable nature of living systems by outlining the challenges faced by the *bête machine* when explaining, or imitating, the irreducibly complex processes of life.
Making Life

Complexity gives the lie to the motto which was so often used in order to claim that everything is clear, at least in principle. ‘This is the same thing that we already understand, just more complicated.’ This was precisely Jacques Monod’s claim: the study of bacteria had produced the secrets of life; the royal road, the only scientifically relevant one, had been opened. For the mouse or the elephant, or man, it would be the same questions, the same road. (Stengers and Lissack 2004, 92)

Mechanistic models of the living realm suppose that life can be built once all the fundamental parts of an organism are identified and fully connected together. In other words, the only difference between life and non-life, is the bête machine’s organisational complexity.

For more than 150 years, scientific experiments aimed towards producing sufficient complexity within systems of organic, as well as mechanical and artificial parts, has failed to work (Hanczyc 2008; Hanczyc 2011), as the living and mechanical realms are not materially equivalent. The machine’s ‘brute’, unagentised ontology, belongs to a deterministic world at relative equilibrium (brute matter), while organic life occupies far-from-equilibrium states (agentised matter) that are situated in a world of flux (Mayr 2004). The theorised challenges in life’s artificial construction, exceed those of reaching sufficiently advanced levels of higher-order complexity to generate life. Living systems arise from persistent hubs of activity, which perform multitudinous operations that are structured by patterns and repetitions, yet descriptions of this process do not comprise a buildable strategy for compiling ‘life’.

Can the emergence of real new properties in complex systems really be explained? If the sciences of complexity offer important new insights, theories, and methodologies
for dealing with complex, higher-order phenomena (as we think they do), and if the traditional view of explanation cannot account for the explanatory strategies we find here, we should look for other accounts of scientific explanation. Perhaps the very idea of scientific explanation as a strictly deductive argument should be reinterpreted and explanations seen in a more dynamic and context-dependent setting, eventually themselves being emergent structures, ‘emergent explanations’. (Baas and Emmeche 1997)

‘Living’ matter is innately agentised, sensitive to environmental conditions and capable of behaving unpredictably. Although various approaches, such as Ganti’s Chemoton model and the Maturana–Varela notion of autopoietic systems, are used to explore its characteristic phenomena, a mature portfolio of accessible apparatuses capable of working with matter at far-from-equilibrium states, is still far from mature.

… *in silico* and *in vitro* investigations are paving the way to a novel research arena that appears to be both very rich (thanks to its intrinsic interdisciplinary character) and promising (because only via synthetic/constructive approaches is it possible to enquire about the features of simple, early cells). This approach also stimulates more theoretical considerations with respect to intriguing questions, such as ‘What is life?’ and further supports abiogenesis as the theoretical framework for understanding the emergence of living systems on Earth. (Stano and Mavelli 2015)

As an experimental discipline, building life from its fundamental ingredients remains as challenging as nailing jellies to walls.
Life as Fundamental Change

The process of inheritance is unaffected by the processes that introduce an adaptive bias to form, and by the process of development. Organisms do not inherit what would be advantageous for them to inherit, instead, for better or worse, they get the traits their parents donate to them at conception. Novel evolutionary characteristics (i.e., mutations) are unbiased by the adaptive demands of the organisms in which they first occur. They are said to occur at random. Neither of the processes of inheritance or development introduced evolutionary changes to biological form. The structure of the inherited material is completely unaffected by the downstream developmental processes that turn programs into organisms. What arises anew in development cannot be genuinely inherited. As neither inheritance, nor development, nor mutation is adaptively biased, there must be another, wholly independent process that introduces adaptive change. Adaptive evolutionary change is the sole province of natural selection. (Huneman and Walsh 2017, 2–3)

Life’s persistence through its self-replication, or reproduction, is at the crux of the modern story of life, which is characterised by the Modern Synthesis that centres on genes. Originating in the early twentieth century, it combines the Mendelian theory of inheritance with the neo-Darwinian theory of population change in evolutionary dynamics (Huneman and Walsh 2017).

According to the Modern Synthesis, genes act on inert organic matter, which has no innate agency. Since genes, which are also ‘just’ molecules,¹ are bequest a special status in their ability to act, they perform the role of the molecular ‘brain’ of the cell,

¹ While crystals have historically been considered ‘primordial seeds’ of life, molecular biology regularly confers chemical structures with agency and even ‘personifies’ them with attributes such as selfishness (Dawkins 2006).
or the soul in the *bête machine*. Their potency is particularly persuasive, since our molecular evidencing systems are developed to further endorse their centrality. Every explanation of the living world in the Modern Synthesis is reduced back to the action of genes, or more recently, their networks. Deviance from the assumed standard of self-similarity of genetic reproduction are caused by genetic ‘errors’—rather than other active organising systems working in parallel with them—that result in ‘modification by descent’. Regarding variation as a second-order narrative, the Modern Synthesis views these unconventionalities as carrying narratives of functional adaptation and identity, which provide ‘Darwinian selection [with the] genetic variation to work on’ (Dawkins 2006, 320). Remaining silent until a time of evolutionary need, they are then expressed wherever difference—not sameness—is the key to survival.

... a transparent worm-like creature [is] moving uncomfortably on the surface of an exploded rock. It has recently ingested a woodlouse. Although the worm’s meal is fully enveloped within its simple gut, the ingested crustacean’s shell has protected it from digestion. The worm is at risk of being split open by the woodlouse, which kicks out against its soft, suffocating intestines. Perhaps an unlikely truce can be struck between them. While the louse continues to struggle in its transparent organic bag, a gelatinous swarm of cells surrounds the coupled bodies—anticipating that one of these battling systems will fail. The amorphous mass pulses as tiny particles moving through its very simple spaces, or veins. Its approach is marked by a trail of translucent slime that exteriorises and records its primitive thinking ... In its own manner and at its own speed, the formless blob attempts to swallow whole the conjoined creatures. (Armstrong 2018a, 87)

Bacteria, which are among the most abundant organisms on Earth (Nature Reviews Microbiology 2011) reproduce by different means than ‘higher’ organisms. Asexually dividing by ‘bi-
nary fission; a bacterial cell prepares for the synthesis of two daughters by enlarging to twice its starting size before it divides. In preparation for fission, a complex system of proteins, which make up the cell division machinery, condenses at the division site. Genetic material is then copied and partitioned to opposite ends of the cell through a complex choreography of structures, which avoids damaging the DNA during the process. The sequence of events starts at the site called the ‘origin’ and appears to be tightly regulated by the cell apparatus, which orchestrates DNA replication, segregation, division site location, cell envelope invagination and new cell wall synthesis. As the cell divides, the cytoplasm splits and a new cell wall is produced around the daughter cells, which are (functionally) identical to the progenitor and are clones of each other.

Although the tiniest bacterial cells are incredibly small, weighing less than $10^{-12}$ grams, each is in effect a veritable micro-miniaturized factory containing thousands of exquisitely designed pieces of intricate molecular machinery, made up altogether of one hundred thousand million atoms, far more complicated than any machinery built by man and absolutely without parallel in the non-living world. (Denton 1986, 250)

Even for such a seemingly straightforward process, the choreography of events is incredibly complex. If each cell is to remain viable and competitive within the bacterial community, division must occur at the right time, in the right place, and bestow each offspring with a full set of essential organelles and genetic material (a circular chromosome). In a dynamic environment, successful organisms also need to respond quickly to altering circumstances. The adaptive plasticity of cells poses problems for the Modern Synthesis, which places genetic mutations at the heart of adaptive change, that take place randomly through ‘error’. However, adaptive changes are not produced at random but in response to specific change, and modifications can confer
advantages at their first appearance.\(^2\) Organisms can also preferentially increase copies of genes in areas of the genome where modifications could be beneficial—a hypothesis called ‘adaptive mutation’ (Cepelewicz 2017).

In bacteria, the whole cell\(^3\) (rather than just its genetic information) can be regarded as the fundamental unit of propagation, particularly since its offspring are self-similar. The advent of multicellularity complicates the biological notion of the ‘self’ in replication, or reproduction, as it tends towards *differential specialisation*. With only a few cells becoming gametes, genetic codes become the unchanging masterplan whose differential expressions leads to various cell types, which are functions of their (invisible) interiority, rather than expressions of the whole creature (phenotype).

Owing to cellular specialism, the lifecycles of multicellular organisms become much more complex. Needing to generate various tissues and organs, their developmental process is regulated by a complex choreography of events in which genes play an important part, but do not determine every event. The choreography between the biological ‘self’ (genes) and these ‘other’ factors (metabolism, environment, infection, epigenetics, culture) is highly complex. Of particular interest is how structural complexity is generated in multicellular creatures, since many different species show significant genetic homologies with others—from bananas to fruit flies, mice, and humans—which over evolutionary time, are highly conserved, and raise questions about exactly what causes them to be so very different (see section 05.6). Within the various forms of embodiment that make up the developing biological ‘self’, differential states of existence capable of performing different functions are expressed,

\(^2\) According to the Modern Synthesis, adaptation is an etiological concept, that is, it refers to a trait that has occurred in the past (Huneman and Walsh 2017, 9).

\(^3\) While the Modern Synthesis places genes as the central organising agents in evolutionary narratives, the role of whole organisms must also be acknowledged in the processes of change namely, development, adaptation, and evolution itself (Huneman and Walsh 2017, 10).
whereby an egg does not directly reproduce another egg and a chicken does not lay another chicken (see section 06.1). Or, as Stephane Leduc notes, ‘the substance of the child is other than that of the ovum, and the substance of the adult is not that of the child’ (Leduc 1911, 3).

*HeLa* cells complicate the concept of multicellular agency even further, since they are the progeny of an immortal cell line of cervical cancer cells taken on February 8 1951 from Henrietta Lacks, a patient who died of cancer on October 4 1951. Characterised only by their genes, rather than the being as a whole, these beings-in-themselves thrive independently from the anatomical conventions that frame other human beings. Although they have not been legally granted personhood, *HeLa* raises critical questions about what it means to be ‘human’ and ‘alive’.

While the Modern Synthesis implies that genes are discrete codes and rule-makers, advances in molecular biology reveal there is no consensus on what a gene actually is. Nor do they act entirely by their own agency, but are influenced by networks of other molecular actors (Keller and Harel 2007).

“… This molecule can’t dance without a team of choreographers”, that [means] “it comes alive only when numerous proteins pull its ‘strings’”. (Pennisi 2003)

This alternative decision-making agency speaks to a dynamic, amorphous realm of metabolism, which is located within the cytoplasm and leaks out into the environment beyond the cell boundary. The formlessness and fluidity of metabolic reactions provides a permissive matrix in which genes, gene systems, and gene networks, become connected to each other within dynamic in a sea of ‘invisible’ exchanges.

The onset of synthetic biology opens a different perspective by leaving aside the question about the evolutionary origin of biological phenomena and focusing instead on the relational logic and the material properties of the corresponding components that make biological system
work as they do. Once a functional challenge arises, the solution space for the problem is not homogeneous but it has attractors that can be accessed either through random exploration (as evolution does) or rational design (as engineers do). Although these two paths (i.e., evolution and engineering) are essentially different, they can lead to solutions to specific mechanic bottlenecks that frequently coincide or converge—and one can easily help to understand and improve the other. Alas, productive discussions on these matters are often contaminated by ideological preconceptions that prevent adoption of the engineering metaphor to understand and ultimately reshape living systems—as ambitioned by synthetic biology. (de Lorenzo 2018)

The fundamental creativity, heterogeneity, and plasticity of biological systems challenges the central doctrine of Neo-Darwinism, which states that every cell in a multicellular organism is identical. Recent findings of a study into the genetic causes of abdominal aortic aneurysms discovered that blood and tissue samples were not genetically identical (Gottlieb et al. 2009). This finding was anticipated by Kevin Kelly in 2006 in The Edge, where he proposed that biological information is not stable, but contextual.

... the DNA in your body (and in the bodies of all living organisms) varies from part to part. I make this prediction based on something we know about biology, which is that nature abhors uniformity. Nowhere else in nature do we see identity maintained to such exactness. Nowhere else is there such fixity. I do not expect intra-soma variation to diverge very much ... if my belief is true, it would matter where in your body a sample of your DNA is taken. And it would also matter when your DNA is sampled, as this variation could change over time. (Kelly 2006, 207–8)
Value systems come into play when translating dynamic cell functions into mechanistic programs, as their established range of concepts eliminate a spectrum of robust material processes, such as development, which are necessary for resilient and versatile forms of life. The terminologies used to indicate the character of these phenomena portray them as flaws, errors, modifications, mutations, adaptations, and variations—deviances from ‘the norm’, where interspecies hybridisations, such as the breeding between polar and grizzly bears observed in the Northwest Territories of Canada, are reported through (unintentionally) value-loaded accounts.

‘Polar bears would most likely prefer to mate with other polar bears and grizzlies with other grizzlies, rather than with an odd-looking hybrid’ … (Roach 2006)

The breakdown of species barriers may start with atypical mating preferences of select individuals; however, the story we present can be traced to a single female polar bear who, along with three of her known F1 offspring, has been killed. (Pongracz et al. 2017, 151)

Such terminology not only spotlights human preferences for biological ‘order’ within the natural realm but also obfuscates the underlying principle of organic life: that material transformation is at the heart of the living realm, rather than being a deviant side effect of pre-determined processes. This fundamental material creativity is expressed in all complex life forms, which are likely to have evolved independently at least 25 times, in groups as diverse as animals, fungi, plants, slime moulds, and seaweeds (Sebé-Pedrós et al. 2013; McGowan 2014). Even within a single lifespan, multicellular organisms may also undergo multiple transitions in their development (like the instar stages of development of insects) and even integrate other organisms into their lifecycles. The intoxicating exchange between bee and orchid during the pollination process captured Marcel Proust’s imagination, where unorthodox modes of sexuality working
together through completely different (and extravagant) life forms, could ensure the diverse and effusive propagation of life.

Like so many creatures of the animal and vegetable kingdoms, like the plant that would produce vanilla, but which, because, in it, the male organ is divided by a septum from the female organ, remains sterile unless humming birds or certain small bees transport the pollen from one to the other, or unless man fertilizes them artificially … their sexual needs depend on the coincidence of too many conditions, too difficult to encounter. (Proust 2003, 30–31)

Reproductive tactics are not always consistent with ‘efficient’, or conservative, reproductive solutions, but are frequently promiscuous, materially indulgent, and highly risky. In fact, the material choreography of reproduction seems to be designed to be as challenging as possible.

According to the doctrine of the selfish gene, life should be stable and change very little over the course of evolution, but this is clearly not the case. Donald Williamson suspects that the variety of body forms that were produced in a geological period of morphological variation, the Cambrian Era, were potentially much more plastic and fluid in their ability to fuse with other beings than modern biology is today willing to acknowledge (Williamson 2006a). In other words, these primitive bodies formed strategic ‘error-generating’ communities.

About 600 million years ago, shortly before the Cambrian, animals with tissues (metazoans) made their first appearance … All Cambrian animals were marine and, like most modern marine animals, they shed their eggs and sperm into the water where fertilization took place. Eggs of one species frequently encountered sperm of another, and there were only poorly developed mechanisms to prevent hybridization. Early animals had small genomes, leaving plenty of spare gene capacity. These factors led to many fruitful hybridizations, which resulted in concurrent
chimeras. Not only did the original metazoans hybridize but the new animals resulting from these hybridizations also hybridized, and this produced the explosion in animal form … (Williamson 2006b, 188)

While genetic studies do not support Williamson’s specific idea that modern larvae evolved by *hybridogenesis* (Oransky 2011), his view is worth mentioning as a tool for considering the story of life through deep time, when the developmental plasticity of bodies may not have been the same as today.

… the great majority of novelties which define the taxa are not led up to via the adaptive continuums that might have endowed selection with causal directive agency. Unfortunately, very few are prepared to follow the logical implication of this absence: namely, that the origin of the basic Types of nature must have been determined or directed by causal factors other than gradual cumulative selection. (Denton 2016, 42)

Those life forms that have very distinct modes of existence and development, which depend on radical transitions and transformations like embryos and larvae, continue to challenge the Modern Synthesis by drawing attention to the possibility of multiple loci of organisation within the biological ‘self”, which organisationally adapt and evolves.

… though the oyster seems the type of dull animal vegetation in its adult condition, it passes through a vagabond, if not stormy youth, between the time in which it is sheltered by the parental roof, and that in which it ‘ranges itself’ as a grave and sedentary member of the oyster community. (Huxley 1884, 47)

They also raise important questions about which aspects of their being are conserved during these radical material reorganisations such as during birth and metamorphosis. Slippages in
these modes of existence are more than the sequential expression of individual genes, but highly orchestrated modes of restructuring that must simultaneously manage physical change and existential continuity, which is characteristic of dissipative systems (see section 08.10).

What is this egg? ... First there is a speck which moves about, a thread growing and taking colour, flesh being formed, a beak, wing-tips, eyes, feet coming into view, a yellowish substance which unwinds and turns into intestines — and you have a living creature. This creature stirs, moves about, makes a noise. I can hear it cheeping through the shell — it takes on a downy covering, it can see. The weight of its wagging head keeps on banging the beak against the inert wall of its prison. Now the wall is breached and the bird emerges, walks, flies, feels pain, runs away, comes back again, suffers, loves, desires, enjoys, it experiences all your affections and does all the things you do. And will you maintain, with Descartes, that it is an imitating machine pure and simple? (Diderot 1976, 158)

In the process of resisting entropy’s call, life’s effusive strategies, exquisite choreographies, paradoxical relationships, and material indulgences, present many challenges for the Modern Synthesis, by indulgently exploring the many strategies for existence beyond the restrictions of the (genetic) bête machine. Life — the ultimate flâneur.
Entelechy is born in the negative spaces of the machine model of nature, in the ‘gaps’ in the ‘chain of strictly physico-chemical or mechanical events’. (Bennett 2010b, 50)

The nature of life’s dynamic character has been considered since ancient times through a broad range of philosophical frameworks, many of which are animistic and so, refuse the logic of the bête machine. Heraclitus compared life to a flame, while Aristotle proposed that ‘entelechy’, a vital substance that was neither truly material nor spiritual (Bennett 2010, 71), was responsible for the operations of living things.

Within these discourses, the flow of matter and liquids are pervasive themes, which are used to discuss the nature of life and are potentially testable. While some of the properties of liquids can be simulated using mechanisms, their full range of non-linear characteristics cannot be exactly replicated even if attempts to do so provide an enchanting spectacle.

Dating from the eighteenth century, the Silver Swan is an automaton that entranced Mark Twain. Driven by three separate clockwork mechanisms, the ornate bird swims upon a stream of twisted glass and moves gracefully to the sound of music. Periodically it catches a golden fish from out of the stream and has done so for around 250 years (Kennedy 2017; Bowes Museum 2017).

I watched the Silver Swan, which had a living grace about his movement and a living intelligence in his eyes, watched him swimming about as comfortably and unconcernedly as if he had been born in a morass instead of a jeweller’s shop. (Kennedy 2017)

Advances in mechanics made possible the development of cybernetic apparatuses, which differ from classical machines by
their methods of control, information exchange, and feedback systems (von Bertalanffy 1950). By performing repeated cycles of work, cybernetic apparatuses provide mechanical models for life’s fundamental flows and processes that are iteratively updated by information flowing into the apparatus (von Bertalanaffy 1968, 18–19). Largely achieving their effects through the repetitions of inert-bodied machines, which are recursively dependent on each other, they transduce work back into the system to maintain a ‘steady state’, or mechanical ‘homeostasis’. Applying systems science to cybernetics, Ludwig von Bertalanffy championed a new ‘natural philosophy’ through his General Systems Theory (GST), which modernised Heraclitus’ view that life is in constant flux, which could be tested through the flowing interactions and connectedness of cybernetic apparatuses (von Bertalanffy 1950). Such concepts prompted the search for self-maintaining machines, such as Ross Ashby’s ‘homeostat’, which was designed as an ‘artificial brain’.

I have been trying to develope [sic] further principles for my machine to illustrate stability, + to develope [sic] ultrastability. (quoted in British Library 2016)

While the fields of GST and cybernetics created a new scientific language, in essence they upheld ‘a model of centralization, a real acting-out of it’ (Ballantyne 2007, 26). Without an ontological shift in the organisation of a physical system, i.e., an evolutionary development, cybernetics actually strengthens the idea that the difference between non-life and life is merely down to its degree of material complexity. By possessing a richer language than classical machines, however, GST and cybernetics invoke testable notions of change and adaptation.

Since life is more than persistent iterations of recursive systems, which feedback on themselves but is also capable of spontaneous, material, and organisational transformation — before an artificial system is capable of radical ‘developmental’ change, it must first attain systemic and material non-linearity.
Autopoiesis

Humberto Maturana and Francisco Varela introduced the concept of autopoiesis into machines, as self-producing, self-maintaining systems. Made up from a network of components and processes of production, they could continuously regenerate themselves through their interactions and transformations, to maintain and produce the network of processes that sustained them. This integrated ‘knot’ of exchanges constituted a ‘unified’ entity whose elements specified the topological domain of its ‘machine’ network.

Professor Humberto Maturana, with his colleague Francisco Varela, have undertaken the construction of a systematic theoretical biology which attempts to define living systems not as they are objects of observation and description, nor even as interacting systems, but as self-contained unities whose only reference is to themselves … they are autonomous, self-referring and self-constructing closed systems — in short, autopoietic systems in their terms. (Maturana and Varela 1928, v)

When open to their environment and able to receive external energy and matter, autopoietic systems perform softer, semipermeable, more agile, and persistent notions of work, and agency than are possible through classical mechanical systems.

*Autopoietic* structures have definite boundaries, such as a semipermeable membrane, but the boundaries are open and connect the system with almost unimaginable complexity to the world around it. (Briggs and Peat 1989, 154)

‘Open’ exchanges between the interior and exterior spaces are not *exactly* circular, but possess ‘circularity’. This is a cyclical concept that is not sealed in an unending loop of precision but allows the corkscrewing of energy and matter into and out of the
system through iterations of events. In this lifelike model of exchange, the idea of object permanence is decentred, as the whole system is constantly remaking, or reasserting, itself through its iterations.

It makes no sense to identify an organism over time with the materials that compose it, given that these are constantly being replenished by the whole. (Nicholson 2018, 23)

When a body is infiltrated by its surroundings, it must manage active change — from self-maintenance, to active growth and (re)production. In classical mechanics, such alterations in baseline conditions are disruptive events with the potential to destabilise the established hierarchies of order that govern the machine’s actions and may threaten catastrophic system failure. In contrast, life’s agile iterations are heteropoietic and at times of stability generate ‘self-similar’ iterations of work. Niles Eldredge and Stephen Jay Gould observed that for most of evolutionary history, these iterations expressed through the morphology of species, is remarkably stable and reaches a condition of ‘stasis’.

‘Nothing will come of nothing.’ Cordelia’s dilemma arises in science when an important (and often pre-dominant) signal from nature isn’t seen or reported at all because scientists read the pattern as ‘no data’, literally as nothing at all. This odd status of ‘hidden in plain sight’ had been the fate of stasis in fossil morphospecies until punctuated equilibrium gave this primary signal some theoretical space for existence. Apparent silence — the overt nothing that actually records the strongest something — can embody the deepest and most vital meaning of all. (Gould 2007, 38)

At times of stress however, living systems are capable of radical shifts in order, which prevent system collapse, and may rapidly confer organisms with the ability to adapt to new conditions. Such abrupt transformations are evidenced in the fossil record as ‘punctuated equilibrium’, where certain new characteristics
like shells, bones, and eyes, appear over relatively short evolutionary time periods.

Evolution is a theory of organic change, but it does not imply, as many people assume, that ceaseless flux is the irreducible state of nature and that structure is but a temporary incarnation of the moment. Change is more often a rapid transition between stable states than a continuous transformation at slow and steady rates. We live in a world of structure and legitimate distinction. Species are the units of nature’s morphology. (Gould 1979, 18)

In a truly open autopoietic system, it might be reasonable to anticipate spontaneous and sudden advances in the configuration of ‘autopoietic machines’, albeit over protracted periods of apparent stability. With such an eventuality, the ontological differences between mechanism and ‘life’ would disappear.
RepRap: Self-replicating Machines

The general struggle for existence of animate beings is not a struggle for raw materials — these, for organisms, are air, water and soil, all abundantly available — nor for energy which exists in plenty in any body in the form of heat, but a struggle for [negative] entropy, which becomes available through the transition of energy from the hot sun to the cold earth. (Boltzmann 1974, 24)

Attempts to produce self-replicating machines focus on the specific (re)placement of components using external ‘intelligence’ and agency, which has been impossible to complete to date. Adrian Bowyer initiated the RepRap (Replicating Rapid-protoyer) project in 2004, which is an open-source, 3D printing apparatus that prototypes plastic objects and also explores the possibility of self-replicating machines. It prints the plastic components for a kit that can be assembled into a new machine, which account for about 70% of the necessary parts — printing the electronic circuity remains particularly problematic (Jones et al. 2011; Giaimo 2019).

Current RepRap machine kits are not self-compiling. They operate a recursive assembly process on pre-given materials, which is hardly autonomous, and kits come with instructions so that gaps in the ‘autopoietic’ process of ‘self’-production, must be completed by (external) human input. Even when it becomes possible to self-print all the components of a 3D printer, RepRap still relies on a maker community to evolve its design. Compare this with a plant, for example, that is able to turn elemental materials into complex, constantly changing, structural systems. The present generation of self-replicating machines therefore do not address the infrastructural conditions in which the entire spectrum of their vital operations takes place and instead, rely on existing human production systems for their completion. Ontologically speaking, these machines not differ from factory-made machines, other than through the degree of automation.
used in the assembly process. While rapid prototyping changes the distribution of economic and social power among people using these tools, it has little effect on the degree of autonomy within the machine itself.
Natural Selection

To suppose that the eye with all its inimitable contrivances for adjusting the focus to different distances, for admitting different amounts of light, and for the correction of spherical and chromatic aberration, could have been formed by natural selection, seems, I confess, absurd in the highest degree … The difficulty of believing that a perfect and complex eye could be formed by natural selection, though insuperable by our imagination, should not be considered subversive of the theory. (Darwin 2010, 82)

Charles Darwin’s theory of ‘natural selection’ proposed that the ‘fitness’ of an organism was reflected in its reproductive success that was passed on through heritable traits. These in turn helped certain types of organisms survive and become more common in a specific population over time — ultimately to produce new species (Paradis 2007, 113). While he gave the principles of his theory, Darwin did not propose a physical process that explained how the actual ‘means of modification by descent’ worked.

Without these details, early critics such as Samuel Butler, accused him of advocating truisms — where ‘survivors survive’ — as a way of avoiding giving real causes and effects (Butler 2008, 351), while George Henry Lewes argued that by referring to ‘chance’ in his explanations, Darwin demonstrated that could not explain the effects he proposed.

Mr. Darwin seems to imply that the external conditions which cause a variation are to be distinguished from the conditions which accumulate and perfect such variation, that is to say, he implies a radical difference between the process of variation and the process of selection. This I have already said does not seem to me acceptable; the selection I conceive to be simply the variation which has survived. (Lewes 1878, 109)
With the advent of the Modern Synthesis, DNA was identified as the agent of heredity and evolutionary change, although not all biologists agree on the principles that govern these processes and natural selection has become a semantic stage upon which technical paradigms related to biological theories continually clash in a wider, and often undeclared, political arena.

In the traditions of ‘Western’ science and politics—the tradition of racist, male-dominant capitalism; the tradition of progress; the tradition of the appropriation of nature as resource for the productions of culture; the tradition of reproduction of the self from the reflections of the other—the relation between organism and machine has been a border war. The stakes in the border war have been the territories of production, reproduction, and imagination. (Haraway 1991)

Those that embrace a Neo-Darwinist, deterministic reality like Richard Dawkins, regard natural selection as governed by ‘real’ interiorised genetic ‘means’, to produce specific outcomes, which may be further modified through environmental and social events (Dawkins 2006).

Neo-Darwinism is an attempt to reconcile Mendelian genetics, which says that organisms do not change with time, with Darwinism, which claims they do. (Brockman 1995, 133)

Others that take a more contingent and therefore probabilistic view of natural selection, like Richard Lewontin and Stephen Jay Gould, look to the myriad forces that shape evolution through the processes of living (Gould and Lewontin 1979). These are so varied and contingent that their effects have many more degrees of freedom and are produced by networks of distributed processes, which enable organisms to dynamically respond to change, even while overarching organisational principles (genetics, laws of physics and chemistry) are at work.
... organisms must be analyzed as integrated wholes, with baupläne so constrained by phyletic heritage, pathways of development, and general architecture that the constraints themselves become more interesting and more important in delimiting pathways of change than the selective force that may mediate change when it occurs. (Gould and Lewontin 1979)

The association of natural selection, with Herbert Spencer’s adage ‘survival of the fittest’, bestows it with a politics, where the most ruthless and uncaring organisms may be regarded as ‘fittest’, since through proactive aggression, they are more likely to survive.

The total amount of suffering per year in the natural world is beyond all decent contemplation. During the minute that it takes me to compose this sentence, thousands of animals are being eaten alive, many others are running for their lives, whimpering with fear, others are slowly being devoured from within by rasping parasites, thousands of all kinds are dying of starvation, thirst, and disease. It must be so. If there ever is a time of plenty, this very fact will automatically lead to an increase in the population until the natural state of starvation and misery is restored. In a universe of electrons and selfish genes, blind physical forces and genetic replication, some people are going to get hurt, other people are going to get lucky, and you won’t find any rhyme or reason in it, nor any justice. The universe that we observe has precisely the properties we should expect if there is, at bottom, no design, no purpose, no evil, no good, nothing but pitiless indifference. (Dawkins 2001, 155)

When used in a Neo-Darwinist context, natural selection also negates the agency of organisms beyond the level of organisa-

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4 Baupläne, or ground plans, is a biological term for a set of morphological features that are common to many members of a phylum of animals.
tion of their molecular hierarchies, which do not directly account for the sophisticated aspects of behaviour (see section 04.7), such as empathy for other beings. While non-humans are frequently treated as if they lack social order, or codes of conduct, certain creatures like capuchin monkeys (Markey 2003) are demonstrably capable of making ethical decisions. Negating the capacity for creatures to act altruistically against their own interests George Price argues there is a ‘rational’ selfish genetic theory underpinning such ‘irrational’ actions, since close family members ‘benefit’ from the sacrifice made by a genetically related individual (Reigner 2016). These accounts assert biological ‘fate’ as a final cause through with a creature’s agency can be denied as: they do not address morality, neither do they engage with a whole spectrum of complex behaviours, nor can they provide a framework that indicates what ought to be done, when faced with a given set of circumstances.

Our culture has the genetics and the nature theory. You come into the world loaded with genes and are influenced by nature, or you come into the world, are influenced by the environment, and are the result of parents, family, social class and education. These theories don’t speak to the individuality or uniqueness that you feel is you. (NurrieStearns 2017)

With the politics of enablement at the core of its ethics, liquid life seeks empowering narratives that return autonomy to all beings through the innate agency of matter at far-from-equilibrium states. By constantly negotiating its relationship with genetics, which is part of its wider community of collaborating agents, liquid beings resist the material programs and mechanisms of power that strive to supress them (Foucault 1998).
04.7

Causal Emergence

Romeo wants Juliet as the filings want the magnet; and if no obstacles intervene he moves towards her by as straight a line as they. But Romeo and Juliet, if a wall be built between them, do not remain idiotically pressing their faces against its opposite sides like the magnet and the filings … Romeo soon finds a circuitous way, by scaling the wall or otherwise, of touching Juliet’s lips directly. (James 1890, 8)

At far-from-equilibrium states, bodies are not governed by the simple interactions between individual atoms, nor through a chain of command initiated by nucleotide programs but ally with the operations emerging within intersecting agentised fields, whose mutual attractions are expressed as ‘causal entropy’ (Wissner-Gross and Freer 2013). When these active fields link together, massive exchanges between populations of molecules take place, which are also dynamically interacting with their local surroundings. Consequently, the resultant phenomena frequently exceed causal explanations at higher levels. In these instances, higher-scale events that arise from the constitutive fields of interaction begin to shape real events observed at the macro-scale. This ‘causal emergence’ challenges existing ideas about the nature of laws, powers of scale and how they relate. This is not only a more efficient way to model complex phenomena, but also constitutes a real force. It is not a cipher for true causes but embodies the actual agents responsible for high-level system behaviours. While at first, it appears counterintuitive that higher-level organisation is more predictable than even the most detailed micro-scale description of systems (Hoel 2017), it is likely to underpin the behaviour of many kinds of emergent phenomena such as superconductivity, murmurations, crystals, and waves, which establish the natural scales that correspond with each other and generate real consequences such as tsunamis, weather, complex behaviours, and the formation of planets (Wolchover 2017b).
Non-linearity

Where chaos begins, classical science stops. For as long as the world has had physicists inquiring into the laws of nature, it has suffered a special ignorance about disorder in the atmosphere, in the turbulent sea, in the fluctuations of wildlife populations, in the oscillations of the heart and brain. The irregular side of nature, the discontinuous and erratic side — these have been puzzles to science, or worse, monstrosities. (Gleick 1997, 3)

A glimpse of dynamical chaos was first provided by Henri Poincaré when he entered a competition held in 1890 by Oscar II, the King of Sweden. One of the challenges was to demonstrate that Newton’s solar system equations were dynamically stable, but his incomplete solution to the classical ‘three-body problem’ indicated that a range of factors could alter the movement of the solar system in ways that defied calculation. These first clues indicated that astonishing chaotic behaviour was possible in the deterministic solar system and enormous incalculable changes could be produced by tiny variations, whose behaviour was shaped by their initial conditions but still obeyed fundamental physical laws. Demonstrating that accurate long-term predictions of chaotic systems were impossible (Peterson 1993), Poincaré later suggested such phenomena were likely to be common in other fields of study such as meteorology. Chaotic systems are also able to produce recognisable patterns with striking characteristics that include; responding to their context, producing persistently repeating patterns, reaching equilibrium states, or undergoing unpredictable changes that are not proportional to their inputs. None of these systems can be decomposed into parts, then subsequently reassembled back into their original state.

… the theory of nonlinear systems is like a theory of non-elephants … It’s impossible to build a theory of nonlinear
With the advent of modern computers in the mid-twentieth century, researchers such as Edward Lorenz began to experiment with the equations of complex dynamic systems in ways that were previously impossible. Lorenz’s ‘toy model’ of atmospheric convection produced a solution with characteristic ‘butterfly wings’. Lorenz argued that this *strange attractor* suggested why it is hard to predict the weather — as it was sensitive to initial conditions. Characteristically, the patterns never settled down to equilibrium, or entered a predictable, ‘periodic’ state (Lorenz 1963). The wing-like trajectories of this model system inspired the aphorism of the ‘butterfly effect’ — where tiny disturbances produced by the flutter of the insect’s wings could be chaotically amplified to ultimately cause a tornado.

Determinism was equated with predictability before Lorenz. After Lorenz, we came to see that determinism might give you short-term predictability, but in the long run, things could be unpredictable. That’s what we associate with the word ‘chaos’. (Dizikes 2011)

Working for IBM, Benoit Mandelbrot was one of the first to use computer graphics to demonstrate how visual complexity could be produced from simple mathematical rules. He codified and popularised them as ‘fractal’ images, which could be taken up into a variety of subjects such as the emerging field of mathematical biology.

Clouds are not spheres … Mountains are not cones. Lightning does not travel in a straight line. The new geometry mirrors a universe that is rough, not rounded, scabrous, not smooth. It is a geometry of the pitted, pocked, and broken up, the twisted, tangled, and intertwined. The understanding of nature’s complexity awaited a suspicion that the complexity was not just random, not just an
accident. It required a faith that the interesting feature of a lightning bolt’s path … was not its direction, but rather the distribution of zigs and zags. Mandelbrot’s work made a claim about the world, and the claim was that such odd shapes carry meaning. The pits and tangles are more than blemishes distorting the classic shapes of Euclidean geometry. They are often the keys to the essence of a thing. (Gleick 1997, 94)

The theory and practice of non-linear systems provides entry into paradoxical spaces and material states where qualitatively new outcomes are possible. In the field of ‘mechanical metamaterials’, non-linear degrees of freedom that arise in suitably designed microstructures are programmed to perform specific mechanical tasks. The aim is to create a new class of controllable, dynamical, and active materials that combine unconventional physical properties such as swelling and non-linear elasticity, with substrates like metagels, which are structured hydrogels that respond to osmotic shock (Florijn, Coulais and van Hecke 2014). An appropriate conceptual and operation framework is therefore needed to anticipate and fully engage the potential of these fields. Precedents already exist within the realm of fluids, such as Rayleigh–Bénard cells and the Bütschli system, which behave according to the laws of chaotic systems but, through their specific materiality, also possess the seeds of technological disruption.
From Hard to Soft Machines

When Stephane Leduc first coined the term ‘synthetic biology’, the difference between lively chemistry and biological systems was regarded as ‘a gradual chemical elaboration, which culminates in those high compounds which, under surrounding influences, manifest those complex changes called vital’ (Leduc 1911, 116). Even today, the question of life is regarded as a challenge for combinatorial chemistry. However, ‘brute’ matter that lacks innate agency is simply unable to account for material ‘decisions’ about becoming. Concepts that engage with a (new) materialist discourse must encapsulate the capacity for the material realm to act autonomously in making decisions about what it might become, without recourse to the influence of external agencies such as divine forces, or genetic ‘intelligence’.

One of the hypotheses Denis Diderot makes in D’Alembert’s Dream, is that not only can matter think, but that all of matter is sensible:

Just as a drop of mercury fuses itself with another drop of mercury, so a sensitive and living molecule fuses itself with a sensible and living molecule … At first there were two drops—after the contact there is only one … Before the assimilation there were two molecules; after the assimilation there is now only one … The sensibility becomes common to the common mass … And, indeed, why not? … In my thinking about the length of an animal fibre, I can distinguish as many parts as I like, but the fibre will remain a unity … yes … a unity. The contact between two homogeneous molecules, perfectly homogeneous, creates the continuity … and it’s an example of the greatest union, cohesion, combination, and identity one could imagine … Yes, philosopher, if these molecules are elementary and simple … but what if they are aggregates, if they are compounds? … The combining will still take place no less than before and the resulting identity and continuity …
and then the usual actions and reactions … It’s certain that contact between two living molecules is something different from the contiguity of two inert masses … (Diderot 1976, 167)

This possibility is examined in a thought experiment, where a marble statue is ground into powder then mixed into the earth. Plants spring from this soil which are eaten by animals and then, by a woman, where this matter is organised in the womb to produce a human life. The inanimate statue therefore becomes a person (Diderot 1976, 150–53)—a process that Diderot calls ‘animalisation’. This journey however, is not an isolated set of transformations but invokes extended fields of potentiality that are more extensive than an ort of matter, like metabolisms, and so, animalisation does not simply work on discrete objects alone but is an account that describes a much more extensive process. For life to be constructed from fundamental units requires more than material complexity but also the right context in which transformation can take place. The specific context that is required, is something that is not easily reducible, but odd (Cairns-Smith 1985, 8).

… just adding complexity to the system in an unprincipled way [is] likely to lead to ‘black tar’ rather than any interesting higher-order behavior — the addition of complexity must be done with care. This leads to an as yet unanswered question: Are there principles to guide us in adding complexity at the right places in the system, or are we essentially left to experiment by trial and error? (Taylor et al. 2016, 413)

Robert Rosen notes that there is no syntactic way across the complexity bridge (Rosen 1991). This could mean that our current knowledge of what we call ‘emergence’ is incomplete, or that we cannot generate sufficient complexity for the construction of ‘life’ to succeed. While complexity, and even those recipes that provoke it can be recognised, they cannot be ‘built’ into a
system through assembling their parts into specific configurations alone and something ‘irreducible’ has to happen for the system to become autonomously agentised. While massive increases in ‘information’ flow through physical systems could potentially ‘solve’ this issue, the nature of this information cannot be general — such as applying a huge amount of heat — it must be ordered and specific, so that it can develop particular relationships — material, energetic, temporospatial — with the host at specific scales of operation. Alternatively, the fundamental premise that life is an incredibly complex machine, which can be assembled from molecular parts, may require radical rethinking.

In the history of science and philosophy there is hardly a less happy expression than that of the bête machine of Descartes. No concept leads to such a distorted view of the problem underlying it, or so greatly falsifies its proper meaning. It might even be said that, in spite of its heuristic success, the notion of the machine has had a destructive effect on the development of biological theory. It has entangled the investigator even today with scholastic artificial problems, and at the same time as prevented the clear discernment of the essential problem of organic nature. Only the displacement of the machine theory … will put an end to the paralysis of biological thinking for which this Cartesian expression has been responsible. (Bertalanffy 1933, 36–37).

A revival of material discourses is needed in view of the present unfolding environmental catastrophe. To advance the theory and practice of building, this must take place in conjunction with alternative narratives, models, and prototypes, to living systems, where ‘the difference between the living and the non-living can become an object of practices instead of definitions … It is no longer a question of a unitary logic, but rather of the creation of new types of artefacts’ (Stengers 2000, 88).

The expanded language, associated metaphors, and conceptual toolsets offered by new materialism and the semiotics of
soft machines, reject notions of instrumentalised ‘brute’ matter and instead, respond to a livelier, agentised non-human realm in constant flux, which implies the devolution of human agency. This is not to say that people are debased, but that ‘if matter itself is lively, then not only is the difference between subjects and objects minimized, but the status of the shared materiality of all things is elevated’ (Bennett 2010a, 12–13). Advances in the life sciences are providing new apparatuses that challenge traditional perspectives of materials, where ‘conversations’ with lively matter can be shaped by altering genes (Caputo 2016), cultivating living tissues (Sandhana 2004) or changing the environments in which responsive (living) materials are placed (Anthill Social 2009). This enlivened realm shifts invokes an age of ‘living’ technology (Armstrong 2015, 31–33), and cyborgs (Haraway 1991), which resist the conventions applied to brute obedience (Bennett 2010a, vii) and move towards a participatory realm of ‘thingly power’ (Bennett 2010a, xiii). Here, the boundaries that separate life from matter, organic from inorganic, human from non-human, man from god, are ‘not necessarily the most important ones to honor’ (Coole 2010, 47). Such ‘vital’ agency invokes the poetics of ‘soft’ machines, whose components (or agents) are loosely coupled and form horizontally organised power structures through groupings (or assemblages) that de-territorialise and re-territorialise within the logic of ‘desiring-production’ (Ballantyne 2007, 18–38; Deleuze and Guattari 1979; Deleuze and Guattari 1983). Such ‘machines’ are not actual apparatuses, but philosophical instruments for (mostly) thinking through how these concepts may be actualised. New materialist perspectives also hybridise with the concepts of speculative realism (Morton 2010), Actor–Network Theory (Latour 1996), and feminist theory, to address a range of issues, including hierarchies, the nature of relationality, and the relationships between nature, society, humans, and other agencies that constitute the living planet. Collectively these perspectives propose the existence of dynamic, emerging, and constantly negotiated ecological relationships across and between unlike bodies that evolve co-constitutive relationships, or anatomies,
such as wasp orchids\(^5\) and thynnine wasps (Deleuze and Guattari 1983, 284); while ‘oceanic’ ontologies (Steinberg and Peters 2015) and hyperobjects (Morton 2013) also generate discursive platforms for exploring massive material flows and irreducible complexity. The orientation of soft machines however, remains ontologically consistent with Descartes’ dualistic corpus and soul substance — albeit with softer and fuzzier boundaries. Jane Bennett, for example, summons Hans Driesch’s interpretation of Aristotle’s entelechy (Driesch 1929, 1–113), and Henri Bergson’s ‘vital’ principle (Bergson 1922, 44) to place emphasis on ephemeral essences as external operative agencies in new materialist discourses; while supreme consciousnesses are implied in James Lovelock and Lynn Margulis’ invocation of Gaia — ‘a tough bitch and is not at all threatened by humans’ (Brockman 2011) — as sources of agency and metaphor for planetary systems (Lovelock 1979). The challenge in adopting such terminology is how to practically apply the proposed ideas without re-articulating them within the context of the \(bête\) machine.

The most successful collaborations that emerge from these alternative transdisciplinary practices are not simply theoretical, but also synthetic (bringing concepts together), which involve ‘making’, or prototyping possibilities to functionality. Isabelle Stengers proposes a constructivist platform that promotes experimental modes of collaboration that may apply to ongoing developments in the characterisation of life, such as coupling and causality in complex systems, which resist easy instrumentalisation (Stengers 2000, 87). These may be brought into proximity with cultural developments. In this ‘ecology of practices’ (Stengers 2005), the aim is not to address the state of knowledge and making right now, but to generate new kinds of methods and discursive prototypes that may underpin alternative approaches to building life in the laboratory. By producing prototypes of the collaborative work, they may be subject to iterative

\(^5\) Part of the wasp orchid has evolved to closely resemble female thynnine wasps, so when males try to mate with these structures, they deposit pollen, which pollinates the flowers (Ballantyne 2007, 23)
interrogation, and as they are developed, may be capable of responding to and incorporating new findings.

Each branch of science at its commencement employs only the simpler methods of observation. It is purely descriptive. The next step is to separate the different parts of the object studied — to dissect and analyze. The science has now become analytical. The final stage is to reproduce the substances, the forms, and the phenomena, which have been the subject of investigation. The science has at last become synthetical. Up to the present time, biology has made use only of the first two methods, the descriptive and the analytical. The analytical method is at grave disadvantage in all biological investigations, since it is impossible to separate and analyze the elementary phenomena of life. The function of an organ ceases when it is isolated from the organism of which it forms a part. This is the chief cause of our lack of progress in the analysis of life. (Leduc 1911, 5)

While the empirical aspects of lively agents can be framed by the machine metaphor, their ‘invisible’ (irreducible) potencies cannot. By changing the framework through which the complex actions of living systems operate, liquid life raises the status and influence of non-human actors — such as the bacteria that Margulis indicated were Gaia’s agents of change (Margulis and Sagan 1995), so that a broader recognition of Earth’s liveliness can be acknowledged, engaged, and valued.