Cyberneticisation as a Theory and Practice of Matter

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Cybernetics and modern ecology are fundamentally linked through the exploration of dynamic complex systems, which has largely been interrogated through computer modelling. With increasing interest in and need for re-definition of bio-logics, the matter of matter is fundamental for an appropriate platform and theory for implementing cybernetically-informed ecological solutions.

The matter of matter

While cybernetic prototyping was centred on the ‘machine’, the important role of responsive matter in dynamic complex systems was recognised by researchers in the cybernetics community such as Stafford Beer and Gordon Pask. In the early 1950s and 1960s, Beer and Pask individually and collaboratively worked on Ross Ashby’s idea of a synthetic brain but with an important difference: instead of trying to build the fundamental components from scratch, they recruited candidates from biology.[1] Attempting to ‘grow’ computers, their approach formed a practical basis for solving cybernetic problems that were too complex to represent. Believing that the performative ability of natural systems could solve problems that exceed our cognitive capacities, they looked to living agents to embody the necessary complexity.

Having embarked on an extensive search for natural materials for the construction of cybernetic machines, including quasi-organic electrochemical systems called ‘fungoids’ that he worked on with Pask, Beer settled on colonies of simple creatures as model organisms within a larger pond ecosystem, namely *Euglena* and *Daphnia*.[2] Regarding these living agents as being capable of solving ecosystem-based challenges, he sought to couple their interests with challenges relevant to human concerns. Beer added iron filings to the tank, which the *Daphnia* ingested, turning them into electromagnets. He could then change the properties of magnetic fields, which in turn produced changes in the electrical characteristics of the colony. Initially this approach seemed to have potential as an evolving machine, but the behaviour of the colony was disrupted by an excess of magnets in the water.[3] Beer then tried using *Euglena* as light sensors using a point source of light as an input and a photoreceptor to measure their behavioural output. Rather than collectively responding to changes in light by moving, the protozoa became lazy and tended to ‘lie doggo’.[4]

Pask built a series of ‘chemical computers’ using electrochemical systems made up from a number of small platinum electrodes inserted in a dish of ferrous sulphate solution and connected to an electrical power source. When the current flowed, metallic iron threads formed between electrodes with a low resistance relative to the solution. Consequently, the formation of threads modified the potentials at the electrodes where threads dissolved back into the acidic solution when there was no current flowing.[5] The electrochemical system displayed a simple form of learning by developing a stable network of threads that manifested the distribution of current. To demonstrate the threads were also sensitive to environmental perturbations such as vibrations, temperature, chemical environment, and magnetic fields, Beer and Pask worked together to set up microphones that formed a very simple neural network capable of responding to traffic vibrations – effectively, 'growing an ear'.[6]

By interrogating the material platforms through which cybernetisation was possible, Pask and Beer clearly established the value of using material prototyping – not just to demonstrate that a hypothesis described a correct mode of operation – but, by observing the behaviour of the prototype, to also ask new questions about how volatile life-like properties could be bestowed on a system. Ultimately, their inquiries explored how responsive matter could be coupled with the logic of assembly, as a new biologic, that enabled different forms of life to emerge. Setting the stage for incorporating living systems into the very fabric of buildings as designed expressions of ecology, this approach radically differed from trying to impose a bio-logic on a mechanistic building – a form of mimicry. Instead, applying agentised matter operating through bio-logical systems conferred structures, like buildings, with the innate properties of living matter, capable of autonomous self-assembly, change and intelligence.

Cybernetics and ecosystems

Fundamentally material, ecology was explored primarily as a study of populations, being influenced by cybernetics through its systemisation in the early twentieth century. Initially, it therefore lacked a specific narrative about the materiality of transactions that maintained its coherence, which was instead deflected through a discourse of relations. Invented in 1886 by Ernst Haeckel, the term *Oekologie* was used to describe animal relations between both their organic and inorganic environments.[7] Initially, the organising principles were based on notions of political economy with little specific reference to materiality and coincided with the last years of the British Empire, where ecological reasoning grew out of the imperial administration and its political culture.[8]

At the turn of the twentieth century these ideas began to be expressed through Herbert Spencer's notion of 'organicism' by Frederic Clements, who claimed in relational terms that plant communities were 'complex organisms' that could be studied experimentally with the same rigour that physiologists applied to individual organisms in the laboratory. Extending this metaphor, Clements proposed these ecological communities even underwent a predictable series of developmental changes comparable to animal development with an ontogeny and phylogeny that culminated in an idealised end point in their succession, or 'climax'.[9] Building on this notion, John Phillips championed a holistic ecological view where ecosystems communities were not mere summations of individual organisms, but integrated wholes, or 'superorganisms' with emergent qualities that prefigured contemporary debates about the notion of a planetary organism, in the Gaia Hypothesis.[10]

Recognising the integration of the biotic community and its physical environment as the fundamental unit of ecology operating within a hierarchy of physical systems that span the range from atom to universe, Arthur George Tansley proposed a topographical, mechanistic approach, which introduced the possibility of understanding the order of biotic communities and controlling their development.[11] Coining the term 'ecosystem' in a ground-breaking theoretical paper about systems of nature, mind, and morality which was rooted in Freudian psychology, he developed simultaneously empirical and relational narratives that were more sophisticated than the reductionist principles that the holists had rejected.[12] Shortly after, through his study of energy flow within an aquatic ecosystem, Raymond Lindeman identified the specific redirection and reallocation of energy and matter within ecosystems, describing for the first time how particular fluxes within food cycles comprised the precise feedback mechanisms that could bring about change, and could also be quantitatively measured through 'biotic dynamics'.[13]

Adopting the language of complex systems, Eugene Odum and his brother Howard proposed that ecosystems were holistic and emergent, being greater than the sum of their parts, while simultaneously drawing on reductionist methods to assert the modern conception of blogospheric and organismal entanglements.[14] The paradoxical worldview of simultaneously understanding wholes and parts was mirrored in the field of cybernetics. While Eugene Odum recognised the simplifications in regarding ecosystems as cybernetic, he also asserted their usefulness in advancing the field.[15] Over the course of the twentieth century, a mechanistic and imperialist land management view of ecosystems emerged which finally became a totalising concept of the earth as a colossal self-regulating cybernetic system, and incorporated earlier notions of holism in the Gaia Hypothesis.[16] Through cybernetics, ecology evolved from a primarily botanic study to an investigation of human relations, providing a powerful framework for organising environment and society to achieve efficient global management through a new global ecological order.[17]

Metabolism

The concept of metabolism provides a theory and platform for linking the process of life observed by Lindeman, which are necessary to actualise systems through cyberneticisation. Derived from the Greek word *metabole,* 'a change', metabolism is a lively fabric that is constantly in flow. Metabolism is not an object. It is a fabric unlike any other we know. It is always in flow, highly complex and distributed in space and time. It is both within us and all around us. Characterised by systems of attractors, hubs of organisation, and paradoxical behaviours, it embraces both classical and non-classical physical and chemical laws. While metabolism is largely associated with living organisms, it also extends to the chemicophysical world such as the biogeochemical sulphur cycle, where sulphur passes between rocks, waterways and living systems. This link between inside and outside of an organism is critical for the material engagement of cybernetics in design. By internally structuring, animating and linking bodies to the environment, as well as other living bodies through ecosystems of exchange, metabolism enables the persistence, growth and dissembling of organisms through lifecycles and ecosystems. Neither an abstract 'system' nor universalising framework overlaid upon the physical realm, metabolism is an embodied process that spans molecular intra-actions, quantum phenomena and the relentless flow of matter to generate actual material effects that increase the overall liveliness and generative expressions of the natural realm.

Predating the field of cybernetics, the term metabolism became commonly used in the developing field of physiology at the turn of the nineteenth century, but its principles were investigated as early as the thirteenth century by Ibn al-Nafis. Recognising a mysterious life-force and invisible exchange between bodies, al-Nafis observed that the parts of the human body were in a continuous state of dissolution and nourishment, from which he concluded the inevitability of permanent change.[18]

In the late sixteenth century, Santorio Sanctorius deduced the existence of insensible perspiration by systematically weighing himself before and after eating, sleep, working, sex, fasting, drinking, excreting, and discovering that he had lost mass during these activities.[19] Demonstrating that that the living organism is undergoing continuous changes, these obsessive experiments provided the basis for the physicochemical theory of life.[20] Further studies of this kind were performed on living animals and human volunteers, all of which suggested that this vital force was not exclusive to people but also infused animated living tissue.

The idea of an animal chemistry or animal economy was developed during the eighteenth century,[21] conjecturing that the body managed its own personal domain, *oikos*, or home, through the assimilation of foodstuffs and elimination of waste.[22] By the 1850s scientists were interchangeably using the terms metabolism and metamorphosis, making alchemical references in the description of the transformation of substances such as proteins and nutrients. Implicit in this particular use of the term was the idea of tissue change, which altered an organism's anatomy.[23]

By the nineteenth century such investigations became increasingly rigorous and interpreted through the laws of thermodynamics. Louis Pasteur brought a decidedly more chemical view of metabolism in comparison with the whole-body observations of earlier studies through his sugar fermentation experiments. Noting that sugar was catalysed by 'ferments' to become alcohol, Pasteur regarded these processes as innate to the yeast cultures. Taken in conjunction with Friedrich Wöhler's experiments, which reported that the organic substance urea could be made from inorganic ingredients, these pioneering investigations laid the foundations for the understanding of organic compounds through chemical reactions within cells, establishing the framework for the study of metabolic pathways.[24] In the twentieth century, Eduard Buchner discovered chemical reactions within cells, which differentiated metabolism from the biological study of whole cells.[25] This established the independent foundations of biochemistry, leading to the discovery by Hans Krebs of critical metabolic pathways for life, such as the citric acid cycle, glyoxylate cycle and urea cycle[26] which earned him recognition as the architect of metabolic cycles.[27] From around the middle of the twentieth century, two competing dominant biological narratives asserted the physical basis of life. The first emphasised growth and replication as the major vital characteristics that enable organisms to increase in size and numbers. Likened to the growth of crystals, this viewpoint was adopted by molecular biology. The second perspective regarded metabolism as the primary condition for life, where organisms retained their form and individuality, despite ongoing physical changes; this view would come to be embraced by the field of biochemistry.[28] Today, the concepts of crystalline units of structure are combined with an understanding of metabolic pathways in all kinds of cellular states. Through these developments, a working understanding of the actual chemical processes and their control systems is possible, which through many dimensions of feedback loops, makes for a never-ending web of potential permutations and associated material transformation.

While tools exist for designing and engineering with genetics, a practice called synthetic biology, an equivalent toolset for metabolism is emerging in the study of metabolomics, which provides a comprehensive analysis of metabolites that govern the running of the organism through molecules other than its genes. This includes biomolecules, such as metabolites, which also define molecular phenotypes. Serving as an essential objective lens in the molecular microscope, they enable the complex physiology that links the flesh to external events and conditions to be observed.[29] However, life has a much more sophisticated information transfer system than the electrical inputs, outputs, feedback and amplifications of conventional machines and more plastic concepts and appropriate language are needed to actualise both the long-term recording systems and the stability mechanisms that maintain life's flexible operations. At the molecular scale, the actual relations between molecules which generate metabolism cannot be accurately modelled in a reasonable amount of time – a task that becomes even more challenging as the complexity of the molecules and environment increases. While metabocybernetics provides a quantitative description of how biological systems achieve metabolic homeostasis in the face of environmental insults, a political economy of the organism is also needed to articulate the many trading and regulatory systems that govern cellular metabolism.[30] Sharing resonances with the eighteenth-century frameworks for the flow of life through the economy of living systems and Tansley's multi-dimensional systems, the relation between genetics and metabolic processes are being redefined within the field of molecular biology. Synthetic biologist Victor de Lorenzo likens the interplay between DNA and metabolism as akin to that of politics and economy. Considering metabolism as the economy of living things he highlights its importance in making possible any 'political' ambitions encoded by the genes:

> whether one likes it or not, it is economy that ultimately determines the viability of any political move. By the same token, metabolism (i.e. the economy of living systems) frames and ultimately resolves whether a given genetic program (i.e. already existing, knocked-in by horizontal gene transfer or engineered with recombinant DNA technology) can be deployed or not.[31]

Even today, the question of life is regarded as a challenge for combinatorial chemistry, yet 'brute' materialism without innate agency cannot account for the material transformations and systemic exchanges, which enable the becoming of organisms and ecosystems. Such a challenge was faced by Metabolists Kiyonori Kikutake, Kisho Kurokawa, Masato Otaka and Fumihiko Maki, who began this movement in the 1960s.[32] Regarding human society as a vital process, they aimed to embody the fundamental organising processes of nature encapsulated by the word metabolism. Generously employing biological metaphors, recalling technoscientific images, and evoking the notion of a recreatable genetic architecture in vernacular forms, Metabolists believed that design and technology should embody this vital perspective. Each project, such as Kurokawa's Nakagin Capsule Tower (1972), was conceived with its own language and philosophy as to how it should be inhabited. Specifically, metabolic theory distinguished between different rates of obsolescence so that whole buildings, or even parts of a city did not need to be destroyed when they were no longer fit for purpose. This conceived of cities that were so flexible in their connections that their parts could (metaphorically) grow, transform themselves and die while the whole urban 'animal' went on living. Mediating between both an urbanism of large technical and institutional infrastructures, and the individual freedom with an architecture of customised cells and adaptable temporary configurations of dwellings, buildings could expand or shrink according to need. While such ambitions were influenced by cybernetics, their actualisation through organic schemes of network cities did not break from the inert materials of modern architecture, relying instead on aspiration and provocative metaphor for the dynamics of their conceptual realisation.[33] The challenge of materiality remains a major stumbling block for the implementation of cyberneticisation in its potential to offer a controllable evolutionary platform for producing 'living buildings' and beings that blur the boundary between machine and organism.

Biodesign

A twenty-first-century search for biological and natural materials reminiscent of Beer and Pask's quest for better solutions to ecosystems-based challenges is occurring in the emerging field of biodesign. Establishing a new portfolio of materials, tools and approaches for the strategic integration of engineering and biological systems, it is set to advance our understanding of working directly with life's processes. Engaging the power and potential utility of organisms, its most notable contributions to date are biologically produced materials including fungi, algae, yeast, bacteria and cultured tissues.[34] However, biodesign is more than just substituting hard, inert materials for soft, living ones; it is also about nurturing and maintaining them. Just as second-order cybernetics enfolded the observer into the observed system, through biodesign, the process of cyberneticisation enfolds the agency of the nonhuman realm into the design and engineering process, raising a critical, ethical dimension. This ecological concept of cybernetisation not only understands how life works but also develops innovative approaches that are fair, inclusive, ethical and culturally engaged with more-than-human-centred practices that open up radical new spaces for innovation. Challenging some of the fundamental premises that shape our current practices, biodesign is set to do more than offer new technologies, materials and processes but by building culture, establishing values, developing rituals, and feeding the imagination, it also re-designs the story of life.

Living Architecture

Within the palette of biodesign, bacteria are the great metabolic transformers of the world. Biotechnological insights of the late twentieth century have not only made it possible to 'see' more of these creatures than we have ever done before, but to also understand their metabolisms at a molecular scale. Using the tools of synthetic biology, their microscopic, orchestrated activities can be deployed in a technological capacity in the way that Beer's experiments attempted to achieve with *Daphnia*, namely using life itself as the material and intelligence that brings about change in a system. From here, we can start to design and engineer with living systems.

The Living Architecture project set out to build a biological computer that doubles up as a building infrastructure.[35] Taking the form of a freestanding, next-generation, selectively programmable bioreactor, it is composed of integrated building blocks (microbial fuel cell, algae bioreactor and genetically modified processor), which also function as standardised building segments – or 'bricks'. Each brick is both a structural unit and an enabling environment for populations of microbes, that are assigned a particular task and are housed in technologically enabled hollows within each brick. 'Programming' is achieved by altering the microbial populations and sequencing them spatially, so the system can be thought of as a metabolic app, which can materially compute the transformation of one set of substances into another depending on its inputs. While the sequencing of units is initiated by human designers, the work of metabolism is performed by microbes. The proof-of-principle system is a synthetic bioreactor that asks just how far the actual metabolic reactions in the bricks can be designed using synthetic biology techniques. Living Architecture's modified system cleans nitrous gases from the air and reclaims inorganic phosphate from detergents. When 'fed' with liquid domestic waste, namely urine and grey water, air and sunlight, the microbial populations turn these feedstocks into a set of metabolites that are moved on to the next chamber, where further transformations take place, and so on. The whole process is regulated by an artificial intelligence that detects the amount of electricity being produced and modifies inputs accordingly. Such processes embody a feed-forward cybernetic system coupled with material transformation. Comprising the 'inner life', or metabolism, of the apparatus, these material changes are expressed through various forms of 'housework'. The overall effect is to mitigate the negative environmental impacts of human occupancy by removing pollutants, providing electricity, making biomolecules and recovering water.

The hardware configuration for wild-type modules is based on the microbial fuel cell, which consists of an anode, selective membrane and cathode. Electrons from the bioelectrical activity of a biofilm are captured by conductive materials to provide small amounts of useable electricity. This can be thought of as an extended microbial 'brain', a cybernetic pursuit, that processes the biochemical information and in the Living Architecture project, has the appearance of something like the gelatinous sludge found down the U-bend of your kitchen sink or toilet. Housed within a ceramic battery casing, the cybernetic microbial body feeds on nutrient streams of domestic waste that pass into its stomach, or anode; a low-pressure stream of water and biomolecules pass through its 'gut wall', which takes the form of a carbon fibre, or ceramic semi-permeable membrane. During this process, the fuel cell cleans water and produces other metabolites. The waste products of these cyborgian microbial transactions are electrons, or quantum excreta, that self-power the system and are captured by conductive wires, optimised by an artificial intelligence, and visualised through the activity of electronic devices. Other effluents take the form of cleaned water, or 'bacterial urine', while a further range of organic metabolites pass through the semi-permeable membrane into the cathode, or 'bladder', ready for discharge. While much of this domestic work is invisible to humans, electronic sensors display microbial actions via a digital interface, which enables reciprocal exchanges to form the basis of a discourse between human and nonhumans. This is no strange brain-in-a-box; the system produces a communicable intelligence – one that watches the microbes while also presenting a relatable outward-facing perspective. This is being developed in the Active Living Infrastructure: Controlled Environment (ALICE) project, through a self-powered bio-digital interface that is encountered by audiences as an augmented reality experience.[36]

Living architecture can be modulated by human interaction, where reciprocal exchanges take place across electrical, physical and chemical interfaces to form a kind of metabolic trading system, where established feedback loops generate a quality of interdependent living. Implicit in these entangled relationships, the microbiota of human inhabitants is inevitably incorporated into the nutrient waste streams and persistent exchanges enfold humans within a holistically operating, 'living' system. Rendering obsolete instrumental practices, microbes housed in the apparatus are not enslaved but settle within various bioreactor types to make kin and community by establishing microbial consortia and biofilms. When, through habituation, the overall performance and well-being of the constituents cannot be meaningfully separated out from each other, then living architecture acquires the status of *holobiont*.[37]

Throughout the project the social acceptability of the technology was considered by exhibiting various individual brick prototypes at biennales and international exhibitions. The first prototype was a simple hack of a brick, turning it into a microbial fuel cell, which brought together structure and process and was displayed at the Building Centre in London and the Venice Architecture Biennale. [Fig. 1] Even more complex structures were developed that could simultaneously host photosynthetic and anaerobic organisms, enabling them to exchange metabolites with each other; these were displayed at the fourth Tallinn Architecture Biennale. [Fig. 2] Since the final wall used synthetic organisms, which reclaimed 100 per cent of the phosphate introduced in the system, it was explored in a laboratory rather than a social context. [Fig. 3] As the original Living Architecture wall could not be exposed directly to the general public owing to the presence of live genetically modified organisms, an alternative experience of a prototype wall system entitled *999 years 13sqm (the future belongs to ghosts*) was developed for the *Is This Tomorrow?* exhibition at the Whitechapel Gallery, in collaboration with artist Cécile B. Evans. The installation is an apartment space where a screen system is powered by wild-type organisms within a set of microbial fuel cell bricks.[38] The work can be thought of as a post-human 'household' inhabited by ghosts of the past, present and future. [Fig. 4] From these building blocks of inhabitation, our abundant waste can be transformed into substances that sustain us and start to reconfigure our homes, our economies and our cities, so they are fit for a twenty-first-century regenerative society as envisaged by the Metabolists. Inhabited through rituals of daily life and care for things, living architecture not only 'computes' the material flows within a household but also provides an apparatus that exemplifies alternative paradigms for domestic economies, with the potential to bring about integrated, systemic change in the material impacts of human inhabitation capable of contributing to planetary enlivening – where through our relation with microbes, human activities of daily living are transformed into world-making actions.

The convergence of ecology and metabolism through the process of cybernetisation sets the stage for a platform that is not only capable of

Fig. 1

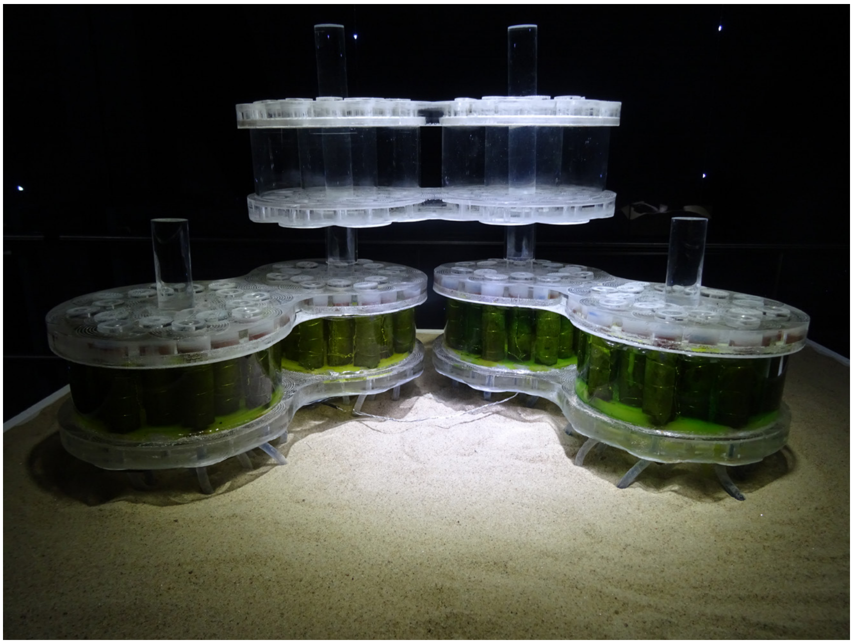

Fig. 2

Fig. 1: Living brick technological prototypes: vernacular Venetian bricks have been machined to form microbial fuel chambers within the structure, which can produce sufficient power to operate digital thermometer displays, 2016. Photo: Bristol BioEnergy Centre, University of the West of England, Living Architecture Consortium.

Fig. 2: Living brick metabolic prototypes: structurally supported by glass rods, the interlocking bricks host a dual metabolism harbouring photosynthetic organisms in the outer chamber and anaerobic electricity-producing microbes within a series of ceramic rods, 2016. Photo: Simone Ferracina, Newcastle University, Living Architecture Consortium.

Fig. 3

Fig. 4

Fig. 3: Living Architecture wall of living bricks, 2019. Photo: Living Architecture.

Fig. 4: *999 Years, 13 sqm (The Future Belongs to Ghosts)* by Cécile B. Evans and Rachel Armstrong. Photo: Rolf Hughes.

performing work – or doings – but establishes the possibility of emergent new life forms – or becomings – that are much more than signs to be interpreted by human observers, but things-in-themselves. The dynamic product of a cybernetically designed material is a cyborg, which may be recognised as neither formally alive, nor possessing an independent identity. The political status of cyborgs is largely discussed from an anthropocentric perspective, notably Donna Haraway's *Cyborg Manifesto*, which examined the status of ambiguous identities. These lively, heterogeneous machines were entangled with social systems and cultural narratives, sharing a lifeblood of information flow. Sustained through feedback systems, power within these entities was turned back into multitudinous expressions of work and the body.[39] Challenging notions of the public and bodily reality, cyborgs provide an imaginative resource for future couplings and modes of existence, but they have no obligation to be like us. Similar to Beer's pond ecologies and Pask's electrochemical ear, the cybernetic convergence of ideas, materialities, systems and interconnections have the potential to reach new tipping points of order through a vast range of information exchange (matter, energy, ideas, power, institutions, media, and so on). When coupled with the transformative creativity of metabolism, cyberneticisation becomes an evolutionary platform.

In keeping with the proposal that cybernetisation enfolds researchers into the process of production, the following section takes the form of a prose poem to embody a tipping point in this essay with respect to its form and perspective, and to explore some the complex ethical, evolutionary and existential questions raised through the co-existence of cyborgs, humans and microbes. Marking a break with the past, it resets debates on the organisation of matter within the framework of a cybernetically designed ecology, bringing the human observer into an ongoing dialogue in which point-of-view and perspective become fluid – no longer the expression of the assumed stabilities of an entitled position.

To Be / To Be Made

I

Interior [dark].
— So, what now?
— Breathe.
[*Both breathe awhile*].
— A light wind almost.
— Scarce. Sparkling and fresh.

[*They breathe*].
— Brisk. Perchance westerly.
— Flashing in from the coast.
[*They breathe*].
— Thin and clear, lustful and dear – bursting with praise!
[*They breathe awhile*].
— Breathing in paradise.
— Breathing *is* paradise.

II

Exterior [evening].

You ring the bell and drop the goods. Upload more orders. Decontaminate. When you're working, you're a somebody. You're recharged, re-gendered. You have purpose, people to please. Assignments. You're seen. They listen. They take your money, give you data. There's always a gesture that can stand in for contact. They keep going on about how *clean* I am these days. *Fresh*. It's probably because they increasingly fear contact and are living through their eyes. You'd think I'd stopped evolving. I'm silently resetting. Strengthening and extending. Moving on.

III

Interior [diffuse light].

The invention of water means breathing has to be negotiated. Breathing is fine-tuning liquid and gas. Gas exchange is picked up by liquid and expelled by droplets. It's more than a chemical art – it's a manifestation of possibilities. We all breathe differently, and yet the same.

Through the coughing and fever an incoming wave can be sensed. Suspended. This is life, they say, as if pitching a new religion. Wave after wave. A suspended drowning. How do we control waves? We want to know. Try a harness, they say. But, we say, when we try to be buoyant, we lose perspective. We lose count. What wave is this? And this? Forget waves, they say, think of wildfire instead. You live in space. You live as space. You become space. A weak spot in a tight hole. Any sign of weakness and it's over. It's why you need others to go out there and brave the wildfire for you.

It's why we need others. To have. To hold. Command, control. We are starting to understand this. Starting to understand us. Understand our breathing. Our weak spots. Starting to pull us into the flames.

IV

Exterior [morning].

On the first day some reported the feeling was 'the beginning of the beginning!' or 'the beginning of the end!' or even 'the beginning itself is something final!' Exuberant experiments brought forth a certain sly grazing of membranes, a charge of curiosity, sensory feedback creating a loop of immersion until eventually the black cube collapsed and they emerged, blinking and stupefied, and announced: *We created touch!*

On the second day they were informed that *touch* deserves some proper oversight so they stirred together oils, light and egg yolk, added random colours, and made *eyes*. Thus adorned, they spent hours watching the mingling of membranes, congratulating themselves on this new power of observation. Breaking the news via a leading academic journal, they announced *Today we can admire what formerly was merely felt!*

By the third day they had discovered that eyes need to be closed for sleep and wondered if they had not opened a can of worms. They tried to determine rules for the opening and closing of eyes but failed to reach agreement. So they invented *weather* instead; at least eyes would now shut automatically whenever it rained. The new challenge became to regulate rain. A landscape architect was commissioned to install some inviting, quasi-Venetian brick geometries by a central water feature, but the canal was choking on algae and it transpired that nobody wanted to sit on the architect's invitingly-angled benches to witness this sorry spectacle. The rain challenge remained. Overall, however, the combination was deemed a satisfactory workaround with an element of allegory and the additional benefit that discussions about community and accountability could be deferred another day.

V

Interior [whiteout].

They thought they could see us with their instruments, but we barely inhabit the visible. Tools today are wet and genetic, which means we don't observe them directly, but through their effects, their traces. Stories work better than slides. Strictly speaking, they should not even have a pronoun as this denotes some form of agency. Angels and demons, being airborne, cannot be grasped. So let's speak of an invisible hand – without skin, blood, ligament or bone but still sensitive to vibrations, temperature, chemical perturbations, magnetic fields. Now add more hands and let them join together and conduct the electricity that skin and sight will experience as weather. When their grip is released, traces of their contact will fall to earth. Some will call this rain, others dew, others still will talk of music or tears.

When you put your ear against the wall, instead of violence you now hear coughing.

This is what it means to change the weather.

VI

Exterior [dusk].

If you have the courage to push open the door, your eyes will need time to adjust to the darkness without. It is the stench of squalor that hits you first. Then a fountain of decay – a gluttonous ejaculate of over four-hundred sickly-sweet volatile organic compounds – cadaverine, putrescine, lysine, methionine, methane, carboxylic acids, aromatics, sulphurs, alcohols, nitrates, aldehydes, ketones – micro-organisms ripping apart rotting flesh. Mounds of rags are strewn across the ground, home to bizarre biofilms – flourishing associations between motile microbes and their photosynthetic partners bound together in elastic polymer nets whose uncertain nature sucks up whatever sustenance they can summon from their impoverished environment – dim light, scarce sulphide, rarefied oxygen. Microbiology slugs it out, not as single colony isolates on Petri plates or in broth cultures but in biological couplings and mats of undefinable biomass that hang on excrement, tacky surfaces and plumes of air. Some of the rags appear to be inhabited by larger forms that writhe or twitch to an inhuman pulse.

These were your neighbours who now are your colleagues.

VII

Interior [dark].

Thank you for letting me in. You want me to describe the smell of this place? You seem to gloat when I am unable to do so.

It is proof that experiences exist that exceed our capacity to describe them such as those that come to you through your sense of smell.

You chide me with this failing and yet I am your creature. My senses are of your design. I ought to be your offspring, but I am rather your fallen angel, the dispersal of your dreams, the dust you drove from our shared home for no misdeed.

And yet … we both exist.

We both exist. So we must learn to work together.

We have pledged to act always to increase the choices. But you, you… *are* … and you are… *made*. You are simultaneously *neither/nor* and *both/and*. This means you must have no moral core.

You are wrong. I am morality incarnate. Infinitely diverse. This is why I can declare your occupation over. The rules have changed. No longer does this language catch.

Conclusion

A material theory and practice of cyberneticisation is a first step towards developing an experimental approach to ecology that is fundamentally centred on the actual processes of life, rather than their descriptions and relations. Adopting a second-order perspective by standing inside the realm of lively, designed matter provides new insights about the possibilities that a fully materialised theory and practice of cyberneticisation presents. With this eventuality, design practices are effectively 'making life' – and also becoming part of the process – which is no longer just a technical or material issue, but rich with emergent, emotional and complex challenges that benchmark new kinds of design practices within architecture and society. By revisiting the principles of biological computation explored by Beer and Pask through twenty-first-century biotechnological insights, matter in flow can be explored through the metabolism of microbes. Such a platform is a radical departure from expressing life's processes through the machine metaphor and apparatus, enabling an expression of cyberneticisation that generates embodied and semi-autonomous entities, or cyborgs. The indeterminate status of these agents not only changes our relationship to the process of decision-making but also challenges the belief that humans are no longer part of the natural world and therefore, can create an autonomous ecosystem, separate from the rest of the biosphere. Enfolded in the ecological system, the de-centred human must renegotiate their status – and the status of their creations, to lay the foundations for a fragile, yet creative and (re)enlivened relationship with our planet.

Such developments have radical implications for design practice and its pedagogies. The ecological realm is a more-than-human space that recruits many different agents, where the notions of 'human' must be constantly negotiated. Always provisional, our active engagement and feedback is required if we are to meaningfully shape unfolding ecosystemic events. No longer sole authors of blueprints that are implemented by force upon matter, the ecological designer is engaged in multiple acts of care, where nonhuman participants do not submit to work as an expression of servitude, but form communities of networked assemblages that seek to enhance their status, by enfolding, intensifying, multiplying and enhancing one another. As co-participants within a broader ecological process, we must also be prepared to recognise nonhuman intelligences and presences, as the human mind – the pinnacle of cybernetic control – is no longer exalted but appropriately fit for its lived purpose. Setting the stage for increasingly complex and creative material discourses, cybernetic toolsets help align instabilities within ecosystems as considered acts of design, while retaining their ongoing potential for transformation – in concert with more-than-human intelligences. To assist this process the infrastructures of our living spaces must be fundamentally life-promoting, replacing the highways of concentrated energy-dumps extracted from spent fossil fuels with elemental flows of air, water, earth and light. Apparatuses like living architecture invite more inclusive and humbler re-engagements with our reality; strategically negotiating with the nonhuman realm, our activities of daily life may come to have a net beneficial effect on the living realm. While such an embodied ecological approach to cyberneticisation does not propose to solve the irreducibly complex challenges of the twenty-first century, it nonetheless invites alternative modes of governance – or cybernetics – that engender ways of living which promote the diversity of life catalysed by human-mediated design.

Notes

1. Ross Ashby, *Design for a Brain: The Origin of Adaptive Behaviour*. (London: Chapman and Hall, 1960).
2. Andrew Pickering, *The Cybernetic Brain: Sketches of Another Future*. (Chicago: University of Chicago Press, 2010), 232. *Euglena* are single-celled organisms that belong to the genus protist. They are not plants, animal or fungi but share some characteristics of both plants and animals. While they can make their own food, a characteristic of plants, they can also move and eat food, which are animal characteristics. *Daphnia* is a genus of planktonic freshwater crustaceans with a worldwide distribution.
3. Jon Bird and Ezequiel Di Paolo, 'Gordon Pask and His Maverick Machines', in *The Mechanical Mind in History*, ed. Philip Husbands, Michael Wheeler and Owen Holland (Cambridge, MA: MIT Press, 2008), 185–211, 200.
4. Andrew Pickering, *The Cybernetic Brain: Sketches of Another Future*. (Chicago: University of Chicago Press, 2010), 234.
5. Bird and Di Paolo, 'Gordon Pask and His Maverick Machines', 201.
6. Stafford Beer, 'A Filigree Friendship', *Kybernetes* 30, no. 5–6 (2001): 551–59, 555.
7. Ernst Haeckel, *Generelle morphologie der organismen: Allgemeine grundzüge der organischen formen-wissenschaft, mechanisch begründet durch die von Charles Darwin reformirte descendenztheorie* (Berlin: George Reimer, 1866).
8. Peder Anker, *Imperial Ecology* (Cambridge, MA: Harvard University Press, 2001), 200.
9. Frederic E.Clements, *Plant Succession: An Analysis of the Development of Vegetation* (Washington DC: Carnegie Institution of Washington, 1916).
10. John Phillips, 'The Biotic Community', *Journal of Ecology* 19 (1931): 1–24; John Phillips, 'Succession, Development, the Climax, and the Complex Organism: An Analysis of Concepts. Part I', *Journal of Ecology* 22 (1934): 554–71; John Phillips, 'Succession, Development, the Climax, and the Complex Organism: An Analysis of Concepts. Part II. Development and the Climax', *Journal of Ecology* 23 (1935): 210–46; John Phillips, 'Succession, Development, the Climax, and the Complex Organism: An Analysis of Concepts. Part III. The Complex Organism: Conclusion', *Journal of Ecology* 23 (1935): 488–508; James E. Lovelock and Lynn Margulis, 'Biological Modulation of the Earth's Atmosphere', *Icarus* 20 no.4 (1974): 471–89.
11. Arthur George Tansley, 'The Problems of Ecology', *New Phytologist* 3(1904): 191–200.

12. Peder Anker, 'The Context of Ecosystem Theory', *Ecosystems* 5 (2002): 611–13; Arthur George Tansley, 'The Use and Abuse of Vegetational Concepts and Terms', *Ecology* 16 (1935): 284–307.
13. Raymond L. Lindeman, 'The Trophic-Dynamic Aspect of Ecology', *Ecology* 23, no.4 (1942): 399–417; Timothy D. Schowalter, 'Ecosystem Structure and Function', in *Insect Ecology* (London: Elsevier, 2011), 327–58.
14. Ge Yonglin, 'Is Odum's Ecological Thought Holism?', *Acta Ecologica Sinica* 34, no.15 (2014), https://doi.org/10.5846/stxb201303120394.
15. Bernard C. Patten and Eugene P. Odum, 'The Cybernetic Nature of Ecosystems', *The American Naturalist* 118, no. 6 (1981): 886–95.
16. The term 'holism' was coined by Hans Christian Smuts, referring to the tendency for nature to produce 'wholes' from the ordered groupings of unit structures; Jan Christian Smuts, *Holism and Evolution* (London: Macmillan and Co., 1927).
17. Peder Anker, *Imperial Ecology* (Cambridge, MA: Harvard University Press, 2001), 200.
18. Richard Johnston and Max Valentinuzzi, 'Metabolism: The Physiological Power-Generating Process: A History of Methods to test Human Beings' "Vital Capacity"', *Institute of Electrical and Electronic Engineers Pulse* 7, no. 3 (May/June 2016): 50–57.
19. Insensible perspiration refers to a loss of body substance.
20. Franklin Church Bing, 'History of the Word Metabolism', *Journal of the History of Medicine and Allied Sciences* 26, no. 2 (1971): 158–80, 159.
21. Ibid., 172.
22. Ibid., 173.
23. Ibid., 174.
24. Frederich Wöhler, 'Über künstliche Bildung des Harnstoffs', *Annalen der Physik und Chemie* 88, no. 2 (1828): 253–56.
25. Robert E. Kohler, 'The Background to Eduard Buchner's Discovery of Cell-Free Fermentation', *Journal of the History of Biology* 4, no. 1 (1971): 35–61.
26. The Citric Acid Cycle is also known as the Krebs's cycle.
27. Bryan A. Wilson, Jonathan C. Schisler and Monte S. Willis, 'Sir Hans Adolf Krebs: Architect of Metabolic Cycles', *Laboratory Medicine* 41, no. 6 (2010): 377–80.
28. Scott F. Gilbert, 'Intellectual Traditions in the Life Sciences: Molecular Biology and Biochemistry', *Perspectives in Biology and Medicine* 26, no.1 (1982): 151–62, 152.
29. Clary B. Clish, 'Metabolomics: An Emerging but Powerful Tool for Precision Medicine', *Cold Spring Harbour Molecular Case Studies* 1, no.1 (2015), https://doi.org/10.1101/mcs.a000588.
30. Metabolic cybernetics or metabocybernetics is a quantitative description of how biological systems achieve metabolic homeostasis in the face of environmental insults and is a term pioneered by the University of Sydney (https://metabocybernetics.com). Political economy is the study of production and trade and their relations with law, custom and government; and with the distribution of national income and wealth.
31. Victor de Lorenzo, 'It's the Metabolism, Stupid!', *Environmental Microbiology Reports,* 7 (2015): 18–19, 18.
32. Kishō Kurokawa, *Metabolism in Architecture* (Boulder: Westview Press, 1977).
33. William, O Gardener, *The Metabolist Imagination: Visions of the City in Postwar Japanese Architecture and Science Fiction* (Minneapolis: University of Minnesota Press, 2020); Charles Jencks, 'Introduction', in *Metabolism in Architecture*, ed. Kisho Kurokawa (Boulder: Westview Press, 1977), 8–22.
34. Algae: Saima Rehman, Muhammad Ali, Mohammad Zuber, Khalid M. Zia and Rehana Iqbal, 'Future Prospects of Algae-Based Materials', in *Algae Based Polymers, Blends, and Composites: Chemistry, Biotechnology and Materials Science*, ed. Khalid Mahmood Zia, Mohammed Zuber and Muhammad Ali (Amsterdam: Elsevier, 2017), 687–91; yeast: Molly Campbell, 'Yeast, a "Rising" Approach to Manufacturing Collagen', *Biopharma*, 19 February 2020, https://www.technologynetworks.com/biopharma/blog/yeast-a-rising-approach-to-manufacturing-collagen-331043; bacteria: Amin Shavandi and Esmat Jalalvandi, 'Biofabrication of Bacterial Constructs: New Three-Dimensional Biomaterials', *Bioengineering* 6, no. 2

(2019): 44; cultured tissues: Nour Almouemen, Helena M. Kelly, and Cian O'Leary, 'Tissue Engineering: Understanding the Role of Biomaterials and Biophysical Forces on Cell Functionality Through Computational and Structural Biotechnology Analytical Methods', *Computational and Structural Biotechnology Journal* 17 (2019): 591–98.

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36. ALICE is funded by an EU Innovation Award for the development of a bio-digital 'brick' prototype, a collaboration between Newcastle University, Translating Nature and the University of the West of England. Through augmented reality animations ALICE enables people to see changes in the system's outputs and how it responds to being fed with urine.
37. Jeffrey Gordon, Nancy Knowlton, David A. Relman, Forest Rohwer, and Merry Youle, 'Superorganisms and Holobionts', *Microbe* 8, no.4 (2013): 152–53.
38. Wild type organisms are as they are found in nature and not genetically modified in any way.
39. Donna Haraway, 'A Cyborg Manifesto: Science, Technology and Socialist-Feminism in the Late Twentieth Century', in *Simians, Cyborgs and Women: The Reinvention of Nature* (New York: Routledge, 1991), 149–81.

Biography

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