

## Chapter 3.3 Material Ecology 1 – Four Ecologies of Engineered Living Materials Research

Martyn Dade-Robertson

Meng Zhang

*“It rose into the evening darkness, a massive city core, dwarfing even Chengdu’s skyscrapers. (...). Soon the growing core would overwhelm the wet-tiled roofs of the old city. Then Huojianzhu, the Living Architecture, would become Chengdu entirely. (...) It grew on lattices of minerals, laying its own skeleton and following with cellulose skin (...) Infrastructure strong and broad, growing and branching, it settled roots deep into the green fertile soil of the Sichuan basin. It drew nutrients and minerals from the soil and sun, and the water of the rancid Bing Jiang; sucking at pollutants as willingly as it ate the sunlight which filtered through twining sooty mist.”*  
(Bacigalupi 2010: 1)

When considering material ecologies in architecture, we can identify two distinct but overlapping definitions. One type of material ecology emerges from architectural thinking from the *new materialist* paradigm in architecture. This category is exemplified in the research of Menges and Oxman and methods such as material based design computation, in which form, material function and fabrication are considered as interrelated parameters and the standardisations of industrial production are rejected (Menges, 2012; Oxman *et al.*, 2015). The second category offers a view of materials and their synthesis as operating in a broader industrial context. This type of material ecology study describes manufacturing from a high level systems view, taking into account all energy and material flows in industrial processes (Collier and Alles, 2010). The use of the term ecology in both categories makes implicit reference to the study of natural ecologies. Both are driven by a biomimetic instinct to transform traditional industrial processes into something more akin to a natural ecology. In other words, to move industrial process towards the efficiencies of energy and matter and the complexity of material organisation we perceive in nature. What if we go beyond biomimicry? What if we address the ecology of materials production found in nature directly and seek to harness it for our own ends?

The quote above from Bacigalupi’s short story *A Pocketful of Dahmer* captures a new material ecology. The idea of growing buildings and buildings as living and breathing organisms is present in contemporary architectural discourse (see for example (Armstrong, 2012) (Imhof and Gruber, 2015)). However, much of the research in this area remains speculative and, as Cogdell has pointed out, far removed from biological reality (Cogdell, 2018). Architecture has also had a superficial relationship with biology, often making reference to idealised and mathematically abstracted biological forms with referencing the processes by which biological form emerges (Hensel, 2006).

Scientific advances are being made, however, that may realise at least some aspects of the speculative architecture imagination. Recent developments in Engineered Living Materials (ELMs) research, for example, channel a similar ambition. Researchers in ELMs offer a vision of fabrication done using living cells as material 'factories'. The ultimate aim is to enable the same feats of self-assembly seen in the growth of a tree for example, where a small package of genetic information (a seed) could be planted and, using the nutrients and energy in its immediate environment, is capable of self-assembling complex structures and composite materials (Nguyen *et al.*, 2018). ELMs research represents a disciplinary intersection between Synthetic Biology and Materials Engineering (Tang *et al.*, 2021) in which Synthetic Biology is understood as the application of 'rational' design principles, from other domains of engineering, to biological systems. These rational principles include the modularisation and standardisation of genetic parts, such that they can be reassembled to make new functional "genetic circuits" (Andrianantoandro *et al.*, 2006).

Approaches to ELMs based on Synthetic Biology, however, appear to be very different from the philosophies guiding material ecology. Where material ecologies move beyond industrial modes of production and recognise complexity in the fabrication of materials, Synthetic Biology looks to de-complexify biology through models of design and engineering which come directly from the design of traditional industrial systems.

This dichotomy and the implications of Synthetic Biology approaches has been critiqued by us and others elsewhere (Dade-Robertson, Ramirez-Figueroa and Zhang, 2015; Dade-Robertson, 2021). Much of the work in Synthetic Biology and, by association, ELMs is nascent and there are profound challenges in scaling (both in terms of size and complexity) given the current approaches. Rather than critiquing current approaches, therefore, I will suggest how ecological thinking may frame research in ELMs. Our focus here, is not on the practical applications of ELMs to the built environment but on how ecological thinking may challenge existing methods in ELMs research and enable the scale up that will allow us to conceive of a future, in which buildings might be grown rather than constructed.

Our aim is to add to the discourse on ecological thinking more generally by referencing what we describe as multiple ecologies in designing with biology. To this end we articulate four connected ecologies with a focus on ELMs and what we define as biological fabrication – the processes by which living cells make materials. ELMs research also addresses the concept of creating materials which retain living or life-like properties after they have been fabricated. These four ecologies have a philosophical and a practical aim, attempting to reframe current methods in ELMs, extending the discourse on new materialism and dispelling myths such as 'DNA as blueprint of life' by introducing older biological thinking (e.g. Waddington's *Creodes*). We will also cite contemporary thinking from systems biology and examples which include considering single celled organisms, such as

microbes, as distributed multicellular organisms. For those outside the field of ELMs (and even more exclusive field of ELMs as applied to the built environment) these biological ecologies may act as useful metaphors or mental models on which to devise design methods and philosophies. Architecture, after all, always exists in the biological contexts of us and the ecosystems of which we are a part.

### **Ecologies of genetic information**

One of the greatest misnomers in biology is that “DNA is a blueprint for life”. This statement implies that the DNA of a cell contains the equivalent of a constructional drawing representing a living organism in its entirety. There is, following this metaphor, a direct relationship between genotype (the organism’s set of genes) and phenotype (the organism’s observable properties). This line, or variations on it, are often used in popular media accounts of biological science and even in contemporary scientific papers (Feitelson and Treinin, 2002). The metaphor is, however, misleading. Genes encode information necessary for the assembly of amino acids into polypeptide chains. These chains then fold to become the complex structures we know as proteins that ultimately become the structural components of the cell and the functional actors in a cell’s metabolism. The choreography of protein assembly, the formation of cellular structures, the dynamic interaction of the cells metabolism, not to mention the formation of complex multicellular organisms requires that information is distributed through the system as a function of the interaction of many billions of parts, and as an emergent phenomenon through information which is not pre-written (Noble, 2008). Furthermore, the DNA ‘blueprint’ is malleable. Genes are themselves often controlled by the protein products they encode for. This process is known as gene regulation and is akin to a building which continually rewrites its own blueprint.

Biological systems are highly responsive to their environment. The information required for a biological system to operate, therefore, is often found outside the organism. This fact is best illustrated when we look at the morphology of organisms with developmental plasticity. A feature of mammalian development is that the early and formative stages of growth is typically done in the highly protected and controlled context of the womb. Plants on the other hand, do their development in direct contact with the outside world and often need to adapt to their surroundings, especially as they are fixed in place and are reliant on their local conditions. This means that no two trees from the same species, for example, are identical in form and size. In fact, they can vary quite radically. They exhibit similar traits and patterns of growth but are profoundly affected by factors such as the distribution of nutrients, availability of sunlight and the proximity and activity of other plants and animals.

We see even more miraculous morphologies from the study of single celled organisms such as bacteria which contain no DNA blueprint for collective pattern formation but, in the right conditions, for example grown on agar plates, exhibit colony morphologies with complex branching, swarming and fractal like patterns (Ben-Jacob, 2009). Form, in these cases emerges as a production of cell motility, nutrient diffusions, and the interaction of cells with each other and the surface of the agar.

This informational complexity occurs because living systems are thermodynamically open (Armstrong, 2015). This contrasts with human engineered systems which tend to be thermodynamically closed. We go to great lengths to protect human engineered systems (especially sensitive mechanical and electrical systems) from environmental perturbations that would cause them to malfunction. In contrast, in viewing biological systems at any scale, we observe that there are energy and matter flows across cell membranes, between organisms and across a networked ecosystem. The conceptual distance between thermodynamically open and closed systems means that applying the framework used to design one to another is limited. Yet in Synthetic Biology we do just that by adopting the language of modular hierarchies and conducting experiments within the thermodynamically closed environments of the lab, the incubator, and the petri dish.

An attempt to engineer a biological system requires finding these external and internal sources of information and altering their content. While, through fields such as Synthetic Biology, we have tools for altering the information content of DNA, we do not yet have the tools to read or write these other information sources or to fully understand the ecology of their interactions and, as importantly I would suggest, we don't yet have the right mental models for the task.

## **Ecologies of epigenetic information**

The discovery of the structure of DNA first reported in 1953 (Watson and Crick, 1953) marked a turning point in the field of biology and mitigated a sense of 'physics envy' for a field that was often as much of an art as a science. Molecular biology has allowed for the development of new methods for observable biological traits to be indexed directly to sequences of molecules. However, the primacy of the gene in biological research has sometimes been at the expense of the less reassuringly precise, but no less necessary, systems view of biology. Prior to the development of molecular biology, fields such as developmental biology, faced with the black box of the cell, needed to develop theories which treated biological systems with abstractions. An influential example of such an abstraction was described by Waddington (Waddington, 2014) in which he describes the process of biological development (where living cells subdivide and transition through states to specialise into tissues) through the metaphor of the 'epigenetic landscape'.

Cells within a multicellular organism all contain the same DNA. Despite this, multicellular organisms have a vast range of cell types which perform different functions. This is because in each cell not all the DNA information is being read in the same way or at the same time. Instead, the expression of genes is regulated, and this regulation is context dependent. Tiny changes in the environment in which the cell develops can alter the developmental pathway for a cell. In Waddington's conceptualisation of this process, he imagines a cell state as represented by a ball rolling down an undulating topography. The ball's position in the landscape relates to its developmental state. The ball starts at the top as an undifferentiated stem cell and rolls down the valleys to a final destination relating to its specialism i.e. the class of tissue it will help to form. Slight changes to the surface of the landscape can cause the ball to roll in a different direction meaning that the cell has a different developmental destiny. This destiny Waddington describes as a '*creode*', meaning necessary path.

The architecture of this landscape (illustrated in Figure 1) is drawn as a surface tied by guide ropes to a field of stakes. The stakes represent genes and the guide ropes are flexible such that they can be articulated to alter the topography of the surface. The guide ropes thus represent gene expression and the alteration to the landscape they bring about are epigenetic changes.

### **[Figure 1 Here]**

We can, using genetic engineering, alter this landscape through the addition or removal of the gene stakes (Figure 2), however this is not the only method.

The depiction of the developmental landscape is a helpful analogy. In our own work we have begun to see the role of biological fabrication as shaping this landscape such that our cells become specialised to produce a particular material. In a further development of Waddington's model, we have suggested that the surface of the landscape should be considered as composed of varying materials, with areas which are 'stretchy' patched with parts which are rigid and unyielding. These different materials can be mapped on to developmental plasticity – where the landscape is amenable to alteration or resistant to influence and change (Figure 3). The gene 'stakes' themselves should also be considered heterogeneous. Some are vital – providing the primary structure on which the landscape is held up. Others, have only subtle impacts on the shape of the surface and could be removed without making a difference. This search for the fundamental gene 'stakes' is associated with research into the minimal cell in which, often simple organisms such as bacteria have genes 'knocked out' to understand the minimum genome possible for the organism to survive (Lachance, Rodrigue and Palsson, 2019).

### **[Figure 2 Here]**

### [Figure 3 Here]

All biological design is essentially about editing this landscape. Our current Synthetic Biology methods involve editing through the removal or insertion of genes 'stakes' and the hope that we don't cause the landscape to collapse in the process. However, there are many other ways in which the landscape could be altered. Since the length of the guide ropes (to further extend the metaphor) are context dependent, the shape of the landscape must, to some extent, be editable from the outside, or as we view the diagram, from above. Cultivating the environment is, essentially an agricultural process and in the work from our lab we have seen a graphical illustration of how the epigenetic landscape can be changed. Dilan Ozkan (Ozkan *et al.*, 2021) has been working with the cultivation of mushrooms to achieve different structures and morphologies. Mushrooms of different species have various stages of development and potential states from the root network, which is morphologically simple and occupies subterranean environments, to the fruiting body, which is morphologically complex and for which there are a vast variety of different types. In working with mushrooms Ozkan has identified different conditions which can inform changes in morphology including humidity and air flow. By altering these environmental conditions, within a purpose-built incubator, Ozkan can predictably alter the morphology of the growing mushrooms within broad tolerances we term a probability space. In the visualisations which emerge from this work we are getting a glimpse into the creode of the organism (Figure 4).

### [Figure 4 Here]

#### **Ecologies of multiple species.**

Biological systems don't exist in isolation from their environment, they also don't exist in isolation from one another. In microbiology, for example microorganisms are often treated as simple single celled species isolated and studied outside their context. In practice however, bacteria of different species live as communities, often in complex multi-microbial communities known as biofilms and sometimes described as 'like cities'. In these city-like communities microbes, occupy different parts of a networked metabolism and build extracellular materials for protection and communication (Watnick and Kolter, 2000). Indeed, bacteria could be considered not as single cell organisms but rather, as highly successful distributed multicellular organisms. Microbial communities have been associated with the creation of geological structures including stromatolites and cave structures such as stalactites and stalagmites which, while mostly formed of calcium carbonates cementing sediments, also show evidence of a wide range of carbonates, iron precipitation, sulphides and silicates (Banfield and Nealson, 1997). Of particular interest are the formation of microbiolites which are mineral forming microbial mats which lead to a range of bio-

geological structures including stromatolites, thrombolites and leiolites. These structures are described as geochemical bioreactors containing microbial 'guilds', with each serving a different function in a complex whole. Different zones of the microbial mat exhibit a range of crystal types of calcium carbonates alongside other organo-minerals and extra-cellular polysaccharides. We are however only just beginning to understand these structures and material processes. Harnessing the intelligence, not of single organisms but as designed synthetic ecosystems may enable us to develop a fundamental new form of biological fabrication. We can already see from experiments on the microbial synthesis of cellulose, for example, that approaches which use multi-microbial communities such as the kombucha method (Goh *et al.*, 2012) are more robust and can be conducted in non-sterile environments compared to monocultures which, in our experience, even in relatively sterile lab environments have issues of contamination.

## **Ecologies of practice**

Our final type of ecology refers to human engagement with the biological processes themselves. This discussion is based on personal and anecdotal experience but is, we believe, an important discussion for this sort of research.

As our group embarked on experiments in the field of biological fabrication and ELMs, it was with the recognition of a growing gulf between the design community and scientific practice. Designers working in this area often have limited access to lab resources and scientific expertise. Conversely, applications lead research in fields such as Synthetic Biology are often narrowly focused on a few domains including medicine, agriculture, and chemical synthesis.

If we are to see biotechnologies as initiating a new industrial revolution, as others have (Ito, 2016), then a much broader application focus and interdisciplinary collaboration will be necessary. It is also common to note that many challenges facing such collaborations stem from differences in language, objectives, and educational contexts etc. Yet it seems to us that there much more profound shifts in the way that such collaborations occur is necessary.

Biological technologies are not like other types of technology development. A challenge to our research has often been the framing of technology advancement in terms of Technology Readiness Levels (TRL). TRL, a concept originally defined by NASA, and now widely used, in different forms, by research agencies internationally, offers a scoring system to indicate the level of maturity for a technology from the discovery of basic principles to final mission or 'flight proven' systems. In biotechnology, however, the 'technology' already exists in some form or other in a sophisticated state. To turn a biological system into a technology involves not invention but a reframing of something considered natural, to become artificial and reconfiguring of already natural

tendencies and capacities to suite a different (and often human centred) functional end. The 'technology' to grow a building, I would contend, is readily observable in the natural environment with, following Bacigalupi's short story, *lattices of minerals laying down the skeleton*, a reference to well-known biomineralization processes; *the cellulose skin* observable in the bacterial cellulose skins we grow in the lab and the *branching settling roots* observable in any number of plants and fungi. The key is knowing to look for these processes and knowing how to find them.

An example of this idea of technology development is illustrated by our *Thinking Soils* project. In the project we suggested the development of a bacteria which could detect mechanical changes in a loaded soil and synthesise a strengthening material in response. In our initial experiments we decided to use a lab strain of the bacteria *Escherichia coli*. *E. coli* is one of the most studied organisms in the world, the first to have its genome catalogued and is the workhorse of many molecular and micro-biology experiments. Despite this, we were surprised to discover that no one has ever asked the question whether *E. coli* could detect small mechanical loads or elevated pressures. The search space for biology is simply too big to ask the bacteria all the questions to uncover its capacities. Through a process known as RNA seq. we did indeed uncover multiple genetic responses to elevated pressures (Guyet *et al.*, 2018) and in subsequent experiments with a soil living bacteria *Bacillus subtilis* we have also seen similar and diverse responses. The pressure sensing technology in biology is out there, and already sophisticated but it is also hidden. We were unlikely to discover it without asking the right questions. However, as we engineer the mechanical sensing system in bacteria we take it from a state of mission tested in its natural context (TRL 9) and move it back to TRL 1 by reconfiguring this response for our own needs and, in the process, decontextualising and simplifying it. For us biotechnologies do not fit easily into the TRL rubric.

The question then arises of what we do if we don't know the right questions to ask. One of the tenets of the new materialist paradigm in design is to work with a materials own *tendencies* and *capacities* (Menges, 2015). For biology though the tendencies and capacities are context dependent. Experimental practices which often involve working in sterile environments and altering single variables within tightly controlled parameters can't hope to fully uncover the tendencies and capacities of biology.

In our own work we have recognised this challenge by conceiving of material experimentation using biology as akin to craft. We encourage our team to engage with relatively open-ended material experiments at the beginning of the process by conducting multi variable experiments. This process allows for the possibility of a 'happy' accident but, perhaps more important, we develop a tacit and embodied understanding of the material and process we are working with. In scientific research this tacit and embodied knowledge is often downplayed. Indeed, in descriptions



of early attempts at genetic engineering the perception of experimental approaches as akin to an 'artisanal craft' is used as a derogatory term (Frow and Calvert, 2013). Yet what emerges from these 'artisanal' experiments is a deep understanding of process and the building of expertise. This expertise allows our researchers to achieve consistent results and successes and gain expertise with a material and process that is very hard for others to replicate. They also gain an instinct, or more specifically, can make better founded hypothesis before developing more closed and focused single variable experiments. This initial phase is sometimes referred to as material tinkering (Parisi, Rognoli and Sonneveld, 2017). We find these approaches especially useful in cases where the search space for potential interesting material properties and fabrication techniques is huge but where we can limit the parameters. Material tinkering also involves a wider range of experimental tests including evaluating the sensory and qualitative aspects of a material as well as its functional performances. These early research exercises do not lead to a complete knowledge of the parameter space for biological fabrication, but they give a glimpse into the creode of biological growth and development and indicate where the epigenetic landscape is most malleable and adaptable to change.

The combination of a beyond the TRL level understanding of technology development and practices such as material tinkering, combining tacit and explicit knowledge of biological systems, challenges a linear notion of technology development from initial discovery through to verified system and suggest an ecology of practices based on both craft and scientific enquiry and of discovery driven by challenges and applications.

## **Conclusion**

This chapter has wrestled with an idea of ecological thinking in the field of ELMs. ELMs represent, the possibility of a radical shift on how materials are fabricated and implemented in built environments. ELMs also represent a different viewpoint on the idea of material ecology. We have attempted to move beyond a shallow idea of biological form to described forms of process and practice in materials and fabrication in biological systems, invoking the metaphor of the creode. We have referenced a number of related biological ecologies through, for example, the formation of microbial guilds. And we have suggested an ecology of experimental practices which invoke craft like processes – generating appropriate questions as well as seeking answers. ELMs research is a nascent field relying on a foundation of material science and Synthetic Biology which are, themselves, evolving and maturing. These fields, however, also come with the baggage of specific mental models from other fields including the hierarchy of structure, modular parts and devices and the linear development of technology. These mental models translate into metaphors which both enable and constrain these fields. We have attempted, in the chapter, to provide some alternative metaphors and models aligned with practical examples that may be applicable beyond ecological

thinking for materials. Learning from biology is no longer a matter of biomimicry but of biological material ecologies embedded in our design thinking.

## Bibliography

Andrianantoandro, E. *et al.* (2006) 'Synthetic biology: new engineering rules for an emerging discipline.', *Molecular Systems biology*, 2, pp. 1–14. doi:10.1038/msb4100073.

Armstrong, R. (2012) *Living Architecture: How Synthetic Biology Can Remake Our Cities and Reshape Our Lives*. New York: TED.

Armstrong, R. (2015) *Vibrant Architecture: Matter as Codesigner of Living Structures*. Warsaw: De Gryter Open.

Bacigalupi, Paolo (2010) 'Pocketful of Dharma', in *Pump Six and Other Stories*. San Francisco: Night Shade Books, pp. 1–14.

Banfield, J. and Neelson, K. (1997) *Geomicrobiology: Interactions between Microbes and Minerals*. Edited by P.H. Ribbe. Washington: Mineralogical Society of America.

Ben-Jacob, E. (2009) 'Bacterial Complexity: More is Different on All Levels', in Nakanishi, S., Kageyama, R., and Watanabe, D. (eds) *Systems Biology: The Challenge of Complexity*. Tokyo: Springer Japan, pp. 25–35. doi:10.1007/978-4-431-87704-2.

Collier, P. and Alles, C.M. (2010) 'Materials Ecology: An Industrial Perspective', *Science*, 330(6006), pp. 919–920. doi:10.1126/science.1197478.

Dade-Robertson, M. (2021) *Living Construction*. London: Routledge.

Dade-Robertson, M., Ramirez-Figueroa, C. and Zhang, M. (2015) 'Material Ecologies for Synthetic Biology: Biomineralization and the state space of design', *Computer-Aided Design*, 60, pp. 28–39.

Feitelson, D.G. and Treinin, M. (2002) 'The blueprint for life?', *Computer*, 35(7), pp. 34–40. doi:10.1109/MC.2002.1016899.

Frow, E. and Calvert, J. (2013) "'Can simple biological systems be built from standardized interchangeable parts?' Negotiating biology and engineering in a synthetic biology competition', *Engineering Studies*, 5(1), pp. 37–41.

Goh, W.N. *et al.* (2012) 'Fermentation of black tea broth (kombucha): I. effects of sucrose concentration and fermentation time on the yield of microbial cellulose', *International Food Research Journal*, 19(1), pp. 109–117.

Guyet, A. *et al.* (2018) 'Mild hydrostatic pressure triggers oxidative responses in Escherichia coli', *PLoS ONE*, 13(7), pp. 1–19. doi:10.1371/journal.pone.0200660.

Hensel, M. (2006) '(Synthetic) life architectures: ramifications and potentials of a literal biological paradigm for architectural design', *Architectural Design*, 76(2), pp. 18–25. doi:10.1002/ad.236.

Imhof, B. and Gruber, P. (eds) (2015) *Built to Grow: Blending Architecture and Biology*. Basel: Birkhauser.

Ito, J. (2016) 'Design and Science: Can design advance science, and can science advance design?', *Journal of Design and Science*, 1(1).

Lachance, J.-C., Rodrigue, S. and Palsson, B.O. (2019) 'Minimal cells, maximal knowledge', *eLife*, 8, p. e45379. doi:10.7554/eLife.45379.

Menges, A. (2012) 'Material Computation', *Architectural Design*, 82(2), pp. 14–21.

Menges, A. (2015) 'Fusing the computational and the physical: Towards a novel material culture', *Architectural Design*, 85(5), pp. 8–15. doi:10.1002/ad.1947.

Nguyen, P. *et al.* (2018) 'Engineered Living Materials: Prospects and Challenges for Using Biological Systems to Direct the Assembly of Smart Materials', *Advanced Materials*, 30(19), pp. 1–34. doi:10.1002/adma.201704847.

Noble, D. (2008) *The Music of Life: Biology beyond genes*. Oxford: Oxford University Press.

Oxman, N. *et al.* (2015) 'Material ecology', *Computer-Aided Design*, 60, pp. 1–2. doi:https://doi.org/10.1016/j.cad.2014.05.009.

Ozkan, D. *et al.* (2021) 'Designing a Living Material Through Bio-Digital-Fabrication – Guiding the growth of fungi through a robotic system', in *Towards and configurable architecture. ECAADE 2021*.

Parisi, S., Rognoli, V. and Sonneveld, M. (2017) 'Material Tinkering. An inspirational approach for experiential learning and envisioning in product design education', *The Design Journal*, 20(sup1), pp. S1167–S1184. doi:10.1080/14606925.2017.1353059.

Tang, T.-C. *et al.* (2021) 'Materials design by synthetic biology', *Nature Reviews Materials*, 6(4), pp. 332–350. doi:10.1038/s41578-020-00265-w.

Waddington, C.H. (2014) *The Strategy of Genes: A Discussion of Some Aspects of Theoretical Biology*. Abingdon: Routledge.

Watnick, P. and Kolter, R. (2000) 'Biofilm , City of Microbes', *Journal of Bacteriology*, 182(10), pp. 2675–2679. doi:10.1128/JB.182.10.2675-2679.2000.Updated.

Watson, J.D. and Crick, F.H.C. (1953) 'Molecular Structure of Nucleic Acids', *Nature*, (171), pp. 737–738.

## Captions

Figure 1: Diagram redrawn from Waddington's original to show the topology of the epigenetic landscape.

Figure 2: Diagram based on Waddington's epigenetic landscape showing how the landscape can be influenced through genetic modification by removing or adding in new gene 'stakes'.

Figure 3: Diagram based on Waddington's epigenetic landscape showing a landscape which is composed of heterogeneous materials and can be influenced from the outside, represented here as contoured shapes pressing down in the landscape and altering its topography.

Figure 4: Diagrams to show the morphology of Oyster mushrooms grown in different conditions including levels of CO<sup>2</sup> and humidity. Images courtesy of Dilan Ozkan.