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Buildings are designed 'top-down' and use external builders. Natural bodies emerge from 'bottom-up' processes at a hierarchy of scales and build themselves by adaptive self-organisation.

Machines for living in: Connections and contrasts between designed architecture and the development of living forms

Jamie A. Davies

The phrase 'machines for living in', quoted in the title of this piece, echoes the words of two French thinkers, widely separated in time. The first is the philosopher René Descartes, who described the human body as a machine for living in, the inhabiting entity being the mind that Descartes famously regarded as being a distinct and independent entity (Cartesian duality).[1] The second is the architect Charles-Édouard Jeanneret-Gris ('Le Corbusier'), who described domestic buildings as machines for living in.[2] Architecture has sometimes drawn inspiration from the proportions of already-formed bodies, an approach associated most famously with Vitruvius but, for most of history, consideration of the processes by which bodies and buildings are constructed has been the business of very different sets of people.

Recently, however, there has been a surge of interest in architecture drawing inspiration not just from the final form of living beings, but from the mechanisms by which their morphogenesis takes place. At one end of the scale, this interest focuses on biomimicry, in which living morphogenetic mechanisms are simulated, perhaps at a different scale, by non-biological means. Examples include folding of sheets to make three-dimensional objects,[3] and robotic spider web-like creation of woven structures.[4] At the other end of the scale are plans for living buildings and structures, in which humans redirect morphogenetic processes to produce a living structure that is structurally useful, or at the very least structurally interesting in an artistic sense. Examples include root bridges[5] and the proposed Fab Tree Hab.[6] Somewhere between these extremes are ideas of enhancing basically inorganic built structures with living systems intended to give some lifelike properties, such as self-repair. An example of this is bioconcrete, in which dehydrated spores of bacteria capable of laying down stony precipitate are incorporated into concrete with dried food to enable them to do this. In dry concrete they remain inert but, if the concrete cracks and rainwater enters, the bacteria are activated; they lay down new mineral, and the crack is healed.[7]

Incorporating natural morphogenesis into the practice of architecture requires an understanding of the differences between the processes and materials of conventional architectonics and those that drive the morphogenesis of living organisms. This comparison is the main topic of this review and the comparison *[*Table 1*]* serves as both a summary and a list of contents for the rest of this article.

Teleology versus *a posteriori* fitness

Conventional architecture proceeds teleologically: a designer has an idea of the purpose of a building (to house a family, to protect a library of books, to inspire young minds, etc.) and designs with this end in mind. The ideas of utility and purpose are therefore a natural part of architectural discourse,

Feature	Architecture	Natural morphogenesis
Desirable qualities are included…	Teleologically	By a *posteriori* fitness
Hierarchical direction of causality:	Top-down (blueprinted)	Bottom up (emergent)
Most information for construction lies..	Outside the structural materials	Inside the materials themselves
Most building is done by…	Construction workers not themselves part of the structure	The structural materials themselves
Use of feedback	Modest, and by external agents	Extensive
Control	Hierarchical	Distributed
Use of scaffolds?	Yes	Yes
Function required in construction phase?	No	Yes
Self-repair	No	Yes

Table 1 **A comparison of conventional architecture and natural biological morphogenesis.**

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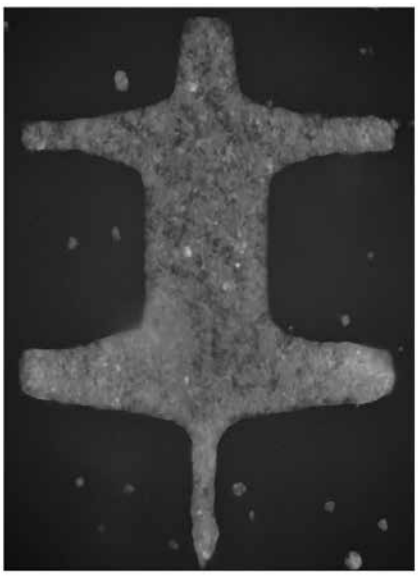
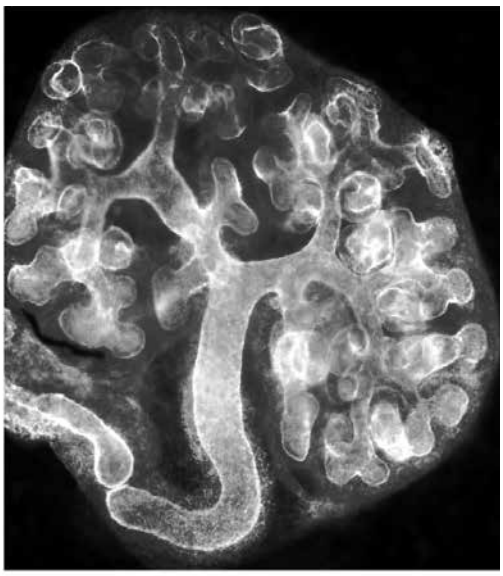


1a



1b

1 Spontaneous patterning by cells. (a) shows 'naïve' human cells that have been engineered to express a synthetic biological patterning module and have been cultured on an animal pelt-shaped island of culture plastic. The cells have produced a de-novo red-green pattern. (b) shows 'natural' patterning by cells that have been recovered from the area of a mouse foetus that would form a kidney and that have been maintained in tissue culture: a complex pattern of tubules has formed within this cell mass.

and they point outwards, in the sense of serving a purpose for the benefit of people or of things about which people care. Quality can be measured at least partly by reference to this external purpose.

Within materialistic, scientific understanding, biological organisms have no purpose except to themselves. As Darwin realised over 150 years ago,[8] the 'quality' of an organism can be measured only circularly, by reference to that organism's ability to perpetuate its own kind either by reproducing directly or by helping others of its species to do so. What is more, this measurement has to be retrospective: quality is detected not as an idea in advance of the outcome but rather by whether the final structure managed to survive and reproduce. This is undisputed by materialist biologists, although our everyday language may obscure it because talk of purpose is such a convenient shorthand ('the lungs exist to oxygenate the blood') that we use it all the time unless we have a reason to be careful: being careful, avoiding terms such as 'design', 'architecture', and even a purposeful 'to', is difficult. As the great physiologist J. B. S. Haldane once remarked, *Teleology is like a mistress to a biologist: he cannot live without her but he's unwilling to be seen with her in public*.[9]

It is important that those who wish to manipulate morphogenesis grasp the point that cells do what they do because of the interaction of their current state and their environment, rather than because they have a goal in mind. In particular, the absence of an internalised end-goal is what allows one to manipulate a biological system without it fighting back, provided the manipulation is intelligently chosen.

2

2 A fruitfly in which a mutation in the control regions of one gene (antennapedia) transform the body parts that should be short, fine antennae, into an extra pair of legs, carried on the head.

Blueprinting versus emergence

The dichotomy between blueprinting and emergence follows from the dichotomy between teleology and its opposite. The classic output of a conventional architect's work is the blueprint, or its electronic equivalent, that specifies the overall form of the final construction. Many decisions made for the construction are made later, in a top-down manner, so that the primary parameters that control construction are those of large-scale final form and small-scale details follow. An architect may, for example, specify the final shape of a roof and carpenters then design beam-to-beam joints and slaters cut slates in order to fit that blueprinted shape. Accepting that architects will sometimes choose to specify some structures at the small scale, it is still generally true that, within limits of what is physically and economically possible, the small-scale is usually subservient to the large, and the means are subservient to the ends.

Natural morphogenesis works bottom-up, and is emergent. Most information lies at the very smallest scale in molecules themselves (the genes of a so-called 'genetic blueprint' specify the structures of individual protein or RNA molecules, nothing larger).[10] Some additional information comes from the environment, and from pre-existing arrangements of molecules. Interactions at the

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molecular level create supramolecular structures by self-assembly. Molecular self-assembly will be familiar to anyone who has ever had a crystal garden as a child but, in biology, there are usually several ways components can interact, to produce different final assemblies, and their choices are partly determined by the actions of other molecules. Molecular complexes assemble into complexes-of-complexes, with a critical level of organisation being reached at the scale of an individual cell.

Cells are self-contained, quasi-autonomous assemblies consisting of tens of thousands of different molecule types connected by extremely complex webs of feedback, and contain everything needed for production of more cells, so long as there are suitable sources of raw materials and energy. In multicellular organisms such as ourselves, cells communicate with one another, by releasing specific proteins or other small molecules that can trigger specific chemical reactions in neighbouring cells, provided that these cells happen to have a 'receptor' molecule for the signalling. The reactions induced change the state of the receiving cell, so that it may for example divide, or change shape, or generate signals in its turn. The behaviours of individual cells (multiplying, dying, moving, becoming sticky either all over or only at certain points, becoming wedge-shaped, etc.) have consequences at larger scales. They can generate spontaneous patterns *[1a]* and, if the patterns make some cells do one thing and some another, then complex tissue shapes can arise *[1b]*.

The critical point is that the form of the final tissue, or indeed body, emerges from the minute details of its smallest components. Even with significant knowledge of final components, final form can be extremely difficult to predict. It follows that biological morphogenesis can be extremely sensitive to even tiny changes in the properties of individual molecules. This is illustrated in *[2]*, which illustrates how a change in the regulatory region of one fruitfly gene can cause the organs that ought to develop into antennae to develop into legs instead.

Construction workers versus a self-build process

Buildings are put together by construction workers of various types, who manipulate building materials but remain distinct from them and go home at the end of the build. They bring with them much external information in addition to the blueprint, information that includes construction skills. This information is not left encoded in the building but leaves with the workers when they go to apply it to another project. Developing organisms have no external builders: the construction materials (for example, molecules, cells) have to perform all of the construction and contain the relevant information to do so. Applied biology *can* include external construction workers – surgeons, for example – but natural morphogenesis does not. There is also little use of external information; most simple organisms use only simple inputs such as the direction of gravity and light, though complex ones such as ourselves use rich sensory information to fine-tune connections in our nervous system, in our lives after birth.

Open-loop control versus feedback and adaptive self-organisation

Being specified in advance by a blueprint, construction of a building generally uses 'open-loop' control. The number of windows required is, for example, specified at the outset rather than by a feedback process in which windows are added until the interior of a building is light enough. Some processes in construction do admittedly use feedback (labourers dig holes until they are deep enough, rather than by counting a set number of shovel operations) but the overall project uses feedback lightly and organises by reference to a plan.

In biological morphogenesis, feedback is used very extensively and is the chief means by which information held on a molecular scale (nanometres) can give rise to functional entities at the scales of cells (micrometres) and organisms (metres). The feedback feeds information about large-scale function back to small-scale mechanisms of construction. One simple example is provided by microfilaments of mammalian cells, which form a tense internal network between rivet-like adhesive junctions that stick neighbouring cells together. The microfilaments are composed of many identical protein subunits joined head-to-tail: each subunit is about a ten-thousandth of the length of a typical microfilament. Microfilaments grow by adding new subunits to their ends, but a growing microfilament can have no idea of where the cell adhesions are. How, then, do the microfilaments end up in the right place, connecting between cell adhesions and thus carrying mechanical forces, rather than distributed randomly and uselessly all over the cell? It turns out that, while microfilament growth is random, microfilament stability is strongly determined by mechanical force. Filaments that happen to extend in the right direction to bridge junctions and carry force survive, while ones that go nowhere in particular are relaxed and quickly destroyed.[11] Thus the structure of the filament system, built entirely from material causes, is determined by how well each filament performs its function. Its self-organisation adapts to what is needed.

The growth of blood capillaries demonstrates adaptive self-organisation at a larger scale. Cells within tissues need to be relatively close to blood capillaries if they are to have enough oxygen, so capillary growth must keep up with tissue growth, even though some of this tissue growth may not be predictable in location or time (think of bodybuilding, pregnancy, obesity, tumours, etc.). When tissue cells detect that oxygen is getting dangerously low, they release a protein called VEGF. This VEGF spreads away from them, becoming more dilute as it spreads.[12] Cells of the blood capillary system carry receptors for VEGF and, if they detect it, they begin to grow towards its source, thus bringing new blood capillaries into the area. Once there is enough capillary supply, oxygen concentrations are restored to normal and VEGF production ceases. In this way, the architecture of the blood system adapts automatically to the tissues it has to serve. There are many other examples like this: the overall point is

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that feedback is used to control the bottom-up, molecule-driven self-assembly processes and thus to achieve a structure fit for purpose without any pre-existing large-scale plan. If this sort of thing happened in the built environment, the wiring of a house would extend automatically to serve each additional electrical appliance.

Hierarchical versus distributed control

In the environment of a typical construction project, there is a hierarchy of control. Someone will be in overall charge of the project, and under that person will be other people who are each in charge of some specific aspect, and so on down through a hierarchy to the people who dig the holes and lay the bricks. In principle, at least, instructions travel in one direction through this hierarchy, although information should ideally flow both ways. In biological systems, the ubiquity of feedback means that control lies everywhere and nowhere. Even basic notions, for example genes being somehow 'in charge', have had to be revised with the observation that putting the (gene-containing) nuclei of cells in one state into the environment of a different cell type causes those genes to respond and take on the character that suits the host. That is how Dolly the Sheep was cloned[13] – genes taken from a mammary gland cell of one animal and put into the egg of another responded to the commands of the contents of the egg and stopped acting as they would in mammary gland, instead following the egg-like path of making a new sheep. Making deliberate changes to systems that show rich feedback and distributed control is non-trivial, and frequently results in unintended consequences.

Use of scaffolds

Scaffolds, which can be defined as temporary structures used to support construction without becoming part of the final structure, are used in biological construction as well as in the building industry. The human placenta and its associated membranes are obvious examples but there are many others. Early in its development, the human embryo is supported, both mechanically and functionally, by a stiff longitudinal rod called the notochord that is later replaced by the vertebral column (small parts remain in the discs between vertebrae, the discs that are 'slipped' in back injuries). As we develop, we produce three pairs of kidneys, but keep only the third pair.[14] Scaffolds are even more obvious in the world of insects: think of a chrysalis within which a caterpillar turns into a butterfly.

Construction phase versus always-on

Human-designed buildings, and other machines, have to be functional function only once they are completed: furthermore, function can be suspended when maintenance and alteration have to take place. Developing bodies, on the other hand, have to be viable throughout. Major alterations to the developing cardiovascular system, for example, have to be done with blood still flowing and the heart still beating, and nothing may be allowed to leak. This imposes major constraints on what is possible and how it can be done.

Maintenance workers versus self-repair

Adaptive self-organisation gives living systems the capacity for considerable self repair. Cells that make sheets, such as the front of the eye, for example, will rest quietly if they detect that they are completely surrounded by neighbours. If, however, they detect a free edge, they will both proliferate, and move in the direction of the vacant space, stopping only when they are again surrounded by neighbours. In this way, a hole or tear is repaired automatically (the healing of adult skin is somewhat more complicated due to the formation of an emergency plug – a scar – but the general principle of self-organisation holds). Similarly, many tissues of the body wear out over time and are replaced from a pool of stem cells that live in very protected sites. Mature tissue cells each produce a very quiet signal to the stem cells saying 'no need to do anything; there are enough of me'. When there really are enough, nothing happens. When mature cells are lost, the volume of the 'no need to do anything' signal diminishes, and the stem cells wake up and start producing replacements. In this way, thanks to the feedback in the system, replenishment automatically balances loss.[15]

The cell-based construction of biological structures lends itself to maintenance because cells can be replaced one-by-one without disturbing the structure of the whole tissue. Some aspects of buildings have this feature, albeit with replacement being done by external agents rather than by the building itself: broken roof slates can, for example, be replaced individually. Other aspects of buildings, for example steel frames, cannot be replaced without very significant disruption, a disruption that no living system could tolerate as it always has to remain alive.

Materials: Fewer differences than might be supposed

The materials common in buildings and in living systems show a large overlap *[*Table 2*]*, partly because some architectural materials such as wood are directly biological in origin and partly because of a convergence of evolution and design, shaped by the properties of inorganic materials such as stone. The main exceptions to common use come from metals, liquids, and gases. Living organisms make much use of metal ions but do not use metals in their bulk, metallic state for structural purposes (indeed use of the metallic state is very rare in biology, being represented by nano-scale bodies that seem to be by-products of some microbial metabolic systems).[16] Liquids are not commonly used as structural elements in architecture, though they may be important for decorative purposes. The incompressible nature of liquids is commonly used structurally in biology, especially in organisms such as earthworms that use hydrostatic forces for structure and locomotion. Gases are used structurally in some specialist buildings, for example inflatable tents for emergency field

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Material type	Examples in buildings	Examples in organisms
lignin-cellulose	beams, floorboards, shingles	tree trunks
mineral composites	brick, concrete	bone, dentine, enamel, shell
protein mesh	leather wall coverings, furniture	skin, most internal animal tissues
cellulose	paper	plant cell walls
silicates	glass windows	diatom walls
polyisoprenes	rubber flooring, fittings	latex (tree healing response)
metals	girders, rebar, frames	–
liquids	–	Ubiquitous through living tissues
gases	Inflatable buildings – eg emergency tents.	–

Table 2 **The materials of conventional and biological architecture.**

medicine: they are not usually used structurally in biology (they are used for metabolism and signalling).

In biology, all materials are used as fine-grained composites rather than as large-scale pure pieces. Even in highly mineralised tissues such as bone, there is a nano-scale alternation between inorganic minerals and organic substances such as proteins. This property, a result of the way in which organic material is laid down, gives the resulting tissue great resilience and resistance to the propagation of cracks. Buildings can use composite materials or large pieces of one pure substance (for example, steel beams, panes of glass), as the architect chooses.

Tensegrity structures, in which shape is determined and maintained by a balance of forces in a network of tension-generating elements and compression-bearing elements, are very common in biology, especially in the animal kingdom. Animal cells themselves make their shapes primarily this way (tension being generated mainly by active contraction of an actin-myosin protein complex similar to the complex that causes muscles to contract to move a limb, and compression being borne by microtubules that radiate from the centre to cells, and by the substrates to which cells attach). At larger scales, while some structures are 'fixed' and solid (for example, the human cranium), much shape is produced by tensegrity, for example by muscle tension working against skeletal compression. Tensegrity structures allow form to alter rapidly (for example, from sitting to standing) in response to environmental changes. Tensegrity structures have been used in the design of buildings and sculptures, and are occasionally used for the purpose of changing form, though this is rare in architecture as a whole.

Connecting principles of biological morphogenesis with architectural practice

There are various reasons to consider making more use of natural morphogenetic principles in architecture: beyond the fact that it is intellectually interesting, this approach might be useful. Even in the most prosaic contexts, some features of living things, such as the ability to heal damage, would be valuable to have in a building. In more exotic contexts, having buildings and similar structures that assemble in ways that adapt to their environment, or that alter aspects of themselves in in response to environmental changes, may be particularly valuable, especially where human construction workers are not easily available (deserts, Antarctica, underwater, space, areas subject to fire, toxins or radioactivity, war zones, etc.).

At present, most interest in the connection between biological development and architecture is centred around the rapidly growing field of synthetic biology, and in particular synthetic morphology,[17,18] which aims to reprogramme living cells to build designed rather than evolved structures. This approach has yielded interesting results where the small scale of living cells is appropriate, for example the self-healing concrete described earlier, but it is not immediately obvious how cell-sized engineering can be scaled up to building-sized applications except where the cells are simply intended to be a coating on conventional roofs and walls. What is more, while the idea of 'growing your own building' may be attractive, a truly living building would have the obvious disadvantage that individual living things are rather easily killed: as Shelley pointed out in Ozymandias,[19] and as fossilised shells silently state with a different kind of eloquence, stone artefacts long-outlast their organic builders.

Another approach is to capture the spirit of biological morphogenesis but to realise it in the inorganic. Here, designs that use conventional materials that can be arranged in different ways, and robotic builders that may be part of the structure or distinct from it, might be a much quicker way to add the advantages of biology without losing the advantages of the solid. Spacecraft builders have already done much work in producing compact structures that unfold when needed (for example, solar panel arrays). One can imagine adapting this type of construction so that a package of panels can decide what panel hinges with which, how far and in which direction the hinge opens, and which new meetings of edges (after unfolding) make new attachments, all in response to the environment. If power were available (for example, solar), these hinges and attachments could perhaps be implemented magnetically. They could then become permanent (for example, by a final squirt of glue into the hinges and meeting places) or left dynamic for the price of energy remaining available, a price also borne by living organisms, for which adaptability carries permanent energy costs. It may seem at first sight that such systems, or their equivalents (for example, a robot with Lego) would require

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phenomenal advances in artificial intelligence to work but this is not so: the number of possible structures will be finite and generally not very large (hundreds or thousands, not billions). With a clear metric for success (for example light capture for energy harvesting, shelter from radiation, stability, reflection of radio waves) a computer in the system could model all possible structures and the detectable relevant aspects of the environment, and choose the winner. Even with more conventional construction (done by human workers), one could imagine construction using easily replaceable modular units that report on their own health or that can be observed by machine, and that can be replaced by machine when they are damaged.

Non-biological constructions such as these would capture much of what is valuable and useful in biological morphogenesis. The one biological feature that would not be replicated is replication itself. Having literal machines that build copies of themselves out of raw materials is still the stuff of science fiction, but *designs* can be replicated quite simply and passed from a successful structure to the systems that will build the next structure. Passing information about good design in a directed way, rather than tolerating the waste of resources inherent in the Darwinian process of over-replication and competition, will allow life-inspired systems to improve on the efficiency shown by life itself.

Closing remarks

Both biology and architecture are at an exciting period of development. Biology is expanding in scope because it has acquired the tools for design of new living systems and for their application to other fields, rather than being trapped, as it has been historically, into mere study of what has happened to evolve. Architecture, at least at the academic end of the field, is increasingly freeing itself from the constraints of immediate bricks-and-mortar application and into more exploration of what is possible in a wider world of design. The time is ripe for fruitful cross-fertilisation between these two fields. Differences in culture, outlook, and assumptions make working across the disciplinary divide difficult but at the same time interesting and graduate students, in particular, seem to be ready to meet the challenge for the sake of all that might be achieved.

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