# Part 1: A Process View of Nature: multi-functional integration and the role of the construction agent

| | |
|---|---|
| Journal: | *Intelligent Buildings International* |
| Manuscript ID: | 14-IB154-OP.R1 |
| Manuscript Type: | Opinion Piece |
| Keywords: | Agent Technology, Innovation, Integration, Intelligent Building |
| | |

# Part 1: A Process View of Nature: multi-functional integration and the role of the construction agent

This is the first of two linked articles which draws on emerging understanding in the field of biology and seeks to communicate it to those of construction, engineering and design. Its insight is that nature 'works' at the process level, where neither function nor form are distinctions, and materialisation is both the act of negotiating limited resource and encoding matter as 'memory', to sustain and integrate processes through time. It explores how biological agents derive work by creating 'interfaces' between adjacent locations as membranes, through feedback. Through the tension between simultaneous aggregation and disaggregation of matter by agents with opposing objectives, many functions are integrated into an interface as it unfolds. Significantly, biological agents induce flow and counterflow conditions within biological interfaces, by inducing phase transition responses in the matter or energy passing through them, driving steep gradients from weak potentials (i.e. shorter distances and larger surfaces). As with biological agents, computing, programming and, increasingly digital sensor and effector technologies share the same 'agency' and are thus convergent.

Keywords: physiology, biological membranes, biomimetics, agent -based modelling, agency,

## Introduction

As a practitioner in the emerging field of 'digital AEC', I am drawn to the singular question, 'when we make things, can we integrate functions in the way we perceive they are in nature'. In part 1, I summarise my own and other's observations and conclusions around the subject of 'biological interfaces or membranes', and how processes (which we describe as functions) are integrated within them to set the scene for Part 2, which will explore what this understanding means in the context of our theme of intelligent (or, intelligence in) buildings and, ultimately, to building envelopes as physiological extensions of ourselves.

When we use the term intelligence within the context of living, manufactured or built objects, an important element is feedback. To some engineers, feedback will be understood as an immediate mechanical or electrical condition, but to many biologists and computer programmers, feedback occurs through a flow of information to the organism (or program) about the influence of its last action, for which it has sensory input. Though they are similar, the distinction exists as to how information exists, which can get tricky. We perceive the change a device or organism imparts to its system as being positive (amplifying a condition), or negative (reducing a condition), and in organisms it appears that both may be set in a dynamic tension to each other and may form the bounds or constraints within which the organism exists. Generally, we associate positive feedback with the amplification of a state and also the instability in that state, and negative feedback we associate with a level of control or regulation of a state. But, is feedback alone intelligence? Is the centrifugal or 'flyball' governor on a steam engine, for example, intelligent? It is a widely recognised mechanical example of negative feedback regulating, potentially catastrophic, positive feedback to keep the machine within bounds. I suspect most would argue that feedback alone may not be enough. So what if we add memory to feedback, in the way we recognise ROM in a computer, where we can store information about the past and act on it, is that any better? Or, is something intelligent when we add RAM, where memory is linked to feedback from which objectives emerge and decisions are made based on the past, and projected into the future. I suspect we are in the right direction.

I wish to argue that, whether in the context of intelligent buildings, devices or organisms, a threshold is crossed when you include the presence of an 'agent', intent on stabilising or 'projecting certainty' (by reducing uncertainty) into its and every other agent's environment. In the context of nature, the product of myriad interacting biological agents may be organisms, species or cultures, but the devices and structures they 'stabilise uncertainty' with, are boundaries, interfaces and membranes. Here, I must avoid conflating definitions of what is recognised as a biological membrane or interface (mitochondrial, nuclear or cellular) with that of an intelligent building envelope. Where the former would be recognised by a biologist as a 'pliant coherent layer', it may not be recognised as a rigid porous structure, such as a building envelope (where a biologist would see this as analogous to a 'skin' or 'barrier'). For this essay, I want to avoid using 'skin', because of the anthropomorphic association, and 'barrier', because it invokes separation. I accept that 'membrane' is no perfect term, so I must argue the case for its inclusion here. In architecture, 'membrane' refers to a thin material with a minimum surface energy topology under tension and, as we shall see, engineers understand membranes to be selectively permeable devices or structures. I accept that building envelopes are currently rigid barriers but I am looking forward to a point where they will be 'pliant' (through time) with attributes possibly analogous to biological membranes and I beg you to allow others to decide its fate.

Biological agents actively negotiate matter, itself in limited supply, along an interface between two adjacent regions, in which they seek a gain by regulating the flow of traffic from one side to the other. We know this, due largely to the detail which digital imaging and computational analysis now gives us. I believe we are at a similar threshold of understanding of 'how nature works' at the level of the agent because, through 'unconscious selection' (as Darwin put it), we have generated technologies imbued with 'agency', from which we can study nature with unprecedented acuity. From this knowledge comes insight into that most elusive of subjects, the generation of the 'biological membrane' and the seamless and deep integration of multiple functions. If correct, we are close to generating biological membranes for our own habitats, partly because we are agents and partly because we have evolved the tools of agency. What we class as intelligence in nature is converging with what we may class as intelligence in the built environment. As we redefine life through a lens of agency we may well describe, one day, our buildings as 'living'.

## Intelligence from an Agent Perspective

Within this context, I will define intelligence as "*the regulation of matter, energy or information (MEI) states, by agents with objectives*". Here, I am reducing the term 'intelligence' to a mechanistic or deterministic interpretation, whereby intelligence emerges within a process with feedback (positive or negative), tied to the regulation of ME(I) states. I have placed the (I), in MEI, in parenthesis as I am stepping beyond generally accepted definitions by including 'information states' with those of matter and energy where there is scant evidence but much supposition, to support it. Where Szilard resolved 'Maxwell's demon', by recognising that 'information' is the additional factor in Maxwell's matter/energy conundrum, and Bremermann defined a theoretical limit by which matter can process information as $10^{47}$ bits/gram/sec, I am not aware of a 'power' relationship (measurable in say Watts or Joules) between the potential difference (as we apply volts or pressure in energy and matter states) between a source and sink of information, and the 'current' or capacity of information flow which a system can sustain. Importantly, to our discussion, Umpleby (2007) identifies information as a temporal phenomenon which generally emerges in a change (or 'not' change) of matter or energy states to, as Von Foerster (1984) stated, an object or thing observing or sensing them. For example, we can use a device to regulate information but whether that means there are 'information states' as there are higher or lower energy and matter sates, I cannot say. I suspect that, like quantum theory, the presence of 'an observer' is what distinguishes our understanding of matter and energy states from what may or may not be 'information states'. I must also avoid misunderstanding between intelligence 'as a process of feedback matched to objectives', and that of a perception of 'purpose' and, similarly, 'intention', when observed and interpreted by an organism with developed cognition, such as ourselves.

## The 'Intention' of Matter

Let me give an example of a 'perception of purpose' which challenges our understanding of something as 'inanimate' as matter. As a material passes from one physical state to another, it must either absorb or give up energy (commonly as heat), to complete the transition in its order or structure. To the observer, whereas the material's environment cools linearly in time, the material's physical temperature does not. As the material approaches the transition between say, the liquid to solid state, its physical temperature hovers at or above its solidification temperature. This happens because the material must give up an amount of heat (which passes back to the environment cooling it) so that it can transition to the solid state, whereupon its physical temperature suddenly drops to match that of its environment. For some reason or rule (of nature), matter 'appears' to act to preserve an existing state or order before transitioning to a new order and this could be interpreted, by an observer with cognitive abilities, as purpose or intent. A liquid exhibits this behaviour at both ends of it's 'state of liquidness' and this appears similar to how organisms strive to stay within 'bounds'. In the classic description of homeostasis in humans, we strive to stay within thermal bounds by either perspiring or shivering as we approach the extremes.

I realise I'm stretching a point, but if you look at nature as ME(I) states with 'apparent' purpose, then living, animate or homeostatic organisms exhibit a similar principle of 'state conservation' and our species, because we can store and project information from the past into the future, can confuse this natural state with a higher meaning. Having said this, a physicist or physiologist will tell you there is a clear difference between these two conditions. Living systems are not at equilibrium with the universe and must locate and sustain sources of 'free energy' to thrive (minimise entropy), whereas matter may be at equilibrium and will try to minimise 'free energy' (maximise entropy).

I use the example for matter states, but it is equally true for energy states and, it is hypothesised, information states, and this is not unlike 'homeostasis'. In the case of homeostasis, we perceive some element of calamity, catastrophe or termination as we push beyond the 'bounds' an organism strives to sustain, but there are many examples of homeostasis at play in an organism and not all necessarily result in extinction when the 'bounds of a conserved state' are exceeded, as is the case for ME(I) states. As the upper and lower thresholds are exceeded, the system's stasis changes to a new order which is not 'catastrophe' but an equally stable state and this, too, is 'of nature'. Either knowledge of phase states, or acting directly on phase states, is important for life because an organism sitting within an ME(I) system, structure or membrane can get an extra 'kick' out of the system it is in, for example, where it can induce matter or energy transitions from one phase state to another, thereby releasing or absorbing energy (or information) to do so.

## Agency and Process

My opening definition implies the regulation of states within pre-subscribed objectives by something. This something could be an organism, a culture, a programme, a device etc. and I will use the term 'agent' to describe it. The word agent may not be the best description, but it has the longest lineage. We are familiar with commercial agents acting on behalf of a client, and may be familiar with 17th century spice traders acting as agents for the crown and, unfortunately, we all interact with government agencies as organisations where a transfer of power has taken place. In the past, the word 'agency' has been used to describe effects, as in 'the rock was eroded by the agency of water'. We have applied the word within the context of social theory and, recently, to computer programming, such as agent based modelling (ABM), which is relevant to our discussion. Here, I will conflate all of this and expand a recent popular mantra to state, *'at a local level, an agent acts autonomously, but is* *acting out objectives (of someone or something) at a* _global_ *level'*. Again, I must not get drawn into what someone's, or something's, global objectives are, to avoid the subject of intention, but I can state that by referring to 'global objectives' these may be nothing more mysterious than the 'rules' applied by a programmer to an ABM system, or the 'rules' of nature, of which we accept that one is natural selection. However, I must put a face on this component which sits between cause and effect, or action/reaction, where, in science, we have avoided doing so, for good reason.

I therefore define an agent as '*an object, organism, structure or device capable of sensing specific information (of a change in an ME(I) state) before applying a transformation or operation, based on pre-programmed or encoded objectives, which modifies the system to favour its objectives*'. What I have just defined is also confusingly known as a 'process', where a process is a descriptive term for an agent system going about its business, and the two are interchangeable, as agents perform transformations to ME(I) states as processes, to draw work (or benefit) from the system they are in. From this definition, we can see that an agent and/or process possesses three fundamental components and here I must again conflate accepted terms found in biology, systems engineering and computer science (for example as Doursat (2012) defines within 'morphogenetic engineering') to name but a few. These process elements are:

i) a sensor or sensory component, by which the (change, or 'not' change of) state of an environment is measured as inputs within upper and lower thresholds,
ii) a manipulator (for which a better term may be 'processor'), by which the strength, frequency, duration and threshold of inputs are assessed against 'a set of encoded objectives' and
iii) an effector, by which a change to the environment is output to modify that environment in line with its objectives.

Whereas most can agree on what either a sensor or effector is, as either the input and output to a system, of these three components, the second is the most challenging to define, or seek agreement, between disciplines. I am using the biological reference here but, within robotics, a 'manipulator' would be recognised as an 'effector', and, in programming or systems engineering, we would be familiar with the term 'processor', but this has all three elements, whereas Deutsch (2013) refers to a 'constructor' sitting between inputs and outputs. Indeed, in many biological texts, dealing with organ, cellular or gene function, there is much written about sensor and effector pathways and little about the cell, protein or even RNA sitting at its core, partly because of the need to remove discussions of purpose or intent from biological texts.

As with ME(I) states, an agent works within upper and lower thresholds, over which the agent may fail to respond or change to a different set of encoded objectives. In electronics, input sensors are 'saturated' when over threshold, and in computing, inputs are monitored within threshold limits, as conditional or 'IF or WHEN' statements, from which transformations or algorithms are applied as

'THEN' statements to the data or to the physical world, as outputs. So, whether we refer to technology, systems, electronics, manufacturing, software, biology or nature as a whole, though they have different terms, an agent is composed of the same triptych of inputs (or sensor), manipulator (or processor) and outputs (or effector) and this is the fundamental 'process' or means by which a 'transformation' takes place. Biological organisms, whether acting independently or as a collective or swarm, are composed of agents which continuously monitor their environment, looking for inputs which fall within a specific range (or, indeed, above or below a range), on which they act, based on encoded objectives, to modify the system they are in and bring the system into phase with its objectives. Cells as agents, for example, express unique combinations of objectives or functions but, more importantly, we are realising that they are expressing and embody processes.

Life, as agents, will seize and co-opt available and 'appropriate' process elements (either physical or encoded) to produce novel process combinations which drive, as Darwin described them, 'the wedges' (of speciation) into the 'yielding surface' (of life), to produce a better fit to the environment that they, and hence their progeny, are in. This statement fits partly with the 'reductionist' view that the 'plasticity' of the organism randomly mutates to exploit a changing environment. However, Turner (2004) identifies a trick, intrinsic to life, which casts light on evolutionary fitness and opens up our discussion about intelligent buildings. Life 'pushes back' against the environment as it modifies and 'strives' to stabilise its environment (i.e. reduce uncertainty) for the benefit of itself and its kin, by extending its physiology using a structured, or modified, habitat that it creates. I use the term 'strive', because there is no end position in this struggle, it is constant and changing, and I use the term 'habitat' instead of 'building', because, in nature, the term 'habitat' is used to infer a 'stabilised' environment or an environment being stabilised by an organism (where a better term may be 'where uncertainty is reduced'). This is done through the assembly of matter, into structures which preserve a condition (objective or function) through time. Importantly, through the aggregation of physical matter, a biological agent is encoding successful processes, and process information, for the future and for use by other agents, as effectively as if it were modifying DNA (epigenetically). Where we may be familiar with a concept of biological agents storing information, as memory, about the regulation of ME(I) states, we are less familiar with the concept of biological agents storing information on the regulation of ME(I) states, by encoding (aggregating) matter within the physical structures they create. This is because agents need 'noise', or information as feedback, to act on, and processes need something to be contained within. These structures are biological interfaces or membranes.

## Unpicking the Biological Membrane

By understanding how biological agents embody processes simultaneously within biological membranes (I will also refer to them as 'construction' agents to denote agents that resolve matter and hence physical structures), we can change the way we perceive and generate our own habitats and, I assert, generate an architectural and construction methodology for ‘biological membranes’, because we now have the generative design, simulation and digital fabrication tools, which, themselves, possess the same process triptych as biological agents, which will be explored in Part 2. The following is not meant to be a prescriptive design methodology for biological membranes, it is merely the sum of my observations and experiments to explore how processes emerge, how matter is negotiated, how information is encoded and how process elements are simultaneously integrated by agents, into biological membranes:

i) **Construction agents drive processes by delaying universal entropy at or around phase transition points.** Biological (construction) agents assemble matter and store information to reduce entropy and preserve the processes they are regulating, <u>through time</u>. Biological agents exploit the ‘self assembly’ of matter because, as we saw in the beginning, matter responds to energy in different ways at different thresholds to preserve an order. Biological agents use the ‘natural’ self-assembly of matter to form structures containing processes and these structures may be formed around themselves (where they act as the ‘manipulator’), or as structures into which they can ‘project’ their agency. Embodied processes are driven by any reduction in entropy, where the presence of the structure (or membrane) produces a potential difference between the two or more spaces it lies adjacent to. This structure is selectively permeable to whatever ME(I) phase state is passing through it (e.g. solid, liquid or gas in the case of matter), which the agent is exploiting. Matter induced to pass selectively through the structure may also be at or close to a phase transition boundary, because agents can use the transition behaviour to nudge, enhance or impede (i.e. regulate) its flow. Matter flowing within the structure can be enhanced or impeded as it encounters the matter of the structure it is passing through, for example, by interaction with its geometry (tortuosity, texture, expansion/contraction of diameter), the structure’s porosity and temperature (adsorbing/desorbing or condensing/evaporating) or by having a charge added or stripped from it. In this way the agent can use these interactions with the structure to shunt heat (or electrons) into, or out of, the matter flow and thereby regulate the flow to its own ends. Fundamentally, our starting position for generating selectively permeable membranes, as building envelopes from which work is derived and comfort regulated, is to establish the ME(I) sources and sinks (be it heat/coolth, light, hydration, access, waste, etc.) as potential differences from which gradients can be derived within any emergent structure generated.

ii) **Construction agents share process elements to squeeze more functions into less form.** As a component or outcome of evolutionary fitness, organisms seek to reduce the space (described as ‘the form’) in which processes (described as ‘functions’) are embodied. We are familiar with the expectation that evolution favours lighter, leaner, stronger, cleverer and faster, but here I will modify this to state that evolution fundamentally favours ‘integration’, because, successful integration satisfies all these objectives. If construction agents were to express, embody and materialise the myriad processes and process elements, as we do in engineering and architecture, as separate functions and components, then any organism which finds a way to share process elements across more than one process, wins out. Organic agents, therefore, seek alliance with other agents to share process components within the same structure. At all scales of life, we see remarkable examples of integration. At the cellular scale, an example of an interface agent is an epithelium cell, sited on (usually) a collagenous basement membrane. An interface membrane, such as the epithelium, may be made up of one or more layers of epithelial cells, acting as a barrier to regulate (secrete) the flow of matter and energy (hormones, enzymes etc) across the interface. Epithelial cells do not establish potentials through themselves, but across the layer and, collectively, they may be either the effector or sensor in our process model. Not exclusively, cells at an interface will secrete a hair-like structure called a cilium and, as we shall see, the combination of epithelial membrane and cilia is the fundamental sensor and effector device in our agent/process model. The very existence of a cilium in a eukaryote cell, itself is a remarkable story of the co-opting of a bacteria to integrate a function within another cell, but let's not get drawn in. The cilium may be either non-motile, or motile depending, on whether it is acting as a sensor or effector (often called a flagellum in the effector context). Wissam *et al* (2009) state that a single cilium may be constructed of around 1000 proteins, many of whose specific functions are unknown. The cilium has specific chemical receptors, ion channels and signalling molecule structures and is present in almost all epithelial or membrane surfaces. As a passive (sensor) device, cilia can sense pressure, flow, pulses, viscosity, molecules, ions and much more. Likewise, epithelia, as an effector device, will modify or induce changes to an environment it encloses, based on the sensed ME(I) inputs from a cilium. This arrangement is completely reversible in that the membrane can be the sensor, and a cilium the effector, and this a common arrangement where a cilium is actively moving a fluid over or around a surface. Another example is the sperm, which uses its membrane to sense and move down a hormone gradient to an egg, propelled along by one (or more) active cilium or flagellum. Potentially the combination of both hair and membrane may be ubiquitous to sensing and effecting for all ME(I) states within a single structure, and this is both massively integrated and staggeringly innovative. Simultaneous process integration is, therefore, paramount in nature, which can be disconcerting to anatomists who seek to define visible and distinguishable organs by a single function or set of functions, when they have many. It is widely reported that the liver alone is estimated to perform over 500 functions but, by this logic, the sensor and effector elements for many of these functions may be integrated simultaneously into a single cellular 'agent' device.

**iii)** **Biological membranes are transient not steady state devices**. Agents aggregate matter, as biological membranes, to form ME(I) gradients between two or more adjacent regions from which work is derived and, hence, processes are supported. For the transport of any specific nutrient, there is a multiplicity of molecular modifying processes to shunt matter in one direction while shunting (another term here may be 'ratchet') waste or by-product matter in the other direction, with the membrane in a constant state of flux. Biological membranes must be transient to shunt matter (i.e. mass transfer) at the molecular level, through complex and tortuous cellular (or inter-cellular) structures, without blocking or clogging over time. Where transient systems are good at sustaining selective mass transfer, steady-state flows are not. The analogy is a paper filter restricting the flow of muddy water. Under the steady-state condition, the filter will gradually clog with solid particulate and the flow will decline through time. Now, make the flow of muddy water oscillatory (or tidal). An oscillating flow has a forward flow, and backward flow component, even though the net flow is still in one direction. If the stroke length and the membrane geometry are 'tuned', then the forward stroke allows clean water to pass through it up to a point where the filter will begin to clog, and the back stroke will then partially clear it. The net effect is that clean water has moved through the filter and, though the net flow may be slower than the steady-state flow, the transient flow condition will extend the life of the filter. This is simplifying a complex condition, but Matthew *et al* (2006) demonstrate this principle through the perfusion and tidal distribution of nutrients and waste into, and out of, coral reefs, which are 'tuned' to exploit the transient state of waves surging through them and produce diffusion rates 1.6-2.9 times greater than in steady state conditions. Our own work (Soar *et al* 2014), shows the same effect in the termite mound where an imposed transient oscillation of air, acting through the mound skin, produces enhanced migration of $O_2$ into, and $CO_2$ out of, the mound, whilst theoretically conserving (in a dynamic sense) temperature and moisture within the mound.

iv) **Agents manipulate gradients around transient phase transition states**. As Vogel (2009) observes, at the scale of cellular organisms, the potential chemical, solute or gas differences on either side of biological membranes may be small, compared with those we encounter in engineering applications, but the gradients within them are as steep. In engineering, we use the term membrane loosely to imply specific permeability, as in a filter or osmotic barrier. In both, we induce large steady-state, potential differences, in either physical or chemical pressure. In neither, do we find agents manipulating weak potential gradients around the transition points of the phase state of matter passing through it, from which matter, energy, or information, can be transferred in both directions. Though cell turgidity, through osmotic pressure, is important to all cellular life to maintain primary support, it is rarely exclusive or a steady state condition. In biological membranes, agents create and manipulate matter gradients within a membrane, be it hormones, solutes, respiratory gasses, nutrients or waste, passing selectively through it. The flow and counterflow relationship must be tightly integrated and this can only occur through transient or oscillatory flows. Commonly, where a potential gradient is established for a specific molecule, the migration of that molecule can drive a potential gradient for another molecule in the opposite direction, for example, where an agent strips or adds electrons to produce a molecule with an opposite potential gradient, through the membrane. Alternatively, construction agents assemble matter which itself interacts with a mass flow passing through it, at or around a phase transition point. Consider water vapour in air encountering a strongly hygroscopic and porous membrane. Within a transient scenario, and under the right vapour pressure conditions, water vapour will freely condense onto this material and evaporate from its surface at a specific and narrow transition temperature, as it passes through it. Think about this a moment, as either adsorption (condensing), or desorption (evaporation), of vapour onto a porous medium takes place, heat is being actively shunted into or out of the solid medium. It won't be much and it will be brief, but if this porous membrane is as 'fractal' and the material composition as 'deliquescent' (i.e. responsive to moisture) as we see in the external 'membrane' of a termite mound, then we have a potential mechanism for sustaining a transient or dynamic stasis of temperature and moisture within the mound, whilst exchanging respiratory gasses through the mound skin.

v) **Agents negotiate matter through time and not space**. Agents do not construct structures or membranes as abstracted design and construction. Agents 'negotiate' matter around embedded and integrated processes through time. Agents resolve multiple process objectives simultaneously, many conflicting, through fierce and negotiated aggregation and disaggregation. By an objective, I mean whatever encoded response (transformation) an agent is acting on from its immediate environment. No matter how many 'objectives' are being resolved in a membrane system, construction agents have only two options to affect the system they are negotiating, they can either add matter, or remove it from a specific location. Only through the dynamic tension or conflict between agent objectives, can matter be used sparingly, energy moved efficiently and information integrated logically within the structures we see in nature. From termite mounds to bone trabeculae, agents resolve conflicts and aggregate matter in time (i.e. transiently) and not space (i.e. steady state), which we will return to. Agents sense for specific changes in their environment, the structure before them, or between each other. If a condition is sensed which matches that of an encoded objective, then they will make a modification to the structure. Actions can be reinforced between agents - aggregating a sensor by one agent may be attractive to another who wishes to share it. As likely though, where one agent places matter down to support a process objective (say to support structural integrity), it is likely another agent will 'read' this as conflicting to its objective and will remove it, i.e. the placed matter may affect its own requirement to allow the flow of a fluid or gas. If both agents have diametrically opposing objectives, and were simultaneously acting on a single piece of matter in a single location, and a single point in time, then a stalemate would ensue. This rarely happens, as agents have methods for resolving a stalemate condition (for example, prolonged sensory inputs decay over time, and, for 'decay', read 'boredom'). More often though, stalemate does not occur, because resolution and modification occur through time, and constantly. Because the agent works as a processor itself (i.e. it is composed of sensor, manipulator and effector), any single action has probably taken place before another agent senses it, and, even where stalemate occurs, then there is always another agent to nudge them out of stalemate by its actions. There is an analogy to ants moving food to its nest. Ants gather around a morsel of food and push in many directions simultaneously, but, because one ant acts in response to another, instead of a stalemate then a rocking action or oscillation ensues. Ants begin to synchronise their decisions and actions, as fireflies do, and a net direction of the morsel is negotiated and resolved as a shunting motion, without any ant needing a specific cognitive function for this resolution. Is this efficient, and is it any different from what we do in our minds before we commit to a single direction? The action\reaction, aggregation\disaggregation, or activator\inhibitor cycles are erratic and, to the observer, appear complex and sometimes wasteful, but, from them, comes a temporal resolution and collective differential calculus being played out constantly through time.

**vi) Agents increase the efficiency of the membrane through folding**. Biological agents construct membranes to establish strong ME(I) gradients, from weak potential differences in two or more connected regions, by folding. Folding a plane around a single axis increases the surface area within a given volume, which produces membrane thickness and, potentially, micro gradients within the folds themselves. Folding in three dimensions produces foams and lattices, with extraordinary 'fractal dimensions' (the ratio of surface to volume), and physical properties. Everything we have discussed so far has been from the perspective of the individual agent resolving matter around its own process objectives, within the context of other agents resolving their own, and we have set this within the term 'negotiation'. Here, we must introduce a further constraint which is that no ME(I) resource is infinite, there is always a limit, and even shortage, of matter with which to resolve (or negotiate) all objectives simultaneously. Darwin recognised that nature produces an excess of organisms struggling to exploit limited resource and this produces predator/prey relationships as complex boundaries between competing species, and if we could visualise these boundaries they would appear folded but changing both in space and time. Within the context of biological membranes, it is unclear whether the aggregation/disaggregation process inevitably produces folded solutions, but I suspect that they are an emergent property where a finite resource is being negotiated between 'opposing' agent objectives. An agent, focussed on shunting a specific molecule from one region to another, is measuring the gradient of the molecular potential from its sensor to its effector (its field of influence), and is placing or removing matter to regulate this. It appears that the agent is resolving a dynamic condition (i.e. from one moment to the next) of either adding, or subtracting, matter to sustain the process of moving the molecule through time, and therefore folding is 'emergent' due to, i) the 'natural' self assembly properties of the matter used to make the membrane, ii) the requirement of space (i.e. non-matter) for the molecule to move through, iii) the proximity of the molecule being moved to the matter which makes up the membrane, because there will be a phase transition change in either the molecule being shunted or the membrane itself, to drive the molecule either down the gradient or against the gradient and, iv) the matter available to the agent to take this action. Up to now, we have portrayed the biological agent as almost immobile, as if the agent itself is present in the membrane as part of the process. However, the implication is that biological construction agents can equally 'programme' the matter, which makes up the membrane, to behave as if they were present, because they have assembled matter around a phase transition threshold which itself becomes a 'decision gate' (in systems engineering terminology).

vii) **Agents express genotypical processes within phenotypical process space.** Biological agents produce a wide variety of structures capable of embodying and integrating multiple process objectives (functions) simultaneously. At a genotype level, a biological agent can theoretically draw on a broad range of processes and process elements but, as time goes on (i.e. as the organism ages), this number diminishes as the agent, cells, organism or organs differentiate (specialise). What I have called a 'process objective' is analogous to saying there is a 'rule', algorithm or conditional statement being acted out by an agent interacting with the external world (to the agent). It is unclear how a biological agent decides which process objective, of the many it could execute, will be acted upon at any particular moment. It is likely that an agent will select one objective over another based on the strength (amplitude), duration (frequency) and change (phase) in any signal arriving at the sensor. If the signal lies within a sensory boundary (upper and lower threshold), all other objectives may be temporarily suppressed while an action is executed at the effector. As we have discussed, this is like a conditional statement such as an IF, or WHEN, followed by a THEN statement in programming. We have already stated that agents resolve multiple objectives in time and not space, but let's look at that again and imagine the process taking place. Imagine a cohort of construction agents all acting out different objectives from a pre-encoded source (i.e. the genome), within the same space where all agent decisions boil down to an action to either add or subtract a unit of matter. The environment in which the membrane is negotiated is the phenotype, and an analogy may be the growth of a brain coral which begins from a source and grows outwards, as matter is negotiated at the surface in successive layers through time. Within the first fictitious time frame, or layer, of our coral, we could imagine that the many conflicting construction agent objectives are somehow resolved as a 'differential calculation' to find an 'optimal' solution for all objectives at once, before the first layer is aggregated (as we do with optimisation programmes). However, I can find no evidence of this. What I believe takes place is that, within the first timeframe, some agents will have their objectives met more than others and this resolution is fixed into the 'first layer' of the emerging structure. As we move to the next timeframe (or layer), those agents whose objectives were previously met 'the most' will have a diminished input at the sensor, and those whose objectives were not met, will have an enhanced input at the sensor. As the second timeframe (or layer) is negotiated (by agents adding and subtracting matter), it ends with a solution where, again, some objectives are met more than others, but the objectives resolved have a greater probability of being different than those resolved in the first time frame. Within this simplified analogy, we can begin to perceive how multiple embedded processes (functions) may be resolved simultaneously within an unfolding membrane, and see how agents express or select genotypical processes (objectives or functions) within a phenotypical process space. That we have no clear beginning, or end, to process integration in nature is a challenge to either a designer or engineer wishing to recreate this for building envelopes, but it does point a way to resolving multiple process objectives within the digital domain.

## Conclusions

This paper discusses the 'how', and 'why', biological agents construct and negotiate matter simultaneously around embedded processes to induce and regulate the flow of matter, energy and (controversially) information within biological membranes. The intention is to draw an analogy between, and identify a line of enquiry for, generating building envelopes as an extension of our own physiology, as occupier, modifier and user of these systems. By understanding how biological agents manipulate matter around phase transitions and encode information for other agents to act upon, we can explore and understand how nature integrates functions (as processes) at a fundamental level not realised in engineering, architecture and construction to date. This is the time to do this and in Part 2, we will show that we possess the design, simulation and fabrication tools to physically mimic the processes which biological agents execute, to draw work from the weaker energy potentials present in the environment and which they sustain, through time, in the face of uncertain material resource and energy availability, a condition we are facing ourselves with the built environment.

There is intelligence in nature at a mechanistic level of information feedback, storage and reaction, to modify the environment in line with encoded objectives, to remain within threshold boundaries. This we call homeostasis, and it is homeostasis that Turner (2014b) is proposing as a '2nd law of nature' (the 1st being natural selection). Intelligence is embodied in biological membranes either actively, through the presence of an agent, or passively, by agents negotiating the assembly of simple materials which induce a phase transition to matter and energy being shunted (transiently) through them, to create potential gradients from which 'work' can be derived.

## Acknowledgments

The author would like to thank the contribution of many worthy scientists who have shown endless patience, and supported me in this journey. In particular, special thanks must go to J Scott Turner for believing that we can make a connection between field research and our physical commercial world. Thanks must go to the reviewers who took the time to give excellent criticism, so good that I have been forced to quote them. I must thank the Human Frontiers Science Program for their support and funding, and my academic institute Nottingham Trent University.

## References

Deutsch, D., (2013) Constructor theory, Synthese, December 2013, Volume 190, Issue 18, pp 4331-4359.

Doursat, R., Sayama, H., Michel, O., (2012) Morphogenetic Engineering: Toward Programmable Complex Systems, ISSN 1860-0832 ISSN 1860-0840 (electronic), DOI 10.1007/978-3-642-33902-8.

Matthew A. Reidenbach, Jeffrey R. Koseff, Stephen G. Monismith, Jonah V.Steinbuck and Amatzia Genin, The Effects of Waves and Morphology on Mass Transfer within Branched Reef Corals, Limnology and Oceanography, Vol. 51, No. 2 (Mar., 2006), pp. 1134-1141.

Soar, R.C., Turner, J.S. and Andreen, D., (2014) Respiratory gas exchange through transient convection in termite mound egress complex, submitted to The Royal Society, Proceedings A.

Turner, J.S. (2004) Extended phenotypes and extended organisms, Biology and Philosophy, Kluwer Academic Publishers, 19(3): 327-352.

Turner, J.S. (2014a) Semiotics of a Superorganism,  Approaches to Semiosis of Evolution Kalevi Kull, Jesper Hoffmeyer and Aleksei Shariv (eds), in press.

Turner, J.S. (2014b) Biology's Second Law. Homeostasis, Purpose and Desire, In: Brian G Henning and Adam Scarfe (eds), Beyond Mechanism: New Frontiers in Biology and Evolutionary Theory, in press.

Umpleby, S.A., (2007) Physical Relationships among Matter, Energy and Information, Systems Research and Behavioral Science, Vol. 24, No. 3, 2007, pp. 369-372.

Vogel, S, 2009, Glimpses of Creatures in Their Physical Worlds, Princeton University Press, ISBN: 9780691138077.

Von Foerster, H., (1984) On Constructing a Reality, Originally published in 1974.  Reprinted in Understanding Understanding, Springer, 2003.

Wissam A. Abou Alaiwi *, Shao T. Lo and Surya M. Nauli, (2009) Primary Cilia: Highly Sophisticated Biological Sensors, Sensors 2009, 9, 7003-7020; doi:10.3390/s90907003, ISSN 1424-8220 www.mdpi.com/journal/sensors.

# Part 2: Pushing the Envelope: A process perspective for architecture, engineering and construction

In this article, I am building on an emerging 'process view of nature' and how biological membranes emerge through the combined action of (locally) autonomous construction agents. In Part 1, we considered the simultaneous aggregation and disaggregation of matter around embedded processes, used to create, sustain and regulate matter, energy and information gradients from which 'work' is derived for the benefit of the agents or organisms present in the system. In Part 2, I intend to demonstrate that emerging digital design, simulation and fabrication techniques, when linked to sensory and effector feedback, memory and actions, directed by pre-encoded objectives (as rules or algorithms), produce the same fundamental unit of 'agency' as biological agents possess. By understanding how biological membranes emerge in nature, as the outcome of *'negotiated agency'*, to regulate matter, energy and information exchange between adjacent spaces, we can begin to consider the building envelope as a biological interface or membrane from which 'work' can be derived from the environment we inhabit, as a physiological extension of ourselves.

## Introduction

In Part 1, we looked at how intelligence in nature comes about through feedback, and I summarised observations and experiments from various fields of research to describe how biological interfaces and membranes emerge through the actions of construction agents, embodying processes and process elements in ever decreasing spaces. I highlighted the deep integration of process elements by agents intent on stabilising and supporting their objectives, by sharing process elements and by resolving or negotiating their objectives as physical matter, through time. I identified seven 'traits' by which processes are deeply integrated and in this paper I will explore this knowledge in the light of architecture, engineering and construction practice, to look for insight into both its meaning and implications.

I was recently asked to consider the design of a building "as nature would". The question was intended to draw on my experience of observing the construction of termite mounds and project this knowledge into our own domain of habitat modification, which we call the built environment. Pawlyn (2011) writes extensively on the need for sustainable architecture and points us towards the field of biomimicry as inspiration to guide us. To ask whether architecture can reflect a building "as nature would" is perfectly reasonable, but is difficult to respond to readily. I have an interest in biomimicry (or bionics), because my research naturally fits with its objectives, but, like building intelligence, we are yet to realise the potential of biomimicry for the same reasons. Within this field, probably the greatest scientific contribution is Vincent (2006) and the many colleagues with whom he has collaborated. Vincent extended work, begun in Russia, on a methodology for seeking inventive principles in the patent literature, called TRIZ, to ask a fundamental question as to whether this approach could be applied to innovation and innovative principles in biology, now commonly referred to as BioTRIZ.  There is much written to define ‘biomimicry’, but the focus which BioTRIZ brings to ‘innovation through information’ forces our discussion that surely an intelligent building is one that can be ‘informed by nature’?

## Innovation through Parallel Construction

Within the field of biomimicry, one running discussion is “why is innovation in nature different from innovation in engineering”?  There is much written on this subject and the technicalities of innovation. Vincent must be correct, that our ability to act largely on information about energy and matter ‘transformations’, instead of acting directly on matter or energy transformations, as many organisms do, is an outcome of a ‘developed’ prefrontal cortex.  The only thing I will add to this is *how* innovation comes about in nature, by saying that generally, “in nature, innovation occurs in parallel (i.e. concurrently or simultaneously), whereas in engineering it occurs in series”.

This is not new knowledge.  We are beginning to understand its implications and see the logic played out in many aspects of human technology.  As an engineer, we bring about innovation by taking raw materials through a series of transformations in which the materials are shaped, finished and assembled, through a series of operations, each of which add a value to the final product. The product is designed as a series of components, each introducing one or more functions to the whole, and the process which realises them is a series of incremental material transformations using arrays of machines which cut, mould, bond, fix and add elements, again in a series.  This works well, particularly where many identical items are required, but it has its shortcomings, especially when we apply this method to biomimetics.

For a long time I struggled to see why engineers fell short of adopting, precisely, a process which mimics how nature designs and fabricates objects, organic or inorganic.  Why would ‘biomimicists’ choose a definition which merely ‘sought inspiration’ from nature and not actually innovate as nature would.  The answer is in the series approach to innovation.   A designer may look around to find a form (or even a function) in nature which lends something to a problem they wish to resolve.  Let us use the now famous boxfish studies for a better car design.  Putting aside the discussions regarding what inspired what, any designer knows that they are on shaky ground, for example, when they find a form in nature and then apply this to a car.  A fish swims in water, a car moves through air.  A fish moves at a few miles per hour, the car much more, but let’s put this aside and plough on.  We accept that a boxfish has some ‘aerodynamic to volume’ relationship which adds something interesting to a family saloon.  It’s quirky.  Now we take the same  solution we find in nature,  rip its guts out,  stick wheels in the corner,  cram in an engine, a family and safety features, as a series of steps, and as we add each step we must make compromises to the original form of the boxfish.  Beyond the original intention of the boxfish solution, each of the stakeholders in a design (i.e. everyone from the customer, or beyond, to the recycler) must input their requirements and each distorts the original solution.  It is inevitable that, as we progress a design through manufacturing and to the customer, we can feel the distance open up between our starting position and the end point.  It is no surprise that we can only ever state we are using nature as inspiration. We have long known this problem. A solution is to cluster the stakeholders into a single space so that each inputs their intentions, objectives or interests, in parallel, as the design unfolds. These approaches are embodied in systems engineering methodologies, and concurrent, or simultaneous engineering, forces us to get input from the stakeholders early on.

But what if we constructed or manufactured in parallel? Imagine a construction site, or car plant (to draw the box fish example out a bit further), where we load the space with competent 'constructors'. They each have a skill set which makes them proficient in building objects. They may each have a set of specialisms, such as a material transformation skill or a skill to deliver a specific function to an unfolding object, and these functions probably represent the same stakeholders in an integrated design methodology. There is no plan, but there is an objective to produce a car, and all of them begin construction simultaneously. Everything about this scenario screams 'chaos'. One envisions a metal worker battling with a glazier, - one trying to resolve a structure around a seated family unit to keep them safe at speed, while the glazier is pulling that solution apart so that they can see where they are going. Let us assume these two find some sort of resolution, but then there's also an aerodynamicist forcing the object lower to the ground and eliminating sections which generate turbulent eddies which cause drag. All this is happening, as a power unit and drive train are emerging, and the object begins to move through air at speed, so the aerodynamicist can get the feedback needed to make modifications. Simultaneously, there are holes appearing seemingly at random, where lights and sensors are being resolved by 'opticians' and electricians, with a 'recyclist' trying to work out how they will take it apart in 20 years time, and a 'fashionist' who's screaming that it's 'just not looking nice enough'.

This happens in nature, and if we relate this back to our knowledge about the emergence of biological interfaces (in Part 1) and membranes, then this analogy of parallel construction still falls someway short. We know that an organism, or agent, needs feedback between its input (sensors) and output (effectors), and, in the case of our 'biomimetic car', this would equate to putting a light meter in the unfolding car so that the glazier has a direct measure of the amount of light entering the occupant's eyes (an indirect measure of how much road they can see). If the light level drops below a threshold, they will remove material from the solution, if it goes above a threshold, they may do nothing and allow the metal worker to keep filling metal in to make it stronger. Likewise, the metal worker is 'sensing' structural integrity by the aerodynamic loading, and crash simulation loading, being experienced (yes, our car must be permanently crashed) and, in fact, each and every worker has to have feedback of the physical object as it unfolds, both in the physical world and in any projected scenario it may face in the future. Each constructor requires a set of rules by which they will interact with all the other constructors, and with the matter, energy and information they are acting upon. We know that biological agents 'negotiate' matter (i.e. the dynamic tension which exists between simultaneous aggregation and disaggregation), which has either a phase transition around a condition which helps them preserve their objective within the solution, or they negotiate matter which interacts with the phase transition of matter or energy passing through the interface. Both produce an interface which creates a potential difference in matter, energy or information passing through it, from which it can derive further work. We know that 'optimisation' comes about because there is always a scarcity of both matter and energy by which the solution can be produced, and this forces constructors to share sensor and effector elements so they can sustain their activities and preserve their intentions, within ever diminishing resource. When we apply this to our biomimetic car, we begin to glimpse the complexity in our constructor agent behaviour, which we see in nature.

We know that the construction rules, by which agents act, are encoded at the gene level and play out within a constantly varying phenotype and that the physical structure they are negotiating, itself, is coded to inform other agents around it. We are unclear how any specific rule (of the myriad rules an agent could execute in any particular timeframe) takes priority over another, but we can assume that an agent will respond strongly to an input signal which attains a threshold limit, and that, over time, agents will 'specialise', making them better at integrating certain functions over others. We no longer see a window, a door, a monocoque, engine and so on. These objects will be so tightly integrated that we will struggle to see the boundaries between them. However, we still will 'see' these boundaries, because we are pattern seeking organisms ourselves, and, as with anatomy, we will perceive regions of specialist activity where multiple integrated functions are clustered.

This is a process which directly 'mimics' how innovation emerges in nature. It is not 'inspired by' or 'drawing lessons from' nature, it is physically executed in the way of biological organisms and, because it emerges through a (construction) agent's intent on preserving its objectives into the future, through feedback, it is intelligent. Why we should suddenly have this insight is intriguing. We have evolved digital tools which allow us to observe, record and replicate this process, both within the physical and digital domains, which is why I support arguments which speculate that technology may be an extension of our own evolutionary development. I would go further, and say that the emergence of digital tools are a physical extension, or outsourcing, of the agent system at work in our minds which enables humanity to self-assemble into a more complex organism, playing out at a global scale.

To understand the scale of activity in our minds, then consider a social swarm like the Driver, or Army ant bivouac, as Anderson *et al* (2002) did, in which the ants, analogous to neurons, self-organise as 'functional' units within their own mass. By making this analogy, I am highlighting the difference between what Turner (2007) calls 'a perception of designedness' in nature, and design by humanity. Organisms achieve 'cognitive' abilities in the physical world, by negotiating fiercely for resources between each other over varying but relatively short timescales. As design engineers, when we look at a termite mound we are not seeing a 'lasting' solution, even though the mound may 'exist' for many decades. In any year, termites construct a solution with little if any 'margin of safety' or 'reserve' (such as a relationship of material property to the duration of the structure). It is unlikely the solution will outlast the wet season, and its (partial) collapse may see the death of many termites. To 'nature', these are 'acceptable' losses, whereas in humans they are not. In the case of buildings, we have evolved an internalised, agent negotiated system, which is linked to extended memory. The result is that we can stabilise our futures (reduce uncertainty) by referring to the past, to a greater degree than many organisms, and the outcome of this, in engineering terms, is the margin of safety. Though there must always be 'acceptable losses', we can make predictions of how, and what, a building must withstand to ensure the safety of an occupant over many years. However, as design engineers, we should be cautious when looking at 'optimisation' in nature, as we shall discuss. Despite this, we seem inexorably drawn towards ‘agency’ and ‘innovation’ in nature, and I believe that this is the outcome of emerging digital technologies which increasingly reflect ‘innovation’ in nature, and demand we take a closer look.

## A Process View of Architecture

In this issue, I have previously described how biological agents negotiate matter, integrate process elements, distribute and compete for resource to regulate matter, energy and information (ME(I)) flows within biological membranes. This produced seven overarching observations on agency in nature:

1. Construction agents drive processes by delaying universal entropy at, or around, phase transition points.
2. Construction agents share process elements, to squeeze more functions into less form.
3. Biological membranes are transient, not steady state, devices.
4. Agents manipulate gradients around transient phase states.
5. Agents negotiate matter through time, and not space.
6. Agents increase the efficiency of the membrane, through folding.
7. Agents express genotypical processes within phenotypical process space.

These do not constitute a set of rules, nor do they define a design methodology. They are merely intended to give a lead into the discussion of what architecture, engineering and construction may become, by understanding these phenomena. In light of these, I would like to begin by asking “What can we draw from a process perspective of nature which supports a sustainable architecture, innovation in engineering and intelligence in construction?”

i. **Squeezing greater function into less form.** Figure 1 (a-f), shows a sequence of concept images, in collaboration with David Andreen and Petra Jenning, relating to the generation of a parametric ‘script’ whose function was to map and integrate services and utilities (as functions) into a building envelope, and output the digital fabrication of ‘a node’ from the integrated solution. This was done, not only to demonstrate that scripting tools can do more than ‘form finding’ (possibly function finding), but also to raise the similarity between how biological agents respond to ‘sources and sinks’ of matter and energy, and negotiate matter to drive gradients within the ‘habitat stabilisers’ (structures) they construct, and how we could also generate a building envelope within the digital domain, using the same principles. Figure 1a, shows a parametric script as an assembly of algorithms, which establish the relationships between various ME(I) flows (for example water, waste, heating/coolth, data, power) into, and out of, the building as bidirectional ‘sources and sinks’. Each living space would have a set of constraints to produce a probability distribution, for specific ME(I) demand (flux) and location (coordinate) for that space, from which a series of vectors can be plotted as a network through the design space. In Figure 1b, the network is a reticulated grid (a fishnet structure), as opposed to a bifurcated network, of runs (conduits) and nodes (manifolds). The reticulated structure introduces redundancy at the nodes, whereby blockages or failures can be routed (by opening and closing valves at the node) around any neighbouring set of nodes and runs (technically termed 'edges') in the network. In essence, the parametric script is analogous to the phenotype in a biological system, whereby extrinsic 'environmental factors' (geology, topology, proximity, spatial resolution, loads, forces, access, planning constraints, aesthetics etc.) constrain the 'materialisation' of the building envelope, as geometry, around the functional ME(I) processes embodied within it. In our example, this would equate to the length of a run, its direction and thickness (cross sectional volume) for each ME(I) source leading into or out of the system, and the number, arrangement of services (folded around each other as concentric spaces) and their vectors, leading to and from any specific node. Figures 1c & 1d, show how the network would resolve as a Voronoi solution, to reduce or eliminate orthogonal vectors from the nodes. What we could not consider at the time, was the structure shown in Figure 1e, whereby the right hand elements represent the parametric script (or phenotype) described, and the left hand elements represent a 'database of all functions, transformations and ME(I) properties' (or genotype), with an agent based modelling (ABM) system working between them (analogous to RNA), as these do not yet exist. Digital architecture is exploring a phenotype and, remarkably, engineering is exploring a genotype, in the form of Vincent's (2014) Ontology of Biomimicry. Systems like the Ontology of Biomimicry will exploit 'innovative principles' from nature, by understanding and (auto) generating 'algorithms of transformation' (i.e. conditional logic statements) in the way biological agents execute transformations from a pre-encoded resource of all processes, which we call DNA. This cannot be done by an individual agent (though Vincent himself may be the exception) and is the natural domain for massively parallel computing such as ABM. In our example, we would have 'materialisation agents', where each agent represents a single material and whose objective is to 'negotiate' a minimum or optimum amount of that material (based on constraints of cost, time, availability, structural integrity etc) across as many different ME(I) processes as possible. For example, an agent representing a specific metal can satisfy a function requiring the conduction of heat, or electrons, or properties of strength and EM shielding. Its solution can be welded, melted, printed, machined or folded into ducts, tubes and conduits. Inversely, an agent for a specific polymer would satisfy functions requiring an insulator of heat, or electrons, or of optical clarity, colour and EM transmission, as well as being flexible, mouldable, printable and machinable. So forming a metal conduit for hot and cold water (flow and return) can be linked to a function to shunt heat, electrons or data through the same system. This would be a brutal process, where an agent finds a solution for its material only to find itself culled, because another materialisation agent meets the constraints better. Figure 1f, shows how Farid Fouchel, and I (manually), attempted this process for 3D printing, using a photo reactive thermoset polymer (itself not strong enough to support pressurised fluids and gasses) which we resolved as a series of concentric spaces, separating each service/utility, moving from optical data (in the centre), through mains water, waste extraction, hot and cold water and central heating flow/return. Note that there are three more (concentric) spaces than the services listed because, between some services, we either injected low melt alloy (as simultaneous low voltage power supply, structural integrity, sealing, between node and run, and EM shielding) or optical grade silicone (as simultaneous optical data transmission, flexible sealing, between node and run, and thermal insulation for heat/coolth supply). By 'injection casting' these materials within the concentric spaces between a run and node, we could assemble the runs to the nodes quickly, by abutting them and injecting across the join, and were able to demonstrate that the solution was sealed at working pressures. The '*integrated utility node*' is not obviously a membrane, but the structure in which it would be generated (i.e. the building envelope) begins to push this perception. It shows how available technology can move us towards a process centric view of design integration at the functional level of architecture.

ii. **At the heart of an intelligent system is an agent - us**. We assume building intelligence to imply embedded electronics and technology, but it should not. In architecture, the most complex and cheapest agent is ourselves, the occupier. We are the most sensitive to change and can make complex forecasts and predictions for our requirements, ahead of demand. As readily as adding or shedding clothes, we should occupy an architecture which allows us to modify any number of variables within our environment. Instead of one ventilation (window) in any single wall, there should be many. There should be vertical connectivity linked to deep horizontal compartmentalisation, and there should be fragmentation and gradients of connectivity between adjacent rooms, with tactile and controllable vents and valves from which complex cross ventilation strategies can be explored by the occupier (through feedback) and remembered. These modifications could be sensed electronically, so that a digital memory is encoded of optimal performance for a range of environmental conditions specific to the building, and beyond any single tenant. The spaces should be configurable, to create thermal cores (heat or coolth) in periods of maximum temperature drift from seasonal average, and the concept of comfort should be a transient state where changes are felt and induce a modification by the tenant.

iii. **Basic construction materials can be smart.** We revel in the properties of newly synthesised materials, embodied into novel structures with feedback, as either smart or intelligent. However, basic construction materials are as smart, even though, traditionally, their performance in 'smart applications' is not as predictable. Naturally porous materials (such as mud, wood and straw), have fractal dimensions (i.e. large surfaces per unit volume). Clay, whether used in adobe construction or termite mounds, responds to water vapour in remarkable ways and this interaction makes them natural phase change materials, as I will explain. Mud may be composed of fine clays, aggregates, organic matter and gels (where algae and fungi are present), and clay, alone, will swell as water vapour is adsorbed (condensed) onto it, and this effect increases further with the presence of cellulosic matter and organic gels. Between two adjacent clay particles, or between the clay lamellae themselves, a 'water bridge' exists as water, trapped or suspended at a natural equilibrium force between the grains, which, when pushed from this state (as either water is added to, or removed from, the natural bridge), will attempt to restore the disequilibrium state. The effect is that where an elevated water vapour pressure acts on one face of a mud wall, it will produce a vapour gradient through the clay structure, almost as quickly as vapour diffusing through air. As impressive, is that over certain thresholds of water vapour, clays transition between selectively permeable and impermeable states. This combination means that natural materials with strong vapour interactions such as clays, muds, plasters or cellulosic materials, are natural 'phase change materials', but not in the sense that the material, itself, is transitioning from one phase state to another (say solid to liquid), but in the sense that the phase state of water vapour (as a gas) transitions as it passes through the structure, and condenses on the porous material it encounters, and, to do this, it must also shunt heat into or out of the material it has condensed on, as Vainer (2008) so elegantly visualised. Termites, as agents, appear to regulate mound permeability as a function of water potential which is linked directly to the construction process. Though our ancestors may not have known the mechanism, they knew 'through trial and error' that mud, plasters, straw, timber, and even stone, act as moisture buffers and regulators to stabilise their environment. We can go further. With simulation, scripting and modelling of non-linear systems linked to digital fabrication tools, we should be able to produce structured water vapour adsorbing/desorbing materials with extremely large (folded) surfaces. In effect, basic materials, including plaster and concrete, become phase change structured membranes. This moves us from a position of using porous materials as humidity buffers, to a position where we are regulating the flow of heat into and out of a structure, based on geometry and the natural transition point of water vapour which, of course, corresponds to the mean comfort temperature we enjoy.

iv. **Transient membranes not impermeable barriers.** Cladding buildings in fibrous, insulating or selectively structured materials, resolves thermal management issues, but allowing building envelopes to be permeable to transient movements of gas through them, potentially brings about 'breathing' or the exchange of respiratory gasses between the inside and outside, whilst conserving a stasis of comfort for heat/coolth and moisture within. This is unlike bulk 'steady-state' air exchange systems, where heat/coolth and moisture must be recovered during complete air exchanges. Taylor *et al* (1996) and Imbabi (2013) have explored both dynamic building envelopes and dynamic insulation as steady state solutions, which work by inducing a constant negative pressure differential from the outside to the inside of the building, through the envelope (or the insulation in the envelope). The logic is that, assuming a uniformly permeable building envelope, the migration of 'fresh' air into the building can retard or counter the flow of heat (or coolth) out of the building. In practice, using current construction capabilities, sustaining a uniform negative pressure differential across a building envelope is difficult, because of the way we assemble buildings, and, depending on the interplay of external weather and the internal temperature/moisture ratio, there can be problems with interstitial condensation. Vogel (2009) takes this further to demonstrate a principle, observed in nature, which explores a transient solution which separates the need to conserve heat inside a building with the need to exchange respiratory air to the outside. Called 'the nose house', a tidal flow of air is generated into, and out of, a hypothetical building space along long metal fluted ducts, placed either side of the living space. However, as Vogel states, the walls would need to be around 6 metres thick to achieve this. Though impractical by this constraint, this becomes feasible when we consider that we can fold many metres of channels into a building envelope, using the digital design, simulation, and fabrication tools we have at our disposal, and link this to the vapour phase transition abilities of vapour sensitive construction materials, to exploit passive systems in buildings.

I hope I have shown how a few underlying principles of 'agency' can be linked to an architectural/construction capability and to digital integration and design to fabrication methodologies. I have made the deliberate connection between biological agents and digital agents, a difference being that biological agents tend to manipulate matter states, and technology agents tend to manipulate information states. I make this distinction to drive my next point. Can we link information technology 'processors' to biological matter 'processors'? I'm trying to cut through an image of millions of 'nano-agents' controlling individual molecules in a smart building envelope. I will attempt to link the digital capabilities we have now, to the negotiated aggregation and disaggregation of matter in biological membranes, where energy gradients are created and used across processes embodied in engineered artefacts, and, potentially, to building envelopes.

## Digital Construction by Rules

Currently, we define digital fabrication processes as falling within three broad categories of additive (deposition), subtractive (machining) and (de)formative processes. The latter (formative), involves squeezing and bending, and the former (additive), includes additive manufacturing (AM) or 3D Printing (3DP), but also joining and assembly processes. Additive processes have been compared to nature, in that complex shapes can be reproduced, similar to those seen in nature. This is not nature though. If I print a bone trabeculae structure, in bone (e.g. hydroxyapatite), it will not perform as bone trabeculae when I implant it. Additive machines are not like nature, by current definition, because they only add materials and replicate a specific geometry fed to them, whereas, in nature, as I have previously discussed, construction agents act out rules (algorithms) and must add, form, and subtract, for the reason that it is the only way to resolve many variables or objectives, many diametrically opposed, within a temporally resolved structure. Computational design optimisation lies behind the success of commercial AM technologies, as it can resolve several opposing criteria to produce a structure of optimal (typically matter minimised) form, for a specific material, and additive processes are the ideal method to outputting a geometric solution into the physical world, as it builds in layers. But then, so does construction. In fact, traditional construction integrates elements of additive (layer by layer), subtractive (cutting), and formative (moulding and casting) processes, for good reason. A purely additive process cannot make any geometry. Extra material is required to support overhangs (as in centring), and enclosed volumes have material trapped which must be removed after the build phase.

What if we combined elements of additive and subtractive (even formative) processes, as nature does, within a single digital fabrication machine? Here, we imagine a machine with one or more aggregation devices (effectors) with a capability to selectively deposit a packet of material, and one or more disaggregation devices, to remove a packet of material with both classes (aggregation/disaggregation) of effector working within the same build envelope. At the end of each effector is a sensor, which can feedback physical information from the structure being built, which itself is being acted upon by the environment in which the structure is being built. Each effector is controlled by a processor (termed a 'manipulator' in biological circles), which plays out algorithms corresponding to the multiplicity of functions to be embodied in the materialised solution, which fall within either actions which result in material being added (aggregated), or material being removed (disaggregated), from the build. We now have the architecture for a '*stigmergic printer*', as both aggregation/disaggregation agents have the 'process triptych' (i.e. sensor, processor, effector) set in 'dynamic tension' to each other within the same domain. The actions of the aggregation agent (AA) may be as simple as sensing the condition of the build (e.g. deflection around mean, temperature dissipation etc.), and acting to make the structure thicker/stronger (i.e. less deflection or cooler). Conversely, the disaggregation agent (DA) may sense the build and act to subtract material to reduce mass (i.e. derived from a net mass/temperature measurement). With each iteration of the build (i.e. the next time index, and negotiation over a single voxel), the AA/DA processors interrogate sets of encoded process objectives (i.e. conditional statements\algorithms pertaining to the processes to be integrated within the build), and may select one process objective over another, based on specific sensory information coming from the build, or possibly a probabilistic allocation of one process objective over another, as described, for example, in ants by Bogatyreva and Shillerov (2005). At any specific time index during the build, the allocation of a specific objective algorithm may be selected by the AA or DA which may act to add or remove material, based on explicit criteria, such as, in the case of architecture, light penetration, ventilation, access, substrate and final volume (possibly even aesthetics and planning regulations), or implicit criteria for the regulation of ME(I) transformations, where each objective will have measurable feedback from the build to the AA\DA.

Assuming all agent objectives have an appropriate sensor and feedback, can all objectives be resolved as they appear to be in natural structures? The answer should be no, only if we are expecting the machine to produce a single static solution with a stop point, which is how we run optimisation simulations today. However, as the structure unfolds in time, I hypothesise, the machine will produce a structure which, to the observer, may appear to integrate a multi-variable solution. As we move along the time line (which we can equate to the z axis, or build direction, or as concentric growth such as the layers of an onion), then at any single time index, some objectives are met, and in the next, another set of objectives are met.

## Resolving Multi-Variable Problems in Time

This hypothesis does not feel correct, as any set of objectives ‘oscillate’ from being resolved and not being resolved, as we move through the build. Surely this does not mean that the whole is able to have a net resolution of all the variables, or does it? Here, I’d like to invoke Turing’s (1952) reaction diffusion model, where he described the interaction of two chemicals interacting, one with long range activation and one with short range, or local inhibition, with feedback between the two states. I would like to (tentatively) infer, in the face of little evidence, that this is analogous to a dynamic (dis)equilibrium between positive (aggregation) and negative (disaggregation) elements, in a system where a finite ME(I) resource exists to be negotiated between positive and negative elements. The outcome of this interaction is the formation of a boundary, whose emergent property is folding at the interface between the two domains in dynamic tension. Turing was interested in the patterning which emerges in time, which is a complex and spatially resolved solution, he hypothesised, which could explain (morphogenetic) self-ordering in nature.

When we view a computer simulation of the reaction/diffusion process through time, we are presented with moving images, at around 25 frames per second, of the boundary between two ME(I) ‘species’ resolving in time. The boundary is in constant flux, as the thresholds between two scavenging chemicals shifts constantly. Now, imagine that each frame of the simulation extends rearward from the current frame (in the z axis) as a physical stack, and we apply some medical imaging trickery to find all the edges and form a spatially resolved equivalent of that stack in the z-axis. I did this with Isaac Eastgate, who was investigating video analogue feedback and was getting reaction diffusion structures as the video camera forced a threshold between black and white pixels, of which a single frame (of hundreds) is shown in figure 2a. We took all the frames, stacked them in the z-axis, and plotted the edges to produce the cross-section (looking through the z-axis) of the stack in figure 2c, and the 3D isometric plot in figure 2d. You see in figure 2c, that the 3D model has the same folded relationship in the z axis (ignoring some lens aberration at the edges), as it does in each x,y axis frame and, in figure 2d, we have one of the most elaborate, fractal and folded heat/mass exchanger structures I have encountered. This may be obvious, but it's not until you see the resolution in the z-axis that you realise that there is a structure 'in time' (which we have plotted in the z-axis) which you are not aware of when viewing the simulation. My point is threefold. What we see in the unfolding, reaction-diffusion simulation, are many physical phenomena (variables) reduced to just two 'opposing' regions around which tight folding emerges, because of the 'scavenging' nature of the two regions to each other. Secondly, I believe this applies to the tension between aggregation and disaggregation processes in nature (as in figure 2b), from which folding emerges as 'resources' are fought over, and, thirdly, where biological agents 'lock' a partial solution to resolving multiple variables simultaneously, at each time increment, there may well be a temporal rather than a steady state or spatial solution.

In Soar (2012), we ran an experiment as part of the Smart Geometry Symposium, where we asked a cohort of volunteers to be 'construction agents' for four days. Figure 3a, and 3c, shows the outcome, where each agent was randomly assigned objectives (for illumination, structural integrity, traffic flow-through, spatiality and ventilation), and each was given a means by which they could measure each objective within the structure they were to 'negotiate'. They were given cardboard truncated polyhedra, and a glue gun to add polyhedra within the space, and a hot air gun to remove any polyhedra they measured as conflicting with their objective. The agents measuring 'illumination' took light measurements at specific locations, and assessed the measurements as either falling inside, or outside, a pre-agreed threshold. If the light levels fell below the threshold, they would seek to remove polyhedra, to allow greater light penetration and, inversely, they could add polyhedra if the measurements were above threshold. For 'integrity' and 'internal flow' feedback, each deposited polyhedra was digitally scanned, as seen in figure 2a, and the 'real-time' structure was measured against a digital representation of a 'perfect' polyhedra model (i.e. not subjected to gravity or errors in assembling the units). If an element began to bend beyond a threshold limit, this could be seen in the digital model and corrected by the agent on the physical structure. Likewise, agents of 'internal flow' ran real-time CFD analysis to make assessments for ventilation and 'dead zone avoidance'. Some agents looked for access through the structure, as it was built in the middle of a busy intersection of many other workshops going off around it. None of the agents were allowed to plan or verbally communicate, but they could coerce and encourage other agents around them with gestures.

Over four days, complex interactions, negotiations (stalemates rarely emerged over such a large structure), and behaviours (clades, coercion, culling etc.), emerged to the point where the structure itself exhibited morphological and sensory aspects. By the second day, some agents would place single polyhedra in open and distant locations to the main structure, and then wait to see if those polyhedra were trodden on or damaged by the constant stream of traffic which came through the solution. If they were not, then other agents would build off them, until they eventually joined with the whole.

It was not possible to measure the final structure against each process objective, to establish whether it satisfied all process objectives embodied within it, and this is the next step. An interesting outcome was that, as we scanned the x,y,z, coordinate of each deposited polyhedra, we assigned them a colour to denote which objective (function) was being addressed at that point in time. The resultant colour coded digital image of the polyhedra structure, in figure 3b, shows how widely distributed each of the primary functions (i.e. a primary colour for each) were in the final solution, and we believe this approximates the process of multi-variable temporal resolution of functions we find in organic structures and biological membranes. At the very least, it is strange to see humans resolve organic solutions (bottom up), without recourse to cognitive (top down) planning.

## The Dilemma of Mixing Biology and Architecture

Where we accept that habitat stabilisation, in nature, emerges through negotiation tied to immediate feedback from, i) the environment an agent, or agents, are acting within, ii) the structure as it is built (which is continuous), and iii) between the construction agents themselves (where multiple agents are engaged), then we are forced to question how this can take place in human architecture, where humans draw a cognitive distinction between a design phase, a construction phase, and an occupancy phase, and currently give little thought to modification and re-use. For cognitive organisms, we are able to make these distinctions because they bring about advantage (i.e. resolve problems in the future). Because we can both project and communicate our intentions into the future, based on past knowledge, then we can negotiate many aspects of construction within the constraints imposed by our culture, and assess these decisions based on the probability, or risk, of a successful outcome (i.e. profit). As we know, this appears to come at a price, where we resort to solutions which mitigate risk (the most) and ensure the greatest return. This leads to over- engineering, simplification, and aesthetics over performance. However, we are now entering a new paradigm where, using digital sensor, processor and effector technologies, we can potentially draw more information from the environment, process greater information, and output the solutions using digital fabrication techniques, which, in itself, approaches nature. This has a long way to go, but it is already impacting on what we expect architecture and construction to become. As we measure our environment with greater frequency (hence accuracy), we perceive greater change around us and some of this appears alarming. It is only natural that, as a culture of greater sensitivity to environmental flux, we are demanding that our habitats should reflect this. But here lies the problem.

We have evolved a developed prefrontal cortex precisely to allow us to stabilise our future because, inherently, we know that living and responding to our environment, purely in the present, brings out the worst in nature. On the one hand, we are aspiring to be like nature, but, on the other we wish to avoid being like nature (in tooth and claw). So as designers, as negotiators of human habitats, seeking to introduce a paradigm of design 'like nature', this is tricky. Nature is messy, it is fractal, it is textured, it is smelly, it is noisy, it is impermanent, it is recycled, it is aggressive, because each organism seeking to stabilise its habitat, is sensing all other organisms seeking to stabilise their own. Organisms undermine (each other's) structures to the point of collapse, and we see this as 'optimum'. Based on this, it is easy to see why mutuality, symbiosis and parasitism emerge as strategies to share space and resource between organisms, and we can see why highly folded, selectively permeable, transient boundaries emerge between conflicting agents resolving matter as membranes. As a cognitive culture, historically, we have striven to move away from this, even though we still exhibit all these traits as cognitive abilities. Since the industrial revolution, we believe our culture 'achieved' separation and primacy above nature (because we can plan ahead of uncertainty), but this is mainly because we were ignorant of nature (i.e. we were not able to sense and understand processes). We are now on a journey where we are 'sensitive' of nature and we are asking questions like, "if nature built this, how would it do it?", and we are in a good position to answer it, but the reality is that instead of taking us forward to an architecture of the future, it is taking us back to an architecture of the past, an architecture before mass production and 'efficiency through scale'. Technology is part of our evolution to allow our culture to engage (i.e. sense, process and effect) with nature, and we call this intelligence. We want intelligent buildings and products, but do we want to push this as far as nature itself i.e. the very thing we evolved to fear, for which we developed our sense of 'civilisation' (i.e. stabilising a transient environment)? Biophilia, and Biomimetics, are the first step along this path. It is the safest way in which we can still put across a message that we are not wanting to be 'of nature', but be inspired, or borrow ideas and principles (structures, forms and functions) from it, which we can introduce into an offline process of design and engineering and negotiate the risks, so that we are not fighting when we begin the construction, habitat or modification phases. As the popular mantra goes, "think globally, and act locally", which alludes to an appropriate place along a spectrum of bottom-up negotiation at one end, and top-down hierarchical control at the other. Agency allows us to occupy this interface.

## Conclusion

Where we accept that design is a necessary offline operation, because it resolves conflict in the future (we hope), can we take the next step along the path of designing or building as nature would? We have a clue where this path will take us, in the form of 'agent architecture' or 'an architecture of rules', where we sense or measure the variables of a site (geology, topography, hydrology, insolation etc), the constraints of existing inhabitants or neighbours, the cultural and planning demands and the returns, and assign them to individual digital agents who will negotiate and construct a digital solution of incredible immediacy, which we will 'output' to fabrication machines. Further along this path, we will use robotic construction agents to undertake the same process of negotiation, but, on-site, for the immediate negotiation of environmental constraints and, potentially, further (driven by off-world and high risk applications), whereby robotic construction agents will negotiate and inhabit the structure as part of the process of continuous modification and reuse. This will be unlike an architecture with which we are currently familiar, where I see a future of robot agents fighting, poor design solutions and construction agents being 'removed' from the gene pool, and, because agents need to sense, they will produce solutions which can be easily sensed by other agents, so  will be smelly, noisy, textural etc., and they will form mutual solutions.

As designers, our next logical steps to extend what many believe to be biomimetics, may be the steps I have outlined, where we begin to look at how nature uses, and shares, processes and resources in highly folded structures, to harness the weak energy gradients we see in biological membranes.  This forces us to look at the entire supply chain of construction-as-process, but with the embodiment of the regulator of those processes, i.e. the agent, and the strongest message I have is that we, the occupier or tenant, are the best agent in this approach.  Because we now have the technology to allow us to handle orders of magnitude more information, we can reduce the time between design and construction because we can link digital fabrication to electronic sensing, processing, and materialisation, in the same way nature does.  As importantly, with non-linear mathematics, we can predict the behaviour of those basic and traditional materials we know to be most responsive to agent interaction, from which intelligence arises and which we can exploit commercially.  Scott Turner, and I, have named this 'physiomimetics', which may be a departure from biomimetics, or it may simply be the next evolutionary step for biomimetics and our objective to realise intelligent buildings.

## Acknowledgments

The author would like to thank the contribution of many worthy scientists who have shown endless patience and support during this journey.  In particular, special thanks must go to J Scott Turner for believing that we can make a connection between field research, and our physical commercial world.  Thanks must go to the reviewers, who took the time to give excellent criticism, so good that I have been forced to quote them.  I must thank the Human Frontiers Science Program for their support and funding and my academic institute Nottingham Trent University.

## References

Anderson, C., Theraulaz, G., Deneubourg J.-L. (2002) Self-assemblages in insect societies, Insectes soc. 49 (2002) 99 – 110, http://cognition.ups-tlse.fr/_guyt/documents/articles/43.pdf

Bogatyreva, O. & Shillerov, A. (2005) Robot Swarms in an Uncertain World: Controllable Adaptability, pp. 187 - 196, International Journal of Advanced Robotic Systems, Volume 2, Number 3 (2005), ISSN 1729-8806.

Goel, A.K., McAdams, D.A., Stone, R.B.,(2014), Biologically Inspired Design: Computational Methods and Tools, ISBN: 978-1-4471-5247-7, Chapter 11: An Ontology of Biomimetics, Julian F. V. Vincent, pp 269-285

Imbabi, M.S., Passive-active dynamic insulation systems for all climates, International Journal of Sustainable Built Environment (DOI10.1016/j.ijsbe.2013.03.002)

Pawlyn, M. (2011) Biomimicry in Architecture, RIBA Publishing, ISBN 978-1-8594-6375

Soar, R., Andreen, D., (2012) The Role of Additive Manufacturing and Physiomimetic Computational Design for Digital Construction, Architectural Design, Special Issue: Material Computation: Higher Integration in Morphogenetic Design, Volume 82, Issue 2, pages 126–135, March/April 2012, DOI: 10.1002/ad.1389.

Vincent J.F.V., Bogatyreva O.A., Bogatyrev N.R., Bowyer APahl A-K., (2006) Biomimetics: its practice and theory, doi: 10.1098/rsif.2006.0127, J. R. Soc. Interface 22 August 2006 vol. 3 no. 9 471-482.

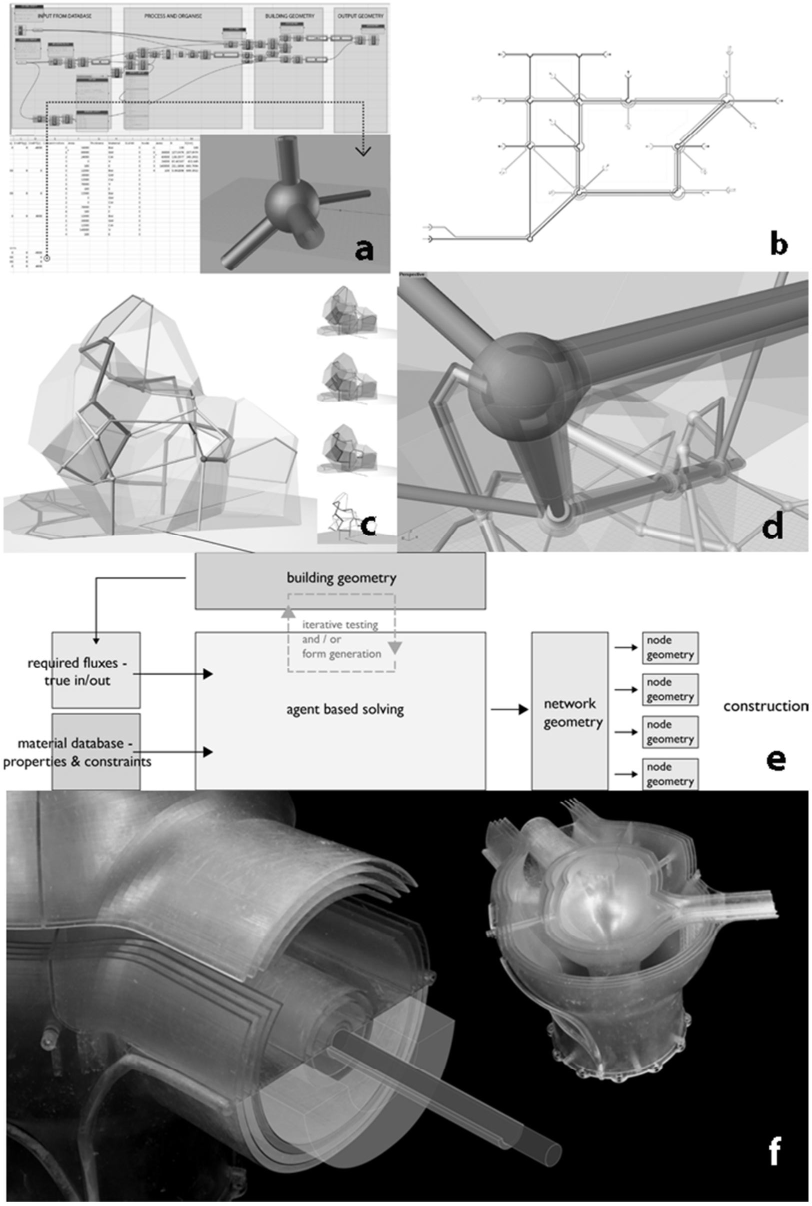
Turner, J.S., (2007) The Tinkerer's Accomplice: how design emerges from life itself, Harvard University Press, ISBN 978-0674-02353-6.

Taylor, B.J., Cawthorne, D. A., Imbabi, M. S., Analytical investigation of the steady-state behaviour of dynamic and diffusive building envelopes, Building & Environment, 31(6), p519-525, 1996.

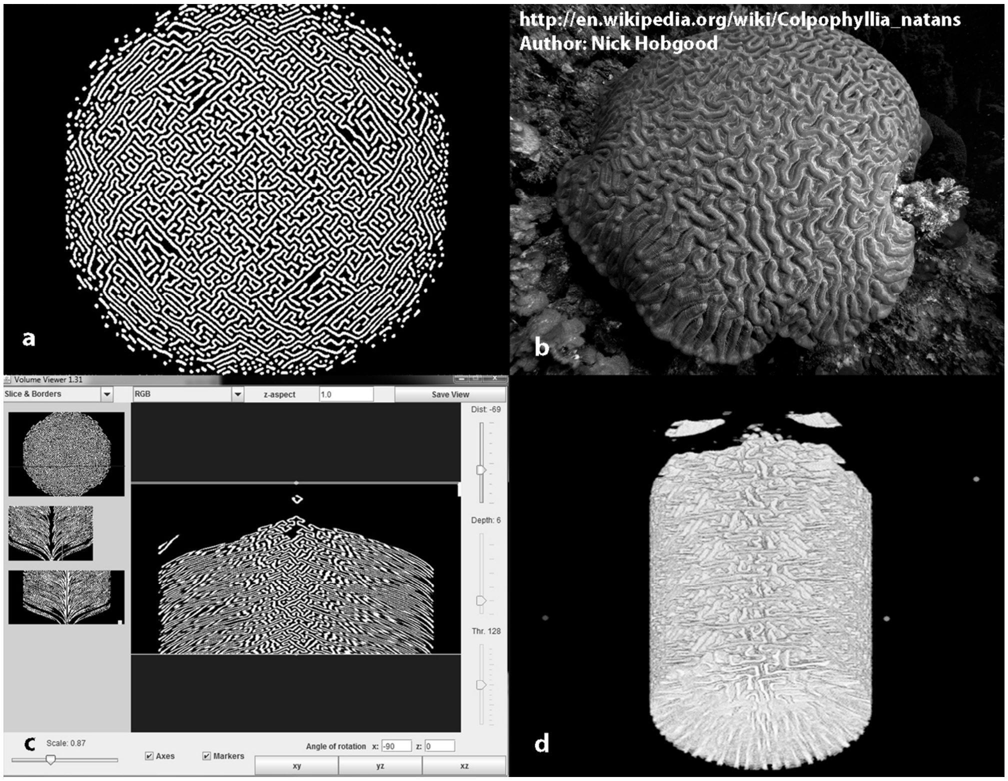
Turing, A., (1952) The Chemical Basis of Morphogenesis, Phil. Trans. R. Soc.237, 37-72.

Vainer, B., (2008) Quantitative characterization of vapour adsorption on solid surfaces and estimation of emissivity of solids using infrared thermography, proceeding from the 9th Int Conf, on Quantitative Infrared Thermography, July 205th, 2008, Krakow, Poland.

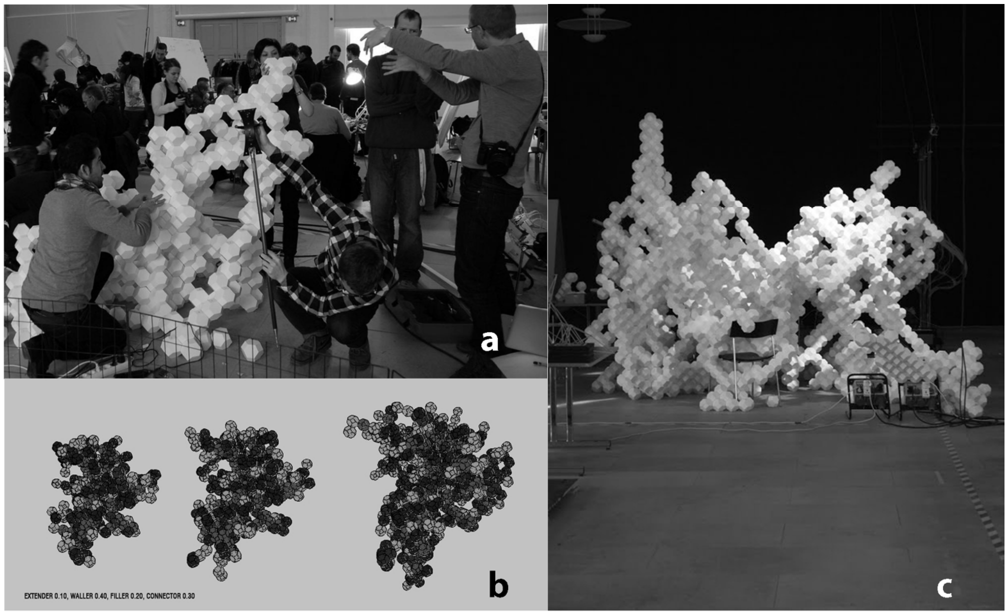
Vogel, S., 2009, Nosehouse: heat-conserving ventilators based on nasal counterflow exchangers, Bioinspiration & Biomimetics. 4 (2009) 046004 (4pp), IOP Publishing, doi:10.1088/1748-3182/4/4/046004.



259x386mm (72 x 72 DPI)



254x196mm (150 x 150 DPI)



341x208mm (150 x 150 DPI)