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

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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.

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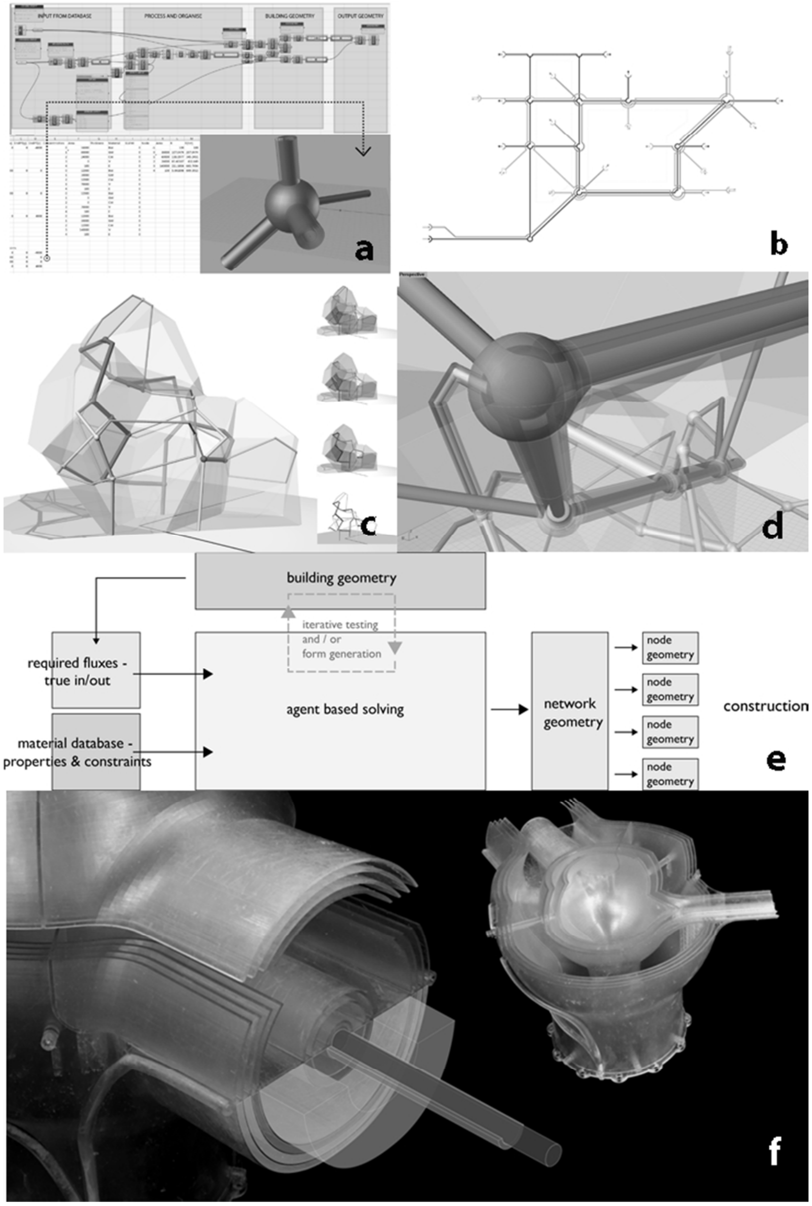

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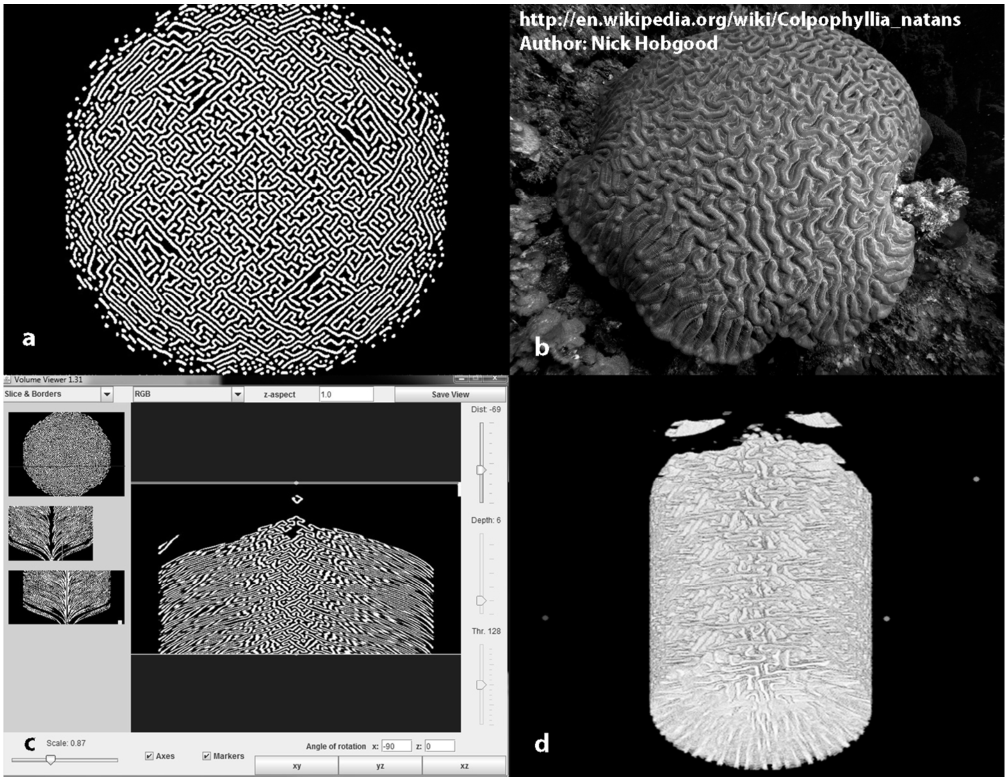
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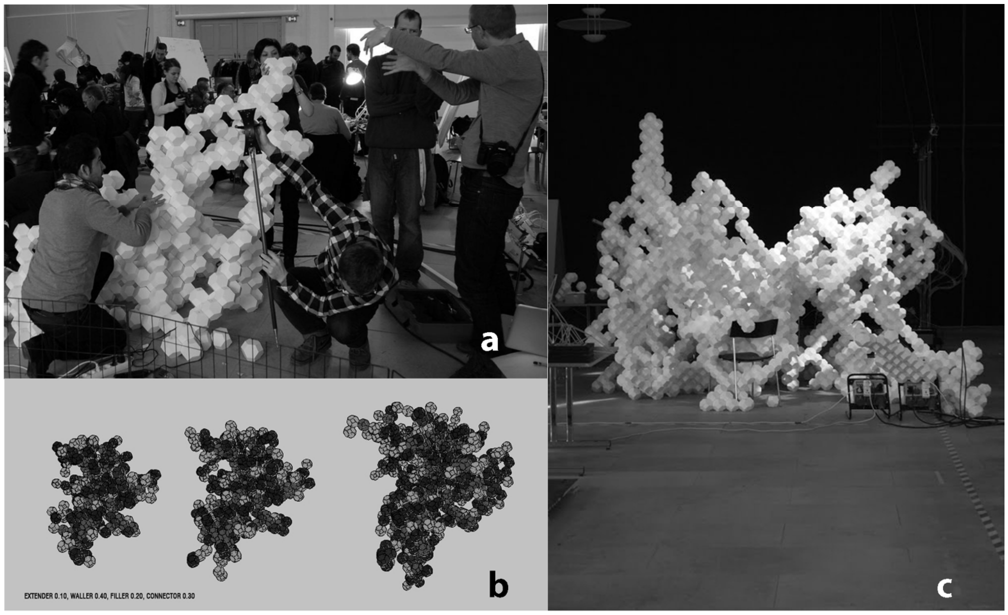

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