Bright Lights, Bug City

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The buttressed towers are three miles high and five miles across, and home to a million people. They are air-conditioned and humidity-regulated by natural methods that use not a watt of electricity. They are constructed entirely from natural, biodegradable materials, and have nurseries, gardens and waste dumps. Water is provided by wells dipping miles into the earth. And with their curved contours and graceful arches, they look rather beautiful too.

This is what future cities might be like if they followed the design of termite nests. It's no wonder, then, that some architects are starting to develop a keen interest in the architecture of insects, wondering what we might learn from it. Already these dreams are bearing fruit: according to its architect Mick Pearce, the Eastgate Centre in Harare, which has passive ventilation and cooling, was inspired by a termite nest.

The Eastgate Centre in Harare, Zimbabwe, was inspired by termite nests.

But that's just a tentative beginning. With the aim of galvanizing the field, biologists, computer scientists, physicists, architects and designers came together in Venice in late September 2009 at a workshop that explored what insects can tell us about how to make buildings. 'Some real contacts began to emerge', says termite specialist Scott Turner of the State University of New York, who was at the Venice gathering. 'There was a prevailing idea among the biologists that architects could learn much from us. I think the opposite is also true.'

Cathedrals of spit and shit

Animal building is probably closest, in terms of materials, methods and aims, to the traditional 'vernacular' styles of construction and design that have often been sidelined in architectural history: made from natural materials readily to hand (mud, clay, plant fibre), assembled quickly, constantly remodeled and recycled, exquisitely attuned to their specific environment – and all about survival. 'The clay structures of various swallows and wasps resemble structures of American Indians', says architect Juhani Pallasmaa of the Helsinki University of Technology, while he compares the woven huts of traditional African cultures with birds' nests. Today, in contrast, Pallasmaa says we have the luxury to 'develop absurd architectural ideas without the punishment of natural selection'. Yet environmental considerations – greenhouse-gas emissions, energy costs, water shortages or floods – are now forcing architects to become more pragmatic again. And they are looking for guidance not only in old human traditions but in nature, and particularly in the spectacular construction projects of social insects.

It's not a case of simple technology transfer, however – and not least because we often still don't really know how or why insects build what they do. 'The building mechanisms and the design principles that make the nests' properties possible aren't completely well understood', says Guy Theraulaz, one of the organizers of the Venice workshop and director of the CNRS Research Centre on Animal Cognition in Toulouse, France. That's why, for all the success of the Eastgate Centre, it doesn't really work like termite mounds do. Not only was it based on faulty models of termite nests, says Turner, but it didn't adhere to the models anyway. Happily, that doesn't prevent the building from working well. But it shows that there's plenty more to be done if we want to use nature's tricks wisely.

Turner has spent years studying the mounds of termites of the genus *Macrotermes* in Namibia, representing just a few of the roughly 2,000 termite species on the planet. Like most termites, they are geared to tropical climes, where management of heat and water is crucial. Termites live off cellulose, the recalcitrant constituent of plant matter that humans can't digest. In fact, neither can termites. Instead, *Macrotermes* species cultivate 'gardens' of cellulose-eating fungi, which then they eat themselves. Tending the gardens demands good climate control.

A nest made by *Macrotermes michaelseni* in Namibia.

Macrotermes mounds are typically around 2.5m high (but can be at least three times higher), and are made of clay and soil grains painstakingly assembled by the worker insects. The mounds are riddled inside with an elaborate network of tunnels, not just to provide access routes but to harvest the wind for gas exchange: getting rid of the carbon dioxide (CO_2) produced by insect respiration and decomposition of fungal compost, and replacing it with fresh air. This ventilation is vital, because the growth of the fungus is very sensitive to CO_2 levels. A typical mound with about two million insects inside may bring in around 1,000 litres of air each day.

The structure of the tunnels in termite nests is very complex and hard to deduce from cross-sectional slices. So Turner and Soar have captured the full three-dimensional shape in dramatic fashion, filling the nest with plaster and then dissolving away the clay walls.

It was suggested in the 1960s by the Swiss entomologist Martin Lüscher that heat from the fungus garden and the termites' bodies makes warm CO_2-laden air rise up by convection to a central chimney from where it fans out into the porous walls and escapes. As it does, fresh air is sucked into the mound from below. This is what the Eastgate Centre set out to mimic. But Turner, working with British engineer Rupert Soar (now CEO of the Nottingham-based company Freeform Engineering), has found that it's not as simple as that.

The two species on which Turner and Soar have focused – *M. michaelseni* and *M. natalensis* – make so-called closed-chimney mounds, in which gases are exchanged to and from the tunnels through a porous surface. In the central core of the mound, fungi are cultivated in a convoluted, cellular comb made from half-digested faeces. But the air in the porous outer walls of the mound mixes rather little with that in the core. Turner and Soar established that the two air masses are largely independent by injecting a tracer gas into each of them and seeing where it went. When added to the central nest system, it didn't all flush through to the walls in one go, but got there slowly in a series of small puffs. So gas exchange happens only gradually and sporadically, not by steady convective circulation.

What's more, the walls are usually warmer than the central nest, opposing any buoyant outward flow of CO_2-rich air. Turner and Soar think that the mixing is wind-driven. But they say that this is very different from wind-powered ventilation in human buildings, in which fresh air simply blows through vents and flushes stale air out. That works fine with steady winds, but they are usually turbulent – full of energy, but in a fluctuating form that Turner compares to alternating electrical current rather than direct current.

'Termite mounds are sophisticated manipulators of the a.c. energy inherent in turbulent winds', he says. The outer network of tunnels acts as a low-pass frequency filter: deeper within the mound, high frequencies in wind energy are filtered out, and only the low frequencies remain. The net effect, he says, is that the boundary between the nest air and the wall air gets sloshed around, releasing transient puffs of stale air into the walls' tunnel system. Gas exchange in the human lung is also an 'a.c.' system that works in similar fashion: you might say that the mound acts as a kind of giant lung that constantly breathes in and out.

Might we design buildings with porous walls that harness the energy of turbulent wind gusts for ventilation in similar ways? 'We could turn the whole idea of the wall on its head', Turner suggests. 'Instead of opening a window to let fresh air in, it would now be the wall that does it, but carefully filtered and managed the way termite mounds do.'

It also seems that the ventilation system has little to do with either heat or humidity regulation. The temperature is kept steady simply because the nest has ample contact at its base with the heat sink of the surrounding soil. Changes in the mound temperature closely follow those of the soil temperature through the seasons.

The nest's moisture level is kept quite steady even though the outside humidity changes dramatically through the year. But it's still not clear why. Turner and Soar speculate that the comb in which the fungus is grown, made from a slurry of chewed wood and grass with a typical mass of around 40 kg, might act as a water reservoir. They estimate that this gigantic absorbent sponge holds around 60-80 litres of water, providing an ample sink or source to counteract any humidity fluctuations. 'The comb has a moisture content equivalent to a humidity of around 80-90 percent, and evaporates water when ambient humidity falls below that', says Turner. 'And at humidities higher than that, the comb is hygroscopic and will take up excess water vapour. That, combined with the organization of the nest into dozens of small galleries with combs, should damp any local fluctuation of humidity.'

Some other termites build quite different types of mound. Biologist Judith Kolb of the University of Osnabrück in Germany has studied *M. bellicosus*, which typically make many-spired 'cathederal' mounds on the savannah of East and West Africa. She says that heat gradients drive air circulation that sinks through the nest and rises in the walls during the day, and goes the opposite way at night.

The ‘cathedral’ mounds of *Macrotermes bellicosus*.

But in the forests of northern Côte d’Ivoire, the same species builds dome-shaped mounds that work more as Lüscher proposed, with a simple buoyant column of air rising through the next and escaping through small holes in the central spire and side chimneys. This design seems to trap more heat, making sure that the fungus is kept at its warmer than the surrounding forest: there is a trade-off between trapping heat and expelling waste gases.

Meanwhile, the *Amitermes meridionalis* termites of Australia build mounds elongated in a north-south direction by means of magnetic alignment. This exposes the broad eastern face to the rising sun early in the morning, helping the mound to warm up quickly after the cool nights and thus keeping the temperature relatively constant.

The mounds of the Australian termite *Amitermes meridionalis* are magnetically oriented.

That doesn't however, explain quite why the mounds are elongated – a dome-shaped mound, having a lower surface-to-volume ratio, would lose less heat at night in the first place. The reason for the flat shape isn't yet clear, but seems to be connected to the fact that such structures are made in flood-prone regions. Perhaps the high surface-to-volume ratio helps rapid drying when the plains get seasonally flooded, Kolb suggests.

Emergent architecture

The lessons for architects might not stop at the way nest structure offers low-energy functions such as temperature control and ventilation. What about the construction process itself? Human structures are built to a blueprint, planned and designed in advance by an architect. But no master-termite nor wasp or ant architect drew up plans for their nests. The building process is decentralized, the result of thousands of individuals all labouring on their own little bit of the whole. In this respect, insect nests are more akin to old cities, which have acquired their shapes organically through self-organization rather than from some master plan.

Why, though, is the result not chaos but a structure exquisitely attuned to its purpose? Studies of natural processes as diverse as crystal growth, sand dune formation, bird flocking and the embryonic development of animal patterns have shown that complex yet globally ordered patterns and structures can emerge from systems of entities interacting only via local rules, in which each entity senses and responds to what its near neighbours does. The same is true of nest formation.

Termites and ants, for example, coordinate their building activities by emitting chemical pheromones – a word coined by Lüscher in 1959. As termite nest-builders chew soil pellets into a cement-like paste, their saliva adds a chemical which, for just a few minutes, can be 'smelled' by others over a distance of a centimetre or so. This pheromone draws other workers to the source, encouraging them to add their pellets to the structure there. That sets up positive feedback: the more a pillar is augmented, the stronger a pheromone source it becomes. In the 1970s, Jean-Louis Deneubourg of the Free University of Brussels in Belgium showed theroetically that this process creates spots of preferential pellet deposition – incipient pillars – with roughly even spacing.

Deneubourg, Theraulaz and their coworkers have more recently postulated that the termites may emit other pheromones during nest building which induce individuals to follow each other, and under some conditions of air flow these 'trail pheromones' can lead to the construction of walls either side of the trail, and eventually to galleries. These structures in turn may modify the air flow, inducing further new architectural features. Perhaps gyrating currents wafting along channels help to guide construction of the extraordinary helical ramps that, in some termite tests, connect one tier to the next.

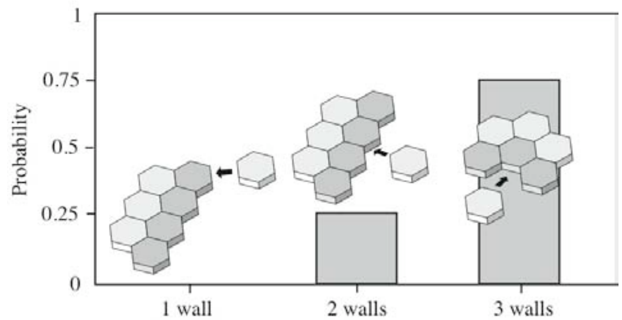
The key point is that each insect need respond only to rules based on 'local' information: there's no need for a global blueprint. It's an approach that is starting to appeal to human architects, too. It opens up the possibility of adapting the building process in response to constraints that change during construction and to factors such as air currents, temperature and light. “There’s a huge opportunity for robotics to build systems of agents linked by a distributed intelligence that can remodel a building’s structure as conditions change”, says Turner. “This is contrary to the normal practice now, which is to have centralized building energy management systems.”

What are the local rules that insects actually use? One of the most thoroughly studied nest-building activities of social insects is that of the wasps of the widespread genus *Polistes*, often called paper wasps because of the fibrous material from which they make their combs. Each nest is typically round and consists of 150 or so tubular cells with hexagonal cross-sections.

A nest made by *Polistes* paper wasps.

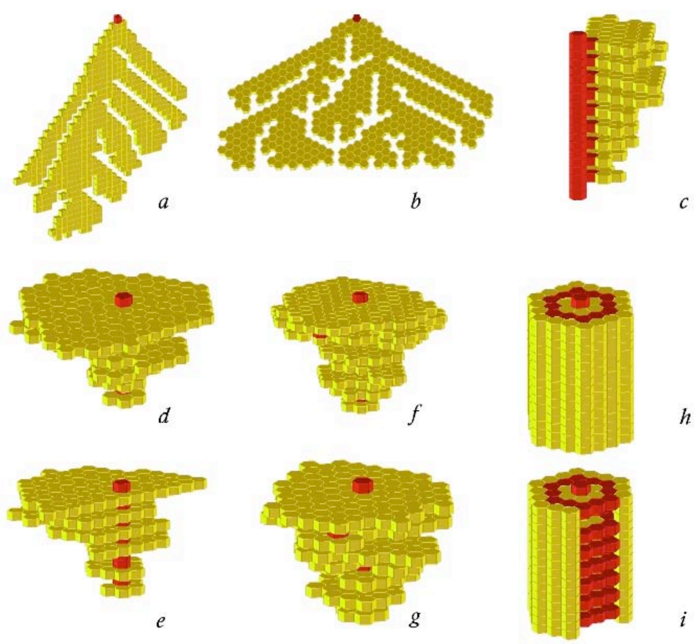
Polistes nest construction can be tracked step by step in the laboratory: supply the wasps with differently coloured paper for building at different stages and the result is a colour-coded record of the progress of construction. In this way, Theraulaz found that the *Polistes dominulus* wasps observe general rules for adding new cells to the structure, rather than just adding them at random. ‘To decide where to build a new cell, the wasps make use of the information provided by the local configurations of cells on the outer circumference of the comb, which they sense with their antennae’, he says. ‘I found that wasps have a greater probability to build new cells to a corner area, where three adjacent walls are already present.’ In contrast, ‘the probability to start a new row, by adding a cell on the side of an existing row, is very low.’

Theraulaz and his colleague Eric Bonabeau have devised a model for investigating what kinds of structures might appear in such a process, governed by local rules that define the probability of a cell being added at particular types of site. With two ‘tiling’ rules specifying the probabilities that a new cell would be added at sites with either two or three existing walls in place, and also allowing the possibility of stacking cells into layers, they could simulate the growth of three-dimensional nest structures.



Probabilistic rules for the addition of new cells in the computational nest-building model of Theraulaz and Bonabeau

The model generated a wide range of nest shapes, depending on the probabilities chosen for the two rules. Many of these structures resemble those made by real wasps of different species, showing that all that is needed to produce this architectural diversity is a slight change in the propensities with which the wasps add new cells. The insects don't work to different blueprints, but merely have small differences in how they lay their tiles. When they begin, they have no more idea than we do of what the final pattern will be: in effect it makes itself.



Some wasp nest architectures made by simple tiling rules for the addition of new cells.

That's an approach to building design that is starting to appeal to architects (see box: 'Building by numbers'). Building by the iteration of 'local' rules also opens up the possibility of making the building process adaptive to constrains that change during construction. At the Venice workshop, Tom Wiscombe of the Southern California Institute of Architecture described a software system that generates a structure while taking account of the stresses it experiences, rather like the way the compartmentalized structures of bone and of trees adapt to stress as they grow. Theraulaz says that the local building rules could also be adapted to take account of factors such as air currents, temperature and light.

Living buildings

He also points out that one of the key differences between our buildings and the nests of insects is that our designs tend to be static – once they're up, they don't change – whereas the dwellings of insects are ever-changing. 'Their nests are not frozen structures', he says. 'They are much more like a living system. There is a constant remodeling activity from the insects that continuously changes the form and structure of the nest.' *Macrotermes* mounds lose around 200 kg of soil each year to wind and rain, which is constantly being replaced. If a hole appears in a mound, workers are drawn to it and immediately create a plug. Having completed these emergency repairs, they then remodel the plug over several months to convert it from a kind of 'scar tissue' into something resembling the rest of the tunnel network.

Scott Turner has found that *Macrotermes* termites add new material to the mound only during the rainy season. This leads him to think that the primary function of the mound is actually to manage water: when there's too much of it, the workers transport it away as wet clay which they deposit in the mound. When water is scarce, some workers seek it out deep in the soil and drink it up, only to spit it back out in the water storage tanks of the fungus comb. Kolb suggests that all termite mounds are designed to produce homoeostatic conditions – keeping their inner environment as constant as possible – and that the very different environments in which they are found dictate diverse strategies for achieving this.

Maintaining a consistent, comfortable set of conditions is also a common concern of architects. So what might they learn from this? Turner says that buildings in hot climates might emulate the 'damping' schemes of termites to keep heat and humidity relatively steady. They could be embedded deeply in the thermal sink of the soil and, more importantly (because high humidity is worse than high heat alone), manage water content with tanks that mimic the reservoir of the fungus comb. And if we can find ways of harvesting 'a.c.' wind energy, the turbulence and variability of winds – currently a hindrance to wind power – might be turned to advantage. As we come to understand more about how insect nests work, says Turner, 'this opens up a vast universe of new bio-inspired design principles'.

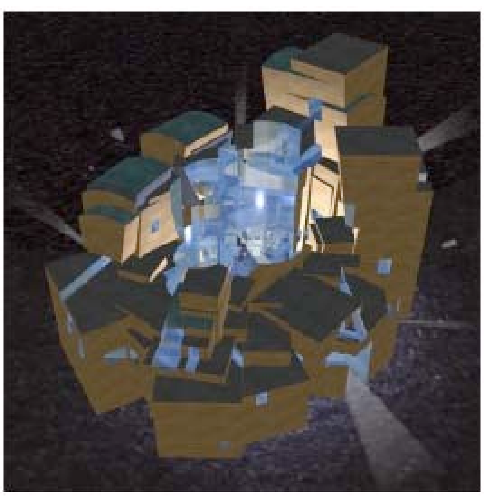
But ultimately the lessons could be much more dramatic. 'The mound', says Turner, 'is in many ways as alive as the termites that build it.' Perhaps, then, architecture needs to go beyond making buildings inspired by nature 'to making buildings that are, in a sense, alive themselves.'

Building by numbers

Architects aren't fixated on function, but also like to pursue design for its own sake. 'Design needs no justification', says Tom Wiscombe of the Southern California Institute of Architecture. So several architects are excited by the possibilities of emergence and self-organization not because they offer improved practical performance but because they suggest a new way of creating forms. During the 1990s this notion gave rise to a movement called swarm architecture, which makes use of algorithmic techniques inspired by the iterative rules that insects and other social animals seem to apply.

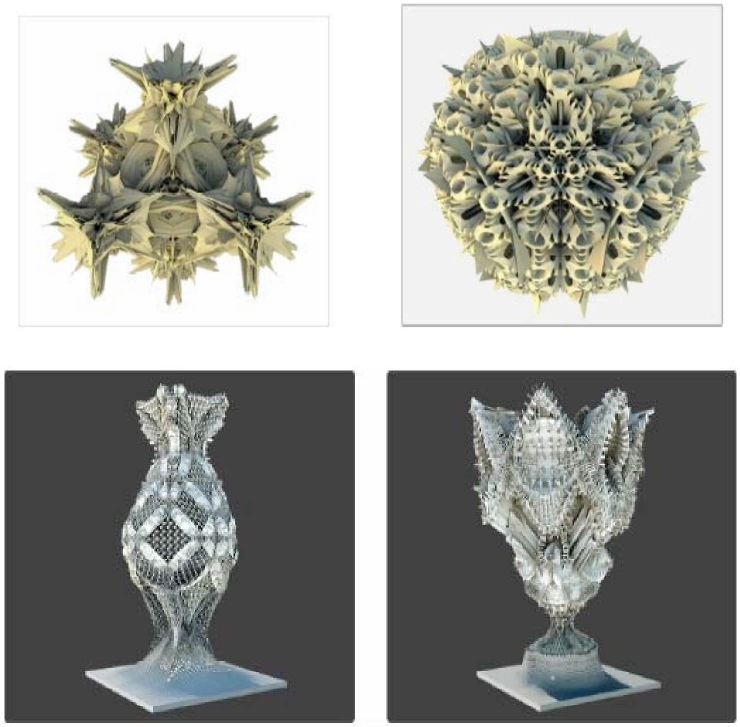
It's a somewhat controversial field, partly because it is so open-ended and exploratory. 'Research' in this area sometimes amounts to figuring out what an algorithm does, not trying to solve any particular problem – and the criterion of success is often aesthetic, not technical. Moreover, there is a tension between the notion of self-organization, which goes its own way, and the instinct of architects and designers to nudge processes towards a preferred goal. This sort of architecture therefore sometimes aspires to be a 'science' without really knowing what the question is. The challenge, according to Wiscombe, is to 'harness the wonderful iterative and evolutionary capabilities of computation in architecture without losing the serendipity, breadth and relevance of designed work'.

Despite these uncertainties, the explorations have yielded some visually arresting results. Designer Nicolas Reeves of the University of Quebec, for example, has taken literally the old adage that 'architecture is frozen music' by translating an excerpt from Monteverdi's opera *Orfeo* into numerical input for a computer algorithm called a three-dimensional cellular automaton that produces a building plan from an assembly of cells. He then had a model made in resin by the technique of rapid prototyping.



Computer visualization, and resin model, of Nicolas Reeves' *Gestatio o [Slum/Opera]*, made by algorithmic design using a three-dimensional cellular automaton.

And Michael Hansmeyer of ETH in Zurich, Switzerland, has devised an algorithm for iteratively subdividing a polygonal mesh into new forms, with results that look poised between the mathematical and organic, reminiscent of baroque viruses, snowflakes or plants.



Some of the forms generated by Michael Hansmeyer’s ‘subdivision’ algorithm.

Thanks to new techniques in construction, approaches like this which generate complex forms can now be rendered in real glass, steel, concrete and composites. That’s what makes possible the elaborate, algorithmically shaped tower proposed by Wiscombe’s company Emergent for the city centre of Huaxi in Guiyang, southwest China. Whether it will ever be made is another matter.

The Guiyang Tower designed in 2008 by Emergent.