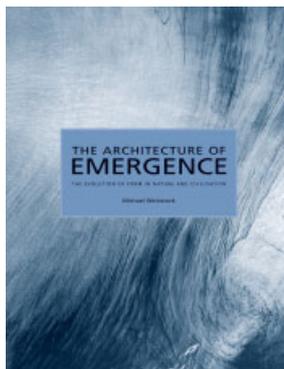


EMERGENCE AND THE FORMS OF METABOLISM

Earlier this year, **Michael Weinstock** published a seminal book, *The Architecture of Emergence: The Evolution of Form in Nature and Civilisation*, which challenges established cultural and architectural histories. The conventional worldview is expanded by placing human development alongside ecological development: the history of cultural evolution and the production of cities are set in the context of processes and forms of the natural world. As well as providing a far-reaching thesis, Weinstock's book gives lucid and accessible explanations of the complex systems of the physical world. In this abridged extract from Chapter 5, Weinstock explains the dynamics of individual and collective metabolisms from which intelligence and social and spatial orders emerge.



Michael
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Humans and all other living beings emerge from and exist within the dynamic processes and phenomena of the natural world, and they have had and continue to have a profound effect upon it. All the forms of nature and all the forms of civilisation have 'architecture', an arrangement of material in space and over time that determines their shape, size, behaviour and duration, and how they come into being. D'Arcy Thompson argued that the morphology of living forms has a 'dynamical aspect, under which we deal with the interpretation, in terms of force, of the operations of Energy'.¹ Living forms construct and maintain themselves by the exchange of energy and material through their surfaces, and in doing so they excrete changed materials and energy back into the environment. Metabolism is the 'fire of life',² and its processes transform and transport energy through the interior of the living form. All metabolic processes cease without a constant source of energy, although most living forms are capable of storing some energy in chemicals to survive temporary fluctuations in supply.

There is a relationship between energy and the lifespan and body mass of living systems. Small organisms are typically more metabolically active than larger ones, and the larger the organism, the slower the metabolism. A fast life is a short life: 'The light that burns twice as bright burns half as long.'³ Whatever the size or shape of a living form, they all must capture and transform energy from their environment, and transport it in fluids to every cell. These processes require surfaces and fluid transportation networks, and there are geometrical parameters in the branching networks of living forms that are constant across all scales, from microbes to the largest trees and animals. The rate of energy that flows through a metabolism determines other variables that scale in relation to mass, such as the rate of fluid flow and the cross-section of the aorta or phloem vessels, or the number of heart beats in a lifespan.

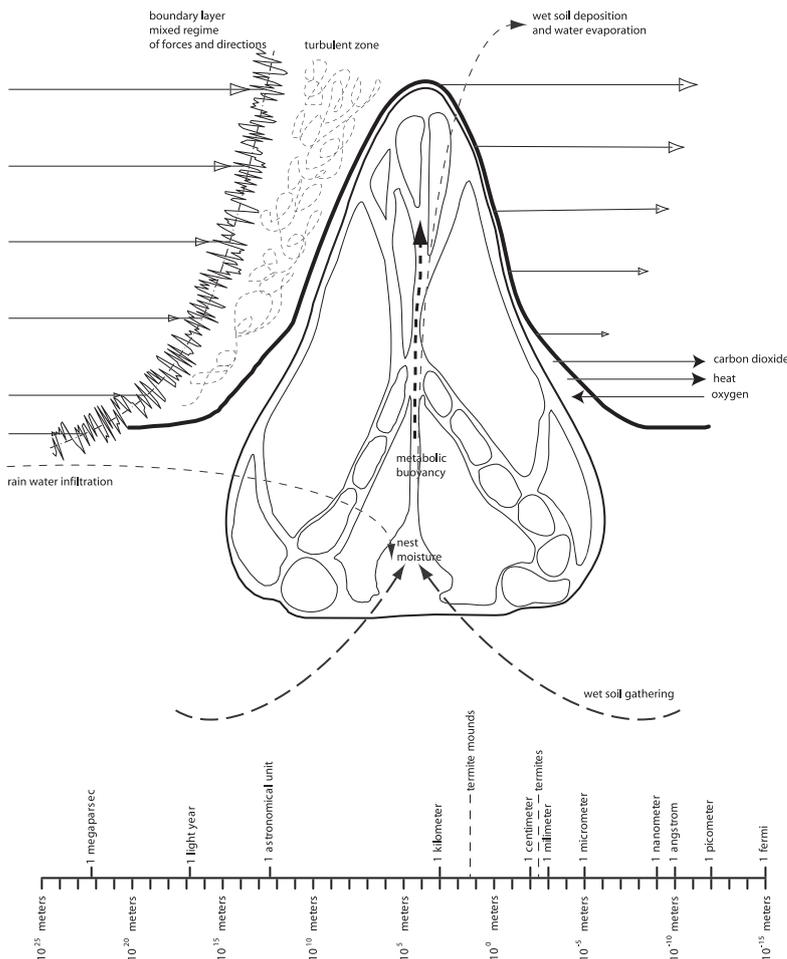
It has long been a mystery as to why so many biological phenomena, such as lifespan, heart beats and respiratory rates should be related to body mass by $3/4$, $1/4$ or minus $1/4$ powers. The quantitative model of West, Brown and Enquist rests on the development of an abstract mathematical model of the maximally efficient branching network for the distribution of metabolic products and fluids. It provides a theoretical logic for the scaling of metabolic rate, and many other morphological parameters, in relation to the mass of a living form. There are three constants in the model: first, the network branches in a hierarchical series to supply all parts of the living form, so that the branches are self-similar, reducing in cross-section and length by a constant ratio; second, the end points of the smallest branches are always the same size no matter what the size or species of the living form is; and third, the branching network minimises the time and energy used to distribute the fluids and metabolic products, and the metabolic rate of the whole living form scales at the $3/4$ power of the body mass.

Since its first publication in 1997, the model developed by West, Brown and Enquist has been successfully tested with the available observational data for all living forms.

The metabolic scaling characteristics emerge from the parameters of branching networks in the vascular system of trees and in both the cardiovascular and respiratory system of mammals. The model applies to the whole system of an organism, and it is argued that it incorporates both structural and hydrodynamic constraints, and is capable of accurately predicting many other allometric variables that scale in relation to mass, such as the parameters of fluid flow and the related dimensions of the vessels, the maximum height of trees, and ecological patterns of distribution of plant populations and communities.⁴ Recent investigations are focused on the application of this model to cities.

Ecological organisation emerges from the interaction of the metabolic processes of all the forms of life that co-exist within a territory or habitat. All species, including humans, have a range or spatial area from which they gather energy, and over which they have an effect. An individual tree, for example, is anatomically organised to support its three-dimensional array of leaves for its photosynthetic metabolism. It will modify the soil and the atmosphere of its local environment by its metabolic processes – the transpiration of water drawn up from the ground will modify the structure of the soil, and the water

vapour and gases excreted by the leaves will modify the temperature, humidity and oxygen content of the atmosphere. This in turn will affect the metabolism of other trees near to it, as will the shade it casts. The spatial pattern of a mature forest, the density and distribution of varying sizes and species of plants, emerges from the interaction of all the plant metabolisms within it. Furthermore, the collective effect of the totality of metabolic actions produces the environment that other species inhabit; the bacteria and fungi, the insects, birds and animals that co-exist with the forest and within it. The processes of multiple individual systems, each acting across a range of spatial and temporal scales, interacts with the soil and topography, with sunlight and climate, water and atmosphere, to construct an ecological system. The flow of energy and material through an ecological system is thus regulated by the collective metabolism of all the living forms within it, and over time the regime of natural selection within the ecological system may be modified. At a finer scale, populations of individual living forms have an effect on their local environment, and in doing so they modify their own ‘niche’⁵ within the larger ecological system. Their descendants inherit and extend that local environment, and over many generations this changes the local regime of ‘fitness’ and, consequently, the dynamics of natural selection.



Termite behaviour and orders of magnitude

Colonies can produce three-dimensional material forms that are typically five or more orders of magnitude larger than the individual; for example the termite *Macrotermes bellicosus*, each individual only a few millimetres long, produces a fully developed nest that is up to 10 metres (32.8 feet) high and 30 metres (98.4 feet) in radius. The nest constructions of wasps, bees, ants and termites exhibit a wide range of forms, but all of them provide a thermally and chemically regulated environment, so extending the suitable climatic range for the species and modifying the energy requirements and metabolic rates of its individuals.

Many living forms extend their metabolism by a material construction that reduces the load or stress on some aspects of their metabolic processes. Insect colonies have highly structured social organisations, with restricted reproductive roles for individuals, generations that overlap in time, collaborative care of the offspring, and in many cases morphological distinction or castes for specialised roles. The material forms of the constructions of social insects are spatially complex and exhibit collective metabolic processes that are dynamically regulated to a very fine degree over time. The complex material organisation emerges from the interaction of millions of simple actions of individuals, each with a very small set of innate behaviours or 'motor programmes' that are triggered by chemical, thermal or hygroscopic stimuli. Individuals have differing thresholds and degrees of response to these stimuli, and so collective intelligent behaviour emerges from millions of slightly different interactions with the fluctuating internal and external material and metabolic conditions.

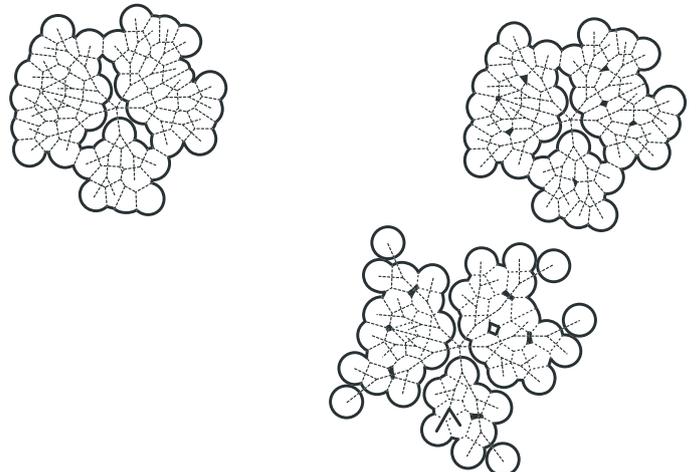
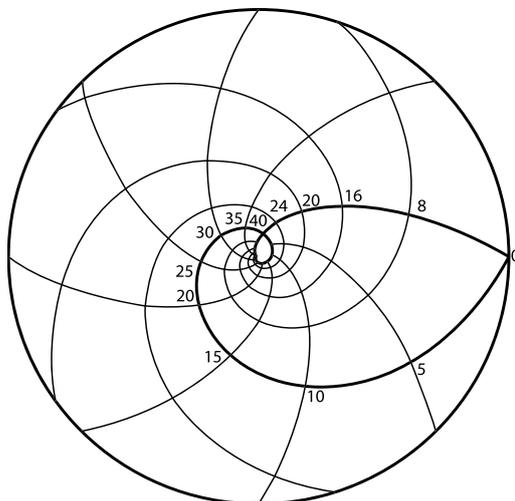
The extended metabolism of insect colonies has a fixed spatial relationship to the territory over which they range, with the nest or hive tending to be more or less centrally located. Intelligence, spatial organisation and material artefacts emerge from the collective extension of metabolism of the social insects. Insect collectives continually modify and regulate their exterior environment, and over time modify their ecological niche, and so enhance their 'fitness' in that environment. The close interrelation between the extended metabolism of the collective and their environment changes the regime of natural selection in their favour. In insect collectives there are no individuals with a capacity for processing information, and no system for the flow of

information to a dominant decision-making individual or group. Responses to internal and external changes emerge from the actions of individuals, so that behavioural complexity emerges at the organisational scale of the collective. The emergence of distributed intelligence, of social and spatial organisation, of collective and materially extended metabolism, is reinforced and developed by positive feedbacks acting across a range of spatial and temporal scales.

The metabolism and social organisation of the great apes determine a very different spatial relationship of their material constructions to the territory over which they range. In chimpanzees the collective group is typically up to a hundred individuals with a territory that is determined by the distribution of the fruit, leaves and herbs that they feed on. This may be as much as 35 square kilometres (13.5 square miles) of forest, and a very much greater area in more open and mixed habitats. The whole community moves across their territory in loose association, split into smaller subgroups of four or six individuals, but moving closer together at night and weaving branches and leafy twigs into either tree or ground nests that collectively are arranged in an approximately circular plan. Chimpanzees make and use tools, extracting honey or insects with twigs, breaking open nuts with rocks, and using leaves to sip water. It is observed that knowledge and expertise of nest construction, tool-making and use is passed down through generations, immature individuals learning by imitating older, more proficient adults. However, variations do exist between communities in different regions with different climates, and with differing food quantity and quality. This suggests a material 'culture'⁶ that involves the social transmission of knowledge that modifies the inherited and genetically conserved responses to environmental stimuli.

Phyllotaxis

The arrangement of leaves on a twig or stem, phyllotaxis or leaf ordering, is significantly related to the avoidance of self-shading. Leaves spring from a twig or stem at more or less the same angle, but in sequence are rotated so that they are offset from each other.



It is clear is that there are many similarities as well as differences between the dynamics of 'collectives' of the various taxa and species of apes and of insects. What is common between them is the large number of individuals with a range of different response thresholds, emerging from very small variations in the process of embryological development. Both positive and negative feedback occur in their interactions with each other and within their environment; in general, the gradation of responses across the population is either reinforced and accelerated by positive feedback, or inhibited by negative feedback. There is a high degree of redundancy in the relation of individuals to the collective, so that the numbers committed to specialised roles can be varied according to the circumstances – it is probable that this characteristic is also produced by the varied response thresholds of the multitude of individuals.

The relations of the spatial pattern of extended metabolic processes and material constructions are very different. The spatial pattern of the great apes arises from the ecological distribution and seasonality of food plants across the large defended territory of the group, and individuals move in loose association. Material constructions are temporary and individual, but closely grouped at night for defence. The spatial pattern of the social insects also arises from the ecological distribution of food plants, but the material construction tends to be centrally located in their territory, and is permanent. The evolution of human forms and culture involves both spatial patterns, extensive environmental modifications or 'niche construction' that is genetically conserved, and the emergence of a complex system for the transmission of knowledge over time. $\Delta +$

Michael Weinstock, *The Architecture of Emergence: The Evolution of Form in Nature and Civilisation* (John Wiley & Sons, 2010), is available in paperback at £29.99 (PB ISBN: 978-0-470-06633-1) from www.wiley.com and www.Amazon.co.uk.

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Notes

1. D'Arcy Thompson, 'Prologue', *On Growth And Form* (first published 1917), Cambridge University Press (Cambridge), 1961, p 19.
2. M Kleiber, 'Body size and metabolism', *Hilgardia* 6, 1932, pp 315–51.
3. '... and you have burned so very, very brightly, Roy.' From *Blade Runner*, 1982, directed by Ridley Scott, The Ladd Company, USA.
4. See BJ Enquist, 'Allometric scaling of plant energetics and population density', *Nature* 395, September 1998, pp 163–5; GB West, JH Brown and BJ Enquist, 'A general model for the origin of allometric scaling laws in biology', *Science* 276, 1997, pp 122–6; and DL Turcotte, JD Pelletier and WI Newman, 'Networks with side branching in biology', *Journal of Theoretical Biology* 193, August 1998, pp 577–92.
5. See KN Laland, FJ Odling-Smee and MW Feldman, 'The evolutionary consequences of niche construction: a theoretical investigation using two-locus theory', *Journal of Evolutionary Biology* 9: 1996, pp 293–316; and KN Laland, FJ Odling-Smee and MW Feldman, 'Niche construction, biological evolution and cultural change', *Behavioral and Brain Sciences* 23(1), 1999, pp 131–46.
6. See A Whiten, J Goodall, WC McGrew, T Nishida, V Reynolds, Y Sugiyama, CEG Tutin, RW Wrangham and C Boesch, 'Cultures in chimpanzees', *Nature* 399, 1999, pp 682–5; and A Whiten, V Horner and S Marshall-Pescini, 'Cultural panthropology', *Evolutionary Anthropology* 12, 2003, pp 92–105.

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Metabolic scaling

The quantitative model of West, Brown and Enquist rests on the development of an abstract geometrical model of the maximally efficient branching network for the distribution of metabolic products and fluids. There are three constants in the model. One, the network branches in a hierarchical series to supply all parts of the living form, so that the branches are self-similar, reducing in cross-section and length by a constant ratio; Two, the end points of the smallest branches are always the same size no matter what the size or species of the living form is; Three, the branching network minimises the time and energy used to distribute the fluids and metabolic products, and the metabolic rate of the whole living form scales at the 3/4 power of the body mass.

