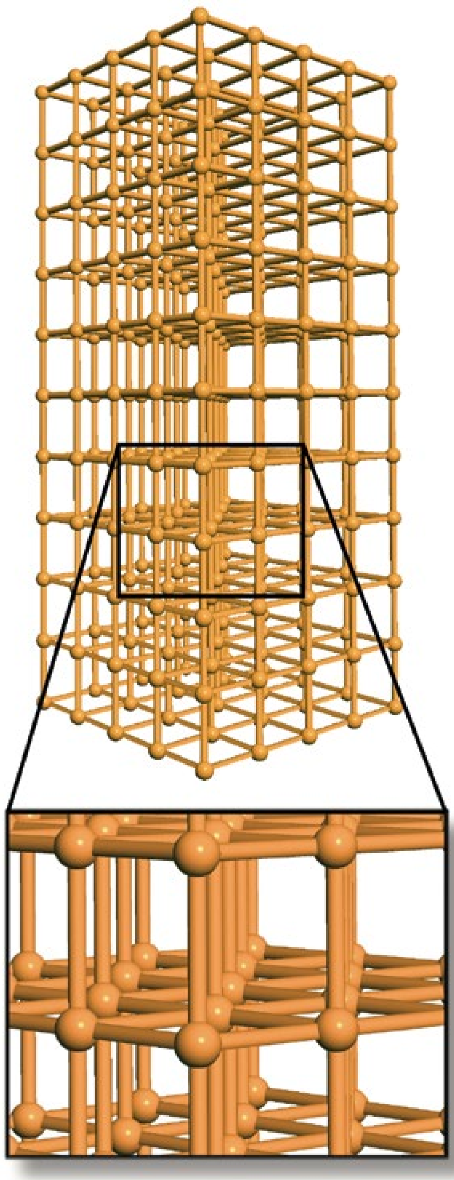
Sergi Valverde and Ricard V Solé

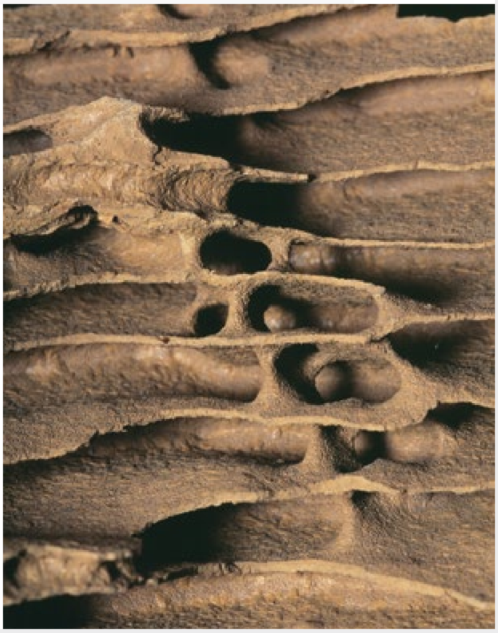
NETWORKS AND THE CITY

'Cities need to change to survive. As living beings that are constantly replacing their cells, rebuilding their veins and arteries, and pumping energy and matter or producing waste, cities are also growing and evolving as they age.' Just how complex, though, are cities? **Sergi Valverde and Ricard V Solé** of the the ICREA-Complex Systems Lab at the Universitat Pompeu Fabra in Barcelona look at how network theory and emergent dynamics might be bringing us closer to an overarching theory of urban organisation.



Sergi Valverde, Skeleton frame of a virtual skyscraper, ICREA-Complex Systems Lab, Universitat Pompeu Fabra, Barcelona, 2013
The skeleton of a building forms a uniform grid of horizontal layers. This highly regular organisation is the fingerprint of design and conscious planning.

Termite nest
Detail of a spiral staircase structure in a nest built by the Apicotermes termites found in Africa. In termite nests like this, horizontal layers are connected by staircases, an example of which can be partially seen at the centre of this sectioned view. There are also ventilating airshafts leading to the surface of the nest, which is constructed from soil and woody material.



In Italo Calvino's book *Invisible Cities* (1972)[1] the young Marco Polo describes to the ageing emperor Kublai Khan his recollections about imaginary lost towns. The cities described by the imagined Venetian are themselves the products of imagination, equally poetic and surreal. But in many cases the descriptions capture the essence of what cities are or what they should be. The city of Zora, for example, is said to have something special in the patterns emerging from its streets, doors and windows, sharply remembered by the traveller 'as in a musical score'.[2] However, in order to be easily remembered, the city needed to remain 'motionless and always the same'.[3] As a consequence, 'Zora languished, disintegrated, disappeared. The earth has forgotten her.'[4]

Real cities display complex patterns, which our mind organises and identifies not because of some special set of features, but according to the underlying relationships among buildings, streets and the mark left by time on every object. Indeed, cities need to change to survive. As living beings that are constantly replacing their cells, rebuilding their veins and arteries, and pumping energy and matter or producing waste, cities are also growing and evolving as they age. They need to constantly adapt. Perhaps as it is told in another famous book, Lewis Carroll's *Through the Looking-Glass* (1871), where Alice and the Red Queen run and run as fast as possible, every city needs to constantly change in order to remain in the game. As the Red Queen said to Alice: 'Now, here, you see, it takes all the running you can do, to keep in the same place.'[5]

Cities are at the forefront of our changing civilisation; they will largely shape our future and play a key role in the challenges yet to be faced. And yet we are far from understanding them. As happens with other complex systems, a large number of metaphors have been used in the past to capture their tangled nature and our role in their development, growth and – sometimes – decay. The city has been cast as a steam engine, as an organism or communication network. It is interesting to notice that similar analogies have been used for the brain, probably the greatest challenge for both scientists and philosophers. How complex is a city? A satisfactory answer to this question requires an appropriate view of complexity beyond qualitative metaphors. In the last 20 years, researchers from physics and complex systems sciences have introduced powerful techniques of data analysis that are changing our perspective of cities and suggest that a theory of city organisation might not be far from our reach.[6] Among the weaponry recruited for this goal, network theory appears as an essential component.[7] Networks pervade complexity, and the development of a theory of their origins and meaning (both in natural and man-made systems) has paved our way towards the dream of an overarching urban theory.

Networks are everywhere. Streets define more or less ordered grids enabling the flow of people and vehicles.[8] And buildings are themselves reticulated networks embedded in space and themselves filled by other networks providing the matter, energy and information needed to sustain our lives. There are also some remarkable similarities between city processing mechanisms and biological metabolism. One case study is that of the collective behaviour and nest construction of social insects.[9]

Termites are particularly revealing as examples of emergent dynamics. Individuals are blind and receive information from nearest nest mates. They do not possess a global picture of the nest structure, and yet they are able to build it. The result is a structure that at a termite's scale is colossal (termite mounds can reach heights of several metres),

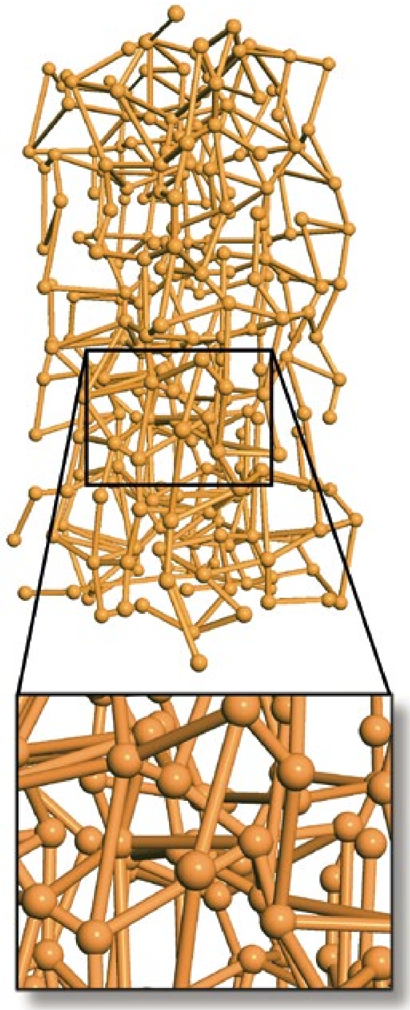
Collective building behaviour
Social insects like termites form very large colonies composed of many individuals that display collective behaviour, for example building complex nest structures.

and within which the colony sustains itself and provides a stable, safe environment by means of extensive cooperation and parallel information processing.

What kind of structure describes a termite nest? The skeleton of a virtual nest, which has been simulated and compared to real data from 3-D computer tomography techniques after replacing their chambers and the corridors connecting them by nodes (balls) and edges (links), can be visualised in a simplified graph representation.[10] Chambers are used within a colony to store food, take care of eggs and larvae or simply provide shelter. Corridors are excavated by termites as the nest is built to link the different parts of the whole structure. The network of corridors and chambers heats or cools the mound,[11] maintaining a nearly constant internal temperature of 30°C (86°F). Not surprisingly, termite mounds have inspired designs for efficient climate control in buildings.

A closer examination reveals that the internal web of connections is like a distorted lattice that has been created in some disorganised way. This can be seen as a spatial lattice made up by randomly connecting chambers in such a way that the 3-D distribution of them is optimal: a minimal number of corridors has been used that guarantees that the termite colony exploits the greatest amount of space at the lowest cost of expended energy.[12] In this way, the colony of 'blind architects' spontaneously generates a building that, despite its apparent disorder, hides a high degree of structural order. Although not fully obvious from visual inspection, quantitative measures allow the detection of the presence of a noisy lattice: a hidden order has been created out of individual disorder. Though no conscious plans or maps exist, the structure's blueprint is captured internally by the nature of the interactions between individuals. The web of social exchanges defines, to a large extent, the organisational plan, but something else is needed.

Like other man-made artefacts, buildings are the result of purposeful design; however biological structures are not,[13] as their lack of top-down planning requires alternative forms of construction based on bottom-up rules. Such rules very often follow what the French biologist François Jacob named 'tinkering':[14] the massive tendency to reuse made by biological evolution which – as pointed out by Richard Dawkins – operates as a blind watchmaker,[15] unable to foresee the future. When termites build their nests, there is a complex process of interaction between the growing structure and individual behaviour. This interaction between the agents and the inert, changing structure they are building is called 'stigmergy',[16] and defines an additional noticeable difference between collective intelligence and its artificial counterpart. As the structure grows and changes, so does the way the individuals behave. The structure influences the way the rules evolve so that individual behaviour and structure somewhat change each other. This pattern is also present in biological development, where gene networks responsible for pattern formation are affected by their spatial locations through gradients and boundaries. However, there are limitations to what is actually possible, and this makes biology and technology closer than might be expected. Physics and even mathematical limitations play a leading role here, which can be better appreciated on a larger scale.



Sergi Valverde, Structure of gallery networks in a termite nest, ICREA-Complex Systems Lab, Universitat Pompeu Fabra, Barcelona, 2013
Virtual cast of a termite nest using 3-D computer tomography. The picture was obtained from volumetric data providing sectional images of a real nest. The 3-D galleries and chambers within the nest were reconstructed from these sections. The structures were then further simplified into a network model, which can be directly visualised in a computer and also enables quantitative measurements of the nest structure.

Webs within Webs: Convergence

Buildings appear to be one easily identifiable component within a nested hierarchy of webs. They are embedded within local street maps that are part of the global pattern defining the city distribution. Cities are not disconnected elements either: they are connected through several types of transportation networks. The hierarchy ends up in the global web that defines the limitless boundaries of our civilisation.

The realisation that a nested set of webs is at work is important for many reasons. On the one hand, different levels allow us to formulate different questions: typically, what happens at one scale cannot be reduced to the properties of low-level structures. Looking at individual termites does not tell us anything about nest building in the same way that single buildings tell us nothing about city growth. On the other hand, a complete theory of city dynamics should be able to explain multiple levels of organisation, which may require abandoning some well-established assumptions.

An example of the decoupling between levels is provided by the observation that the boundaries of cities often grow in disorganised ways characterised by the same rules that seem to operate for growing tissues. Using Berlin or London as case studies, physicists studying the time evolution of urban boundaries discovered that they expand in ways similar to those of cell cultures or bacteria in Petri dishes.[17] In this case, a very simple model lacking any kind of central control was able to explain the growth of large cities by considering them as living populations expanding to their nearest locations. Denser clusters of local populations would be more likely to occupy nearest, empty spots around them. The global result was a pattern of growth not dissimilar to the rugged boundaries of a growing tumour.

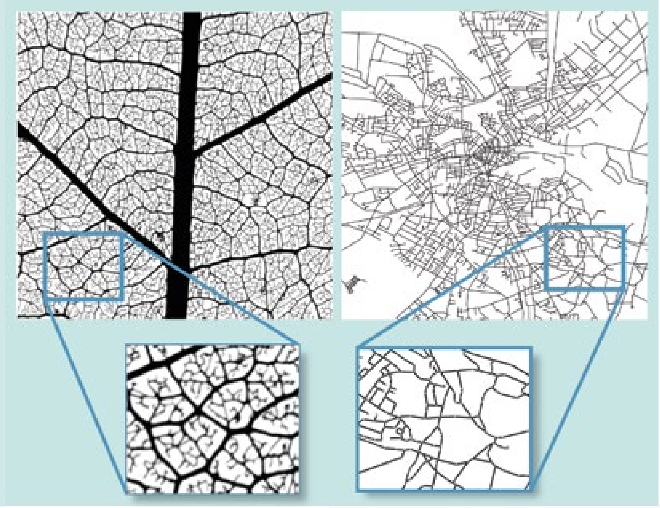
Many natural and artificial networks share common features because they operate under similar constraints including spatial embedding, optimisation and self-organisation. Cities, ant nests and leaf veins are all examples of systems embedded within efficient transportation networks. They are spatial networks whose nodes and links are embedded in space, limiting the density of connections per unit of area. Spatial inhomogeneities, natural barriers and environmental templates also influence their organisation. As a consequence, the physics of pattern formation in these disparate systems leads to common solutions that we perceive as observable regularities. When looking at street maps, we can appreciate a whole spectrum of possible designs: from trees and grids to the more disordered (or organic) patterns. Interestingly, some of these patterns are shared by the galleries excavated by ants.[18] Transportation systems optimised for efficiency and cost are treelike, in that they have no loops. However, observation of leaf veins reveals that many closed loops are required to protect against external damages and fluctuations in load.

London city network
This night aerial view from Bank onto the City of London enables us to compare the flow of urban traffic with the flow of ants within their nests. Cities and nests have comparable scales: millions of individuals live in the city and in the nest. The large scale of these systems requires a transportation network that enables an efficient flow of goods and individuals.

Organic city slums
Aerial view of the Vidigal favela, a slum on the hills behind Copacabana in Rio de Janeiro. All cities have their slums and informal settlements, often on the edges of built-up areas. In the 18th and 19th centuries, the term 'rookery' was given to a city slum of poor people due to the perceived similarities between their disordered layout and the large, noisy colonies of multiple nests made by rooks. On the other hand, slums appear to be an inevitable component of dynamic and rapidly changing cities.

Is this similar in cities? Many large cities were, at their origin, a collection of small, disconnected towns. Population flows expanded towns' borders towards nearby local centres, eventually merging them within a larger urban system. What were once empty landscapes of isolated urban centres are now crossed by spatial networks that enable traffic flows and social exchanges. Street planning can be regarded as an optimisation problem that can be expressed as 'for a given number of centres find the transportation network that connects them, and ensure that the density of connections is sufficient to ensure that a path to navigate from one location to another in the network can always be found'.

A modest increase in link density might enable a sudden transition from a disconnected system to a so-called 'percolating network', and this encapsulates an enormous number of important phenomena known to occur in complex systems. It defines the boundary between a set of disconnected objects and a true system where any part is connected to any other through some path. As in leaf veins, further increases in the density of links yield loops and many alternative paths connecting any pair of endpoints, and this in turn leads to safer traffic and a rational distribution of space.[19] The resulting street network is what we easily identify with the city's skeleton, and its statistical organisation (once again) shares many features in common with leaf veins. What is the consequence of this convergent design?



Transportation networks
A comparison of natural and artificial transportation networks reveals common principles of organisation. Leaf veins have many closed loops in order to be robust to exogenous perturbations, like damage and load fluctuations. Likewise, increased density of streets may lead to a rational distribution of traffic loads and efficient transportation systems.

Design Through Self-Organisation

Although the tangled organisation of city streets seems too complex in organisation to fit into a simple model, simple computational models can reproduce phenomena that involve the most complex agents such as humans. Physicists Mark Barthélemy and Alessandro Flammini presented a very simple computational model that takes into account spatial embedding and local optimisation rules to generate synthetic (but realistic) urban systems.[20] Several versions of the model exist, and one of the most successful incorporates the interactions between population density and road formation. In broad terms, a road segment is formed, then grows and expands to connect different local 'centres', or neighbourhoods, by linking them in the most efficient way and therefore reducing costs. There is no complex planning, yet very good agreement between the real and the virtual city. The model captures several independent features of real street networks as well as the spatial and temporal organisation of the populations around them – a big achievement for the blind architect.

Is nature telling us something useful about human designs and potential alternative ways of thinking about them? Can future urban planning benefit from exploiting self-organisation in an effective manner? At the largest scale, self-organisation might inevitably occur beyond our control unless large-scale plans are at work before the system starts to grow (a rather unlikely scenario). Allowing self-organisation to be part of the design principles can bring unsuspected novelties, but also undesirable outcomes. It can be a source of spontaneous order, but it has also been recognised as the origin of large fluctuations that eventually result in

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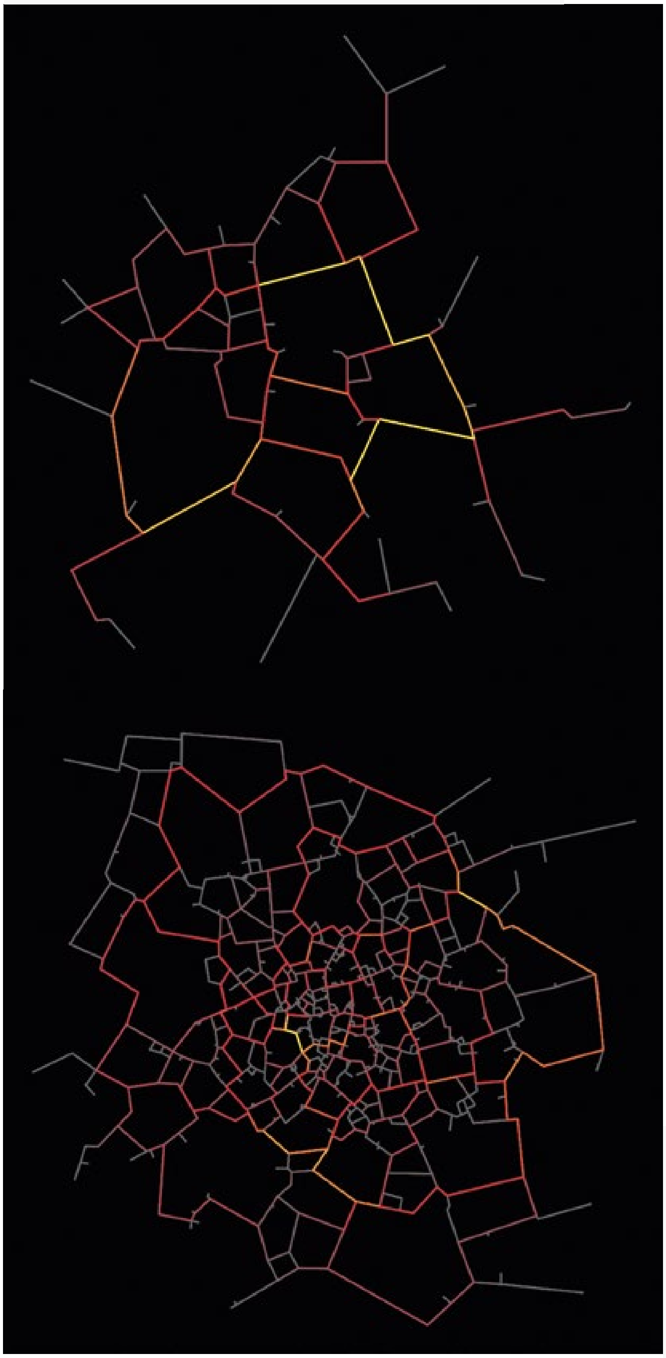
Sergi Valverde, Growing *in silico* cities, ICREA-Complex Systems Lab, Universitat Pompeu Fabra, Barcelona, 2013
Two snapshots of a computational urban model used to grow *in silico* cities. A colour link weight is here used to indicate the amount of traffic crossing the virtual street network. As can be seen, a spontaneous backbone of looping structures, the equivalent of loops in leaves, has been also formed.



catastrophe. So before we consider using it, we need (as scientists do) to start to understand it.

It is not possible to even imagine what kind of social engineering experiment could modify the large-scale evolution of urban structures. However, at some smaller scales some useful lessons can be extracted. Consider, for example, flows. Networks of flows propagate across the city. Some involve energy and matter while others carry information. And one very special type of agent involves all of them: humans. Due to their obvious relevance and the vast amounts of data that can be acquired about them, pedestrians have been the subject of intense scientific analysis. Walking humans in different scenarios define a particularly interesting problem, and understanding the nature of their collective motion has become a large area of study, for example, for physicists including Dirk Helbing and co-workers.

Helbing and colleagues showed that – against our intuitions – human crowds behave statistically in a rather particle-like fashion.[21] We might think that since these complex agents are intelligent beings, there is no simple model that describes, for example, the spontaneous formation of trails in parks and gardens. Pedestrians prefer to walk frequently used paths: the increased visibility with a large number of footprints results in a reinforcement process and the emergence of a stable trail system. Interestingly, the emergence of trails is very robust and largely independent of specific details of pedestrian behaviour, and they reappear despite the subsequent efforts of urban planners to restore original areas. The lesson? Here crowds act as 'blind designers', and do so against previous (rational) plans and through collective behavioural patterns.

Lessons from *Physarum*

Top-down planning is limited because of the intrinsic difficulties associated with making accurate predictions of the future evolution and growth of cities. But the similarities between natural and artificial networks suggest that we can perhaps learn how to reuse biological solutions. Recent experiments with the slime mould *Physarum Polycephalum* illustrate one remarkable possibility.[22] Here researchers used this single-cell organism to uncover optimal forms of

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connecting nodes in a graph using efficient transportation paths. Imagine, for example, a set of cities located on a map. We want to design a low-cost, efficient transportation network connecting these locations. As the number of cities grows, so rapidly does the potential number of solutions. The problem becomes a nightmare and no systematic approach can be used to test every solution. However, our organism solves it.

A piece of food is placed in each city location, and the fungus allowed to search through space. Each time it detects a 'city' it grows there, at the same time creating hollow tubes transporting food between neighbouring cities. The tubes are created and destroyed as the living web explores its surrounding space, and the dynamics are dominated by a spontaneous minimisation of the transport system. The final result is a quite well-designed structure that has been shown to give a design solution that is often better than human-designed networks. The potential and elegance of this method allow its application in a disparate range of spatial systems requiring cost minimisation while maintaining a fluid communication. It has yet to be generalised in domains beyond road maps, but its efficiency in quite different case studies is already established and could be a source of novel approaches to network design at different scales. This single-cell living web not only defines optimal paths connecting a complex array of locations, but can also find its way out of the labyrinth. The blind designer might therefore teach us some valuable lessons as to how to escape from our own design traps. ⌀

Notes

1. See the English translation from the original published in 1972 in Italian: I Calvino, *Invisible Cities*, Harcourt Brace & Company (San Diego, CA), 1978.
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3. Ibid, p 16.
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15. R Dawkins, *The Blind Watchmaker*, Norton & Company (New York), 1986.
16. E Bonabeau and G Theraulaz, 'A Brief History of Stigmergy', *Artificial Life* 5, 1999, pp 97–116.
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19. E Katifori, GJ Szollosi and M Magnasco, 'Damage and Fluctuations Induce Loops in Optimal Transport Networks', *Physical Review Letters* 104, 2010, p 048704.
20. M Barthélemy and A Flammini, 'Modeling Urban Street Patterns', *Physical Review Letters* 100, 2008, p 138702.
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Self-organised human trails
A spontaneously created path between two roads close to the Barceloneta beach in Barcelona. Pedestrians eschewed the established walkways (the diagonal red-brick path and the horizontal path at the bottom) and created their own paths. Once created, other pedestrians subsequently reinforce the most attractive trails as they reduce physical and navigational costs.