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Editorial

Whither network science?

In his book *Out of Control: The New Biology of Machines, Social Systems, and the Economic World*, Kevin Kelly, the editor-at-large of *Wired Magazine*, argued that the divide between the industrial and postindustrial world is encapsulated in the idea of the 'network'. Indeed he argued that, just as the atom was the icon of the 20th century, the network would be the icon of the 21st century. His argument was that the old way of organizing things from the top down, using centralised hierarchical control, was rapidly giving way to new forms of network economy and society, focused around the development of emergent order, from the bottom up. In fact, he went so far as to argue that stable and sustainable systems could only be built this way, that "the only organization capable of unprejudiced growth, or unguided learning, is a network" (Kelly, 1995, page 26), and he concluded that "the central act of the coming era is to connect everything to everything" (page 201).

It is in this milieu that network science has flourished. Although networks date back to general systems theory, which came of age over fifty years ago, until recently they have remained highly descriptive and they were essentially articulations of system structure, identified in terms of their connectivity but rarely linked to process and never used as a means for classifying systems into different types; that is perhaps surprising, given that they provide a rich way of measuring and defining interactions. In design and planning, the notion of networks was mainly used to show how interactions within the design process could be used to guide its logic, and there were rudimentary attempts to examine graphs within building structures in analogy with the use of networks in cities, from which accessibilities could be computed (Batty and Tinkler, 1979; March and Steadman, 1974). In sociology the use of networks to measure power structures led to the beginnings of social network theory, although these applications lay relatively dormant until the network paradigm really took off in the 1990s.

That networks might be classified in terms of different graph-theoretic structures is an old concept, but it did not become significant until some ten years ago when formal articulation was given to a particular kind of network called a 'small world'. A small world is a system whose properties enable elements or nodes in its interaction network to display local and tight clustering as well as relatively short average distance or connectivity to the rest of the system. In this sense small worlds represent the 'best' of any graph, in which one can communicate quickly both locally and globally. Graphs based on purely local structure—where there are no short cuts linking disparate parts, in contrast to random graphs composed only of links between these disparate parts—represent the extremes of this classification. Watts and Strogatz (1998) found that small worlds not only included social networks, as in the idea of six degrees of separation, but also characterised many other systems in natural and man-made worlds, thereby suggesting that such systems had perhaps evolved to such structured connectivity for a purpose. Moreover, this way of thinking was supported by the idea that different graphs might display statistical properties that could be used in their classification. It was quickly discovered that the frequencies of connections characterising many graphs could be said to be scaling, or scale-free (Barabási and Albert, 1999), and that such agglomeration or scaling could be simulated using simple dynamic processes.

Using the idea that well connected nodes are always at an advantage in attracting new nodes, such processes mirror the long-standing notion in many competitive systems that, as the rich get richer, the poor get poorer. In this way the dynamic behaviour of networks was broached, and these ideas were linked directly into models emerging from statistical physics, one of the mainstays of complexity theory.

There has been an explosion of such ideas since these initial papers, but most have been concerned with measuring and comparing structures or generating simple scale-free networks using processes of agglomeration. Applications to different fields have not tended to adapt this new network science to the particular characteristics of the systems being examined, nor has there yet been a conscious attempt at linking network processes to related processes of change and evolution in different domains. For example, in architecture and urban planning there have been some attempts to measure street systems and their connectivity, with analogies to space syntax (see Porta et al, 2006), but in general most applications have been to systems in which the nodes and links, and even the flows on these links, are relatively fixed. If we simply consider the logic of this fixity for different kinds of urban system then it is immediately apparent that the domain of application is very narrow.

In cities and regions all movement implies some kind of network, but, at the most local scale, where man and animals are moving, the nodes and the arcs between them have a fluidity that makes grounding the network before the motion takes place problematic. There are well worn tracks and paths in cities on which we can define networks, but the fact that a person moving has almost complete control over where he or she can move to, in free space that is, complicates enormously the definition of networks at this scale where man-made technologies are not used to aid walking. Where such technologies are used and are at the same scale as the person, as in the case of bikes, then networks are better established, but still there is fluidity over the definition of nodes and arcs that makes network science difficult to apply. When moving with technologies such as the automobile, arcs tend to be fixed, whereas nodes are a little less so. Car drivers can stop along arcs at an infinite number of places and such vehicles can also be used off the road. As we move to bigger technologies, such as rail, then nodes and arcs tend to be fixed, owing to economies of operation, and it is here that we see network science being of most obvious use with little fine tuning needed for the particular situation. As we make the location of nodes and arcs more and then less fluid in this way, then the range of the technology tends to increase. Airlines have the greatest fluidity in terms of the arcs they fly, whereas their nodes are usually fixed. As we change focus from moving people to information, the fixity of node and arc changes once again. In transmitting information, nodes tend to be quite fluid, whereas the arcs which generate transmission tend to depend on a mixture of fixed land lines and wireless connectivity, which in turn provide a continually changing mix of fixity and fluidity in term of nodes and arcs.

The range of movement, which in turn depends upon the technology but also the purpose as well as the intensity of flows, conditions the applicability of network science to any domain. Moreover, we must make a distinction between different network systems, in that the physical infrastructure—the channels through which movement takes place—is intrinsically different from movement per se. This is best seen in the fact that fixed node and arc infrastructures can be used by more than one kind of interaction: pedestrians can use both their own paths and also the paths associated with cars; buses in turn use the road infrastructure but have much greater constraints in terms of the nodes they serve, while there are clear distinctions between different types of road infrastructure which many trip types share, thus confounding any analysis. In fact, the notion of a small world in Euclidean space is in itself problematic, because short cuts which are necessary to bind disparate parts of the system together can only take place if new technologies are used to transport people at faster speeds. Small worlds in cities are thus only likely to be observed when different route systems are put together, when street, main road, motorway, light and heavy rail, and ultimately air are put together to enable local dense clustering to assert itself in the face of rapid communication at a global level (Batty, 2001).

What is needed in our own field is a synthesis in the light of all these developments in complexity theory and network science. We need to consider the way networks can be used to characterise the various flow systems in cities that enable energy and materials to be transported, and, in this sense, we need to relate networks to the scaling theory and allometry being pioneered by West et al (1997). We need to consider hierarchies of networks which relate to different movements over different ranges using different technologies, for only then can we consider properties of the overall system that relate to its function, efficiency, and sustainability. We need to consider how all these movement patterns from the material to the virtual world interlock spatially and functionally, while at the same time underpinning location and agglomeration theory. We need to map all of this onto ways in which we can build operational models of transport and land use in cities, thus generating new and much richer ideas about accessibility. Embedding all this into processes of urban evolution and change is an enormous challenge, but we stand at a threshold from which much can be accomplished if we broach this synthesis.

There is also a lot to do in network science itself however. It cannot stay still in developing yet more ideas about structure, and the models of its processes are simplistic. There are empirical challenges to be grasped which will change the processes and structures that characterise the existing science, and there is an urgent need to link structure to flows. Spatial interaction theory as developed in transportation and regional science has still not been linked to network science. Most of the tools available still deal with networks which are topological rather than planar, are dichotomous or binary with respect to the existence or otherwise of an arc, and are thus not yet focused on how flow patterns interact with their underlying infrastructure. I have spoken many times in these editorials during the last twenty years about the need to integrate and synthesise, which implies the need for cross-disciplinary and interdisciplinary research. Network science could be the necessary focus for this to reach fruition and, as ever, the pages of this journal are open for the dissemination and discussion of these ideas.

Michael Batty

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