A networked world

Mark Buchanan and **Guido Caldarelli** chart the remarkable rise of network science, examine why it has become so popular, and predict what its future may bring

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Just over a decade ago, in June 1998, a curious three-page paper appeared in *Nature*. In it, the authors – two applied mathematicians – reported a link between the structure of the US electrical grid and the wiring of a nematode worm's neural system. They also noted that these patterns were strikingly similar in their structure to the social networks of Hollywood actors, one of the few such networks for which the authors could find extensive data. It is hard to imagine a more bizarre melding of topics in one study.

Yet this strange paper (*Nature* **393** 440) by Duncan Watts and Steve Strogatz – then both at Cornell University – initiated an explosion of further research. In "Collective dynamics of small-world networks" the pair showed that a new type of mathematical network – neither fully random, nor fully ordered like a regular lattice – could be an exceptionally useful tool for describing real-world networks. The paper has since garnered thousands of citations and launched an entirely new quantitative science of disordered networks, with applications in fields from epidemiology and public transport to genetic regulation, linguistics and economics.

This is itself an extraordinary accomplishment, but the speed at which this new field has gathered momentum is perhaps even more remarkable. The citation history (see figure on page 24) shows that the Watts and Strogatz paper – like other key papers in this area, such as one by Albert-László Barabási and Réka Albert in 1999 on the World Wide Web (*Science* **286** 509) – has accrued citations at a rate faster even than a number of famous papers that launched previous scientific mini-revolutions. One example is Edward Lorenz's landmark 1963 paper "Deterministic non-periodic flow", which demonstrated how fully deterministic equations in a model of atmospheric dynamics could give rise to highly irregular and essentially unpredictable behaviour. It became one of a handful of seminal works in the theory of deterministic chaos, which was one of the major conceptual revolutions of physics and engineering in the latter part of the 20th century. Even so, neither this nor similar founding papers in areas such as spin glasses or self-organized criticality – both key sub-fields within the broader category of "complexity science" – have come close to matching the citation popularity of these papers on networks.

The surging interest in networks reflects the action of forces bigger than science, and a resonance between the ideas of this field and recent developments in human culture

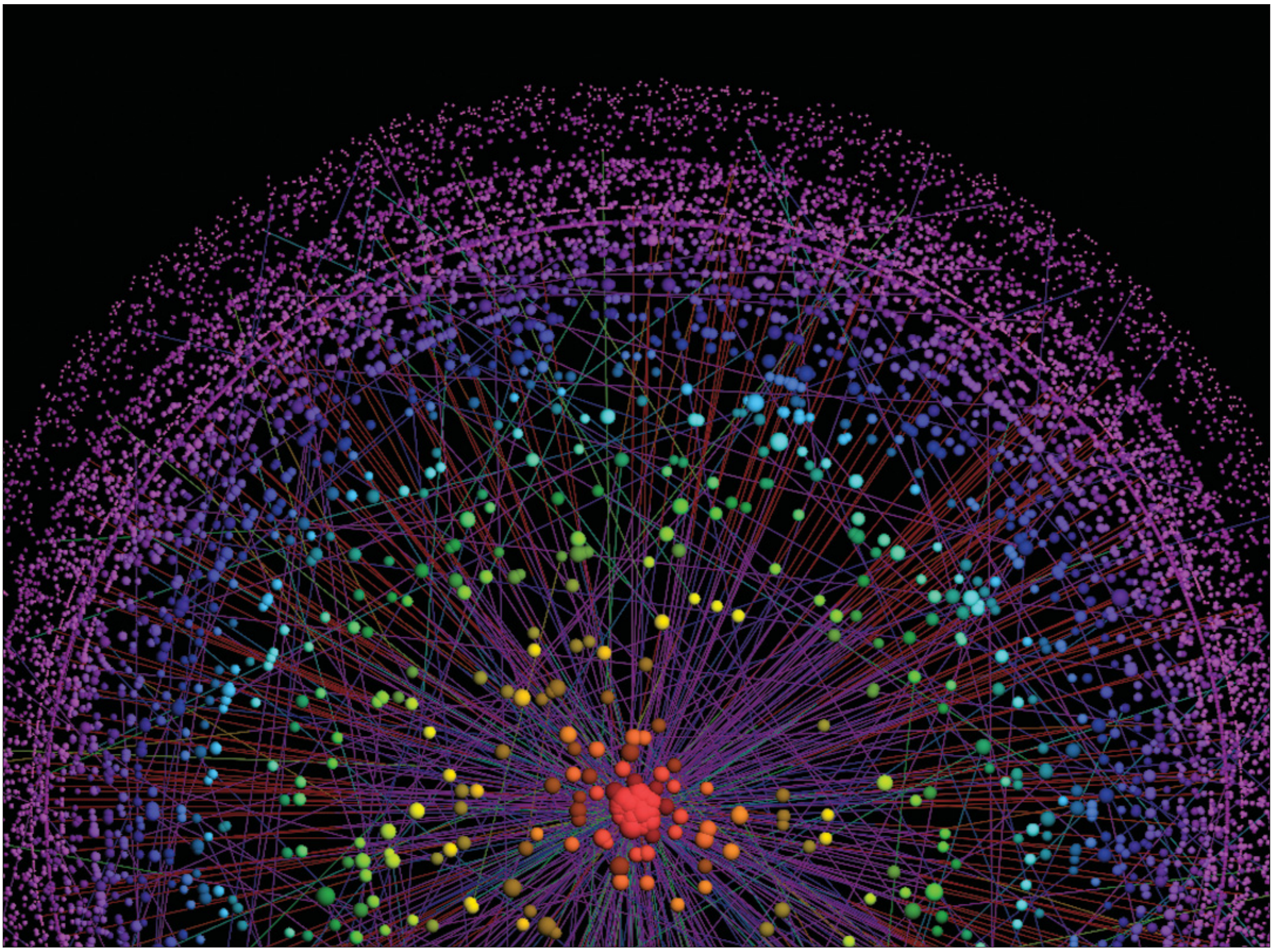
A social-network world

It could be, of course, that this explosion is the scientific equivalent of a financial bubble. Science has its fashions like any social activity, as researchers decide what to study in part by seeing what other people are working on. Moreover, the availability of cheap and powerful computers has made it relatively easy to collect and analyse data on real-world networks. Once the low-hanging fruit is picked, runs the argument, the flood of papers in network science might fade to a trickle and slip into history alongside earlier fashions such as catastrophe theory or general systems theory.

But another, more likely, possibility is that the surging interest in networks reflects the action of forces bigger than science, and a resonance between the ideas of this field and recent developments in human culture. After all, these landmark network papers appeared at a time of rapidly growing awareness of globalization, as people became increasingly interconnected thanks to cheap air travel and the advance of modern telecommunications. The explosive growth in network science may simply reflect a phase transition in human culture between the years of about 1990 up to the present. Arguably, our move towards a more networked existence has amplified the importance of network science.

For example, the term "globalization" only gained prominence in the mid-1990s, as social scientists, politicians and business leaders began noting the increasingly decentralized nature of human movements and enterprises. Although the Internet has existed since the early 1970s, it too emerged as a global force in the 1990s, and soon spawned the greatest repository of information in human history in the shape of the World Wide Web. The Internet search company *Google* was formally founded in September 1998, just three months after the Watts and Strogatz paper appeared. The "open source" software movement took off that same year, as the Linux operating system demonstrated how the Internet and Web could act as organizing infrastructures for a powerful collective or network intelligence.

Not all these societal developments were benign, of course. The terrorist attacks of 2001 helped bring the dark side of networks into the public mind, with talk of "sleeper cells" working within decentralized, extended



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Only connect
This image shows the hierarchical structure of the Internet, the rise of which has paralleled the increasing importance of network science.

and hard-to-defeat networks of malign individuals. Yet even the unpleasant aspects of networks helped thrust the idea into prominence at many levels simultaneously, as part of a "perfect storm" of globalization.

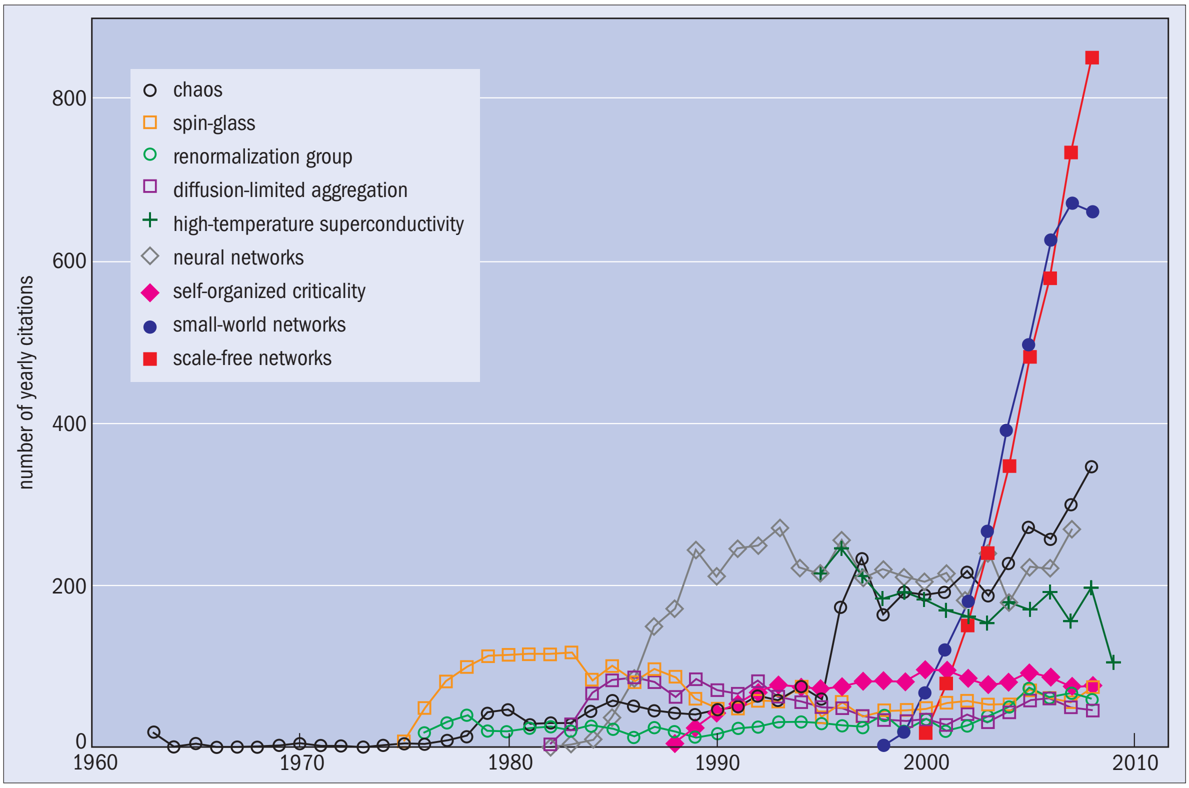
Scientific feedback

Overall, it is probably fair to say that the explosive growth of network awareness has carried network science along with it. But looming issues within science also reinforced this network-centric transformation. When biologists released a complete draft of the human genome in 2003, it was both a landmark achievement and a demonstration of the limitations of a traditional way of doing science. The Human Genome Project found that human beings have roughly 30 000 genes, far fewer than the 100 000 expected. In contrast, some species of rice *do* have about 100 000 genes, suggesting that it is not the raw number of genes that makes for our complexity but the way these genes interact. In other words, the key issue is the subtle organization of the genetic network. Many, if not most, diseases and functions in organisms can only be understood by thinking in terms of a dense web of interactions and feedback.

Of course, this problem of feedback is not specific to biology, and it lies behind the recent growth of complexity science – a broad field that aims to understand the more holistic properties of systems by penetrating their dense webs of interactions. In areas ranging from materials and climate science to ecology and anthropology, scientists have recognized that many of their most pressing problems can no longer be solved simply by breaking systems into parts and understanding those parts. Understanding the behaviour of electrons within a single atom, for example, is not nearly enough to allow physicists to grasp the complex collective organization underlying superconductivity, or even the abrupt transformation of water from liquid to ice at 0 °C. Rather, it is the synthesis that matters the most – understanding the network of interactions among the parts and how those interactions lead to properties such as solidity or electrical conduction, or, in other settings, adaptability, robustness in the face of challenges, or intelligence.

In some sense, the ideas of network science can be likened to calculus. Much as calculus can be applied to radio communications or to the swimming motion of a bacterium, network science is providing the general concepts and perspective needed to address problems typical of a wide range of complex systems. It provides a theoretical framework for analysing the Web and the Internet, the web of interactions in a social group, the network of molecular interactions underlying cellular metabolism, correlations in the stock prices of many organizations, and so on.

Remarkably, and despite their differences, these sys-



Networks take off This graph of the number of citations garnered by a handful of groundbreaking physics papers shows that even within this elite group, the popularity of papers on networks has been unprecedented.

tems show strong similarities in their architecture. In almost all cases, real-world networks have a "small world" character, meaning that it takes only a handful of steps to move between any two points in the network, even one that includes many millions of elements. Likewise, most (though not all) real-world networks show an enormous variance in the way links get shared out between the network elements; typically, a small few have an enormous number of links, while most have very few.

Where do we go from here?

One thing that is still missing from this picture is a complete theory of why nature is so fond of networks. Such a theory would need to explain why the natural world, whether in physics or biology, has so often settled on particular, archetypal network structures, and why our human-engineered structures so often recreate similar designs. On a more practical level, it would offer useful guidance for anyone wishing to design a network – an electrical grid, say – with desirable properties like information-processing efficiency or resilient performance.

Yet even without such a complete theory, the tools of this new science have already become indispensable to a world of new network-based businesses, which are the main drivers of our freshly network-centric world. The software algorithms underpinning the popular social-networking website *Facebook*, for example, count the number of common friends a person has in order to identify new people he or she may want to meet. Similarly, the software used by the online retailer *Amazon* keeps a record of items bought by various users to recommend new interests in books, films, electronics etc.

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It will be interesting to see how long this explosive growth of network science lasts. However, recent developments – for example, the highly influential PageRank algorithm in computer science, which vastly improved the results of Web searches – suggest a rich future. Some researchers, such as biologist Carl Woese and physicist Nigel Goldenfeld, have recently suggested that evolutionary biology is due for a network revolution of its own. They believe that as biologists absorb the fact that bacteria and viruses are always exchanging genetic material "horizontally" – shuttling it between individuals in ways that have little to do with traditional mechanisms of evolution – biology at a fundamental level will need to focus on the network connections between individuals in a way it has not done in the past.

Similarly, in the social sciences, modern techniques for gathering data have stimulated a renewed interest in human interactions, which has led some researchers to suggest that a lot of human intelligence is not based in the individual at all, but instead resides in the relationships and connections within groups of individuals. If true, this might imply that we have a form of "collective" intelligence – that humans can be ant-like as well as ape-like.

If this kind of broad transformation into network thinking is the real explanation for the fast growth of network science, then this exciting new field should continue to grow apace for some time. Network science may be explosive science because it is very general science; it is busy building up the basic physics and mathematics needed to understand, or at least speak intelligently about, webs of interactions among all kinds of things.