

# How robust is the Internet?

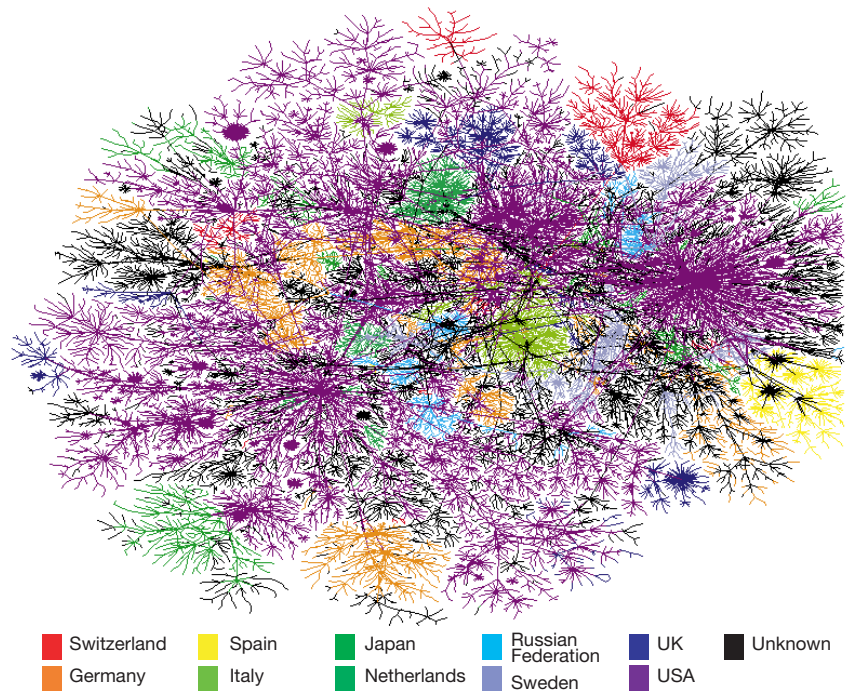
Yuhai Tu

Complex systems, such as the Internet, are surprisingly resistant to random errors. But a new study warns against complacency — the feature that makes the Internet immune to accidents also makes it vulnerable to attack.

**W**e are living in a connected world. Networks permeate every aspect of our lives. Our consciousness is based on the network of neurons in our brain. Our society is formed by various social, economical and political networks. The Internet, which is profoundly changing the way we live, is nothing but a network of information resources. Our overall well-being depends to a large extent on the stability and health of many networks. Yet we live in a constantly changing and often hostile environment. It is therefore important to understand how robustly these networks respond to disruptions. On page 378 of this issue, Albert, Jeong and Barabási<sup>1</sup> address this problem in a simple and elegant way. They find that the tolerance of networks to different types of perturbation depends critically on the network structure.

Given a set of nodes and links, a simple network can be built by linking pairs of nodes at random until we use up all the available links<sup>2</sup>. Such a random network belongs to the class of 'exponential networks' because each node has roughly the same number of connections (it is statistically homogeneous) and the frequency of highly connected nodes decreases exponentially. But most naturally occurring networks have much more intricate hierarchical structures; for example, the frequency of highly connected nodes often decays as a simple power law. Power laws are found in many areas, from the distribution of population sizes to the frequency of scientific citations. Networks that follow power laws are called 'scale-free networks' because they are not tied to a specific scale. This means they are extremely inhomogeneous: whereas most nodes have one or two links, a few highly connected nodes will have a large number of links and so play a key role in the behaviour of the network.

Albert and co-workers<sup>1</sup> wisely simplify their study of network tolerance by focusing on these two classes of network structure: the random, exponential network and the self-organized, scale-free network. To measure the quantitative performance of a network, the authors use the average distance between two nodes in the network, where distance is defined by the minimum number of links between these two nodes. The authors also consider two types of destructive perturbation: randomly occurring error, which is due



**Figure 1** What does the Internet look like? No map exists of the entire Internet, but these lines show the paths an e-mail might take across some of the largest networks. The lines branch at each network router, or node, along the way. Colours were assigned according to the geographic domain (for example, .se for Sweden) where each network router was registered. The map was created using the skitter tool (developed by D. McRobb at CAIDA)<sup>7</sup>, which sends out small packets of data from a source to many destinations through the Internet. The data collected by skitter give a snapshot of the Internet at a particular moment. (Graph created by B. Huffaker using graph layout code provided by B. Cheswick and H. Burch.)

to random malfunction of the nodes; and an intentional attack, which is aimed at the most connected nodes.

For an exponential network, Albert and co-workers find that the accumulation of random errors has a deteriorating effect on the network performance. This decrease in network performance occurs because each deletion of a node destroys some local paths, which leads to an increase in the distance between the nodes involved in these paths. The above argument seems quite reasonable and general. But in the case of a scale-free network, Albert and co-workers make a surprising discovery: they find that the performance of the scale-free network is almost unchanged by the random removal of nodes up to a large deletion rate.

The immunity of this network's performance to random error suggests two features about the network structure: first, most of

the nodes are just 'end users', the removal of which does not affect the paths between other nodes; second, there are 'degenerate paths' between nodes, which implies the existence of highly connected nodes. These two competing requirements have apparently found the perfect balance in the scale-free network. Further study is needed to understand this network's immunity to random error — one can only speculate that the reason lies deep in the scale-free nature of the network structure.

However, the structure that makes the scale-free network superior to the exponential network in the case of random error becomes its Achilles' heel under hostile attack. The most effective way of destroying a network is to attack its most connected nodes. For the scale-free network, in which there are nodes of high connectivity, the effect of targeted attack is much more severe



100 YEARS AGO

Snake-stones are fairly common in South Africa, and are described as white, porous stones, which, when applied to the place where the snake has bitten a person, adhere till all the poison is drawn out into them, after which they are placed in milk, which in turn draws the poison from the stones, and renders them again fit for use. The farmers firmly believe they are taken from the head of a snake. It is suggested that snake-stones are made of pumice. To the uneducated, the structure of pumice has a close resemblance to that of bone, and this may possibly explain the popular delusion that snake-stones are made of bone... The fact that the fable of the stone having been taken from the head of a snake is exactly the same in the Malay States as is prevalent in South Africa is interesting, though the Malay slaves which the early Dutch obtained from Batavia in exchange for quaggas, zebras, ivory, &c., may have carried the legend with them. It is not an uncommon custom in Germany for people to carry about with them nuggets of raw gold to draw out of their bodies all the more subtle evils, such as those produced by spirits and devils, while for the grosser evils they carry a potato. Is the snake-stone legend a derivative of these, or are they subsequent to the snake-stone?  
From *Nature* 26 July 1900.

50 YEARS AGO

The mango, a favourite tropical fruit, which is widely cultivated in India, belongs to the Malaysian genus *Mangifera* Linn. (fam. Anacardiaceae). Taxonomic study shows that it contains forty-one valid species, three of which, *M. indica* L. (wild and cultivated), *M. sylvatica* Roxb. (wild in the hilly forests of north-east India), and *M. khasiana* Pierre (a species of doubtful occurrence) have been reported from India. About a thousand cultivated varieties of mango occur in India, all of which are included in the single species, *M. indica* L. They differ from one another mainly in fruit characters, on the basis of which they have been classified into three groups: round-, ovate-oblong, and long-fruited... The three species investigated — *M. indica* L. (including twenty-three grafted varieties, and one wild race), *M. sylvatica* Roxb. and *M. caloneura* Kz. (a Burmese wild species) — show striking stability in their chromosome numbers, all having  $n = 20$  and  $2n = 40$  chromosomes.  
From *Nature* 29 July 1950.

than that for the exponential network, in which all nodes are statistically identical. To put their theory to test, Albert and co-workers analyse two of the most popular networks: the Internet and the World-Wide Web. Although many people use these terms interchangeably, for the purposes of this study they are considered as separate entities. The World-Wide Web is defined as the network of web pages (the nodes) joined together by hyperlinks, whereas the Internet is the physical communication network linked together by routers (Fig. 1). Albert and co-workers discover that the error tolerance of these two networks has exactly the same characteristics as that of the scale-free network. This result, together with earlier studies<sup>3-5</sup> revealing the power-law structures of these networks, confirms the connection between network structure and performance. More importantly, it provides valuable insight into the structure and weakness of these essential networks.

What can we learn from this study? The good news is that we do not have to worry about random fluctuations of these networks. The bad news is that Internet terrorists could cause great damage by targeting the most connected routers or web sites. The average performance of the Internet is reduced by a factor of two if just 1% of the most connected nodes are destroyed; and with only 4% of its most important nodes destroyed, the Internet loses its integrity, becoming fragmented into small disconnected domains. Of course, modelling the real Internet means taking into account such details as the bandwidth of different links,

the varying error susceptibility of different nodes and, most importantly, different communication protocols. It remains to be seen how these detailed considerations will affect the conclusions of the current study. Nonetheless, this work represents a notable first step towards understanding the robustness of the Internet.

More generally, the work of Albert and co-workers provides a useful framework for qualitatively describing and analysing network performance. It will be interesting to see what we could learn about other complex network systems, such as neural networks or gene regulatory networks<sup>6</sup>, by using similar analysis. In these biological systems, error tolerance is not just a passive property of the network structure; rather, it is part of the driving force by which evolution selects the network structure. Perhaps if we could understand why certain network topology is preferred and selected by nature, such knowledge could ultimately help us design more robust artificial networks. ■

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Cell cycle

# Conducting the mitotic symphony

David Cortez and Stephen J. Elledge

The process by which chromosomes condense and segregate during mitosis (nuclear division) can be likened to a symphony in which many instruments, working individually, are coordinated to produce a collective piece of elegance and beauty. The conductor, with a wave of the baton, ensures that each musical instrument enters the symphony at the proper time. The conductors of the mitotic symphony, called ‘checkpoints’, do much the same thing, and prevent errors in chromosome segregation that can lead to diseases such as Down’s syndrome and cancer. On page 430 of this issue<sup>1</sup>, Scolnick and Halazonetis identify a new conductor that monitors early movements in the mitotic symphony, and describe a possible link between cancer and a failure of this conductor to do its job.

Before mitosis in an animal cell can

proceed, the chromosomes must duplicate and the cell must build a ‘spindle’ — a machine, based on cytoskeletal filaments called microtubules, that will transport the chromosomes into the two daughter cells (Fig. 1). The spindle forms outside the nucleus, between two microtubule-organizing centres (centrosomes). This dual origin of the spindle means that it is bipolar. As the spindle forms, the chromosomes within the nucleus begin to condense into a more compact form that allows them to move more easily; this phase of mitosis is called prophase. The nuclear ‘envelope’ then breaks down during prometaphase, allowing each pair of duplicated chromosomes to attach to the spindle. The chromosomes align in a plane between the spindle poles during metaphase, and await a signal that abruptly separates the