The best is yet to come

Optimality is a key organizing principle of science, but the patterns of connections within real-world networks do not always respect it.

Mark Buchanan

An 'optimal' solution to a problem is, in some sense, the 'best' solution. It's the shortest route to work, or the way of packing oranges that takes up the least volume. In science, optimality has long been an organizing principle. Mathematical physics views the Universe as unfolding with dynamics that minimize a quantity known as the 'action', whereas economists and other social scientists often take optimality as a guide to human behaviour: we act, they say, to maximize our utility, be it financial or otherwise.

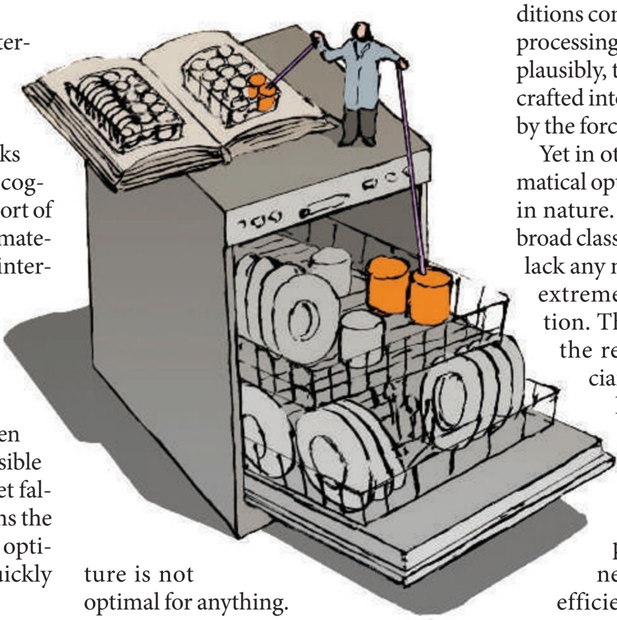
Looking at our networked and interconnected world, we may wonder whether anything is optimal here, from the food webs that underlie ecosystems, to technological networks such as the Internet. And science recognizes that the real world often falls short of optimality. Physicists know of many materials in which, as in glass, complex interactions among the molecules prevent the ordered arrangement of lowest (free) energy; these materials persist naturally in disordered, suboptimal confusion. Meanwhile, the economists' *Homo economicus* has been replaced by a biologically more plausible creature acting on the basis of fast yet fallible instincts. We solve life's problems the way we pack the dishwasher — not optimally, after long calculation, but quickly and more or less efficiently.

What about networks? Is the Internet optimal, in any sense? Is there a 'best' way to design the connections that link together a collection of cells, people or computers? This question has many possible answers — which always depend on what, if anything, a network is 'designed' to do.

In 1964, American engineer Paul Baran conceptualized a layout for the command and control network of the US military aiming to withstand an attack by the Soviet Union. He visualized it as a meshwork, something like a fishnet, with roughly the same number of links emanating from each element. No one element would be a communications hub — and primary target — and the natural redundancy of paths would allow messages to find a route through the network even if much of it was destroyed.

A few years later, US researchers had Baran's meshwork in mind while developing the ARPANET, the seed of today's Internet. Yet the Internet itself has turned out to be wildly different from Baran's hubless ideal. Although decentralized like Baran's meshwork, it is in fact conspicuous for its communications hubs — network routers (or clusters of routers) that accumulate far more connections than most others. The network is especially sensitive to any failure of these centres. In terms of resilience, it is clearly not optimal.

Of course, the forces driving Internet growth have never been channelled towards resilience, and its architecture reflects the independent actions and decisions of untold millions of people and organizations. Quite possibly, its architecture is not optimal for anything.



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Yet in other settings the notion of network optimality may have considerable value. Suppose the population in a certain country has a known geographical distribution. How should facilities such as hospitals be located most conveniently? One recent study suggests a relatively simple, if somewhat peculiar, answer: that the density of facilities shouldn't just be proportional to that of people, but to that density raised to the power of two-thirds. This puts more facilities where there are more people, but not so many more that they become redundant. It is unlikely that urban planners currently adhere to this principle, but it presents a clear target for future policies.

Another problem that a network might solve is coordinating the activity of a set of elements — by helping them to synchronize their behaviour, for example. The elements could be living cells such as neurons, or anything else with rhythmic activity, and interact through signals of some kind — electrical or chemical signals for cells, or light for fireflies in a tree. It turns out that the way such a network synchronizes partly reflects its community structure, a community being any cluster with far more links between its own elements than to elements elsewhere in the network. Studies show that under broad conditions, the smallest and densest communities tend to synchronize first, with larger-scale synchronization arriving later.

This suggests that a modular structure of communities within communities may allow for rich and varied dynamics — conditions conducive to efficient information processing and storage. In this sense, quite plausibly, the wiring of the brain has been crafted into optimal or near-optimal form by the forces of evolution.

Yet in other cases, even proven mathematical optimality may lack any exemplars in nature. Researchers have identified a broad class of networks that conspicuously lack any modular structure, yet support extremely efficient global coordination. These networks — named after the renowned Indian mathematician Srinivasa Ramanujan — have highly uniform architectures, with additional long loops lending them an 'entangled' character. They seem to be almost optimal for many purposes, for example by providing networks that can be easily and efficiently searched while avoiding congestion. Even so, no one as yet has found any natural network that adopts this style.

What all this suggests is that questions of optimality are rarely straightforward. A network will probably reveal optimal form only if it has a ready means for evolving towards it, and time to do so. And the nature of such optimality always depends on the network's function. In many cases today, even that remains at least a partial mystery. ■

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FURTHER READING

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