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Why are networks stable? Researchers solve a 50-year-old puzzle

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A single species invades an ecosystem causing its collapse. A cyberattack on the power system causes a major breakdown. These types of events are always on our minds, yet they rarely result in such significant consequences. So how is it that these systems are so stable and resilient that they can withstand such external disruptions? Indeed, these systems lack a central design or blueprint, and still, they exhibit exceptionally reliable functionality.

In the early 70s, the field of ecology was split on the question of whether biodiversity was a good or a bad thing for an ecosystem. In 1972 Sir Robert May showed, mathematically, that an increase in biodiversity causes less ecological stability. Hence, a large ecological system cannot sustain its stable functionality beyond a certain level of biodiversity and will inevitably collapse in the face of even the smallest twitch.

May's conclusion not only goes against current knowledge and empirical observations of real ecosystems, but, more broadly, seems to defy everything commonly known about interaction networks in social, technological and biological systems. While May's prediction suggests that all these systems are unstable, our experience is in direct contradiction. Our biology is manifested by genetic interaction networks, our brain operates based on a complex web of neuron and synapses, our social and economic systems are driven by social networks, and our technological infrastructure, from the Internet to the power grid, are all large complex networks which actually function quite robustly.

May himself understood the shortcomings of his solution, leading him to ask, "What then are nature's devious strategies to ensure the stability of complex networks?" This question, known in the field as the diversity-stability paradox, has continued to plague researchers for over five decades.

In a study published today (April 20, 2023) in the journal *Nature Physics,* researchers from Bar-Ilan University in Israel have solved this puzzle by offering, for the first time, a fundamental answer to this lingering question.

The researchers found that the missing piece of the puzzle in May's original formulation is that the patterns of interaction in social, biological and technological networks are highly non-random. Random networks tend to be rather homogeneous and all nodes within these networks are roughly the same. For instance, the probability of one individual having many more friends than average is tiny. Such networks may be sensitive and unstable. Real-world networks, on the other hand, are extremely diverse and heterogeneous. They include a combination of average, typically sparsely connected nodes, with ones that have many more links—hubs—that may be ten, 100 or even 1,000 times more connected than average.

When the Bar-Ilan team did the math, they found that this heterogeneity can fundamentally alter the behavior of the system. Quite surprisingly, it actually enhances stability. The analysis indicates that when a network is large and heterogeneous it acquires a guaranteed stability that is extremely robust against external forces. This clearly explains the fact that most networks around us—from the Internet to our brain—exhibit highly resilient functionality despite enduring constant perturbations and obstructions.

"This extreme heterogeneity can be seen in almost all networks around us, from genetic networks, to social and technological networks," says Prof. Barzel, of Bar-Ilan University's Department of Mathematics and Gonda (Goldschmied) Multidisciplinary Brain Research Center, the study's lead author.

"To put this in context, consider your friend on Twitter who has 10,000 followers, a thousand times the average. In everyday terms, if the average person is roughly two meters tall, such thousand-fold deviation would be tantamount to meeting a two kilometer tall individual, which is obviously impossible. But it is what we observe every day in the context of social, biological and technological networks," adds Barzel in explaining the strong link between abstract mathematical analysis and seemingly simple, everyday phenomena.

Large and heterogeneous complex networks not only can be stable, but, in fact, they often must be stable. Uncovering the rules that make a large complex system stable can offer new guidelines for tackling the pressing scientific and policymaking challenge of designing stable infrastructure networks that can not only protect against viable threats, but also strengthen the resilience of crucial, yet fragile, ecosystems.

More information: Chandrakala Meena, Emergent stability in complex network dynamics, *Nature Physics* (2023). DOI: 10.1038/s41567-023-02020-8. www.nature.com/articles/s41567-023-02020-8

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