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Cutting costs: Sustainability matters even in complex networks

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You're driving down the highway in your Honda Civic. You press the pedal to the metal and the speedometer flips to 90 as you torque into the fast lane. How much effort have you, and the car, expended?

No, this is not a pop quiz in a physics class.

It's an example of how, every day, we expend energy when we control the networks in our lives—in this case, a network whose components include the car's accelerator, steering wheel, and brake. Knowing how much that effort "costs" can help determine which components to manipulate—and to what degree—to ensure the smoothest, safest ride as you acclerate from 55 to 90 miles per hour.

On Monday, Northeastern researchers revealed just such a measuring strategy in a new paper published in ***Nature Physics***.

"We provide a metric—called 'control energy'—to characterize the amount of effort needed to control real-world complex systems," says first author **Gang Yan**, a postdoctoral research associate in Northeastern's **Center for Complex Network Research**, which is directed by **Albert-László Barabási**, Robert Gray Dodge Professor of Network Science and the paper's corresponding author.

These self-organized networks, unlike an engineered one under your car's hood, include cellular networks,

social networks, and mobile-sensor networks. That makes potential applications of Yan's metric wide-ranging: from helping to identify key points in the metabolic pathways of bacterial cells that new drugs might target to determining the most critical areas to monitor and protect in an online security system.

"Estimating the control energy, or effort, is key in executing most control applications, from controlling digital devices to understanding the control principles of the cell," says Barabási. "These results have multiple applications in many different domains where control of the network becomes a key objective."

The evolution of a network

A network comprises points of connection, or "nodes"—individual units, such as a metabolite, a gene, a person, or even a gas pedal—and the links or interactions tying those nodes to one another. "Driver nodes" are the select nodes that network administrators zap with external signals in order to control the system. The condition of a driver node—for example, a gene coding a protein or a person expressing his opinion about a political candidate—evolves over time as a result of both the node's internal dynamics and how it connects with its neighbors.

Previous studies of the control mechanisms of complex systems focused on identifying these driver nodes, says Yan. His finding goes further, enabling a kind of network cost-benefit analysis. With it, network scientists could identify not only the minimum number of driver nodes to target for input signals but also the "cheapest," most energy-efficient ones.

"It would be extremely difficult to control a large network by inputting signals to only one driver node," says Yan. "But it's not practical to input signals to all the nodes—that would take a huge toll on the system. Our finding provides a way to make a tradeoff between the number of driver nodes and the cost of controlling the system."

Barabási, who **co-authored** a breakthrough ***Nature* paper** describing an algorithm to ascertain the number of driver nodes required to control complex networks, points to the important insights of Yan and his colleagues in the application of control.

"Most networks are not functional if they cannot control themselves," he says. "Indeed, that need for control determines the system's architecture, whether the network is a brain, a cell, or a technological system. A key question in this process is the amount of effort needed to control the system. The paper by Yan and his colleagues offers fundamental results on this subject, by showing that moving a system in some directions can be easy, but in others can be excruciatingly difficult or costly."

Georgios Tsekenis, now a postdoctoral research fellow at Harvard University, is the paper's co-first author. Researchers Baruch Barzel, Jean-Jacques Slotine, and Yang-Yu Liu from Bar-Ilan University, the Massachusetts Institute of Technology, Harvard Medical School, and the Dana Farber Cancer Institute, respectively, also contributed to the paper.