Leaf veins inspire a new model for distribution networks (w/ Video)

February 9 2010

(PhysOrg.com) -- Following the straight and narrow may be good moral advice, but it's not a great design principle for a distribution network. In new research, a team of biophysicists describe a complex netting of interconnected looping veins that evolution devised to distribute water in leaves. The work, which bucks decades of thinking, may compel engineers to revisit some common assumptions that have informed the building of many human-built distribution networks.

A straight line may be the shortest path from A to B, but it's not always the most reliable or efficient way to go. In fact, depending on what's traveling where, the best route may run in circles, according to a new model that bucks decades of theorizing on the subject. A team of biophysicists at Rockefeller University developed a mathematical model showing that complex sets of interconnecting loops — like the netted veins that transport water in a leaf — provide the best distribution network for supplying fluctuating loads to varying parts of the system. It also shows that such a network can best handle damage. The findings could change the way engineers think about designing networks to handle a variety of challenges like the distribution of water or electricity in a city.

Operations researchers have long believed that the best distribution networks for many scenarios look like trees, with a succession of branches stemming from a central stalk and then branches from those branches and so on, to the desired destinations. But this kind of network is vulnerable: If it is severed at any place, the network is cut in two and cargo will fail to reach any point "downstream" of the break.

By contrast, in the leaves of most complex plants, evolution has devised a system to distribute water that is more supple in at least two key ways. Plants are under constant attack from bugs, diseases, animals and the weather. If a leaf's distribution network were tree-like and damaged, the part of the leaf downstream of the damage would starve for water and die.

In some of the Earth's more ancient plants, such as the gingko, this is the case (see video, bottom). But many younger, more sophisticated plants have evolved a vein system of interconnected loops that can reroute water around any damage, providing many paths to any given point, as in the lemon leaf (see video, top). Operations researchers have appreciated that these redundancies are an effective hedge against damage. What's most surprising in the new research, according to Marcelo O. Magnasco, head of the Laboratory of Mathematical Physics at Rockefeller University, is that the complex network also does a better job of handling fluctuating loads according to shifts in demand from different parts of the system — a common real-world need within dynamic distribution networks.

"For decades, people have believed that the tree-like network was optimal for fluctuating demand," Magnasco says. "These findings could seriously shake things up. People will have to take another look at how they design these kinds of systems."

In a paper published as the cover story of the January 29 *Physical Review Letters*, Magnasco, lead researcher Eleni Katifori, a fellow at Rockefeller's Center for Studies in Physics and Biology, and colleagues lay out a model that assigns a cost to each section of leaf vein proportional to how much water it can carry. They looked for networks that suffered the least strain in the face of two challenges common in both leaves and human-built networks: damage to a randomly chosen segment of the network and changes in the load demanded by different parts of the network. In both scenarios, they found the most robust system was a complex, hierarchical network of nested loops, similar to the fractal-like web of veins that transport water in leaves. This loopy network design is also found in the blood vessels of the retina, the architecture of some corals and the structural veins of insect wings.

Katifori is now extending the research to delve more deeply into how distribution networks handle fluctuating loads, guided by nature's own solution in the leaf.

"It is tempting to ignore the loops, because the central veins stand out and have a tree-like form," Katifori says. "But they are all connected, and the loops are right there to see, if you just look at the leaf."

More information: *Physical Review Letters* 104: 048174 (January 29, 2010). Damage and Fluctuations Induce Loops in Optimal Transport Networks, Eleni Katifori, Gergely J. Szöllősi and Marcelo O. Magnasco

Provided by Rockefeller University