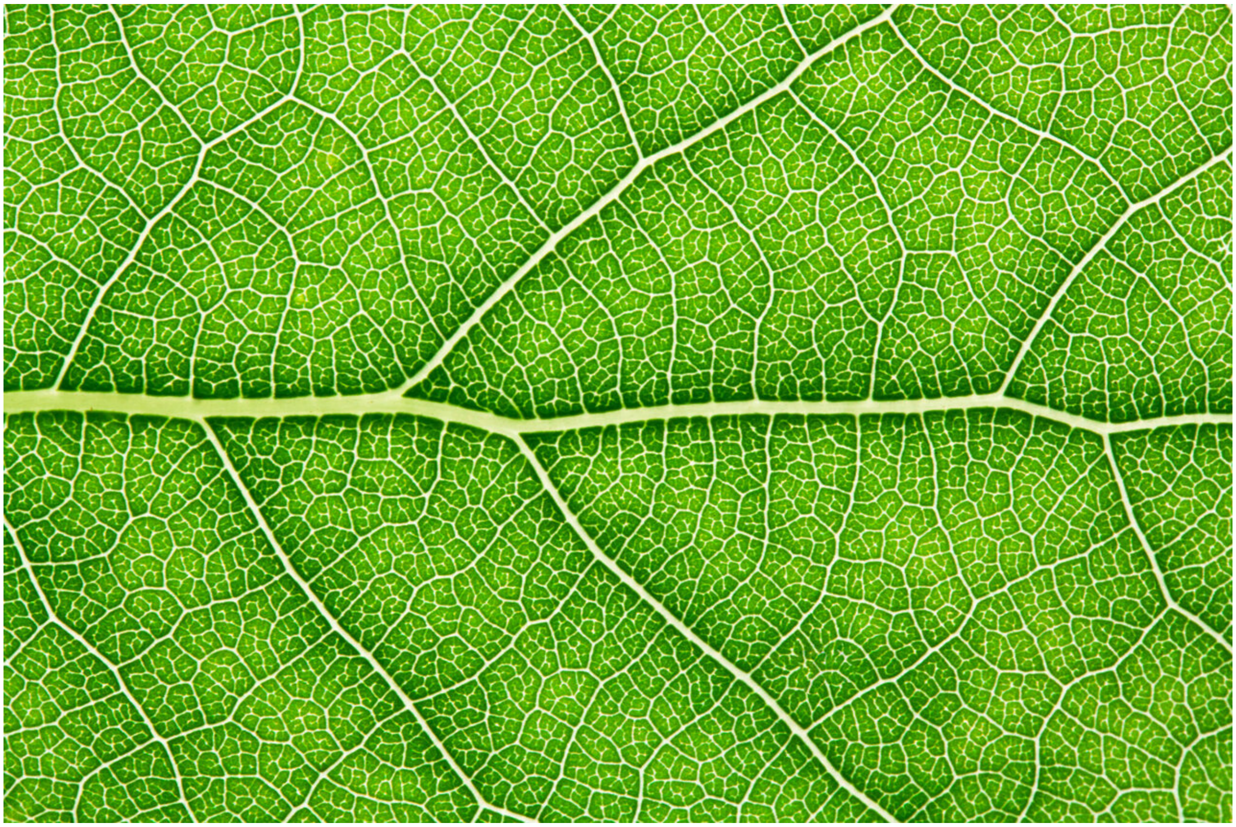
How biology creates networks that are cheap, robust, and efficient

January 17 2020, by Erica K. Brockmeier



No two leaves share the same exact vessel patterns, yet each has a consistently structured network that allows water and nutrients to be transported across its surface. Insights from physics show how vascular networks like these can evolve into a wide array of shapes and structures from a single starting point. Credit: University of Pennsylvania

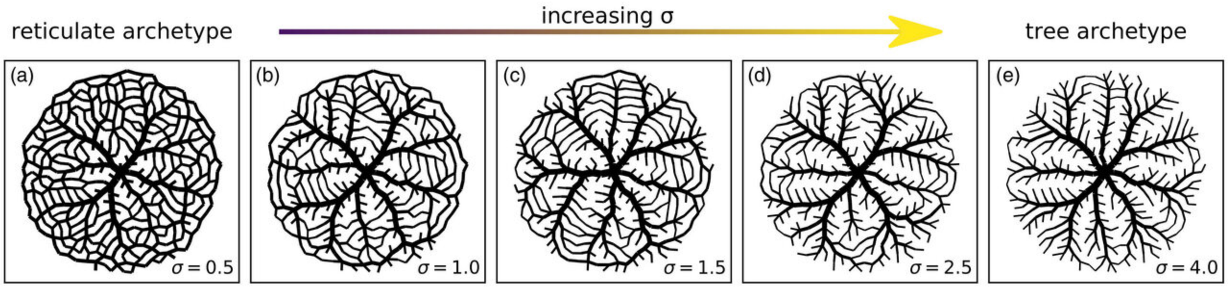
From veins that deliver oxygen to tissues to xylem that send water into stems and leaves, vascular networks are a crucial component of life. In biology, there is a wide range of unique patterns, like the individualized structures found on leaves, along with many conserved structures, such as named arteries and veins in the human body. These two observations led scientists to think that vascular networks evolved from a common design, but how, exactly, could nature create so many complex structures from a single starting point?

A new study shows how a wide variety of vascular networks can be created by changing only a small number of a network's attributes. Published in Physical Review Letters, the work of two physicists, former Penn postdoc Henrik Ronellenfitsch and professor Eleni Katifori, shows that vascular networks evolve through a tradeoff between how well the network can transport fluid, a network's "cost," or how many cells it takes to build the network, and its robustness, or how well the system works if part of the structure is damaged.

This research builds off Katifori and Ronellenfitsch's previous work on "adaptation equations," mathematical models of systems that are good at a specific function, such as moving fluid. In this study, they wanted to see if their adaptation equation could get vascular networks to "self-organize" into the most efficient structure possible.

To test their idea, the researchers applied their adaptation equation on a large collection of simulated vascular networks to see what combinations of attributes could be changed to create new structures. Ronellenfitsch then took the resulting networks and applied a mathematical tool, one commonly used in economics and finance, to compare the efficiency of different network designs.

When researchers want to analyze the costs and benefits of different trade-offs, they rely on a concept known as Pareto efficiency. As an example, in renovating a house with new insulation under a limited budget, one can either spend a lot of money and have a house that is well-insulated, or spend less money and do little to improve the insulation. The most efficient set of options, on the spectrum of low to high cost and from few to many renovations in the illustrative example, is known as the Pareto frontier. Using this approach, Ronellenfitsch was able to see which attributes were the most important to create efficient vascular networks. "The networks that we identify are those where you cannot improve any of these requirements without getting worse at one of the others," he says.



Example networks that start with one fluid inlet at the center. Every node, or branch from the center, is a fluid outlet, and each node needs the same amount of fluid. On the left (reticulated archetype) are networks that are very robust but, because of their loopy structure, are very costly to make. On the right (tree archetype) are networks that are less robust, because they lack redundancy and can fail if one branch is broken, but are easier to make. Credit: Eleni Katifori and Henrik Ronellenfitsch

The researchers found that vascular network efficiency was driven by how robust the network was to damage and how "expensive" it was to build. Across a spectrum of changes to these two attributes, researchers could create a wide variety of structures from intricately interwoven networks that were robust against damage to simpler designs that wouldn't stand up to breakage.

But how does nature know how to balance cost with robustness? By simulating fluctuations, or changes in the average amount of fluid that moved through parts of the network, they found that changes in flow rates impact whether a network should be robust or not. "If you want something that is cheap but not robust, you'd better not have a lot of fluctuations," says Katifori.

In the near future, Katifori's lab will compare their models with data on vessel networks in plants. "A cursory look seems to confirm that the types of networks in the simulations more or less exist in the real world, but we haven't quantified that in explicitly. It's difficult to explore them quantitatively in a controlled fashion because if you try to disrupt fluctuation, you disrupt so many other things," she says.

Beyond its implications in biology and evolution, this theory could also prove useful in designing engineered networks such as power grids. "You would expect power grids to follow similar principles; you would want the power grid to be cheap but also robust against outages, so that you don't get blackouts, and efficient at transporting power," says Ronellenfitsch.

It's also another example of how ideas on efficiency and resource allocation, which are typically linked to applied fields like economics and finance, also connect to evolution and biology. "Biology might have to solve the same problem regardless of the organism," Katifori says, "and that problem is making a network that is good at something particular. Exactly how biology implements that rule is beyond our purview, but we believe that biology has found a universal way to solve the same problem by implementing it differently."

More information: Henrik Ronellenfitsch et al. Phenotypes of Vascular Flow Networks, *Physical Review Letters* (2019). DOI: 10.1103/PhysRevLett.123.248101

Provided by University of Pennsylvania

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