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From branches to loops. The physics of transport networks in nature.

*An international team of researchers from the Faculty of Physics at the University of Warsaw, the Laboratoire Matière et Systèmes Complexes, and the Institut des Sciences de la Terre d'Orléans described how loops, crucial for the stability of such networks, occur in transport networks found in nature. The researchers observed that when one branch of the network reaches the system's boundary, the interactions between the branches change drastically. Previously repelling branches, begin to attract each other, leading to the sudden formation of loops. The findings were published in the prestigious journal "Proceedings of the National Academy of Sciences". The process described appears in a surprisingly large number of systems - from electrical discharge networks to instabilities in fluid mechanics, to biological transport networks like the canal system in the jellyfish *Aurelia aurita*.*

Nature offers us a wide spectrum of spatial, transport networks, from networks of blood vessels in our bodies to electrical discharges in a storm. "Such networks take various shapes", explains Stanisław Żukowski, a PhD student from the University of Warsaw and Université Paris Cité and lead author of the publication. "They can have a tree-like geometry, where branches of the network only split and repel each other during growth. In other cases, when branches attract and reconnect during growth, we deal with looping structures." Networks with many loops are widespread in living organisms, where they actively transport oxygen or nutrients and remove metabolic waste products. An important advantage of looping networks is their reduced vulnerability to damage; in networks without loops, the destruction of one branch can cut off all connected branches, whereas, in networks with loops, there is always another connection to the rest of the system. Recently, researchers from the Faculty of Physics at the University of Warsaw described the mechanism responsible for the stability of already existing loops*. However, the dynamic process leading to their formation remained unclear.

How are loops formed?

Many transport networks grow in response to a diffusive field, such as the concentration of a substance, the pressure in the system, or the electric potential. The fluxes of such a field are much more easily transported through the branches of the network than through the surrounding medium. This affects the distribution of the field in space - lightning conductors attract electrical discharges precisely because they have lower resistance than the surrounding air. The large difference in resistance between the network and the medium around leads to competition and repulsion between the branches.

However, the attraction of branches in growing networks, leading to loop formation, remained undescribed for a long time. The first attempt to understand the formation of loops in such

systems was made a few years ago by the group of Prof. Piotr Szymczak from the Faculty of Physics at the University of Warsaw.

"We showed that a small difference in resistance between the network and the medium can lead to attraction between growing branches and the formation of loops," says Piotr Szymczak.

The work led to a joint project, in the form of Stanisław Żukowski's joint doctorate, carried out in Piotr Szymczak's group and that of Annemiek Cornelissen, a researcher at the Laboratoire Matière et Systèmes Complexes. "In our laboratory, we study the morphogenesis of the gastrovascular network in jellyfish. It's a beautiful example of a transport network with many loops," says Annemiek Cornelissen. "When I saw Annemiek's presentation at a conference in Cambridge a few years ago, I immediately thought that our models might apply to the growth of canals in jellyfish," adds Piotr.

Breakthrough in loop formation

"The formation of loops when one of the branches reaches the boundary of the system - a phenomenon we describe in our latest publication - was first noticed in the network of canals of the jellyfish gastrovascular system, says Stanisław Żukowski. "Analysing the development of these canals over time, I noticed that when one of them connects to the jellyfish's stomach (the boundary of the system) then the shorter canals are immediately attracted to it and form loops".

The same phenomenon was observed by scientists in gypsum fracture dissolution experiments conducted at the University of Warsaw by Florian Osselin; in the so-called Saffman-Taylor experiment, in which the boundary between two fluids is unstable and transforms into finger-like patterns; and also encountered in the literature on electrical discharge. "The wealth of systems in which we discovered very similar dynamics convinced us that there must be a simple, physical explanation for this phenomenon" says Annemiek Cornelissen. In their publication, the researchers presented a model describing interactions between branches. They focused on how these interactions change when one of the branches approaches the boundary of the system and a breakthrough occurs. "The competition and repulsion between branches then disappears and attraction appears", explains Stéphane Douady. "This inevitably leads to the formation of loops".

"Our model predicts that the attraction between neighboring branches after a breakthrough occurs regardless of the geometry of the network or the difference in resistance between the network and the surrounding medium", says Piotr Szymczak. "In particular, we showed that near breakthrough loops can form in systems with a very large difference in resistance, which was previously thought to be impossible. This explains why this phenomenon is so prevalent in physical and biological systems.

"In cases where the growth mechanisms are still not clear this will be a strong indication that the system dynamics are controlled by diffusive fluxes," adds Stanisław Żukowski. "We are extremely curious to see in which other systems we will observe loop formation near breakthrough.

* Radost Waszkiewicz, John Burnham Shaw, Maciej Lisicki, and Piotr Szymczak Goldilocks Fluctuations: Dynamic Constraints on Loop Formation in Scale-Free Transport Networks Phys. Rev. Lett. 132, 137401 – (2024)
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Faculty of Physics of the University of Warsaw

Physics and astronomy at the University of Warsaw appeared in 1816 as part of the then Faculty of Philosophy. In 1825, the Astronomical Observatory was established. Currently, the Faculty of Physics at the University of Warsaw consists of the following institutes: Experimental Physics, Theoretical Physics, Geophysics, the Department of Mathematical Methods in Physics, and the Astronomical Observatory. The research covers almost all areas of modern physics on scales from quantum to cosmological. The Faculty's research and teaching staff consists of over 250 academic teachers. About 1,100 students and over 170 doctoral students study at the Faculty of Physics UW. The University of Warsaw is among the 150 best universities in the world, educating in the field of physics according to Shanghai's Global Ranking of Academic Subjects.

SCIENTIFIC PUBLICATION:

Stanisław Żukowski, Annemiek Johanna Maria Cornelissen, Florian Osselin, Stéphane Douady, Piotr Szymczak, Breakthrough-induced loop formation in evolving transport networks Proceedings of the National Academy of Sciences, July 2024, DOI: 10.1073/pnas.2401200121

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GRAPHIC MATERIALS:

FUW240925b_fot01.jpg
https://www.fuw.edu.pl/tl_files/press/images/2024/FUW240927b_fot01.jpg. Loops forming when one of the branches reaches the boundary of the system - a phenomenon that researchers describe in the recent publication they first noticed in the canal network of the Aurelia jellyfish gastrovascular system. (Source: Stanisław Żukowski, *Laboratoire Matière et Systèmes Complexés, Université Paris Cité & Wydział Fizyki UW*)