Complex systems

Prof Elsa Arcaute

Centre for Advanced Spatial Analysis (CASA)
University College London

In2Science
15th August 2022

Which of these 2 do you think is a complex system?

Starling
Source: Wikipedia

Flock of starlings creating a *murmuration*
Source:
https://www.nationalgeographic.co.uk/animals/2021/03/these-birds-flock-in-mesmerising-swarms-of-thousands-but-why-is-still-a-mystery

Both!!!!!

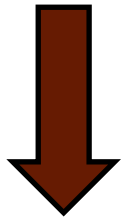
What is a complex system?

What is a complex systems?

System = Interacting component 1 + Interacting component 2

+ Interacting component 3 + Interacting component 4

+ ... + Interacting component n



Emergent behaviour

collective behaviour not observed at the level of an individual component

"More is different"

50 years of Anderson's paper published in Science

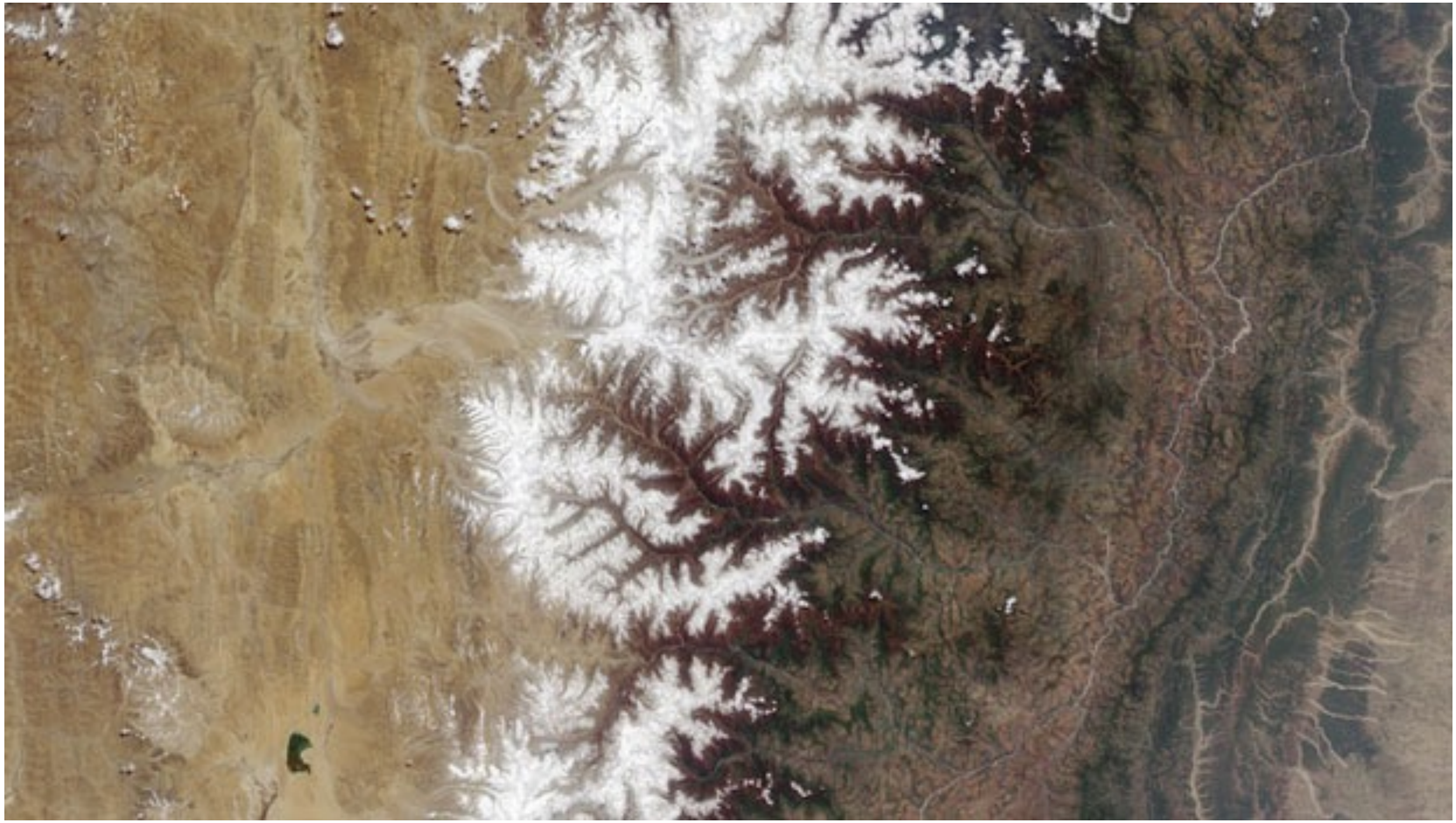
Bird versus flock

1) What is the behaviour observed in the flock that cannot be observed in the bird?

2) So why is the bird a complex system?

Patterns in nature

Himalayas



What do you think these patterns are?

Benoit B. Mandelbrot (20 November 1924 – 14 October 2010)

He wanted to describe the objects encountered in nature. These cannot be described in terms geometrical smooth objects. Benoit developed a mathematical description of the ***roughness*** of objects in nature.

Fractal → **From Latin *fractus***

↓

Broken

Fractal Britain

Paradox in measuring the coast of Britain: THERE'S NO CONSISTENT SIZE!!!!

Unit = 200 km,
Length = 2400 km (approx.)

Unit = 100 km,
Length = 2800 km (approx.)

Unit = 50 km,
Length = 3400 km (approx.)

Why fractals, why patterns?

Evolution

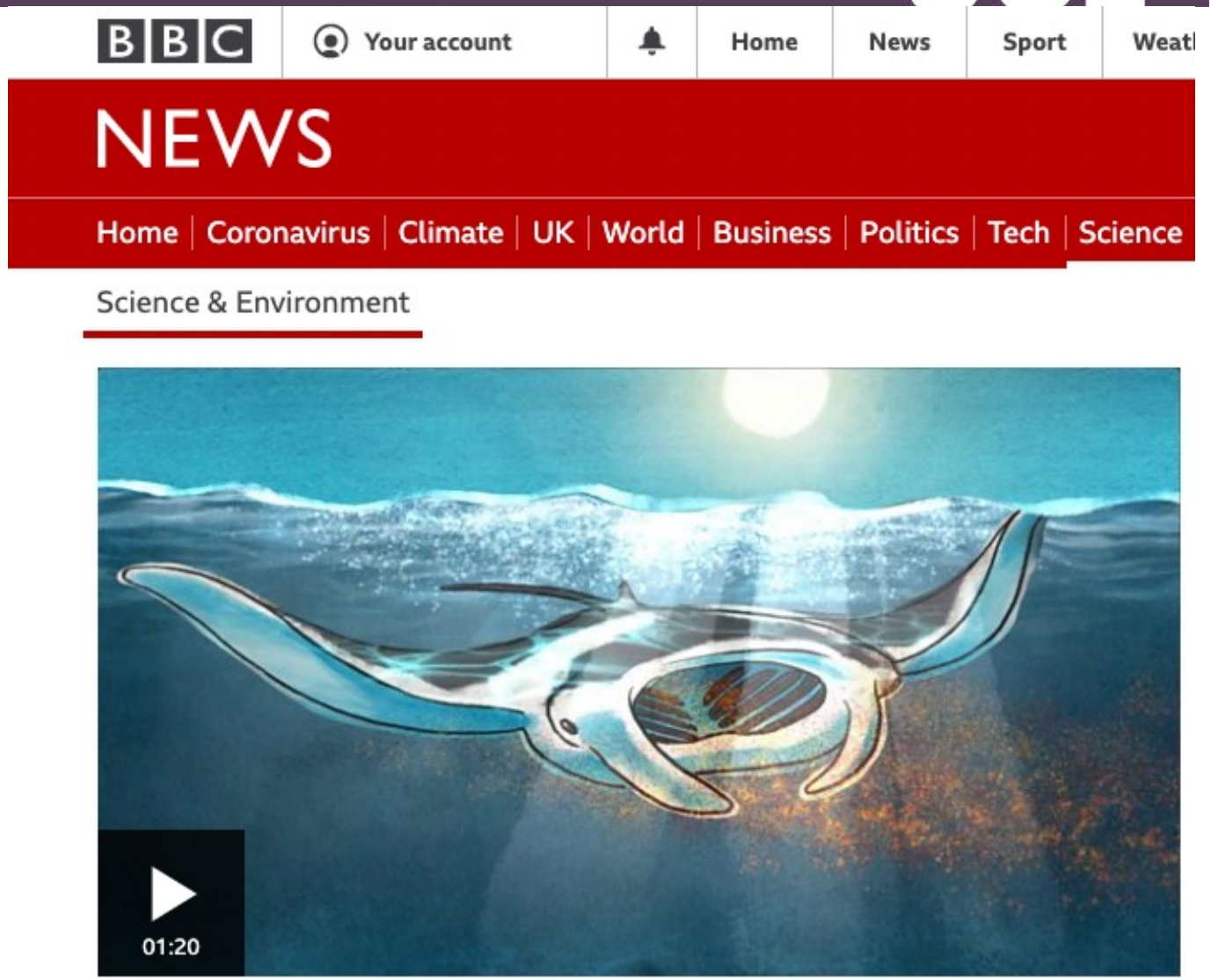
The patterns observed are the outcome of evolutionary processes: they represent a SOLUTION

→ survival
→ reproduction
→ resilience
→ etc.

→ The solutions are **long term solutions**: adjustments made by Nature for future generations, and **not for the immediate well-being** of specific individuals within a species.

Biomimicry

Can we copy Nature to find more **sustainable** solutions?



Applications

Understanding processes that lead to fractals → e.g. percolation can be used for oil extraction

ELSEVIER

Physica A: Statistical Mechanics and its Applications

Volume 266, Issues 1–4, 15 April 1999, Pages 107-114

Predicting oil recovery using percolation

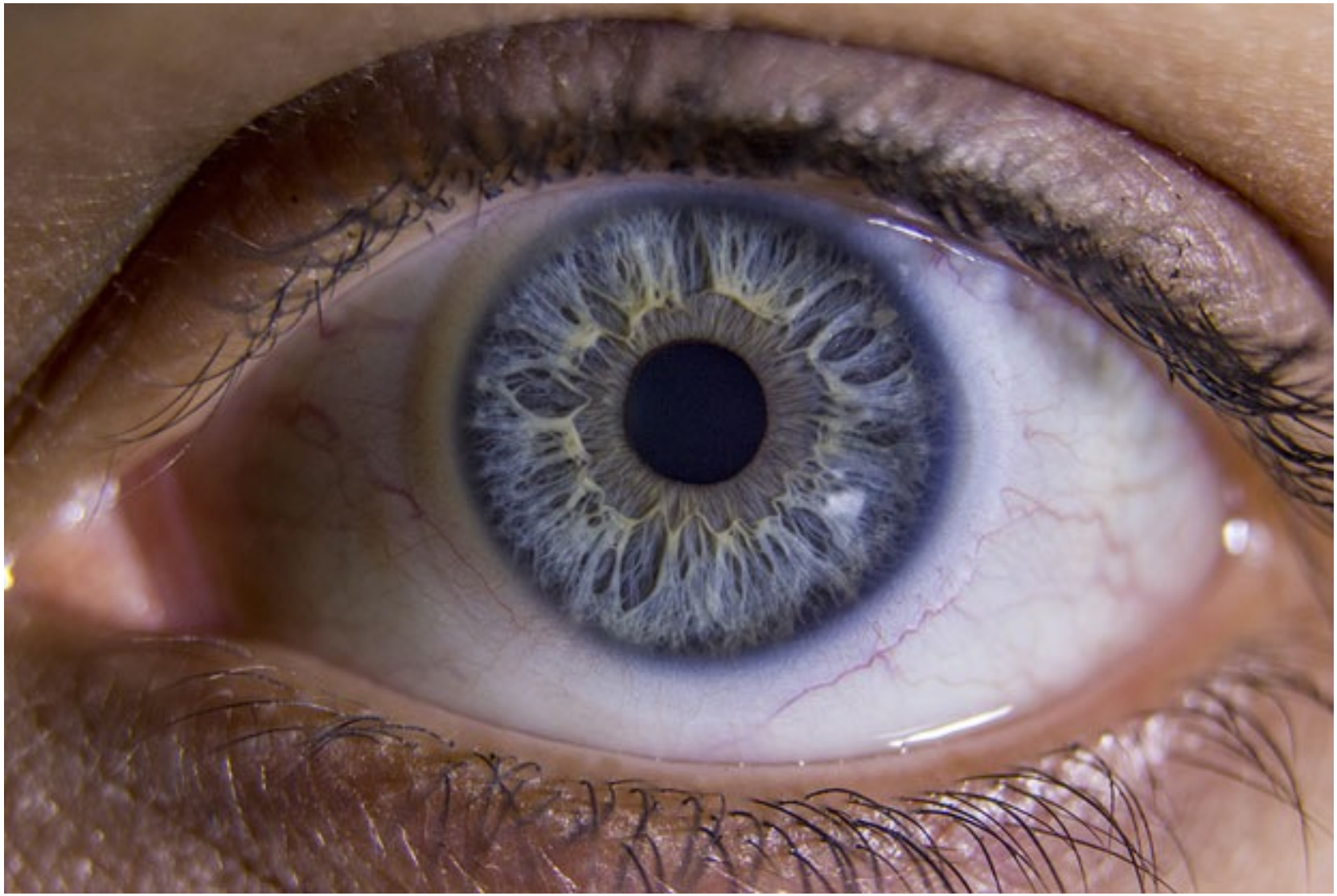
Peter R. King [a, b], José S.Andrade Jr. [c], Sergey V. Buldyrev [d], Nikolay Dokholyan [d], Youngki Lee [d], Shlomo Havlin [e], H.Eugene Stanley [d]

Show more

+ Add to Mendeley Share Cite

https://doi.org/10.1016/S0378-4371(98)00583-4 Get rights and content

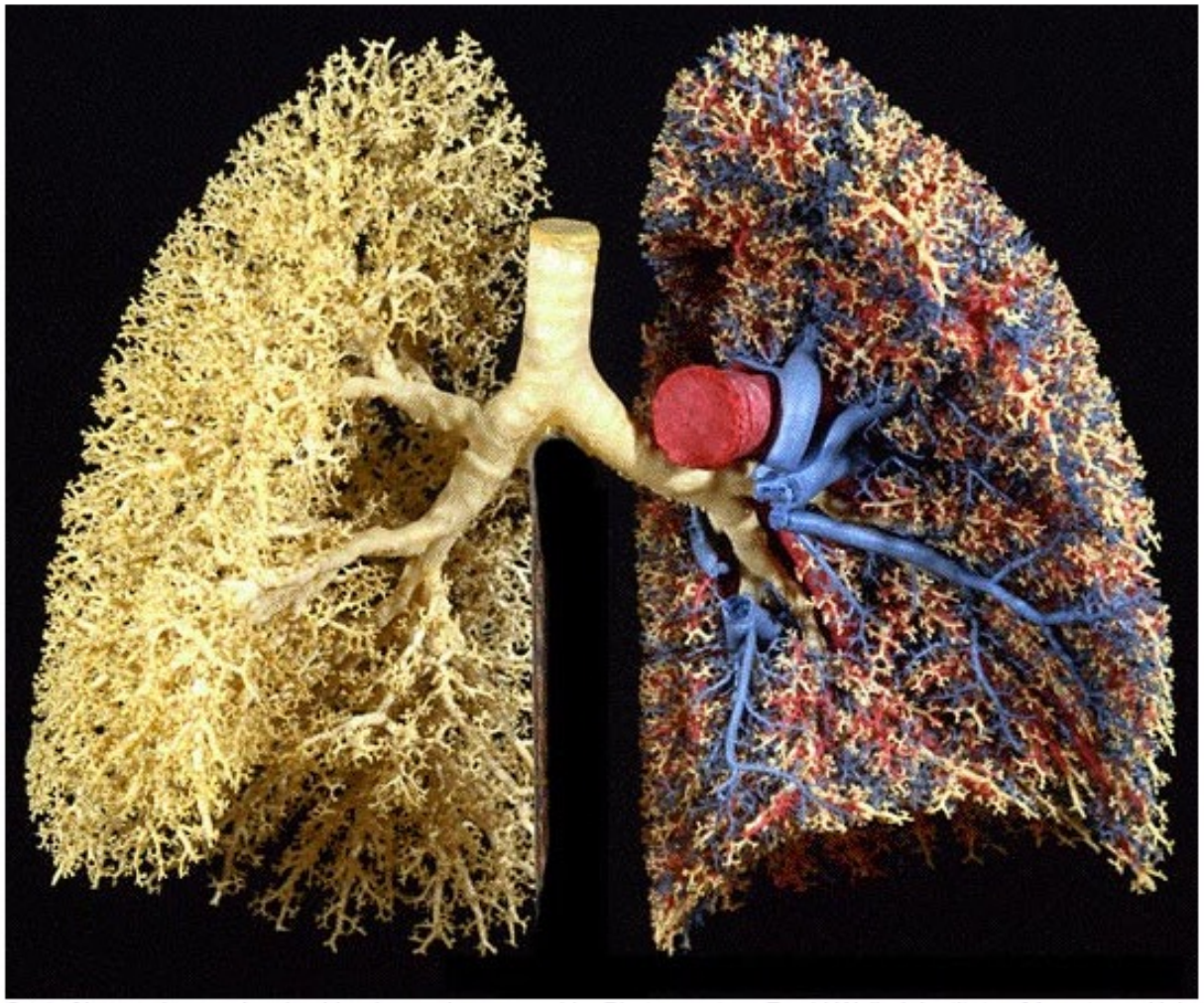
Fractal perspective



Although a joke, it may be the case!

Fractals in the Body

Not only are fractals in the world all around us - they are even INSIDE us! In fact, many of our internal organs and structures display fractal properties.

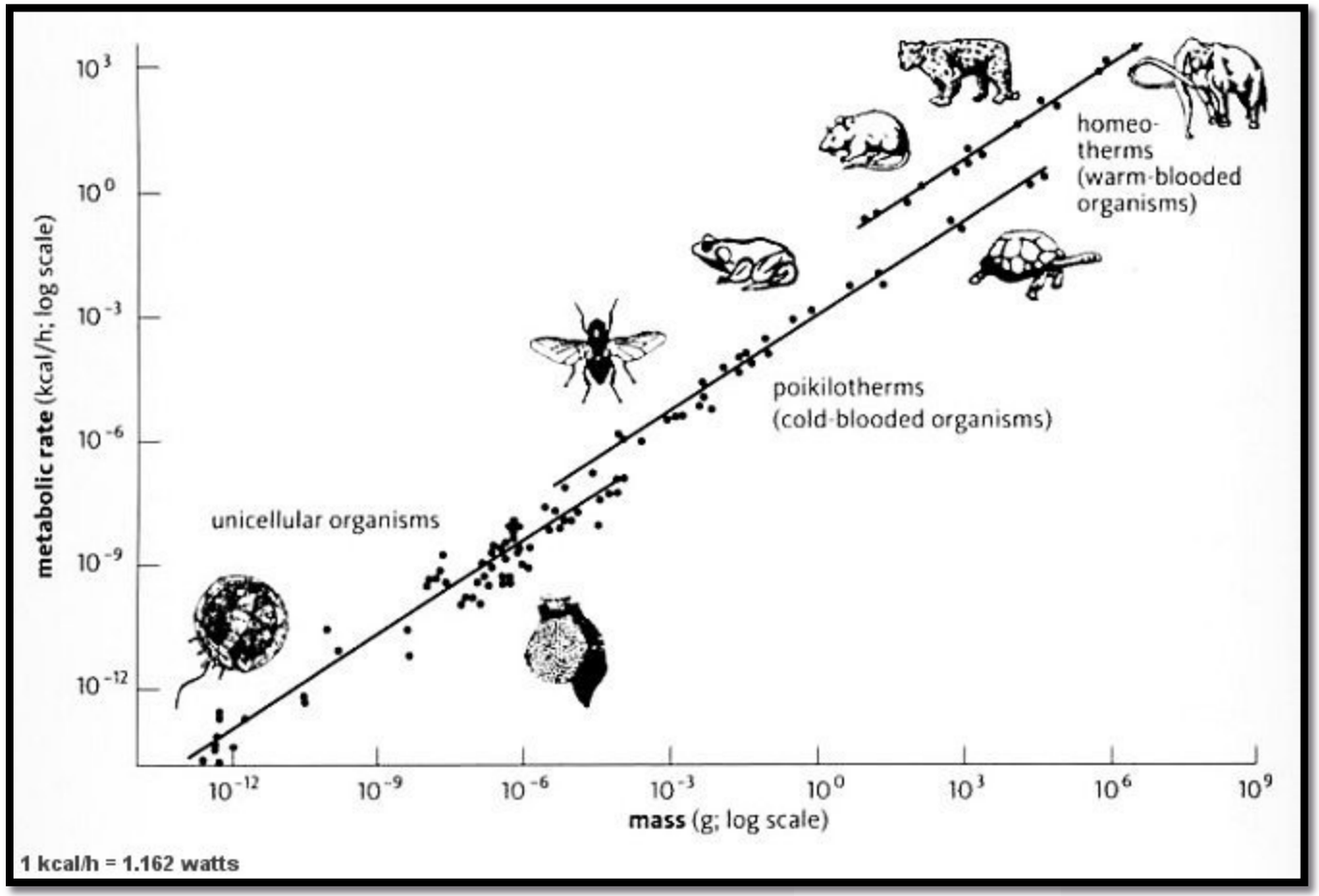


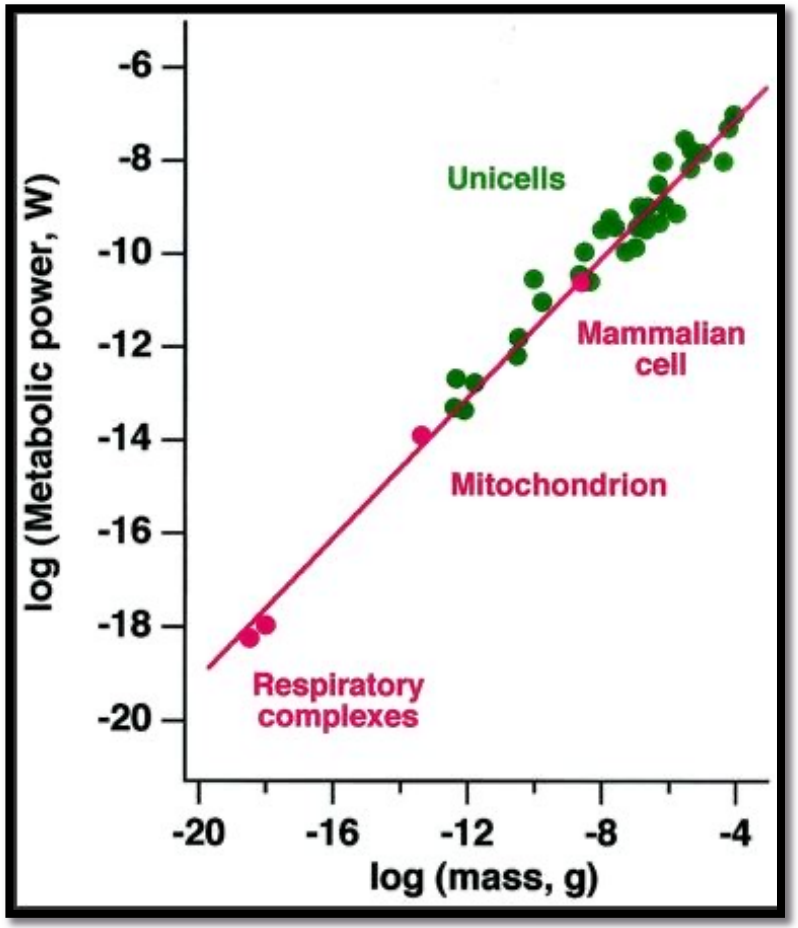
Cast of human lungs, showing blood vessels on one side. Photo courtesy Ewald Weibel, Institute of Anantomy, University of Berne.

The lungs are an excellent example of a natural fractal organ. If you look at the tree upside-down (mouse over the image), you can see that the lungs share the same branching pattern as the trees. And it is for good reason! Both the trees and lungs have evolved to serve a similar function - respiration. Since they

Kleiber's Law and the fractal mammal

Kleiber's law: $R \sim M^{3/4}$ metabolic efficiency





Original results published in:
Kleiber M.(1947), "Body size and metabolic rate". *Phys. Rev.* **27** (4): 511–541.

Kleiber's Law and the fractal mammal

Science

Current Issue First release papers Archive About Submit manuscript

HOME > SCIENCE > VOL. 276, NO. 5309 > A GENERAL MODEL FOR THE ORIGIN OF ALLOMETRIC SCALING LAWS IN BIOLOGY

A General Model for the Origin of Allometric Scaling Laws in Biology

GEOFFREY B. WEST, JAMES H. BROWN, AND , BRIAN J. ENQUIST Authors Info & Affiliations

SCIENCE • 4 Apr 1997 • Vol 276, Issue 5309 • pp. 122-126 • DOI: 10.1126/science.276.5309.122

Allometric scaling relations, including the 3/4 power law for metabolic rates, are characteristic of all organisms and are here derived from a general model that describes how essential materials are transported through space-filling fractal networks of branching tubes. The model assumes that the energy dissipated is minimized and that the terminal tubes do not vary with body size. It provides a complete analysis of scaling relations for mammalian circulatory systems that are in agreement with data. More generally, the model predicts structural and functional properties of vertebrate cardiovascular and respiratory systems, plant vascular systems, insect tracheal tubes, and other distribution networks.

Kleiber's Law and the fractal mammal

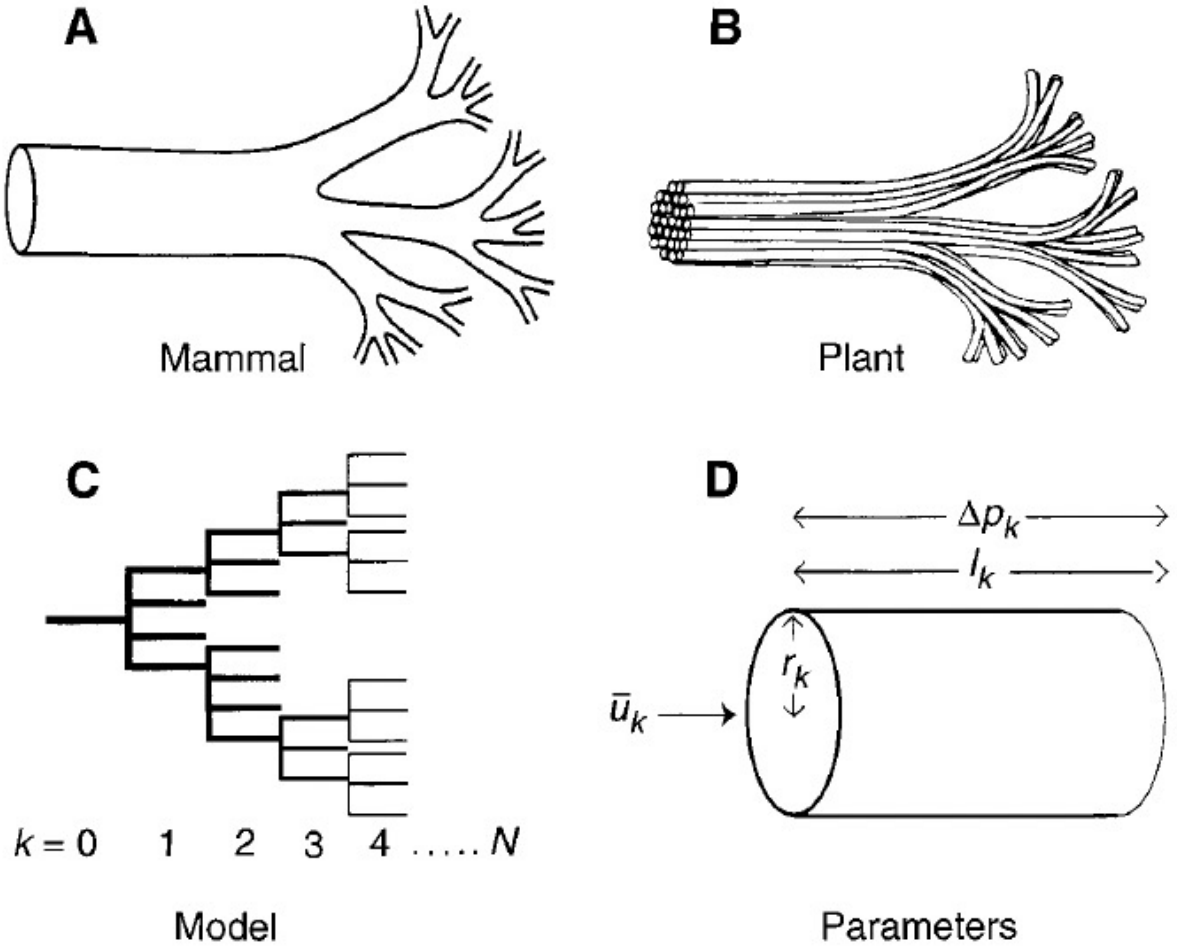
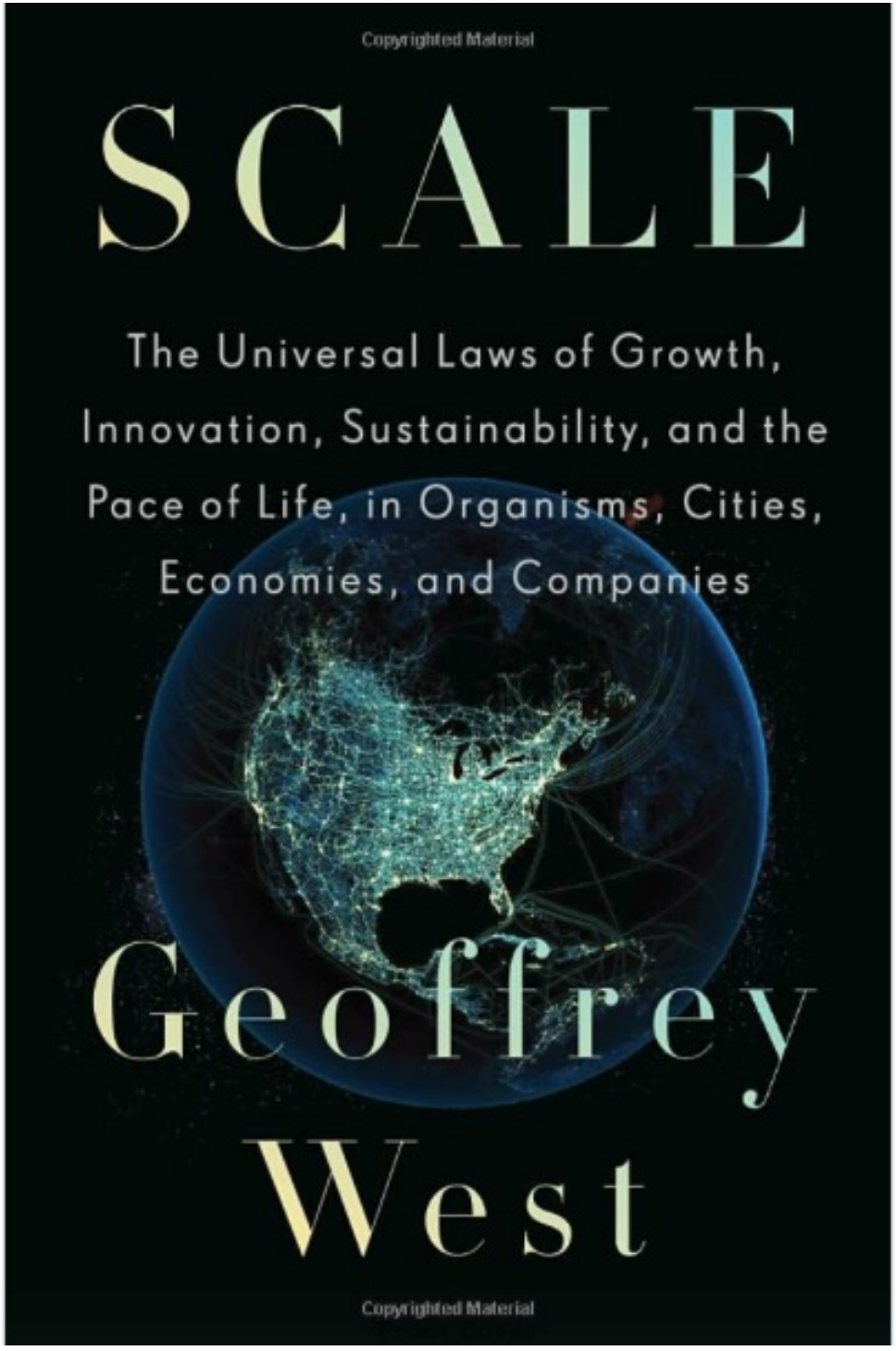


Fig. 1. Diagrammatic examples of segments of biological distribution networks: (**A**) mammalian circulatory and respiratory systems composed of branching tubes; (**B**) plant vessel-bundle vascular system composed of diverging vessel elements; (**C**) topological representation of such networks, where k specifies the order of the level, beginning with the aorta ($k = 0$) and ending with the capillary ($k = N$); and (**D**) parameters of a typical tube at the kth level.

→ If circulatory system wasn't a fractal it wouldn't work….

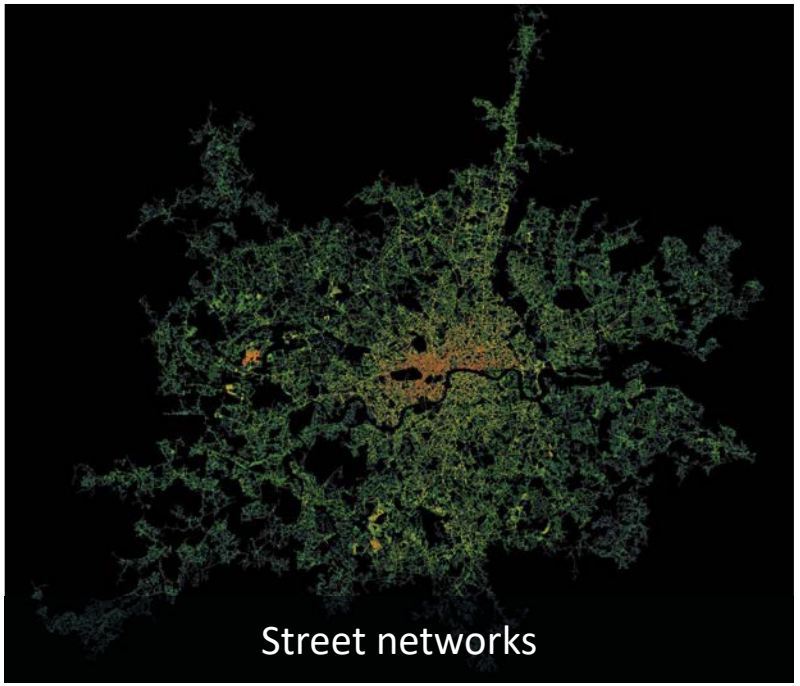
→ Actually, if respiratory system wasn't a fractal, we wouldn't be alive!


Copyrighted Material
SCALE
The Universal Laws of Growth, Innovation, Sustainability, and the Pace of Life, in Organisms, Cities, Economies, and Companies
Geoffrey West
Copyrighted Material

Flocks create murmurations, what about humans?

Examples of emergent patterns collectively created by people

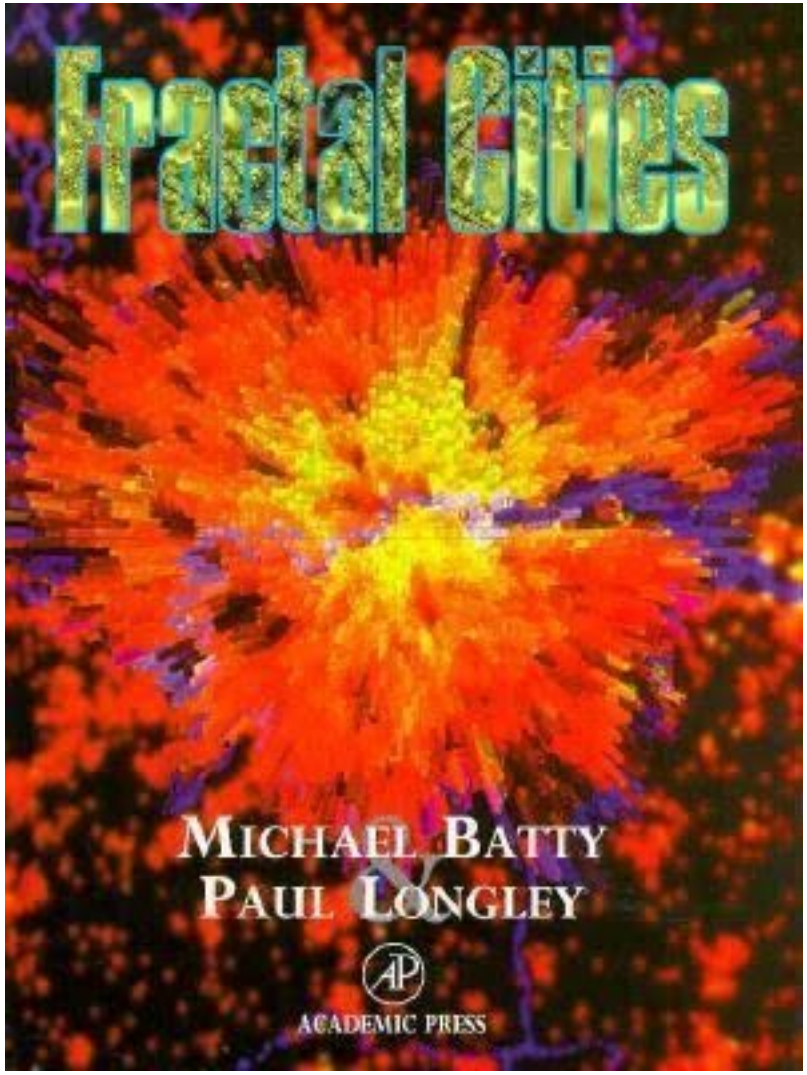

Agricultural fields


Street networks

Stock market

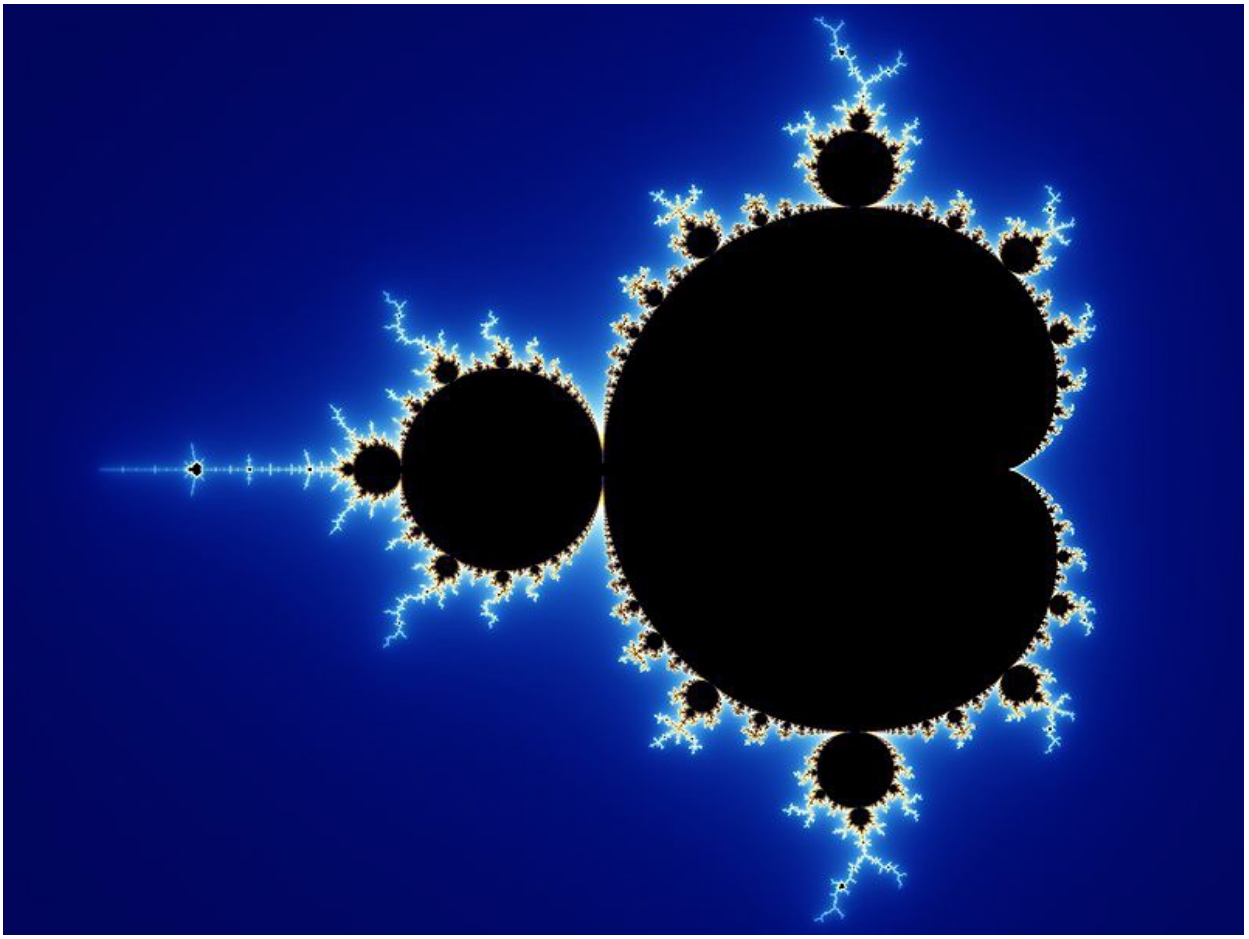

Traffic jams

Fractal Cities



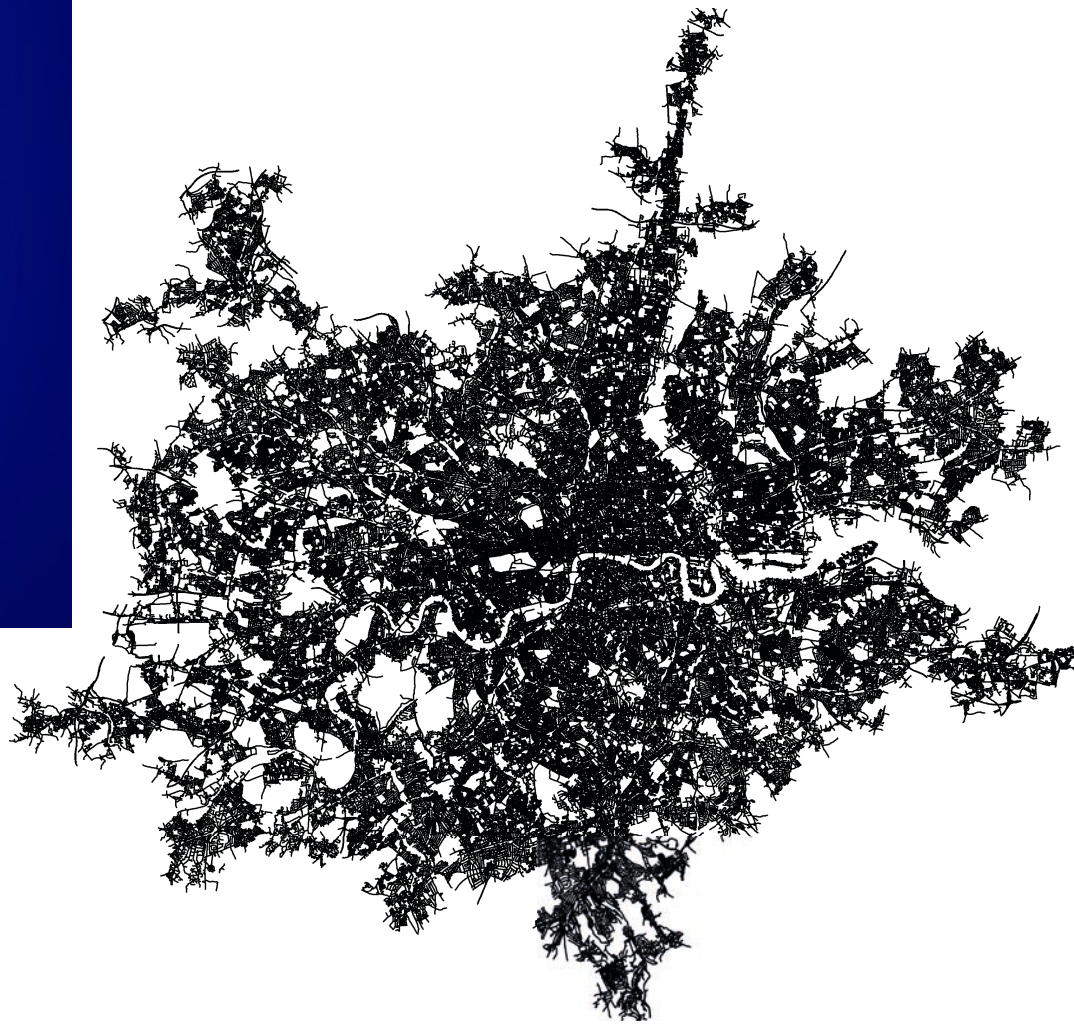
Michael Batty is one of the original proposers of considering cities as fractals! The other person is Frankhauser. Both in 1994.

Regular vs random fractals



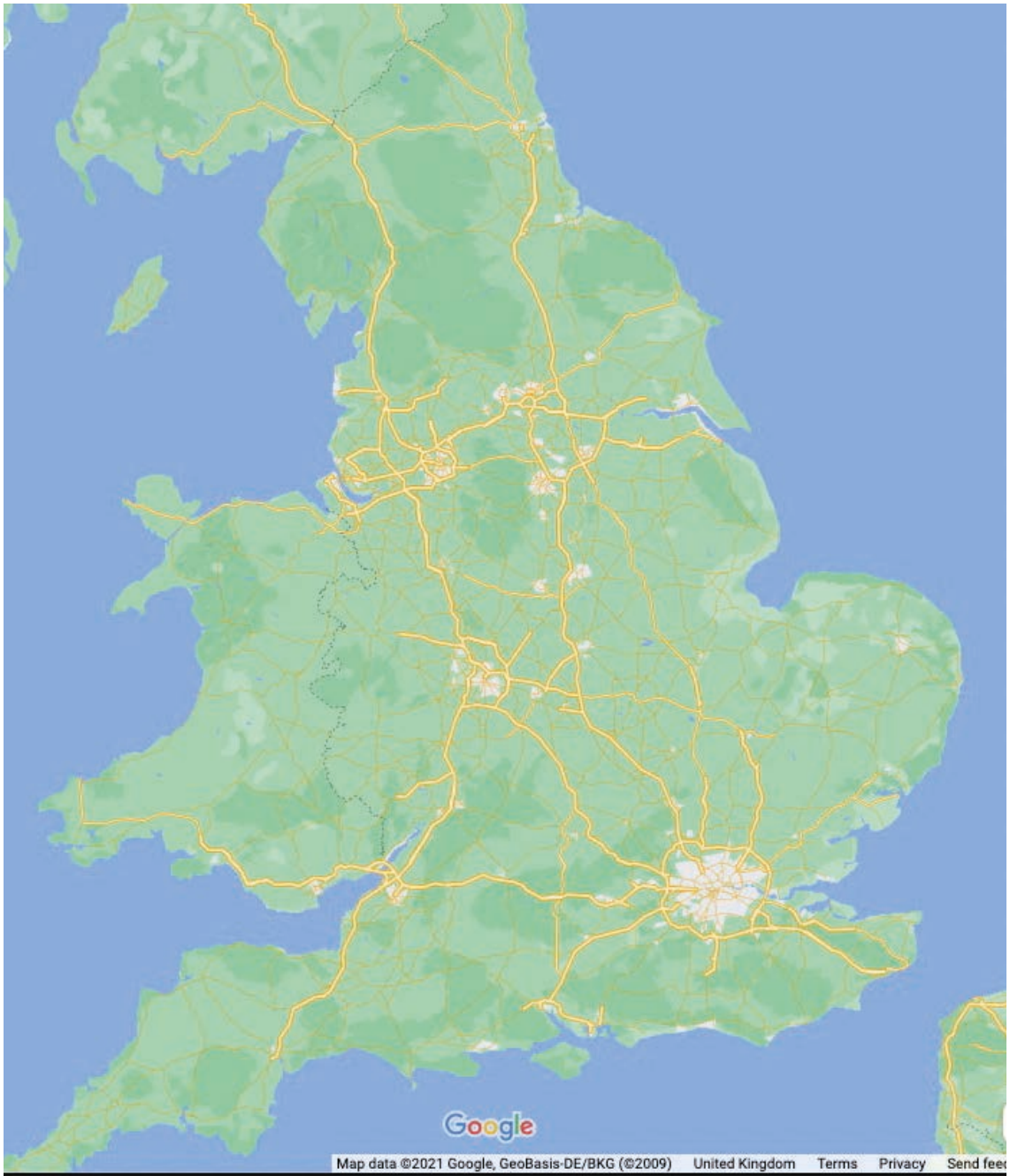
The Mandelbrot set

London street network

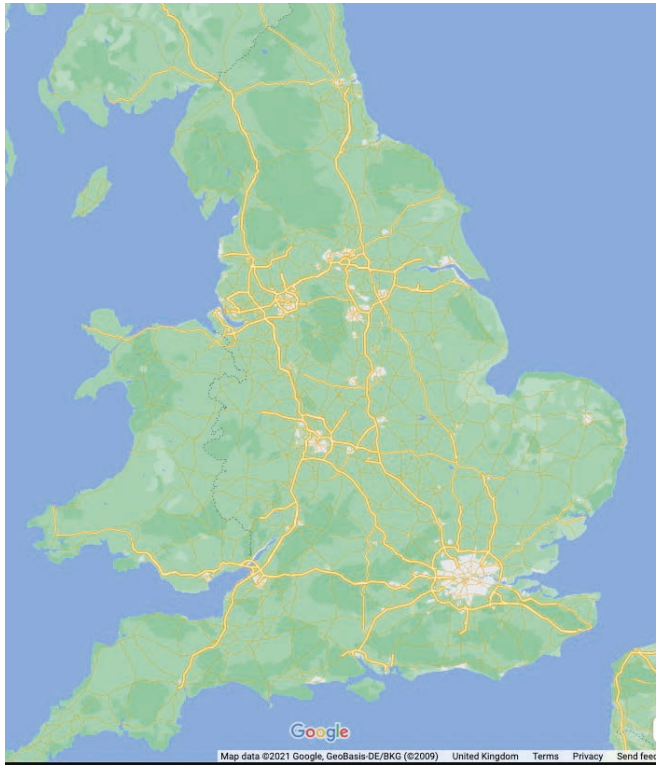


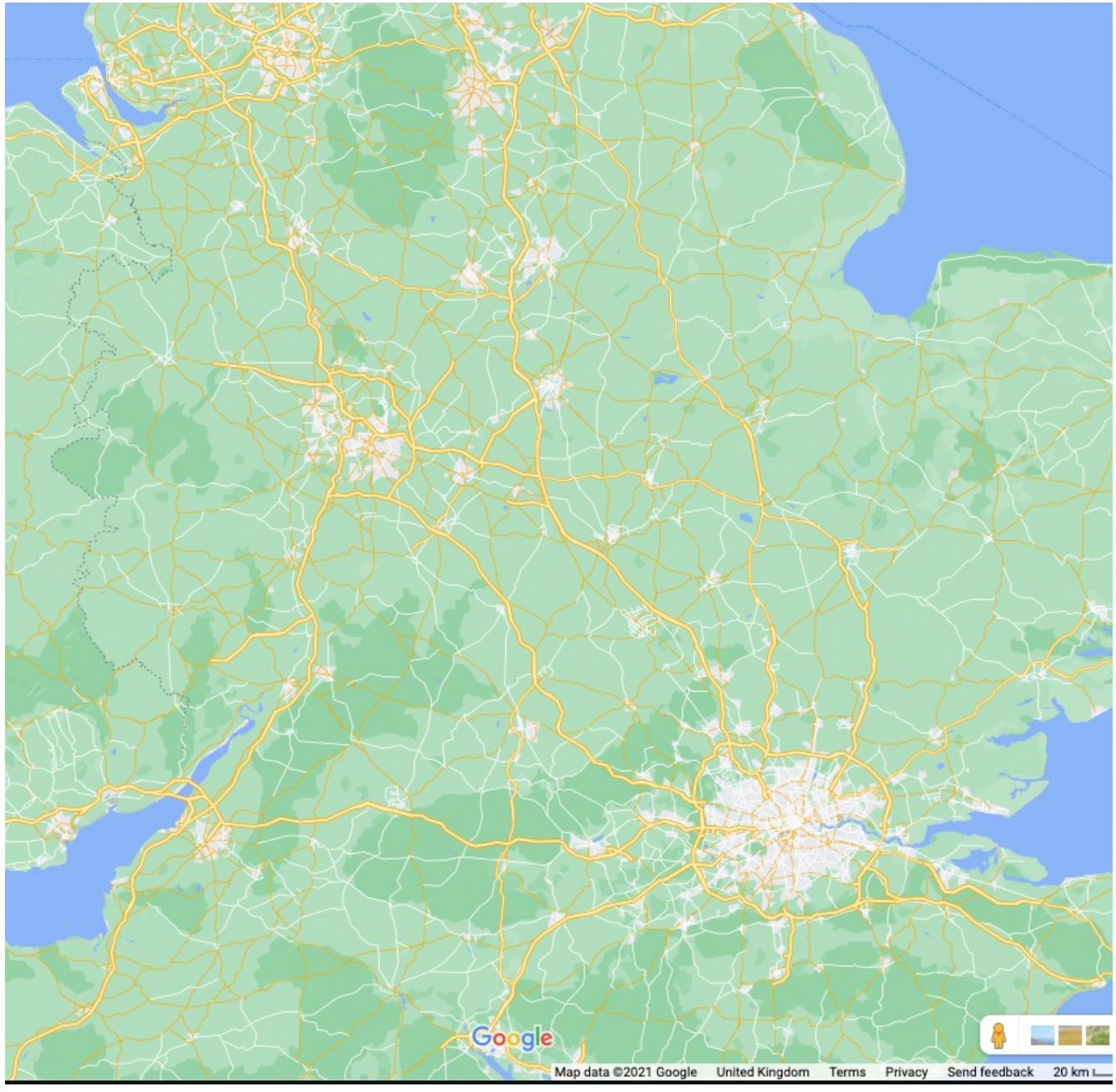
So we are fractals, and we collectively created fractal cities?

Physical trails: the street network

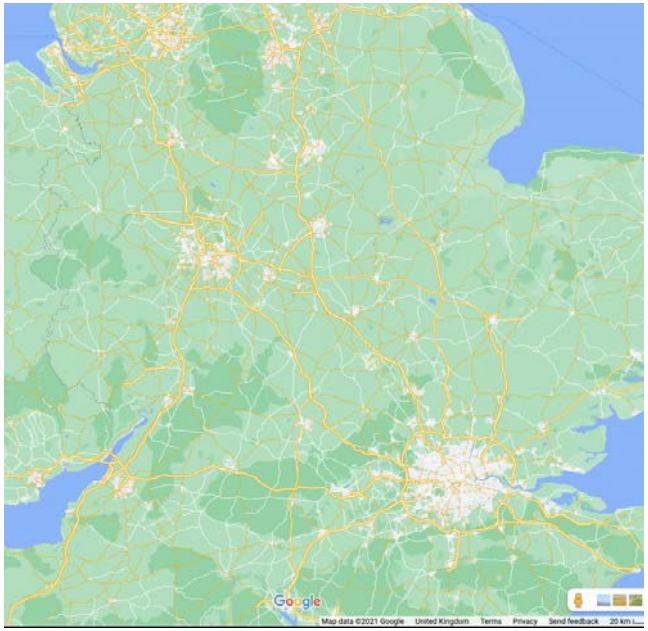


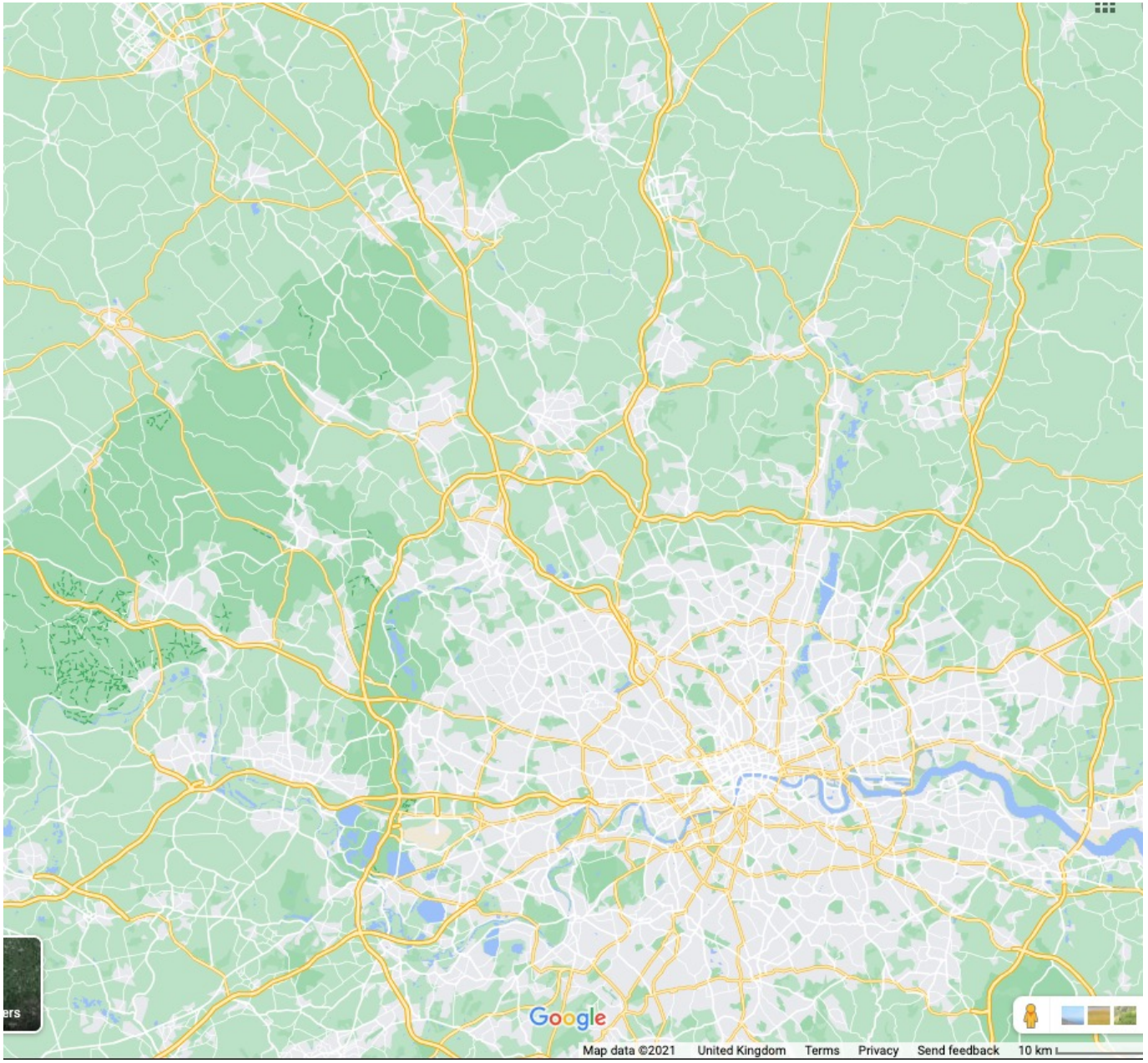
Physical trails: the street network



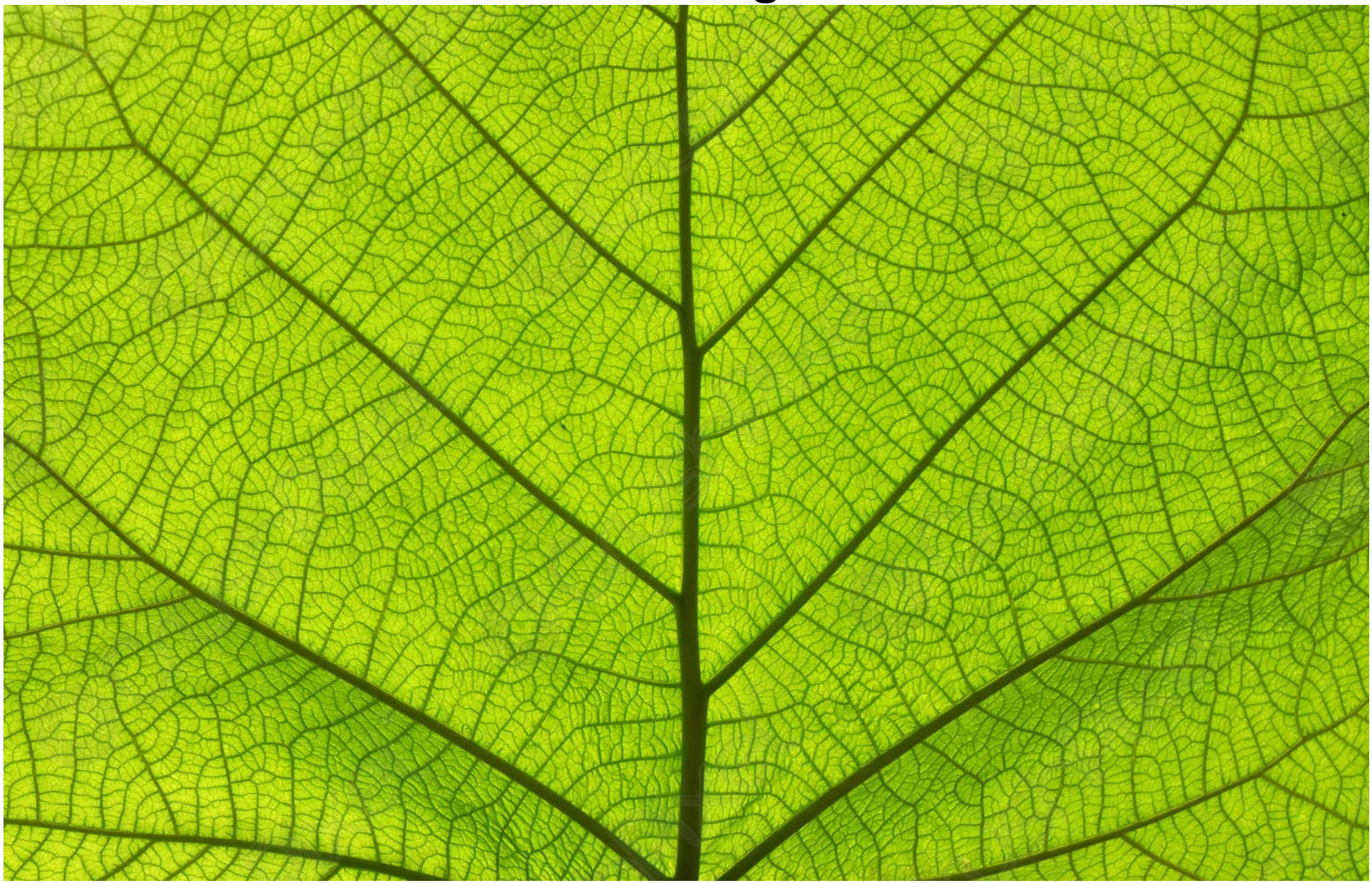


Physical trails: the street network

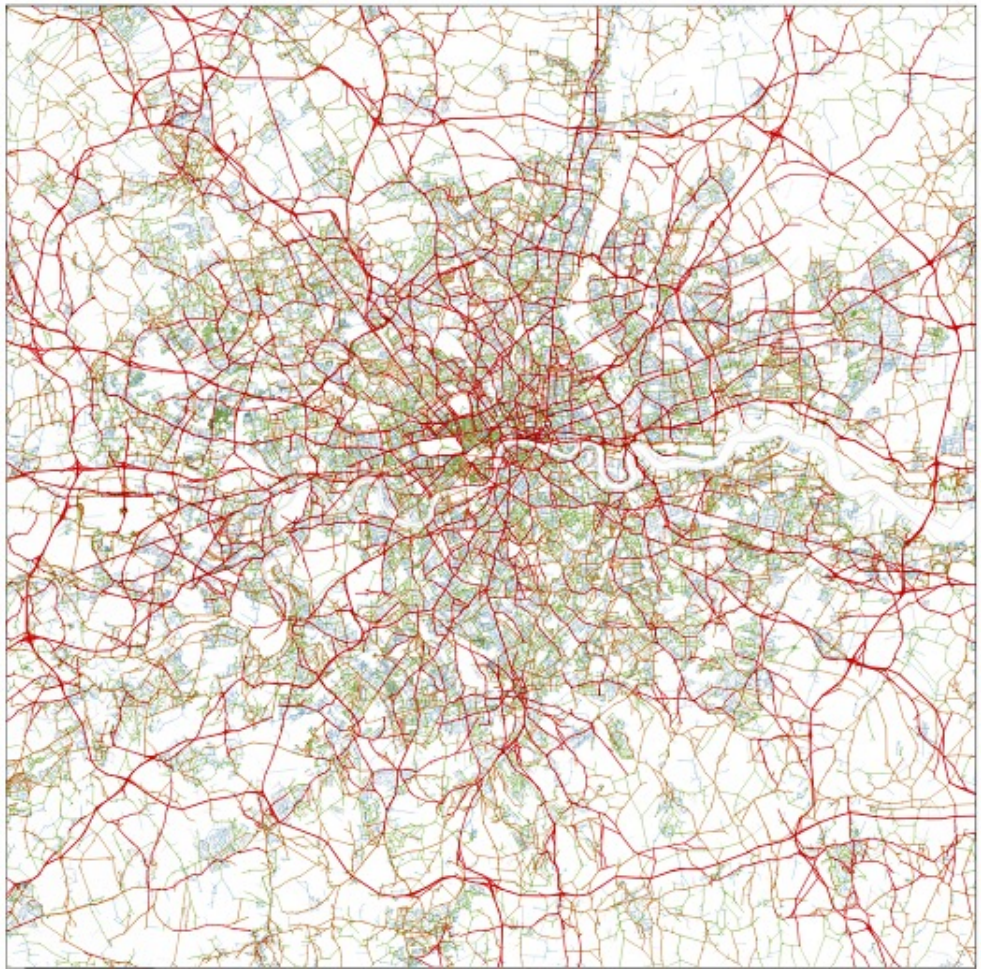




Fractals and their hierarchical organisation



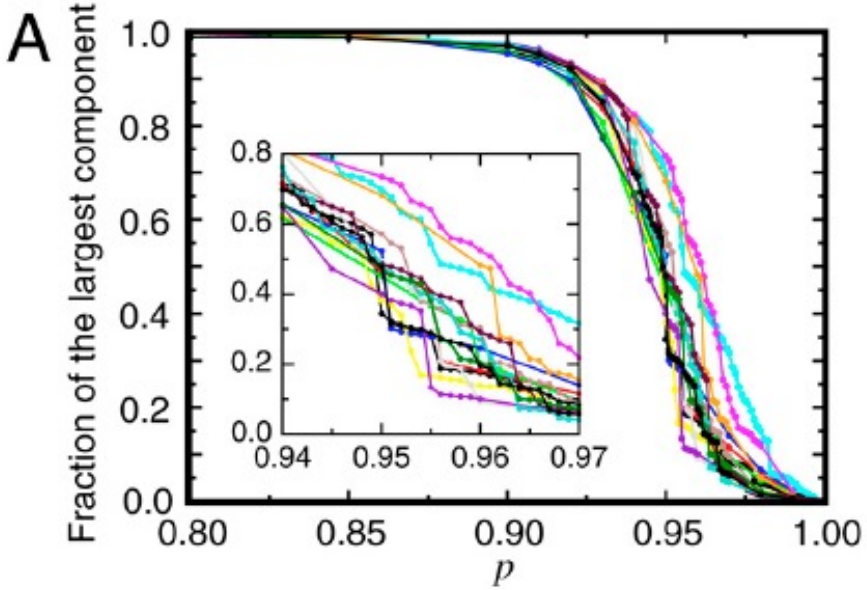
Hierarchical organisation of the street network

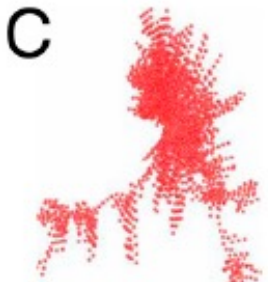


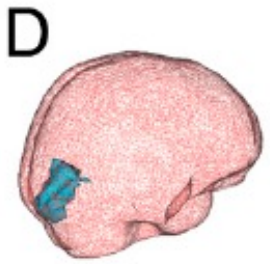
The brain also has a hierarchical structure given by the connectivity between modules!!!

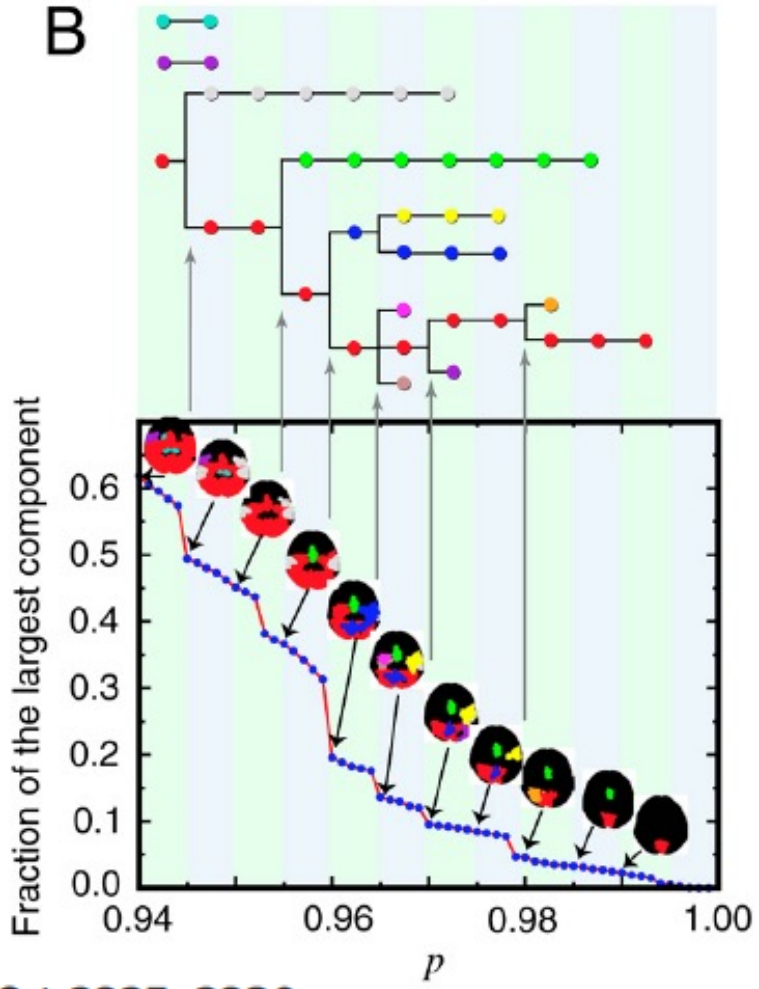
A small world of weak ties provides optimal global integration of self-similar modules in functional brain networks

Lazaros K. Gallos[a], Hernán A. Makse[a,b,1], and Mariano Sigman[b]





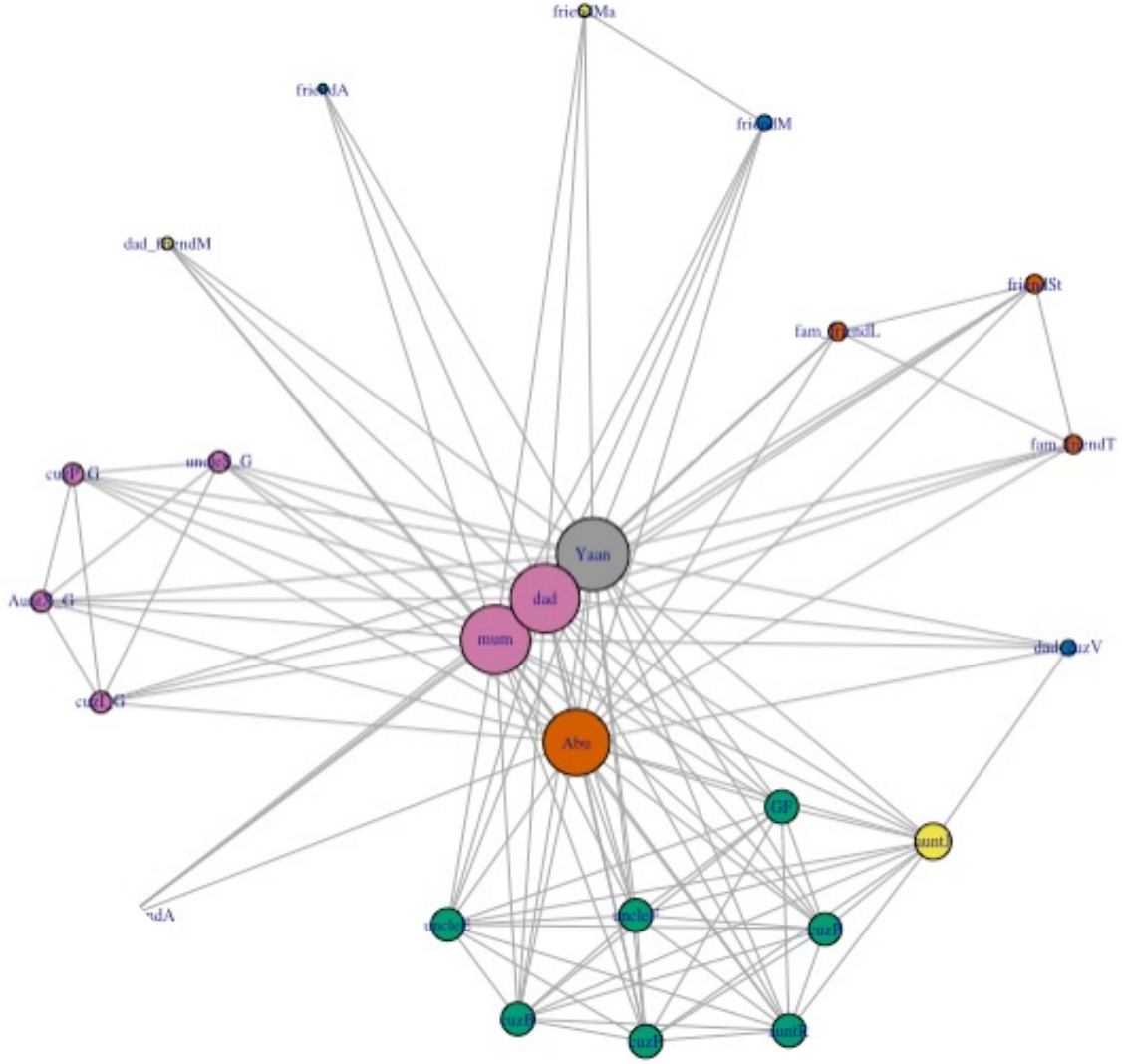




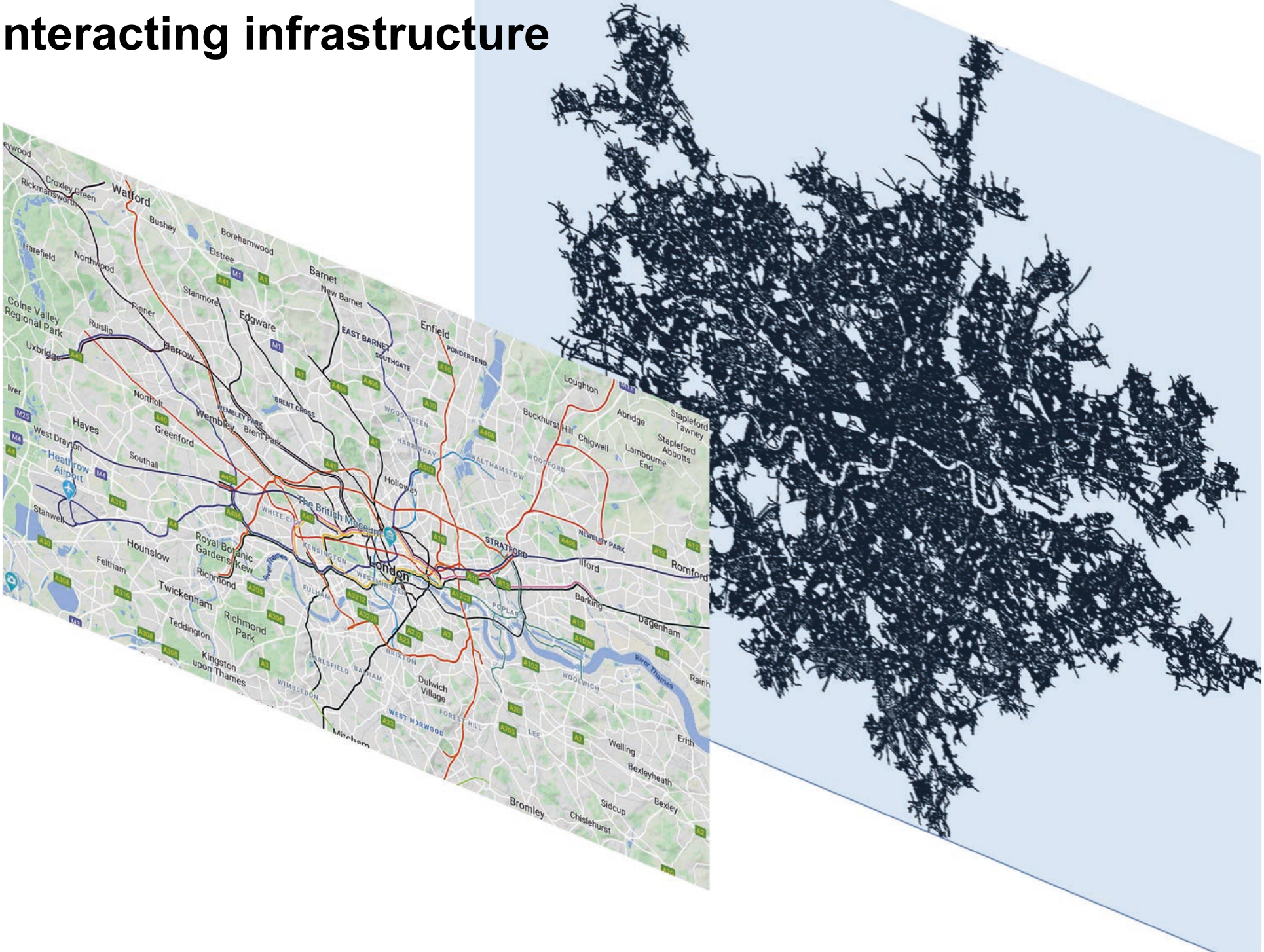
PNAS | February 21, 2012 | vol. 109 | no. 8 | 2825–2830

We can study urban systems and cities in a similar way that we study the brain, getting a closer look at the networks of connectivity that we have created!

People: (Non-)spatial representation of interacting communities



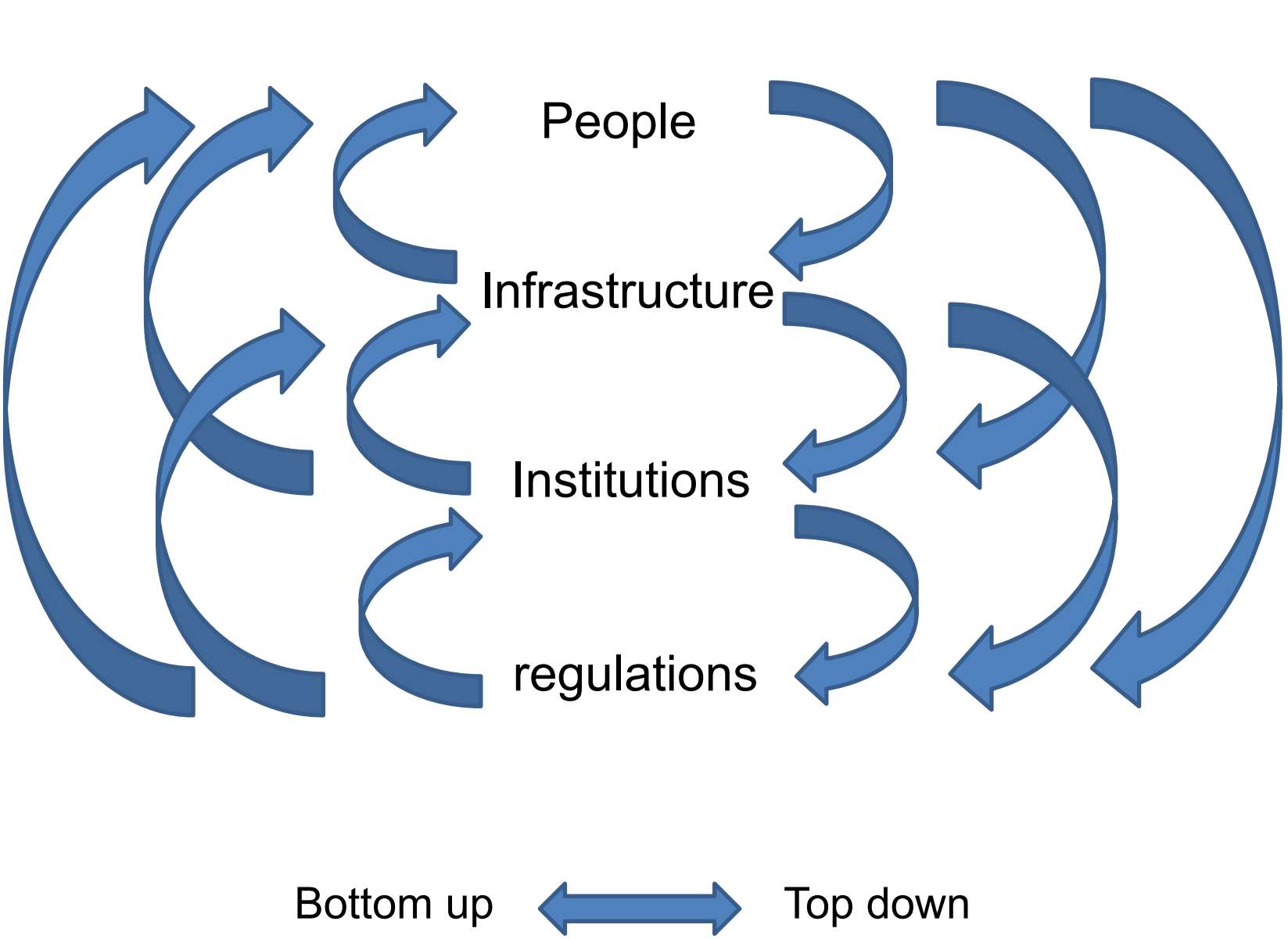
Interacting infrastructure



Systems interact at various scales

City level

Cities as Complex Systems



Conclusions

- Complex systems are systems where **more is different**! Local interactions lead to emergent behaviour: patterns
- Each of us is unique, individuality seems to permeate in every decision we take. We are NOT like the others at school, we have different experiences, and sometimes different cultures leading to different ways of life. BUT!!!! **We are all fractals**, and we collectively produce fractals and hierarchical organisations.
- Nature also produces patterns, nevertheless, those patterns are the outcome of solutions towards more sustainable systems: species **and** the environment.
- Our patterns are far from sustainable solutions, can we find better solutions? Can we understand the drivers to move to a different state?