Review doctoral dissertation Morphodynamic systems: from initial instability to network formation- Stanisław Żukowski, M.Sc.

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Introduction

The candidate introduces the concept of a morphodynamic system originating from geomorphology. In the introduction this concept is applied in several disciplines: geomorphology, physics, and morphogenesis in biology. In the introduction a very intriguing research question is raised about the inverse problem: ``Given a shape, how can we determine the details of its growth process or, more broadly, identify the fundamental mechanism behind its emergence". This is an extremely fundamental research question. In the summary of the thesis (p 35) the research question is even made stronger: ``Once the growth laws are known, we can predict the shape of the network in the future, but also in the past"

In the introduction the theory on growth patterns is discussed and demonstrated that it has long history in physics (Stefan problems, experiments with Hele-Shaw cells, viscous fingering, etc.). Here the connection is made with classical work ``On Growth and Form" by DÁrcy Thompson and the classical paper by Turing ``The Chemical basis of morphogenesis"

In the introduction also the network models of Watts and Strogatz on small-world networks Barabási and Albert on scale free networks is mentioned. This network model has been applied to model man-made networks such as the World Wide Web or the network of scientific articles connected by citations. Models such as the *Watts–Strogatz model* or the *Barabási–Albert model* explained emergent properties of these network graphs. The author is fully correct that treating networks as a set of vertices connected by links is may be useful in the context of engineered networks, but not in networks from nature. Most of the physical networks in nature have to be represented in space, they emerge in a (for example) Laplacian growth process, and are sometimes remodelled and have very different properties.

In this chapter a thorough introduction is provided into the theory of Laplacian growth processes. Here the problem is discussed that Laplacian growth models produce self-avoiding tree-like structures, while in growth phenomena in nature (e.g. venation patterns in leaves, vascular systems, the gastrovascular canal network in jelly fish etc.) frequently loops are formed. This a fundamental question: the growth process in many processes in nature seem to be well-described by a Laplacian growth model, but still loops are formed, even sometimes in a highly systematic way (e.g. the venation in leaves) The gastrovascular canal networks in jelly fish are good research topic since both patterns (self-avoiding branching Laplacian growth patterns and highly anastomosing networks) are found in the jelly fish. The argument that each jellyfish has a unique gastrovascular canal pattern and indicates that a physical explanation of the growth process is required and is not pre-patterned by genetics is a very good one.

Chapter 2 Invariant forms of dissolution fingers

The second chapter focusses on finger shaped channels formed in fractured and porous media (e.g. lime stone), a topic from geomorphology. This chapter has been published in a high-ranking physics journal (Phys. Rev Lett). The author has done experimental work with Hele-Shaw cells and compares microfluidic experimental results with theoretical results. In this comparison advanced image analysis were required. An important result in this work was that invariant shapes could by described by using reactive-transport theory from physics. By using the slope of solution pipes the flow in natural fingers could be estimated, which could have important implications in environmental science

Chapter 3 Through history to growth dynamics: deciphering the evolution of spatial networks.

The third chapter is on the evolution of spatial networks and about the research question: can growth dynamics by inferred from the analysis of the final pattern ? As a case study the growth of river network in Vermont USA is used. The work was published in high-ranking journal Scientific Reports. In the paper the thin finger model is introduced. Fig. 4 in the paper shows some very interesting morphologies generated with the thin finger model. The interesting point in this paper is that the authors could reconstruct the growth dynamics of a natural system (a river network) by using a backward evolution algorithm. They tested the method with synthetic networks.

Chapter 4 Breakthrough-induced loop formation in evolving transport networks

This chapter is about networks formed in for example, rivers and vascular systems. The topic is the formation of the networks where loops are being formed, and a theory based on Laplacian growth explained the growth and form of networks with loops. The chapter is published in a top journal (PNAS). The authors show that in Laplacian growth fingers are formed and at the moment these fingers reach the boundary of the system loops are induced. The paper is an important theoretical contribution to the field Laplacian growth processes; it demonstrates that there are mechanisms in Laplacian growth processes to create loops. This theory can be applied in a wide range of scientific fields where these growth patterns are found.

Chapter 5 and 6 Morphogenesis of the gastrovascular canal network in Aurelia jellyfish

This chapter is about one of the most fundamental problems in biology: understanding the morphogenesis of an organism. In these chapter the authors use the jellyfish Aurelia as a case study. The work of these chapters is (partly) published in Frontiers in Physics. The gastrovascular canal network in Aurelia is a good example of a Laplacian growth pattern where loops are formed. In the paper the authors show beautiful experimental work done on Aurelia, in Figs 5 and 6 they visualize the gastro vascular system in this jellyfish. The figures nicely illustrate the variability of the branching system and the formation of loops on large old jelly fish. In the paper two mechanisms are discussed to explain the formation of loops: twodimensional stress could lead to cracks and canals are reconnected and form a reticulate network. A second mechanism is pressure creating gradients within the fingers and allowing to make reconnections to side fingers.

Conclusion

The doctoral dissertation shows clearly that the candidate has a deep theoretical understanding of growth processes in nature. He applied this theory in a range of disciplines: geomorphology, physics, and biology. The work has been published in four scientific papers. In the papers the candidate shows that can use theoretical knowledge and compare his theoretical results with experimental observations, this is a clear demonstration that the candidate is capable to do independently scientific work.

One of the main topics in thesis is to understand Laplacian growth patterns and the formation of loops. The candidate shows that he developed a new theoretical framework for understanding these processes. The dissertation is very original where the candidate applies this new theory in different fields of science.

In conclusion I am very positive about this dissertation, I consider it one of the best dissertations which I have read. The candidate published (as first author) in three high-ranking journals, Phys Rev Lett and PNAS are among the top journals. The candidate has introduced a new scientific framework for understanding growth of networks that can be applied in many different disciplines . In my opinion the thesis deserves distinction.

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