

April 13, 2026

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Report on the doctoral thesis of Mr. Stanisław Żukowski titled “Morphodynamic systems: from initial instability to network formation”

The doctoral thesis of Mr. Stanisław Żukowski titled “Morphodynamic systems: from initial instability to network formation” has been accomplished jointly at the Faculty of Physics, University of Warsaw, and in the Laboratory of Matter and Complex Systems, Paris Cité University, under the supervision of Prof. Piotr Szymczak and Prof. Stéphane Douady. The doctoral dissertation of Mr. Stanisław Żukowski is properly structured. It consists of an abstract (in English, Polish and French), acknowledgments, list of scientific articles contained in the dissertation, six chapters that form the core of the dissertation, bibliography containing 167 items, and summary (in Polish and French).

Chapter 1 is an introduction comprising five sections. In section 1.1, morphodynamic systems are defined and general characteristics of their evolution are explained. Section 1.2 starts from a historical perspective on research on hydrodynamic instabilities and pattern formation processes. Then a concept of invariant forms in nature is introduced. Next, the Laplacian growth model is introduced and discussed. In section 1.3, two crucial processes responsible for morphodynamics of physical networks — namely, remodeling and tip growth — are described. Next, networks are categorized on the basis of their topology into branching networks and looping networks. Then the so-called Laplacian networks are defined and discussed in the context of research presented in chapters 4, 5 and 6 of the dissertation. Section 1.4 provides an overview of the methods used and systems considered in the dissertation. Namely, in subsection 1.4.1, the thin-finger model is introduced and a numerical approach to the network growth problem is summarized. Next, in subsection 1.4.2, the Hele-Shaw cell and its modified version — namely, the Hele-Shaw cell with

a soluble bottom — are discussed. Finally, subsection 1.4.3 is devoted to gastrovascular canal networks in jellyfish. In particular, the morphogenesis of the gastrovascular canal network in *Aurelia* jellyfish is described and discussed in the context of research presented in chapters 5 and 6. Taken together, sections 1.1-1.4 provide the scientific background needed to understand the research presented in chapters 2-6. Lastly, in section 1.5, the doctoral thesis is summarized, explaining how chapters 2-6 form a series of thematically related scientific problems.

Chapter 1 is 39 pages long and contains 24 figures. It is written very well, with attention given to detail, and contains only very minor flaws. For example, it seems that ϵ on the right-hand side of equation (1.18) on page 23 has not been defined. One can also note that the following piece of text appears on page 1 and then again on page 34: “Natural shapes are often viewed as the result of an optimization process, or as being predetermined, for instance by a genetic program. This overlooks the problem of how shapes appear in the first place. To understand this, we must examine the underlying growth mechanism”. Such repetitions are unnecessary.

The mathematical description of the Hele-Shaw flow, as presented in section 1.4.2, may require some minor clarifications. Namely, it is mentioned on page 21 that “The plates are sufficiently close together, so that the nonlinear and time dependent terms in Eq. (1.10) can be neglected leading to Stokes flow”. This statement is not obvious and probably requires some comment. It would be nice to explain the assumptions and physical conditions under which the Navier-Stokes equation (1.10) is actually reduced to the Stokes equation (1.12). Also, it would be interesting to estimate the maximum separation of the plates at which the nonlinear and time-dependent terms in the Navier-Stokes equation can in fact be neglected.

Despite the aforementioned minor issues, chapter 1 is very good in general and provides the background needed to follow the remaining chapters of the doctoral dissertation. Importantly, it also demonstrates that Mr. Stanisław Żukowski has the general theoretical knowledge in soft matter physics and, in particular, in hydrodynamics and network dynamics.

Chapter 2 contains the research article titled “Invariant forms of dissolution fingers” published in 2025 in Physical Review Letters. It presents experimental results indicating that an individual dissolution finger can emerge with a certain shape that is invariant from its inception, which is different from the classical Saffman-Taylor fingers that only obtain their invariant shapes in a long time limit. The aforementioned article also presents a model based on reactive-transport theory that correctly captures this

invariant shape. The authors of this article are Stanisław Żukowski, Silvana Magni, Florian Osselin, Filip Dutka, Max Cooper, Anthony J. C. Ladd, and Piotr Szymczak. According to the author declaration on page 40 of the doctoral dissertation, Mr. Stanisław Żukowski has made fundamental contributions to this article.

Chapter 3 comprises the research article titled “Through history to growth dynamics: deciphering the evolution of spatial networks” published in 2022 in *Scientific Reports*. It introduces a backward evolution algorithm that be used to predict the growth dynamics of a physical network from only a final snapshot of the network. An application of the backward evolution algorithm is illustrated on an example of a river network. The authors of the article are Stanisław Żukowski, Piotr Morawiecki, Hansjörg Seybold, and Piotr Szymczak. According to the statement on page 52 of the doctoral dissertation, the contributions of Mr. Stanisław Żukowski to this publication were essential.

Chapter 4 contains the research article titled “Breakthrough-induced loop formation in evolving transport networks” published in 2024 in the *Proceedings of the National Academy of Sciences of the United States of America*. It reports on a general mechanism of loop formation in physical networks, which can be observed in diverse processes — from unstable fluid flows to gastrovascular canal systems in jellyfish. This mechanism originates from finite-size effects. Namely, when the longest branch of a network reaches the outlet of the system, shorter branches revive and accelerate toward the longest one, leading to branch reconnections and looping. The authors of the aforementioned article are Stanisław Żukowski, Annemiek Johanna Maria Cornelissen, Florian Osselin, Stéphane Douady, and Piotr Szymczak. According to the declaration on page 71 of the doctoral dissertation, Mr. Stanisław Żukowski has made essential contributions to this scientific article.

Chapter 5 comprises the research article titled “Morphogenesis of the gastrovascular canal network in *Aurelia* jellyfish: Variability and possible mechanisms” published in 2023 in *Frontiers in Physics*. It reports on structural variability of the gastrovascular canal system in the *Aurelia* jellyfish. The observed variability is interpreted as an indication of instabilities arising from noise, suggesting that the structure of the canal system emerges in a self-organized manner. The self-organized process is in turn related by the authors to mechanical stresses within the jellyfish body during swimming, as indicated by their numerical simulations. The authors of the aforementioned article are Solène Song, Stanisław Żukowski, Camille Gambini, Philippe Dantan, Benjamin Mauroy, Stéphane Douady, and Annemiek J. M.

Cornelissen. According to the declaration on page 79 of the doctoral dissertation, Mr. Stanisław Żukowski has made relevant contributions to this publication.

Chapter 6 is titled “Morphogenesis of the gastrovascular canal network in *Aurelia* jellyfish: growth dynamics” and follows up the article presented in chapter 5. As far as I understand, chapter 6 contains only unpublished results. A major problem, in my opinion, is that there is no statement of author contributions in chapter 6. I would assume that Mr. Stanisław Żukowski is the only author of the manuscript draft forming chapter 6. However, the use of passive voice (“The experiments were conducted...”, “... the jellyfish are transferred...”, “... the jellyfish are fed...”, etc.) suggests that other researchers might have been involved in the experiments reported in chapter 6. Since I can not establish how Mr. Stanisław Żukowski has actually contributed to the research reported in chapter 6, I am not able to properly evaluate this chapter of his doctoral dissertation. Nevertheless, the amount and quality of scientific results presented in chapters 2-5 is more than enough for a doctoral dissertation in soft matter physics.

In conclusion, this doctoral dissertation demonstrates that Mr. Stanisław Żukowski has both the general theoretical knowledge in soft matter physics and the ability to conduct research independently. The subject matter of his doctoral dissertation are original solutions to a series of thematically related scientific problems. The PhD thesis of Mr. Stanisław Żukowski titled “Morphodynamic systems: from initial instability to network formation” thus meets the requirements for doctoral dissertations as specified in Art. 187, Act of 20 July 2018, the Law on Higher Education and Science. I hereby recommend that Mr. Stanisław Żukowski be admitted to subsequent stages of the doctoral thesis defense. Furthermore, I suggest to distinguish the doctoral thesis of Mr. Stanisław Żukowski for the exceptionally high scientific quality of the series of publications that form the core of his doctoral dissertation.

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