



Reply to comment

Physarum inspires research beyond biomimetic algorithms Reply to comments on “Does being multi-headed make you better at solving problems?”

Chao Gao ^a, Chen Liu ^b, Daniel Schenz ^c, Xuelong Li ^d, Zili Zhang ^a, Marko Jusup ^{e,*},
Zhen Wang ^f, Madeleine Beekman ^g, Toshiyuki Nakagaki ^{c,h}

^a College of Computer and Information Science & College of Software, Southwest University, Chongqing 400715, China

^b Center for Ecology and Environmental Sciences, Northwestern Polytechnical University, Xi'an 710072, China

^c Institute for Chemical Reaction Design and Discovery (WPI-ICReDD), Hokkaido University, Sapporo 001-0021, Japan

^d Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710119, Shaanxi, China

^e World Research Hub Initiative (WRHI), Institute of Innovative Research, Tokyo Institute of Technology, Tokyo 152-8550, Japan

^f School of Mechanical Engineering & Center for OPTical IMagery Analysis and Learning (OPTIMAL), Northwestern Polytechnical University, Xi'an 710072, China

^g School of Life and Environmental Sciences, The University of Sydney, NSW 2006, Australia

^h Global Station for Soft Matter, Global Institution for Collaborative Research and Education, Hokkaido University, Sapporo 060-0815, Japan

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Abstract

We look at a recent expansion of *Physarum* research from inspiring biomimetic algorithms to serving as a model organism in the evolutionary study of perception, memory, learning, and decision making.

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Comments [1–7] on our review “Does being multi-headed make you better at solving problems?” [8] raise a wide variety of pending issues in *Physarum* research, yet again illustrating the richness of this scientific domain, as well as the many opportunities to make important new discoveries. This state of affairs, however, also makes it difficult to address all the issues brought up by the commentators, especially within the limited space available herein. We are

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* Corresponding author.

E-mail address: mjusup@gmail.com (M. Jusup).

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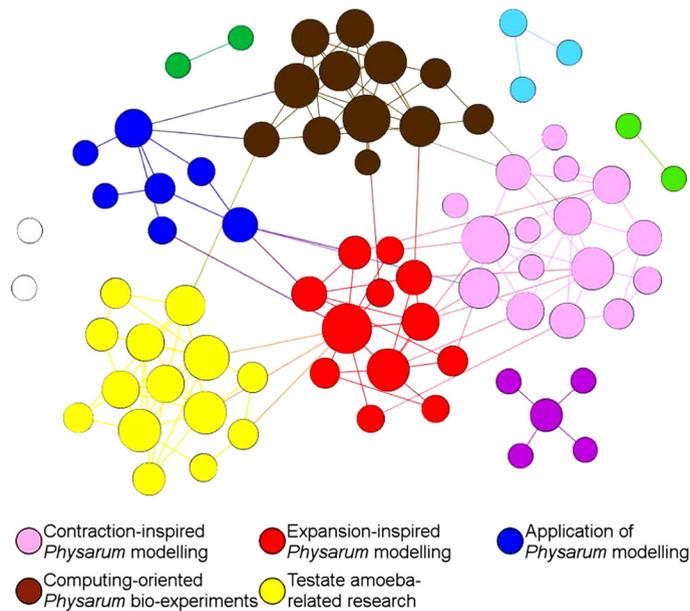


Fig. 1. A better classification of the *Physarum* literature. Using the same algorithm as in Fig. 1 of review [8], but enhanced with the *Physarum*-based algorithm from Ref. [10], we managed to redistribute “Other bio-experiments on *Physarum*” between two larger domains, “Contraction-inspired” and “Expansion-inspired” *Physarum* modelling.

therefore forced to relinquish the ideal of covering a lot of ground, gaining in return a chance to focus on particularly promising research problems and directions.

Describing the debate in Refs. [1–7] in the broadest of terms, the key issues appear to be (i) fundamental properties and advantages of *Physarum* over other model organisms and (ii) the role of *Physarum*- and other bio-inspired algorithms in relation to neighbouring domains such as exploratory data mining and machine learning, or even more distant domains such as neuroscience and cognitive psychology. In this latter context, we have already documented situations (e.g., see Section 3.6.3 of review [8]) in which *Physarum*-based algorithms, instead of being in the driver’s seat, aid other heuristic algorithms to either provide a better solution or to reach the solution of the same quality faster. Another case in point is the classification of *Physarum* research in Fig. 1 of review [8], produced using a well-known method for the detection of communities in complex networks [9]. Here instead, we re-classified *Physarum* research with the same method, but now enhanced with the *Physarum*-based algorithm from Ref. [10], described in Section 3.6.4 of review [8] (Fig. 1). The application of this enhancement increases modularity from $Q = 0.62$ to $Q = 0.65$, which may not seem much, but it is in fact sufficient to redistribute “Other bio-experiments on *Physarum*” between two larger domains, “Contraction-inspired” and “Expansion-inspired” *Physarum* modelling (Fig. 1). This perfectly illustrates that heuristic algorithms yield approximate solutions with some room for improvement, but then again, such improvements may not always fundamentally alter the underlying message. We posit that pursuing even minor improvements is worthwhile if it brings secondary benefits in the form of, e.g., faster convergence to candidate problem solutions or otherwise reduced computational load. We thus also agree with Ref. [3] that an easy-to-use toolbox is a necessity with which *Physarum*-inspired engineers must grapple in the near future if there is to be hope for the adoption of *Physarum* algorithms by wider data-mining and machine-learning communities.

Returning to the issue of fundamental properties and advantages of *Physarum* over other model organisms, Reid [6] rightfully points out that our criticism of many scientists or engineers who try to design algorithms based on biological systems but then steer away from biological realism, is a little harsh. After all, in the case of non-biological algorithms a particular problem needs to be solved, whereas a biological algorithm (i.e., one employed by an actual biological entity such as the slime mould) hardly, if ever, has evolved to solve one problem only. Simplifications and/or modifications based on the actual problem thus make sense. Similarly, the biological system best suited to inspire the development of a non-biological algorithm should depend on the specifics of the problem that needs to be solved.

Latty [7] adds to the discussion by stating that in order to determine whether *Physarum* is a superior biological model over ant colonies, one really needs to compare algorithms based on both biological systems under the same conditions; in other words, there is a need for benchmarking. It could well be that the ants outperform the slime mould under certain conditions while the reverse may be the case under a different set of conditions. The importance of benchmarking results for practical applications is hard to overemphasise, yet there may be circumstances beyond just performance superiority that fuel *Physarum*'s attractiveness. We reckon that one such circumstance is complexity or the lack thereof in *Physarum* relative to ants or other social insects.

As pointed out by Reid [6], each individual in an insect colony has access to its own brain, thus giving the colony as a whole the ability to run (in stylised manner of speaking) a multitude of behavioural computations in parallel. *Physarum*, by contrast, displays far lesser levels of complexity, lacking in fact any centralised information-processing organelles. Observed *Physarum*'s behaviours thus must be a result of de-centralised biophysical mechanisms. It is therefore unsurprising that when models inspired by *Physarum*'s extreme de-centralisation actually produce results that we usually associate with centralised conscious effort (such as designing a country's railroad network), we necessarily wonder in what way that conscious effort is actually relevant for generating the said results. Slime mould for sure is incapable of conscious effort, but then what information processing mechanisms does *Physarum* employ as it goes about its business? Answering this question has been emerging as a promising line of *Physarum* research. So far, it has been found that *Physarum* uses external memory in the form of a trail of extra-cellular slime that is avoided unless there is a strong attractive chemo-gradient to follow [11]. In this way, the organism avoids revisiting poor environments [11]. *Physarum* is also known to habituate to environmental cues as a form of learning [12]. If required to cross a repellent-covered bridge in order to reach food, the organism will show a diminished response by increasingly extending over the repellent as the time passes [12]. Such habituation requires the ability to store information about the environmental cues, providing evidence of internal memory whose mechanistic underpinnings are currently unknown. Elucidating these mechanisms, apart from satisfying general biological curiosity, may prove useful in developing applied algorithms for, e.g., data mining and/or machine learning.

This new line of *Physarum* research also transcends seeing the organism as an inspiration for biomimetic algorithms, and goes as far as looking at slime mould as a model organism for devising a theory around the evolution of cognition [13]. A guiding concept in this context is "minimal cognition", which calls for abandoning a human-centric view on what cognition entails based on the premise that all behaviours originate from an organism's need to secure sufficiently high survival and fecundity of surviving individuals for the population growth to be positive; otherwise, the population would go extinct (the famous Lotka-Euler equation is a mathematical formulation of this statement). Ultimately, survival and fecundity are to a large degree determined by the organism's feeding conditions and, by extension, metabolism. Following this line of thought, minimal cognition is interpretable as a border at which metabolism ends and cognition begins [14,15], thus opening the door for coupled metabolic-evolutionary models [16, 17] to mathematically underpin the emergence of cognition on the tree of life. To be more specific where the border between metabolism and cognition lies, we can imagine an organism's response to hunger, which may either be a "reflex" action to search for food in a broadest possible sense or a "learned" action to search for food at a specific location or by specific means that resulted in the highest ingestion in the past. It is again *Physarum*'s lack of complexity, now in conjunction with a proven ability to memorise and learn as mentioned above, that make slime mould an attractive model organism in the emerging line of research focused on the evolution of perception, memory, learning, and decision making as the key components of minimal cognition [13].

In conclusion, much has been said about *Physarum*-inspired algorithms. Now seems to be the right time to implement them in an easy-to-use toolbox for R, Python, and/or other popular programming environments, as well as to subject them to benchmarking, especially against other biomimetic algorithms. Without such implementations and benchmarking, it is hard to expect adoption by wider data-mining and machine-learning communities. Moving beyond algorithms, a renewed interest in *Physarum* seems to be arising in the context of memory, learning, and more generally minimal cognition. Owing to its relative lack of complexity, but intricate capabilities, *Physarum* indeed possess the qualities of an ideal model organism. We therefore expect this line of research to generate exciting progress fairly soon.

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