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Personal Section:

Physarum polycephalum is an organism that one cannot help but find interesting. This single-celled amoeboid is able to self-organize and self-optimize without the help of any sort of central nervous system. It can find the shortest path connecting any number of food sources, “solve” mazes created by physical barriers, and create paths that avoid light. I was introduced to this organism by my mentor, a member of the Laboratory of Mathematical Physics at The Rockefeller University in Manhattan, New York. The general theme that connected the research within this laboratory was optimized networks; researchers worked on everything from the venation in plant leaves to the structure of rat brains. There was no work being done with *Physarum polycephalum* at the time, but my mentor cited its venation patterns as examples of optimized networks.

My interest was piqued by a brief description of the organism’s capabilities, so I began researching *Physarum polycephalum* further. As I learned about its growth-process, I grew increasingly interested in the work that had been done on modeling its behavior. There are a number of static mathematical models that have been built from the principles of fluid dynamics and that accurately predict the organism’s adaptive behavior. I began to wonder if I could take these mathematical models a step further by creating a computer program that could model the organism’s behavior continuously rather than discretely. This would not only provide useful insight into the optimization process itself, but would also be an educational exercise in creating a dynamic simulation from a static model.

Because the mathematical models that would serve as the basis of my computer program were derived from the principles of fluid dynamics, I first obtained a basic understanding of this field. I used my knowledge of electrical circuits to create an analogy that allowed me to more easily understand the necessary principles. Before I could begin developing my computer program, I also had to learn a new programming language. I chose to work in Python because I wanted to take advantage of a module called NetworkX. As I was already familiar with computer science skills through my experience with Java, I was able to teach myself Python through a series of exercises. I worked on simple programs until I became more comfortable with the semantics and eventually worked myself up to more complicated tasks.

My research experience demonstrated the applicability of computer science to the fields of science and mathematics and emphasized the value of interdisciplinary research. I was able to combine computer science, mathematics, physics, and biology into a single study that provided insight into each of the four fields. I am now planning to study computer science at the undergraduate level and hope to continue similar research that appeals to my interests, not only in computer programming, but also in science and mathematics.

Perhaps the most valuable lesson I learned from conducting research throughout high school is the importance of stupidity. This phrase, borrowed from the title of an essay by Martin Schwartz, means that before you can focus on discovering, you have to free yourself from the burden of knowing. You will almost inevitably encounter roadblocks throughout the research process, and it is important not to let the feeling of stupidity discourage you from continuing. The truth is comforting: when one is conducting research, he or she is not expected to have the answers. We enter the unknown in the pursuit of knowledge, and what we discover brings us closer to understanding.

Research Section:

Modeling the Adaptive Venation Network of *Physarum polycephalum*

Abstract:

Physarum polycephalum is a large, single-celled amoeboid composed of a network of veins responsible for transporting nutrients, signals, and body mass. Rhythmic contractions of the organism's cytoskeleton allow these veins to change in thickness, form or vanish, and "crawl" in order to obtain an optimized network that balances minimum distance and minimum "risk," a measurement based on the intensity of light that is encountered by the network. Previous studies of the organism's adaptive behavior have introduced static mathematical models that produce patterns comparable to the organism's optimized venation networks. This research presents a computer program that, by maintaining consistency with fluid dynamics, provides a realistic simulation of the organism's adaptive behavior and allows for the implementation of dynamic environments. This model not only generates the final pattern created by the organism's adaptation process, but also illustrates how the network develops and changes in response to its environment. This study will allow for a more complete understanding of the organism's growth-process and will expand the possible applications of its optimized systems. In addition, understanding how to create a dynamic simulation from a static model will allow for the creation of realistic, computer-powered models that can account for variable environmental conditions.

Introduction:

Physarum polycephalum is a large, single-celled amoeboid made up of a network of tubes through which the organism is able to transport nutrients, signals, and body mass [3]. Commonly known as slime mold, the organism is historically classified as a fungus; however, molecular data now show that it is most closely related to the Dictyostelidae, a group of cellular slime molds [1]. As long as nutrition is available, *Physarum polycephalum* grows continually through a series of nuclear divisions, synchronized by a constant pumping of the cytoplasm. If the organism is growing in a nutrient rich environment, it forms a flat, coherent layer. Otherwise, the organism forms a mesh-like network of veins. Rhythmic contractions of the cytoskeleton allow these veins to change in thickness, form or vanish, and "crawl." As a result, the organism is able to adapt its venation pattern in order to create an optimized network [2].

Studies of *Physarum polycephalum* have demonstrated that the organism is able to find the shortest path between food sources and can "solve" mazes created by physical barriers [5]. Because the organism grows best in the absence of light, its optimized venation networks also take into account illumination; the intensity of light at a given location in the organism's environment defines the "risk" at that point. The optimization process therefore demonstrates a balance between finding the shortest path between food sources and avoiding areas of high risk [3]. Mathematical models derived from the observation of *Physarum polycephalum* are extremely useful in navigating complex networks (e.g. road traffic or internet systems) as both distance and "risk" can be implemented to reflect real-world scenarios [4]. For example, if applied to road traffic, the model would have nodes at locations that correspond to intersections and areas of "risk" that correspond to construction or other traffic inhibitors.

Previous research on *Physarum polycephalum* has focused primarily on modeling the organism's venation pattern at a specific moment in time rather than over a period of time. Although these studies have acknowledged that the shape of the organism's venation changes drastically in response to "environmental changes and external stimulation," a model that incorporates varying environmental conditions has yet to be presented [5]. This research therefore focuses on developing a computer program that is able to simulate the optimization process of *Physarum polycephalum* in time-dependent conditions. In addition, by implementing the fluid dynamics that scientists currently believe affect the development of the organism's venation pattern, the program can provide us with a more complete understanding of the optimization process itself, including its capabilities and limitations in application.

Materials and Methods:

In order to simulate the growth process of *Physarum polycephalum*, an algorithm that incorporates fluid dynamics was developed and coded in Python™. A grid with randomly distributed nodes was constructed using the module NetworkX. The nodes were connected to form a mesh-like network using the Delaunay triangulation function, which ensured that each node was connected to at least one other node and that no two nodes were connected more than once. In order to initialize the graph, each edge was assigned a uniform conductivity (C) and a specified level of risk (α). In addition, each of the nodes was assigned a net flow (I_0) of zero. Food sources were then "placed" by re-assigning the I_0 of specified nodes to a non-zero value (e.g. in the case of two food sources, one positive value and one negative value). A series of three update functions were then iterated in order to simulate the adaptation process of *Physarum* *polycephalum*. The first two functions calculated the fluid pressure drops and currents at the time of the iteration and the third function updated the conductivities using the formula:

$$C_{ij} = t_i * \left(\left|I_{ij}\right| - \alpha * C_{ij}\right) + C_{ij}$$

where C_{ij} is the conductivity of the edge connecting nodes *i* and *j*, t_i is the time increment, and I_{ij} is the current flowing between nodes *i* and *j*. To monitor and analyze the simulations, a function was written to display the network.

After the program was developed, numerous simulations were run in order to ascertain optimal parameters, including the number of nodes on the lattice, the size of the time increment, and the number of iterations. Results presented in previous studies of *Physarum polycephalum* were replicated in order to ensure the validity of the computer program. Various time-dependent environments were created by making slight modifications to the code, and the networks produced by these simulations were analyzed.

Results:

The computer program developed in this study simulates the adaptive behavior of *Physarum polycephalum*. Because the program is consistent with fluid dynamics, the way the simulation changes over time reflects the way the organism's veins reorganize to form what scientists believe are optimized networks. This model demonstrates a more realistic adaptation process. For example, in the case of two food sources and uniform risk, a reasonably straight line connecting the food sources is expected. The new program obtains this result by maintaining consistency with fluid dynamics and allowing the most conductive edges to connect and become the primary path (see figures 1-5). This produces the same result as previously presented models and avoids using mathematical path-finding algorithms that do not realistically model the organism's behavior, such as Dijkstra's algorithm.

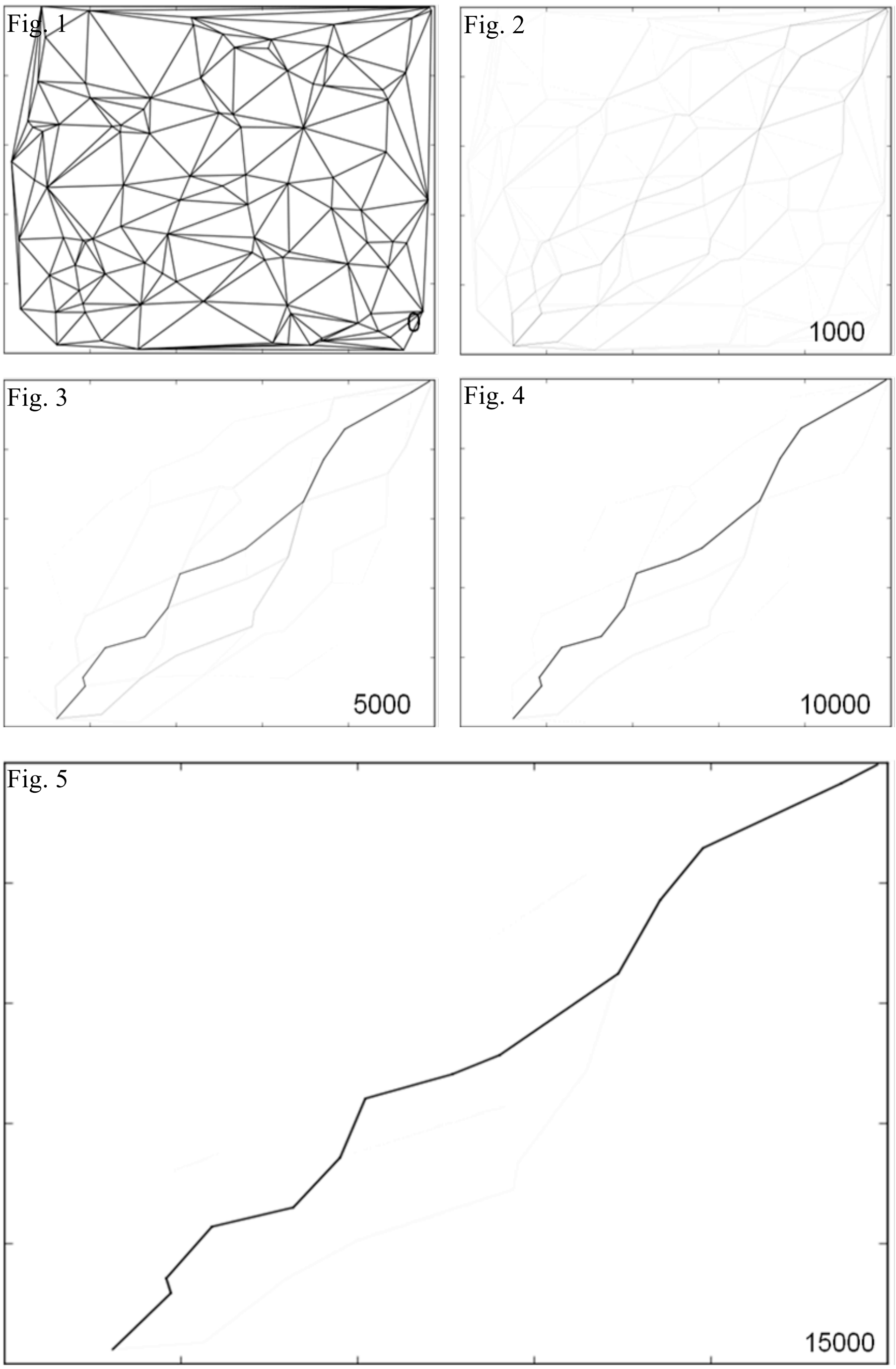
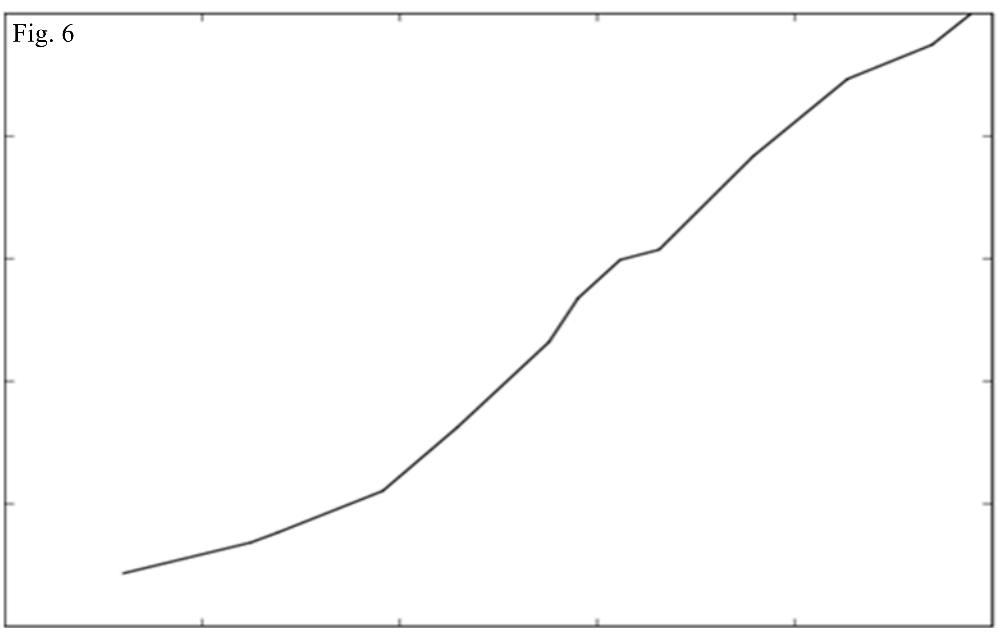


Figure 1-5: Shown above are outputs of the computer program that models the adaptive behavior of *Physarum polycephalum*. Each plot consists of 100 nodes with food sources in the lower left and upper right corners, and the update functions have been iterated 0, 1000, 5000, 10000, or 15000 times as indicated. Because the risk is uniform in this particular environment (i.e. the intensity of light is homogeneous) a roughly straight line connecting the two food sources is expected as it is the minimum distance path.

Because environmental changes have a significant impact on the growth-process of *Physarum polycephalum*, it is also important to have a computer model that is able to capture the organism's response to variation, whether it be the location of food sources or the distribution or level of risk. The new program allows users to implement changing environments and observe the organism's simulated reactions. One such environment created in this study began with two food sources and uniform risk. After an optimized path was produced, a section of the environment was assigned an elevated level of risk (see figures 6-7). In an experiment, this would mean increasing the intensity of light in a certain section of the environment. The network was able to adapt to this change by moving its primary path to avoid the area of elevated risk. How far the path moved away from this area depended on the level of risk; as the value was increased, the path moved farther away. This situation was implemented so that the program's ability to simulate the organism's reaction to environmental changes could be observed and analyzed.

Fig. 6



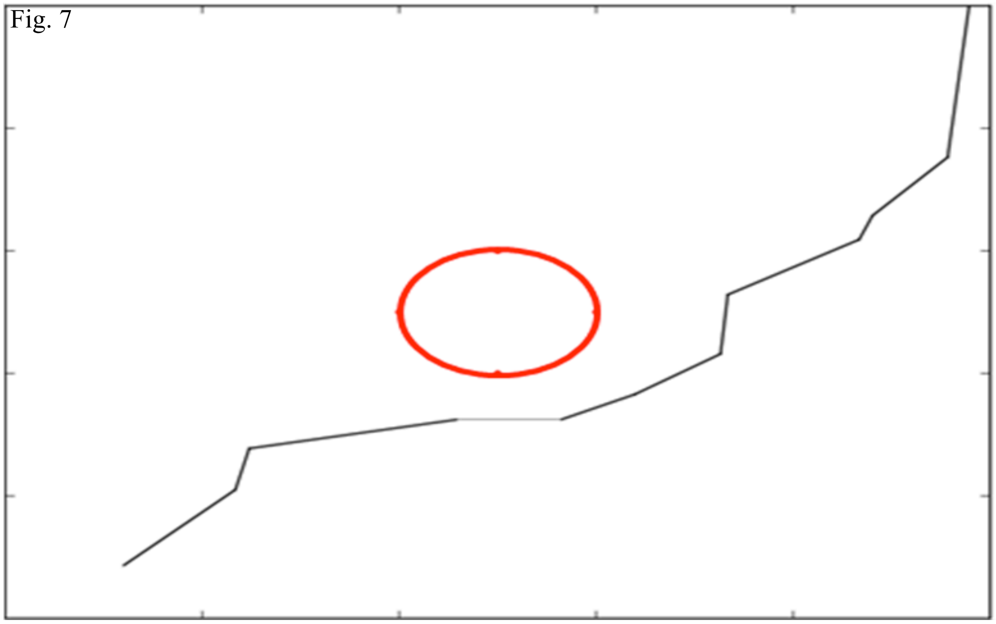


Figure 6-7: Shown above are outputs of the computer program that models the adaptive behavior of *Physarum polycephalum*. Each plot consists of 100 nodes with food sources in the lower left and upper right corners. The first plot is the optimized path created after 20,000 iterations of the update function. An area (enclosed by the circle in the second plot) was then assigned elevated risk (3 times greater), and the update functions were iterated another 20,000 times to produce the second plot. The primary path connecting the two food sources shifted in order to avoid the area of elevated risk, demonstrating how the simulation of the organism responds to changes in its environment.

Another situation created in this study implemented a sinusoidal risk pattern in order to determine the effect of environmental changes that occur at a speed comparable to the rate of the network's growth (see figures 8-12). The intensity of light shining on a given horizontal position varied based on a sinusoidal equation. The networks formed under these conditions include not only a primary path, but also a number of slightly thinner, less conductive paths, demonstrating that it is impossible to create an optimized network with a single path. This configuration is ideal: as the risk changes and interferes with the parts of the main path, the organism can compensate by using the secondary paths. Whereas previously presented models of the growth-process of *Physarum polycephalum* could only be applied to static environments, this computer program offers insight into the organism's ability to grow, optimize, and adapt in dynamic settings.

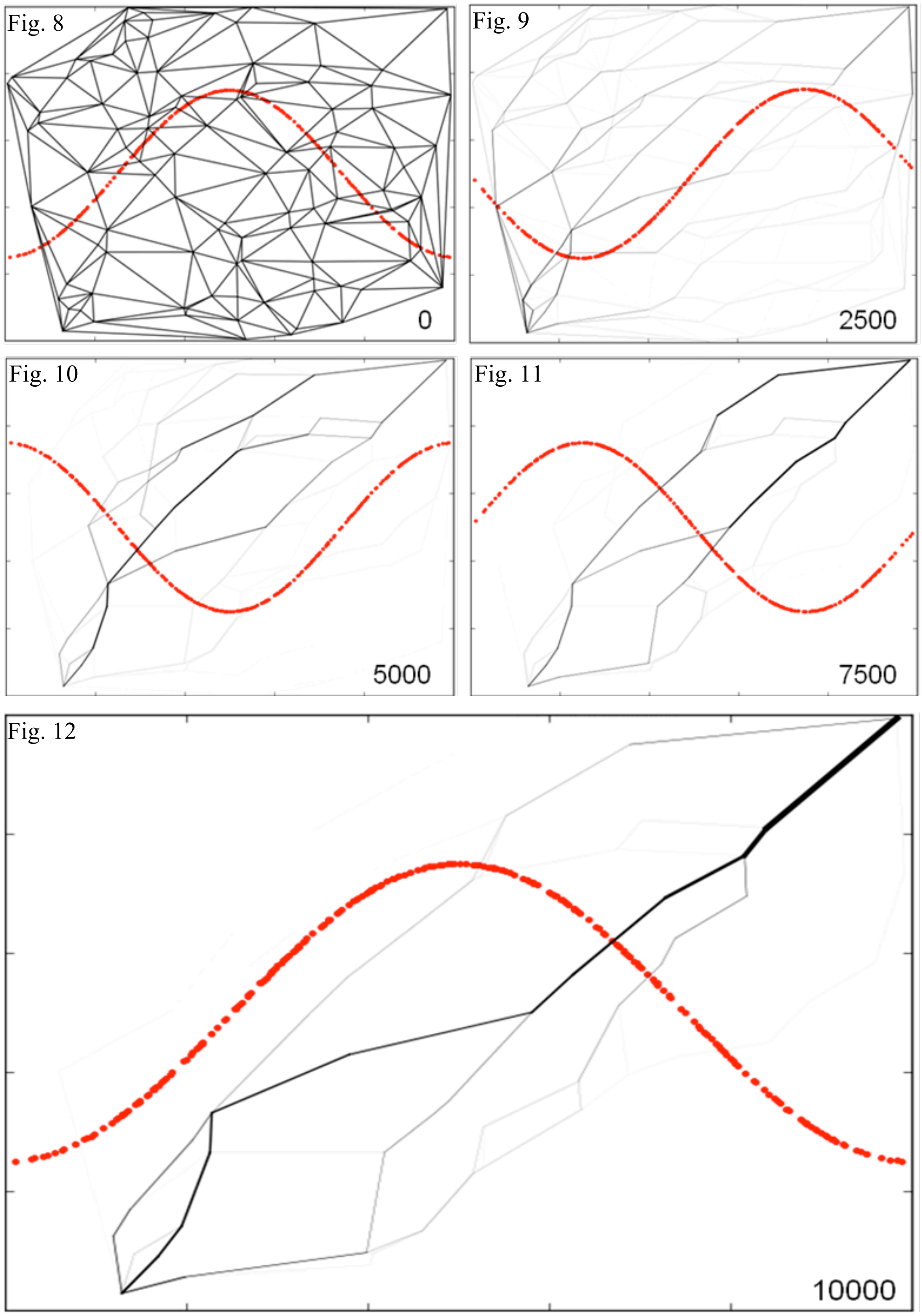


Figure 8-12: Shown above are outputs of the computer program that models the adaptive behavior of *Physarum polycephalum*. The sinusoidal curve shown above indicates the relative level of risk at each horizontal position at the given time. Each plot consists of 100 nodes with food sources in the lower left and upper right corners, and the update functions have been iterated 0, 2500, 5000, 7500, or 10000 times as indicated. In this time-dependent environment, it is expected that there will not be one optimal path as the conditions are changing at a speed comparable to the rate of adaptation.

Discussion:

The computer program presented in this study accurately simulates the adaptive behavior of *Physarum polycephalum* in time-dependent environments. Each simulation begins with a random mesh of veins and adapts until a network that demonstrates a balance between minimum distance and minimum risk is formed. Previous path-finding algorithms were written to optimize networks in static environments and do not provide a realistic model of the adaption process. This study's computation, however, is consistent with the principles of fluid dynamics that give rise to the evolution of the tube network and, as a result, is able to realistically simulate the organism's growth-process. As with any method of optimization, it is necessary to analyze not only the product, but also the process of the organism's adaptation. Understanding how *Physarum polycephalum* modifies its venation will provide a better understanding of the adaptation process.

Because the growth of *Physarum polycephalum* is greatly influenced by even slight changes in the organism's environment, it is important that this study is time-dependent and applicable to dynamic environments. This program allows conditions to change and demonstrates how the organism acts in response. Time-dependence provides not only more realistic simulations, but also enhances the potential applications of the organism's optimized network. Many of the complex networks that *Physarum polycephalum* can navigate are constantly changing, and a computer program simulating the necessary venation adaptations must be able to handle dynamic environments. For example, in the case of traffic flow, an accident may suddenly cause traffic on a certain road to slow or stop altogether. This situation could be implemented in a time-dependent program by elevating the level of risk in that particular area and allowing the network to adapt to the change. The computer program presented here provides a more complete understanding of the capabilities of *Physarum polycephalum* and can help to expand the uses of its optimized networks in engineered systems.

Conclusion and Future Work:

The computer program presented in this study provides a realistic simulation of the growth-process of *Physarum polycephalum* and allows for the implementation of dynamic environments. Because it maintains consistency with fluid dynamics, the program allows users to observe the gradual changes made throughout the adaptation process. In addition, dynamic environments (e.g. environments in which risk changes in degree and distribution) can be implemented, and the organism's simulated reaction can be observed.

Continued research includes growing and photographing samples of *Physarum polycephalum* in controlled environments and implementing various distributions of risk. The networks formed by the organisms will then be compared to those produced by the computer program in order to further ensure that the simulation produces realistic results. In addition, the computer program will be modified in an attempt to increase overall efficiency. When possible, the program's "for loops" will be replaced with another method of iteration that is more efficient in Python™. Additional research should be conducted to assess whether other programming languages or computing platforms are better suited for these simulations.

This research not only allows us to progress in the study of *Physarum polycephalum*, but also provides inspiration for the field of dynamic network simulations as a whole. Recognizing the need for an explicitly time-dependent environmental variable was central to the development of this computer program, and the method used here can be utilized in the creation of other models of dynamic systems. These simulations will in turn allow scientists to analyze and, in the case of engineered structures, improve these complex structures. Man-made networks (e.g. utility distributions and public transportation) can then be adapted in order to meet varying demands or conditions based on the results of similar simulations. As the potential applications of computer simulations continue to grow in number and significance, understanding how to model dynamic systems in a realistic manner becomes increasingly important. This study is therefore valuable beyond its application to *Phyasarum polycephalum* as it is a significant contribution to the development of other time-dependent computer simulations.

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