EXPLORE-AND-FUSE: A *PHYSARUM*-INSPIRED APPROACH TO THE STEINER TREE PROBLEM

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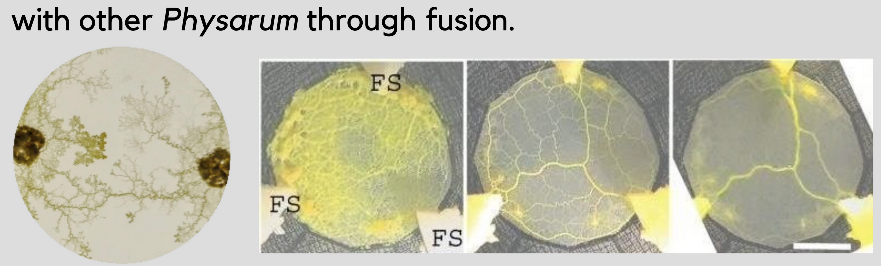
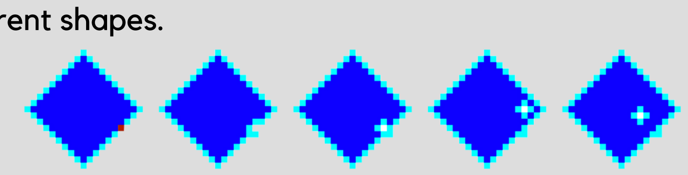
Explore-and-fuse is a novel approach to difficult problems. This approach is inspired by the intelligent slime mold *Physarum Polycephalum* which can form Steiner trees, solve the traveling salesmen problem, and share information by fusing with other Physarum organisms. Explore-and-fuse uses many *Physarum* organisms that gather information in parallel before sharing information through fusion. We demonstrate the explore-and-fuse approach on the NP-hard Steiner tree problem, creating the *Physarum* Steiner Algorithm. We then use the *Physarum* Steiner Algorithm to generate road networks, layout fiber optic cabling in neighborhoods, design VLSI chips, and find Steiner trees on topological surfaces.

01 BACKGROUND

Physarum Polycephalum is a unicellular neon green slime mold. It has the ability to solve mazes, form Steiner trees, solve the traveling salesmen problem, and share information with other *Physarum* through fusion.



The cell model is a cellular automata model of *Physarum*. *Physarum* is modeled on a grid where every square is in one of three states: outside (not part of cell), cytoskeleton (boundary of cell), and cytoplasm. At every iteration of the model, a bubble, or piece of the outside, is introduced into the organism. The bubble swaps with adjacent squares of cytoplasm or cytoskeleton, moving through the cell. By repeatedly introducing bubbles and swapping squares of cytoplasm, the cell begins to move as a whole and take on different shapes.

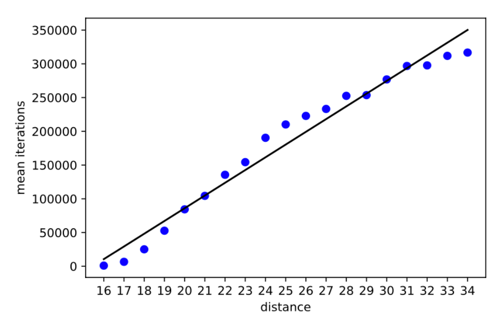


The Steiner tree problem essentially finds the minimal-length tree connecting a set of points. A real life example is to find the shortest road network needed to connect a set of cities.

02 MULTIPLE *PHYSARUM* MODEL

The Multiple *Physarum* Model simulates the fusion of multiple *Physarum* and therefore forms the basis for the explore-and-fuse approach. An example of the model is shown in the below image, where we initially spawn two diamond-shaped cells of equal size. We see the cells slowly fuse and mix cytoplasm until they are essentially one cell.

We validate this model against expected biological observations: (1) the further apart cells are, the longer it takes for them to merge, (2) the closer together cells are, the more likely they are to merge together, (3) the smaller cells are, the more mobile they should be, and (4) the smaller cells are, the better their cytoplasm mixing should be when fusing.



To validate (1), we run a series of experiments varying the distance between the two cells. We find a positive linear relationship between the distance and iterations.

We conduct similar experiments to validate (2), (3). and (4). We thus conclude that for our purposes, the Multiple *Physarum* Model accurately models interactions between cells.

03 EXPLORE-AND-FUSE

We next utilize the Multiple *Physarum* Model to create the explore-and-fuse approach. Considering *Physarum*'s skill at solving the traveling salesmen and Steiner tree problems plus its ability to share knowledge through fusion, *Physarum* is the perfect organism for explore-and-fuse. Multiple *Physarum* organisms can independently explore, quickly gaining local knowledge, and then this information can be shared via fusion, allowing for global optimization. This method of parallel exploration fusing into global optimization strikes a balance between speed and optimality.

The first step of this approach is to spawn multiple *Physarum*. Each organism then independently explores, partially solving portions of the problem. Organisms also come into contact with each other and fuse, beginning to share knowledge and combine partial solutions. Eventually, all the *Physarum* fuse into one large organism that has global knowledge. This organism can then fully solve the problem, taking into account all the local knowledge previously gathered.

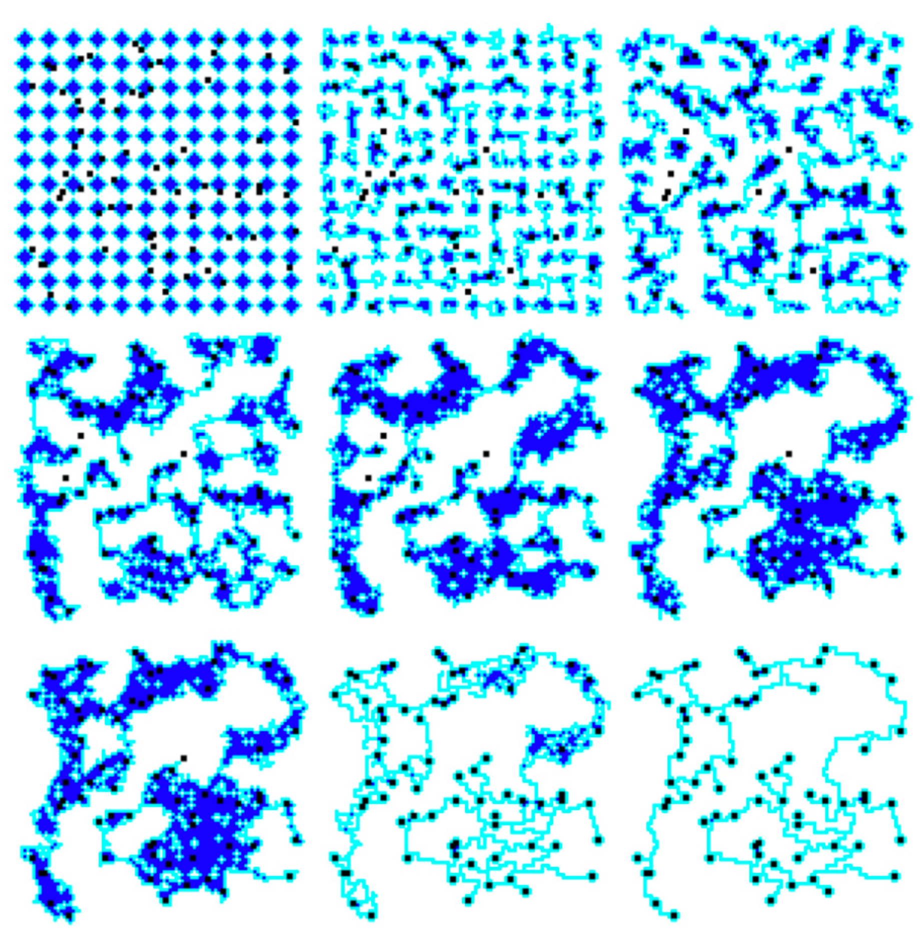
The explore-and-fuse approach can be seen as a less rigid form of divide-and-conquer. We believe that it can be applied to various NP-hard problems such as the Steiner tree problem or traveling salesmen problem, and can inspire other ways to soften divide-and-conquer.

04 *PHYSARUM* STEINER ALGORITHM

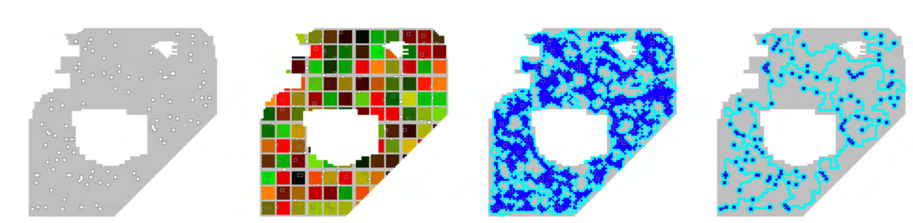
Using the explore-and-fuse approach, we create the *Physarum* Steiner Algorithm, which uses the Multiple *Physarum* Model to generate approximate solutions to the Euclidean Steiner tree problem.

The *Physarum* Steiner Algorithm consists of two phases: foraging and shrinking. We represent the points we want to find a tree between as 2x2 black squares. After spawning cells, the algorithm begins in the foraging phase. The purpose of the foraging phase is for individual organisms to gain intelligence and fuse. The foraging phase ends when all cells fuse into one large organism that is in contact with all points. At this point, the shrinking phase begins. Cytoplasm is removed as the cell finds the minimal tree.

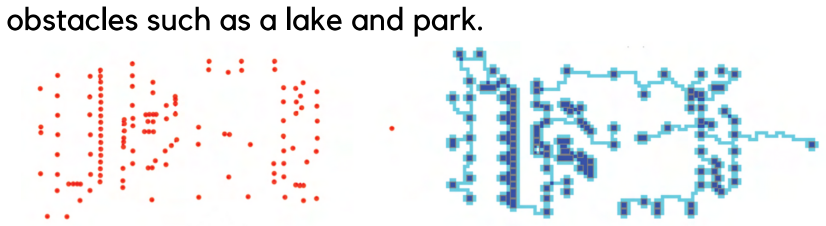
We conduct an empirical analysis of the time complexity of this algorithm, which suggests that this algorithm will scale well to large scale problems. We also consider the effect of parameters such as cell shape and number on the algorithm. We find that square cells are faster, while diamond-shaped cells produce better solutions. In addition, we find that using more cells allows us to explore bigger search areas, find shorter solutions, and solve problems faster.



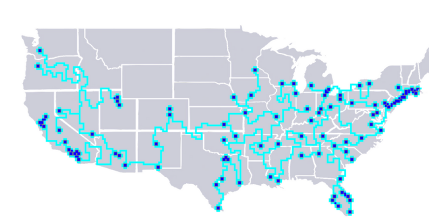
05 APPLICATIONS



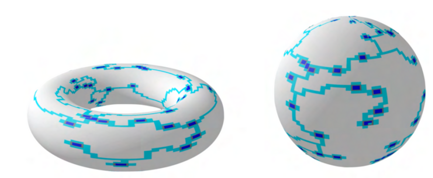
Route fiber optic cable to connect households while avoiding obstacles such as a lake and park.



VLSI (very large scale integration) chips design is one of the largest real-world applications for the Steiner Tree. Here, we route connections between 131 pads on an electronic board.



A road network among large cities in the USA.



Find Steiner trees on topological surfaces.

06 CONCLUSION

We present a novel explore-and-fuse approach to solving difficult problems that cannot be solved by traditional divide-and-conquer. Explore-and-fuse can be seen as a less rigid form of divide-and-conquer that can better handle problems that cannot be decomposed into independent subproblems.

We demonstrate the explore-and-fuse approach by creating the *Physarum* Steiner Algorithm. This algorithm has the ability to incrementally find Steiner trees. The first solution tends to contain many loops that are removed with additional iterations of the algorithm. This incremental improvement is particularly useful for applications such as road and cable networks where some degree of redundancy in the connectivity is desired. The algorithm operates on a rectilinear grid and is particularly applicable to rectilinear Steiner tree problems such as those that often arise in VLSI design. In addition, the algorithm performs well on the obstacle-avoidance Euclidean Steiner tree problem.

We look forward to seeing the explore-and-fuse approach applied to other difficult problems such as the traveling salesmen problem and hope it inspires future study on ways to soften divide-and-conquer.