Monte Carlo Physarum Machine:
An Agent-based Model for Reconstructing Complex 3D Transport Networks

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Abstract
We introduce Monte Carlo Physarum Machine: a dynamic computational model designed for reconstructing complex transport networks. MCPM extends existing work on agent-based modeling of Physarum polycephalum with a probabilistic formulation, making it suitable for 3D reconstruction and visualization problems. Our motivation is estimating the distribution of the intergalactic medium—the cosmic web, which has so far eluded full spatial mapping. MCPM proves capable of this task, opening up a way towards answering a number of open astrophysical and cosmological questions.

Problem Background
Physarum polycephalum (Guttes et al., 1961), a type of slime mold, has been used as an unconventional ‘biological computer’ to solve problems like maze navigation (Nakagaki et al., 2000), shortest path finding (Nakagaki et al., 2001), transportation system design (Tero et al., 2010) and the travelling salesman problem (Jones and Adamatzky, 2014), among numerous others (Adamatzky, 2010, 2016). Such works leverage the organism’s propensity to systematically explore its environment for food and grow intricate yet natural networks (Whiting et al., 2016; Sun, 2017).

To overcome the limitations of cultivating the actual organism (slow growth and small input sizes), computational models of Physarum polycephalum—“virtual Physarum machines”—have been developed in different domains (Jones, 2010, 2015; Kalogeiton et al., 2015; Dourvas et al., 2019; Schumann and Pancerz, 2016). These methods mimic the organism’s foraging behavior, and adapt it to application-specific needs. Food sources act as proxies for input data, and different chemical and physical stimuli are available as tunable devices that steer Physarum’s simulated growth.

This work introduces the Monte Carlo Physarum Machine (MCPM) model, developed in the astronomical context for a particular task: to reconstruct the largest identified structure in the Universe, the cosmic web. Composed mainly of hot gas and plasma, this quasi-fractal megastructure (Scrimgeour et al., 2012) is theorized (Fukugita et al., 1998) to contain a significant portion of Universe’s matter. Although widely predicted by large-scale cosmological simulations (Springel et al., 2005; Schaye et al., 2014; Klypin et al., 2016), the cosmic web has largely eluded direct observation (Umehata et al., 2019). In the effort to reconstruct the cosmic web, we have been guided by the theoretical predictions given by astrophysics: that the combined attraction of gravity and expansion due to dark energy have shaped the universe into an immense unified network of galactic knots, gaseous filaments and empty voids (Zel’Dovich, 1970; Doroshkevich, 1970; Icke, 1973), underlined by a scaffolding of dark matter.

Relying on the model organism’s ability to approximate optimal transport networks over sparse inputs, we feed to MCPM galaxies and dark matter halos as 3D point attractors. MCPM agents navigate the input points to trace the most probable paths between them: the total aggregate of their trajectories then forms the candidate filamentary network. We capture these trajectories as a density field in 3D space (Figure 1), interpreting it as a proxy of the intergalactic gas and dark matter distribution, and as such providing us with an estimate for the cosmic web structure for further numerical analysis (Burchett et al., 2020; Simha et al., 2020).

Monte Carlo Physarum Machine
The MCPM model generalizes the seminal method of Jones (2010). We chose Jones’s model due to its easy parallelizability and potential to construct precise trajectories out of sparse data. We expand this work in multiple aspects:
MCPM has a **discrete** and a **continuous** component. The discrete component is an ensemble of particle-like agents that can freely navigate the simulation domain, representing individual cells/nuclei of the virtual organism. The continuous component is a 3D scalar lattice that represents a concentration of a marker deposit field, which is emitted by the data, and optionally by the agents as well. The resulting model’s behavior is a feedback loop between these two components, executed in two alternating steps – we denote these as **propagation** and **relaxation**.

(1) **The propagation step** is executed in parallel for each of the agents, which are the model’s device for exploring the simulation domain. Each agent’s state is represented by a position and velocity, which are updated to navigate through the deposit field by three probabilistic alternating steps: **sensing**, **branching** and **movement**. The deposit effectively guides the agents towards the data: the agents move with higher likelihood to the regions where deposit values are greater. Successive propagation steps build up the agents’ trajectories (‘random walks’), which follow the structure of the deposit field, and are recorded in the trace field by temporal averaging.

(2) **The relaxation step** ensures that the simulation eventually reaches an equilibrium. Here, the deposit field is spatially diffused by a small isotropic kernel, and attenuated. The trace field is also attenuated but does not diffuse in order to preserve geometric features in the agents’ distribution, which the trace represents. The simulation reaches its equilibrium when the amount of deposit and trace injected into the respective fields in the propagation step equals the amount removed by the attenuation in the relaxation step; typically in 300–600 MCPM iterations.

**Application**

We have employed MCPM as a pattern finder to reconstruct the astronomical data, as well as a visualization platform. Implemented as a GPU based tool named Polyphorm (Elek et al., 2020), we are able to simulate and render 10–100M agents within $1024^3$ deposit and trace grids in interactive speeds, and obtain a fit in mere minutes. This approach has enabled the construction of a mapping between MCPM trace density and cosmic overdensity and a first successful detection of cosmic web structures through correlation with spectroscopic absorption measurements (Burchett et al., 2020), as well as quantitative analysis of a fast radio burst signal dispersion (Simha et al., 2020). In the future, we will continue this line of inquiry, and work towards improving the robustness and applicability of MCPM in different domains.
References


