Physarum Telam

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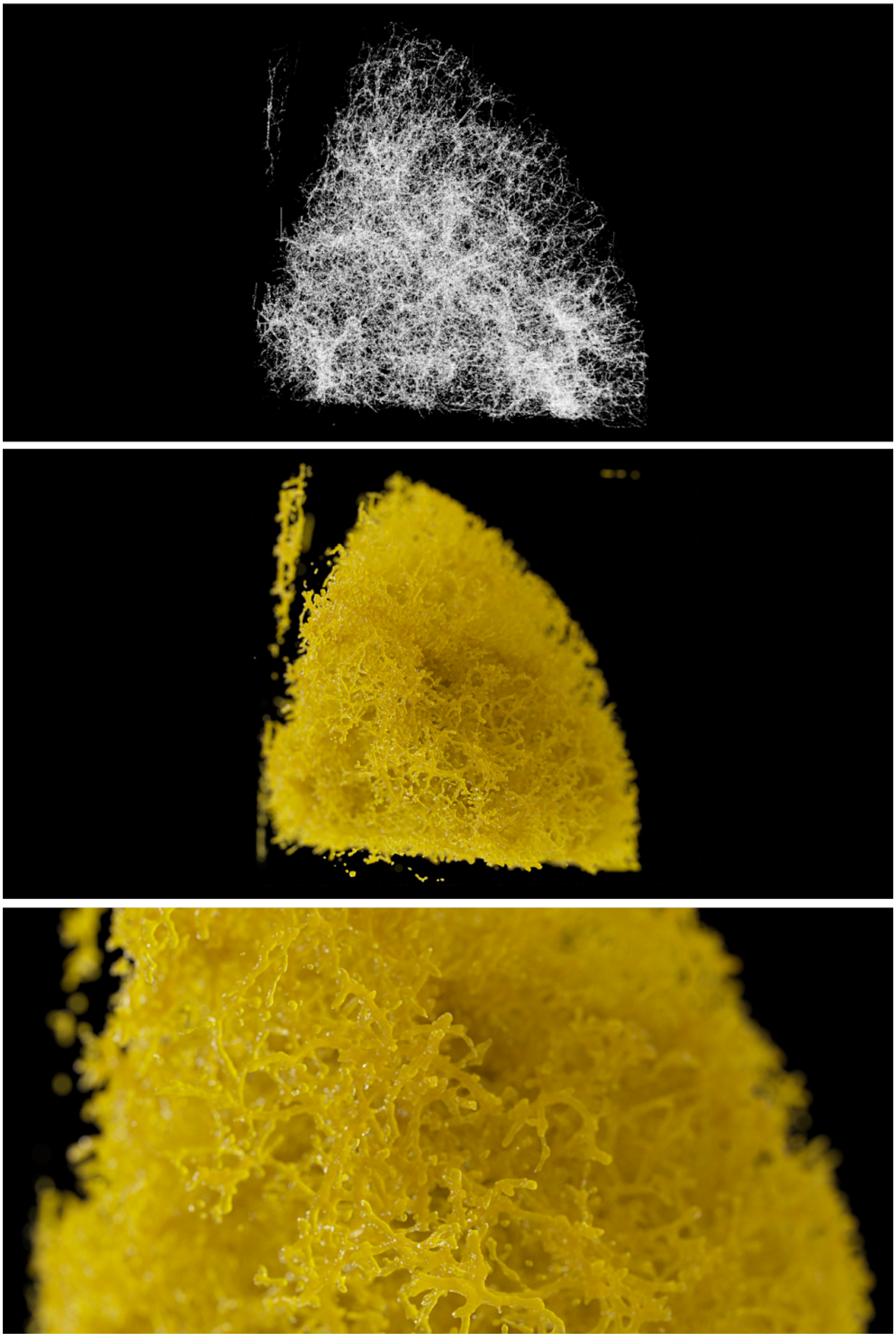
Draped over the galaxies inhabiting our Universe is a fabric-like structure called the Cosmic Web, in actuality composed of gas, plasma, and dark matter. The metaphor of fabric has been taken quite literally by some [Diemer and Facio 2017] and is fitting given the Cosmic Web's quasi-fractal features. Looking into the night sky we see no indication of this vast form; yet it is present in all directions. And despite its elusive nature, it forms a scaffold around the galaxies, functioning as a transport network of particulate material that feeds their star formation processes.

Physarum Telam is an interactive online installation reimagining our team's research project *Polyphorm*, which has been documented across several recent scientific works including cosmological modeling [Burchett et al. 2020, Simha et al. 2020] and interactive visualization [Elek et al. 2021, Zhou et al. 2020]. More details are provided in [Appendix: Data]. The core of *Polyphorm* is an agent-based simulation engine [Elek et al. 2020] inspired by the growth of Physarum polycephalum 'slime mold'. Through *Physarum Telam* we celebrate the slime mold, its awesome weirdness and inexplicable familiarity. For an undifferentiated yellow blob, it boasts remarkable skills – learning, adaptation, navigation – which has led to its experimental use as an analog wetlab computer [Adamatzky 2016] and inspired both physical [Barnett and collective] and digital artworks [Jenson and Kuksenok 2020]. But in spite of these outstanding abilities, it is Physarum's appearance that makes it instantly recognizable amongst earthly living forms. In order to reproduce its yellow slimy translucent exterior, we designed a custom physically based appearance model dubbed **Slimex**. This composite model consists of two components: (1) a glossy surface reflectance/transmittance model (BSDF) representing the organism's thin transparent membrane and (2) a volume scattering and absorption model representing the yellow-pigmented cytoplasmic fluid. **Slimex** is parametrized mainly by the scalar field dataset derived from the Cosmic Web estimate produced by *Polyphorm*, and therefore it visually represents its structure. We implemented **Slimex** in a custom GPU Monte Carlo path tracer – details are provided in [Appendix: Rendering]. The images produced by path-traced **Slimex** provide physically realistic depictions of Physarum, or rather, its imaginary 3D equivalent.

Physarum Telam takes the audience on a tour around the Cosmic Web data generated by *Polyphorm*. In this interactive online application [Appendix: Application Details] the observer can freely navigate and examine the data rendered with a standard 3D volume visualization technique called maximum intensity projection, or **MIP** in short. The style of **MIP** will be familiar to most, as it is commonly used in medical and scientific 3D visualizations. In addition to the dataset, the visualization also contains several spherical nodes functioning as portals: when clicked, the camera smoothly transitions to the respective node position, and switches to one of the images pre-rendered by **Slimex**. This novel view of the data reveals to the observer the true nature of its original inspiration: a humble yellow squishy blob with affinity for connecting, for bridging things. The observer can then select different perspectives within the given view, choose to be transported to another pre-rendered view, or continue examining the data in the interactive **MIP** style.

On the meta-level, *Physarum Telam* carries a message about representations of multi-dimensional and multi-modal data. Edward Tufte's data minimalism [Tufte 1992] is the de-facto standard philosophy of visualizing quantitative information, but unfortunately it does not directly apply to multi-dimensional data: there is no analog way of presenting such data – one always has to compress, or project, or reduce it somehow. The pragmatism of minimizing junk ink and maximizing data ink becomes hard to interpret when every single pixel on the screen carries 'data ink': multiple times over, in fact, due to the aforementioned need to project the data. The impact of this inevitable transformation is illustrated (and deliberately exaggerated) by the **Slimex** visualization style – which certainly adds a lot of unnecessary visual frills to the raw data. That, however, is only a distraction: even **MIP**, the most basic of volume visualization methods, already distorts the dataset by non-linearly projecting its entire columns onto the screen. And in the cases of higher-dimensional data, the corresponding transformations get even more convoluted and non-linear, as in the widely used methods UMAP and t-SNE. The fate of most scientific data is to never be seen in their true raw form, that is, *without reinterpretation*.



Interactive rendering of the Cosmic Web dataset using the **MIP** style in *Physarum Telam* (top), the corresponding render in the **Slimex** style (middle) and a macro shot (bottom).

References

Heather Barnett and collective. *The Physarum Experiments*, https://heatherbarnett.co.uk/work/the-physarum-experiments

Joseph N. Burchett, Oskar Elek, Nicolas Tejos, J. Xavier Prochaska, Todd M. Tripp, Rongmon Bordoloi, Angus G. Forbes. 2020. *Revealing the dark threads of the Cosmic Web*, The Astrophysical Journal Letters (891)

Benedikt Diemer and Isaac Facio. 2017. *The fabric of the universe: Exploring the Cosmic Web in 3D prints and woven textiles*, Publications of the Astronomical Society of the Pacific (129)

Oskar Elek, Joseph N. Burchett, J. Xavier Prochaska, Angus G. Forbes. 2020. *Monte Carlo Physarum Machine: An Agent-based Model for Reconstructing Complex 3D Transport Networks,* Proceedings of Artificial Life

Oskar Elek, Joseph N. Burchett, J. Xavier Prochaska, Angus G. Forbes. 2021. *Polyphorm: Structural analysis of cosmological datasets via interactive Physarum polycephalum visualization*, Transactions of Visualization and Computer Graphics (27)

Sage Jenson and Kit Kuksenok. 2020. *Exploratory modelling with speculative complex biological systems*, Proceedings of xCoAx

Matt Pharr, Wenzel Jakob, Greg Humphreys. 2016. *Physically based rendering: From theory to implementation*, Morgan Kaufmann, 3rd edition

Sunil Simha, Joseph N. Burchett, J. Xavier Prochaska, Jay S. Chittidi, Oskar Elek, Nicolas Tejos and collective. 2020. *Disentangling the Cosmic Web toward FRB 190608*, The Astrophysical Journal (901)

Klaus V. Wolf, Hans-Ulrich Hoffmann, and Wilhelm Stockem. 1981. *Studies on microplasmodia of Physarum polycephalum II: Fine structure and function of the mucous layer*, Protoplasma (107)

Henry Zhou, Oskar Elek, Pranav Anand, Angus G. Forbes. 2020. *Bio-inspired structure identification in language embeddings*, Proceedings of Visualization for the Digital Humanities

Appendix: Data

Physarum Telam builds on a dataset generated by our team's research project *Polyphorm* [https://github.com/CreativeCodingLab/Polyphorm] in the context of cosmological modeling. The core of *Polyphorm* is an agent-based simulation engine inspired by the growth of Physarum polycephalum 'slime mold', implemented as a parallel GPU program using C++ and HLSL compute shaders. The program's input is a set of weighted points in 3D space, usually counting between 10^3 and 10^6. Its output is a continuous network: a 3D scalar field $f(x,y,z) \in \mathbb{R}^+$ with an interconnected structure, representing the spatio-temporal density of the model agents' trajectories and spanning the input data points. Arguably the most significant finding about *Polyphorm* is that the produced density fields well correlate with the structure of the Cosmic Web [Burchett et al. 2020, Simha et al. 2020], suggesting similarities in their underlying theoretical descriptions.

In *Physarum Telam* the input dataset is a subset of the Sloan Digital Sky Survey (SDSS) catalog. It contains roughly 325 thousand galaxies within a relatively wide angular section of the sky, in distances between 0.14 and 1.37 billion light years from us. For each galaxy in the catalog, the salient parameters are its position in 3D space and mass. We applied a yet unpublished correction for the 'Fingers of God' effect, which compensates for known systematic bias in the galaxies' radial position. The resulting galaxy data are fed to *Polyphorm*, which produces an estimate of the Cosmic Web structure, represented as a 3D scalar density field $f(x,y,z) \in \mathbb{R}^+$. It is this density field that is visualized in *Physarum Telam* using the **MIP** and **Slimex** styles.

Appendix: Rendering

This section provides technical details on the rendering techniques behind *Physarum Telam*. We follow the nomenclature and conventions from established rendering literature, e.g. [Pharr 2016].

The interactive **MIP** visualization relies on the WebGL API implemented in the Javascript library Three.js [https://threejs.org]. The **MIP** algorithm visualizes the 3D Cosmic Web density field by casting and traversing a ray for each pixel and displaying the maximum density value found along each respective ray. By selecting one of the yellow nodes or 'portals', the camera is smoothly moved to its position, and the corresponding **Slimex** render is blended into view. In this view, the observer can switch between multiple renders of the same geometry but with different lighting and depth-of-field settings applied. By adding depth of field, we emphasize the small scales on which we normally find the organism in nature.

The **Slimex** appearance model is implemented in a custom GPU-based Monte Carlo path tracer, with HLSL compute shaders as GPU kernels and C++ for CPU integration. We use a perspective camera extended by a thin-lens model to simulate the variable depth of field. The surface of the Physarum 'body' is defined as an isosurface of the Cosmic Web density field, using an isovalue small enough to yield good separation of the 'tubes', but still large enough to result in a thoroughly interconnected structure. We use Fresnel's law to determine the probability of reflecting versus refracting on the surface, and Snell's law to calculate the refraction into the volume. For these sampling decisions, the surface normal is calculated as the density gradient at the sampled location. For the volumetric transport inside the tubes, delta-tracking is used to generate unbiased collision distances and importance sampling of the Henyey-Greenstein phase function to generate scattered directions. After 10 bounces of the path tracer (on surface or in volume) we apply Russian roulette with 50% termination probability, and continue tracing up to the maximum of 15 bounces. The result of these strategies is a physically plausible appearance model. Due to the complexity of the light transport under these conditions, it takes up to 10k paths per pixel for the solution to converge. This amounts to roughly 20-30 minutes per 1080p frame on an NVIDIA RTX 2070 Super.

The optical parametrization of the Physarum body uses the refractive index of 1.45, base optical thickness of 0.7 mm^{-1} (modulated by the density field inside the 'tubes'), RGB scattering albedo of (0.98, 0.9, 0) and scattering anisotropy of 0.85. We estimated these parameters from photographs of Physarum (in the plasmodium stage) and confirmed their plausibility with literature [Wolf et al. 1981]. The size of the entire dataset is 608 x 1080 x 600 mm, which is also the voxel resolution of the 3D field dataset. The lighting is a combination of a spherical 'key' light source with smooth radial falloff, and a weak ambient 'fill' light, both with spectrally neutral emission profiles.

We post-processed the resulting HDR renders using the Taichi library in Python [https://taichi.graphics] for GPU acceleration of all image-processing tasks. The retouching pipeline combines the gamma tone mapping, unsharp masking for edge enhancement, and gentle tone balancing to emphasize yellows and oranges.

Appendix: Application Details

Physarum Telam can be accessed through the following URL: http://isseim.com/physarum-telam
A high-resolution version is located at: http://isseim.com/physarum-telam/hi-res

The project requires an up-to-date web browser with support for WebGL 2.0 (tested in Chrome and Edge). Due to the size of the dataset which needs to be downloaded on startup (around 100MB), a decent internet connection is needed. Phones and other mobile systems are not fully supported at the moment.

To achieve optimal viewing experience, we recommend a discrete GPU (tested with NVidia RTX 2070, NVidia RTX 3070, and Mac M1). Integrated GPUs are supported (tested with Intel UHD Graphics 620) but might not provide a smooth navigation in the interactive **MIP** mode; downscaling the browser window will improve the rendering performance. If using Chrome, please make sure that the "Use hardware acceleration when available" option is enabled in Settings > Advanced > Systems. If your system has multiple GPUs, check whether the browser is using the best GPU available on the system (For NVIDIA GPUs and Chrome browser: NVIDIA Control Panel ->Manage 3D Settings -> Program Settings -> Select your default browser and set "High-Performance NVIDIA processor", instead of "Integrated Graphics". Now in Chrome, go to chrome://flags and set "Choose ANGLE graphics backend to OpenGL").