Democratizing Microscopy training through Digital Surrogates

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Abstract

Advanced microscopy is foundational to STEM education and materials research, yet student access to live, high-end instruments remains limited by cost, infrastructure, and scheduling constraints. Recent advances in AI-enabled microscopy analysis and digital surrogates demonstrate an opportunity to shift microscopy education from instrument-centric training toward data-centric, concept-driven learning.[1]

Building on recent work in data-driven microscopy and interpretable machine learning as well as our prior research linking structure–property relationships in porous materials[2], we present an educationally focused digital microscopy framework developed for the 2025 Microscopy Hackathon.[3] The framework enables students to analyze and predict microstructural evolution directly from microscopy datasets, without requiring continuous access to physical microscopes.

This study employed bulk CO_2 foam experimental data to develop a surrogate model that predicts the dynamic behavior of CO_2 bubbles across various experimental conditions. The model maps the inputs, including foam height, surfactant type, and nanoparticle concentration, to outputs that describe bubble characteristics. This approach offers significant potential for both scientific research and industry by enabling automated prediction of bubble evolution and relating bulk-scale behavior to the microscopic mechanisms. The pipeline is fully compatible with digital microscopy infrastructures using HDF5 (H5) formats and is instrument-agnostic, making it readily extendable across optical microscopy, AFM, SEM, and STEM. This work demonstrates how AI-driven digital surrogates can lower barriers to microscopy education, support experiential learning at scale, and enable equitable access to advanced scientific training.

[1] Utkarsh Pratiush *et al* 2025 *Mach. Learn.: Sci. Technol.* **6** 040701**DOI** 10.1088/2632-2153/ae1f5d

[2] S. Bonakala, A. Abutaha, P. Elumalai, A. Samara, S. Mansour, and F. El-Mellouhi, *ACS Omega* **7**, 46515–46523 (2022).

[3] https://kaliningroup.github.io/mic_hackathon_2/