Geometric generative AI for cosmology and beyond

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Project Outline

The current evolution of our Universe is dominated by the influence of dark energy and dark matter, which constitute 95% of its content. However, an understanding of the fundamental physics underlying the dark Universe remains critically lacking. Forthcoming experiments have the potential to revolutionalise our understanding of the dark Universe. Both the ESA Euclid satellite and the Rubin Observatory Legacy Survey of Space and Time (LSST) will come online imminently, with Euclid successfully launched in July 2023 and the Rubin LSST Observatory having recently achieved first light. Furthermore, the Simons Observatory is in advanced stages of construction. Sensitive statistical and deep learning techniques are required to extract cosmological information from weak observational signatures of dark energy and dark matter.

Deep learning has been remarkably successful in the interpretation of standard (Euclidean) data, such as 1D time series data, 2D image data, and 3D video or volumetric data, now exceeding human accuracy in many cases. However, standard deep learning techniques fail catastrophically when applied to data defined on other domains, such as data defined over networks, 3D objects, or other manifolds such as the sphere. This has given rise to the field of geometric deep learning (Bronstein et al. 2017, arXiv:1611.08097; Bronstein et al. 2021, arXiv:2104.13478).

In cosmology, wide field observations are made on the celestial sphere giving rise to spherical 360° data, such as observations of the cosmic microwave background (CMB) relic radiation from the Big Bang and observations of cosmic shear of galaxies, which can be used to better understand the nature of dark matter and dark energy. Upcoming experiments such as Euclid and Rubin Observatory LSST will capture wide-field data for which the underlying spherical geometry must be accurately modelled. Thus, geometric deep learning techniques constructed natively on the sphere will be essential for next-generation deep learning analyses to extract cosmological information from these upcoming datasets.

McEwen and collaborators have recently developed efficient generalised spherical convolutional neutral networks (Cobb et al. 2021, arXiv:2010.11661) and spherical scattering networks (McEwen et al. 2022, arXiv:2102.02828) that have shown exceptional performance. In a recent work they have developed the DISCO framework that is for the first time scalable to high resolution data (Ocampo et al. 2022, arXiv:2209.13603) opening up dense prediction tasks like cosmological imaging. The DISCO framework provides a saving in computation of 9 orders of magnitude and a saving in memory of 4 orders of magnitude. Moreover, it provides state-of-the-art accuracy in all benchmark problems considered to date. Furthermore, McEwen and collaborators have been developing generative geometric AI techniques based on differentiable spherical harmonic, wavelet and scattering transforms, with a number of papers to be submitted imminently.

The focus of the current project is two-fold. First, further foundations of geometric deep learning on the sphere will be developed, including new types of spherical deep learning layers and architectures, in order to address the open problems in the field, such as scalability, interpretability, and generative models. Second, geometric deep learning techniques on the sphere will be applied to the analysis of cosmological data of the CMB and of cosmic shear, in particular from Euclid and the Rubin Observatory, in order to better understand the nature of dark matter and dark energy. Furthermore, additional applications beyond cosmology, such as for diffusion MRI in medical imaging, may also be considered. The precise focus between these different areas will depend on the interests and expertise of the student.

The student should have a strong mathematical background and be proficient in coding, particularly in Python. The student will gain extensive expertise during the project in deep learning, going far beyond the straightforward application of existing deep learning techniques, instead focusing on novel foundational deep learning approaches and their application to novel problems in cosmology and beyond. The expertise gained in foundational deep learning will prepare the student well for a future career either in academia or industry. In particular, geometric deep learning is a speciality highly sought after in industry by companies such as Twitter, Facebook, Amazon and many others.