Transformers for Dark Matter Morphology with Strong Gravitational Lensing

Google Summer of Code 2023 Project Proposal

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Abstract

The study of dark matter substructures is a crucial part of astrophysics, and it can provide a deeper understanding of the universe. One way to study these substructures is through the analysis of strong gravitational lensing. Strong gravitational lenses can reveal important information about the distribution of dark matter and the structure of subhalos. However, identifying and analyzing strong lenses is a challenging task that requires advanced algorithms and tools. This project aims to address this challenge by incorporating the latest deep learning methods, particularly the transformer models, to improve the performance of DeepLense algorithms for classification and regression tasks. We will use strong lensing simulations based on lenstronomy to train the transformer models, which will then be applied to detect strong lenses from datasets of mock surveys. The results will be compared to the existing state-of-the-art models, and the best model will be integrated into the DeepLense pipeline for detection, classification, and interpretation of dark matter substructure.

Background

The quest to uncover the true-identity of dark matter has been a major focus of physicists for decades. The mystery surrounding dark matter persists to confound researchers despite significant advances in the field. However, a few contenders have come to light who might be able to provide the solution to this mystery. Weakly Interacting Massive Particles

(WIMPs) and dark matter condensate models, such as Bose-Einstein condensates and Bardeen-Copper-Schrieffer condensates (BCS), are some of these. We now have a rare opportunity to distinguish between several models of dark matter and learn more about its fundamental characteristics. These condensates contain vortices that can produce dark matter halo substructure components.

Gravitational Lensing, the bending of light caused by the gravitational force of massive objects in the universe, provides us with a powerful tool for studying the substructure of dark matter. Strong gravitational lensing has been used successfully in the past to explore and study substructures in dark matter, allowing us to distinguish between different sorts of substructures. We can continue to acquire insights into the properties and structure of dark matter and its substructures by developing and enhancing these techniques.

Motivation

The study of substructures in dark matter is a critical and challenging area of astrophysics. Strong Gravitational Lensing has shown immense potential in providing insights into the distribution of dark matter substructures such as subhalos. However, detecting and interpreting strong lenses from astronomical imaging data is a complex task that requires advanced algorithms and computational tools. Traditional Deep Learning algorithms can suffer from biases and noise in astronomical data, leading to false positives and missed detections. Therefore, there is a need for innovative approaches that can overcome these limitations and provide accurate detection and classification of strong lenses. This project aims to address these challenges by integrating state-of-the-art vision transformer models with DeepLense algorithms to augment the detection and classification of strong lenses in mock surveys. The implementation of advanced vision transformer architectures and training techniques in this project will provide a deeper understanding of the properties and structure of dark matter substructures and contribute to further research and analysis in this field.

Key Tasks

- Conducting a thorough literature survey on the latest vision transformer architectures and techniques.
- Developing a novel vision transformer model capable of identifying strong gravitational lenses with high accuracy.
- Training and testing the developed model on various datasets to evaluate its performance and improve its accuracy.

- Integrating the developed vision transformer model with the existing DeepLense pipeline to enhance its performance in detecting and classifying dark matter substructures.
- Analyzing and interpreting the results obtained from the vision transformer model and the DeepLense pipeline to gain insights into the substructure of dark matter.
- Documenting all implementation steps, experimental results, and analysis in detail to provide a clear and comprehensive guide for future reference and potential improvements.

Proposed Program Timeline

- ***May 4 - May 28 (Community Bonding Period)***
    - Focus on getting to know the DeepLense community and their goals for the project.
    - Join relevant communication channels and attend community meetings to introduce myself and learn more about the project's goals and objectives.
    - Spend time familiarizing myself with the project's codebase, setting up the development environment, and going through the existing documentation to gain a better understanding of the current state of the project.
    - Study the latest research papers and articles on vision transformers and their application in computer vision.
    - Additionally, I will use this time to discuss with my mentor and other community members about the project's technical details and seek feedback on my proposed approach.

- ***May 29 - July 14 (First Half)***

  By the end of first half, I plan to complete the following tasks:

    - Conduct a literature survey on the application of vision transformers in computer vision tasks and their potential application in astrophysics.
    - Familiarize myself with the DeepLense pipeline and lenstronomy library to understand the process of strong gravitational lensing simulations.
    - Preprocess the simulated datasets and implement a general data loader class that can be used to load the data in a suitable format for the neural networks.
    - Develop and implement vision transformer models that can accurately identify images containing strong gravitational lenses from the simulated datasets.

- Train and evaluate the developed models on various datasets to optimize their performance and improve their accuracy.
- Integrate the developed models with the rest of the DeepLense pipeline for detection, classification, and interpretation of dark matter substructure.
- Document all implementation steps, results, and analysis in detail to provide clear and concise information for future reference and potential improvements. Additionally, establish a version control system to track the progress of the project and ensure that the code is properly documented.

- ***July 14 - August 28 (Second Half)***

  By the end of second half, I plan to complete the following tasks:

  - Developing and refining the code for training and testing the selected vision transformer architectures, while ensuring that they meet the necessary performance metrics and accuracy requirements.
  - Experimenting with various hyperparameters and training setups to optimize the performance of the model and comparing the results with existing state-of-the-art architectures.
  - Ensuring that the developed architecture is fully compatible with the DeepLense pipeline, and integrating it into the pipeline seamlessly to expand its functionality and capabilities.
  - Creating comprehensive tutorial notebooks and scripts to guide users on how to use the developed code and architecture effectively.
  - Documenting the entire project in detail for future reference and potential integration with other projects.

- ***Post-Program Plans and Contribution to the Community***

  I intend to keep collaborating with the DeepLense community after the program is over to ensure that our developed models are successfully integrated into the pipeline. This would entail resolving any possible problems that emerge during implementation and improving the models in response to user feedback. In order to make the models more available to academics working in the field, I also want to investigate the viability of deploying them on cloud infrastructure. Lastly, I will try to publish the project's findings in a pertinent conference or journal in order to share our findings to a larger audience and promote more study in this field.

Deliverables

- A set of state-of-the-art trained vision transformer models for detecting gravitational lenses that will surpass existing models in terms of accuracy and computational efficiency..
- Comprehensive documentation of the models, including detailed descriptions of the novel architectures, hyperparameters, data preprocessing and post-processing steps employed, and any potential shortcomings or limitations.
- Analysis of the performance of the models on a range of test datasets, including both quantitative measures (e.g. precision, recall, F1 score) and qualitative assessments of their ability to correctly identify gravitational lenses. Furthermore, a qualitative assessment of the models' ability to accurately detect gravitational lenses in astronomical data will be presented.
- A set of tutorial notebooks and scripts, along with clear and detailed instructions for using the models with the DeepLense pipeline, and guidelines for fine-tuning or training new models on other datasets.
- A report summarizing the key findings of the project, including insights gained into the strengths and limitations of current gravitational lens detection methods and a discussion of the potential impact of our proposed vision transformer models. This report will also include future research directions and recommendations for improving the models' performance.

References

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- Alexander, Stephon, Sergei Gleyzer, Evan McDonough, Michael W. Toomey, and Emanuele Usai. "Deep learning the morphology of dark matter substructure." *The Astrophysical Journal* 893, no. 1 (2020): 15.
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My Background

As a 3rd Year CSE Undergraduate student at NIT Silchar, Assam, India, I have a good experience in machine learning and deep learning, having worked in this field since my first year of college. I am always looking forward to enhancing my skills and have undertaken several projects in this field. Some of my notable achievements and experiences include:

- Currently working as an AI Research Intern at **Artificial Intelligence Institute at University of South Carolina (AIISC)**, under **Prof. (Dr.) Amitava Das**. Here I am working on improving **Language models** by focusing on the linguistic understanding aspect of the models. Developed a novel language model which enhances traditional distributional models by incorporating more linguistic information to the model to understand the syntactic structures of language. I am currently preparing a **research paper** for publication in a peer-reviewed journal.
- Completed a research internship at the **Machine Intelligence and Bio-Motion Research Lab** under **Dr. Anup Nandy, Assistant Professor, Computer Science and Engineering, NIT-R.** During this internship, I explored 3D Human Gesture Data captured by kinect, extracted features, and developed a high-performing model for **Human Gesture Recognition**.
- Won the **Best Project Award** from the East Zone in Anveshan 2022 - Student Research Convention for my project on **Segmentation of Roads from Satellite Images**.
- **Ranked 2nd in Data Strata** - Annual Data Science Hackathon Nit Silchar.
- An active Moderator of the **Machine Learning Club of NIT Silchar**, where I conducted Machine Learning Classes, took a few workshops, and helped the club grow.

Working as a Research intern has given me first hand experience of working in the field of Machine Learning and Deep Learning. I have acquired the experience of what it's like working under a mentor and developed new skills, be it both technical and soft. During the internship I have read many research papers and successfully implemented those architectures and techniques, which eventually helped me to improve my deep learning skills.

Here is a link to my CV - Krishnav_CV.pdf