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Equivariant Neural Networks for Dark Matter Morphology with Strong Gravitational Lensing

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ABSTRACT

When the light emitted by galaxies/stars or other celestial objects passes through other massive objects, it is bent (distorted) due to the gravitational pull of these bodies. This phenomenon is termed gravitational lensing. Strong gravitational lensing offers a way for astronomers to study the substructure and distribution of dark matter in these galaxies. Deep learning models have the potential to aid astronomers in this pursuit by accurately identifying images containing substructure, and helping differentiate WIMP particle dark matter from other well-motivated models, including vortex substructure of dark matter condensates and superfluids.

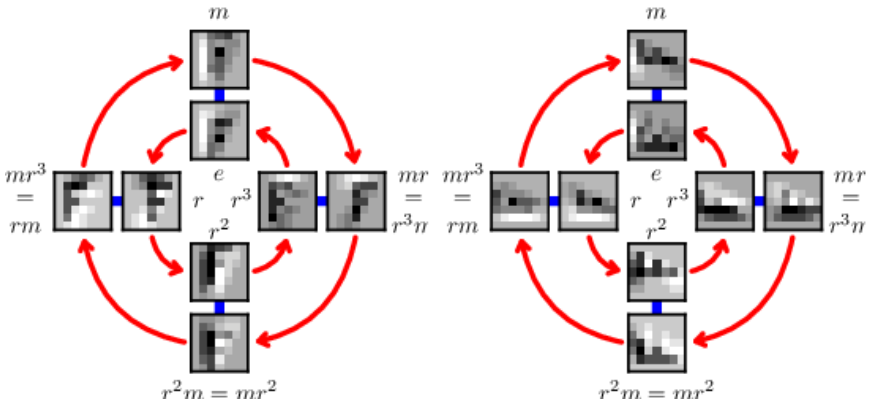
The DeepLense pipeline combines state-of-the-art deep learning models with strong lensing simulations initially based on PyAutoLens for strong gravitational lens modeling. This project aims to **enhance this pipeline using equivariant neural networks** for stable training of DeepLense simulation models.

INTRODUCTION AND GOALS

A function f is equivariant if when its input x is transformed by a symmetry group g, the output is transformed by the same symmetry,

$$f(g \cdot x) = g \cdot f(x)$$

The main aim of equivariance in neural networks is the preservation of symmetry in the system. As the size of datasets increases, it becomes increasingly difficult to process such a large amount of information. This is where equivariance comes in. Earlier studies have shown that equivariant CNNs can yield state-of-the-art results on classification tasks, even when they only enforce equivariance to small groups of transformations.



A p4 feature map with rotation r

Source: *Group Equivariant Convolutional Networks*, T. Cohen, M. Welling, ICML 2016

The sole and primary goal of this project is to **expand the DeepLense functionality with equivariant neural networks** suitable for computer vision tasks applicable to DeepLense data. This would enable the model predictions to get better by harnessing the superior abilities of equivariant neural networks over non-variant neural networks.

One of the examples of equivariant neural networks is E(2)-Equivariant Steerable CNNs, which can be implemented with the help of the **e2cnn** library in Python. In contrast to conventional CNNs, E(2)-equivariant models are more data-efficient since they unify and generalize a wide range of isometry equivariant CNNs in one single framework. I would be trying to implement these as well.

PROJECT TIMELINE

Before May 17, 2021

During this period, I'll be focussing on the mathematical and physics background of the project. Gravitational lensing is an exciting field of research and I believe that understanding it more deeply will certainly help me to contribute better to the DeepLense pipeline. I will also be honing my skills by building some small projects with the help of neural network models and deep learning frameworks.

May 17, 2021 - June 7, 2021 (Community Bonding Period)

- I would be using this period to bond with the ML4SCI community.
- I will further finalize the ideas regarding the project by corresponding with the mentors as well as the members of the community.

(Official Coding Period starts)

Week 1-3: June 7, 2021 - June 28, 2021

I have compiled a list of papers that I would be studying during this period.

- **Steerable CNNs**, *Taco S. Cohen, Max Welling* - https://arxiv.org/abs/1612.08498
- **E(n) Equivariant Graph Neural Networks**, *Victor Garcia Satorras, Emiel Hoogeboom, Max Welling* - https://arxiv.org/abs/2102.09844v1
- **Incorporating Symmetry into Deep Dynamics Models for Improved Generalization**, Rui Wang, Robin Walters, Rose Yu - https://arxiv.org/abs/2002.03061
- **Rotation-equivariant convolutional neural network ensembles in image processing**, *Liyao Gao, Hongshan Li, Zheying Lu, Guang Lin* - https://www.researchgate.net/publication/335767380_Rotation-equivariant_convolutional_neural_network_ensembles_in_image_processing

- **RED-NN: Rotation-Equivariant Deep Neural Network for Classification and Prediction of Rotation**, *Rosemberg Salas, Petr Dokládal, Eva Dokladalova* - https://hal.archives-ouvertes.fr/hal-02170933
- **Equivariant neural networks and equivarification**, *Erkao Bao, Linqi Song* - https://arxiv.org/abs/1906.07172

I will try to implement 2 or 3 of these procedures during this period of 3 weeks. This also includes learning the e2cnn which is a PyTorch extension used for equivariant deep learning and complements some of the papers listed above.

Week 4: June 28, 2021 - July 5, 2021

This week would involve the pre-processing of DeepLense model simulation data so that it can be fed to our equivariant neural networks. This will involve resizing, rotating, restructuring the images as per the equivariant NN needs.

Week 5: July 5, 2021 - July 12, 2021

I would start training the selected models with the data.

PHASE 1 EVALUATIONS (July 12, 2021 - July 16, 2021)

Week 5 will mark the end of the first phase of GSoC period. By then, it is expected that the equivariant neural network model would be ready, and being trained on the pre-processed data.

Week 6: July 12, 2021 - July 19, 2021

Listing down of issues that might have been encountered till now and will try to resolve them. Will continue with the training of the models.

Week 7: July 19, 2021 - July 26, 2021

By now, the models would’ve been trained well. This stage will mainly involve the integration of the Equivariant Neural Network with the rest of the DeepLense pipeline.

Week 8: July 26, 2021 - August 3, 2021

Intensive testing of the model and resolving any of the bugs or errors which might have been encountered earlier. Begin working on the documentation of the approach.

Week 9: August 3, 2021 - August 10, 2021

Buffer week for any of the tasks which were not completed within the specified timeframe. Taking feedback from the ML4SCI community as well. This week I would start working on the final project report as well.

Week 10: August 10, 2021 - August 16, 2021

Resolving any remaining bugs and submitting the report to mentors for evaluation.

FINAL EVALUATIONS (August 16, 2021 - August 23, 2021)

This would mark the end of the GSoC period. I expect all work would have been completed by this time. I will be providing the performance evaluations to the mentor. I will be in constant touch with my mentor and will be contributing to the project if anything remains.

PERSONAL INFORMATION

- **Name** : Dhruv Rawat
- **Residence** : Noida, Uttar Pradesh, India
- **Major** : Economics and Computer Science
- **University** : Birla Institute of Technology and Science, Pilani
- **Timezone** : Indian Standard Time (UTC +5:30)
- **GitHub** : thedhruvrawat
- **LinkedIn** : thedhruvrawat
- **CV** : [link]

MOTIVATION

I have been working with Machine learning models and frameworks for the past year and have been building projects and honing my skills in the same. This project would give me an opportunity to apply these skills in something which not only is exciting but is an extremely vast area of research and opportunity.

I worked hard to learn a new Python library - PyAutolens in a short span of time and I believe it was a greatly enriching learning experience. Implementing PyTorch and calculating ROC and AOC was also something that I learned while doing this.

WORKING INFORMATION AND SCHEDULE

I'll be mostly working full-time on the code during the summer. Except for my university's Practice School program, I have no other indulgence during this period. My awake hours would usually be between 10 AM IST (4:30 AM UTC) to 1 AM IST (7:30 PM UTC) and I'm comfortable working anytime during this period. Since most of the educational institutions in the country are closed, I'll be having no other absences. Anyhow, in cases of emergency, I'll responsibly notify my mentor of the same with enough detailing.

COMMUNICATION

I'm very flexible with my schedule and already have the habit of working at night and hence any kind of timezone variation (with mentors) won't be an issue. I'm comfortable with any form of communication that suits my mentor. Below are the various options available:

- Email : dhruv.noida175@gmail.com, f20190537@pilani.bits-pilani.ac.in
- Phone (Call/WhatsApp) : (+91) 9810178170

REFERENCES

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5. **Naturally Occurring Equivariance in Neural Networks**, Chris Olah, Nick Cammarata, Chelsea Voss, Ludwig Schubert, Gabriel Goh - https://distill.pub/2020/circuits/equivariance/