

Generative Adversarial Networks for Galaxy Classification Using Convolutional Neural Networks

Polina Petrova

ppetrova@umass.edu

Aryan Singh

arysingh@umass.edu

Abstract

The classification of galaxies poses significant challenges due to inherent data imbalances among various morphological classes. This research addresses the pressing issue of accurately classifying galaxies using Convolutional Neural Networks (CNNs), where traditional approaches often struggle with underrepresented categories. To mitigate this problem, we propose a novel combined model utilising a Conditional Generative Adversarial Network (*cGAN*) to generate synthetic images that augment the Galaxy Zoo 2 dataset, which contains approximately 270,000 labelled galaxy images. Our methodology begins with enhancing image resolution using Super Resolution GANs (SRGAN), followed by training the *cGAN* to produce additional samples for each class, thereby addressing class imbalance without resorting to deeper networks. We draw on foundational works, including studies on deep generative models for galaxy image simulations and prior CNN applications in galaxy classification, to inform our approach. Our model's performance will be rigorously evaluated, comparing results from training on both real and synthetic data against traditional CNNs trained on the original dataset. Through this work, we aim to contribute to the ongoing efforts to improve automated galaxy classification and provide a scalable solution to the prevalent issue of data imbalance in astronomical research.

1. Introduction

With rapid development in technology comes a phenomenon that is referred to as the *data deluge*, – a consequence of an overwhelming influx of data and insufficient resources to process it. Astronomers, in particular, contend with this challenge; estimates suggest the observable universe holds between 100 billion and 200 billion galaxies [3]. A single photograph of a small sky section can capture up to 25,000 galaxies, and the resulting daily data volume overwhelms the limited pool of experts available to classify them [9]. To address this challenge, astrophysicists launched the *Galaxy Zoo* project in 2007, inviting citizen

scientists to help classify over 900,000 galaxies, marking a transformative moment in data processing through public participation [8].

Following the success of the *Galaxy Zoo*, advancements in machine learning spurred efforts to automate galaxy classification. Modern approaches employ Convolutional Neural Networks (CNNs) to recognise patterns with minimal human input. However, a persistent challenge is the quality and distribution of available data. While the *Galaxy Zoo* project provided a substantial dataset, imbalances in class representation can skew training, causing models to favour more frequent classes. Our research specifically addresses this class imbalance in the Galaxy Zoo 2 dataset – a collection of categorised images taken from the Sloan Digital Sky Survey (SDSS) – where certain galaxy types are underrepresented. Building deeper networks is a common workaround to address this issue, but we argue that this approach only sidesteps the core problem.

Ideally, a large, balanced dataset would improve model accuracy, but limitations in space imaging and classification complexity make this difficult. To tackle this, we propose a novel solution using Generative Adversarial Networks (GANs) to generate synthetic images for underrepresented galaxy classes in the Galaxy Zoo 2 dataset, which we then use to train a CNN. We expect that by augmenting our data with synthetic images, we can improve classification accuracy across all classes. Our evaluation will compare the GAN-CNN model's performance against traditional CNNs trained on imbalanced data, particularly examining accuracy gains in classifying underrepresented classes. With this combined GAN-CNN model, we aim to address class imbalance directly, eliminating the need for deeper networks as a compensatory measure.

2. Related work

Lahav et al. [5] offers one of the first discussions of using neural networks in the galaxy classification problem. The study clarifies the role of Artificial Neural Networks (ANNs) in galaxy classification by demonstrating their ability to replicate human classification using ESO-LV galaxy data. ANNs achieve comparable accuracy to human ex-

perts, operating within 2 T-type units. The authors argue that ANNs provide a robust statistical framework, improving on linear methods through their capacity for non-linear modelling. While the paper does not cover all classification methods, it emphasises the potential of unsupervised algorithms to discover new features in galaxy data without external guidance. It also highlights the importance of integrating dynamic properties and multiwavelength data to enhance the classification process, as we now have in the Galaxy Zoo 2 dataset. This study lays the groundwork for our exploration into data-driven galaxy classification.

Fussell and Moews [2] demonstrate the effectiveness of using GANs to augment limited datasets of galaxy images. The authors find that the original DCGAN architecture can generate realistic galaxy images that align closely with real galaxy data when statistically evaluated. To achieve higher-resolution synthetic galaxies, they introduce a chained approach using StackGAN as a second stage, which overcomes DCGAN’s limitations at higher resolutions. By evaluating physical property distributions of the generated galaxies and confirming their similarity to real data, the study suggests these synthetic images can effectively expand real galaxy datasets. This augmentation is beneficial for various tasks, including galaxy classification, segmentation, deblending, and calibration of shape measurement algorithms. Ultimately, this research highlights GAN architectures as valuable resources for astronomy, providing scalable data for deep learning models that require extensive training samples. We will adopt a similar approach, benchmarking our GAN-generated data against real data in our model pipeline before feeding them into our CNN.

Kim and Brunner [4] address the limitations and potential improvements for using CNNs in galaxy classification, emphasising concerns about overfitting due to limited training data. The authors note that while CNNs have shown promise, their model did not significantly outperform traditional machine learning models relying on summary catalog data, likely due to data constraints. Collecting additional spectroscopic training images could mitigate overfitting and enhance CNN performance. However, they argued that the process is costly and time-intensive. For future work, the authors suggest training multiple network architectures and combining them, a strategy that has proven effective in other galaxy classification challenges. Integrating CNN with other classifiers in a hybrid model could also yield improvements, as demonstrated in past studies where blending diverse classification approaches outperformed any single method. We will directly address these concerns in our research, providing a hybrid model that will even out and expand our training data to mitigate overfitting.

Walmsley et al. [1] focus on the limitations of deep learning for galaxy morphology, which often overlook uncertainty in labelling. They introduce a Bayesian CNN model

to capture probabilistic predictions for galaxy morphology, leveraging sparse Galaxy Zoo labels. Using Monte Carlo Dropout and active learning, their model selects informative galaxies for labelling, enhancing classification accuracy with fewer labels. This approach, essential for large-scale surveys, offers insights into morphology and astrophysical connections. We aim to incorporate similar probabilistic and active learning strategies in future iterations of our model for effective scaling.

3. Method

3.1. Galaxy Dataset

RECOMMENDATION FROM PROFESSOR: Additionally, provide an overview of the dataset post-augmentation to show the changes in its composition.

The Galaxy Zoo 2 dataset contains detailed galaxy morphology data that is classified into labels using the decision tree structure detailed in Figure 1. It contains a total of 37 morphological galaxy classes of broad types: ellipticals, spirals, intermediate spirals, barred spirals and irregulars. There was a severe imbalance in the dataset that posed a serious model training issue, with the most frequent class containing over 210,000 instances and the least frequent class containing only 6 instances.

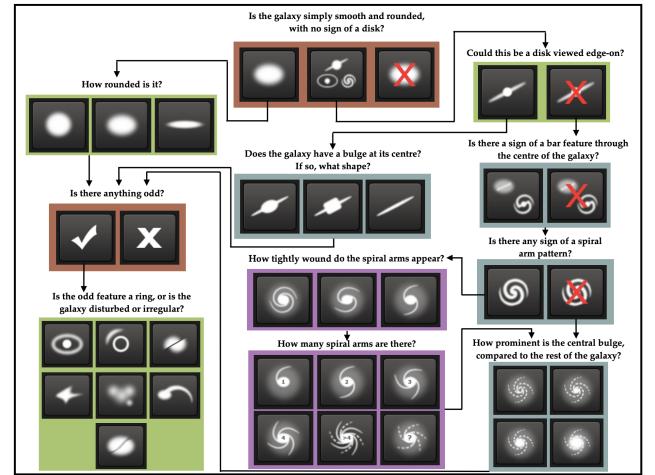


Figure 1. Image representation of the Galaxy Zoo 2 decision tree from the official Galaxy Zoo 2 Data Release [11].

To provide a more holistic perspective on Galaxy Zoo 2 (GZ2), we selected the Galaxy10 dataset to use directly in our algorithms. The Galaxy10 dataset combines the original GZ2 data, which includes over 270,000 SDSS galaxy images, with additional images from the DESI Legacy Imaging Surveys (DECaLS), totalling over 440,000 images. The Galaxy10 dataset minimised class imbalance by merging the data into 10 broader classes and collectively sampling

approximately 18,000 images from the SDSS and DECaLS data, offering a more even class distribution.

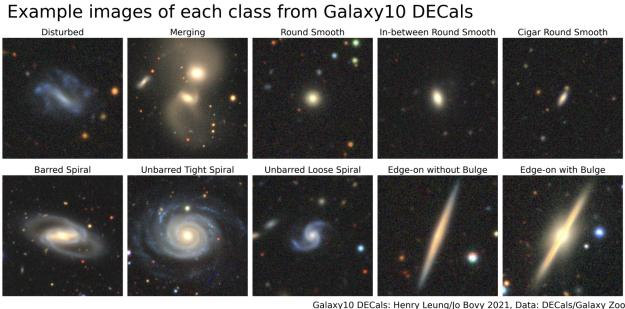


Figure 2. Example images from each class in Galaxy10 DECaLS. Taken from the official [Galaxy10 documentation](#).

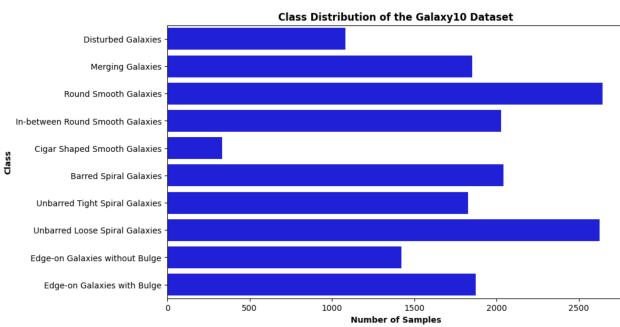


Figure 3. Class distribution in the Galaxy10 dataset.

The most frequent class, *Round Smooth Galaxies*, contains 2,645 images and the least frequent class, *Cigar Shaped Smooth Galaxies*, contains 334 images. While this distribution is much more even than the Galaxy Zoo 2 dataset, the CNN model still faced significant difficulties in training due to the relatively smaller number of examples in some classes, which will be detailed in this paper.

3.2. CNN Training on the Galaxy10 DECaLS Dataset

Prior to generating artificial galaxy images using the cGAN, we trained the CNN on the original Galaxy10 dataset. For smoother model training, we used the PyTorch library to construct our Convolutional Neural Network. The network contained three 2D convolutional layers with 32, 64 and 128 filters, respectively, followed by a dense fully-connected layer containing 512 neurons. This architecture was chosen for its simplicity and reliability in training. We wanted to avoid building deep architectures for the CNN in order to reduce runtime and better evaluate the effectiveness of the cGAN's artificial data generation on the model's performance.

As expected, the training accuracy was significantly higher than the testing accuracy, reaching 99.29% by the 10th epoch, while testing accuracy dropped from a maximum of 57.44% during the 3rd epoch to 48.59% during the 10th epoch. A similar dip in performance can be seen in Figure 5, where the model was evaluated using precision, recall and F1-score metrics. The results are indicative of the class imbalance mentioned previously, with the network learning instances of the majority classes very well and failing to effectively categorise underrepresented classes.

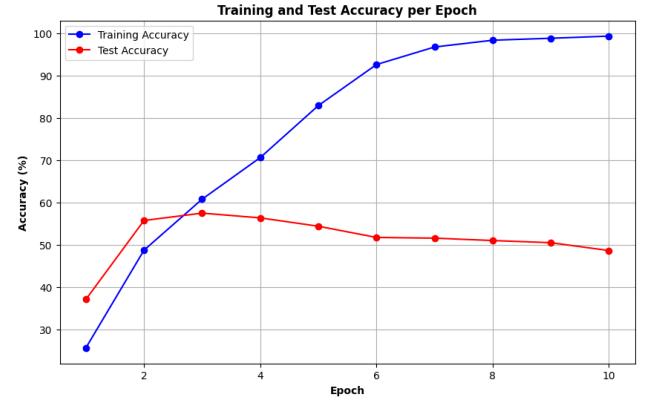


Figure 4. CNN performance on the original Galaxy10 dataset. Evaluated using training and testing accuracy.

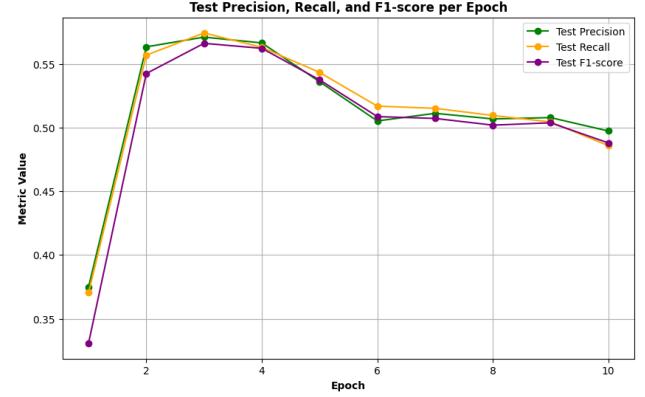


Figure 5. CNN performance on the original Galaxy10 dataset. Evaluated using precision, recall and F1-score metrics.

3.3. Image Enhancement Using SRGAN

The first task required in generating the synthetic galaxy images is to enhance their quality by implementing a Super-Resolution Generative Adversarial Network. We ran the SRGAN on 100 epochs, producing upscaled images with improved resolution to better capture the fine details crucial for accurate classification. The final SRGAN hyperparameters were tuned to contain 8 generator layers and 9 discrimi-

nator layers, which provided optimal high-resolution image enhancement without introducing additional artifacts.

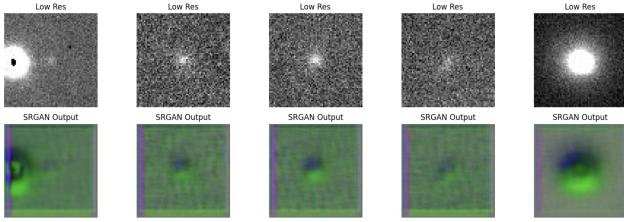


Figure 6. Galaxy images in low resolution and up-scaled using SRGAN.

3.4. Synthetic Data Generation Using cGAN:

To address the data imbalance across galaxy classes, we will implement a Conditional Generative Adversarial Network (cGAN) to generate additional samples for each class. The cGAN will be conditioned on class labels, ensuring that synthetic images resemble galaxies of specific morphological types. By generating images conditioned on each class, we aim to balance the dataset, allowing the CNN to learn from a more uniform distribution of galaxy characteristics. Hyperparameters, such as the batch size, learning rate and the trade-off between generator and discriminator objectives will be carefully selected to ensure diverse image generation.

3.5. GAN-CNN Pipeline Integration

The generated synthetic images, alongside the SRGAN-enhanced real images, will be used to train the CNN model. The CNN architecture will feature several convolutional and pooling layers to extract relevant features from galaxy images, followed by fully connected layers for classification. Each layer configuration, activation function, and regularisation strategy will be optimised specifically for galaxy image data. Initially, the CNN will be trained solely on the original dataset to establish a baseline performance. Then, we will re-train the CNN using a combination of real and synthetic data, assessing improvements in classification accuracy and robustness across all classes.

4. Results

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Evaluation: We will use accuracy, precision, recall, and F1-score as quantitative metrics to evaluate the CNN's classification performance. Additionally, we will compare results from the CNN trained on original images alone against those trained with the augmented dataset, quantifying improvements attributable to our image generation. Visualisations, such as ROC curves, will provide further insights

into class-wise performance, highlighting the impact of the GAN-CNN pipeline on addressing class imbalances.

The SRGAN model has been trained to upscale images by a factor of 2x. Visual inspection of the up-scaled images shows noticeable improvements in clarity and detail, especially in smaller galaxy structures. We achieved an average PSNR value of 24.5 across the up-scaled images, indicating a high degree of similarity between the generated high-resolution images and their lower-resolution counterparts.

5. Conclusion

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