Graph Neural Networks for End-to-End Particle Identification with the CMS Experiment

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for ML4SCI on Google Summer of Code 2023

Common Task 3. Deep Learning based Quark-Gluon Classification Datasets:

https://cernbox.cern.ch/index.php/s/hqz8zE7oxyPjvsL

Description: 125x125 matrices (three channel images) for two classes of particles quarks and gluons impinging on a calorimeter. For a description of 1st dataset please refer to the link provided for the dataset.

Choose 2 Graph-based architectures of your choice to classify jets as being quarks or gluons. Provide a description on what considerations you have taken to project this point-cloud dataset to a set of interconnected nodes and edges.

Discuss the resulting performance of the 2 chosen architectures.

Please use a Convolutional Neural Network (CNN) architecture of your choice to achieve the highest possible classification on this dataset (in your preferred choice of framework for example: Tensorflow/Keras or Pytorch). Please provide a Jupyter notebook that shows your solution.

Solution:

(From 3 separate datasets available, here we used the jet0_run1)

For this task, here is the model description for classifying whether the output would be a quark or a gluon, with features X_jets, mean transverse momentum and mass. We are using the same preprocessed data as Task 2 (normalization), then with the generation of graph with edges to be used for training the model.

This graph-based architecture model was designed for purpose in effectively learns complex patterns from the graph representation of the input data, which includes Laplacian and Hessian features and additional features like mean transverse momentum and mass. The combination of GATConv and ChebConv layers allows the model to efficiently learn spatially localized patterns on the graph and consider the importance of neighboring nodes. The global average pooling, dense, and dropout layers help to create a robust classifier for quark-gluon classification.

1. Data preprocessing and graph creation

The create_graph_from_features function creates a graph using Laplacian and Hessian features, along with additional features (mean transverse momentum and mass). You add edges to the graph based on k-nearest neighbors and Delaunay triangulation.

1. Spektral Graph creation

The create_spektral_graph function takes the NetworkX graph and converts it into a Spektral Graph object, which includes the node attributes and adjacency matrix.

1. Jet Classifier

- Input layers: Two separate input layers for the node features (X) and adjacency matrix (A).
- GATConv layers: Three GATConv layers with 32, 64, and 128 filters, and 4 attention heads each. These layers help the model learn different representations of the input graph while considering the importance of neighboring nodes during the learning process.
- ChebConv layers: Three ChebConv layers with 128, 64, and 32 filters, and K=2 (Chebyshev order). ChebConv layers are spectral convolutional layers that efficiently learn spatially localized patterns on the graph. These layers help the model learn more complex patterns in the graph representation of the input data.
- GlobalAvgPool layer: This layer computes the average of the node features, creating a global feature vector that represents the entire graph.
- Dense and Dropout layers: Two dense layers with GELU and ReLU activation functions, respectively, learn higher-level abstractions of the global feature vector. Dropout layers (with a rate of 0.5) are used to prevent overfitting.

1. Output layer

• The final dense layer with one unit and a sigmoid activation function produces a probability value between 0 and 1, representing the likelihood of the input belonging to the positive class (either quark or gluon).

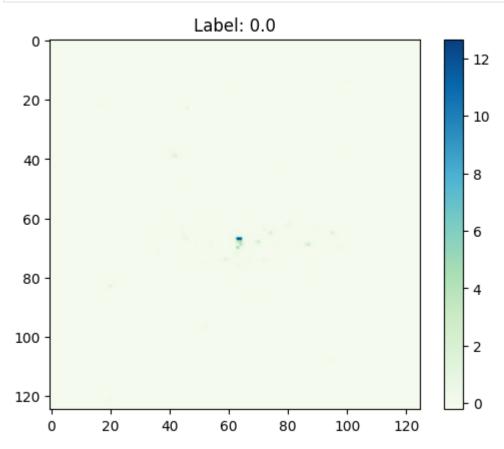
```
import os
import numpy as np
import pandas as pd
import tensorflow as tf
from tensorflow.keras.models import Sequential
from tensorflow.keras.layers import Conv2D, MaxPooling2D, Flatten, Dense, Dropout
from tensorflow.keras.optimizers import Adam
from tensorflow.keras.callbacks import ModelCheckpoint, EarlyStopping
from sklearn.model_selection import train_test_split
```

```
In [ ]: import pyarrow.parquet as pq
```

```
def save data batches(file path, output folder, batch size=2267):
             os.makedirs(output folder, exist ok=True)
             file name = os.path.basename(file path)
             prefix = file name.split('.')[0]
             parquet file = pq.ParquetFile(file path)
             for i, batch in enumerate(parquet file.iter batches(batch size=batch size)):
                 batch df = batch.to pandas()
                 output file name = f"{prefix} batch {i+1}.parquet"
                 output file path = os.path.join(output folder, output file name)
                 batch df.to parquet(output file path)
         data path = "/content/drive/MyDrive/GSoC/tasks 2 and 3"
         file names = [
              "QCDToGGQQ IMGjet RH1all jet0 run0 n36272.test.snappy.parquet",
             "QCDToGGQQ IMGjet RH1all jet0 run1 n47540.test.snappy.parquet",
             "QCDToGGQQ IMGjet RH1all jet0 run2 n55494.test.snappy.parquet"
         for file name in file names:
             file path = os.path.join(data path, file name)
             output folder = os.path.join(data path, "batches", file name.split('.')[0])
             save data batches(file path, output folder)
In [ ]:
         # Assign folder containing the batch files
         batch folder = "/content/drive/MyDrive/GSoC/tasks 2 and 3/batches/QCDToGGQQ IMGjet RH1all jet0 run0 n36272"
         batch file = os.path.join(batch folder, "QCDToGGQQ IMGjet RH1all jet0 run0 n36272 batch 1.parquet")
         df batch = pd.read parquet(batch file)
In [ ]:
         import matplotlib.pyplot as plt
         X jets = np.stack([
             np.array(
                 [item for sublist1 in x for sublist2 in sublist1 for item in sublist2],
                 dtype=np.float32
             ).reshape(len(x), len(x[0]), len(x[0][0]))
             for x in df batch['X jets'].values
         1)
         index = 0
```

```
image = X_jets[index]

plt.imshow(image[1], cmap='GnBu') # Display the first layer of the 3D array
plt.colorbar()
plt.title(f"Label: {df_batch.iloc[index]['y']}")
plt.show()
```



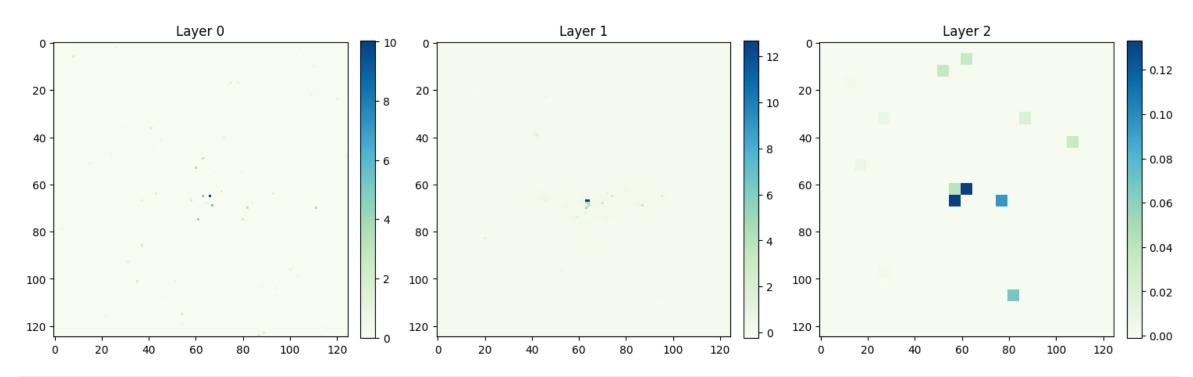
```
index = 0
image = X_jets[index]
label = df_batch.iloc[index]['y']
label_str = "Quark" if label == 0.0 else "Gluon"

# Display each Layer separately
fig, ax = plt.subplots(nrows=1, ncols=3, figsize=(15, 5))
im0 = ax[0].imshow(image[0], cmap='GnBu')
ax[0].set_title("Layer 0")
```

```
fig.colorbar(im0, ax=ax[0], fraction=0.046, pad=0.04)
im1 = ax[1].imshow(image[1], cmap='GnBu')
ax[1].set_title("Layer 1")
fig.colorbar(im1, ax=ax[1], fraction=0.046, pad=0.04)
im2 = ax[2].imshow(image[2], cmap='GnBu')
ax[2].set_title("Layer 2")
fig.colorbar(im2, ax=ax[2], fraction=0.046, pad=0.04)

# Add a single title above all subplots
fig.suptitle(f"Label: {label_str}", fontsize=16, y=1.00)
plt.tight_layout()
plt.show()
```

Label: Quark



```
# Locate extracted X_jets parquets data
batch_folder = "/content/drive/MyDrive/GSoC/tasks_2_and_3/batches/QCDToGGQQ_IMGjet_RH1all_jet0_run0_n36272"
x_jets_folder = os.path.join(batch_folder, "X_jets")
```

```
In [3]:
         import numpy as np
         import cv2
         from skimage import feature
         from skimage.feature import peak local max
         from skimage.segmentation import felzenszwalb
         import networkx as nx
         import json
         def laplacian blob detector(image, sigma=1.0):
             # Convert the image to a floating-point format
             image = image.astype(np.float32)
             # Apply Laplacian of Gaussian (LoG) filter
             log image = cv2.GaussianBlur(image, (0, 0), sigma)
             log image = cv2.Laplacian(log image, cv2.CV 32F)
             # Find Local maxima in the filtered image
             maxima = peak local max(log image, min distance=1, threshold abs=0.05, exclude border=False)
             return maxima
         def hessian blob detector(image, sigma=1.0):
             # Apply Hessian matrix
             hessian matrix = feature.hessian matrix(image, sigma)
```

```
eigenvalues = feature.hessian matrix eigvals(hessian matrix)
             # Find local maxima in the response function
             local maxima = feature.peak local max(eigenvalues)
             return local maxima
         def graph based segmentation(image, scale=100, sigma=0.5, min size=50):
             # Apply Felzenszwalb-Huttenlocher algorithm for graph-based segmentation
             segments = felzenszwalb(image, scale=scale, sigma=sigma, min size=min size)
             return segments
         def preprocess jet data(jet images, additional features, output folder):
             os.makedirs(output folder, exist ok=True)
             for idx, image in enumerate(jet images):
                 # Extract features using Laplacian-Blob Detector
                 laplacian features = [laplacian blob detector(layer).tolist() for layer in image]
                 # Extract features using Hessian-Blob Detector
                 hessian features = [hessian blob detector(layer).tolist() for layer in image]
                 # Perform graph-based segmentation on each layer
                 segmented images = [graph based segmentation(layer).tolist() for layer in image]
                 # Save the preprocessed data to a parquet file
                 df = pd.DataFrame({'features': [json.dumps((laplacian features, hessian features, segmented images))],
                            'additional features': [additional features[idx]]})
                 df.to parquet(os.path.join(output folder, f'preprocessed data {idx}.parquet'))
                 del laplacian features, hessian features, segmented images, df
In [4]:
         # Preprocess the data
         output folder = '/content/drive/MyDrive/GSoC/task 3/preprocessed data/jet0 run0 preprocessed data'
         preprocess jet data(X jets combined, pt m0 all, output folder)
In [3]:
         num images = len(X jets combined)
         del X jets combined, pt m0 all
         print(f'There should be a total of {num images} images.')
```

Compute the eigenvalues of the Hessian matrix

There should be a total of 18136 images.

```
In [4]:
         # Read and concatenate all the saved X jets parquet files
         import ison
         output folder = '/content/drive/MyDrive/GSoC/task 3/preprocessed data/jet0 run0 preprocessed data'
         preprocessed data = []
         # List for storing non-skipped batches of data because of google drive crash
         processed indices = []
         for idx in range(num_images):
             parquet file = os.path.join(output folder, f'preprocessed data {idx}.parquet')
             if os.path.exists(parquet file):
                 try:
                     df = pd.read parquet(parquet file)
                     print(f'Reading and appending preprocessed data {idx}.parquet')
                     preprocessed data.append((json.loads(df['features'][0]),
                                               df['additional features'][0]))
                     processed indices.append(idx)
                 except Exception as e:
                     print(f'Error while processing preprocessed data {idx}.parquet: {e}')
                     continue
             else:
                 print(f'Skipping preprocessed data {idx}.parquet as it does not exist')
         # Get the corresponding labels
         y processed = y all[processed indices]
```

Streaming output truncated to the last 5000 lines.

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import networkx as nx
from scipy.spatial import Delaunay
from sklearn.neighbors import NearestNeighbors

def add_knn_edges(G, k=5):
   nodes = list(G.nodes(data=True))
   positions = [data["position"] for _, data in nodes]
   node ids = [node id for node id, in nodes]
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```
nbrs = NearestNeighbors(n neighbors=k, algorithm='ball tree').fit(positions)
   distances, indices = nbrs.kneighbors(positions)
   for idx, neighbors in enumerate(indices):
        current node = node ids[idx]
        for neighbor idx in neighbors:
           if current node != node ids[neighbor idx]:
                G.add edge(current node, node ids[neighbor idx])
def add delaunay edges(G):
   nodes = list(G.nodes(data=True))
   positions = [data["position"] for , data in nodes]
   node ids = [node id for node id, in nodes]
   delaunay = Delaunay(positions)
   for simplex in delaunay.simplices:
       for i in range(simplex.size):
           for j in range(i + 1, simplex.size):
               G.add_edge(node_ids[simplex[i]], node_ids[simplex[j]])
def create graph from features(features, additional features):
   laplacian features, hessian features, segmented images = features
   # Create an empty graph
   G = nx.Graph()
   # Create nodes from Laplacian features and Hessian features
   for layer idx, (laplacian layer, hessian layer) in enumerate(zip(laplacian features, hessian features)):
       for laplacian feature in laplacian layer:
           node id = f"L {layer idx} {laplacian feature[0]} {laplacian feature[1]}"
           G.add node(node id, feature type="laplacian", layer=layer idx, position=tuple(laplacian feature), features=[1, 0]) # Add node features as a list
       for hessian feature in hessian layer:
           node id = f"H {layer idx} {hessian feature[0]} {hessian feature[1]}"
           G.add node(node id, feature type="hessian", layer=layer idx, position=tuple(hessian feature), features=[0, 1]) # Add node features as a list
    # Add global features (mean transverse momentum and mass) as graph attributes
   G.graph["mean transverse momentum"] = additional features[0]
   G.graph["mass"] = additional features[1]
   # Add k-NN edges
   add knn edges(G, k=5)
   # Add Delaunay edges
    add delaunay edges(G)
```

In [8]:

return G

from networkx.readwrite import json graph

graph output folder = '/content/drive/MyDrive/GSoC/task_3/graph_data/new/jet0_run0_graph_data'

```
os.makedirs(graph output folder, exist ok=True)
              iet graphs = []
              for idx, (jet features, add features) in enumerate(preprocessed data):
                  jet graph = create graph from features(jet features, add features)
                  jet graphs.append(jet graph)
                  # Convert the graph to JSON data
                  graph json data = json graph.node link data(jet graph)
                  # Save the JSON data to a file
                  with open(os.path.join(graph output folder, f'graph data {idx}.json'), 'w') as f:
                       json.dump(graph json data, f)
    In [15]:
               !pip install spektral
              Looking in indexes: https://pypi.org/simple, https://us-python.pkg.dev/colab-wheels/public/simple/
              Collecting spektral
                Downloading spektral-1.2.0-py3-none-any.whl (140 kB)
                                                         - 140.1/140.1 KB 4.6 MB/s eta 0:00:00
              Requirement already satisfied: pandas in /usr/local/lib/python3.9/dist-packages (from spektral) (1.4.4)
              Requirement already satisfied: scikit-learn in /usr/local/lib/python3.9/dist-packages (from spektral) (1.2.2)
              Requirement already satisfied: tqdm in /usr/local/lib/python3.9/dist-packages (from spektral) (4.65.0)
              Requirement already satisfied: lxml in /usr/local/lib/python3.9/dist-packages (from spektral) (4.9.2)
              Requirement already satisfied: joblib in /usr/local/lib/python3.9/dist-packages (from spektral) (1.1.1)
              Requirement already satisfied: numpy in /usr/local/lib/python3.9/dist-packages (from spektral) (1.22.4)
              Requirement already satisfied: scipy in /usr/local/lib/python3.9/dist-packages (from spektral) (1.10.1)
              Requirement already satisfied: networkx in /usr/local/lib/python3.9/dist-packages (from spektral) (3.0)
              Requirement already satisfied: tensorflow>=2.2.0 in /usr/local/lib/python3.9/dist-packages (from spektral) (2.12.0)
              Requirement already satisfied: requests in /usr/local/lib/python3.9/dist-packages (from spektral) (2.27.1)
              Requirement already satisfied: grpcio<2.0,>=1.24.3 in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (1.53.0)
              Requirement already satisfied: protobuf!=4.21.0,!=4.21.1,!=4.21.2,!=4.21.3,!=4.21.4,!=4.21.5,<5.0.0dev,>=3.20.3 in /usr/local/lib/python3.9/dist-packages (from t
              ensorflow>=2.2.0->spektral) (3.20.3)
              Requirement already satisfied: astunparse>=1.6.0 in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (1.6.3)
              Requirement already satisfied: libclang>=13.0.0 in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (16.0.0)
              Requirement already satisfied: opt-einsum>=2.3.2 in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (3.3.0)
              Requirement already satisfied: six>=1.12.0 in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (1.16.0)
localhost:8888/nbconvert/html/Google Summer of Code/GSoC Task 3 (jet0 run0).jpynb?download=false
```

```
Requirement already satisfied: keras<2.13,>=2.12.0 in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (2.12.0)
Requirement already satisfied: gast<=0.4.0,>=0.2.1 in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (0.4.0)
Requirement already satisfied: jax>=0.3.15 in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (0.4.7)
Requirement already satisfied: tensorboard<2.13,>=2.12 in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (2.12.0)
Requirement already satisfied: h5py>=2.9.0 in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (3.8.0)
Requirement already satisfied: wrapt<1.15,>=1.11.0 in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (1.14.1)
Requirement already satisfied: absl-py>=1.0.0 in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (1.4.0)
Requirement already satisfied: typing-extensions>=3.6.6 in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (4.5.0)
Requirement already satisfied: google-pasta>=0.1.1 in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (0.2.0)
Requirement already satisfied: flatbuffers>=2.0 in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (23.3.3)
Requirement already satisfied: tensorflow-estimator<2.13,>=2.12.0 in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (2.12.0)
Requirement already satisfied: tensorflow-io-gcs-filesystem>=0.23.1 in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (0.32.0)
Requirement already satisfied: termcolor>=1.1.0 in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (2.2.0)
Requirement already satisfied: packaging in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (23.0)
Requirement already satisfied: setuptools in /usr/local/lib/python3.9/dist-packages (from tensorflow>=2.2.0->spektral) (67.6.1)
Requirement already satisfied: pytz>=2020.1 in /usr/local/lib/python3.9/dist-packages (from pandas->spektral) (2022.7.1)
Requirement already satisfied: python-dateutil>=2.8.1 in /usr/local/lib/python3.9/dist-packages (from pandas->spektral) (2.8.2)
Requirement already satisfied: charset-normalizer~=2.0.0 in /usr/local/lib/python3.9/dist-packages (from requests->spektral) (2.0.12)
Requirement already satisfied: idna<4,>=2.5 in /usr/local/lib/python3.9/dist-packages (from requests->spektral) (3.4)
Requirement already satisfied: certifi>=2017.4.17 in /usr/local/lib/python3.9/dist-packages (from requests->spektral) (2022.12.7)
Requirement already satisfied: urllib3<1.27,>=1.21.1 in /usr/local/lib/python3.9/dist-packages (from requests->spektral) (1.26.15)
Requirement already satisfied: threadpoolctl>=2.0.0 in /usr/local/lib/python3.9/dist-packages (from scikit-learn->spektral) (3.1.0)
Requirement already satisfied: wheel<1.0,>=0.23.0 in /usr/local/lib/python3.9/dist-packages (from astunparse>=1.6.0->tensorflow>=2.2.0->spektral) (0.40.0)
Requirement already satisfied: ml-dtypes>=0.0.3 in /usr/local/lib/python3.9/dist-packages (from jax>=0.3.15->tensorflow>=2.2.0->spektral) (0.0.4)
Requirement already satisfied: tensorboard-data-server<0.8.0,>=0.7.0 in /usr/local/lib/python3.9/dist-packages (from tensorboard<2.13,>=2.12->tensorflow>=2.2.0->
spektral) (0.7.0)
Requirement already satisfied: werkzeug>=1.0.1 in /usr/local/lib/python3.9/dist-packages (from tensorboard<2.13,>=2.12->tensorflow>=2.2.0->spektral) (2.2.3)
Requirement already satisfied: google-auth-oauthlib<0.5,>=0.4.1 in /usr/local/lib/python3.9/dist-packages (from tensorboard<2.13,>=2.12->tensorflow>=2.2.0->spekt
ral) (0.4.6)
Requirement already satisfied: google-auth<3,>=1.6.3 in /usr/local/lib/python3.9/dist-packages (from tensorboard<2.13,>=2.12->tensorflow>=2.2.0->spektral) (2.17.
Requirement already satisfied: markdown>=2.6.8 in /usr/local/lib/python3.9/dist-packages (from tensorboard<2.13,>=2.12->tensorflow>=2.2.0->spektral) (3.4.3)
Requirement already satisfied: tensorboard-plugin-wit>=1.6.0 in /usr/local/lib/python3.9/dist-packages (from tensorboard<2.13,>=2.12->tensorflow>=2.2.0->spektra
1) (1.8.1)
Requirement already satisfied: rsa<5,>=3.1.4 in /usr/local/lib/python3.9/dist-packages (from google-auth<3,>=1.6.3->tensorboard<2.13,>=2.12->tensorflow>=2.2.0->s
pektral) (4.9)
Requirement already satisfied: pyasn1-modules>=0.2.1 in /usr/local/lib/python3.9/dist-packages (from google-auth<3,>=1.6.3->tensorboard<2.13,>=2.12->tensorflow>=
2.2.0->spektral) (0.2.8)
Requirement already satisfied: cachetools<6.0,>=2.0.0 in /usr/local/lib/python3.9/dist-packages (from google-auth<3,>=1.6.3->tensorboard<2.13,>=2.12->tensorflow>
=2.2.0- spektral) (5.3.0)
Requirement already satisfied: requests-oauthlib>=0.7.0 in /usr/local/lib/python3.9/dist-packages (from google-auth-oauthlib<0.5,>=0.4.1->tensorboard<2.13,>=2.12
->tensorflow>=2.2.0->spektral) (1.3.1)
Requirement already satisfied: importlib-metadata>=4.4 in /usr/local/lib/python3.9/dist-packages (from markdown>=2.6.8->tensorboard<2.13,>=2.12->tensorflow>=2.2.
0->spektral) (6.1.0)
Requirement already satisfied: MarkupSafe>=2.1.1 in /usr/local/lib/python3.9/dist-packages (from werkzeug>=1.0.1->tensorboard<2.13,>=2.12->tensorflow>=2.2.0->spe
```

ktral) (2.1.2)

```
Requirement already satisfied: zipp>=0.5 in /usr/local/lib/python3.9/dist-packages (from importlib-metadata>=4.4->markdown>=2.6.8->tensorboard<2.13,>=2.12->tensorboard
          rflow>=2.2.0->spektral) (3.15.0)
          Requirement already satisfied: pyasn1<0.5.0,>=0.4.6 in /usr/local/lib/python3.9/dist-packages (from pyasn1-modules>=0.2.1->google-auth<3,>=1.6.3->tensorboard<2.1
          3, \ge 2.12 - \text{tensorflow} = 2.2.0 - \text{spektral}) (0.4.8)
          Requirement already satisfied: oauthlib>=3.0.0 in /usr/local/lib/python3.9/dist-packages (from requests-oauthlib>=0.7.0->google-auth-oauthlib>=0.5,>=0.4.1->tensor
          board<2.13,>=2.12->tensorflow>=2.2.0->spektral) (3.2.2)
          Installing collected packages: spektral
          Successfully installed spektral-1.2.0
In [16]:
          def create spektral graph(G):
              # Extract the node attributes
              node attrs = {attr: np.array([d[attr] for , d in G.nodes(data=True)]) for attr in ["position", "features"]}
              x = node attrs["features"].astype(np.float32) # Use node features as input features
              # Extract the adjacency matrix and edge attributes
              a = nx.adjacency matrix(G).astype(np.float32)
              return Graph(x=x, a=a)
In [17]:
          import tensorflow as tf
          import spektral
          from spektral.layers import GATConv, ChebConv, GlobalAvgPool
          from spektral.data import BatchLoader, Dataset, Graph
          from sklearn.model selection import train test split
          class CustomDataset(Dataset):
              def __init__(self, graphs, **kwargs):
                  self.graphs = graphs
                   super(). init (**kwargs)
              def read(self):
                  return self.graphs
              def len (self):
                  return len(self.graphs)
          class CustomBatchLoader(BatchLoader):
              def init (self, dataset, labels, batch size, **kwargs):
                  self.labels = labels
                  super(). init (dataset, batch size=batch size, **kwargs)
              def load(self):
```

```
while True: # Add while loop to repeat data loading for multiple epochs
            index = 0
            batch counter = 0
            current batch = []
            for graph in self.dataset:
                current batch.append(graph)
                batch counter += 1
               if batch counter == self.batch size:
                    batch = self.collate(current batch)
                    x, a = batch # Unpack the tuple
                    y = self.labels[index:index + self.batch size]
                    index += self.batch size
                   y = y.reshape(-1, 1) # Reshape the labels to (batch size, 1)
                    yield (x, a), y
                    batch counter = 0
                    current batch = []
# Convert the jet graphs to a Spektral Graph list
spektral graphs = [create spektral graph(g) for g in jet graphs]
# Split the data into training and testing sets
train graph list, test graph list, y train, y test = train test split(spektral graphs, y processed, test size=0.2)
# Create CustomDataset objects for training and testing
train dataset = CustomDataset(train graph list)
test dataset = CustomDataset(test graph list)
# Create the CustomBatchLoaders for training and testing
batch size = 32
train loader = CustomBatchLoader(train dataset, y train, batch size=batch size)
test loader = CustomBatchLoader(test dataset, y test, batch size=batch size)
```

```
In [18]: # Define the JetClassifier using the Keras functional API
def build_jet_classifier():
    x_in = tf.keras.Input(shape=(None, 2), name="X") # Change input shape to (None, 2)
    a_in = tf.keras.Input(shape=(None, None), sparse=True, name="A")

    x = GATConv(32, attn_heads=4, concat_heads=True)([x_in, a_in])
    x = GATConv(64, attn_heads=4, concat_heads=True)([x, a_in])
    x = GATConv(128, attn_heads=4, concat_heads=True)([x, a_in])

    x = ChebConv(128, K=2)([x, a_in])
```

```
x = ChebConv(64, K=2)([x, a_in])
   x = ChebConv(32, K=2)([x, a in])
   x = GlobalAvgPool()(x)
   x = tf.keras.layers.Dense(256, activation="gelu")(x)
   x = tf.keras.layers.Dropout(0.5)(x)
   x = tf.keras.layers.Dense(128, activation="relu")(x)
   x = tf.keras.layers.Dropout(0.5)(x)
   x = tf.keras.layers.Dense(1, activation="sigmoid")(x)
   model = tf.keras.Model(inputs=[x_in, a_in], outputs=x)
   return model
# Instantiate the model
model = build jet classifier()
# Compile the model
model.compile(optimizer=tf.keras.optimizers.RMSprop(learning rate=1e-3),
             loss=tf.keras.losses.BinaryCrossentropy(), # Change the Loss function to BinaryCrossentropy
              metrics=["accuracy"])
model.summary()
```

/usr/local/lib/python3.9/dist-packages/keras/initializers/initializers.py:120: UserWarning: The initializer GlorotUniform is unseeded and being called multiple t imes, which will return identical values each time (even if the initializer is unseeded). Please update your code to provide a seed to the initializer, or avoid using the same initalizer instance more than once.

warnings.warn(
Model: "model"

Layer (type)	Output Shape	Param #	Connected to
X (InputLayer)	[(None, None, 2)]	 0	[]
A (InputLayer)	[(None, None, None)]	0	[]
gat_conv (GATConv)	(None, None, 128)	640	['X[0][0]', 'A[0][0]']
<pre>gat_conv_1 (GATConv)</pre>	(None, None, 256)	33536	['gat_conv[0][0]', 'A[0][0]']
<pre>gat_conv_2 (GATConv)</pre>	(None, None, 512)	132608	['gat_conv_1[0][0]', 'A[0][0]']

In [20]:

```
cheb conv (ChebConv)
                                                           ['gat_conv_2[0][0]',
                             (None, None, 128)
                                                131200
                                                            'A[0][0]']
                                                           ['cheb_conv[0][0]',
cheb conv 1 (ChebConv)
                             (None, None, 64)
                                                16448
                                                            'A[0][0]']
                                                           ['cheb_conv_1[0][0]',
cheb conv 2 (ChebConv)
                             (None, None, 32)
                                                4128
                                                            'A[0][0]']
global avg pool (GlobalAvgPool (None, 32)
                                                0
                                                           ['cheb_conv_2[0][0]']
dense (Dense)
                             (None, 256)
                                                8448
                                                           ['global avg pool[0][0]']
dropout (Dropout)
                                                0
                                                           ['dense[0][0]']
                             (None, 256)
dense 1 (Dense)
                             (None, 128)
                                                32896
                                                           ['dropout[0][0]']
dropout_1 (Dropout)
                             (None, 128)
                                                0
                                                           ['dense 1[0][0]']
                                                           ['dropout 1[0][0]']
dense 2 (Dense)
                             (None, 1)
                                                129
______
Total params: 360,033
Trainable params: 360,033
Non-trainable params: 0
# Train the model
epochs = 20
history = model.fit(
    train loader.load(),
    steps_per_epoch=train_loader.steps_per_epoch,
    epochs=epochs,
    validation data=test loader.load(),
    validation_steps=test_loader.steps_per_epoch,
Epoch 1/20
404/404 [===============] - 225s 556ms/step - loss: 0.7337 - accuracy: 0.5335 - val loss: 0.6747 - val accuracy: 0.6142
Epoch 2/20
```

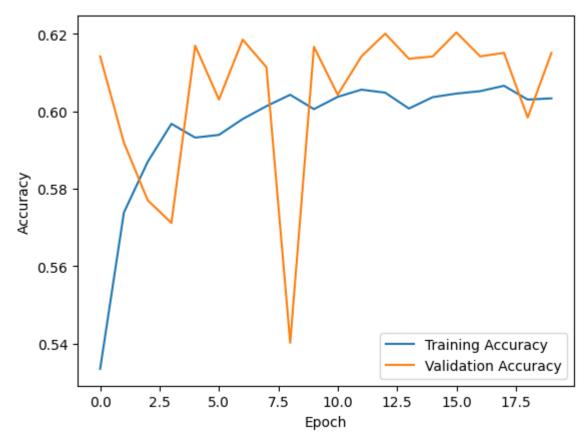
404/404 [==============] - 219s 542ms/step - loss: 0.6837 - accuracy: 0.5739 - val loss: 0.6685 - val accuracy: 0.5919

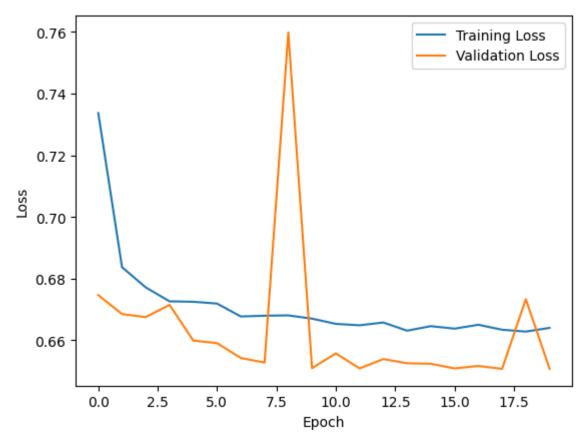
Epoch 3/20

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```
404/404 [=============] - 218s 539ms/step - loss: 0.6772 - accuracy: 0.5869 - val loss: 0.6675 - val accuracy: 0.5770
      Epoch 4/20
      404/404 [===============] - 217s 538ms/step - loss: 0.6726 - accuracy: 0.5968 - val loss: 0.6715 - val accuracy: 0.5712
      Epoch 5/20
      Epoch 6/20
      Epoch 7/20
      Epoch 8/20
      404/404 [===============] - 218s 540ms/step - loss: 0.6680 - accuracy: 0.6013 - val loss: 0.6528 - val accuracy: 0.6114
      Epoch 9/20
      404/404 [============== ] - 218s 540ms/step - loss: 0.6681 - accuracy: 0.6043 - val loss: 0.7598 - val accuracy: 0.5402
      Epoch 10/20
      404/404 [===============] - 216s 536ms/step - loss: 0.6670 - accuracy: 0.6006 - val loss: 0.6510 - val accuracy: 0.6166
      Epoch 11/20
      404/404 [=============== ] - 218s 539ms/step - loss: 0.6654 - accuracy: 0.6037 - val loss: 0.6558 - val accuracy: 0.6043
      Epoch 12/20
      404/404 [============= ] - 219s 542ms/step - loss: 0.6649 - accuracy: 0.6056 - val loss: 0.6509 - val accuracy: 0.6142
      Epoch 13/20
      Epoch 14/20
      404/404 [===============] - 218s 540ms/step - loss: 0.6631 - accuracy: 0.6007 - val loss: 0.6526 - val accuracy: 0.6136
      Epoch 15/20
      404/404 [===============] - 218s 540ms/step - loss: 0.6646 - accuracy: 0.6037 - val loss: 0.6524 - val accuracy: 0.6142
      Epoch 16/20
      404/404 [============== ] - 217s 537ms/step - loss: 0.6638 - accuracy: 0.6046 - val loss: 0.6509 - val accuracy: 0.6204
      Epoch 17/20
      Epoch 18/20
      Epoch 19/20
      404/404 [===============] - 218s 541ms/step - loss: 0.6628 - accuracy: 0.6030 - val loss: 0.6734 - val accuracy: 0.5984
      Epoch 20/20
      404/404 [============== ] - 219s 542ms/step - loss: 0.6640 - accuracy: 0.6033 - val loss: 0.6508 - val accuracy: 0.6151
In [21]:
      # Evaluate the model
      test loss, test accuracy = model.evaluate(test loader.load(), steps=test loader.steps per epoch)
      In [22]:
      model.save weights('/content/drive/MyDrive/GSoC/task_3/model/model_jet0_run0_weights.h5')
```

```
In [23]:
          import matplotlib.pyplot as plt
          # Plot training and validation accuracy
          plt.figure()
          plt.plot(history.history["accuracy"], label="Training Accuracy")
          plt.plot(history.history["val_accuracy"], label="Validation Accuracy")
          plt.xlabel("Epoch")
          plt.ylabel("Accuracy")
          plt.legend()
          plt.show()
          # Plot training and validation loss
          plt.figure()
          plt.plot(history.history["loss"], label="Training Loss")
          plt.plot(history.history["val_loss"], label="Validation Loss")
          plt.xlabel("Epoch")
          plt.ylabel("Loss")
          plt.legend()
          plt.show()
```





```
In [24]:
          def load(self, repeat=False):
              while True:
                  index = 0
                  batch_counter = 0
                  current_batch = []
                  for graph in self.dataset:
                      current_batch.append(graph)
                      batch counter += 1
                      if batch_counter == self.batch_size:
                          batch = self.collate(current_batch)
                          x, a = batch
                          y = self.labels[index:index + self.batch_size]
                          index += self.batch_size
                          y = y.reshape(-1, 1)
                          yield (x, a), y
```

```
batch_counter = 0
    current_batch = []

if not repeat:
    break
```

```
In [26]:
          from sklearn.metrics import roc curve, roc auc score
          # Create a CustomBatchLoader with batch size=1 for predictions
          pred loader = CustomBatchLoader(test dataset, y test, batch size=1)
          # Get predictions
          y pred = model.predict(pred loader.load(), steps=pred loader.steps per epoch)
          y pred = y pred.squeeze()
          # Calculate ROC curve
          fpr, tpr, thresholds = roc_curve(y_test, y_pred)
          # Calculate ROC-AUC score
          roc_auc = roc_auc_score(y_test, y_pred)
          # Plot the ROC curve
          plt.figure()
          plt.plot(fpr, tpr, label="ROC curve (area = %0.2f)" % roc auc)
          plt.plot([0, 1], [0, 1], "k--")
          plt.xlim([0.0, 1.0])
          plt.ylim([0.0, 1.05])
          plt.xlabel("False Positive Rate")
          plt.ylabel("True Positive Rate")
          plt.title("Receiver Operating Characteristic (ROC)")
          plt.legend(loc="lower right")
          plt.show()
```

3231/3231 [=============] - 24s 7ms/step

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