Project 4: Supervised vs Unsupervised Anomaly Detection

With shallow and deep learning methodologies

1 Objective

The goal of this laboratory is to apply **Shallow and Deep Learning anomaly detection** techniques in the context of cybersecurity. Specifically, the lab evaluates how to create **Intrusion Detection Systems**.

To this end, students will analyze a dataset consisting of network traffic data labeled as either normal or one of several types of attacks (DoS, Probe, R2L). Each row describe a connection and its associated features. Each connection describes the sequence of network packets between a source and a destination over a period of time, summarized into a single record with features describing its characteristics (e.g., duration, protocol, number of bytes, number of failed login attempts).

The core objective of the lab is to leverage shallow learning and deep learning for anomaly detection and data rappresentation to solve the *Intrusion Detection Systems (IDS)* task. Throughout the lab, students will:

- Learn possible strategies to **analyze datasets** composed of normal and anomalous traffic.
- Understand the **impact of different assumptions in the anomaly detection process**, e.g., knowing the class label or not.
- Experiment with **different anomaly detection methods** and compare their performance.
- **Use linear and non-linear data representation techniques** to visualize cybersecurity anomalies or reduce the number of available features and evaluate changes in anomaly detection performance.

2 Submission Rules

- Groups consist of 3 students.
- Each group must submit a zip file containing the following:
  - A report (maximum 10 pages) describing the approach, experiments and results, including tables and plots.
  - The Juypyter notebook(s) and the code (e.g., libraries with classes and functions written by you) to solve the tasks.
    - **Best practice**: Add comments and headers (Markdown) sections to understand what you are doing. They will i) help you tomorrow to understand what you did today and ii) help us to interpret your solution correctly.
    - **The notebook needs to be executed**: code and results must be visible so that we can interpret what you have done and what the results look like.

  * **Must run**: the code must work if we need to run it again.
  * **Submission format**: Include the notebook file (`.ipynb`) and an HTML export for easier review.

- Each group must upload the zip file to the teaching portal via Moodle before the deadline.

3 Dataset: Intrusion Detection System (IDS)

In this laboratory, you will use **connection-level logs from a network-based Intrusion Detection System (IDS)**.

Intrusion Detection Systems monitor and analyze network traffic to detect unauthorized or malicious behavior. They log metadata about each network connection, which is then used for offline training and evaluation of anomaly detection and classification algorithms. These connection records summarize communication sessions between two endpoints and include both statistical and behavioral features extracted from raw traffic.

You are provided with two datasets:

- `train.csv`: a curated set of labeled network connections used for training. This subset includes a balanced number of benign and malicious samples across several attack categories: Denial of Service (`dos`), Probing (`probe`), Remote-to-Local (`r2l`). In addition to the specific attack **label**, each label is labeled with a **binary_label** equal to `0`; for all `normal` connections `1` for all attacks, i.e., the anomalies.

- `test.csv`: a more heterogeneous set of network connections collected in varied conditions. You will use this dataset to assess whether the model you trained *generalize* to different settings.

Each connection record is described by **features**, divided into three main categories:

- **Basic features** describe attributes such as the connection duration, protocol type (e.g., TCP, UDP), service (e.g., HTTP, FTP), and status flags from the transport layer.

- **Content features** capture information from the payload content of the packets, including the number of failed login attempts, access to sensitive files, or commands executed in the session.

- **Traffic features** summarize network-level statistics such as the number of connections to the same host or service in a specific time window, helping to identify scanning and flooding behaviors.

The final two columns of each record are the attack **label** and the **binary_label** indicating the attack category and whether the connection is normal or associated with a malicious activity. This structure enables the development of supervised, self-supervised and unsupervised learning models for intrusion detection.

Note: These datasets simulate real-world network activity and present realistic challenges such as class imbalance, redundant patterns, and evolving attack strategies. The goal is to design robust models.

4 Tasks

Students will go through a multi-step machine learning pipeline for anomaly detection:

- **Dataset characterization**: Examine the dataset to understand the number of categorical and numerical features. Check how the attack **labels** and **binary_label** is distributed.
- **Shallow anomaly detection**: Use One-Class SVM in a supervised and unsupervised setting.
- **Deep anomaly detection and representation**: Use Autoencoder for anomaly detection and compare the ability to create a meaningful data representation comparing it with PCA.
- **Unsupervised detection and interpretation**: Use clustering results and visualization techniques to explore a situation where anomaly detection does not have the label to learn the patterns.

Task 1: Dataset Characterization and Preprocessing

- **Explore the dataset**: Before preprocessing the data, explore your data to understand the available features.
  Q: What are your dataset characteristics? How many categorical and numerical attributes do you have?[1] How are your **attack labels** and **binary_label** distributed?
- **Preprocessing**: As usual, preprocess your features before performing any AI/ML algorithms.
  Q: How do you preprocess categorical and numerical data?
- **Study your data from a domain expert perspective**: When dealing with unsupervised learning, domain expert must frequently analyze data by hand. For this we can rely on heatmaps describing the *statical characteristics* of each feature for each attack **label**. As such plot and report the following 3 heatmaps:
  - **Mean heatmap**: 'groupby' the data points for each attack **label** and extract the *mean* of each feature. Then, plot and report the result as an heatmap.
  - **Standard Deviation heatmap**: group the data points for each attack **label** and extract the *standard deviation* of each feature. Then, plot and report the result as an heatmap.
  - **Median Heatmap**: group the data points for each attack **label** and extract the **median** of each feature. Then, plot and report the result as an heatmap.

  Q: Looking at the different heatmaps, do you find any main characteristics that are strongly correlated with a specific attack?

[1] **Notice**: we consider 0/1 features as numerical.

Task 2: Shallow Anomaly Detection - Supervised vs Unsupervised

Start leveraging the OC-SVM in a Supervised vs Unsupervised for anomaly detection.

- **One-Class SVM with Normal data only**: First, train a One-Class Support Vector Machine (OC-SVM) with benign (normal) traffic only using a `rbf` kernel. Then, evaluate the performance using all training data (normal + anomalies).
  Q: Considering that you are currently training only on normal data, which is a good estimate for the parameter `nu`[2]? Which is the impact on the training performance? Try both your estimate and the default value of `nu`.

- **One-Class SVM with All data**: Now, train the OC-SVM with both normal and anomalous data. Estimate `nu` as the ratio of anomalous data over the entire collection. Then, evaluate the performance using all training data (normal + anomalies).
  Q: Which model performs better? Why do you think it is the case?

- **One-Class SVM with normal traffic and some anomalies**: Evaluate the impact of the percentage of anomalies while training the OC-SVM. Train several OC-SVMs with an increasing subsample of the anomalous classes ([0%, 10%, 20%, 50%, 100%] of anomalies). Estimate the `nu` parameter for each scenario. Then, evaluate each model using all training data (normal + anomalies).
  Q: Plot the `f1-macro` score for each scenario. How is the increasing ratio of anomalies impacting the results?

- **One-Class SVM model robustness**: Test the models trained with normal data only(point 1); all data (point 2); and 10% of anomalous data on the test set (point 3).
  Q: Is the best-performing model in the training set also the best here? Compare the results of the best model in the test set with its results in the training set. Can it still spot the anomalies? Does it confuse normal data with anomalies?

Task 3: Deep Anomaly Detection and Data Representation

Second, we can insert Deep Learning into the game for either Anomaly Detection or Data Representation only.

- **Training and Validating Autoencoder with Normal data only**: Define an Auto-Encoder architecture of your choice: the architecture must have a shrinking encoder and an expansion decoder, with a bottleneck in between. Use normal data only; split this set into a training and validation sets, and use the validation set to pick the best number of epochs and learning rate.

- **Estimate the Reconstruction Error Threshold**: Once you trained the model, you have to estimate a threshold over which, if the model has a higher reconstruction error, you define the point as an anomaly. To estimate this threshold, calculate the reconstruction error in the validation set. Plot the EDCF curve of the reconstruction error over your validation data and estimate your reconstruction error threshold. Remember: you trained with normal data only.
  Q: How did you choose the threshold? Which is its value?

[2]Remember: normal data **always** contains errors. 0 is **NOT** a good estimate.

- **Anomaly Detection with reconstruction error**: Now, use the model to compute the reconstruction errors for each point in the full training set (normal data + anomalies) and test set.
  Q: Plot and report the ECDF of the reconstruction errors for each point i) in the validation set; ii) in the full training set; iii) in the test set. Why the reconstruction errors are higher on the full training set than on the validation one? And why the reconstruction errors in the test set are even higher?

- **Auto-Encoder's bottleneck and OC-SVM**: Another way of using the auto-encoder is to leverage the encoder's bottleneck for data representation. Use the encoder you previously trained to extract the bottleneck embeddings of the normal data in the training set. Use these embeddings to train a OC-SVM. Then, extract the bottleneck embeddings of the test data, and use the trained OC-SVM to predict normal data vs anomalies.
  Q: Compare results with the best original OC-SVM. Describe the performance and where the model performs better or worst w.r.t. the original OC-SVM.

- **PCA and OC-SVM**: For data representation, an other option is to use the Principal Components Analysis (PCA). Use the PCA analysis on the training set of normal data only to analyze the explained variance using the PCA increasing the number of components and find the elbow point in the *number of components*. Fit and transform the training set of normal data only using the found *number of components*. Then, transform the test set with the same number of components. Finally, use the components from the training set with normal data only to train a OC-SVM and test the performance using the components of the test set.
  Q: compare results with original OC-SVM and the OC-SVM trained using the Encoder embeddings. Describe the performance of the PCA-model w.r.t. the previous OC-SVMs.

Task 4: Unsupervised Anomaly Detection and Interpretation

Finally, many problems cannot rely on labelled data to detect anomalies. For those cases, expertise is crucial to interpret unsupervised data-driven analysis.

- **K-means with little domain knowledge**: As a domain expert, you may know the number of common attacks on your network, but not their actual attack label. Under this assumption, fit k-means with 4 clusters and the full training data (normal + anomalous).

- **K-means cluster interpretation**: After creating clusters that are completely unsupervised, we need to examine them to understand their quality.
  Q: How big are the clusters? How are the attack labels distributed across the clusters? Are the clusters *pure* (i.e., they consist of only one attack label)?
  Q: How high is the silhouette per cluster? Is there any clusters with a lower silhouette value? If it is the case, what attack labels are present in these clusters?
  Q: Use the t-SNE algorithm to obtain a 2D visualization of your points. Plot and report: i) t-SNE using all training data and as label the cluster ID. To do this, try different values (max 3) of perplexity to determine the best visualization[3]. ii) Use the t-SNE with the best perplexity and plot all the training data with the **attack label**. Can you find a difference between the two visualizations? What are the misinterpreted points?

[3]Only from a visual point of view. See: `https://distill.pub/2016/misread-tsne/`

- **DB-Scan anomalies are anomalies?**: Finally, DB-Scan is a clustering algorithm designed to detect anomalous patterns that may represent anomalies. One way to estimate **min_points** is to evaluate the k-means result and look for the smallest cluster that consists only of normal data. This enables the definition of clusters with normal behavior. Set **min_points** according to this analysis. Next, use the elbow rule to determine the ϵ parameter based on the increasing distance between each point and its **min_points** neighbor.
  Q: Create the clustering results using the entire training set (normal + anomalous) using the parameters **min_points** and ϵ. Does the DB-Scan noise cluster (cluster -1) consist only of **anomalous** points (cross-reference with real attack labels)?
  Q: Next, consider the 10 largest clusters by size - **DO NOT** consider cluster -1. How are the labels distributed across these clusters, i.e. how are they composed of a single label?
  Q: Use the t-SNE for visualization. Visualize and report: i) t-SNE using all training data and as label the cluster ID of the top 10 clusters - keep the same previously found perplexity. ii) Use the t-SNE with the best perplexity and plot all the training data with the **attack label**. Can you find a difference between the two visualizations? What are the misinterpreted points?
  Q: Why do you think that DB-Scan cannot separate the normal anomalous points well?