**Detecting Anomalies with Autoencoders: A Deep Learning Approach to ECG Signal Analysis**

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**Introduction: What Is Anomaly Detection?**

In many machine learning tasks, we aim to classify known patterns or predict outcomes based on historical trends. But sometimes, we want to detect something **unexpected** — patterns that differ from the norm. This is called **anomaly detection**.

Anomaly detection is used in:

* **Medical diagnostics** (e.g., irregular ECG or MRI scans)
* **Cybersecurity** (e.g., network intrusion detection)
* **Banking and finance** (e.g., fraud detection)
* **Manufacturing** (e.g., machine failure prediction)

It is especially valuable when:

* Anomalies are **rare**
* We have **very few labeled anomalies**
* The "normal" class is well-defined, but outliers vary and evolve

**What Are Autoencoders?**

An **autoencoder** is a special type of **neural network** designed to reconstruct its input. It consists of two parts:

|  |  |
| --- | --- |
| **Component** | **Description** |
| **Encoder** | Compresses input data into a low-dimensional representation (called a "latent space") |
| **Decoder** | Reconstructs the input from the compressed encoding |

The goal of an autoencoder is to **minimize the difference between the input and its reconstruction**. If trained only on "normal" data, the model becomes good at reconstructing normal patterns — but **fails to reconstruct anomalies**, which results in a **high reconstruction error**.

*Autoencoders were first introduced in the 1980s (Rumelhart et al., 1986) and have since become foundational in unsupervised deep learning and representation learning.*

**How Autoencoders Detect Anomalies**

Here's the intuition:

* **Step 1**: Train the autoencoder on normal data only
* **Step 2**: Use the trained model to reconstruct **all** inputs
* **Step 3**: Compare input vs. reconstruction → compute **reconstruction error**
* **Step 4**: Set a **threshold**: if the error is high, label it an anomaly

This makes autoencoders ideal for unsupervised or semi-supervised anomaly detection tasks.

**Why ECG Data?**

ECG (Electrocardiogram) records the electrical activity of the heart. Anomalies in ECG patterns can indicate serious heart conditions such as arrhythmias. Detecting these anomalies **automatically and early** can be lifesaving.

In this tutorial, we’ll use a high-dimensional ECG dataset, where:

* Each row is a time series sample (e.g., 140 datapoints from an ECG signal)
* Labels indicate whether the signal is **normal** or **anomalous**

We’ll train an autoencoder **only on normal signals**, then use reconstruction error to detect anomalies — a real-world application of unsupervised deep learning.

**Summary of Concepts You’ll Learn**

* What are autoencoders, and how do they work?
* Why reconstruction error helps detect anomalies
* How to implement an autoencoder in TensorFlow/Keras
* How to evaluate anomaly detection using precision, recall, and ROC curves
* How to visualize and interpret reconstructions

**Full Code Explanation:**

**Autoencoder for ECG Anomaly Detection**

**Step 1: Importing Required Libraries**

In the first step, we import the essential Python libraries that enable us to handle the ECG dataset, build the deep learning model, and evaluate our results. pandas and numpy are standard tools for data handling and computation. We also use matplotlib.pyplot and seaborn for visualizing the data and reconstruction errors. From sklearn, we import functions to split the data and compute performance metrics. Finally, we use tensorflow.keras to construct and train the autoencoder model. We also suppress warnings for cleaner output using warnings.filterwarnings('ignore').

A screenshot of a computer code

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**Step 2: Loading the Dataset**

We load the ECG dataset using pd.read\_csv(). This dataset consists of 141 columns — the first 140 represent time-series ECG signal values, while the last column represents the class label: 1 for normal and 0 for anomalous signals. We separate the dataset into X (features) and y (labels). This format allows us to work with the input signals directly and detect anomalies based on signal reconstruction.

A close-up of a code

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**Step 3: Exploratory Data Analysis (EDA)**

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A basic countplot is created using seaborn to visualize the distribution of normal vs anomalous classes. This quick plot reveals class imbalance — typically, the dataset contains far more normal signals than anomalies. This imbalance justifies the use of an unsupervised approach where the model learns only from the dominant class (normal) and flags unusual signals as anomalies.

A graph of a distribution of normal

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**Step 4: Data Splitting**

**A screenshot of a computer

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We create the training and testing datasets. Importantly, we **only use samples with label 1 (normal)** to train the autoencoder. This is because an autoencoder learns to recreate normal behavior. During testing, we include both normal and anomalous samples to evaluate how well the model can differentiate based on reconstruction error. This simulates real-world conditions where anomalies are unknown at training time.

**Step 5: Building the Autoencoder Model**

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We define a simple but effective autoencoder using Keras’ Functional API. The encoder part compresses the 140-dimensional input into 64 and then 32 dimensions using Dense layers with ReLU activation. The decoder symmetrically reconstructs the original 140-dimension input. The final layer uses a linear activation to produce a continuous output that can closely match the original signal. We compile the model using adam optimizer and mean squared error (MSE) as the loss function — since our goal is to minimize the difference between input and output.

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**Step 6: Training the Autoencoder**

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We fit the model on X\_train, where both input and target are the same (since an autoencoder is trained to reconstruct its input). The model runs for 50 epochs using a batch size of 32. We also include validation data using the same X\_train, which allows us to monitor the reconstruction performance during training.

A table of numbers and numbers

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**Step 7: Reconstruction and Error Calculation**

After training, we use the model to **reconstruct all test samples**, including both normal and anomalous signals. We compute the **mean squared error (MSE)** for each sample between the actual ECG signal and the model’s reconstruction. This gives us a numerical score representing how well the model was able to reconstruct each signal. We expect low MSE for normal samples (well reconstructed) and high MSE for anomalies.

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**Step 8: Threshold Determination**

We need to decide how large an error constitutes an anomaly. To do this, we compute the **95th percentile** of reconstruction errors for the **normal samples only** (those with label 1). This threshold assumes that 95% of normal data should be reconstructed with lower error, and anything beyond that is considered unusual or anomalous. This method works well in imbalanced datasets where anomalies are rare.

A close-up of a computer code

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**Step 9: Anomaly Detection and Evaluation**

We classify a sample as an anomaly if its reconstruction error exceeds the threshold. We convert our original labels such that 1 represents anomalies (to align with evaluation metrics). We then compute a **confusion matrix**, **classification report** (precision, recall, F1-score), and **ROC AUC score** to evaluate the model’s performance.  
🛠️ **Important fix**: If any reconstruction error values are NaN, we use np.nan\_to\_num() to replace them and avoid errors in roc\_auc\_score().

A screenshot of a computer screen

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**Step 10: Visualization of Reconstruction Error**

To visually analyze how well the model separates normal from anomalous signals, we create histograms of reconstruction errors for both classes. We also plot the threshold line, making it easy to see where anomalies begin. This visual tool is incredibly useful for interpreting the performance of unsupervised models and setting threshold-based decisions.

A graph of error distribution

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**Recap:**

By the end of this pipeline, students understand:

* The full flow of anomaly detection using autoencoders
* How to handle class imbalance without requiring labels for anomalies
* How to build and interpret deep learning models for unsupervised tasks
* How to apply practical metrics and visualizations to support model performance

**GitHub Guidance table:**

|  |  |
| --- | --- |
| **File/Folder Name** | **Description** |
| ecg\_autoencoder\_anomaly\_detection.ipynb | Jupyter Notebook containing full code, markdowns, and visualizations |
| README.md | Explanation of the project, steps, usage, model, and purpose |
| requirements.txt | List of Python dependencies for the project |
| ecg 2.csv | Dataset used for training and testing the model |
| LICENSE | Open-source license (e.g., MIT License) |

**Repository Link**

<https://github.com/username/ecg-autoencoder-anomaly-detection>

**References**

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2. Chollet, F. (2015). *Keras: Deep learning for humans*. GitHub Repository.  
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3. Zhang, Y., & Jin, R. (2006). **Understanding classification performance metrics**.  
   https://scikit-learn.org/stable/modules/model\_evaluation.html
4. UCI Machine Learning Repository. (n.d.). *ECG5000 Dataset*.  
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   <https://www.kaggle.com/code/devavratatripathy/ecg-anomaly-detection-using-autoencoders>

**Accessibility Statement**

To ensure that this tutorial is accessible to all learners:

* **Alt-text and captions** are used for all visualizations
* Color palettes were selected to be **colorblind-friendly**
* All markdown explanations are screen reader compatible
* All code follows **PEP-8** standards for readability
* Variable names and markdowns use **clear and concise** educational language
* Code can be run fully in **Google Colab** (no local GPU required)