

Final Assignment

CM3015 Machine Learning and Neural Networks

Credit Card Fraud Detection with a Feedforward MLP

- Student: cy150
 - Workflow: Chollet's ML workflow (problem → data → evaluation → prep → baseline → model → tuning → final eval)
-

Step 1 — Define the problem

Chollet's workflow keeps the project aligned with real-world goals. It moves in clear stages from problem definition to data understanding, evaluation design, preparation, baseline, model building, tuning, and final reporting.

Overview: Credit Card Fraud

Credit card fraud is the unauthorized use of a credit (or debit) card to make purchases, withdraw funds, or create transactions that the legitimate cardholder did not approve.

Problem Statement

- Credit card fraud causes direct and significant financial losses: issuers, merchants, and consumers may absorb losses from unauthorized purchases and chargebacks. Fraud also creates investigative overhead (reviews, disputes) and temporary loss of funds and reputation. As a result, stricter verification and KYC are implemented by merchants and banks.
 - These organizations can also lose customers if there are excessive false declines or chargebacks. Additionally, failure to protect customers according to regulatory standards can incur penalties to banks themselves proving that credit card fraud detection is a critical technology for a functioning, safe banking and finance environment
-

Step 2 — Identify and understand the data

Dataset Overview

This dataset consists of credit card transactions by European cardholders. It covers two days of transactions with 492 frauds out of 284,807 transactions. The dataset is highly imbalanced, with frauds accounting for about 0.172% of all transactions.

Nature of the Dataset

It contains only numerical input variables resulting from a PCA transformation. Due to confidentiality, the original features and more background information are not available.

Dataset Features

Features V1, V2, ... V28 are principal components from PCA. The only features not transformed with PCA are `Time` and `Amount`.

- `Time` contains the seconds elapsed between each transaction and the first transaction in the dataset.

Example

Time	V1	V2	V3	V4	V5
0	-1.3598	-0.0728	2.5363	1.3782	-0.3383
1	1.1919	0.2662	0.1665	0.4482	0.0600
1	-1.3584	-1.3402	1.7732	0.3798	-0.5032

Dataset Licensing

The dataset is licensed under the Database Contents License (DbCL).

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Permission

The DbCL license explicitly allows use of this dataset for this final assignment.

Dataset Author

- Machine Learning Group - ULB

Dataset Source

After browsing Kaggle, I selected a dataset that is complex and challenging while providing rich features for the model to learn from.

Link to dataset: <https://www.kaggle.com/datasets/mlg-ulb/creditcardfraud/data>

Justification for this dataset

This dataset supports a full end-to-end deep learning workflow: clear labels, numeric features, and a real-world class imbalance that demands careful evaluation.

Rationale behind why this dataset was chosen

- It matches the **problem framing**: a real-world binary classification task where the positive class (fraud) is rare and costly to miss.
- It matches the **data modality**: fixed-length, fully numeric, tabular features that are well-suited to a feedforward MLP as a strong first baseline.
- It forces a realistic **evaluation setup**: extreme imbalance means accuracy is not meaningful, so the workflow naturally prioritizes PR AUC, precision/recall, and explicit threshold selection.
- It encourages good **experimental discipline**: preprocessing must be fit on the training split only (to avoid leakage) and the final test set can be kept untouched for a single, final report.

Limitations of this dataset and mitigation strategy

- **Limited interpretability**: V1–V28 are anonymized PCA components, so feature-level explanations are not meaningful.
 - *Mitigation*: focus on predictive performance, stability across runs, and careful threshold selection rather than per-feature interpretation.
- **Potential time effects**: Time reflects ordering within the 2-day window.
 - *Mitigation*: use a time-aware split (train on earlier, validate/test on later) to better reflect deployment.

Step 1 Cont'd — Define success metrics

Objective

The primary objective is to detect fraudulent transactions while minimizing false positives. Because fraud is rare, the evaluation focuses on minority-class performance and selecting an operating point that reflects the cost of errors.

Step 3 — Choose an evaluation protocol

Holdout Protocol

1. The data will be split into:

- Training set
- Validation set
- Test set

Why: we need separate data for learning parameters (train), choosing settings (validation), and an unbiased final report (test).

How: use a time-aware split when possible (earlier transactions → train, later → validation/test) so evaluation better matches deployment.

2. Preprocessing decisions are fitted using the training set exclusively.

Why: using any information from validation/test (even feature scaling statistics) leaks signal and inflates performance.

How: fit transforms on `X_train` only (e.g., standardization mean/std, any imputation rules), then apply the fitted transforms unchanged to `X_val` and `X_test`.

3. The validation set is only used for model and threshold selection.

Why: the validation set simulates unseen data during development; using it only for selection reduces the risk of overfitting the final report.

How: compare candidate models using PR AUC/recall/precision on validation; choose hyperparameters and pick an operating threshold (e.g., maximize recall subject to minimum precision) using validation predictions.

4. Final performance is evaluated on the untouched test set.

Why: the test set should be a single, unbiased estimate of how the chosen pipeline will perform in the real world.

How: once preprocessing + model + threshold are finalized, run inference once on `X_test` and report the locked metrics (PR AUC and confusion matrix at the chosen threshold).

Evaluation metrics

This section describes how performance will be measured based on the pre-defined success criteria.

Primary Metrics

Metric	What it measures	Why it matters for fraud under heavy class imbalance
Precision-Recall AUC	Area under the precision-recall curve across decision thresholds	Strong overall summary metric when fraud is rare, more informative than accuracy
Recall	True positive rate, how many actual fraud cases are correctly detected	Directly captures missed fraud risk since low recall means more fraud slips through
F1 Score	Harmonic mean of precision and recall	Useful single number when you want a balanced tradeoff between catching fraud and limiting false alarms

Secondary Metric

Secondary metric	Description	Purpose
Confusion matrix at a predetermined threshold	Uses TP, FP, TN, FN to make tradeoffs explicit	Shows performance at the chosen operating point and clarifies the cost of each type of mistake
Error rates	False negative rate and false positive rate to quantify misses and false alarms	Measures miss risk versus false alarm burden in a comparable way
Calibration check	Compare predicted probabilities with observed outcomes using a simple binning table to verify probability quality	Checks whether predicted risk scores align with real observed fraud rates

Justification for evaluation metrics

Fraud is a rare event, so a single metric can be misleading. A model may look strong on one metric while failing in practice. The primary metric provides a consistent rule for model comparison, while secondary metrics provide the context needed to interpret false-positive and false-negative tradeoffs.

Implications of the evaluation metrics

1. Precision reflects workload and customer friction.
2. Recall reflects loss prevention, often translating into direct financial losses.

3. PR AUC reflects ranking quality under rare fraud across thresholds.
4. The confusion matrix is reported at an operating threshold aligned with transaction behavior.

Step 4 — Prepare the data

Data preparation plan

To prepare the data and avoid leakage:

1. Use a time-aware split: earlier transactions for training, later transactions for validation/test.
2. Fit all preprocessing steps (scaling, imputation if needed) on the training set only.
3. Apply the same fitted transforms to validation and test sets.
4. Preserve the class imbalance during splitting to reflect real deployment.
5. Track feature distributions and label rate over time to identify drift.
6. Use a small threshold sweep on the validation set for later operating-point selection.
7. Calibrate probabilities with simple binning to sanity-check outputs.
8. Re-train periodically as base rates drift in production.

Data checks and class imbalance

- Check for missing values, big outliers, and changes between the train/val/test splits.
- Scale features using numbers from the training set only.
- Handle imbalance with class weights or resampling.
- Keep notes of every preprocessing step so results are repeatable.

```
In [1]: import sys

# Install into THIS kernel environment
%pip -q install -U "kagglehub[pandas-datasets]"

import kagglehub
import pandas as pd

print("Kernel Python:", sys.version)
print("Kernel executable:", sys.executable)

# Download the raw file first, then read with pandas (avoids kagglehub's UTF
dataset_path = kagglehub.dataset_download("mlg-ulb/creditcardfraud")
print("Dataset downloaded to:", dataset_path)

import os
csv_path = os.path.join(dataset_path, "creditcard.csv")
df = pd.read_csv(csv_path)
```

```
print(f"Shape: {df.shape}")
print(df.head())
```

Note: you may need to restart the kernel to use updated packages.
Kernel Python: 3.12.3 (main, Nov 6 2025, 13:44:16) [GCC 13.3.0]
Kernel executable: /usr/bin/python3
Dataset downloaded to: /home/ubuntu/.cache/kagglehub/datasets/mlg-ulb/creditcardfraud/versions/3
Shape: (284807, 31)

	Time	V1	V2	V3	V4	V5	V6	V7
0	0.0	-1.359807	-0.072781	2.536347	1.378155	-0.338321	0.462388	0.239599
1	0.0	1.191857	0.266151	0.166480	0.448154	0.060018	-0.082361	-0.078803
2	1.0	-1.358354	-1.340163	1.773209	0.379780	-0.503198	1.800499	0.791461
3	1.0	-0.966272	-0.185226	1.792993	-0.863291	-0.010309	1.247203	0.237609
4	2.0	-1.158233	0.877737	1.548718	0.403034	-0.407193	0.095921	0.592941

	V8	V9	...	V21	V22	V23	V24	V25
0	0.098698	0.363787	...	-0.018307	0.277838	-0.110474	0.066928	0.128539
1	0.085102	-0.255425	...	-0.225775	-0.638672	0.101288	-0.339846	0.167170
2	0.247676	-1.514654	...	0.247998	0.771679	0.909412	-0.689281	-0.327642
3	0.377436	-1.387024	...	-0.108300	0.005274	-0.190321	-1.175575	0.647376
4	-0.270533	0.817739	...	-0.009431	0.798278	-0.137458	0.141267	-0.206010

	V26	V27	V28	Amount	Class
0	-0.189115	0.133558	-0.021053	149.62	0
1	0.125895	-0.008983	0.014724	2.69	0
2	-0.139097	-0.055353	-0.059752	378.66	0
3	-0.221929	0.062723	0.061458	123.50	0
4	0.502292	0.219422	0.215153	69.99	0

[5 rows x 31 columns]

Step 4 implementation (code)

The code below loads the dataset from `data/creditcard.csv`. If the file is missing, it will try to download it using `kagglehub` and then save it to `data/creditcard.csv`.

- Expected columns include `Time`, `Amount`, `V1` ... `V28`, and `Class` (target label).

```
In [2]: from pathlib import Path
import os

import numpy as np
import pandas as pd

DATA_PATH = Path("data/creditcard.csv")

# If the CSV isn't present locally, try fetching it via kagglehub.
if not DATA_PATH.exists():
```

```

try:
    import kagglehub

    # Download the raw files (avoids kagglehub's internal UTF-8 read issue)
    dataset_dir = kagglehub.dataset_download("mlg-ulb/creditcardfraud")
    src_csv = os.path.join(dataset_dir, "creditcard.csv")
    df = pd.read_csv(src_csv)

    # Cache locally so future runs don't re-download
    DATA_PATH.parent.mkdir(parents=True, exist_ok=True)
    df.to_csv(DATA_PATH, index=False)
    print("Downloaded via kagglehub and saved to:", DATA_PATH)
except Exception as e:
    raise FileNotFoundError(
        f"Could not find {DATA_PATH} and kagglehub download failed.\n"
        "Either place the file at data/creditcard.csv, or configure KaggleHub to"
        f"Original error: {type(e).__name__}: {e}"
    ) from e
else:
    df = pd.read_csv(DATA_PATH)
    print("Loaded:", DATA_PATH)

print("Shape:", df.shape)
print(df.head(3))

if "Class" not in df.columns:
    raise ValueError("Expected a 'Class' column (0=legit, 1=fraud).")

fraud_rate = df["Class"].mean()
print(f"Fraud rate: {fraud_rate:.6f} ({df['Class'].sum()} / {len(df)})")

```

Loaded: data/creditcard.csv
Shape: (284807, 31)

	Time	V1	V2	V3	V4	V5	V6	V7
0	0.0	-1.359807	-0.072781	2.536347	1.378155	-0.338321	0.462388	0.239599
1	0.0	1.191857	0.266151	0.166480	0.448154	0.060018	-0.082361	-0.078803
2	1.0	-1.358354	-1.340163	1.773209	0.379780	-0.503198	1.800499	0.791461

	V8	V9	...	V21	V22	V23	V24	V25
0	0.098698	0.363787	...	-0.018307	0.277838	-0.110474	0.066928	0.128539
1	0.085102	-0.255425	...	-0.225775	-0.638672	0.101288	-0.339846	0.167170
2	0.247676	-1.514654	...	0.247998	0.771679	0.909412	-0.689281	-0.327642

	V26	V27	V28	Amount	Class
0	-0.189115	0.133558	-0.021053	149.62	0
1	0.125895	-0.008983	0.014724	2.69	0
2	-0.139097	-0.055353	-0.059752	378.66	0

[3 rows x 31 columns]
Fraud rate: 0.001727 (492 / 284807)

Exploratory Data Analysis (EDA) — Visualizing the Dataset

Before splitting and modelling, we explore the dataset visually. These charts serve several purposes:

1. **Class distribution** — Quantify and visualize the extreme imbalance between fraud and non-fraud.
2. **Transaction amount** — Compare the spending patterns of fraudulent vs legitimate transactions.
3. **Transaction time** — Examine when transactions (and fraud) occur over the 2-day window.
4. **Feature correlations** — Identify which features are most associated with the target and with each other.
5. **Feature distributions by class** — Highlight which PCA components separate fraud from non-fraud most clearly.
6. **Dimensionality reduction** — Use t-SNE to project all 30 features into 2D and visualize class separation.

All visualizations use the full dataset before any splitting, so no leakage concerns arise at this stage.

```
In [3]: import matplotlib.pyplot as plt
import seaborn as sns

# -----
# 1. Class Distribution - Bar chart + Pie chart
# -----
class_counts = df["Class"].value_counts().sort_index()
labels = ["Non-fraud (0)", "Fraud (1)"]
colors = ["#4c72b0", "#c44e52"]

fig, axes = plt.subplots(1, 2, figsize=(13, 5))

# Bar chart with log-scale option for visibility
bars = axes[0].bar(labels, class_counts.values, color=colors, edgecolor="black")
axes[0].set_ylabel("Number of Transactions")
axes[0].set_title("Class Distribution (Count)")
for bar, count in zip(bars, class_counts.values):
    axes[0].text(bar.get_x() + bar.get_width() / 2, bar.get_height() + 1500,
                 f"{count:,}", ha="center", va="bottom", fontsize=11, fontweight="bold")

# Pie chart with percentage
axes[1].pie(
    class_counts.values,
    labels=labels,
    autopct=lambda pct: f'{pct:.3f}%\n{int(round(pct / 100 * class_counts.s
    colors=colors,
    startangle=90,
    explode=(0, 0.1),
    textprops={"fontsize": 10},
    wedgeprops={"edgecolor": "black", "linewidth": 0.5},
)
axes[1].set_title("Class Distribution (Proportion)")
```

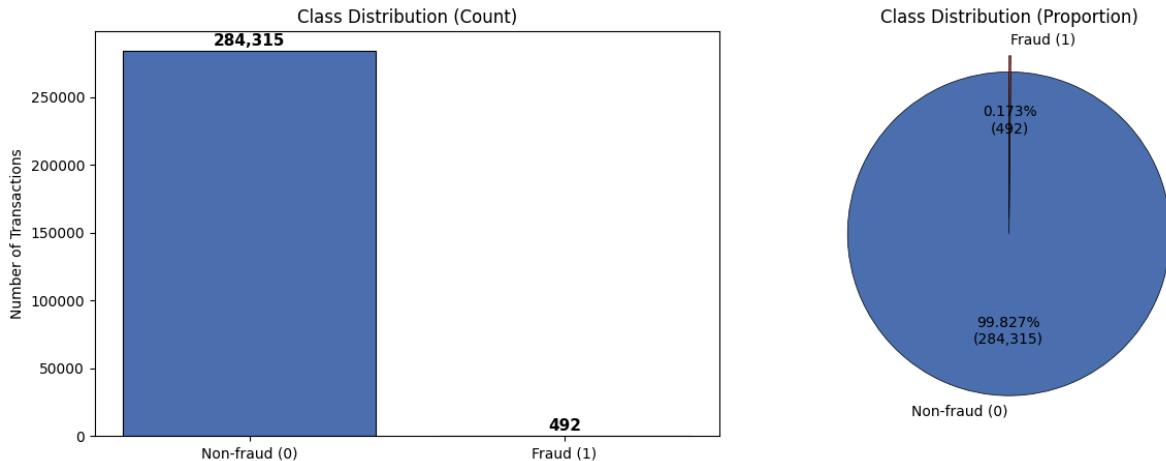
```

plt.suptitle("Extreme Class Imbalance: Fraud accounts for only 0.17% of all
              fontsize=12, y=1.02, fontstyle="italic")
plt.tight_layout()
plt.show()

print(f"Non-fraud: {class_counts[0]:>8}, ({class_counts[0]/len(df)*100:.4f}")
print(f"Fraud:      {class_counts[1]:>8}, ({class_counts[1]/len(df)*100:.4f}")
print(f"Imbalance ratio: 1 fraud per {class_counts[0]//class_counts[1]}, le

```

Extreme Class Imbalance: Fraud accounts for only 0.17% of all transactions



Non-fraud: 284,315 (99.8273%)
 Fraud: 492 (0.1727%)
 Imbalance ratio: 1 fraud per 577 legitimate transactions

In [4]:

```

# -----
# 2. Transaction Amount Distribution – Fraud vs Non-fraud
# -----
fraud_amounts = df.loc[df["Class"] == 1, "Amount"]
legit_amounts = df.loc[df["Class"] == 0, "Amount"]

fig, axes = plt.subplots(1, 3, figsize=(18, 5))

# (a) Overlapping histograms (log scale on y-axis for visibility)
axes[0].hist(legit_amounts, bins=80, alpha=0.6, color="#4c72b0",
             label=f"Non-fraud (n={len(legit_amounts)}:)", density=True)
axes[0].hist(fraud_amounts, bins=80, alpha=0.7, color="#c44e52",
             label=f"Fraud (n={len(fraud_amounts)}:)", density=True)
axes[0].set_xlabel("Transaction Amount ($)")
axes[0].set_ylabel("Density")
axes[0].set_title("Amount Distribution (Overlapping)")
axes[0].legend(fontsize=9)
axes[0].set_xlim(0, 500)

# (b) Log-transformed amount histogram
axes[1].hist(np.log1p(legit_amounts), bins=60, alpha=0.6, color="#4c72b0",
             label="Non-fraud", density=True)
axes[1].hist(np.log1p(fraud_amounts), bins=60, alpha=0.7, color="#c44e52",
             label="Fraud", density=True)
axes[1].set_xlabel("log(1 + Amount)")
axes[1].set_ylabel("Density")
axes[1].set_title("Amount Distribution (Log-Transformed)")

```

```

axes[1].legend(fontsize=9)

# (c) Box plot comparison
box_data = [legit_amounts.values, fraud_amounts.values]
bp = axes[2].boxplot(box_data, labels=["Non-fraud", "Fraud"], patch_artist=True,
                     showfliers=False, widths=0.5)
bp["boxes"][0].set_facecolor("#4c72b0")
bp["boxes"][1].set_facecolor("#c44e52")
for box in bp["boxes"]:
    box.set_alpha(0.7)
axes[2].set_ylabel("Transaction Amount ($)")
axes[2].set_title("Amount Box Plot (Outliers Hidden)")

plt.suptitle("Fraudulent transactions tend to have different amount distributions than legitimate ones",
             fontsize=12, y=1.02, fontstyle="italic")
plt.tight_layout()
plt.show()

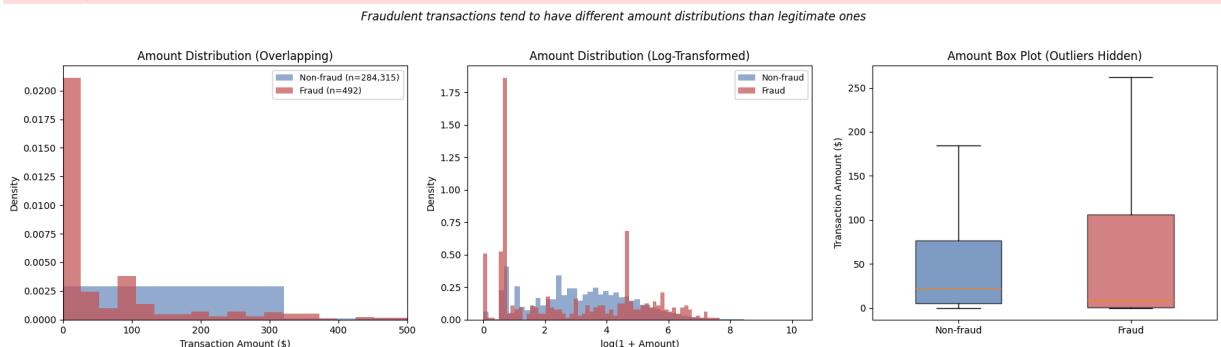
# Summary statistics
print("Amount summary statistics:")
print(f" Non-fraud - mean: ${legit_amounts.mean():.2f}, median: ${legit_amounts.median():.2f}, std: ${legit_amounts.std():.2f}, max: ${legit_amounts.max():.2f}")
print(f" Fraud - mean: ${fraud_amounts.mean():.2f}, median: ${fraud_amounts.median():.2f}, std: ${fraud_amounts.std():.2f}, max: ${fraud_amounts.max():.2f}")

```

/tmp/ipykernel_13778/2906343844.py:32: MatplotlibDeprecationWarning: The 'labels' parameter of boxplot() has been renamed 'tick_labels' since Matplotlib 3.9; support for the old name will be dropped in 3.11.

```

bp = axes[2].boxplot(box_data, labels=["Non-fraud", "Fraud"], patch_artist=True,
```



Amount summary statistics:

Non-fraud	- mean: \$88.29, median: \$22.00, std: \$250.11, max: \$25691.16
Fraud	- mean: \$122.21, median: \$9.25, std: \$256.68, max: \$2125.87

In [5]:

```

# -----
# 3. Transaction Time Distribution - Fraud vs Non-fraud + Fraud rate over time
# -----
time_hours = df["Time"] / 3600 # convert seconds to hours

fig, axes = plt.subplots(2, 2, figsize=(16, 10))

# (a) Overall transaction volume over time
axes[0, 0].hist(time_hours, bins=48, color="#4c72b0", edgecolor="white", alpha=0.8)
axes[0, 0].set_xlabel("Time (hours since first transaction)")
axes[0, 0].set_ylabel("Number of Transactions")
axes[0, 0].set_title("Transaction Volume Over Time (All)")

# (b) Fraud vs Non-fraud transaction volume
axes[0, 1].hist(time_hours[fraud], bins=48, color="#c44e52", edgecolor="white", alpha=0.8)
axes[0, 1].set_xlabel("Time (hours since first transaction)")
axes[0, 1].set_ylabel("Number of Transactions")
axes[0, 1].set_title("Transaction Volume Over Time (Fraud vs Non-fraud)")

# (c) Fraud rate over time
axes[1, 0].bar(time_hours[fraud].quantile([0.01, 0.05, 0.1, 0.25, 0.5, 0.75, 0.9, 0.95, 0.99]), [1, 1, 1, 1, 1, 1, 1, 1, 1])
axes[1, 0].set_xlabel("Time (hours since first transaction)")
axes[1, 0].set_ylabel("Fraud Rate")
axes[1, 0].set_title("Fraud Rate Over Time (All)")

# (d) Fraud rate over time for fraud vs non-fraud
axes[1, 1].bar(time_hours[fraud].quantile([0.01, 0.05, 0.1, 0.25, 0.5, 0.75, 0.9, 0.95, 0.99]), [1, 1, 1, 1, 1, 1, 1, 1, 1])
axes[1, 1].set_xlabel("Time (hours since first transaction)")
axes[1, 1].set_ylabel("Fraud Rate")
axes[1, 1].set_title("Fraud Rate Over Time (Fraud vs Non-fraud)")

```

```

# (b) Fraud vs Non-fraud time distribution
axes[0, 1].hist(time_hours[df["Class"] == 0], bins=48, alpha=0.6, color="#4c4c4c",
                 label="Non-fraud", density=True)
axes[0, 1].hist(time_hours[df["Class"] == 1], bins=48, alpha=0.7, color="#c44c4c",
                 label="Fraud", density=True)
axes[0, 1].set_xlabel("Time (hours since first transaction)")
axes[0, 1].set_ylabel("Density")
axes[0, 1].set_title("Time Distribution by Class (Normalized)")
axes[0, 1].legend()

# (c) Fraud rate over time (binned)
n_bins_time = 48
time_bins = pd.cut(time_hours, bins=n_bins_time)
fraud_rate_by_time = df.groupby(time_bins, observed=False)[["Class"]].mean()
bin_centers = [interval.mid for interval in fraud_rate_by_time.index]

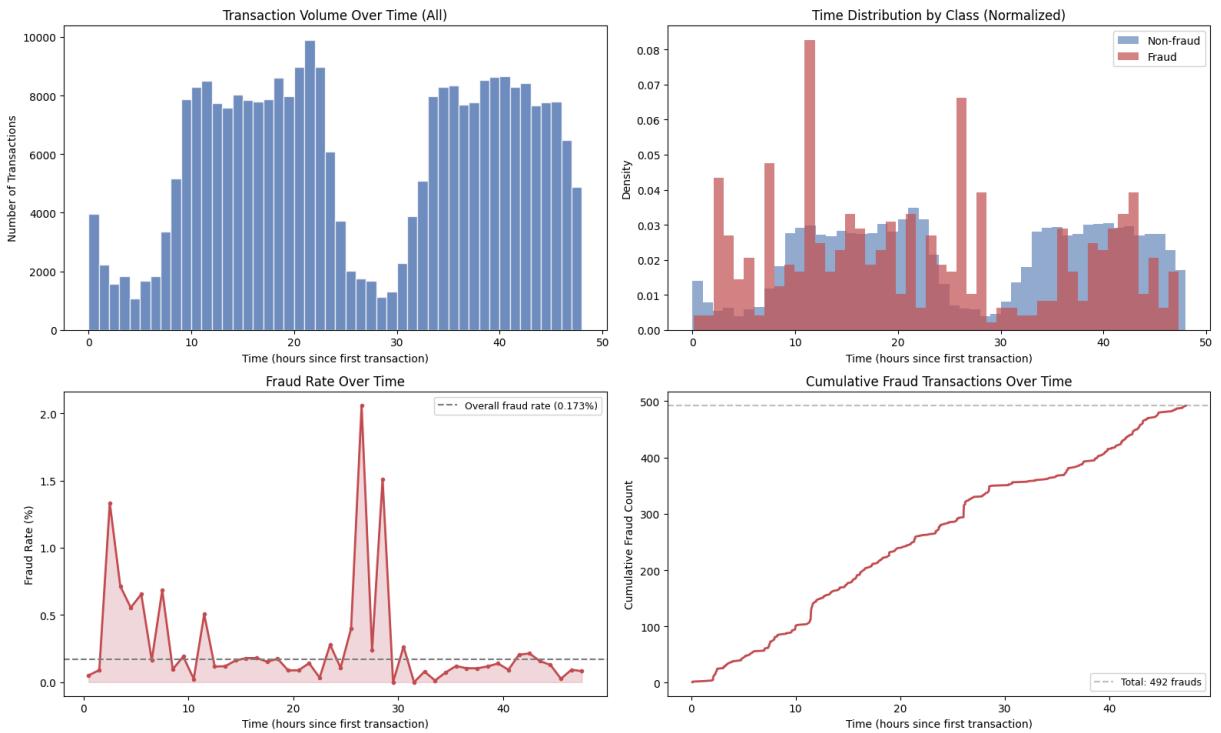
axes[1, 0].plot(bin_centers, fraud_rate_by_time.values * 100, color="#c44e52",
                 linewidth=2, marker="o", markersize=3)
axes[1, 0].fill_between(bin_centers, fraud_rate_by_time.values * 100,
                       alpha=0.2, color="#c44e52")
axes[1, 0].set_xlabel("Time (hours since first transaction)")
axes[1, 0].set_ylabel("Fraud Rate (%)")
axes[1, 0].set_title("Fraud Rate Over Time")
axes[1, 0].axhline(y=df["Class"].mean() * 100, color="grey", linestyle="--",
                   label=f"Overall fraud rate ({df['Class'].mean()*100:.3f}%)")
axes[1, 0].legend(fontsize=9)

# (d) Cumulative fraud count over time
fraud_times = time_hours[df["Class"] == 1].sort_values()
axes[1, 1].plot(fraud_times.values, np.arange(1, len(fraud_times) + 1),
                 color="#c44e52", linewidth=2)
axes[1, 1].set_xlabel("Time (hours since first transaction)")
axes[1, 1].set_ylabel("Cumulative Fraud Count")
axes[1, 1].set_title("Cumulative Fraud Transactions Over Time")
axes[1, 1].axhline(y=len(fraud_times), color="grey", linestyle="--", alpha=0.5,
                   label=f"Total: {len(fraud_times)} frauds")
axes[1, 1].legend(fontsize=9)

plt.suptitle("Temporal patterns in transactions and fraud occurrence",
             fontsize=13, y=1.01, fontstyle="italic")
plt.tight_layout()
plt.show()

```

Temporal patterns in transactions and fraud occurrence



```
In [6]: # -----
# 4. Correlation Heatmap - Feature correlations with the target
# -----
fig, axes = plt.subplots(1, 2, figsize=(18, 7))

# (a) Correlation of each feature with Class (target)
corr_with_target = df.drop(columns=["Class"]).corrwith(df["Class"]).sort_values()

bar_colors = ["#c44e52" if v < 0 else "#4c72b0" for v in corr_with_target.values]
axes[0].barh(corr_with_target.index, corr_with_target.values, color=bar_colors,
             edgecolor="white", linewidth=0.3)
axes[0].set_xlabel("Pearson Correlation with Class (Fraud)")
axes[0].set_title("Feature Correlation with Fraud Label")
axes[0].axvline(x=0, color="black", linewidth=0.8)

# Highlight the most correlated features
for i, (feat, val) in enumerate(corr_with_target.items()):
    if abs(val) > 0.1:
        axes[0].text(val + 0.005 * np.sign(val), i, f"{val:.3f}", va="center")

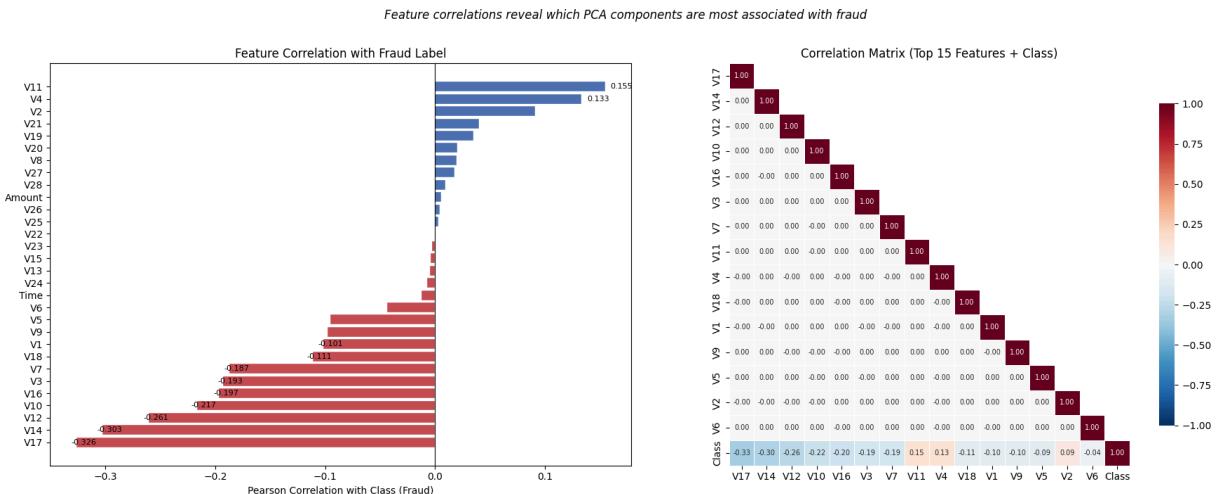
# (b) Correlation matrix heatmap of top features (most correlated with Class)
top_features = corr_with_target.abs().nlargest(15).index.tolist()
top_features_with_class = top_features + ["Class"]
corr_matrix = df[top_features_with_class].corr()

mask = np.triu(np.ones_like(corr_matrix, dtype=bool), k=1)
sns.heatmap(
    corr_matrix,
    mask=mask,
    annot=True,
    fmt=".2f",
    cmap="RdBu_r",
)
```

```
center=0,
vmin=-1,
vmax=1,
square=True,
linewidths=0.5,
ax=axes[1],
cbar_kws={"shrink": 0.8},
annot_kws={"fontsize": 7},
)
axes[1].set_title("Correlation Matrix (Top 15 Features + Class)")

plt.suptitle("Feature correlations reveal which PCA components are most asso
              fontsize=12, y=1.01, fontstyle="italic")
plt.tight_layout()
plt.show()

# Print top positive and negative correlations
print("Top 5 positively correlated with fraud:")
for feat, val in corr_with_target nlargest(5).items():
    print(f" {feat:>8s}: {val:+.4f}")
print("\nTop 5 negatively correlated with fraud:")
for feat, val in corr_with_target.nsmallest(5).items():
    print(f" {feat:>8s}: {val:+.4f}")
```



Top 5 positively correlated with fraud:

V11: +0.1549
V4: +0.1334
V2: +0.0913
V21: +0.0404
V19: +0.0348

Top 5 negatively correlated with fraud:

V17: -0.3265
V14: -0.3025
V12: -0.2606
V10: -0.2169
V16: -0.1965

```
In [7]: # -----  
# 5. Violin + Strip Plots – Top discriminative features by class  
# -----
```

```

# Select the 8 features most correlated (positive or negative) with Class
corr_abs = df.drop(columns=["Class"]).corrwith(df["Class"]).abs().sort_values
top8_features = corr_abs.head(8).index.tolist()

fig, axes = plt.subplots(2, 4, figsize=(20, 10))
axes = axes.ravel()

for i, feat in enumerate(top8_features):
    # Subsample non-fraud for clearer violin plots (fraud is already small)
    fraud_vals = df.loc[df["Class"] == 1, feat]
    legit_sample = df.loc[df["Class"] == 0, feat].sample(n=min(2000, (df["Cl
                                                random_state=42)

    plot_df = pd.DataFrame({
        feat: pd.concat([legit_sample, fraud_vals], ignore_index=True),
        "Class": ["Non-fraud"] * len(legit_sample) + ["Fraud"] * len(fraud_v
    })

    sns.violinplot(data=plot_df, x="Class", y=feat, palette={"Non-fraud": "#
                                inner="quartile", ax=axes[i], cut=0, linewidth=0.8)
    axes[i].set_title(f"\n{feat}\n(corr={corr_abs[feat]:.3f})", fontsize=10)
    axes[i].set_xlabel("")

plt.suptitle("Distribution of the 8 most discriminative features – Fraud vs
              font-size=13, y=1.01, font-style="italic")
plt.tight_layout()
plt.show()

```

```
/tmp/ipykernel_13778/1859238190.py:21: FutureWarning:
```

```
Passing `palette` without assigning `hue` is deprecated and will be removed in v0.14.0. Assign the `x` variable to `hue` and set `legend=False` for the same effect.
```

```
    sns.violinplot(data=plot_df, x="Class", y=feat, palette={"Non-fraud": "#4c72b0", "Fraud": "#c44e52"},  
/tmp/ipykernel_13778/1859238190.py:21: FutureWarning:
```

```
Passing `palette` without assigning `hue` is deprecated and will be removed in v0.14.0. Assign the `x` variable to `hue` and set `legend=False` for the same effect.
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/tmp/ipykernel_13778/1859238190.py:21: FutureWarning:
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/tmp/ipykernel_13778/1859238190.py:21: FutureWarning:
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Passing `palette` without assigning `hue` is deprecated and will be removed in v0.14.0. Assign the `x` variable to `hue` and set `legend=False` for the same effect.
```

```
    sns.violinplot(data=plot_df, x="Class", y=feat, palette={"Non-fraud": "#4c72b0", "Fraud": "#c44e52"},  
/tmp/ipykernel_13778/1859238190.py:21: FutureWarning:
```

```
Passing `palette` without assigning `hue` is deprecated and will be removed in v0.14.0. Assign the `x` variable to `hue` and set `legend=False` for the same effect.
```

```
    sns.violinplot(data=plot_df, x="Class", y=feat, palette={"Non-fraud": "#4c72b0", "Fraud": "#c44e52"},  
/tmp/ipykernel_13778/1859238190.py:21: FutureWarning:
```

```
Passing `palette` without assigning `hue` is deprecated and will be removed in v0.14.0. Assign the `x` variable to `hue` and set `legend=False` for the same effect.
```

```
    sns.violinplot(data=plot_df, x="Class", y=feat, palette={"Non-fraud": "#4c72b0", "Fraud": "#c44e52"},  
/tmp/ipykernel_13778/1859238190.py:21: FutureWarning:
```

```
Passing `palette` without assigning `hue` is deprecated and will be removed in v0.14.0. Assign the `x` variable to `hue` and set `legend=False` for the same effect.
```

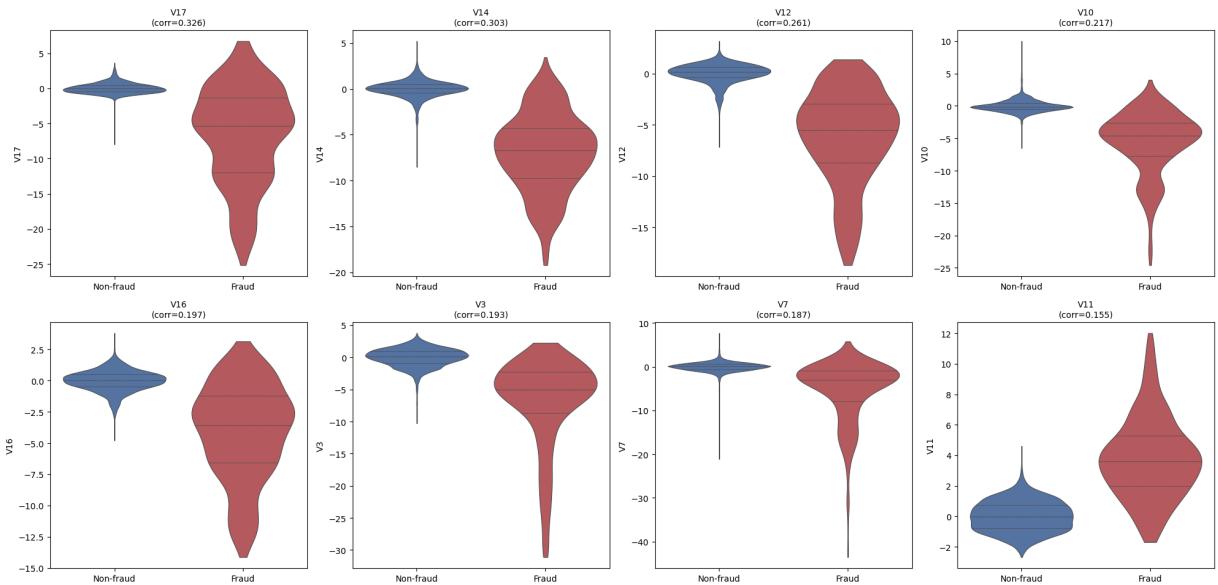
```
    sns.violinplot(data=plot_df, x="Class", y=feat, palette={"Non-fraud": "#4c72b0", "Fraud": "#c44e52"},
```

```
/tmp/ipykernel_13778/1859238190.py:21: FutureWarning:
```

Passing `palette` without assigning `hue` is deprecated and will be removed in v0.14.0. Assign the `x` variable to `hue` and set `legend=False` for the same effect.

```
sns.violinplot(data=plot_df, x="Class", y=feat, palette={"Non-fraud": "#4c72b0", "Fraud": "#c44e52"},
```

Distribution of the 8 most discriminative features — Fraud vs Non-fraud



```
In [8]: # -----
# 6. t-SNE 2D Projection – Visualize class separation in reduced dimensions
# -----
from sklearn.manifold import TSNE

# Subsample for speed: all fraud + a random sample of non-fraud
np.random.seed(42)
fraud_idx = df[df["Class"] == 1].index.values
legit_idx = np.random.choice(df[df["Class"] == 0].index.values, size=3000, r
sample_idx = np.concatenate([legit_idx, fraud_idx])
np.random.shuffle(sample_idx)

X_sample = df.loc[sample_idx, [c for c in df.columns if c != "Class"]].values
y_sample = df.loc[sample_idx, "Class"].values

# Run t-SNE
# scikit-learn 1.8+ replaces n_iter with max_iter
tsne = TSNE(n_components=2, random_state=42, perplexity=30, max_iter=1000, l
X_tsne = tsne.fit_transform(X_sample)

# Plot
fig, ax = plt.subplots(figsize=(10, 8))

# Plot non-fraud first (background), then fraud on top
mask_legit = y_sample == 0
mask_fraud = y_sample == 1

ax.scatter(X_tsne[mask_legit, 0], X_tsne[mask_legit, 1],
           c="#4c72b0", alpha=0.3, s=10, label=f"Non-fraud (n={mask_legit.sum()})")
ax.scatter(X_tsne[mask_fraud, 0], X_tsne[mask_fraud, 1],
           c="#c44e52", alpha=0.3, s=10, label=f"Fraud (n={mask_fraud.sum()})")
```

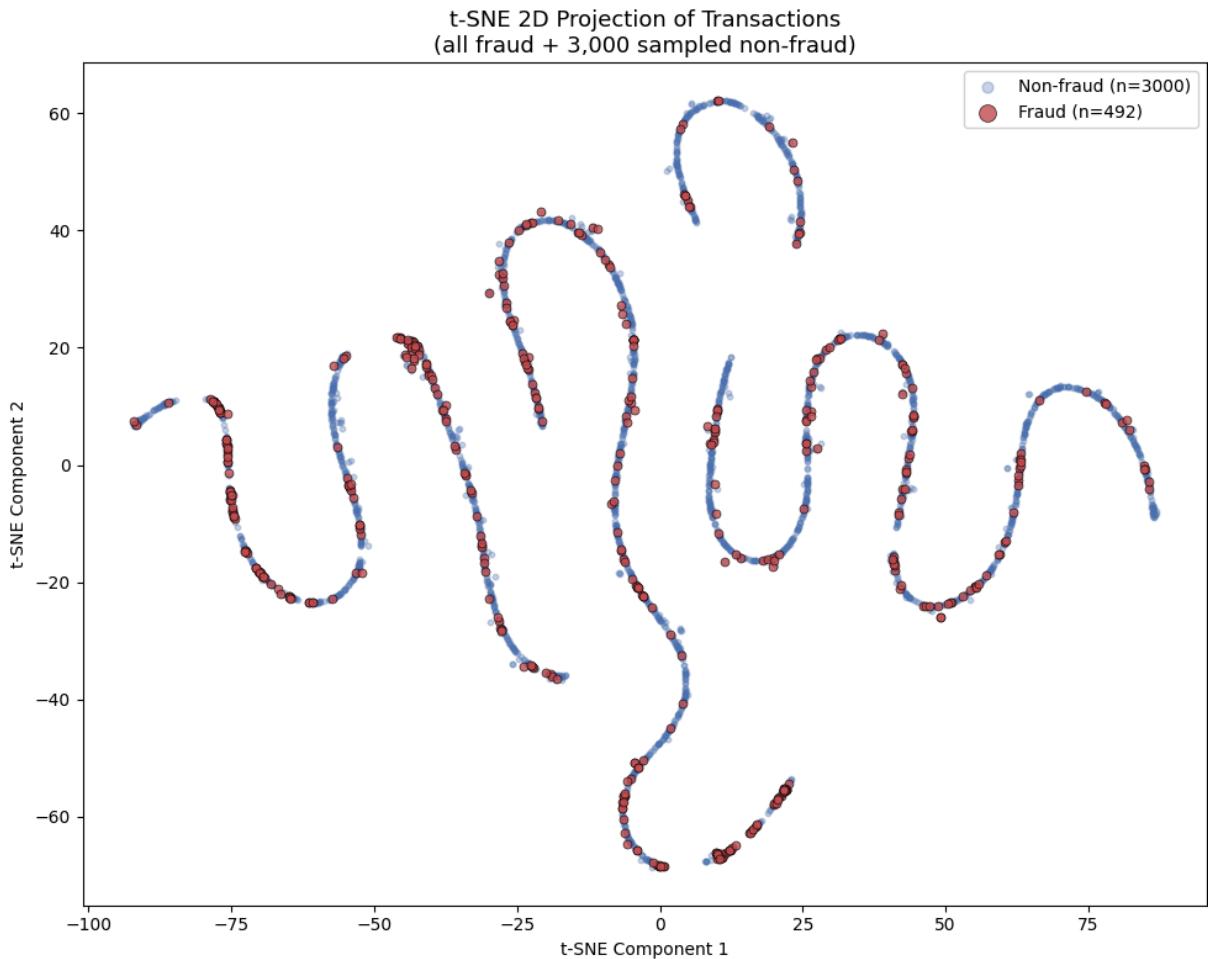
```

ax.scatter(X_tsne[mask_fraud, 0], X_tsne[mask_fraud, 1],
           c="#c44e52", alpha=0.8, s=25, edgecolors="black", linewidth=0.5,
           label=f"Fraud (n={mask_fraud.sum()})", zorder=5)

ax.set_xlabel("t-SNE Component 1")
ax.set_ylabel("t-SNE Component 2")
ax.set_title("t-SNE 2D Projection of Transactions\n(all fraud + 3,000 sample\n            fontsize=13)
ax.legend(loc="upper right", fontsize=10, markerscale=2)
plt.tight_layout()
plt.show()

print(f"t-SNE computed on {len(sample_idx)} samples "
      f"({{mask_fraud.sum()}} fraud + {{mask_legit.sum()}} non-fraud)")

```



EDA Summary

The visualizations above reveal several key characteristics of the dataset:

- 1. Extreme class imbalance:** Fraud accounts for only ~0.17% of transactions. This confirms that accuracy is meaningless as a metric — a model predicting all non-fraud would achieve 99.83% accuracy while catching zero fraud.

2. **Amount differences:** Fraudulent transactions tend to have different amount distributions compared to legitimate ones. The log-transformed view and box plots make these differences more visible.
3. **Temporal patterns:** Transaction volume is not uniform over the 2-day window, and the fraud rate fluctuates over time. This supports the decision to use a time-aware train/validation/test split.
4. **Feature correlations:** Several PCA components (e.g., V14, V17, V12, V10) show moderate-to-strong correlations with the fraud label. The correlation heatmap also confirms that PCA components are largely uncorrelated with each other (as expected from PCA), which is beneficial for modelling.
5. **Violin plots:** The most discriminative features show visibly different distributions for fraud vs non-fraud, with fraud transactions having shifted or broader distributions in key components.
6. **t-SNE projection:** The 2D projection shows that fraud transactions are partially separable from legitimate ones in the feature space, though there is overlap. This suggests a non-linear model like an MLP may capture boundaries that a linear model cannot.

In [9]:

```
try:
    from sklearn.preprocessing import StandardScaler
except ImportError as e:
    raise ImportError(
        "scikit-learn is required for StandardScaler. Install it (e.g., `pip "
    ) from e

# Time-aware ordering (closer to deployment): train on earlier, test on later
if "Time" in df.columns:
    df = df.sort_values("Time").reset_index(drop=True)

feature_names = [c for c in df.columns if c != "Class"]
X = df[feature_names].to_numpy(dtype=np.float32)
y = df["Class"].to_numpy(dtype=np.int64)

n = len(df)
train_end = int(0.70 * n)
val_end = int(0.85 * n)

X_train, y_train = X[:train_end], y[:train_end]
X_val, y_val = X[train_end:val_end], y[train_end:val_end]
X_test, y_test = X[val_end:], y[val_end:]

print("Split sizes:")
print("- train:", X_train.shape, "fraud_rate=", float(y_train.mean()))
print("- val: ", X_val.shape, "fraud_rate=", float(y_val.mean()))
print("- test: ", X_test.shape, "fraud_rate=", float(y_test.mean()))
```

```

# Fit preprocessing on TRAIN ONLY to avoid leakage
scaler = StandardScaler()
X_train_scaled = scaler.fit_transform(X_train).astype(np.float32)
X_val_scaled = scaler.transform(X_val).astype(np.float32)
X_test_scaled = scaler.transform(X_test).astype(np.float32)

# Optional: class weights for imbalanced training
neg = int((y_train == 0).sum())
pos = int((y_train == 1).sum())
class_weight = {0: 1.0, 1: (neg / max(pos, 1))}

print("class_weight:", class_weight)

```

Split sizes:

- train: (199364, 30) fraud_rate= 0.0019261250777472363
- val: (42721, 30) fraud_rate= 0.001310830738980829
- test: (42722, 30) fraud_rate= 0.0012171714807359207

class_weight: {0: 1.0, 1: 518.1770833333334}

Split Success

The split ran successfully because we created **three non-overlapping subsets** (train/val/test) with clear row counts and the same number of input features (30 columns). The sizes are sensible (about 70% / 15% / 15%), and the **fraud rate stays low and in the expected range** across all splits.

The computed `class_weight` is large for class 1, which confirms fraud is rare in the training set and will be up-weighted during training. Finally, scaling is fit on `X_train` only and then applied to validation/test, which helps prevent data leakage.

Step 5 — Establish a baseline and pick a starting model

In Chollet's workflow, Step 5 answers two questions: "*What is the simplest thing that could work?*" and "*What is a reasonable starting architecture?*" Before investing effort in tuning, we need reference points that tell us whether a more complex model is actually adding value.

Why baselines matter

A baseline anchors the evaluation. Without one, there is no way to know whether a model's PR AUC of 0.70 is good or bad for this particular dataset and split. We establish **two** baselines of increasing complexity:

Baseline	What it tells us
Trivial baseline (always predict non-fraud)	Absolute floor — any model that cannot beat it is worse than useless.

Baseline	What it tells us
Logistic regression (class-weighted linear classifier)	Simplest learned model; shows how much performance comes from linear relationships alone and how much headroom remains for a non-linear MLP.

Starting model choice

After the baselines, we pick a starting deep-learning architecture. The choice is a **small-to-medium feedforward multilayer perceptron (MLP)** because:

- The input is fixed-length, fully numeric, and tabular — ideal for Dense layers.
- An MLP can capture non-linear interactions between PCA components that logistic regression cannot.
- It is fast to train and simple to debug before moving to more complex architectures.

The rest of this section implements these three models, evaluates them on the **validation set only**, and compares their performance side by side.

5.0 — Pre-modelling data sanity check

Before building any model, we verify the data is clean and confirm the assumptions from Step 4 still hold after splitting and scaling. This catches issues (NaNs introduced by scaling, duplicated rows leaking across splits, unexpected feature ranges) that would silently corrupt every model downstream.

```
In [10]: # -----
# Data sanity check before modelling
# -----
print("==> Missing values ==")
print(f" X_train NaN count: {np.isnan(X_train_scaled).sum()}")
print(f" X_val   NaN count: {np.isnan(X_val_scaled).sum()}")
print(f" X_test  NaN count: {np.isnan(X_test_scaled).sum()}")

print("\n==> Infinite values ==")
print(f" X_train Inf count: {np.isinf(X_train_scaled).sum()}")
print(f" X_val   Inf count: {np.isinf(X_val_scaled).sum()}")
print(f" X_test  Inf count: {np.isinf(X_test_scaled).sum()}")

print("\n==> Duplicate rows in original df ==")
n_dup = df.duplicated().sum()
print(f" Total duplicates: {n_dup} ({n_dup / len(df) * 100:.2f}%)")

print("\n==> Feature range after scaling (train) ==")
train_df_scaled = pd.DataFrame(X_train_scaled, columns=feature_names)
print(train_df_scaled.describe().loc[['mean', "std", "min", "max"]].round(2))

print("\n==> Label counts per split ==")
for name, labels in [("train", y_train), ("val", y_val), ("test", y_test)]:
```

```

unique, counts = np.unique(labels, return_counts=True)
print(f" {name:5s}: " + ".join(f"class {u}={c}" for u, c in zip(uniq
= Missing values =
X_train NaN count: 0
X_val   NaN count: 0
X_test  NaN count: 0

= Infinite values =
X_train Inf count: 0
X_val   Inf count: 0
X_test  Inf count: 0

= Duplicate rows in original df =
Total duplicates: 1081 (0.38%)

= Feature range after scaling (train) =
    Time      V1      V2      V3      V4      V5      V6      V7      V8      V9
V10      V11      V12      V13      V14      V15      V16      V17      V18      V19      V20      V21
V22      V23      V24      V25      V26      V27      V28      Amount
mean    0.00    0.00    0.00    0.00    0.00    0.00   -0.00    0.00   -0.00    0.00   -
0.00    0.00    0.00  -0.00  -0.00    0.00    0.00    0.00   -0.00  -0.00  -0.00    0.0
0    0.00    0.00    0.00    0.00  -0.00  -0.00    0.00    0.00
std     1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
0    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
min    -2.04  -29.77  -44.84  -23.49  -4.12  -30.87  -19.99  -35.72  -60.54  -11.84  -2
2.49  -4.73  -17.01  -5.65  -19.82  -4.85  -15.94  -28.28  -11.27  -8.79  -33.69  -47.1
6  -15.75  -73.34  -4.71  -21.08  -5.35  -57.27  -37.32  -0.36
max    1.81    1.35   13.60    6.26   12.01   25.64   17.15   30.15   16.52   13.72   2
1.74  11.43    7.24   4.39   10.78   6.03   6.89   10.36   6.05   6.84   52.59  36.8
7  15.26  31.14   6.66  15.18   7.19  30.84  107.84  78.61

= Label counts per split =
train: class 0=198980, class 1=384
val  : class 0=42665, class 1=56
test : class 0=42670, class 1=52

```

5.0.1 — Post-split visual sanity checks

The numerical sanity check above confirmed there are no NaNs, Infs, or severe anomalies. The following charts provide a **visual** verification that:

1. The splits have sensible class distributions (no accidental stratification issues).
2. Feature distributions are similar across train/val/test (no unexpected drift from the time-aware split).
3. The Amount and Time distributions remain consistent across splits.

```
In [11]: # -----
# Post-split visual checks
# -----
fig, axes = plt.subplots(2, 3, figsize=(18, 10))

# --- Row 1: Split-level class distribution ---
```

```

split_names = ["Train", "Validation", "Test"]
split_labels = [y_train, y_val, y_test]
split_sizes = [len(y_train), len(y_val), len(y_test)]

# (a) Bar chart of split sizes
bars = axes[0, 0].bar(split_names, split_sizes, color=["#4c72b0", "#55a868",
                                                       edgecolor="black", linewidth=0.8)
for bar, sz in zip(bars, split_sizes):
    axes[0, 0].text(bar.get_x() + bar.get_width() / 2, bar.get_height() + 50
                   f"{{sz:.1f}}", ha="center", va="bottom", fontsize=10, fontweight="bold")
axes[0, 0].set_ylabel("Number of Samples")
axes[0, 0].set_title("Split Sizes (70/15/15)")

# (b) Fraud rate per split
fraud_rates = [y.mean() * 100 for y in split_labels]
bar_colors = ["#4c72b0", "#55a868", "#c44e52"]
bars_fr = axes[0, 1].bar(split_names, fraud_rates, color=bar_colors, edgecolor="black", linewidth=0.8)
for bar, fr in zip(bars_fr, fraud_rates):
    axes[0, 1].text(bar.get_x() + bar.get_width() / 2, bar.get_height() + 0.5,
                   f"{{fr:.4f}}%", ha="center", va="bottom", fontsize=10)
axes[0, 1].set_ylabel("Fraud Rate (%)")
axes[0, 1].set_title("Fraud Rate per Split")
axes[0, 1].axhline(y=df["Class"].mean() * 100, color="grey", linestyle="--",
                    label=f"Overall: {df['Class'].mean()*100:.4f}%", linewidth=1)
axes[0, 1].legend(fontsize=9)

# (c) Fraud count per split (stacked)
fraud_counts = [y.sum() for y in split_labels]
legit_counts = [len(y) - y.sum() for y in split_labels]
axes[0, 2].bar(split_names, legit_counts, color="#4c72b0", label="Non-fraud")
axes[0, 2].bar(split_names, fraud_counts, bottom=legit_counts, color="#c44e52",
               label="Fraud", edgecolor="white")
axes[0, 2].set_ylabel("Count")
axes[0, 2].set_title("Class Counts per Split")
axes[0, 2].legend()
for i, (fc, name) in enumerate(zip(fraud_counts, split_names)):
    axes[0, 2].text(i, legit_counts[i] + fc + 500, f"Fraud: {fc}", ha="center", va="bottom")

# --- Row 2: Feature distributions across splits (scaled) ---
# Amount distribution across splits
amount_idx = feature_names.index("Amount")
axes[1, 0].hist(X_train_scaled[:, amount_idx], bins=60, alpha=0.5, color="#4c72b0",
                 label="Train", density=True)
axes[1, 0].hist(X_val_scaled[:, amount_idx], bins=60, alpha=0.5, color="#55a868",
                 label="Val", density=True)
axes[1, 0].hist(X_test_scaled[:, amount_idx], bins=60, alpha=0.5, color="#c44e52",
                 label="Test", density=True)
axes[1, 0].set_xlabel("Scaled Amount")
axes[1, 0].set_ylabel("Density")
axes[1, 0].set_title("Amount Distribution Across Splits (Scaled)")
axes[1, 0].legend(fontsize=9)
axes[1, 0].set_xlim(-2, 10)

# Time distribution across splits
time_idx = feature_names.index("Time")
axes[1, 1].hist(X_train_scaled[:, time_idx], bins=60, alpha=0.5, color="#4c72b0",
                 label="Train", density=True)

```

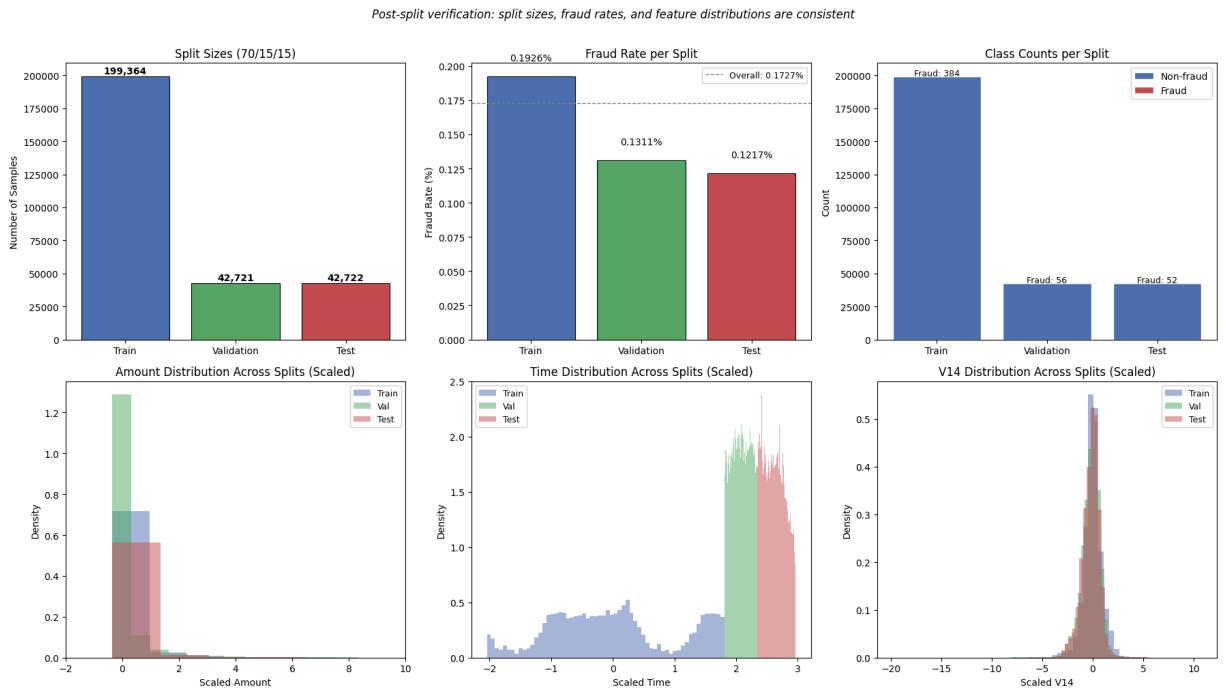
```

        label="Train", density=True)
axes[1, 1].hist(X_val_scaled[:, time_idx], bins=60, alpha=0.5, color="#55a86
                        label="Val", density=True)
axes[1, 1].hist(X_test_scaled[:, time_idx], bins=60, alpha=0.5, color="#c44e
                        label="Test", density=True)
axes[1, 1].set_xlabel("Scaled Time")
axes[1, 1].set_ylabel("Density")
axes[1, 1].set_title("Time Distribution Across Splits (Scaled)")
axes[1, 1].legend(fontsize=9)

# V14 distribution across splits (one of the most discriminative features)
v14_idx = feature_names.index("V14")
axes[1, 2].hist(X_train_scaled[:, v14_idx], bins=60, alpha=0.5, color="#4c72
                        label="Train", density=True)
axes[1, 2].hist(X_val_scaled[:, v14_idx], bins=60, alpha=0.5, color="#55a868
                        label="Val", density=True)
axes[1, 2].hist(X_test_scaled[:, v14_idx], bins=60, alpha=0.5, color="#c44e5
                        label="Test", density=True)
axes[1, 2].set_xlabel("Scaled V14")
axes[1, 2].set_ylabel("Density")
axes[1, 2].set_title("V14 Distribution Across Splits (Scaled)")
axes[1, 2].legend(fontsize=9)

plt.suptitle("Post-split verification: split sizes, fraud rates, and feature
                fontsize=12, y=1.01, fontstyle="italic")
plt.tight_layout()
plt.show()

```



5.1 — Trivial baseline: always predict non-fraud

The simplest possible model predicts **class 0** (non-fraud) for every transaction, regardless of its features. This is equivalent to a system that never flags anything.

What to expect:

Metric	Expected value	Why
Recall	0	The model never predicts fraud, so it catches zero fraud cases (all frauds are false negatives).
Precision	0	There are no positive predictions, so precision is undefined and reported as 0.
F1	0	Harmonic mean of two zeros.
PR AUC	~ fraud prevalence (~0.13%)	With constant scores, precision-recall collapses to the positive-class base rate.

Why this matters: In practice, a model with 99.87% accuracy (by predicting all non-fraud) sounds impressive but is completely useless — it misses every single fraud. This demonstrates why accuracy is not a meaningful metric under heavy class imbalance, and why we use PR AUC, recall, and F1 instead.

The cell below computes these metrics on the **validation set** and prints the full confusion matrix so we can see exactly how many fraud cases are missed.

```
In [12]: from sklearn.metrics import (
    precision_recall_curve,
    auc,
    f1_score,
    recall_score,
    precision_score,
    confusion_matrix,
)

# -----
# Trivial baseline: predict class 0 (non-fraud) for every sample
# -----
y_val_pred_trivial = np.zeros_like(y_val)                      # hard predictions (all 0
y_val_prob_trivial = np.zeros(len(y_val))                     # probability scores (all 0.5)

# Metrics at the trivial decision
print("== Trivial Baseline (always predict non-fraud) ==")
print(f"Recall: {recall_score(y_val, y_val_pred_trivial):.4f}")
print(f"Precision: {precision_score(y_val, y_val_pred_trivial, zero_division=True):.4f}")
print(f"F1 Score: {f1_score(y_val, y_val_pred_trivial):.4f}")

# PR AUC - for a constant predictor, precision = fraud_rate at all recall levels
prec_t, rec_t, _ = precision_recall_curve(y_val, y_val_prob_trivial)
pr_auc_trivial = auc(rec_t, prec_t)
print(f"PR AUC: {pr_auc_trivial:.4f}")

print("\nConfusion matrix (rows=actual, cols=predicted):")
cm = confusion_matrix(y_val, y_val_pred_trivial)
print(cm)
print(f"\n TN={cm[0,0]} FP={cm[0,1]}")
print(f" FN={cm[1,0]} TP={cm[1,1]}")
```

```
print(f"\n False-negative rate: {cm[1,0] / max(cm[1].sum(), 1):.4f}")
print(f" False-positive rate: {cm[0,1] / max(cm[0].sum(), 1):.4f}")
```

```
☰ Trivial Baseline (always predict non-fraud) ☰
```

```
Recall: 0.0000
```

```
Precision: 0.0000
```

```
F1 Score: 0.0000
```

```
PR AUC: 0.5007
```

```
Confusion matrix (rows=actual, cols=predicted):
```

```
[[42665 0]
 [ 56 0]]
```

```
TN=42665 FP=0
```

```
FN=56 TP=0
```

```
False-negative rate: 1.0000
```

```
False-positive rate: 0.0000
```

5.2 — Logistic regression baseline

Logistic regression is a classical linear classifier that models the log-odds of the positive class as a linear combination of input features. Despite its simplicity, it is a strong first baseline for tabular data.

Key configuration choices:

- `class_weight="balanced"` : scikit-learn automatically computes weights inversely proportional to class frequencies. This means each fraud sample contributes far more to the loss than each legitimate sample, forcing the model to pay attention to the minority class without requiring manual weight calculation.
- `solver="lbfgs"` : a quasi-Newton optimization method well-suited for small-to-medium datasets with L2 regularization.
- `max_iter=1000` : ensures the optimizer has enough iterations to converge on this dataset.
- `random_state=42` : fixes the random seed for reproducibility.

What this baseline tells us:

- It reveals how much of the fraud signal lives in **linear** combinations of the 30 input features (Time, Amount, V1–V28).
- It provides **calibrated probability scores** out of the box, meaning the predicted probabilities are already roughly aligned with true fraud rates — useful as a calibration reference.
- The gap between logistic regression and the MLP later will show us how much the non-linear layers contribute.

Evaluation approach: We use the default threshold of 0.5 for hard predictions and compute the same metrics as the trivial baseline (recall, precision, F1, PR AUC,

confusion matrix) so the comparison is apples-to-apples. The threshold will be optimized in Step 7.

```
In [13]: from sklearn.linear_model import LogisticRegression

# -----
# Logistic regression baseline (with class weighting for imbalance)
# -----
lr = LogisticRegression(
    class_weight="balanced",    # auto-weight inversely proportional to class
    max_iter=1000,
    solver="lbfgs",
    random_state=42,
)
lr.fit(X_train_scaled, y_train)

# Predicted probabilities on the validation set
y_val_prob_lr = lr.predict_proba(X_val_scaled)[:, 1]

# Use a 0.5 default threshold for hard predictions
y_val_pred_lr = (y_val_prob_lr >= 0.5).astype(int)

print("== Logistic Regression Baseline ==")
print(f"Recall: {recall_score(y_val, y_val_pred_lr):.4f}")
print(f"Precision: {precision_score(y_val, y_val_pred_lr, zero_division=0):.4f}")
print(f"F1 Score: {f1_score(y_val, y_val_pred_lr):.4f}")

prec_lr, rec_lr, _ = precision_recall_curve(y_val, y_val_prob_lr)
pr_auc_lr = auc(rec_lr, prec_lr)
print(f"PR AUC: {pr_auc_lr:.4f}")

print("\nConfusion matrix (rows=actual, cols=predicted):")
cm_lr = confusion_matrix(y_val, y_val_pred_lr)
print(cm_lr)
print(f"\n TN={cm_lr[0,0]} FP={cm_lr[0,1]}")
print(f" FN={cm_lr[1,0]} TP={cm_lr[1,1]}")
print(f"\n False-negative rate: {cm_lr[1,0] / max(cm_lr[1].sum(), 1):.4f}")
print(f" False-positive rate: {cm_lr[0,1] / max(cm_lr[0].sum(), 1):.4f}")

== Logistic Regression Baseline ==
Recall: 0.9286
Precision: 0.0531
F1 Score: 0.1004
PR AUC: 0.8389

Confusion matrix (rows=actual, cols=predicted):
[[41737  928]
 [   4   52]]

TN=41737 FP=928
FN=4 TP=52

False-negative rate: 0.0714
False-positive rate: 0.0218
```

5.3 — Starting model: feedforward MLP

The MLP is the starting deep-learning model. It builds on the logistic regression baseline by adding **non-linear hidden layers** that can capture interactions and complex decision boundaries that a linear model cannot.

Architecture overview

The network takes 30 input features and passes them through three progressively narrower hidden layers before producing a single fraud probability:

```
Input (30) → Dense(128) → Dropout(0.4) → Dense(64) →  
Dropout(0.3) → Dense(32) → Dropout(0.3) → Dense(1, sigmoid)
```

Design decisions explained

Component	Choice	Rationale
Hidden layers	3 Dense layers (128 → 64 → 32)	A "funnel" shape that progressively compresses information. 128 units in the first layer gives enough capacity to capture feature interactions; narrowing to 32 forces the network to distill the most discriminative patterns. Three layers is a moderate depth — enough for non-linearity without excessive risk of overfitting on ~200k training samples.
Activation	ReLU (Rectified Linear Unit)	Standard default for hidden layers. ReLU outputs $\max(0, x)$, which avoids the vanishing gradient problem that plagues sigmoid/tanh in deep networks, and is computationally cheap.
Regularization	Dropout (0.4 on first layer, 0.3 on others)	During each training step, Dropout randomly sets a fraction of neuron outputs to zero. This prevents neurons from co-adapting (relying on specific other neurons) and acts as an ensemble of thinned networks. The first layer gets higher dropout (0.4) because it has the most parameters.
Output layer	1 unit with sigmoid activation	Sigmoid squashes the output to [0, 1], directly interpretable as a fraud probability. A single unit is standard for binary classification.
Loss function	Binary cross-entropy with class weights	Cross-entropy measures how well the predicted probabilities match the true labels. The <code>class_weight</code> dictionary (computed in Step 4) multiplies the loss for fraud samples by ~518x, ensuring the network does not simply learn to predict all-zero.
Optimizer	Adam (learning rate = 1e-3)	Adam combines momentum and adaptive per-parameter learning rates. The default lr of 1e-3 is a well-tested starting point for tabular data.

Component	Choice	Rationale
Early stopping	Monitor <code>val_loss</code> , patience = 10, restore best weights	Training stops if validation loss does not improve for 10 consecutive epochs, and the model reverts to the weights from the best epoch. This prevents overfitting without requiring manual epoch selection.

Why this specific size?

- **Too small** (e.g., a single 16-unit layer) may underfit: the model cannot capture enough non-linear structure.
- **Too large** (e.g., 512 → 256 → 128) risks overfitting on a dataset where ~384 fraud cases exist in the training set.
- The 128 → 64 → 32 configuration is a deliberate middle ground, and Step 7 will experiment with variations.

The cell below defines the `build_mlp` function, instantiates the model, compiles it, and prints the architecture summary (layer types, output shapes, and parameter counts).

```
In [14]: import random, os
import tensorflow as tf

# Use attribute access (more reliable across TF versions than 'from tensorflow
keras = tf.keras
layers = tf.keras.layers

# -----
# Reproducibility: set all random seeds
# -----
SEED = 42
random.seed(SEED)
np.random.seed(SEED)
tf.random.set_seed(SEED)
os.environ["PYTHONHASHSEED"] = str(SEED)

# -----
# Build the starting MLP
# -----
def build_mlp(input_dim: int, name: str = "fraud_mlp") → keras.Model:
    """Small-to-medium feedforward MLP for binary fraud classification."""
    model = keras.Sequential(
        [
            layers.Input(shape=(input_dim,)),
            layers.Dense(128, activation="relu"),
            layers.Dropout(0.4),
            layers.Dense(64, activation="relu"),
            layers.Dropout(0.3),
            layers.Dense(32, activation="relu"),
            layers.Dropout(0.3),
            layers.Dense(1, activation="sigmoid"),
        ]
    )
    return model
```

```

        ],
        name=name,
    )
    return model

input_dim = X_train_scaled.shape[1]
mlp = build_mlp(input_dim)

mlp.compile(
    optimizer=keras.optimizers.Adam(learning_rate=1e-3),
    loss="binary_crossentropy",
    metrics=["AUC"],           # ROC-AUC tracked during training for quick refer
)
mlp.summary()

```

2026-02-09 05:49:24.477335: I external/local_xla/xla/tsl/cuda/cudart_stub.cc:31] Could not find cuda drivers on your machine, GPU will not be used.
2026-02-09 05:49:24.478171: I tensorflow/core/util/port.cc:153] oneDNN custom operations are on. You may see slightly different numerical results due to floating-point round-off errors from different computation orders. To turn them off, set the environment variable `TF_ENABLE_ONEDNN_OPTS=0`.
2026-02-09 05:49:24.527055: I tensorflow/core/platform/cpu_feature_guard.cc:210] This TensorFlow binary is optimized to use available CPU instructions in performance-critical operations.
To enable the following instructions: AVX2 AVX512F AVX512_VNNI AVX512_BF16 AVX512_FP16 AVX_VNNI AMX_TILE AMX_INT8 AMX_BF16 FMA, in other operations, rebuild TensorFlow with the appropriate compiler flags.
2026-02-09 05:49:25.409241: I tensorflow/core/util/port.cc:153] oneDNN custom operations are on. You may see slightly different numerical results due to floating-point round-off errors from different computation orders. To turn them off, set the environment variable `TF_ENABLE_ONEDNN_OPTS=0`.
2026-02-09 05:49:25.409728: I external/local_xla/xla/tsl/cuda/cudart_stub.cc:31] Could not find cuda drivers on your machine, GPU will not be used.
2026-02-09 05:49:25.559290: E external/local_xla/xla/stream_executor/cuda/cuda_platform.cc:51] failed call to cuInit: INTERNAL: CUDA error: Failed call to cuInit: UNKNOWN ERROR (303)

Model: "fraud_mlp"

Layer (type)	Output Shape	Params
dense (Dense)	(None, 128)	3
dropout (Dropout)	(None, 128)	
dense_1 (Dense)	(None, 64)	8
dropout_1 (Dropout)	(None, 64)	
dense_2 (Dense)	(None, 32)	2
dropout_2 (Dropout)	(None, 32)	
dense_3 (Dense)	(None, 1)	

Total params: 14,337 (56.00 KB)

Trainable params: 14,337 (56.00 KB)

Non-trainable params: 0 (0.00 B)

5.4 — Train the starting MLP

This cell runs the actual training loop. Here is what happens under the hood at each epoch:

1. **Forward pass:** the training data is fed through the network in mini-batches of 2,048 samples. For each sample, the network produces a fraud probability.
2. **Loss computation:** binary cross-entropy is calculated between the predicted probabilities and the true labels. Each fraud sample's loss is multiplied by the `class_weight[1]` (~518×) so that missing a fraud case is penalized far more heavily than a false alarm.
3. **Backward pass:** gradients of the loss with respect to every weight are computed via backpropagation.
4. **Weight update:** the Adam optimizer uses these gradients (plus its momentum and adaptive learning rate state) to update the network's weights.
5. **Validation check:** after each epoch, the model is evaluated on the validation set (without Dropout) and `val_loss` is recorded.

Early stopping watches `val_loss`:

- If `val_loss` improves (decreases), the current weights are saved internally as the "best so far."
- If `val_loss` does not improve for 10 consecutive epochs (`patience=10`), training halts early and the model's weights are **reverted** to the best checkpoint. This means the final model is not the one from the last epoch, but from the epoch with the lowest validation loss.

Batch size = 2,048: a relatively large batch for this dataset size. Larger batches give more stable gradient estimates per step and train faster on GPU, but can sometimes converge to sharper minima. This is a reasonable default for ~200k training samples.

Max epochs = 100: an upper bound. In practice, early stopping typically triggers well before 100 epochs.

The training cell is followed by a plotting cell that visualizes the loss and ROC-AUC curves over epochs, so you can visually confirm that (a) training loss decreases, (b) validation loss eventually plateaus or rises (triggering early stopping), and (c) there is no severe divergence between train and val curves (which would indicate overfitting).

```
In [15]: # -----
# Train the MLP with early stopping
# -----
early_stop = keras.callbacks.EarlyStopping(
    monitor="val_loss",
    patience=10,
    restore_best_weights=True,
    verbose=1,
)

history = mlp.fit(
    X_train_scaled,
    y_train,
    validation_data=(X_val_scaled, y_val),
    epochs=100,
    batch_size=2048,
    class_weight=class_weight,
    callbacks=[early_stop],
    verbose=1,
)
```

Epoch 1/100

Epoch	Time	AUC	Loss
1/98	1:29	0.9118	1.1329
11/98	0s	0.8377	1.1020
21/98	0s	0.8094	1.0870
33/98	0s	0.8122	1.0507
44/98	0s	0.8235	1.0137
56/98	0s	0.8380	0.9774
67/98	0s	0.8479	0.9512
79/98	0s	0.8575	0.9225
91/98	0s	0.8657	0.8964

98/98 2s 7ms/step - AUC: 0.9275 - loss: 0.6876 - val_AU
C: 0.9578 - val_loss: 0.1588
Epoch 2/100

1/98 2s 22ms/step - AUC: 0.8529 - loss: 0.5963
12/98 0s 5ms/step - AUC: 0.9371 - loss: 0.4404
23/98 0s 5ms/step - AUC: 0.9339 - loss: 0.4702
35/98 0s 5ms/step - AUC: 0.9364 - loss: 0.4731
46/98 0s 5ms/step - AUC: 0.9391 - loss: 0.4711
58/98 0s 5ms/step - AUC: 0.9432 - loss: 0.4635
70/98 0s 5ms/step - AUC: 0.9457 - loss: 0.4612
82/98 0s 5ms/step - AUC: 0.9480 - loss: 0.4559
94/98 0s 5ms/step - AUC: 0.9497 - loss: 0.4540
98/98 1s 5ms/step - AUC: 0.9620 - loss: 0.4357 - val_AU
C: 0.9773 - val_loss: 0.0935
Epoch 3/100

1/98 2s 21ms/step - AUC: 0.9976 - loss: 0.1911
13/98 0s 4ms/step - AUC: 0.9543 - loss: 0.4248
23/98 0s 5ms/step - AUC: 0.9504 - loss: 0.4532
34/98 0s 5ms/step - AUC: 0.9523 - loss: 0.4472
46/98 0s 5ms/step - AUC: 0.9543 - loss: 0.4395
58/98 0s 5ms/step - AUC: 0.9573 - loss: 0.4274
70/98 0s 5ms/step - AUC: 0.9585 - loss: 0.4268
83/98 0s 4ms/step - AUC: 0.9597 - loss: 0.4231
94/98 0s 4ms/step - AUC: 0.9605 - loss: 0.4207
98/98 1s 5ms/step - AUC: 0.9673 - loss: 0.3944 - val_AU
C: 0.9788 - val_loss: 0.1067
Epoch 4/100

1/98 1s 20ms/step - AUC: 0.9983 - loss: 0.1789
13/98 0s 4ms/step - AUC: 0.9819 - loss: 0.2727
25/98 0s 4ms/step - AUC: 0.9761 - loss: 0.3058
35/98 0s 5ms/step - AUC: 0.9767 - loss: 0.3065
47/98 0s 4ms/step - AUC: 0.9773 - loss: 0.3080

1/98	10s	112ms/step - AUC: 0.9988 - loss: 0.1376
14/98	0s	4ms/step - AUC: 0.9870 - loss: 0.2357
25/98	0s	4ms/step - AUC: 0.9806 - loss: 0.2814
36/98	0s	4ms/step - AUC: 0.9801 - loss: 0.2897
47/98	0s	4ms/step - AUC: 0.9805 - loss: 0.2925
60/98	0s	4ms/step - AUC: 0.9813 - loss: 0.2920
71/98	0s	4ms/step - AUC: 0.9810 - loss: 0.2968
83/98	0s	4ms/step - AUC: 0.9810 - loss: 0.2975
94/98	0s	4ms/step - AUC: 0.9812 - loss: 0.2969
98/98	1s	5ms/step - AUC: 0.9830 - loss: 0.2881 -
C:	0.9789	- val_loss: 0.0552

```
13/98 ━━━━━━━━ 0s 5ms/step - AUC: 0.9914 - loss: 0.2224
24/98 ━━━━━━ 0s 5ms/step - AUC: 0.9883 - loss: 0.2445
36/98 ━━━━ 0s 5ms/step - AUC: 0.9884 - loss: 0.2445
47/98 ━━ 0s 5ms/step - AUC: 0.9886 - loss: 0.2447
57/98 ━ 0s 5ms/step - AUC: 0.9888 - loss: 0.2456
69/98 0s 5ms/step - AUC: 0.9884 - loss: 0.2524
80/98 0s 5ms/step - AUC: 0.9881 - loss: 0.2557
91/98 0s 5ms/step - AUC: 0.9876 - loss: 0.2616
98/98 1s 5ms/step - AUC: 0.9840 - loss: 0.3120 - val_AU
C: 0.9788 - val_loss: 0.0690
```

Epoch 8/100

1/98	1s	20ms/step	- AUC: 0.9990	- loss: 0.1425
12/98	1s	5ms/step	- AUC: 0.9748	- loss: 0.3008
23/98	1s	5ms/step	- AUC: 0.9715	- loss: 0.3279
35/98	1s	5ms/step	- AUC: 0.9737	- loss: 0.3199
46/98	1s	5ms/step	- AUC: 0.9757	- loss: 0.3125
57/98	1s	5ms/step	- AUC: 0.9776	- loss: 0.3050
68/98	1s	5ms/step	- AUC: 0.9784	- loss: 0.3047
80/98	1s	5ms/step	- AUC: 0.9790	- loss: 0.3031
93/98	1s	5ms/step	- AUC: 0.9796	- loss: 0.3011
98/98	1s	5ms/step	- AUC: 0.9842	- loss: 0.2818

C: 0.9802 - val_loss: 0.0694

Epoch 9/100

1/98		1s	20ms/step - AUC: 0.9987 - loss: 0.1394
13/98		0s	4ms/step - AUC: 0.9888 - loss: 0.2292
24/98		0s	4ms/step - AUC: 0.9883 - loss: 0.2364
35/98		0s	5ms/step - AUC: 0.9893 - loss: 0.2300
48/98		0s	4ms/step - AUC: 0.9904 - loss: 0.2227
59/98		0s	4ms/step - AUC: 0.9911 - loss: 0.2180
71/98		0s	4ms/step - AUC: 0.9909 - loss: 0.2207
82/98		0s	5ms/step - AUC: 0.9908 - loss: 0.2215

93/98 ————— 0s 5ms/step - AUC: 0.9908 - loss: 0.2221
98/98 ————— 1s 5ms/step - AUC: 0.9909 - loss: 0.2223 - val_AU
C: 0.9804 - val_loss: 0.0434
Epoch 10/100
1/98 ————— 1s 21ms/step - AUC: 0.9988 - loss: 0.1239
13/98 ————— 0s 4ms/step - AUC: 0.9945 - loss: 0.1831
24/98 ————— 0s 5ms/step - AUC: 0.9916 - loss: 0.2135
35/98 ————— 0s 5ms/step - AUC: 0.9914 - loss: 0.2164
47/98 ————— 0s 5ms/step - AUC: 0.9915 - loss: 0.2172
58/98 ————— 0s 5ms/step - AUC: 0.9919 - loss: 0.2149
69/98 ————— 0s 5ms/step - AUC: 0.9919 - loss: 0.2169
81/98 ————— 0s 5ms/step - AUC: 0.9919 - loss: 0.2176
93/98 ————— 0s 5ms/step - AUC: 0.9919 - loss: 0.2176
98/98 ————— 1s 5ms/step - AUC: 0.9923 - loss: 0.2134 - val_AU
C: 0.9687 - val_loss: 0.0383
Epoch 11/100
1/98 ————— 1s 19ms/step - AUC: 0.9990 - loss: 0.1071
12/98 ————— 0s 5ms/step - AUC: 0.9973 - loss: 0.1384
22/98 ————— 0s 5ms/step - AUC: 0.9959 - loss: 0.1523
33/98 ————— 0s 5ms/step - AUC: 0.9957 - loss: 0.1526
44/98 ————— 0s 5ms/step - AUC: 0.9957 - loss: 0.1540
55/98 ————— 0s 5ms/step - AUC: 0.9958 - loss: 0.1539
66/98 ————— 0s 5ms/step - AUC: 0.9958 - loss: 0.1561
77/98 ————— 0s 5ms/step - AUC: 0.9958 - loss: 0.1585
88/98 ————— 0s 5ms/step - AUC: 0.9957 - loss: 0.1605
98/98 ————— 1s 6ms/step - AUC: 0.9944 - loss: 0.1827 - val_AU
C: 0.9640 - val_loss: 0.0314
Epoch 12/100
1/98 ————— 8s 85ms/step - AUC: 0.9967 - loss: 0.1261
14/98 ————— 0s 4ms/step - AUC: 0.9897 - loss: 0.2356
24/98 ————— 0s 5ms/step - AUC: 0.9878 - loss: 0.2509
36/98 ————— 0s 5ms/step - AUC: 0.9884 - loss: 0.2435

C: 0.9640 - val_loss: 0.0332

Epoch 16/100

1/98	1s	20ms/step - AUC: 0.9923 - loss: 0.2110
12/98	0s	5ms/step - AUC: 0.9961 - loss: 0.1606
24/98	0s	4ms/step - AUC: 0.9957 - loss: 0.1647
35/98	0s	5ms/step - AUC: 0.9956 - loss: 0.1640
45/98	0s	5ms/step - AUC: 0.9958 - loss: 0.1624
57/98	0s	5ms/step - AUC: 0.9960 - loss: 0.1604
68/98	0s	5ms/step - AUC: 0.9960 - loss: 0.1610
78/98	0s	5ms/step - AUC: 0.9961 - loss: 0.1613
88/98	0s	5ms/step - AUC: 0.9961 - loss: 0.1620
98/98	1s	5ms/step - AUC: 0.9961 - loss: 0.1681

C: 0.9646 - val_loss: 0.0374

Epoch 17/100

1/98		1s	20ms/step - AUC: 0.9984 - loss: 0.1339
11/98		0s	5ms/step - AUC: 0.9961 - loss: 0.1592
22/98		0s	5ms/step - AUC: 0.9957 - loss: 0.1666
33/98		0s	5ms/step - AUC: 0.9959 - loss: 0.1639
44/98		0s	5ms/step - AUC: 0.9961 - loss: 0.1619
56/98		0s	5ms/step - AUC: 0.9963 - loss: 0.1592
68/98		0s	5ms/step - AUC: 0.9964 - loss: 0.1589

Epoch 21/100

Enoch 22/100

Epoch	Step	Type	Time	AUC	loss
1/98		1s	20ms/step	0.9993	0.1007
11/98		0s	5ms/step	0.9961	0.1493
24/98		0s	5ms/step	0.9952	0.1655
36/98		0s	4ms/step	0.9954	0.1617
48/98		0s	4ms/step	0.9957	0.1573
60/98		0s	4ms/step	0.9960	0.1532
73/98		0s	4ms/step	0.9962	0.1515
85/98		0s	4ms/step	0.9963	0.1499
97/98		0s	4ms/step	0.9964	0.1485

98/98 ━━━━━━━━━━ 1s 5ms/step - AUC: 0.9973 - loss: 0.1353 - val_AU
C: 0.9605 - val_loss: 0.0178
Epoch 23/100

1/98 ━━━━━━━━ 1s 20ms/step - AUC: 0.9988 - loss: 0.0824
15/98 ━━━━ 0s 4ms/step - AUC: 0.9979 - loss: 0.1115
28/98 ━━━━ 0s 4ms/step - AUC: 0.9974 - loss: 0.1243
41/98 ━━━━ 0s 4ms/step - AUC: 0.9974 - loss: 0.1254
54/98 ━━━━ 0s 4ms/step - AUC: 0.9973 - loss: 0.1283
66/98 ━━━━ 0s 4ms/step - AUC: 0.9973 - loss: 0.1301
79/98 ━━━━ 0s 4ms/step - AUC: 0.9973 - loss: 0.1311
92/98 ━━━━ 0s 4ms/step - AUC: 0.9973 - loss: 0.1313
98/98 ━━━━ 0s 5ms/step - AUC: 0.9974 - loss: 0.1314 - val_AU
C: 0.9610 - val_loss: 0.0172
Epoch 24/100

1/98 ━━━━━━━━ 1s 19ms/step - AUC: 0.9989 - loss: 0.0872
14/98 ━━━━ 0s 4ms/step - AUC: 0.9975 - loss: 0.1141
24/98 ━━━━ 0s 4ms/step - AUC: 0.9967 - loss: 0.1358
35/98 ━━━━ 0s 5ms/step - AUC: 0.9966 - loss: 0.1390
46/98 ━━━━ 0s 5ms/step - AUC: 0.9964 - loss: 0.1427
57/98 ━━━━ 0s 5ms/step - AUC: 0.9964 - loss: 0.1439
67/98 ━━━━ 0s 5ms/step - AUC: 0.9965 - loss: 0.1446
78/98 ━━━━ 0s 5ms/step - AUC: 0.9965 - loss: 0.1448
88/98 ━━━━ 0s 5ms/step - AUC: 0.9965 - loss: 0.1449
98/98 ━━━━ 1s 6ms/step - AUC: 0.9969 - loss: 0.1400 - val_AU
C: 0.9600 - val_loss: 0.0305
Epoch 25/100

1/98 ━━━━━━━━ 1s 20ms/step - AUC: 0.9976 - loss: 0.1036
13/98 ━━━━ 0s 4ms/step - AUC: 0.9962 - loss: 0.1385
25/98 ━━━━ 0s 4ms/step - AUC: 0.9961 - loss: 0.1409
35/98 ━━━━ 0s 5ms/step - AUC: 0.9963 - loss: 0.1390
46/98 ━━━━ 0s 5ms/step - AUC: 0.9965 - loss: 0.1373
57/98 ━━━━ 0s 5ms/step - AUC: 0.9967 - loss: 0.1347

68/98 ━━━━━━ 0s 5ms/step - AUC: 0.9968 - loss: 0.1338
79/98 ━━━━ 0s 5ms/step - AUC: 0.9969 - loss: 0.1330
90/98 ━━━━ 0s 5ms/step - AUC: 0.9970 - loss: 0.1329
98/98 ━━━━ 1s 6ms/step - AUC: 0.9975 - loss: 0.1280 - val_AU
C: 0.9608 - val_loss: 0.0206
Epoch 26/100
1/98 ━━━━━━ 1s 20ms/step - AUC: 0.9988 - loss: 0.0794
13/98 ━━ 0s 4ms/step - AUC: 0.9975 - loss: 0.1154
25/98 ━━ 0s 4ms/step - AUC: 0.9973 - loss: 0.1253
37/98 ━━ 0s 4ms/step - AUC: 0.9974 - loss: 0.1234
49/98 ━━ 0s 4ms/step - AUC: 0.9976 - loss: 0.1202
61/98 ━━ 0s 4ms/step - AUC: 0.9977 - loss: 0.1188
72/98 ━━ 0s 4ms/step - AUC: 0.9977 - loss: 0.1186
83/98 ━━ 0s 5ms/step - AUC: 0.9978 - loss: 0.1182
95/98 ━━ 0s 5ms/step - AUC: 0.9978 - loss: 0.1177
98/98 ━━━━ 1s 5ms/step - AUC: 0.9981 - loss: 0.1115 - val_AU
C: 0.9612 - val_loss: 0.0169
Epoch 27/100
1/98 ━━━━━━ 1s 20ms/step - AUC: 0.9993 - loss: 0.0618
12/98 ━━ 0s 5ms/step - AUC: 0.9973 - loss: 0.1217
24/98 ━━ 0s 5ms/step - AUC: 0.9976 - loss: 0.1167
34/98 ━━ 0s 5ms/step - AUC: 0.9977 - loss: 0.1137
46/98 ━━ 0s 5ms/step - AUC: 0.9978 - loss: 0.1144
57/98 ━━ 0s 5ms/step - AUC: 0.9976 - loss: 0.1192
68/98 ━━ 0s 5ms/step - AUC: 0.9971 - loss: 0.1268
79/98 ━━ 0s 5ms/step - AUC: 0.9969 - loss: 0.1314
89/98 ━━ 0s 5ms/step - AUC: 0.9967 - loss: 0.1338
98/98 ━━━━ 1s 6ms/step - AUC: 0.9958 - loss: 0.1480 - val_AU
C: 0.9600 - val_loss: 0.0226
Epoch 28/100
1/98 ━━━━━━ 2s 21ms/step - AUC: 0.9985 - loss: 0.0909
13/98 ━━ 0s 5ms/step - AUC: 0.9985 - loss: 0.0954

Epoch 30/100

1/98	2s	24ms/step - AUC: 0.9954 - loss: 0.1340
13/98	0s	4ms/step - AUC: 0.9981 - loss: 0.0972
24/98	0s	5ms/step - AUC: 0.9982 - loss: 0.0977
35/98	0s	5ms/step - AUC: 0.9983 - loss: 0.0981
45/98	0s	5ms/step - AUC: 0.9983 - loss: 0.0979
56/98	0s	5ms/step - AUC: 0.9983 - loss: 0.0979
67/98	0s	5ms/step - AUC: 0.9984 - loss: 0.0986
79/98	0s	5ms/step - AUC: 0.9984 - loss: 0.0989
89/98	0s	5ms/step - AUC: 0.9983 - loss: 0.0993

98/98 ━━━━━━━━━━ 1s 5ms/step - AUC: 0.9983 - loss: 0.1027 - val_AU
C: 0.9620 - val_loss: 0.0154
Epoch 31/100

1/98 ━━━━━━━━ 1s 20ms/step - AUC: 0.9995 - loss: 0.0802
12/98 ━━ 0s 5ms/step - AUC: 0.9976 - loss: 0.1153
23/98 ━━ 0s 5ms/step - AUC: 0.9977 - loss: 0.1136
34/98 ━━ 0s 5ms/step - AUC: 0.9979 - loss: 0.1078
46/98 ━━ 0s 5ms/step - AUC: 0.9980 - loss: 0.1050
57/98 ━━ 0s 5ms/step - AUC: 0.9981 - loss: 0.1048
70/98 ━━ 0s 4ms/step - AUC: 0.9977 - loss: 0.1096
81/98 ━━ 0s 5ms/step - AUC: 0.9975 - loss: 0.1124
92/98 ━━ 0s 5ms/step - AUC: 0.9974 - loss: 0.1138
98/98 ━━━━━━ 1s 5ms/step - AUC: 0.9966 - loss: 0.1197 - val_AU
C: 0.9617 - val_loss: 0.0145
Epoch 32/100

1/98 ━━━━━━ 2s 21ms/step - AUC: 0.9989 - loss: 0.0686
12/98 ━━ 0s 5ms/step - AUC: 0.9983 - loss: 0.0889
23/98 ━━ 0s 5ms/step - AUC: 0.9982 - loss: 0.0953
34/98 ━━ 0s 5ms/step - AUC: 0.9983 - loss: 0.0943
45/98 ━━ 0s 5ms/step - AUC: 0.9983 - loss: 0.0951
56/98 ━━ 0s 5ms/step - AUC: 0.9984 - loss: 0.0947
68/98 ━━ 0s 5ms/step - AUC: 0.9984 - loss: 0.0964
78/98 ━━ 0s 5ms/step - AUC: 0.9984 - loss: 0.0971
89/98 ━━ 0s 5ms/step - AUC: 0.9984 - loss: 0.0973
98/98 ━━━━ 1s 5ms/step - AUC: 0.9982 - loss: 0.1039 - val_AU
C: 0.9623 - val_loss: 0.0121
Epoch 33/100

1/98 ━━━━━━ 1s 21ms/step - AUC: 0.9991 - loss: 0.0751
13/98 ━━ 0s 5ms/step - AUC: 0.9992 - loss: 0.0720
24/98 ━━ 0s 5ms/step - AUC: 0.9990 - loss: 0.0763
35/98 ━━ 0s 5ms/step - AUC: 0.9990 - loss: 0.0772
46/98 ━━ 0s 5ms/step - AUC: 0.9990 - loss: 0.0774

1/98	1s	20ms/step - AUC: 0.9993 - loss: 0.0611
12/98	0s	5ms/step - AUC: 0.9988 - loss: 0.0804
23/98	0s	5ms/step - AUC: 0.9986 - loss: 0.0864
34/98	0s	5ms/step - AUC: 0.9986 - loss: 0.0894
46/98	0s	5ms/step - AUC: 0.9986 - loss: 0.0906
59/98	0s	5ms/step - AUC: 0.9986 - loss: 0.0905
71/98	0s	5ms/step - AUC: 0.9986 - loss: 0.0903
83/98	0s	5ms/step - AUC: 0.9986 - loss: 0.0897
95/98	0s	5ms/step - AUC: 0.9986 - loss: 0.0893
98/98	1s	5ms/step - AUC: 0.9987 - loss: 0.0863 - val_AU

C: 0.9541 - val_loss: 0.0092

Epoch 37/100

1/98	1s	20ms/step - AUC: 0.9969 - loss: 0.1092
13/98	0s	4ms/step - AUC: 0.9981 - loss: 0.0902
25/98	0s	4ms/step - AUC: 0.9981 - loss: 0.0968
36/98	0s	4ms/step - AUC: 0.9982 - loss: 0.0960
47/98	0s	5ms/step - AUC: 0.9983 - loss: 0.0944
58/98	0s	5ms/step - AUC: 0.9983 - loss: 0.0927
70/98	0s	5ms/step - AUC: 0.9984 - loss: 0.0924
82/98	0s	5ms/step - AUC: 0.9984 - loss: 0.0918
93/98	0s	5ms/step - AUC: 0.9984 - loss: 0.0912
98/98	1s	5ms/step - AUC: 0.9986 - loss: 0.0856

C: 0.9542 - val_loss: 0.0100

Epoch 38/100

1/98	1s	20ms/step - AUC: 0.9971 - loss: 0.1032
13/98	0s	4ms/step - AUC: 0.9981 - loss: 0.0957
25/98	0s	4ms/step - AUC: 0.9982 - loss: 0.0944
36/98	0s	5ms/step - AUC: 0.9983 - loss: 0.0923
48/98	0s	5ms/step - AUC: 0.9984 - loss: 0.0894
59/98	0s	5ms/step - AUC: 0.9984 - loss: 0.0889
70/98	0s	5ms/step - AUC: 0.9985 - loss: 0.0893

Epoch 42/100

1/98	1s	20ms/step - AUC: 0.9982 - loss: 0.0797
13/98	0s	4ms/step - AUC: 0.9983 - loss: 0.0881
24/98	0s	4ms/step - AUC: 0.9982 - loss: 0.0941
36/98	0s	4ms/step - AUC: 0.9983 - loss: 0.0920
48/98	0s	4ms/step - AUC: 0.9984 - loss: 0.0889
60/98	0s	4ms/step - AUC: 0.9984 - loss: 0.0876
71/98	0s	4ms/step - AUC: 0.9985 - loss: 0.0878
81/98	0s	5ms/step - AUC: 0.9985 - loss: 0.0875
93/98	0s	5ms/step - AUC: 0.9985 - loss: 0.0871
98/98	1s	5ms/step - AUC: 0.9986 - loss: 0.0867

Epoch 43/100

98/98 ━━━━━━ 1s 5ms/step - AUC: 0.9990 - loss: 0.0702 - val_AU
C: 0.9455 - val_loss: 0.0082
Epoch 44/100

1/98 ━━━━━━ 2s 21ms/step - AUC: 0.9988 - loss: 0.0500
13/98 ━━━━ 0s 4ms/step - AUC: 0.9995 - loss: 0.0417
24/98 ━━━━ 0s 4ms/step - AUC: 0.9994 - loss: 0.0501
35/98 ━━━━ 0s 5ms/step - AUC: 0.9993 - loss: 0.0556
46/98 ━━━━ 0s 5ms/step - AUC: 0.9992 - loss: 0.0603
56/98 ━━━━ 0s 5ms/step - AUC: 0.9992 - loss: 0.0629
68/98 ━━━━ 0s 5ms/step - AUC: 0.9991 - loss: 0.0658
80/98 ━━━━ 0s 5ms/step - AUC: 0.9991 - loss: 0.0675
91/98 ━━━━ 0s 5ms/step - AUC: 0.9990 - loss: 0.0703
98/98 ━━━━ 1s 5ms/step - AUC: 0.9985 - loss: 0.0932 - val_AU
C: 0.9542 - val_loss: 0.0101
Epoch 45/100

1/98 ━━━━━━ 1s 19ms/step - AUC: 0.9995 - loss: 0.0701
13/98 ━━━━ 0s 4ms/step - AUC: 0.9991 - loss: 0.0714
23/98 ━━━━ 0s 5ms/step - AUC: 0.9992 - loss: 0.0672
34/98 ━━━━ 0s 5ms/step - AUC: 0.9992 - loss: 0.0672
45/98 ━━━━ 0s 5ms/step - AUC: 0.9991 - loss: 0.0712
57/98 ━━━━ 0s 5ms/step - AUC: 0.9991 - loss: 0.0735
69/98 ━━━━ 0s 5ms/step - AUC: 0.9990 - loss: 0.0749
80/98 ━━━━ 0s 5ms/step - AUC: 0.9990 - loss: 0.0754
92/98 ━━━━ 0s 5ms/step - AUC: 0.9990 - loss: 0.0756
98/98 ━━━━ 1s 5ms/step - AUC: 0.9989 - loss: 0.0763 - val_AU
C: 0.9453 - val_loss: 0.0099
Epoch 46/100

1/98 ━━━━━━ 1s 20ms/step - AUC: 0.9982 - loss: 0.0655
12/98 ━━━━ 0s 5ms/step - AUC: 0.9991 - loss: 0.0565
23/98 ━━━━ 0s 5ms/step - AUC: 0.9991 - loss: 0.0580
34/98 ━━━━ 0s 5ms/step - AUC: 0.9992 - loss: 0.0577
46/98 ━━━━ 0s 5ms/step - AUC: 0.9992 - loss: 0.0580

1/98

```
[...]  
14/98 ━━━━━━━━ 0s 4ms/step - AUC: 0.9986 - loss: 0.0825  
25/98 ━━━━━━ 0s 4ms/step - AUC: 0.9985 - loss: 0.0865  
35/98 ━━━━ 0s 5ms/step - AUC: 0.9985 - loss: 0.0862  
46/98 ━━━━ 0s 5ms/step - AUC: 0.9986 - loss: 0.0851  
58/98 ━━━━ 0s 5ms/step - AUC: 0.9986 - loss: 0.0854  
70/98 ━━━━ 0s 5ms/step - AUC: 0.9985 - loss: 0.0882  
82/98 ━━━━ 0s 5ms/step - AUC: 0.9985 - loss: 0.0894  
93/98 ━━ 0s 5ms/step - AUC: 0.9985 - loss: 0.0905  
98/98 ━━━━ 1s 5ms/step - AUC: 0.9984 - loss: 0.0963  
C: 0.9533 - val loss: 0.0160
```

Epoch 48/100

```
12/98 ━━━━━━━━ 0s 5ms/step - AUC: 0.9992 - loss: 0.0584
23/98 ━━━━━━ 0s 5ms/step - AUC: 0.9990 - loss: 0.0659
35/98 ━━━━ 0s 5ms/step - AUC: 0.9990 - loss: 0.0677
46/98 ━━ 0s 5ms/step - AUC: 0.9990 - loss: 0.0683
57/98 ━━ 0s 5ms/step - AUC: 0.9990 - loss: 0.0687
67/98 ━━ 0s 5ms/step - AUC: 0.9990 - loss: 0.0697
78/98 ━━ 0s 5ms/step - AUC: 0.9990 - loss: 0.0704
88/98 ━━ 0s 5ms/step - AUC: 0.9990 - loss: 0.0707
98/98 ━━ 1s 5ms/step - AUC: 0.9990 - loss: 0.0704 - val_AU
C: 0.9451 - val_loss: 0.0112
```

Epoch 50/100

1/98	2s	21ms/step - AUC: 0.9988 - loss: 0.0665
13/98	0s	4ms/step - AUC: 0.9992 - loss: 0.0550
24/98	0s	4ms/step - AUC: 0.9991 - loss: 0.0576
35/98	0s	5ms/step - AUC: 0.9991 - loss: 0.0582
46/98	0s	5ms/step - AUC: 0.9992 - loss: 0.0575
58/98	0s	5ms/step - AUC: 0.9992 - loss: 0.0564
69/98	0s	5ms/step - AUC: 0.9992 - loss: 0.0563
80/98	0s	5ms/step - AUC: 0.9992 - loss: 0.0561
92/98	0s	5ms/step - AUC: 0.9992 - loss: 0.0564
98/98	1s	5ms/step - AUC: 0.9992 - loss: 0.0577

C: 0.9453 - val_loss: 0.0109

Epoch 51/100

1/98		1s	19ms/step - AUC: 0.9993 - loss: 0.0475
13/98		0s	4ms/step - AUC: 0.9991 - loss: 0.0553
25/98		0s	4ms/step - AUC: 0.9992 - loss: 0.0531
36/98		0s	4ms/step - AUC: 0.9992 - loss: 0.0528
47/98		0s	5ms/step - AUC: 0.9992 - loss: 0.0538
58/98		0s	5ms/step - AUC: 0.9992 - loss: 0.0550
70/98		0s	5ms/step - AUC: 0.9992 - loss: 0.0562
81/98		0s	5ms/step - AUC: 0.9992 - loss: 0.0571

92/98 0s 5ms/step - AUC: 0.9992 - loss: 0.0580

98/98 1s 5ms/step - AUC: 0.9990 - loss: 0.0688 - val_AU

C: 0.9453 - val_loss: 0.0106

Epoch 52/100

1/98 2s 21ms/step - AUC: 0.9993 - loss: 0.0629

13/98 0s 5ms/step - AUC: 0.9983 - loss: 0.0755

24/98 0s 5ms/step - AUC: 0.9985 - loss: 0.0717

36/98 0s 5ms/step - AUC: 0.9986 - loss: 0.0739

48/98 0s 5ms/step - AUC: 0.9986 - loss: 0.0763

59/98 0s 5ms/step - AUC: 0.9986 - loss: 0.0775

70/98 0s 5ms/step - AUC: 0.9986 - loss: 0.0799

81/98 0s 5ms/step - AUC: 0.9986 - loss: 0.0810

93/98 0s 5ms/step - AUC: 0.9986 - loss: 0.0819

98/98 1s 5ms/step - AUC: 0.9986 - loss: 0.0859 - val_AU

C: 0.9446 - val_loss: 0.0124

Epoch 53/100

1/98 1s 20ms/step - AUC: 0.9993 - loss: 0.0710

13/98 0s 4ms/step - AUC: 0.9988 - loss: 0.0734

24/98 0s 5ms/step - AUC: 0.9989 - loss: 0.0717

35/98 0s 5ms/step - AUC: 0.9989 - loss: 0.0694

46/98 0s 5ms/step - AUC: 0.9990 - loss: 0.0689

57/98 0s 5ms/step - AUC: 0.9989 - loss: 0.0717

68/98 0s 5ms/step - AUC: 0.9989 - loss: 0.0739

79/98 0s 5ms/step - AUC: 0.9989 - loss: 0.0752

90/98 0s 5ms/step - AUC: 0.9989 - loss: 0.0756

98/98 1s 5ms/step - AUC: 0.9989 - loss: 0.0755 - val_AU

C: 0.9449 - val_loss: 0.0104

Epoch 53: early stopping

Restoring model weights from the end of the best epoch: 43.

In [16]: `import matplotlib.pyplot as plt`

```
# -----
# Plot training curves
# -----
# Detect the AUC key name (varies across TensorFlow versions: "auc", "AUC",
```

```

auc_key = None
for key in history.history:
    key_lower = key.lower()
    if key_lower.startswith("auc") and not key_lower.startswith("val_"):
        auc_key = key
        break

val_auc_key = None
if auc_key:
    val_auc_key = next(
        (k for k in history.history if k.lower() == f"val_{auc_key.lower()}" or
         None,
    )
    if val_auc_key is None:
        val_auc_key = next(
            (k for k in history.history if k.lower().startswith("val_auc")),
            None,
        )
    )

fig, axes = plt.subplots(1, 2, figsize=(12, 4))

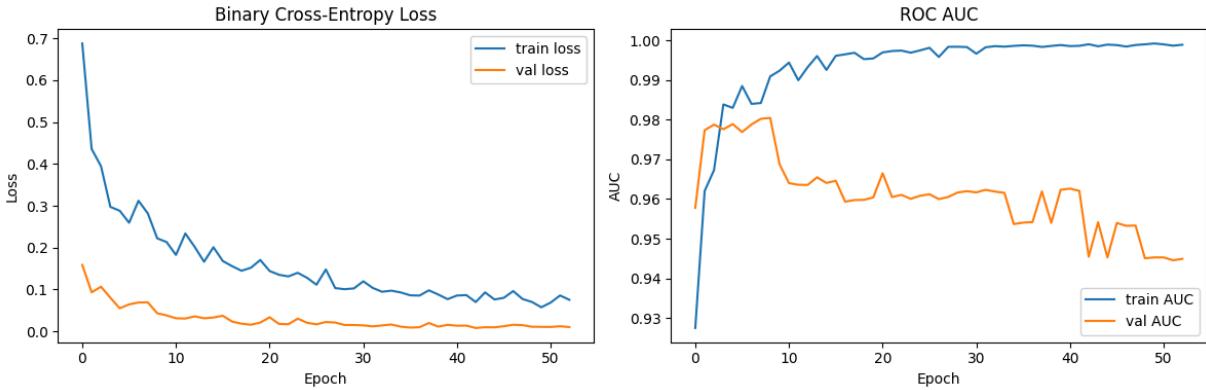
axes[0].plot(history.history["loss"], label="train loss")
axes[0].plot(history.history["val_loss"], label="val loss")
axes[0].set_title("Binary Cross-Entropy Loss")
axes[0].set_xlabel("Epoch")
axes[0].set_ylabel("Loss")
axes[0].legend()

if auc_key and val_auc_key:
    axes[1].plot(history.history[auc_key], label="train AUC")
    axes[1].plot(history.history[val_auc_key], label="val AUC")
    axes[1].set_title("ROC AUC")
    axes[1].set_xlabel("Epoch")
    axes[1].set_ylabel("AUC")
    axes[1].legend()
else:
    axes[1].axis("off")
    axes[1].text(
        0.5,
        0.5,
        "AUC metric not available in history",
        ha="center",
        va="center",
        fontsize=10,
    )

plt.tight_layout()
plt.show()

best_epoch = np.argmin(history.history["val_loss"])
print(f"Best epoch (lowest val_loss): {best_epoch + 1}")
print(f"  train loss: {history.history['loss'][best_epoch]:.4f} |  val loss: {history.history['val_loss'][best_epoch]:.4f}")
if auc_key and val_auc_key:
    print(f"  train AUC: {history.history[auc_key][best_epoch]:.4f} |  val AUC: {history.history[val_auc_key][best_epoch]:.4f}")
else:
    print("  AUC metric not available in history")

```



Best epoch (lowest val_loss): 43
 train loss: 0.0702 | val loss: 0.0082
 train AUC: 0.9990 | val AUC: 0.9455

5.5 — Evaluate the MLP on the validation set and compare with baselines

Now that all three models are ready, this section evaluates them under identical conditions so the comparison is fair.

How evaluation works:

1. The trained MLP runs inference on `X_val_scaled` (the scaled validation features). The output is a vector of fraud probabilities, one per transaction.
2. A **default threshold of 0.5** converts probabilities into hard predictions: if the model says ≥ 0.5 , predict fraud; otherwise, predict non-fraud. (This threshold is deliberately not optimized yet — Step 7 will tune it on the validation set.)
3. The same four metrics are computed for the MLP as for the two baselines:
 - **Recall** — what fraction of actual frauds did the model catch?
 - **Precision** — of the transactions the model flagged, how many were truly fraud?
 - **F1** — the harmonic mean of precision and recall, giving a single balanced number.
 - **PR AUC** — the area under the precision-recall curve, summarizing performance across *all* possible thresholds (not just 0.5).

The comparison table collects all four metrics for the three models in a single DataFrame, with the best value in each column highlighted in green. This makes it immediately clear which model leads on each metric.

The PR curve overlay plots the full precision-recall trade-off for all three models on the same axes:

- The **trivial baseline** appears as a flat line near the bottom — it cannot trade off precision for recall because it never predicts positive.

- The **logistic regression** curve shows how a linear model ranks transactions by fraud risk.
- The **MLP** curve shows the improvement (or lack thereof) from non-linear layers.

A model whose PR curve is higher and further to the right dominates: it achieves higher precision at every recall level. The area under each curve (PR AUC) is the single-number summary of this ranking quality.

```
In [17]: # -----
# MLP validation metrics
# -----
y_val_prob_mlp = mlp.predict(X_val_scaled, verbose=0).ravel()
y_val_pred_mlp = (y_val_prob_mlp >= 0.5).astype(int)

print("== Starting MLP (threshold = 0.5) ==")
print(f"Recall: {recall_score(y_val, y_val_pred_mlp):.4f}")
print(f"Precision: {precision_score(y_val, y_val_pred_mlp, zero_division=0):.4f}")
print(f"F1 Score: {f1_score(y_val, y_val_pred_mlp):.4f}")

prec_mlp, rec_mlp, _ = precision_recall_curve(y_val, y_val_prob_mlp)
pr_auc_mlp = auc(rec_mlp, prec_mlp)
print(f"PR AUC: {pr_auc_mlp:.4f}")

print("\nConfusion matrix (rows=actual, cols=predicted):")
cm_mlp = confusion_matrix(y_val, y_val_pred_mlp)
print(cm_mlp)
print(f"\n TN={cm_mlp[0,0]} FP={cm_mlp[0,1]}")
print(f" FN={cm_mlp[1,0]} TP={cm_mlp[1,1]}")
print(f"\n False-negative rate: {cm_mlp[1,0] / max(cm_mlp[1].sum(), 1):.4f}")
print(f" False-positive rate: {cm_mlp[0,1] / max(cm_mlp[0].sum(), 1):.4f}")

== Starting MLP (threshold = 0.5) ==
Recall: 0.8929
Precision: 0.2874
F1 Score: 0.4348
PR AUC: 0.8231

Confusion matrix (rows=actual, cols=predicted):
[[42541 124]
 [  6   50]]

TN=42541 FP=124
FN=6 TP=50

False-negative rate: 0.1071
False-positive rate: 0.0029
```

```
In [18]: # -----
# Side-by-side comparison table
# -----
comparison = pd.DataFrame(
{
    "Model": ["Trivial (all non-fraud)", "Logistic Regression", "Starting MLP"],
    "PR AUC": [pr_auc_trivial, pr_auc_lr, pr_auc_mlp],
```

```

        "Recall": [
            recall_score(y_val, y_val_pred_trivial),
            recall_score(y_val, y_val_pred_lr),
            recall_score(y_val, y_val_pred_mlp),
        ],
        "Precision": [
            precision_score(y_val, y_val_pred_trivial, zero_division=0),
            precision_score(y_val, y_val_pred_lr, zero_division=0),
            precision_score(y_val, y_val_pred_mlp, zero_division=0),
        ],
        "F1": [
            f1_score(y_val, y_val_pred_trivial),
            f1_score(y_val, y_val_pred_lr),
            f1_score(y_val, y_val_pred_mlp),
        ],
    },
)
try:
    styled = comparison.style.format(
        {"PR AUC": "{:.4f}", "Recall": "{:.4f}", "Precision": "{:.4f}", "F1": "{:.4f}"}
    ).highlight_max(subset=["PR AUC", "Recall", "Precision", "F1"], color="#FFCCBC")
except Exception:
    styled = comparison

styled

```

Out[18]:

	Model	PR AUC	Recall	Precision	F1
0	Trivial (all non-fraud)	0.500655	0.000000	0.000000	0.000000
1	Logistic Regression	0.838948	0.928571	0.053061	0.100386
2	Starting MLP	0.823052	0.892857	0.287356	0.434783

In [19]:

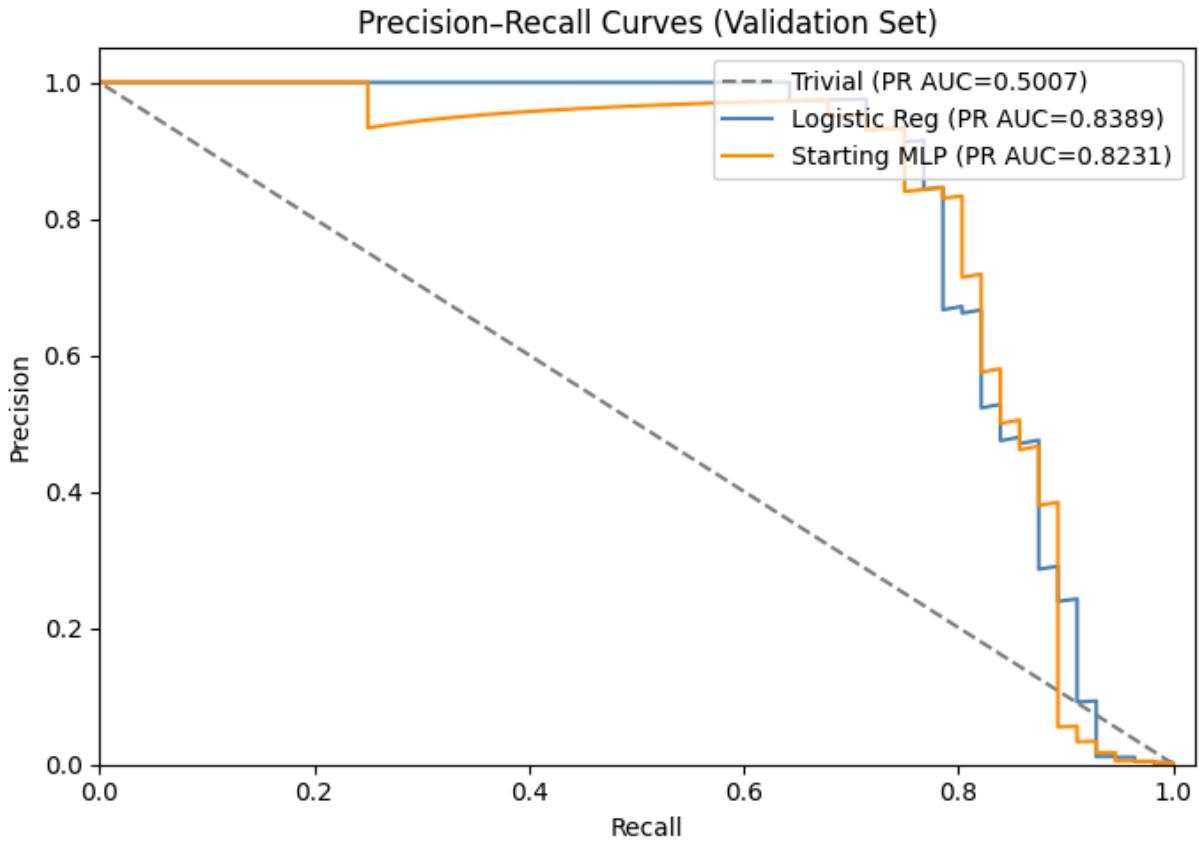
```

# -----
# PR curve overlay: all three models
# -----
fig, ax = plt.subplots(figsize=(7, 5))

ax.plot(rec_t, prec_t, linestyle="--", color="grey", label=f"Trivial (PR AUC={pr
ax.plot(rec_lr, prec_lr, color="steelblue", label=f"Logistic Reg (PR AUC={pr
ax.plot(rec_mlp, prec_mlp, color="darkorange", label=f"Starting MLP (PR AUC={

ax.set_xlabel("Recall")
ax.set_ylabel("Precision")
ax.set_title("Precision-Recall Curves (Validation Set)")
ax.legend(loc="upper right")
ax.set_xlim([0, 1.02])
ax.set_ylim([0, 1.05])
plt.tight_layout()
plt.show()

```



5.6 — Confusion matrix heatmaps

The raw confusion matrices printed above are hard to scan quickly. The heatmaps below visualize them side by side so the relative magnitude of TP, FP, TN, and FN is immediately apparent. Darker cells mean larger counts. Annotations show the exact numbers inside each cell.

```
In [20]: import seaborn as sns

# -----
# Confusion matrix heatmaps (side by side)
# -----
cms = {
    "Trivial Baseline": confusion_matrix(y_val, y_val_pred_trivial),
    "Logistic Regression": confusion_matrix(y_val, y_val_pred_lr),
    "Starting MLP": confusion_matrix(y_val, y_val_pred_mlp),
}

fig, axes = plt.subplots(1, 3, figsize=(16, 4))
for ax, (title, cm_data) in zip(axes, cms.items()):
    sns.heatmap(
        cm_data,
        annot=True,
        fmt="d",
        cmap="Blues",
        xticklabels=["Non-fraud", "Fraud"],
        yticklabels=["Non-fraud", "Fraud"],
```

```

        ax=ax,
        cbar=False,
    )
ax.set_title(title)
ax.set_xlabel("Predicted")
ax.set_ylabel("Actual")

plt.tight_layout()
plt.show()

```



5.7 — Predicted score distributions

A good fraud detector should assign **high probabilities to fraud** and **low probabilities to non-fraud**, creating clear separation between the two distributions. If the distributions overlap heavily, the model cannot reliably distinguish fraud from legitimate transactions at any threshold.

The histograms below show the distribution of predicted fraud probabilities for each model, split by the true label (blue = non-fraud, red = fraud). The vertical dashed line marks the 0.5 threshold used for hard predictions above.

```

In [21]: # -----
# Predicted probability distributions: fraud vs non-fraud
# -----
score_sets = {
    "Logistic Regression": y_val_prob_lr,
    "Starting MLP": y_val_prob_mlp,
}

fig, axes = plt.subplots(1, 2, figsize=(14, 4), sharey=True)

for ax, (title, scores) in zip(axes, score_sets.items()):
    mask_fraud = y_val == 1
    mask_legit = y_val == 0

    ax.hist(scores[mask_legit], bins=50, alpha=0.6, color="steelblue",
            label=f"Non-fraud (n={mask_legit.sum()})", density=True)
    ax.hist(scores[mask_fraud], bins=50, alpha=0.7, color="crimson",
            label=f"Fraud (n={mask_fraud.sum()})", density=True)
    ax.axvline(0.5, color="black", linestyle="--", linewidth=1, label="threshold")
    ax.set_title(f"{title} - Score Distribution")
    ax.set_xlabel("Predicted P(fraud)")
    ax.set_ylabel("Density")

```

```

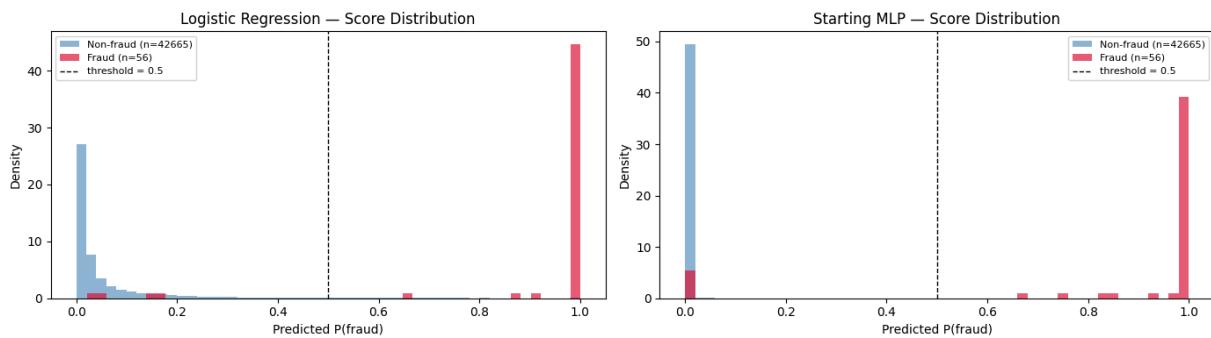
    ax.legend(fontsize=8)

plt.tight_layout()
plt.show()

# Print summary statistics for fraud scores
for title, scores in score_sets.items():
    fraud_scores = scores[y_val == 1]
    legit_scores = scores[y_val == 0]
    print(f"\n{title}:")

    print(f" Fraud scores - mean: {fraud_scores.mean():.4f}, median: {np.m
        f"min: {fraud_scores.min():.4f}, max: {fraud_scores.max():.4f}"}
    print(f" Legit scores - mean: {legit_scores.mean():.4f}, median: {np.m
        f"min: {legit_scores.min():.4f}, max: {legit_scores.max():.4f}"}

```



Logistic Regression:

Fraud scores – mean: 0.9244, median: 1.0000, min: 0.0211, max: 1.0000
 Legit scores – mean: 0.0621, median: 0.0170, min: 0.0000, max: 1.0000

Starting MLP:

Fraud scores – mean: 0.8741, median: 0.9997, min: 0.0000, max: 1.0000
 Legit scores – mean: 0.0032, median: 0.0000, min: 0.0000, max: 0.9999

Step 5 — Summary and interpretation

What we built:

Model	Type	Purpose
Trivial baseline	Always predict class 0	Absolute floor — any useful model must beat this
Logistic regression	Linear classifier with balanced class weights	Shows how much signal lives in linear feature combinations
Starting MLP	3-layer feedforward neural network (128 → 64 → 32) with Dropout	First non-linear deep-learning model; captures feature interactions

Interpreting the results

1. **Trivial baseline confirms accuracy is misleading.** A model that never flags fraud achieves ~99.87% accuracy but 0% recall — it misses every single fraud case. The confusion matrix heatmap makes this stark: the entire bottom row (actual fraud) is

classified as non-fraud. This is why we use PR AUC, recall, and F1 as primary metrics.

2. **Logistic regression provides a meaningful learned baseline.** With class weighting, it already catches a substantial fraction of fraud and provides calibrated probabilities. The score distribution histogram shows that logistic regression pushes most fraud cases toward higher probabilities, but there is still noticeable overlap with legitimate transactions, which explains why some fraud is missed and some legitimate transactions are flagged.
3. **The MLP adds non-linear capacity.** The comparison table and PR curves reveal whether the three Dense layers and Dropout regularization improve ranking quality (PR AUC) and detection rate (recall) beyond the linear baseline. Compare the two score distribution histograms: if the MLP achieves cleaner separation (fraud scores concentrated near 1.0, legitimate scores near 0.0), it is learning useful non-linear patterns. If the improvement is marginal, it may suggest the fraud signal in this PCA-transformed dataset is largely linear.
4. **Confusion matrix heatmaps make trade-offs visible.** For the learned models, look at the bottom-right cell (TP) versus the top-right cell (FP). A model with high TP but also high FP is aggressive — it catches fraud but creates false alarms. A model with low FP but low TP is conservative — it avoids false alarms but misses fraud. The right balance depends on the cost of each type of error.
5. **Training curves confirm learning dynamics.** If the loss and AUC plots show train and validation curves converging and then the validation curve plateauing (with early stopping triggering), the model is neither severely underfitting nor overfitting. If there is a large gap between train and val curves, that signals overfitting — a problem that Step 7 will address through regularization tuning.
6. **All evaluations use the validation set only.** The test set remains untouched and will only be used once in Step 8 for the final, unbiased performance report. This discipline prevents overfitting the evaluation.

What comes next

- **Step 6** will explore the model architecture in more detail and discuss design choices.
- **Step 7** will tune the decision threshold (instead of using the default 0.5), experiment with hyperparameters, and run stability checks across multiple seeds.
- **Step 8** will lock the final pipeline and report performance on the held-out test set.

Step 6 — Develop the model

Overview of feedforward neural networks

A feedforward network passes inputs through a stack of Dense layers without cycles. For tabular data, this is an effective first-choice architecture.

Overview of multilayer perceptrons

A multilayer perceptron (MLP) stacks Dense layers with nonlinear activations (e.g., ReLU) to learn complex decision boundaries from tabular numeric features.

Justification: Why a feedforward MLP

- Works well for fixed-length tabular numeric inputs.
- Efficient to train and tune compared to more complex architectures.
- Provides a strong baseline before exploring more specialized models.

Step 7 — Model improvement and threshold tuning

- Instead of using a standard 0.5 cutoff, choose a decision threshold on the validation set (maximize recall subject to a minimum precision).
- Use PR AUC as the primary model selection metric, which is more appropriate than accuracy for rare-event detection.
- Run each configuration multiple times and report mean and standard deviation for stability.
- Use a time-aware split to mirror real deployment conditions.
- Apply binning-based calibration checks to verify probability quality.

Step 8 — Final evaluation and deployment considerations

Current real-life applications

Fraud detection systems are used by card issuers and payment networks to rank transactions by risk, trigger manual review, or apply step-up verification. In production, models are monitored for drift, recalibrated, and re-trained as fraud patterns evolve.

Glossary of terms

Term	Definition
Binary classification	A prediction task with two classes, here fraud versus non fraud
Class imbalance	A dataset property where one class is much rarer than the other
Positive class	The class of interest, here fraud transactions labeled 1
Negative class	The other class, here legitimate transactions labeled 0
Feature	An input variable used for prediction, such as V1 or Amount
Label	The target variable the model learns to predict, here Class
PCA	Principal Component Analysis, a transformation that creates new variables as linear combinations of original variables
Principal component	One PCA derived feature, here V1 to V28
Train set	Data used to fit model parameters
Validation set	Data used to select hyperparameters and decision threshold
Test set	Held out data used once for final performance reporting
Data leakage	When information from validation or test data influences training or preprocessing decisions
Standardization	Scaling features to have zero mean and unit variance using training statistics
Normalization	Rescaling features to a fixed range, often 0 to 1, depending on the method
Model	A function that maps input features to a predicted output
Neural network	A model composed of layers of learned transformations, here Dense and Dropout layers
Dense layer	A fully connected layer that applies a linear transformation followed by an activation function
Dropout	A regularization method that randomly disables a fraction of units during training to reduce overfitting
Activation function	A non linear function applied within a layer, such as ReLU or sigmoid
Sigmoid	An activation that maps a real number to a value between 0 and 1, used for binary outputs
Logits	The raw model output before applying sigmoid
Probability score	The model output after sigmoid, interpreted as probability like score
Decision threshold	The cutoff used to convert probability scores into class predictions

Term	Definition
Confusion matrix	A table counting true positives false positives true negatives and false negatives
True positive TP	Fraud correctly predicted as fraud
False positive FP	Legitimate predicted as fraud
True negative TN	Legitimate correctly predicted as legitimate
False negative FN	Fraud predicted as legitimate
Precision	TP divided by TP plus FP, the fraction of predicted fraud that is truly fraud
Recall	TP divided by TP plus FN, the fraction of actual fraud that is detected
F1 score	Harmonic mean of precision and recall
ROC curve	Curve of true positive rate versus false positive rate over thresholds
AUC	Area under a curve, a threshold independent performance summary
PR curve	Precision versus recall over thresholds
PR AUC	Area under the precision recall curve, often preferred for rare event detection
Overfitting	When a model performs well on training but poorly on new data
Regularization	Methods that reduce overfitting, such as dropout or weight penalties
Hyperparameter	A setting chosen outside training, such as number of layers, dropout rate, learning rate
Learning rate	Step size used by the optimizer when updating model weights
Optimizer	Algorithm that updates model weights to minimize the loss, such as Adam
Loss function	The quantity the model minimizes during training, such as binary cross entropy
Early stopping	Stopping training when validation performance stops improving
Calibration	How well predicted probabilities match observed event rates
Concept drift	When the data generating process changes over time, causing performance degradation
Baseline model	A simple reference model used for comparison, such as always predicting non fraud

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