

>>> **Privacy-Preserving Data Generation:**
>>> Towards Generating Privacy-Preserving, Synthetic and
Useful Time Series ECG Data for Anomaly Detection

KTH x RISE
Sijun John Tu
March 13, 2024

>>> Outline

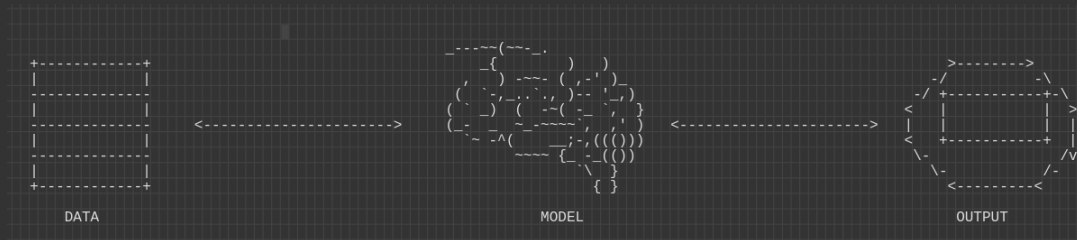
1. Project introduction
2. Dataset: MITBIH ECG data
3. Privacy-preserving Time Series Data Generation
4. Results
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>>> Machine Learning Pipeline

● ● ● Figure: High-level machine learning pipeline



>>> Anomaly detection using privacy-preserving, synthetic time series data

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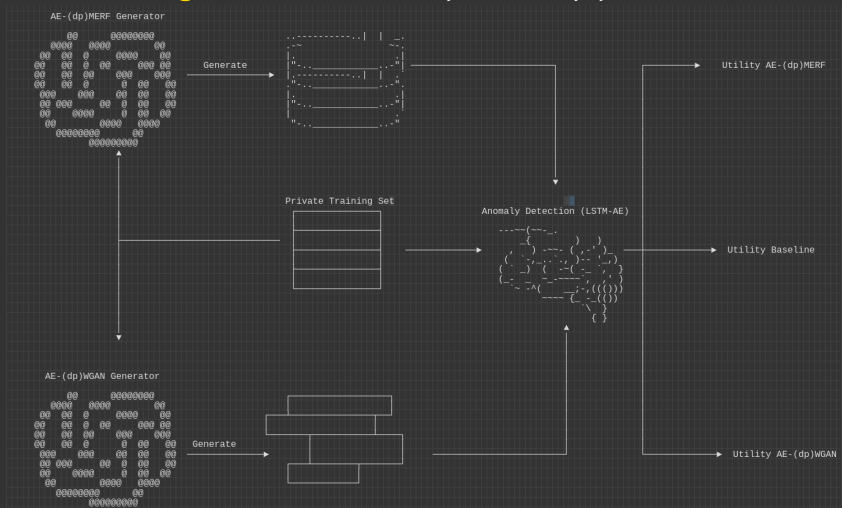
- Promising solution: **synthetic data** with privacy guarantees!
- Synthetic data with **differential private** (DP) guarantees is a promising solution to ensure privacy independent of downstream task.

\$ BUT:

- **Privacy-Utility-Tradeoff**: Commonly, a gain in privacy results in a loss of utility.
- For **anomaly detection** this might not be the case (?).

>>> Structure

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5. **Contaminate** training data with anomalous heartbeats and repeat.

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>>> Heartbeat Arrhythmia

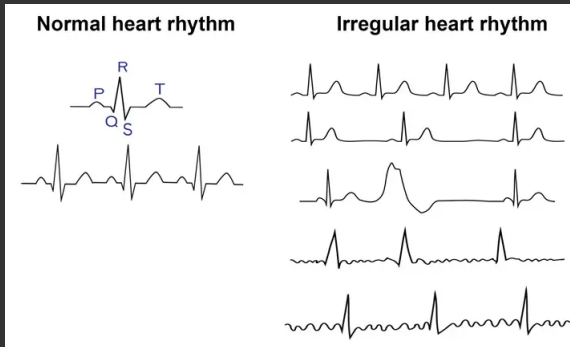


Figure: Different heartbeat arrhythmias ¹

¹source: <https://www.parkwayshenton.com.sg/health-plus/article/arrhythmia-guide>

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We treat the problem of detecting anomalous heartbeats as an anomaly detection problem from machine learning based on the **reconstruction error**:

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- \$ Given an anomalous heartbeat the model should give **higher reconstruction error**.
- \$ Based on an optimal **threshold** for that error we classify this heartbeat as either regular or anomalous.

Two reasons for this semi-supervised approach: high class imbalance and no need for labelling.

>>> Baseline Model

Model is a LSTM-AE that is **trained only on regular, private samples** with the goal to reconstruct normal samples. The classification is made based on the reconstruction error.

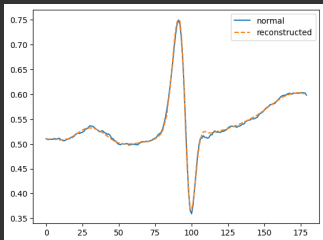


Figure: reconstruction on normal sample

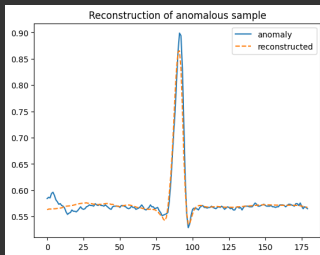


Figure: reconstruction on anomalous sample

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>>> Review: Differential Privacy

Idea. Hide the influence of one particular sample on the output of the model by adding randomness.

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Definition (Differential Privacy)

A randomised algorithm \mathcal{M} is (ϵ, δ) - differentially private if for all sets of outcomes $S \subset \text{ran}\mathcal{M}$ and for all databases x, y , such that they **only differ in one element**, we have

$$\mathbb{P}(\mathcal{M}(x) \in S) \leq e^\epsilon \cdot \mathbb{P}(\mathcal{M}(y) \in S) + \delta \quad , \quad (1)$$

where the probability is taken over the randomness of \mathcal{M} .

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Informally. Replacing one record in the data will not change the outcome of algorithm \mathcal{M} *too much* (specified via privacy budget ϵ). The lower ϵ the stricter the privacy guarantees.

>>> Examples of DP mechanism

\$ Gaussian mechanism

- Add **Gaussian noise** to output of some function.
- For a given function $f : \mathbb{N}^{|\mathcal{X}|} \rightarrow \mathbb{R}^d$, privacy parameters $\epsilon \in (0, 1)$ and $\delta > 0$ define the gaussian mechanism $F(x)$ as follows:

$$F(x) = f(x) + \xi \quad , \quad (2)$$

where $\xi \sim \mathcal{N}(0, \sigma^2 I)$ and $\sigma \geq \frac{2\Delta f}{\epsilon} \ln(\frac{1.25}{\delta})$ to satisfy DP.

\$ DP-SGD

- DP version for training neural networks
- **Add noise to gradients** while training

>>> AE-(dp)MERF: Architecture

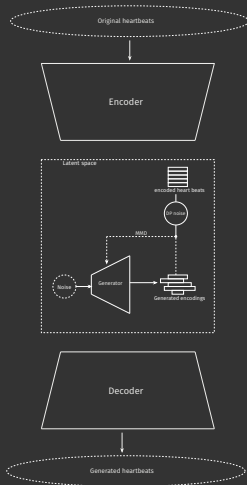


Figure: AE-(dp)MERF architecture

1. Encode dataset X : $X^{enc} = Enc(X)$
2. Generate encodings by sampling from Gaussian noise: $\tilde{X}^{enc} = Gen(z)$
3. Train generator via loss maximum mean discrepancy (MMD) loss:
$$MMD(X^{enc}, \tilde{X}^{enc}) = \left\| \frac{1}{m} \sum_{i=1}^m \hat{\Phi}(x_i^{enc}) - \frac{1}{m} \sum_{j=1}^m \hat{\Phi}(\tilde{x}_j^{enc}) \right\|_{\mathcal{H}}^2$$
where $\hat{\Phi}(x) \in \mathbb{R}^D$ and $\hat{\Phi}_j(x) = \sqrt{\frac{2}{D}} \cos(\omega_j^T x)$.
4. Decode generated encodings:
 $\tilde{X} = Dec(\tilde{X}^{enc})$

>>> AE-(dp)MERF: Differential Privacy

We are making AE-MERF differentially private by adding noise to the loss function:

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$$MMD(X^{enc}, \tilde{X}^{enc}) = \left\| \frac{1}{m} \sum_{i=1}^m \hat{\Phi}(x_i^{enc}) + \xi - \frac{1}{m} \sum_{j=1}^m \hat{\Phi}(\tilde{x}_j^{enc}) \right\|_{\mathcal{H}}^2 \quad , \quad (4)$$

where $\xi \sim \mathcal{N}(0, \sigma^2 I)$

>>> AE-(dp)WGAN: Architecture

1. Encode dataset X : $X^{enc} = Enc(X)$
2. Generate encodings by sampling from Gaussian noise: $\tilde{X}^{enc} = Gen(z)$
3. Discriminator learns to distinguish between real and fake samples.
4. Train Discriminator and Generator jointly.
5. Decode generated encodings:
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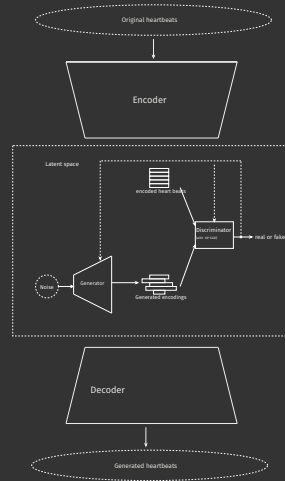


Figure: Architecture of AE-(dp)WGAN

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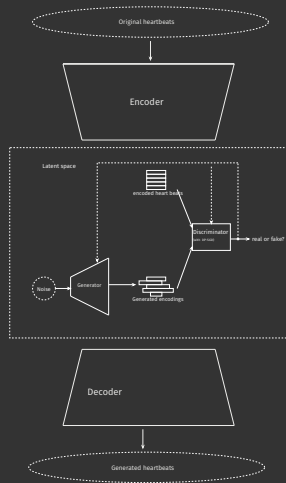


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>>> AE-(dp)MERF

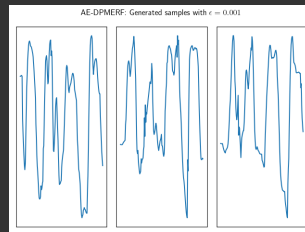
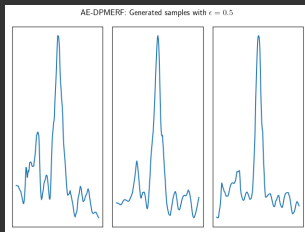
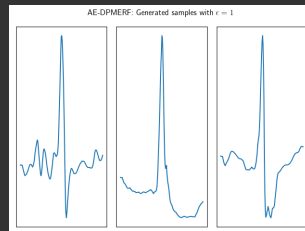
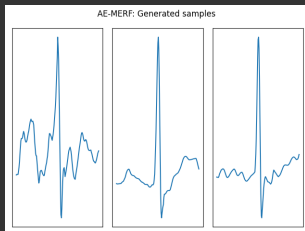


Figure: AE-(dp)MERF generated samples

>>> AE-(dp)MERF: Utility

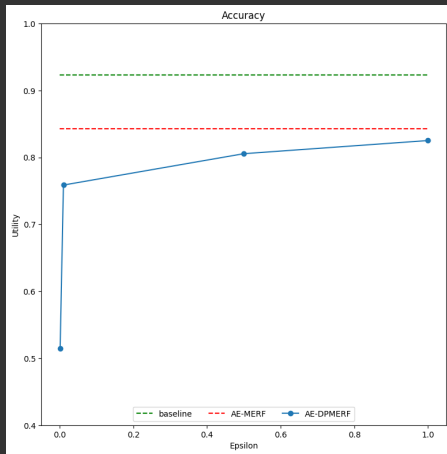


Figure: Results of AE-(DP)MERF with different privacy budgets (lower epsilon means higher privacy)

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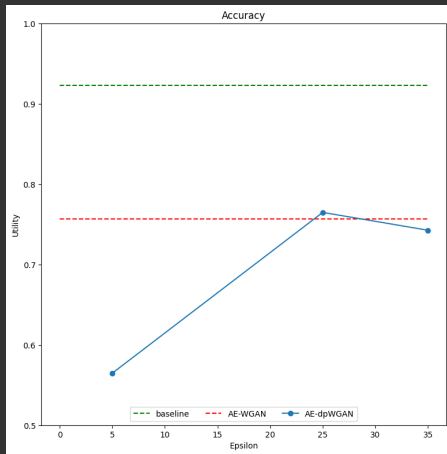


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- \$ AE-(dp)WGAN gives worse utility and can only work with meaningless privacy budgets ϵ .
- \$ We lose utility when replacing original data with non-private synthetic data.
- \$ BUT: Adding privacy does not further degrade the utility for anomaly detection too much until too much noise is added.

>>> Contamination

We **contaminate** the train set that only consists of regular samples with **1%, 2%, 5% anomalous samples** (the percentage of heartbeat arrhythmias is estimated to be around max. 5%).

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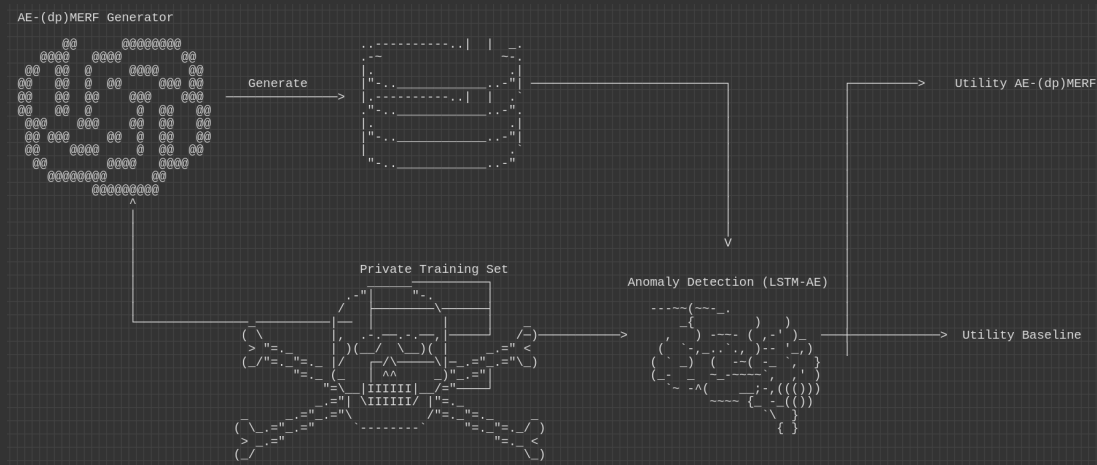


Figure: Structure of Contamination Experiment

>>> Contamination: AE-(DP)MERF

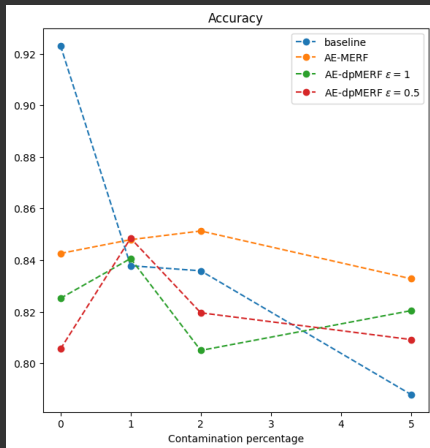
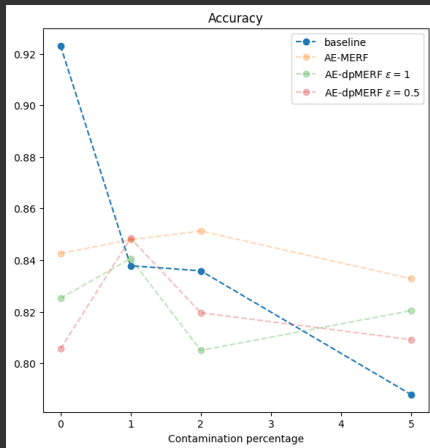


Figure: Contaminated training set: AE-(DP)MERF

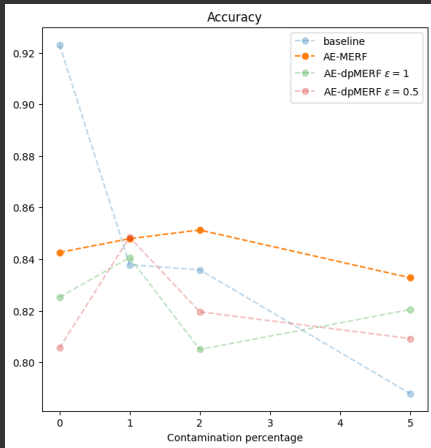
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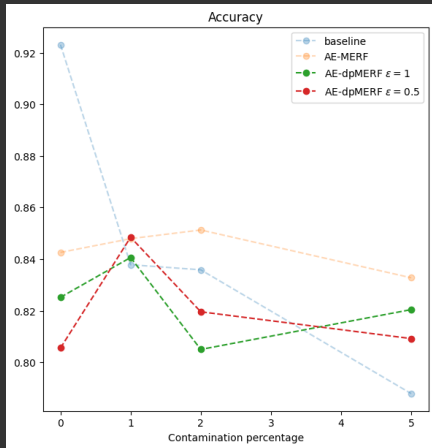


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- \$ Utility of **AE-dpMERF** generated samples first increases and then decrease when contamination is too high.

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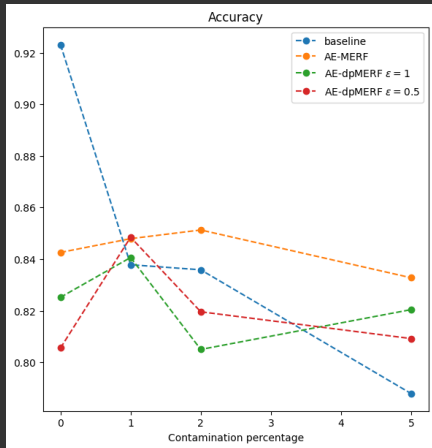


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- \$ **Baseline model** performance degrades with increasing contamination percentage.
- \$ **AE-MERF** generated samples retain stable utility.
- \$ Utility of **AE-dpMERF** generated samples first increases and then decrease when contamination is too high.
- \$ Utility of synthetic data is higher than baseline model

>>> Contamination: AE-(DP)MERF

Hypothesis: Noise added during data generation and DP noise can have a **regularising effect** on the synthetic data which counteracts the contamination.

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- \$ We measured the **utility** of the synthetic data via the downstream task of anomaly detection (heartbeat arrhythmia).
- \$ We investigated the **robustness** of the data generation by **contaminating** the data set with anomalous samples.

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- \$ AE-(dp)MERF works better than GAN based approach.
- \$ The **Privacy-Utility-Tradeoff is more nuanced** and depends on the use case. For anomaly detection, privacy and utility can go hand in hand.
- \$ Synthetic data and DP can add **robustness**.


```
>>> Future Work
```

```
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- \$ Work with **other use cases**, e.g. classification, regression.
- \$ Further investigate **robustness**.
- \$ Verify theoretical privacy guarantees with empirical tests, e.g. **membership inference attacks**.

>>> Privacy-Preserving Acknowledgement

Thank you Aflsono, Adenrs, Apslotsuo,
Hna, Sihahd!

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-  Ang, Yihao et al. (2023). TSGBench: Time Series Generation Benchmark. arXiv: 2309.03755 [cs.LG].
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>>> **BACKUP**

>>> Model Architecture

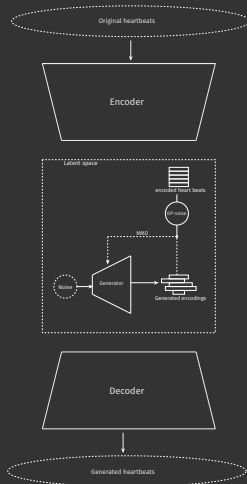


Figure: AE-(dp)MERF architecture

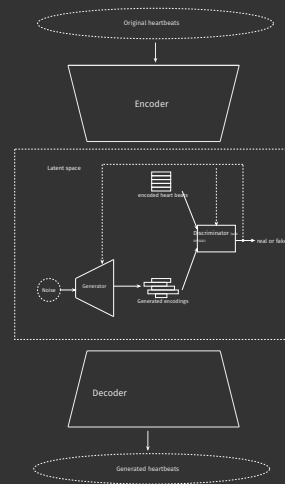


Figure: Architecture of AE-(dp)WGAN

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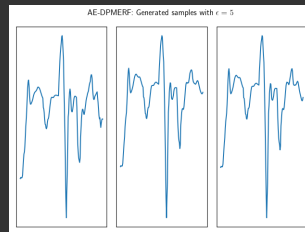
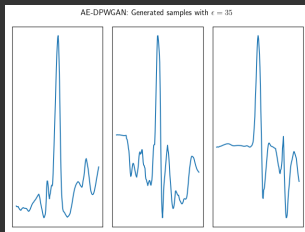
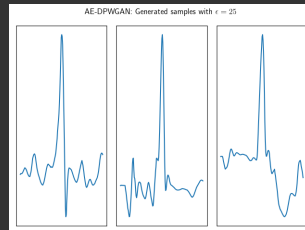
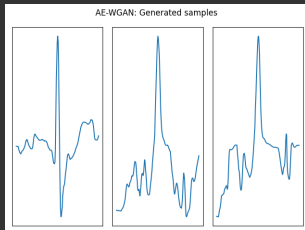


Figure: AE-(dp)WGAN generated samples

>>> Gaussian Mechanism

For a given function $f : \mathbb{N}^{|\mathcal{X}|} \rightarrow \mathbb{R}^d$, privacy parameters $\epsilon \in (0, 1)$ and $\delta > 0$ define the gaussian mechanism $F(x)$ as follows:

$$F(x) = f(x) + \mathcal{N}(0, \sigma^2) \quad (5)$$

where the variance is calibrated by the sensitivity of f and the given privacy level, such that $\sigma \geq \frac{2\Delta f}{\epsilon} \ln(\frac{1.25}{\delta})$

>>> Performance metrics

\$ Accuracy measures the overall percentage of correct classifications:

$$Accuracy = \frac{TP + TN}{TP + FP + TN + FN} \quad . \quad (6)$$

\$ Precision looks only on the samples that are labelled as anomalies and computes the percentages of correctly detected anomalies:

$$Precision = \frac{TP}{TP + FP} \quad . \quad (7)$$

\$ Recall looks at all true anomalies and computes the percentage of correctly detected anomalies

$$Recall = \frac{TP}{TP + FN} \quad . \quad (8)$$

\$ F1 computes the an average of Precision and Recall

$$F1 = \frac{2 \cdot Precision \cdot Recall}{Precision + Recall} \quad . \quad (9)$$

>>> DP Illustrated

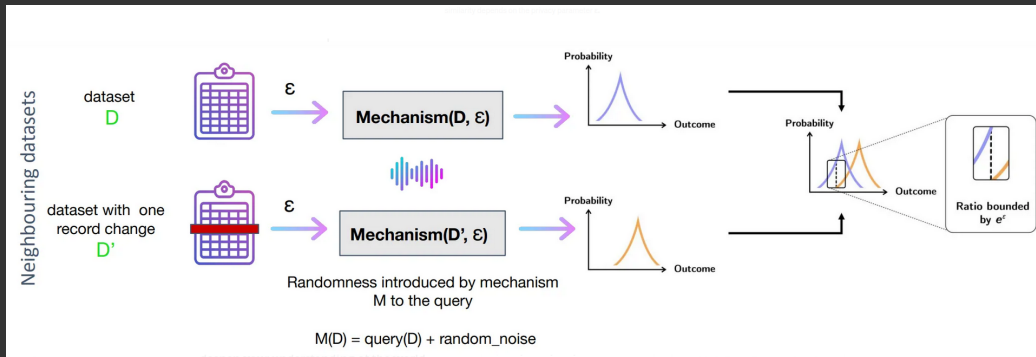
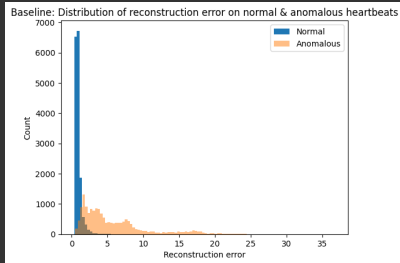


Figure: Illustration of DP²

²taken from: <https://medium.com/dsaid-govtech/protecting-your-data-privacy-with-differential-privacy-an-introduction-abee1d7fcb63>

>>> Classification based on Reconstruction Error



We can clearly see a **difference in error distribution** for regular and anomalous samples. We choose the **threshold that maximises the classification accuracy**.

Figure: Distribution of reconstruction error on regular & anomalous samples

>>> Classification threshold

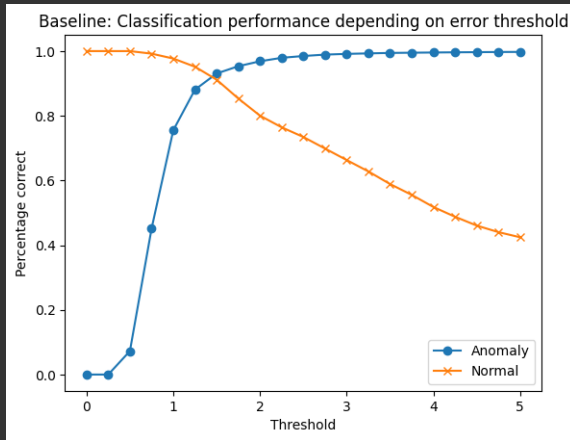


Figure: Adjusting the threshold according to classification accuracy

>>> Models

AE-(dp)MERF

- \$ AE-(dp)MERF is based on DP-MERF (best state of the art generator for tabular data).
- \$ Simple architecture with mathematically sophisticated loss function.
- \$ Does not work with time series data out of the box, but we will modify it so it works.

AE-(dp)WGAN

- \$ Model based on GAN network, which are commonly used in image generation.
- \$ Based on RTSGAN, which delivers state of the art performance for time series data.
- \$ No private counterpart, hence we will implement our own private version.

>>> AE-(dp)MERF: Utility

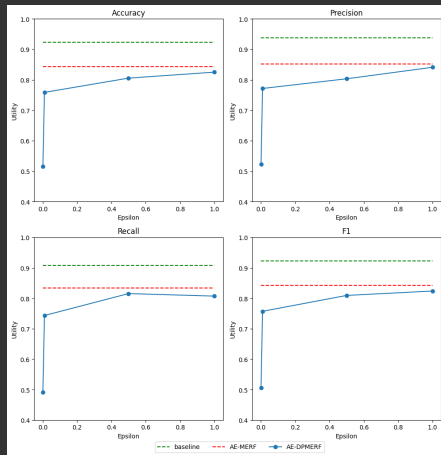


Figure: Results of AE-(DP)MERF with different privacy budgets (lower epsilon means higher privacy)

>>> AE-(dp)WGAN: Utility

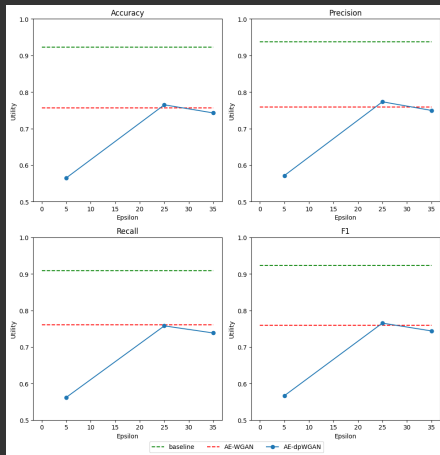
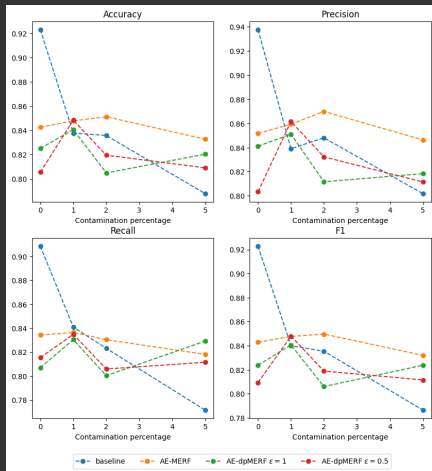


Figure: Results of AE-(dp)WGAN with different privacy budgets (lower epsilon means higher privacy)

>>> Contamination: AE-(DP)MERF



- \$ **Baseline model** performance degrades with increasing contamination percentage.
- \$ **AE-MERF** generated samples retain stable utility.
- \$ Utility of **AE-dpMERF** generated samples first increases and then decrease when contamination is too high.
- \$ Utility of synthetic data is higher than baseline model

Figure: Contaminated training set: AE-(DP)MERF