Synthetic data generation: A literature review

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The generation of synthetic data can be used for anonymization, regularization, oversampling, semi-supervised learning, self-supervised learning and various other tasks. The wide range of applications of these mechanisms motivated the development of new algorithms specialized in generating data for specific types of data and Machine Learning (ML) tasks. As a result, the analysis of the different types of generative models

1 Introduction

Synthetic data is obtained from a generative process based on properties of real data [1]. The generation of synthetic data is essential for various domains and tasks. For example, synthetic data is used as a form of regularizing neural networks (*i.e.*, data augmentation) **[CITATION]**. One form of anonymizing datasets is via the production of synthetic observations (*i.e.*, synthetic data generation) **[CITATION]**. In settings where only a small portion of training data is labeled, some techniques generate artificial data using both labeled and unlabeled data with a modified loss function to train neural networks (*i.e.*, semi-supervised learning) [2]. In imbalanced learning contexts, synthetic data can be used to balance the target classes' frequencies and reinforce the learning of minority classes (*i.e.*, oversampling) [3]. Some active learning frameworks use data generation to improve the quality of data selection and classifier training [4]. Other techniques employ data generation to produce deep neural networks without labeled data (*i.e.*, self-supervised learning) [5].

The breadth of these techniques span multiple domains, such as facial recognition [6], Land Use/Land Cover mapping **[CITATION]**, medical image processing **[CITATION]**, Natural Language Processing [7] or credit card default prediction [8]. According to the domain and data type, the data generation techniques used may vary significantly. Generally speaking, some data generation mechanisms are specific to some domains, data types or tasks. For example, ... Most, if not all, of these techniques are applied on the input or output space.

However, there are various data generation techniques that are invariant to the task or data types used. These techniques can be either applied in the feature space [9] or in problems using tabular data. On the one hand, data generation in the feature space uses a generative model to learn a manifold, lower-dimensional abstraction over the input space [10], defined here as the feature space. At this level, any tabular data generation mechanism can be applied and reconstructed into the input space if necessary. On the other hand, synthetic data generation on tabular data can be applied to most problems. Although, the choice of the generation mechanism is still dependant on (1) the importance of the relationships found between the different features, (2) the ML task to be developed and (3) the motivation for the generation of synthetic data. For example, when generating data to address an imbalanced learning problem (*i.e.*, oversampling), the relationships between the different features are not necessarily kept since the goal is to reinforce the learning of the minority class by redefining an ML classifier's decision boundaries. If the goal is to anonymize a dataset, perform some type of descriptive task, or ensure a consistent model interpretability, these relationships need to be kept.

Depending on the context, evaluating the quality of the generated data is a complex task. For example, for image and time series data, perceptually small changes in the original data can lead to large changes in the euclidean distance [1, 11]. The evaluation of generative models typically account primarily for the performance in a specific task, since good performance in one criterion does not imply good performance on another [11]. However, in computationally intensive tasks it is often impracticable to search for the optimal configurations of generative models. To address this limitation, other evaluation methods have been proposed to assist in this evaluation, which can be distinguished into statistical divergence metrics and precision/recall metrics [12]. The relevant performance metrics found in the literature are discussed in Section 7.

1.1 Motivation and Contributions

This literature review focuses on the generation mechanisms and generative models underlying the different techniques where synthetic data is generated. Specifically, we focus on techniques used in studies published since 2019. We focus on the ML perspective of synthetic data, as opposed to the practical perspective. From a practical sense, synthetic data is used as a proxy of real data. It is assumed to be inaccessible, essential and a secondary asset for tasks like education, software development, or systems demonstrations [13].

We focus on data generation techniques in the tabular and feature space (*i.e.*, embedded inputs), given its breadth in scope. Related literature reviews are mostly focused on specific algorithmic or domain applications, with little to no emphasis on the core generative process. For this reason, these techniques often appear "sandboxed", even though there is a significant overlap between them. There are some related reviews published since 2019. Assefa et al. [1] provides a general overview of synthetic data generation for time series data anonymization in the finance sector. Hernandez et al. [14] reviews data generation techniques for tabular health records anonymization. Raghunathan [15] reviews synthetic data anonymization techniques that preserve the statistical properties of a dataset. Nalepa et al. [16] reviews data augmentation techniques for brain-tumor segmentation. Bayer et al. [17] distinguishes augmentation techniques for text classification into feature and data space, while providing an extensive overview of augmentation methods within this domain. However, the taxonomy proposed and feature space augmentation methods are not necessarily specific to the domain. Shorten et al. [18], Chen et al. [19], Feng et al. [7] and Liu et al. [20] also review data augmentation techniques for text data. Yi et al. [21] review Generative Adversarial Network architectures for medical imaging. Wang et al. [22] reviews face data augmentation techniques. Shorten et al. [23] and Khosla et al. [24] discuss techniques for image data augmentation. Iwana et al. [25] and Wen et al. [26] also review time series data augmentation techniques. Zhao et al. [27] review data augmentation techniques for graph data. The analysis of related literature reviews [1] is shown in Table 1.

[1]Results obtained using Google Scholar, limited to articles published since 2019, using the search

Table 1: Related literature reviews published since 2019.

Reference	Data type	ML problem	Domain	Observations
Assefa et al. [1]	—	Differential privacy	Finance	Analysis of applications, motivation and properties of synthetic data for anonymization.
Hernandez et al. [14]	Tabular	Differential privacy	Healthcare	Focus on GANs.
Raghunathan [15]	Tabular	Differential privacy	Statistics	Focus on general definitions such as differential privacy and statistical disclosure control.
Nalepa et al. [16]	Image	Segmentation	Medicine	Analysis of algorithmic applications on a 2018 brain-tumor segmentation challenge
Bayer et al. [17]	Text	Classification	—	Distinguish 100 methods into 12 groups.
Shorten et al. [18]	Text	Deep Learning	—	General overview of text data augmentation.
Chen et al. [19]	Text	Few-shot Learning	—	Augmentation techniques for machine learning with limited data
Feng et al. [7]	Text	—	—	Overview of augmentation techniques and applications on NLP tasks.
Liu et al. [20]	Text	—	Various	Analysis of industry use cases of data augmentation in NLP. Emphasis on input level data augmentation.
Yi et al. [21]	Image	—	Medicine	Emphasis on GANs.
Wang et al. [22]	Image	Deep Learning	—	Regularization techniques using facial image data. Emphasis on Deep Learning generative models.
Shorten et al. [23]	Image	Deep Learning	—	Emphasis on data augmentation as a regularization technique.
Khosla et al. [24]	Image	—	—	Broad overview of image data augmentation. Emphasis on traditional approaches.
Iwana et al. [25]	Time series	Classification	—	Defined a taxonomy for time series data augmentation.
Wen et al. [26]	Time series	Various	—	Analysis of data augmentation methods for classification, anomaly detection and forecasting.
Zhao et al. [27]	Graph	Various	—	Graph data augmentation for supervised and self-supervised learning.
Khalifa et al. [28]	Image	—	Various	General overview of image data augmentation and relevant domains of application.

query `("synthetic data generation" OR "oversampling" OR "imbalanced learning" OR "data augmentation") AND ("literature review" OR "survey")`. Retrieved on August 11th, 2022. Additional articles were later included whenever found relevant.

The different taxonomies established in the literature follow a similar line of thought, but are often specific to the technique discussed. Regardless, it is possible to establish a broader taxonomy without giving up on specificity.

This study provides a joint overview of the different data generation approaches, domains and ML techniques where data generation is being used, as well as a common taxonomy across domains. It extends the analyses found in these articles and uses the compiled knowledge to identify research gaps. We compare the strengths and weaknesses of the models developed within each of these fields. Finally, we identify possible future research directions to address some of the limitations found. The contributions of this paper are summarized below:

- Bridge different ML concepts using synthetic data generation in its core (Algorithmic applications + Review of the State-of-the-art).
- List the different synthetic data generation/data augmentation taxonomies and characterize all relevant methods accordingly (Data augmentation taxonomy).
- Discuss the ML techniques in which synthetic data generation/data augmentation is used, beyond regularization and consolidate the current data generation mechanisms across the different techniques (Algorithmic Applications).
- Bring to light the key challenges of synthetic data generation and put forward possible research directions in the future.

1.2 Paper Organization

This paper is organized as follows: Section 2 defines and formalizes the different concepts, goals, trade-offs and motivations related to synthetic data generation. Section 3 establishes the taxonomy used to categorize all the methods described in the paper. Section 4 reviews synthetic data generation mechanisms in the feature space. Section 5 reviews synthetic data generation mechanisms in the input space. Section 6 describes the applications of synthetic data in ML methods. Section 7 reviews performance evaluation methods of synthetic data generation mechanisms. Section 8 summarizes the main findings and discusses limitations and possible research directions in the state-of-the-art. Section 9 presents the main conclusions drawn from this study.

2 Background

Motivations:

1. Low-resource languages (NLP)
2. Mitigate bias
3. Fixing class imbalance

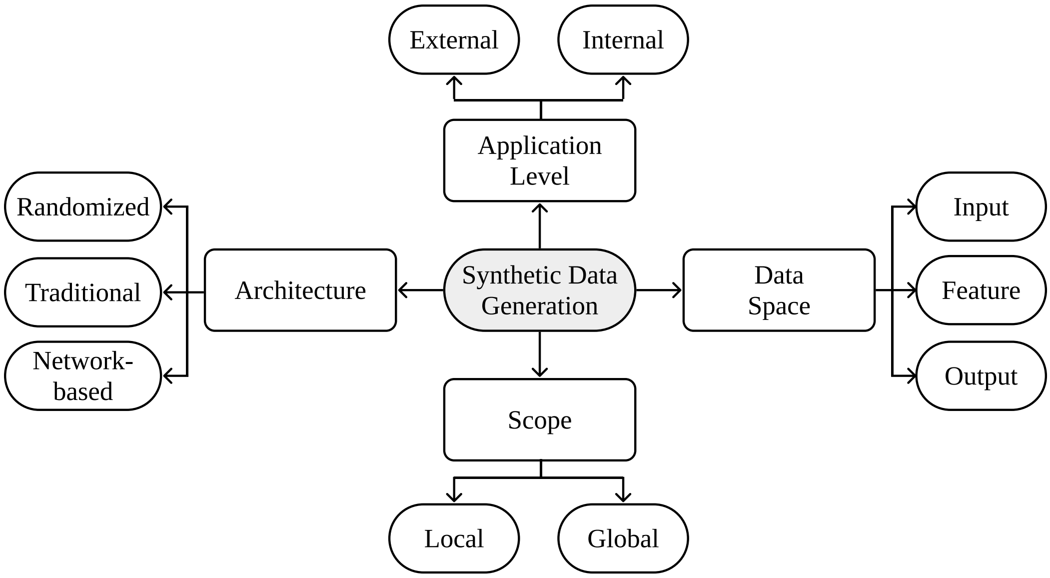

Figure 1: General taxonomy of data generation mechanisms proposed in this paper.

4. Few-shot learning
5. Adversarial examples

3 Data Generation Taxonomy

Image data augmentation taxonomy [28]

There is a distinction between semantic and traditional image data augmentation [29], also discussed in [23]

Synthetic data generation for medical records taxonomy [14] which is incomplete

Data generation mechanisms can be characterized in 4 properties: Architecture, Application level, Scope and Data space. The overall definition of the proposed taxonomy is shown in Figure 1.

1. Level of application (External or Internal)
2. Scope (Local or Global augmentation)
3. Architectural approach (heuristic, network-based or others)
4. Data space (Input, feature or output). Within feature and output: Domain

4 Data Generation in the Feature Space

According to [1]. The generation of synthetic data should aim to fulfil the conditions below:

- Privacy preserving.
- Human readable.
- Compact.

Discuss Auto-augmentation (as mentioned in [22]) or meta learning (as mentioned in [23])

5 Data Generation in the Input Space

In this section, we describe some popular domain and data type-specific data generation techniques. For each data type we include a table with related literature reviews specific to different domains.

5.1 Tabular

5.2 Time series

Generative adversarial networks in time series

5.3 Image

Image-specific data generation mechanisms can be further divided into traditional and semantic techniques [29]. Traditional generation techniques comprise simple modifications such as translation, cropping or random erasing [30]. Semantic generation methods involve more complex tasks, such changing colors of specific attributes, backgrounds and visual angles **[CITATION]**.

Data generation by modifying specific attributes in data points with known perturbations [6]. For example, overlaying facial elements into a picture containing a human face (*e.g.*, adding sunglasses and different hairstyles), introducing perturbations in facial landmarks, different illumination and artificial misalignment are different approaches to generate artificial observations for facial recognition.

Generative Adversarial Networks in computer vision [31]

5.4 Text

NLP also benefit from data augmentation [7].

In NLP, there is the challenge of establishing universal rules for text transformations to provide new linguistic patterns [32]

https://github.com/styfeng/DataAug4NLP

5.5 Graphs

Another relevant paper [33]

Various graph data augmentation methods can be applied to related data types such as text data [18].

An analysis on different graph data augmentation techniques and a new graph data augmentation framework Zhao et al. [34]

List of papers about graph data augmentation: https://github.com/zhao-tong/graph-data-augmentation-papers

6 Algorithmic applications

6.1 Data Privacy

Synthetic data generation is a technique used to produce synthetic, anonymized versions of datasets [35]. It is considered a good approach to share sensitive data without compromising significantly a given data mining task [36, 37]. Traditional data anonymization techniques, as well as federated learning are two other viable solutions for privacy-preserving data publishing tasks, but contain drawbacks [14]. On the one hand, traditional data anonymization requires domain knowledge, is labor intensive and remains susceptible to disclosure [38]. On the other hand, federated learning is a technically complex task that consists on training ML classifiers on edge devices and aggregating temporarily updated parameters on a centralized server, instead of aggregating the training data [39]. Although it prevents sharing sensitive data, its applicability is dependent on the task. Dataset anonymization via synthetic data generation attempts to balance disclosure risk and data utility in the final synthetic dataset. The goal is to ensure observations are not identifiable and the relevant data mining tasks are not compromised [40, 41].

The generation of synthetic datasets allow a more flexible approach to the successful implementation of ML tasks. However,

Anonymizing data using synthetic data generation in the financial sector [1].

Guidelines for effective synthetic data generation [35]

6.2 Regularization in Supervised Learning

The performance of Machine Learning models is highly dependent on the quality of the training dataset used [42, 43]. The presence of imbalanced and/or small datasets, target labels incorrectly assigned, outliers and high dimensional input spaces reduce the prospects of a successful machine learning (ML) model implementation [43, 44, 45]. In the case of deep learning, for example, these models are often limited by a natural inclination to overfitting, label noise memorization and catastrophic forgetting [46]. Regularization methods are the typical approach to address these problems, but producing robust ML solutions is still a challenge [47].

It is frequently assumed that the training data is sampled from a fixed data source, it is balanced and does not contain label noise. Under these conditions, the resulting ML classifier is expected to achieve good generalization performance [48]. Although, in practical applications, this is rarely the case. When the training data is not representative of the true population, or the model is over-parametrized, it becomes particularly prone to overfitting [49]. Regularization methods attempt to address these limitations. They can be divided into three categories [50]:

1. Output level modifications. Transforms the labels in the training data.
2. Algorithmic level modifications. Modifies the classifier's architecture, loss function or other components in the training procedure.
3. Input level modifications. Modifies the training dataset by expanding it with synthetic data.

The last approach, input level modifications, is known as data augmentation. Data augmentation is used to increase the size and data variability of data in a training dataset, by producing synthetic observations [51, 52]. Since it is applied at the data level, it can be used for various types of problems and classifiers [53].

"Su et al. [78] show that 70.97% of images can be misclassified by changing just one pixel" Shorten et al. [23]

6.3 Oversampling

The original author of SMOTE recently published the paper "Efficient Augmentation for Imbalanced Deep Learning" [54]

6.4 Active Learning

6.5 Semi-supervised Learning

6.6 Self-supervised Learning

7 Evaluating the Quality of Synthetic Data

The log-likelihood (and equivalently the Kullback-Leibler Divergence) is a de-facto standard to train and evaluate generative models [11]. Other common metrics include Parzen window estimates, which Theis et al. [11] show that these metrics behave independently and should generally be avoided. Therefore, it is necessary to evaluate generative models with respect to the application these models are being developed for.

The evaluation of generative models should quantify three key aspects of synthetic data [12]:

1. Fidelity
2. Diversity
3. Generalization

The 3-dimensional metric proposed by Alaa et al. [12] quantifies these aspects via the combination of three metrics (α-Precision, β-Recall and Authenticity) for various application domains.

7.1 Statistical Divergence Metrics

7.2 Precision/Recall Metrics

8 Discussion

8.1 Main Findings

The combination of data generation strategies is an approach commonly found in different problems, such as self-supervised learning [5]. It can be more frequently found in text data applications [17] and image data **[CITATION]**.

8.1.1 RQ1: bla bla bla

8.1.2 RQ2: bla bla bla

8.1.3 RQ3: bla bla bla

8.2 Limitations

Research across the different applications appears to be sandboxed even though all techniques integrate synthetic data in its core.

Given the breadth and complexity of input-level and feature-level data generation mechanisms, it is increasingly important to find a method to efficiently determine the most appropriate data generation policies. However, the complexity of this task is determined by various factors: different data types, ML problems, model architectures, computational resources, performance metrics and contextual constraints. Auto-augmentation and meta learning aim to address this challenge and are still subject to active research.

The evaluation of anonymization techniques lack standardized, objective and reliable performance metrics and benchmark datasets to allow an easier comparison across classifiers to evaluate key aspects of data anonymization (resemblance, utility, privacy and performance). These datasets should contain mixed data types (*i.e.*, a combination of categorical, ordinal, continuous and discrete features) and the metrics should evaluate the performance of different data mining tasks along with the anonymization reliability. This problem appears to be universal across domains. For example, Hernandez et al. [14] observed the lack of a universal method or metric to report the performance synthetic data generation algorithms for tabular health records.

Computational cost and inconsistent quality of synthetic data generated with GANs (*e.g.*, mode collapse).

Unlike with data privacy solutions, data augmentation techniques generally do not consider the similarity/dissimilarity of synthetic data.

There is not a clear understanding of what types of data augmentation methods are more appropriate according to different model architectures, ML tasks or domains and the reason why they work better or worse depending on the task. In addition, it is still unclear *why* data augmentation works. Research on this topic lacks depth and fails to address the theoretical underpinnings [7].

There is a lack of research on oversampling solutions to generate synthetic data with mixed data types and datasets with exclusively non metric features.

There is no clear understanding of the most appropriate data augmentation techniques used to train self-supervised models and how their behavior and performance varies according to the data generation method used.

oversampling does not seem to be a relevant source of bias in behavioral research and does not appear to have an appreciably different effect on results for directly versus indirectly oversampled variables [55]

8.3 Research directions

Quantifying the quality of the generated data:

1. Realistic
2. Similarity
3. Usefulness (determine purpose and relevant performance metric)
4. Understand the relationship between the 3 factors

9 Conclusions

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