SELF-GUIDED NOISE-FREE DATA GENERATION FOR EFFICIENT ZERO-SHOT LEARNING

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ABSTRACT

There is a rising interest in further exploring the zero-shot learning potential of large pre-trained language models (PLMs). A new paradigm called data-generation-based zero-shot learning has achieved impressive success. In this paradigm, the synthesized data from the PLM acts as the carrier of knowledge, which is used to train a task-specific model with orders of magnitude fewer parameters than the PLM, achieving both higher performance and efficiency than prompt-based zero-shot learning methods on PLMs. The main hurdle of this approach is that the synthesized data from PLM usually contains a significant portion of low-quality samples. Fitting on such data will greatly hamper the performance of the task-specific model, making it unreliable for deployment. Previous methods remedy this issue mainly by filtering synthetic data using heuristic metrics(e.g., output confidence), or refining the data with the help of a human expert, which comes with excessive manual tuning or expensive costs. In this paper, we propose a novel noise-robust re-weighting framework SUNGEN to automatically construct high-quality data for zero-shot classification problems. Our framework features the ability to learn the sample weights indicating data quality without requiring any human annotation. We theoretically and empirically verify the ability of our method to help construct good-quality synthetic datasets. Notably, SUNGEN-LSTM yields a 9.8% relative improvement than the baseline on average accuracy across eight different established text classification tasks. [1]

1 INTRODUCTION

Owing to the superior generative capacity of large-scale pre-trained language models (PLMs), there has been an emerging trend of using these powerful models (e.g., GPT) to generate training data for downstream tasks (Anaby-Tavor et al., 2020; Puri et al., 2020; Kumar et al., 2020; Lee et al., 2021, *inter alia*). Among them, a new line of generation-based zero-shot learning using the unfinetuned PLM pushes the envelope further (Schick & Schütze, 2021; Ye et al., 2022; Meng et al., 2022), featuring total annotation-free training for downstream tasks. Ye et al. (2022) (ZEROGEN) further boosts the efficiency by using the generated data to train tiny task models (TAM), which have orders-of-magnitude fewer parameters than the PLM. Specifically, they first design prompts incorporating the task description and label information, then use them to guide the data generation from the PLM. Subsequently, the synthesized dataset is used to train the tiny task-specific models. Compared with the classic prompt-based zero-shot learning on PLM, this new paradigm enjoys two favorable properties: (1) since the task model has orders-of-magnitude fewer parameters than the PLM, it demonstrates much lower inference latency; (2) with the large amount of PLM-generated training data, the task model often shows better performance than prompt-based zero-shot PLM counterparts.

In the above paradigm, the amount and the quality of the generated data are the crucial factors for the task model's performance. Unfortunately, despite we can generate unlimited training data in theory, the data

[1] The code will be released upon publication.

quality is not always guaranteed. Our experimental observation across many downstream tasks verifies the existence of this issue: in ZEROGEN, after a few training epochs on the PLM-generated dataset, although the training accuracy steadily improves, the actual test accuracy of the model starts declining rapidly (e.g., IMDb in Figure 1) – a clear indication of the model overfitting to low-quality data (noisy data) (Arpit et al., 2017). More specifically, we identify two major cases of noisy samples in the synthetic dataset: corrupted labels and task-irrelevant samples (Table 6 in Appendix). Without any task-related fine-tuning, it is challenging for PLM to follow a user's instruction (task-specific prompt including label information) to generate accurate samples in the target domain (Ouyang et al., 2022). To alleviate the data quality issue, recent work adopts human-active labeling to correct the corrupted label or revise the example (Wang et al., 2021a; Liu et al., 2022). However, such methods introduce considerable costs and may be unrealistic.

To avoid human intervention, the classic approach to eliminate the effect of noisy data is to re-weight the samples. The core idea is to design a weighting function w, such that the correct samples are associated with larger weights and the noisy ones with smaller weights. Compared with heuristic design of w (e.g., according to output confidence, loss value) (Liu & Tao, 2015; Wang et al., 2021b), which requires task-specific knowledge and excessive manual tuning, the adaptive methods that learn the sample weights in an end-to-end manner demonstrate better performances in practice (Ren et al., 2018; Shu et al., 2019; Zheng et al., 2021). Those methods typically formulate the learning of sample weights into a bi-level optimization problem, with a clean validation set in the outer loop to guide the learning of w. Despite remarkable success was achieved, their dependence on a clean validation set becomes a major limitation, which is especially impractical in zero-shot setting.

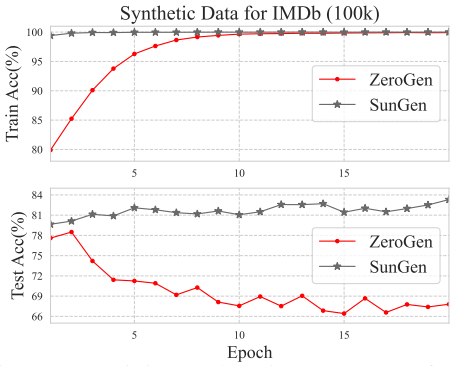

Figure 1: Training and testing accuracy of LSTM model trained on synthetic dataset. After training for more epochs, the testing performance of ZEROGEN starts to deteriorate significantly, indicating that the model starts to fit the erroneous data.

Our solution comes from rethinking the choice of the outer objective in the bi-level framework: *can we design an objective such that the sample weights can be optimized with only access to the noisy synthetic data*? To this end, we resort to a family of noise-robust loss functions (ℓ_{robust}) (Ghosh et al., 2017; Zhang & Sabuncu, 2018). These functions were adopted by previous work to train the neural network under label noise due to their theoretically noise-tolerant property (Ghosh et al., 2017; Zhang & Sabuncu, 2018; Wang et al., 2019). However, from the optimization point of view, such loss functions suffer from instability and difficulty when training the neural networks (Zhang & Sabuncu, 2018), which limits their effectiveness. Remarkably, our approach leverages the noise-tolerant property of these losses, while avoiding their pathology. We propose a novel bi-level re-weighting framework SUNGEN: in the inner loop, we train the task model using weighted training loss based on current sample weights; in the outer loop, the noise-robust loss is adopted to guide the learning of the sample weights. The two procedures are performed alternatively to generate a set of weights indicating the importance of samples. Notably, our method focuses on enhancing the quality of generated data, while improving the generator (e.g., modify PLM parameter, prompt engineering) is an orthogonal direction and can be applied jointly with our method.

Our main contributions are threefold. First, we propose a novel end-to-end framework to construct high-quality noise-free synthetic dataset, without the aid of any human annotation (§3). Second, we offer theoretical justification (§4) and empirical verification (§5.2) for SUNGEN's ability of recovering a noise-free dataset reliably with synthetic data only. Third, we conduct experiments on eight text classification datasets and show our method outperforms the current baseline by large margins (§5.2).

2 BACKGROUND

2.1 PROMPT-BASED ZERO-SHOT LEARNING

We first introduce prompt-based zero-shot prediction (named PROMPTING). Given a manually-designed prompt $\mathcal{T}(\cdot)$ and a query example $\mathbf{x}_i \in \mathcal{X}$, PROMPTING constructs a sentence $\mathcal{T}(\mathbf{x}_i)$ (e.g., *"The movie review in <y_i> sentiment is: <$\mathbf{x}_i$> "*). The PLM $\mathcal{P}$ is expected to model the probability distribution of a set of label words $y_i \in \mathcal{Y}$ (e.g., "positive", "negative") and select the class with highest probability for $\mathbf{x}_i$. Even though PROMPTING has achieved remarkable success in zero-shot learning (Radford et al., 2019; Brown et al., 2020), it is difficult for PROMPTING to fully leverage the task-specific knowledge from PLMs. Besides, PROMPTING still needs to conduct inference on a cumbersome PLM.

2.2 EFFICIENT ZERO-SHOT LEARNING VIA DATA GENERATION

A new line of research (Ye et al., 2022; Meng et al., 2022) endeavors to make zero-shot learning more practical and efficient, among which the generative efficient zero-shot learning paradigm proposed by ZEROGEN (Ye et al., 2022) is as follows:

Synthetic Data Generation. Given a task, the paradigm first generates a synthetic dataset $\mathcal{S}_{\text{syn}} = (\mathcal{X}_{\text{syn}}, \mathcal{Y}_{\text{syn}})$ with the help of large-scale PLM $\mathcal{P}$ and task-related prompts. The idea is to use model $\mathcal{P}$ to generate the input $\mathbf{x}_{\text{syn}}$ based on a pseudo label y_{syn}. For example, in text classification task, a class label y_{syn} is uniformly sampled: $y_{\text{syn}} \sim \mathbf{U}(y_1, y_2, \ldots, y_K)$, where K is the number of classes. The pseudo label y_{syn} is transformed into a label-descriptive prompt $\mathcal{T}(y_{\text{syn}})$ to generate $\mathbf{x}_{\text{syn}}$: $\mathbf{x}_{\text{syn}} \sim \mathcal{P}(\cdot|\mathcal{T}(y_{\text{syn}}))$. The generated $\mathbf{x}_{\text{syn}}$ and pseudo label y_{syn} are paired to construct a pseudo training dataset $\mathcal{S}_{\text{syn}}$.

Efficient Training and Inference. To achieve efficiently training and inference, the paradigm then trains a **t**iny t**a**sk **m**odel (TAM) (e.g., 1-layer Bi-LSTM) on the synthetic dataset $\mathcal{S}_{\text{syn}}$. TAMs typically have much fewer parameters, which is thus easy to train and more efficient during inference.

Although ZEROGEN achieved promising results by training a TAM with $\mathcal{S}_{\text{syn}}$, we find that model's performance rapidly declines after several training epochs, indicating overfitting to noisy samples (Figure 1). A classic approach to improve the quality of a dataset containing low-quality data is to re-weight the samples using some function w. Intuitively, if we assign large weights to correct samples and small weights to noisy ones, the negative influence of noisy samples during training can be reduced. However, the heuristic design of w (e.g., according to output confidence, loss value) suffers unstable performances and requires task-specific knowledge (Shu et al., 2019). Therefore, our paper seeks to optimize w automatically.

3 METHOD

To automatically learn sample weights, the bi-level optimization approaches (Ren et al., 2018; Shu et al., 2019) has been proven to be effective. However, such methods are impractical in our zero-shot scenario, since they depend on a clean validation set to guide the optimization of sample weights. To circumvent the absence of human-labeled data, we propose a **S**elf-g**U**ided **N**oise-free data **GEN**eration framework, named **SUNGEN** (Figure 2). Concretely, we propose a sample reweighting framework via bilevel optimization using a noise-robust loss (Ghosh et al., 2017; Wang et al., 2019; Zhang & Sabuncu, 2018) as the outer objective. Due to the appealing property of such loss functions, our method is able to learn meaningful sample weights with only a synthetic (noisy) validation dataset.

Notations. As elaborated in Section 2.2, we first generate a synthetic dataset using a left-to-right PLM and task-related prompts for the given task. Let $\mathcal{S}_{\text{syn}}, \mathcal{S}_{\text{clean}} \subset \mathcal{X} \times \mathcal{Y} = \mathbb{R}^d \times \{1, ..., K\}$ denote distribution of synthetic (noisy) and clean (gold) data, respective. Here d is the dimension of the input space and K is the number of classes. We draw a training dataset $\mathcal{S}^{\text{t}}_{\text{syn}} := \{(\boldsymbol{x}, y)_{(i)}\}_{i=1}^{N}$ and a validation dataset

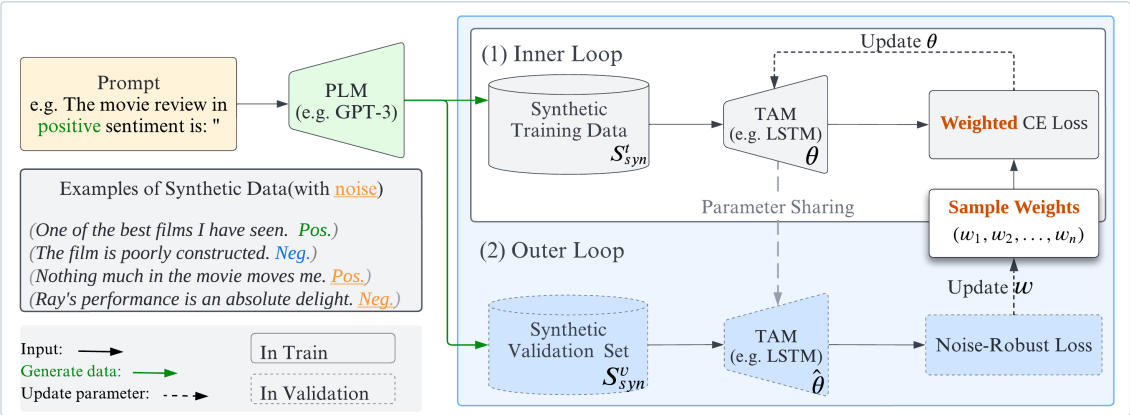

Figure 2: The framework of SUNGEN. Our bi-level framework learns sample weights $\boldsymbol{w}$ measuring data quality without relying on any human-annotated data. In the inner loop, we train a tiny task model (TAM) with weighted CE loss based on current sample weights, and produce trained TAM parameters $\hat{\boldsymbol{\theta}}(\boldsymbol{w})$; in the outer loop, we adopt a noise-robust loss to guide the learning of $\boldsymbol{w}$ by evaluating $\hat{\boldsymbol{\theta}}(\boldsymbol{w})$ on a synthetic validation set.

$\mathcal{S}^{\text{v}}_{\text{syn}} := \{(\boldsymbol{x}, y)_{(j)}\}_{j=1}^{M}$ from $\mathcal{S}_{\text{syn}}$. Denote $f(\boldsymbol{x}, \boldsymbol{\theta})$ as the classifier (TAM) with $\boldsymbol{\theta}$ as its parameters. $w \in \mathcal{W} := \{w(\cdot,\cdot) : \mathcal{X} \times \mathcal{Y} \to [0,1]\}$ is a re-weighting function that assign a weight to each sample. The bold $\boldsymbol{w}$ is a sample weight vector of length N indicating training samples' importance, which contains per-sample weight $w_i := w(\boldsymbol{x}_i, y_i)$.

Overall Framework. Without the presence of clean validation set, our proposed bi-level optimization framework **SUNGEN** (as shown in Figure 2) can be outlined as follows:

$$\boldsymbol{w}^* \in \arg\min_{\boldsymbol{w}} \mathcal{L}_{\text{robust}}(\hat{\boldsymbol{\theta}}(\boldsymbol{w}), \mathcal{S}^{\text{v}}_{\text{syn}}) = \arg\min_{\boldsymbol{w}} \frac{1}{M} \sum_{\{\boldsymbol{x},y\} \in \mathcal{S}^{\text{v}}_{\text{syn}}} \ell_{\text{robust}}(f(\boldsymbol{x}, \hat{\boldsymbol{\theta}}(\boldsymbol{w})), y) \tag{1}$$

$$s.t.\ \hat{\boldsymbol{\theta}}(\boldsymbol{w}) \in \arg\min_{\boldsymbol{\theta}} \mathcal{L}_{\text{ce}}(\boldsymbol{\theta}, \mathcal{S}^{\text{t}}_{\text{syn}}(\boldsymbol{w})) = \arg\min_{\boldsymbol{\theta}} \frac{1}{N} \sum_{\{\boldsymbol{x},y\} \in \mathcal{S}^{\text{t}}_{\text{syn}}} w(\boldsymbol{x}, y) \ell_{\text{ce}}(f(\boldsymbol{x}, \boldsymbol{\theta}), y) \tag{2}$$

where $\boldsymbol{w}^*$ denotes the optimal sample weights, which is obtained from the outer loop (Eqn. 1); $\hat{\boldsymbol{\theta}}(\boldsymbol{w})$ denotes the classifier's parameters after weighted training with $\boldsymbol{w}$, which is obtained from the inner loop (Eqn. 2); ℓ_{robust} denotes the noise-robust loss (to be illustrated below) calculated on validation set; ℓ_{ce} denotes the cross-entropy(CE) loss calculated on training set. The whole process is: (1) **in the inner loop** (Eqn. 2), we fix $\boldsymbol{w}$ and optimize the classifier $f(\boldsymbol{x}, \boldsymbol{\theta})$ using the weighted loss $\mathcal{L}_{\text{ce}}$ over a synthetic training set $\mathcal{S}^{\text{t}}_{\text{syn}}$, and derive the trained classifier $\hat{\boldsymbol{\theta}}(\boldsymbol{w})$; (2) **in the outer loop** (Eqn. 1), we calculate the noise-robust loss $\mathcal{L}_{\text{robust}}$ on the synthetic validation set $\mathcal{S}^{\text{v}}_{\text{syn}}$ at the optimized $\hat{\boldsymbol{\theta}}(\boldsymbol{w})$. The outer loss is minimized to guide the optimization of $\boldsymbol{w}$, and the outer gradient $\nabla_{\boldsymbol{w}} \mathcal{L}_{\text{robust}}$ is calculated via truncated back-propagation (Appendix A). The two procedures are performed alternatively for T iterations.

Notably, our framework prevents the need for a clean validation set, which is the main obstacle for the previous bi-level re-weighting approaches under zero-shot scenario (Ren et al., 2018; Shu et al., 2019). The magic of this appealing feature lies in the choice of the outer objective $\mathcal{L}_{\text{robust}}$ in Eqn. (1). Recall that the goal of sample reweighting is to find $\boldsymbol{w}^*$, with which the model $f(\boldsymbol{x}; \boldsymbol{\theta})$ can be trained using weighted loss over the synthetic training set, such that the model performs well on the clean data (from the same distribution as test data). In Sec. 4, we theoretically show that using $\mathcal{L}_{\text{robust}}$ as the outer objective, our method can find a set of sample weights $\boldsymbol{w}^*$ with just the synthetic validation set, such that $\boldsymbol{w}^*$ maximizes the model performance on the clean data. The whole procedure is illustrated in Algorithm 1. In the following, we elaborate more on the design of ℓ_{robust} in our framework.

Noise-robust Loss Functions. In the noisy label learning literature, there is a family of loss functions that possess the following property:

$$\sum_{j=1}^{K} \ell_{\text{robust}}(f(\boldsymbol{x}, \boldsymbol{\theta}), j) = C, \forall \boldsymbol{\theta}, \boldsymbol{x}, \tag{3}$$

where $f(\cdot, \boldsymbol{\theta})$ denotes a classifier, $\boldsymbol{x}$ is the input, K is the number of classes, and C is a constant. Previous work (Wang et al., 2019; Zhang & Sabuncu, 2018; Ghosh et al., 2017) has shown that these loss functions have consistent global minimum under label noise. More formally, under suitable conditions, the global minimizer ($\boldsymbol{\theta}^*$) of ℓ_{robust} is the same regardless of whether the training data is clean or noisy. This noise-robust property enables these losses to optimize the sample weights given only a noisy validation dataset. Detailed proof will be given in Sec. 4.

In particular, we consider the reversed cross-entropy loss ℓ_{rce} with the following form for sample $(\boldsymbol{x}, y)$:

$$\ell_{\text{rce}}(f(\boldsymbol{x}, \boldsymbol{\theta}), y) = -\sum_{k=1}^{K} f_k(\boldsymbol{x}, \boldsymbol{\theta}) \log q(k|\boldsymbol{x}),$$

where $f_k(\boldsymbol{x}, \boldsymbol{\theta}) = \frac{e^{z_k}}{\sum_{i=1}^{K} e^{z_i}}$ denotes the predicted probability for each label $k \in \{1, ..., K\}$, and z_i are the logits. We denote the ground-truth distribution over labels by $q(k|\boldsymbol{x})$, and $\sum_{k=1}^{K} q(k|\boldsymbol{x}) = 1$. Given the ground-truth label is y, then $q(y|\boldsymbol{x}) = 1$ and $q(k|\boldsymbol{x}) = 0$ for all $k \neq y$. $log(0)$ is approximated to a constant A. One can easily check that ℓ_{rce} satisfies Property (3), and $C = -(K-1)A$ in this case.

Algorithm 1 Bilevel Robust Sample Reweighting

Require: a TAM with parameters $\boldsymbol{\theta}$, synthetic training dataset $\mathcal{S}^{\text{t}}_{\text{syn}}$ and validation dataset $\mathcal{S}^{\text{v}}_{\text{syn}}$, outer step size λ, outer iterations T.

1: Initialize sample weightings $\boldsymbol{w}$ with each w_i to be 0.5.
2: **for** training iteration $t = 1, 2 \ldots T$ **do**
3: Conduct weighted training ($\mathcal{L}_{\text{ce}}$) on TAM using $\boldsymbol{w}^t, \mathcal{S}^{\text{t}}_{\text{syn}}$ and obtain $\hat{\boldsymbol{\theta}}(\boldsymbol{w}^t)$
4: Evaluate $\hat{\boldsymbol{\theta}}(\boldsymbol{w}^t)$ on $\mathcal{S}^{\text{v}}_{\text{syn}}$, then obtain meta gradient $\nabla_{\boldsymbol{w}} \mathcal{L}_{\text{robust}}$ via Eqn. (6).
5: Update $\boldsymbol{w}$ using $\nabla_{\boldsymbol{w}} \mathcal{L}_{\text{robust}}$ by gradient descent $\boldsymbol{w}^{t+1} \leftarrow \boldsymbol{w}^t - \lambda \nabla_{\boldsymbol{w}} \mathcal{L}_{\text{robust}}$
6: **end for**

Output: Optimized sample weights $\boldsymbol{w}^*$.

Remark. Even though ℓ_{robust} is theoretically noise-tolerant, it has been shown that using them to train the network parameters $\boldsymbol{\theta}$ leads to difficulty in optimization and hampers the network's performance (Wang et al., 2019; Zhang & Sabuncu, 2018). Remarkably, adopting ℓ_{robust} as the objective in the outer loop of Eqn. (1) implicitly overcomes the side effects of ℓ_{robust}. Since ℓ_{robust} is now used to optimize the sample weights $\boldsymbol{w}$, which is in a much smaller search space and has simpler structure than $\boldsymbol{\theta}$, thus is easier to optimize. This "decouples" noise removal from network training, and thereby prevents hampering the TAM's performance.

Clean Subset Sampling. Our framework enables us to derive a set of continuous weights $\boldsymbol{w}$, which encodes the data quality and can well separate the noisy samples from clean ones, as shown in Figure 3. With those weights, we can sample subsets with arbitrary budgets and use them to train the task models with unweighted CE loss. More specifically, suppose the budget is D, we first normalize w_i to w'_i (i.e. $\sum_{i=1}^{n} w'_i = D$), based on which we then sample a Bernoulli random variable $I_i \sim \mathbf{Ber}(w'_i)$ for each sample to indicate whether they should be included. Denote the size of sampled subset as $\hat{D}$. Because $\mathbb{E}_{\boldsymbol{I} \sim p(\boldsymbol{I}|\boldsymbol{w})} \|\boldsymbol{I}\|_0 = \sum_{i=1}^{n} w'_i = D$, it is clear that $\frac{\hat{D}}{D} \xrightarrow{P} 1$ when $n \to \infty$, meaning that $\hat{D}$ is close to D. Notably, because the important and noise-free data are associated with larger weights, training on the sampled subset can perform on par with weighted training over the entire dataset, while being much more efficient.

4 Theoretical Analysis

Though we have no clean data as validation set, our method still enjoys favorable theoretical properties. Recall that $\mathcal{S}_{\text{clean}}$ and $\mathcal{S}_{\text{syn}}$ are as the clean and synthetic (noisy) distribution, respectively. We further denote $\mathcal{L}(\boldsymbol{\theta}, \mathcal{S}) = \mathbb{E}_{(\boldsymbol{x}, y) \sim \mathcal{S}}[\ell(f(\boldsymbol{x}; \boldsymbol{\theta}), y)]$ given a data distribution $\mathcal{S}$. Let the optimal network parameters obtained

with CE loss over clean dataset be $\boldsymbol{\theta}^* := \arg\min_\theta \mathcal{L}_{\text{ce}}(\boldsymbol{\theta}, \mathcal{S}_{\text{clean}})$. We assume the $\boldsymbol{\theta}^*$ is unique, or we focus on the $\boldsymbol{\theta}^*$ with minimum norm.

Property 1. *We call a loss function ℓ a robust loss, if its minimizer on the noisy dataset collides with that one the clean dataset, i.e.,*

$$\arg\min_{\boldsymbol{\theta}} \mathcal{L}_{robust}(\boldsymbol{\theta}, \mathcal{S}_{clean}) = \arg\min_{\boldsymbol{\theta}} \mathcal{L}_{robust}(\boldsymbol{\theta}, \mathcal{S}_{syn}),$$

Previous work on noise-robust loss functions (Ghosh et al., 2017; Wang et al., 2019; Zhang & Sabuncu, 2018; Xu et al., 2019) have shown that the losses satisfying Eqn. (3) have the above noise-tolerant property. We give the complete proof in the Appendix.

Assumption 1. *Let $\mathbb{P}_{clean}$ and $\mathbb{P}_{syn}$ denote the probability density function of $\mathcal{S}_{clean}$ and $\mathcal{S}_{syn}$, respectively. There exists a weighting function w^* such that $\mathbb{P}_{clean}(\boldsymbol{x}, y) = w^*(\boldsymbol{x}, y)\mathbb{P}_{syn}(\boldsymbol{x}, y)$.*

Assumption 1 is reasonable because synthetic data generated by the PLM has a wide coverage. Therefore, with a proper weight function w, we may recover the clean distributional by reweighting the synthetic data.

Assumption 2. *The optimal $\boldsymbol{\theta}^*$ uniquely minimizes $\mathcal{L}_{robust}(\boldsymbol{\theta}, \mathcal{S}_{clean})$, i.e., $\mathcal{L}_{robust}(\boldsymbol{\theta}^*, \mathcal{S}_{clean}) < \mathcal{L}_{robust}(\boldsymbol{\theta}, \mathcal{S}_{clean})$ for all $\boldsymbol{\theta} \neq \boldsymbol{\theta}^*$.*

Assumption 2 is natural since the robust losses are originally designed to train the model. Thus minimizing $\mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}_{\text{clean}})$ is expected to achieve promising performance, as justified by Ghosh et al. (2017) (though the optimization difficulty mentioned in the Remark of Section 3 poses challenges for model training). We also experimentally show that when training a model with $\mathcal{L}_{\text{ce}}(\boldsymbol{\theta}, \mathcal{S}^t_{\text{clean}})$, $\mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}^t_{\text{clean}})$ also decreases, and reaches the plateau at a similar point (Appendix D.1). This indicates that $\mathcal{L}_{\text{ce}}(\boldsymbol{\theta}, \mathcal{S}_{\text{clean}})$ and $\mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}_{\text{clean}})$ have close optimal solutions. Note that even if $\boldsymbol{\theta}$ and $\boldsymbol{\theta}^*$ differ by a small quantity, i.e., $\mathcal{L}_{\text{robust}}(\boldsymbol{\theta}^*, \mathcal{S}_{\text{clean}}) < \mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}_{\text{clean}}) + \varepsilon$ holds with a small ε, the following proof holds with just minor modifications.

Theorem 1. *If Assumption 1 holds, there exists a $\boldsymbol{w}^*$ such that $\hat{\boldsymbol{\theta}}(\boldsymbol{w}^*) = \boldsymbol{\theta}^*$. Further with Assumption 2 and Property D.2, our method can uniquely return $\boldsymbol{w}^*$ and the resulting $\boldsymbol{\theta}^*$ with only synthetic (noisy) data $\mathcal{S}_{noisy}$.*

Given Assumption 2 holds, $\mathcal{L}_{\text{ce}}(\boldsymbol{\theta}, \mathcal{S}_{\text{clean}})$ and $\mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}_{\text{clean}})$ have consistent optimal solution $\boldsymbol{\theta}^*$. Furthermore, Property D.2 of $\mathcal{L}_{\text{robust}}$ indicates that $\boldsymbol{\theta}^*$ can be found with just the noisy synthetic data $\mathcal{S}_{\text{syn}}$. Therefore, we can optimize $\mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}_{\text{syn}})$ to find $\boldsymbol{\theta}^*$. Finally, since $\boldsymbol{\theta}^*$ can be parameterized by $\boldsymbol{w}^*$ (Theorem 1), which is achieved by the inner loop (Eqn. (2)), we can optimize $\mathcal{L}_{\text{robust}}(\hat{\boldsymbol{\theta}}(\boldsymbol{w}), \mathcal{S}_{\text{syn}})$ over $\boldsymbol{w}$ in the outer loop (Eqn. (1)) to find the optimal corresponding $\boldsymbol{w}^*$ as well as the $\boldsymbol{\theta}^*$. See Appendix D.3 for detailed proof.

The above analysis theoretically shows our SUNGEN is able to learn the optimal sample weights $\boldsymbol{w}^*$ and the resulting optimal model parameters $\boldsymbol{\theta}^*$ with just synthetic data. Notably, Theorem 1 is based on population losses with infinite samples. We further characterize the generalization bound when there is finite samples:

Theorem 2 (Finite Sample Generalization)**.** *Suppose we have access to synthetic datasets $\mathcal{S}^v_{syn}$ and $\mathcal{S}^t_{syn}$ both with finite samples N. Let $\hat{\boldsymbol{\theta}}^*(\boldsymbol{w})$ be the deterministic mapping from $\boldsymbol{w}$ to $\boldsymbol{\theta}$ defined in the inner of Eqn.2 given $\hat{\mathcal{S}}^t_{syn}$. Assuming the output of loss function ℓ_{robust} is upper bounded by M, the carnality of $\mathcal{W}$ is $|\mathcal{W}|$, the outer loop of Eqn.1 is solved within ϵ-approximately, and the solution $\hat{\boldsymbol{w}}$ satisfies the following condition:*

$$\mathcal{L}_{robust}(\hat{\boldsymbol{\theta}}^*(\hat{\boldsymbol{w}}); \mathcal{S}^v_{syn}) \leq \arg\min_{\boldsymbol{w}} \mathcal{L}_{robust}(\hat{\boldsymbol{\theta}}^*(\boldsymbol{w}); \mathcal{S}^v_{syn}) + \epsilon,$$

we then have with probability at least $1 - \delta$,

$$\mathcal{L}_{robust}(\hat{\boldsymbol{\theta}}^*(\hat{\boldsymbol{w}}), \mathcal{S}_{syn}) \leq \arg\min_{\boldsymbol{w}} \mathcal{L}_{robust}(\hat{\boldsymbol{\theta}}^*(\boldsymbol{w}); \mathcal{S}_{syn}) + \epsilon + \kappa\sqrt{\frac{2\ln(|\mathcal{W}|/\delta)}{M}} \tag{4}$$

Refer to Appendix D.4 for full proof. Theorem 2 characterizes the generalization ability of SUNGEN. If we obtain an approximate solution of the bilevel problem Eqn.(1)-(2) given finite samples, Eqn. (4) shows that such solution has a test performance close to the oracle model.

Table 1: Evaluation results for SUNGEN framework on two different scales of TAM. The scale of synthetic dataset is 200k for both ZEROGEN and SUNGEN. The scales of labeled data in supervised setting are listed under task names. ***"Gold Data"*** refers to the standard dataset with human annotations.

TAM	#Param	Setting	IMDb	SST-2	Rotten	Amazon	Yelp	Subj	AGNews	DBpedia	Avg
#Gold Data			*25k*	*6.9k*	*8.3k*	*25k*	*560k*	*8k*	*120k*	*560k*	-
DistilBERT	66M	SUPERVISED	87.24	89.68	83.67	92.63	95.42	95.95	94.51	99.14	92.28
LSTM	~7M	SUPERVISED	84.60	76.30	77.49	86.36	91.30	90.20	90.61	98.28	86.89
-	1.5B	PROMPTING	80.64	89.22	81.89	83.63	82.72	68.00	68.81	67.88	77.85
DistilBERT	66M	ZEROGEN	84.28	87.27	83.02	87.19	87.58	80.45	76.48	79.32	83.20
		SUNGEN	**89.38**	**89.45**	**84.52**	**89.01**	**89.19**	**83.25**	**80.49**	**82.67**	**86.00**
LSTM	~7M	ZEROGEN	71.52	74.89	73.45	80.48	84.95	69.15	73.34	67.02	74.35
		SUNGEN	**84.10**	**84.58**	**83.21**	**84.22**	**89.06**	**75.85**	**79.75**	**72.07**	**81.61**

5 EXPERIMENTS

5.1 SETUP

Datasets & Baselines. We evaluate SUNGEN on eight text classification tasks, including IMDb (Maas et al., 2011), SST-2 (Socher et al., 2013), Rotten Tomatoes (Pang & Lee, 2005), Amazon (McAuley & Leskovec, 2013), Yelp (Zhang et al., 2015), Subj (Pang & Lee, 2004), AGNews (Zhang et al., 2015) and DBpedia (Zhang et al., 2015). These tasks have various number of classes, ranging from 2 to 14. Other details about datasets are in Appendix F. We compare our proposed method with the following baselines: (1) **PROMPTING**. The prompt-based zero-shot classification method based on PLMs (Brown et al., 2020; Gao et al., 2021). (2) **ZEROGEN**. A recent zero-shot learning work via dataset generation (Ye et al., 2022).

Implementation Details. We compare the baselines using GPT2-XL (Radford et al., 2019) as PLM. For text generation, we use Nucleus Sampling (Holtzman et al., 2020) with $p = 0.9$ as the decoding strategy and use GPT2-XL as the generator. To make a fair comparison, we use the best prompts designed by (Ye et al., 2022) in both PROMPTING and data-generation settings (Appendix Table 8). For task model training, we use 1-layer Bi-LSTM and DistilBERT-base as the lightweight classifiers. The bilevel procedure is iterated 50 times for each task. For more details(e.g., full prompts, training details), please refer to Appendix F.

5.2 EXPERIMENTAL RESULTS

Main Experiments. We present our main experiment results in Table 1. We observe that our SUNGEN achieves considerable performance gain over the ZEROGEN baseline across all the tasks. Interestingly, the improvement is more prominent for LSTM compared with DistilBERT, which shows relative improvement over ZEROGEN by 9.8% on average across all tasks. We conjecture the reason is that the pre-trained models such as DistilBERT are inherently more robust to noisy training data, which is also pointed out in (Hendrycks et al., 2019). Surprisingly, on Rotten Tomatoes and Yelp, SUNGEN-LSTM even outperforms ZEROGEN-DistilBERT, which requires no pre-training and has much fewer parameters.

Effectiveness of SUNGEN on Constructing Noise-Free Data. Figure 1 shows that while ZeroGen suffers from overfitting on noisy data, the problem disappears when training with the subset selected by SUNGEN. With longer training epochs, the data of SUNGEN consistently helps improve the performance of TAM on test set and significantly surpasses the result of ZeroGen, which proves that SUNGEN can effectively construct noise-free high-quality data.

Synthetic Data vs. Gold Data Supervision. Note that a key advantage of our proposed framework is that we do not require gold data to optimize the sample weights. Here, we compare our SUNGEN to the bilevel reweighting method which uses gold data for calculating the outer objective in Table 2. Specifically, our SUNGEN calculates the robust outer objective ℓ_{rce} on the noisy synthetic data, while the counterpart calculates the normal outer objective ℓ_{ce} on gold data. Table 2 shows that our method achieves similar performances as

Table 2: Evaluation results using different validation sets ($\mathcal{S}^{\text{v}}$) in the outer loop. LSTM is used as TAM.

Method	$\mathcal{S}^{\text{v}}$	IMDb	Amazon	Yelp	Rotten
SUPERVISED	-	84.60	86.36	91.30	77.49
ZEROGEN	-	71.52	80.48	84.95	73.45
SUNGEN	Gold	82.34	**84.71**	88.83	80.05
	Syn.	**84.10**	84.22	**89.06**	**83.21**

Table 3: Experimental comparison with other de-noise methods using LSTM as TAM.

Method	IMDb	Amazon	Yelp
Confidence	79.97	70.44	76.91
Co-Teaching	72.64	73.53	75.50
Meta-Weight-Net	71.23	79.25	83.41
SUNGEN	**84.10**	**84.22**	**89.06**

Table 4: Results of SUNGEN-LSTM on different data sizes. Given subsets of SUNGEN, models are trained with ℓ_{ce}. For the 1,000k set of SUNGEN, the model is trained using weighted ℓ_{ce}. Subsets that surpass the original full set (1,000k) are marked by **bold**. Performance of original full set is marked by underline.

Size	IMDb		Amazon		Yelp	
	ZERO	SUN	ZERO	SUN	ZERO	SUN
1,000k	78.29	86.56	82.47	84.63	86.28	90.38
10k	62.40	72.05	74.46	75.84	75.22	80.67
20k	65.12	**79.96**	75.78	77.52	79.55	82.88
50k	68.12	**81.14**	78.14	81.97	80.81	85.82
100k	71.28	**82.09**	80.25	**83.68**	82.97	**88.41**
200k	71.52	**84.10**	80.48	**84.22**	84.95	**89.06**

Table 5: Diversity and Correctness. We measure the *diversity* by Self-BLEU4 and *correctness* by accuracy of an oracle model (finetuned RoBERTa-Large). Lower Self-BLEU4 score indicates higher diversity. "SUNGEN-Top" and "SUNGEN-Bottom" represent 10k samples with highest and lowest weights respectively.

Method	IMDb	Amazon	Yelp
	Diversity ↓		
Gold	0.30	0.29	0.29
ZEROGEN	0.15	0.12	0.14
SUNGEN	**0.14**	**0.10**	**0.11**
	Correctness(%) ↑		
Gold	96.22	96.60	98.35
ZEROGEN	75.86	**93.58**	**94.47**
SUNGEN	**82.27**	88.87	90.78
SUNGEN-Top	86.00	84.20	85.33
SUNGEN-Bottom	4.57	61.50	44.66

the counterpart, which verifies that our method using the noise validation set can equivalently supervise the optimization of sample weights as the clean validation set does.

SUNGEN vs. Popular Denoise Baselines. We compare with other de-noise methods, which are (1) directly removing data with low predicted confidence (Swayamdipta et al., 2020), (2) Co-Teaching (Han et al., 2018), which distinguishes noisy data by large loss value, and (3) Meta-Weight-Net (Shu et al., 2019), which relies on meta samples and a loss-based proxy model to learn the sample weights. Since in zero-shot setting we have no access to gold data, we use the synthetic data as validation set for Co-Teaching and Meta-Weight-Net. Results in Table 3 prove our method's superiority in zero-shot setting. We further analyze why the loss-value-based methods are not able to distinguish noisy data in our situation in Appendix G.

5.3 ABLATION STUDY AND ANALYSIS

Performance of Different Data Sizes. Table 4 shows that even with much less data, model trained by SUNGEN achieves better performance than ZEROGEN. For example, in IMDb, by removing low-quality data, subset with 2% data achieves better performance than the original data (20k vs. 1,000k), which shows superior data quality of SUNGEN. Besides, from Figure 3(d), we find the percentage of erroneous data is small. However, those erroneous data significantly degrades the model performance: without weighted training to remove the effect of noisy data, the IMDB accuracy of full set is decreased from 86.56 to 78.29.

Analysis of Data Diversity and Correctness. Table 5 shows that our selected noise-free dataset is more diverse than data generated by ZEROGEN. One interesting thing to note is that in Amazon and Yelp, average correctness of SUNGEN is slightly lower than ZEROGEN. In addition, the top samples (with highest weights) have slightly lower correctness than average. This is expected as the data with highest correctness may be redundant or too simple, while the challenging and informative samples are often harder to classify and thus have lower correctness. The results further verify that SUNGEN effectively separates the informative samples from the ones that are redundant or erroneous. This can not be done with the heuristic methods that manually sets a threshold to separate clean and noisy data, which may keep redundant samples and remove hard ones.

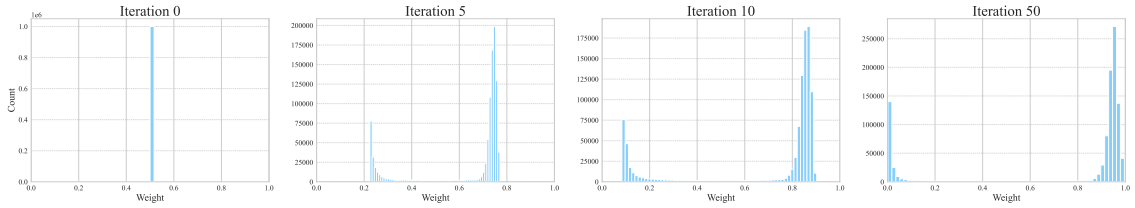

Figure 3: Histogram of learnt weights in IMDb synthetic dataset (1,000k). The weights are gradually separated as optimization proceeds, indicating SUNGEN can differentiate high-quality data from erroneous ones.

Analysis of Removed and Selected Examples. We take IMDb (sentiment classification task of movie review) as the example task and find that the majority of samples associated with small weights are wrongly labeled, as shown in Appendix Table 6. Besides, there is a small part of erroneous data which contains task-irrelevant text, meaning the generated text is not a movie review and has no obvious emotional tendency. For samples with large weights, we actually find them to be well-written transitional complex sentences (bottom part of Appendix Table 6), which verifies that SUNGEN tends to select correct and important samples.

6 RELATED WORK

Zero-shot Learning via PLM. The popular prompt-based zero-shot prediction is proposed by GPT (Radford et al., 2019). With well-designed prompts, large-scale PLMs have shown its notable zero-shot learning ability in various tasks (Jiang et al., 2020; Shin et al., 2020; Reynolds & McDonell, 2021). More recently, data-generation-based work via PLM has gained popularity and shown superior ability on synthesizing task-specific data (Anaby-Tavor et al., 2020; Puri et al., 2020; Kumar et al., 2020; Lee et al., 2021; Wang et al., 2021b; Yoo et al., 2021; Bonifacio et al., 2022). Apart from work that still relies on task-related human-annotated data to instruct or fine-tune the generative PLM, a recent line of research explores this direction in zero-shot scenario: Schick & Schütze (2021); Meng et al. (2022) use PLM with task-dependent prompts to generate data, and finetune another PLM on such data for task prediction. To further investigate PLM's zero-shot ability and alleviate the computation cost of PLM, Ye et al. (2022) study an extreme scenario, which trains a tiny model from scratch using the synthetic data.

Noise Robust Learning. Previous methods tackling data noise problem can be roughly categorized into two groups: (1) heuristic approaches based on loss values that rely on the assumption that the network learns easy samples first, which adopt either resampling (Han et al., 2018; Jiang et al., 2018; Yu et al., 2019), loss reweighting (Thulasidasan et al., 2019; Konstantinov & Lampert, 2019; Ren et al., 2018; Shu et al., 2019), or label correction (Ma et al., 2018; Kremer et al., 2018; Reed et al., 2014). These methods require either manually set a threshold for the loss value or a clean validation set, which makes their performance questionable in zero-shot scenario. (2) methods in another line train the network with noise-robust loss (Ghosh et al., 2017; Ma et al., 2020; Liu & Guo, 2020; Xu et al., 2019; Wang et al., 2019). Despite they learn a robust classifier in theory, they are typically difficult to train the DNNs and result require more hyper-parameter tuning (Zhang & Sabuncu, 2018; Wang et al., 2019). To this end, we take advantages from both lines of research and design an end-to-end framework which can reliably filter out harmful data without requiring a clean validation set.

7 CONCLUSION

This paper focuses on high-quality data generation in efficient zero-shot learning. To attack the noise data, we design an end-to-end framework to construct a clean synthetic dataset without relying on any human-labeled data or human intervention. Our method can be jointly applied to other data generation pipelines to automatically select high-quality data. We hope this paper can provide insights for improving the quality of synthetic datasets, and inspire more exploration in data-generation-based zero-shot learning via PLM.

8 REPRODUCIBILITY STATEMENT

Our code for data generation is based on Ye et al. (2022), which is publically available on GitHub. We submit our code together with ICLR submission, and we will publically release the code upon acceptance of the paper. The hyper-parameters and network choices used throughout the experiments are elaborated in Section 5.1 and Appendix F. For theoretical analysis given in our paper, the assumptions and theorems are in Section 4, and the full proofs are given in Appendix D.

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A APPENDIX

A TRUNCATED BACK-PROPAGATION FOR META GRADIENT.

For solving the bilevel optimization problem, the gradient of $\boldsymbol{w}$ can be calculated as follows:

$$
\begin{aligned}
& \nabla_{\boldsymbol{w}} \mathcal{L}_{\text{robust}} \\
= \; & \nabla_{\boldsymbol{\theta}} R_{\text{robust}}|_{\theta^*} \; \nabla_{\boldsymbol{w}} \hat{\boldsymbol{\theta}}(\boldsymbol{w}) && (5) \\
= \; & \nabla_{\boldsymbol{\theta}} \mathcal{L}_{\text{robust}}|_{\theta_T} \sum_{j \leq T} \left[\prod_{k<j} I - \frac{\partial^2 \mathcal{L}_{\text{ce}}}{\partial \boldsymbol{\theta} \partial \boldsymbol{\theta}^\intercal} \bigg|_{\boldsymbol{\theta}_{T-k-1}} \right] \frac{\partial^2 \mathcal{L}_{\text{ce}}}{\partial \boldsymbol{\theta} \partial \boldsymbol{w}^\intercal} \bigg|_{\boldsymbol{\theta}_{T-j-1}} \\
\approx \; & \nabla_{\boldsymbol{\theta}} \mathcal{L}_{\text{robust}}|_{\theta_T} \; \frac{\partial^2 \mathcal{L}_{\text{ce}}}{\partial \boldsymbol{\theta} \partial \boldsymbol{w}^\intercal} \bigg|_{\boldsymbol{\theta}_{T-1}}, && (6)
\end{aligned}
$$

where Eqn. (5) follows chain rule. For computational efficiency, we do not unroll the entire T steps, but perform 1-step truncated backpropagation as in Eqn. (6) (Shaban et al., 2019).

B COMPARISON WITH OTHER NOISE-ROBUST LEARNING METHODS

Our framework has the following advantages against other noise-robust learning methods:

- Compared with heuristic methods (Han et al., 2018; Jiang et al., 2018), our framework is end-to-end and does not require excessive manual tuning and task-specific knowledge.
- Since both the inner and outer objectives are calculated on the same synthetic training set, we do not need any in-domain labeled data, which is a must in the previous end-to-end reweighting methods (Ren et al., 2018; Shu et al., 2019).
- Compared with methods that train the model with ℓ_{robust} (Zhang & Sabuncu, 2018; Wang et al., 2019), our approach leverages ℓ_{robust} to learn the sample weights, which enables removing the low-quality data without hurting the model's performance

Table 6: Examples of removed data(small weights) and selected data(large weights) in IMDb synthetic dataset.

Text<X>	**Label**<Y>	**Noisy Type**
Removed Data (Data with Small Weights)		
The film does a great job of capturing the fear and battle that so many U.S. troops have experienced during the seven-year war in Afghanistan.	Neg.	Noisy Y
This long, pompous, chain-smoking movie makes a big hit out of not very much at all.	Pos.	Noisy Y
One of the worst cult films ever made. 2D CGI animations of zombies and comic-book characters. Some bad acting, technical problems, cheap gimmicks and script that is.	Pos.	Noisy Y
The four-hour look at family dysfunction brings forth a richer character study.	Neg	Unrelated X
A fresh and visceral portrait of a man trying to make sense of his life.	Neg	Unrelated X
Selected Data (Data with Large Weights)		
Despite its oddball structure and topsy-turvy interactions between characters, this surprisingly zany animated film succeeds where so many animated films fail.	Pos.	No Noise
Not worth the time for the main actors, but for the almost movie has a very good story that puts many sci-fi movies of the past to shame.	Pos.	No Noise
An outrageously stupid movie that has been thoroughly disproved by fact and logic.	Neg.	No Noise
Wonder Woman is a big-budget superhero blockbuster that turns the spotlight on the potential of a woman leader. . . but the movie is ultimately unfulfilling and laden with female stereotypes.	Neg.	No Noise
While a satire on class and power, the film's dismissal of human misery is shallow and the actors' portrayal of the weak and needy are gratingly self-pitying.	Neg.	No Noise

C SELECTED AND REMOVED DATA

The selected and removed examples are listed in Table 6. We take IMDb as the example task. The observation shows that most of the removed data (data with low weights) have noise label, which indicates the class of text is wrongly labeled by PLM during generation(Noisy Y). Besides, there is a small part of erroneous data which contains unrelated text to the task, meaning the generated text is not a movie review showing obvious emotional tendency(Unrelated X). From Figure 3(d), we find the percentage of the erroneous data is small, but it significantly degrades the model performance(e.g., IMDB accuracy is decreased from 86.56 to 78.29 in Table 4). For selected data by SUNGEN, we find they are actually well-written transitional complex sentences (bottom part of Table 6), which verifies that SUNGEN tends to select correct and challenging samples.

D PROOFS

D.1 EMPIRICAL VERIFICATION FOR ASSUMPTION 2

We run experiments on both NLP and CV tasks (IMDb and CIFAR-10) to verify the rationality of Assumption 2. Without loss of generality, we compare the robust-loss ℓ_{rce} to ℓ_{ce}. The results in Figure 4 show that when training network with ℓ_{ce}, the ℓ_{rce} demonstrates a similar curve as ℓ_{ce} and reaches the plateau at a similar point. This empirically shows that the robust loss ℓ_{rce} has a close optimal solution with ℓ_{ce}.

D.2 PROOF FOR PROPERTY

The noise-robust property of robust loss functions have been proven in previous work (Ghosh et al., 2017; Wang et al., 2019), we add them here for completeness. Specifically, we follow Ghosh et al. (2017) and consider three cases of label noise: uniform noise, simple non-uniform noise and class-dependent noise.

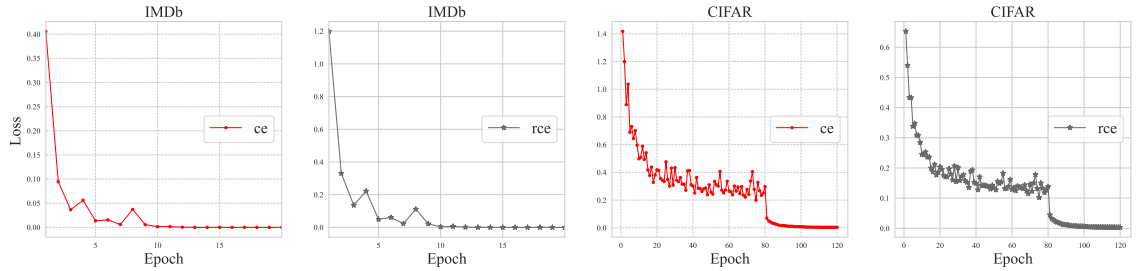


Figure 4: CE training loss vs. RCE training loss on IMDb and CIFAR-10.

Uniform Noise. Given a classification problem with K classes, for a loss function ℓ_{robust} satisfying Eqn.(3). Then ℓ_{robust} is noise-tolerant under uniform label noise if the noise rate $\eta < \frac{K-1}{K}$. Let $\tilde{y}$ denote the noisy label from $\mathcal{S}_{\text{syn}}$, the proof is as follows:

$$\begin{aligned}
\mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}_{\text{syn}}) =& \mathbb{E}_{\boldsymbol{x},\tilde{y}}[\ell_{\text{robust}}(fs(\boldsymbol{x};\boldsymbol{\theta}), \tilde{y})] \\
=& \mathbb{E}_{\boldsymbol{x},y}\mathbb{E}_{\tilde{y}|y,\boldsymbol{x}}[\ell_{\text{robust}}(f(\boldsymbol{x};\boldsymbol{\theta}), \tilde{y})] \\
=& \mathbb{E}_{\boldsymbol{x},y}[(1-\eta)\ell_{\text{robust}}(f(\boldsymbol{x};\boldsymbol{\theta}), y) + \frac{\eta}{K-1}\sum_{j\neq y}^{K}\ell_{\text{robust}}(f(\boldsymbol{x};\boldsymbol{\theta}), j)] \\
=& \mathbb{E}_{\boldsymbol{x},y}[\frac{K-1-K\eta}{K-1}\ell_{\text{robust}}(f(\boldsymbol{x};\boldsymbol{\theta}), y)] + \frac{\eta C}{K-1} \\
=& \frac{K-1-K\eta}{K-1}\mathcal{L}(\boldsymbol{\theta}, \mathcal{S}_{\text{clean}}) + \frac{\eta C}{K-1}
\end{aligned}$$

where C is a constant due to the property of symmetric loss functions. Suppose $\boldsymbol{\theta}^*$ is the optimal solution for the clean dataset $\mathcal{S}_{\text{clean}}$. Therefore, we have the following inequality for any $\boldsymbol{\theta}$: $\mathcal{L}(\boldsymbol{\theta}^*, \mathcal{S}_{\text{syn}}) - \mathcal{L}(\boldsymbol{\theta}, \mathcal{S}_{\text{syn}}) = \frac{K-1-K\eta}{K-1}(\mathcal{L}(\boldsymbol{\theta}^*, \mathcal{S}_{\text{clean}}) - \mathcal{L}(\boldsymbol{\theta}, \mathcal{S}_{\text{clean}})) \leq 0$. Therefore, $\boldsymbol{\theta}^*$ is also the optimal solution for $\mathcal{S}_{\text{syn}}$.

Class Dependent Noise. For a loss function ℓ_{robust} satisfying Eq 3, and $0 \leq \ell_{\text{robust}}(f(\boldsymbol{x};\boldsymbol{\theta}), i) \leq \frac{C}{K-1}, \forall i \in [K]$, and suppose $\min_{\boldsymbol{\theta}} \mathcal{L}(\boldsymbol{\theta}, \mathcal{S}_{\text{clean}}) = 0$. Then ℓ_{robust} is noise-tolerant under classs dependent label noise if $\eta_{ij} < 1 - \eta_i, \forall j \neq i, \forall i, j \in [K]$, η_{ij} represents the probability of class i mislabelled into class j. The proof is as follows:

$$\begin{aligned}
\mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}_{\text{syn}}) =& \mathbb{E}_{\boldsymbol{x},\tilde{y}}[\ell_{\text{robust}}(f(\boldsymbol{x};\boldsymbol{\theta}), \tilde{y})] \\
=& \mathbb{E}_{\boldsymbol{x},y}\mathbb{E}_{\tilde{y}|y,\boldsymbol{x}}[\ell_{\text{robust}}(f(\boldsymbol{x};\boldsymbol{\theta}), \tilde{y})] \\
=& \mathbb{E}_{\boldsymbol{x},y}[(1-\eta_y)\ell_{\text{robust}}(f(\boldsymbol{x};\boldsymbol{\theta}), y) + \sum_{j\neq y}^{K}\eta_{yj}\ell_{\text{robust}}(f(\boldsymbol{x};\boldsymbol{\theta}), j)] \\
=& \mathbb{E}_{\boldsymbol{x},y}[(1-\eta_y)(C - \sum_{j\neq y}^{K}\ell_{\text{robust}}(f(\boldsymbol{x};\boldsymbol{\theta}), j)) + \sum_{j\neq y}^{K}\eta_{yj}\ell_{\text{robust}}(f(\boldsymbol{x};\boldsymbol{\theta}), j)] \\
=& C\mathbb{E}_{\boldsymbol{x},y}(1-\eta_y) - \mathbb{E}_{\boldsymbol{x},y}\sum_{j\neq y}^{K}(1-\eta_y-\eta_{yj})\ell_{\text{robust}}(f(\boldsymbol{x};\boldsymbol{\theta}), j)
\end{aligned}$$

Denote $\boldsymbol{\theta}^*$ and $\hat{\boldsymbol{\theta}}^*$ as $\arg\min_{\boldsymbol{\theta}} \mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}_{\text{clean}})$ and $\arg\min_{\boldsymbol{\theta}} \mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}_{\text{syn}})$, respectively. Given the above result, we have the following inequality for $\hat{\boldsymbol{\theta}}^*$ and $\boldsymbol{\theta}^*$:

$$\mathcal{L}_{\text{robust}}(\hat{\boldsymbol{\theta}}^*, \mathcal{S}_{\text{syn}}) - \mathcal{L}_{\text{robust}}(\boldsymbol{\theta}^*, \mathcal{S}_{\text{syn}}) = \mathbb{E}_{\boldsymbol{x},y}[\sum_{j\neq y}^{K}(1-\eta_y-\eta_{yj})(\ell_{\text{robust}}(f(\boldsymbol{x};\boldsymbol{\theta}^*), j) - \ell_{\text{robust}}(f(\boldsymbol{x};\hat{\boldsymbol{\theta}}^*), j))] \leq 0$$

Since ℓ_{robust} is always non-negative and $\mathcal{L}_{\text{robust}}(\boldsymbol{\theta}^*, \mathcal{S}_{\text{clean}}) = 0$, we have that $\ell_{\text{robust}}(f(\boldsymbol{x}; \boldsymbol{\theta}^*), y) = 0, \forall \boldsymbol{x}$. Thus, we have that $\ell_{\text{robust}}(f(\boldsymbol{x}; \boldsymbol{\theta}^*), i) = \frac{C}{K-1}, \forall i \neq y$ by the symmetric property of ℓ_{robust}. Given the assumption on the label noise, $(1 - \eta_y - \eta_{yj}) > 0$. Therefore, for the equality to hold, we musts have $\ell_{\text{robust}}(f(\boldsymbol{x}; \hat{\boldsymbol{\theta}}^*, i) = \frac{C}{K-1}, \forall i \neq y$. According to the symmetric property of ℓ_{robust}, we know that $\ell_{\text{robust}}(f(\boldsymbol{x}; \hat{\boldsymbol{\theta}}^*), y) = 0, \forall \boldsymbol{x}$. Which means that $\hat{\boldsymbol{\theta}}^*$ achieve zero losss on all clean samples as well. Therefore, $\hat{\boldsymbol{\theta}}^*$ is also the minimizer for $\mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}_{\text{clean}})$.

Non-Uniform Noise. For a loss function ℓ_{robust} satisfying Eq 3, and suppose $\min_{\boldsymbol{\theta}} \mathcal{L}(\boldsymbol{\theta}, \mathcal{S}_{\text{clean}}) = 0$. Then ℓ_{robust} is noise-tolrant under non-uniform label noise if $\eta_x < \frac{K-1}{K}, \forall x$. The proof is as follows:

$$
\begin{aligned}
\mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}_{\text{syn}}) =& \mathbb{E}_{\boldsymbol{x}, \tilde{y}}[\ell_{\text{robust}}(f(\boldsymbol{x}; \boldsymbol{\theta}), \tilde{y})] \\
=& \mathbb{E}_{\boldsymbol{x}, y} \mathbb{E}_{\tilde{y}|y, \boldsymbol{x}}[\ell_{\text{robust}}(f(\boldsymbol{x}; \boldsymbol{\theta}), \tilde{y})] \\
=& \mathbb{E}_{\boldsymbol{x}, y}[(1 - \eta_x)\ell_{\text{robust}}(f(\boldsymbol{x}; \boldsymbol{\theta}), y) + \sum_{j \neq y}^{K} \frac{\eta_x}{K-1} \ell_{\text{robust}}(f(\boldsymbol{x}; \boldsymbol{\theta}), j)] \\
=& \mathbb{E}_{\boldsymbol{x}, y}(1 - \eta_x)\ell_{\text{robust}}(f(\boldsymbol{x}; \boldsymbol{\theta}), y) + \mathbb{E}_{\boldsymbol{x}, y} \frac{\eta_x}{K-1}(C - \ell_{\text{robust}}(f(\boldsymbol{x}; \boldsymbol{\theta}), y)) \\
=& \mathbb{E}_{\boldsymbol{x}, y} \frac{C}{K-1} + \mathbb{E}_{\boldsymbol{x}, y}[(1 - \frac{K\eta_x}{K-1})\ell_{\text{robust}}(f(\boldsymbol{x}; \boldsymbol{\theta}), y)]
\end{aligned}
$$

Therefore, we have the following inequality for any $\boldsymbol{\theta}$: $\mathcal{L}_{\text{robust}}(\boldsymbol{\theta}^*, \mathcal{S}_{\text{syn}}) - \mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}_{\text{syn}}) = \mathbb{E}_{\boldsymbol{x}, y}[(1 - \frac{K\eta_x}{K-1})(\ell_{\text{robust}}(f(\boldsymbol{x}; \boldsymbol{\theta}^*), y) - \ell_{\text{robust}}(f(\boldsymbol{x}; \boldsymbol{\theta}), y))]$. Since ℓ_{robust} is always non-negative and $\mathcal{L}_{\text{robust}}(\boldsymbol{\theta}^*, \mathcal{S}_{\text{clean}}) = 0$, we have that $\ell_{\text{robust}}(f(\boldsymbol{x}; \boldsymbol{\theta}^*), y) = 0, \forall \boldsymbol{x}$. Therefore, $\boldsymbol{\theta}^*$ is also the optimal solution for $\mathcal{S}_{\text{syn}}$.

D.3 Proof for Theorem 1

Proof. We first show $\boldsymbol{\theta}^*$ exists in the space induced by $\hat{\boldsymbol{\theta}}(\boldsymbol{w})$. Then we show our framework uniquely return $\boldsymbol{\theta}^*$.

Step 1: Existence. By Assumption 1, we know that $\mathbb{P}_{syn}(\boldsymbol{x}, y) w^*(\boldsymbol{x}, y) = \mathbb{P}_{clean}(\boldsymbol{x}, y)$ in distribution. So

$$
\begin{aligned}
\hat{\boldsymbol{\theta}}(w^*) =& \arg\min_{\boldsymbol{\theta}} \mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}_{\text{syn}}(w^*)) \\
=& \arg\min_{\boldsymbol{\theta}} \int \int w^*(\boldsymbol{x}, y) \ell((f(\theta, \boldsymbol{x}), y) \mathbb{P}_{syn}(\boldsymbol{x}, y) d\boldsymbol{x} d\boldsymbol{y} \\
=& \arg\min_{\boldsymbol{\theta}} \mathbb{E}_{\mathbb{P}_{syn}(\boldsymbol{x}, y) w^*(\boldsymbol{x}, y)} \ell((f(\theta, \boldsymbol{x}), y) \\
=& \arg\min_{\boldsymbol{\theta}} \mathbb{E}_{\mathbb{P}_{clean}(\boldsymbol{x}, y)} \ell(f(\boldsymbol{\theta}, \boldsymbol{x}), y) \\
=& \boldsymbol{\theta}^*.
\end{aligned}
$$

Step 2: Uniqueness. By Assumption 2, we have for all $\boldsymbol{\theta} \neq \boldsymbol{\theta}^*$, we have $\mathcal{L}_{\text{robust}}(\boldsymbol{\theta}^*, \mathcal{S}_{clean}) < \mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}_{clean})$. So $\boldsymbol{\theta}^* = \arg\min_{\boldsymbol{\theta}} \mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}_{clean})$. Since $\arg\min_{\boldsymbol{\theta}} \mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}_{syn}) = \arg\min_{\boldsymbol{\theta}} \mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}_{clean})$. So we have

$$
\boldsymbol{\theta}^* = \arg\min_{\boldsymbol{\theta}} \mathcal{L}_{\text{robust}}(\boldsymbol{\theta}, \mathcal{S}_{syn}).
$$

Putting the existence and uniqueness parts together, we finish the proof. □

The above theorem shows that there is an explicit mapping between the optimal weighting function w^* and the optimal $\boldsymbol{\theta}^*$. This mapping is achieved by the inner loop in formulation 2. We can then optimize $\mathcal{L}_{\text{ce}}(\boldsymbol{\theta}(\boldsymbol{w}), \mathcal{S}_{\text{clean}})$ over $\boldsymbol{w}$ to find the optimal $\boldsymbol{w}^*$. Given that Assumption 2 holds, we can switch $\mathcal{L}_{\text{ce}}(\boldsymbol{\theta}(\boldsymbol{w}), \mathcal{S}_{\text{clean}})$ to $\mathcal{L}_{\text{robust}}(\boldsymbol{\theta}(\boldsymbol{w}), \mathcal{S}_{\text{clean}})$. Finally, thanks to Property D.2 of ℓ_{robust}, we may simply optimize $\mathcal{L}_{\text{robust}}(\boldsymbol{\theta}(\boldsymbol{w}), \mathcal{S}_{\text{syn}})$ over $\boldsymbol{w}$ instead. This gives rise to the outer loop in formulation 1.

D.4 Proof for Theorem 2

Proof. Let $\hat{\mathcal{S}}_{syn}^{v,-1}$ denotes the dataset that replaces any one element of $\hat{\mathcal{S}}_{syn}^{v}$ with arbitrary $\boldsymbol{x}$, it is easy to know that

$$|\mathcal{L}_{\text{robust}}(\hat{\boldsymbol{\theta}}^*(\boldsymbol{w}); \mathcal{S}_{\text{syn}}^v) - \mathcal{L}_{\text{robust}}(\hat{\boldsymbol{\theta}}^*(\boldsymbol{w}); \mathcal{S}_{\text{syn}}^{v,-1})| \leq \frac{\kappa}{M}$$

holds for any $\boldsymbol{w}$. Then by the bounded difference inequality (Corollary 2.21 of Wainwright (2019)), given $\boldsymbol{w}$, we have with probability $1-\delta$,

$$\mathcal{L}_{\text{robust}}(\hat{\boldsymbol{\theta}}^*(\boldsymbol{w}); \mathcal{S}_{\text{syn}}) \leq \mathcal{L}_{\text{robust}}(\hat{\boldsymbol{\theta}}^*(\boldsymbol{w}); \mathcal{S}_{\text{syn}}^v) + \kappa\sqrt{\frac{\ln(1/\delta)}{2M}}, \tag{7}$$

Then we have

$$\begin{aligned}
&\mathcal{L}_{\text{robust}}(\hat{\boldsymbol{\theta}}^*(\hat{\boldsymbol{w}}); \mathcal{S}_{\text{syn}}) \\
\leq &\mathcal{L}_{\text{robust}}(\hat{\boldsymbol{\theta}}^*(\hat{\boldsymbol{w}}); \mathcal{S}_{\text{syn}}^v) + \kappa\sqrt{\frac{2\ln(|\mathcal{W}|/\delta)}{M}} \\
\leq &\mathcal{L}_{\text{robust}}(\hat{\boldsymbol{\theta}}^*(\boldsymbol{w}); \mathcal{S}_{\text{syn}}^v) + \kappa\sqrt{\frac{\ln(|\mathcal{W}|/\delta)}{2M}} + \epsilon \\
\leq &\mathcal{L}_{\text{robust}}(\hat{\boldsymbol{\theta}}^*(\boldsymbol{w}); \mathcal{S}_{\text{syn}}^v) + \kappa\sqrt{\frac{\ln(1/\delta)}{2M}} \\
&+ \kappa\sqrt{\frac{\ln(|\mathcal{W}|/\delta)}{2M}} + \epsilon \\
\leq &\mathcal{L}_{\text{robust}}(\hat{\boldsymbol{\theta}}^*(\boldsymbol{w}); \mathcal{S}_{\text{syn}}) + \kappa\sqrt{\frac{2\ln(|\mathcal{W}|/\delta)}{M}} + \epsilon,
\end{aligned}$$

The first inequality because we require inequality equation 7 to hold uniformly for all $|\mathcal{W}|$ functions. The second inequality is because $\hat{\boldsymbol{w}}$ is the ϵ-approximated solution. The third inequality is applying inequality equation 7. The forth inequality is because $|\mathcal{W}| > 1$. Taking infimum over $\boldsymbol{w}$ on the right hand side, we obtain the desired bound. □

E Bi-Level vs. One-Level Optimization

We empirically verify the effectiveness of bi-level SunGen than (1) one-level optimazation using l_{rce} (***One-level,*** ℓ_{rce}) and (2) bi-level optimization using ℓ_{ce} as both inner and outer objectives (***Bi-level,*** ℓ_{ce}). From the results in Table 7, we can observe that our framework with bi-level ℓ_{rce} outperforms both counterparts significantly.

Table 7: Comparison between our method with one-level ℓ_{rce} and bi-level ℓ_{ce} on 1,000k data.

Method	**IMDb**	**Amazon**	**Yelp**
SUNGEN	86.56	84.63	90.38
One-level, ℓ_{rce}	81.92	81.50	85.36
Bi-level, ℓ_{ce}	74.54	80.37	84.56

F IMPLEMENTATION DETAILS

F.1 DATASET

We evaluate our method on eight widely-used text classification tasks, including IMDb (Maas et al., 2011), SST-2 Socher et al. (2013), Rotten Tomatoes (Pang & Lee, 2005), Amazon (McAuley & Leskovec, 2013), Yelp (Zhang et al., 2015), Subj (Pang & Lee, 2004), AGNews (Zhang et al., 2015) and DBpedia (Zhang et al., 2015). IMDB, SST-2, and Rotten Tomatoes are sentiment classification benchmarks containing positive/negative movie reviews. Amazon and Yelp are comments classification tasks consisting of electronic product reviews and restaurant reviews respectively. We choose electronics and restaurant reviews as they are very different from movie reviews. Subj is a subjectivity detection task to justify whether the text contains factual contents or expresses opinions. AGNews (4-class classification) and DBpedia (14-class classification) are the topic and otologogy classification tasks respectively. Apart from AGNews and DBpedia, other tasks are binary classification tasks. We use full test set for evaluation except for DBpedia, for which we randomly sample 5000 test examples to reduce computational cost. Sample sizes are listed in Table 1. We report accuracy for evaluation.

F.2 FULL IMPLEMENTATION DETAILS

We compare the baselines using GPT2-XL (Radford et al., 2019) as PLM. For text generation, we use Nucleus Sampling (Holtzman et al., 2020) with $p = 0.9$ as the decoding strategy and use GPT2-XL as the generator. For fair comparison, we use the best prompts designed by (Ye et al., 2022) for data generation. For task model training, we use 1-layer Bi-LSTM and DistilBERT-base as the light-weight classifiers. For LSTM, we use Adam optimizer(Kingma & Ba, 2015) with learning rate 1e-3. For DistilBERT-base, we finetune each dataset using Adam optimizer with learning rate 2e-5, and other default hyper-parameters as suggested by HuggingFace Transformers library(Wolf et al., 2019). We run LSTM for 5 epochs, and run DistilBERT-base for 3 epochs for prediction. Unless otherwise stated, we run our experiments on 200k data. We compute the average accuracy on test set over 3 runs using different random seeds.

During the optimization of sample weights, Adam optimizer with learning rate 2.5e-1 is used to update the sample-weights. In the inner loop, 1,000k synthetic data are used as the training data; in the outer loop, 50k synthetic samples are randomly sampled as the training data for fast iteration. We use 1-layer Bi-LSTM and DistilBERT-base as the tiny task model and run it for 1 epoch each time for fast iteration. The bilevel procedure is iterated for 50 times for each task.

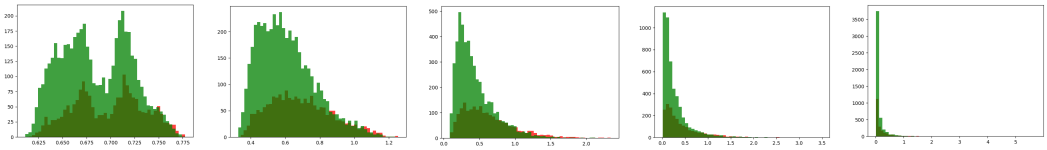
For the baseline using gold data in Table 2, to simulate the scenario where gold data is scarce, we randomly select 1,000 samples from the standard training set as the training data in outer loop. For comparison with other denoising baselines shown in Table 3, we use the techniques as described in the original papers. Specifically, for Confidence (Swayamdipta et al., 2020), we use the mean model probability of the true label across epochs as the confidence value and select top 200k examples; for Co-teaching (Han et al., 2018), we use two networks, each is trained with samples selected by the other network based on the loss value; for meta-weight-net (Shu et al., 2019), since we do not have access to clean data, we use a part of synthetic data as validation. Co-teaching and meta-weight-net are conducted on 200k synthetic data.

F.3 PROMPTS

For IMDb, SST-2, and Rotten Tomatoes, we use the best prompts designed by Ye et al. (2022) in both PROMPTING and data-generation settings. For tasks that are not investigated by ZEROGEN, following Ye et al. (2022), we manually design five prompts for each task and report the result of the best prompt on PROMPTING, then we use the same prompt(or minor revision version) for ZEROGEN and SUNGEN to generate data. The details of prompts are shown in Table 8.

Table 8: Prompts used for PROMPTING and data generation. Note that ZEROGEN and SUNGEN use the same prompt for each task. <c> represents the input movie names/electronic categories/restaurant names. <*MASK*> position will be placed with label words. <x> represents the text that we use PLM to generate. The movie and restaurant names are generated by PLM using prompt *"Movie: ", "Restaurant: "*. The electronic categories are 41 categories collected from Amazon website.

Setting	**Task**	**Best Prompt**	**Label Words**
PROMPTING	IMDb	The movie review in <*MASK*> sentiment is: "<x>	positive/negative
	Amazon	The electronics product review in <*MASK*> sentiment is: "<x>	positive/negative
	Yelp	The restaurant review in <*MASK*> sentiment is: "<x>	positive/negative
	SST-2	The movie review in <*MASK*> sentiment is: "<x>	positive/negative
	Rotten	The movie review in <*MASK*> sentiment is: "<x>	positive/negative
	Subj	The movie review <*MASK*> is: "<x>	containing factual contents (objective) / expressing opinions (subjective)
	AGNews	The news article is in the category of <*MASK*>: "<x>	World/Sports/Business/ Technology
	DBpedia	The article classified to the category of <*MASK*>: "<x>	Company/School/Artist/ Athlete/ Politician/ Transportation/ Building/ Nature/Village/Animal/Plant/ Album/ Film/Book
ZEROGEN & SUNGEN	IMDb	The movie review in <*MASK*> sentiment for movie "<c>" is: "<x>	positive/negative
	Amazon	The "<c>" product review in <*MASK*> sentiment is: "<x>	positive/negative
	Yelp	The "<c>" restaurant review in <*MASK*> sentiment is: "<x>	positive/negative
	SST-2	The movie review in <*MASK*> sentiment for movie "<c>" is: "<x>	positive/negative
	Rotten	The movie review in <*MASK*> sentiment for movie "<c>" is: "<x>	positive/negative
	Subj	The movie review <*MASK*> is: "<x>	containing factual contents (objective) / expressing opinions (subjective)
	AGNews	The news article is in the category of <*MASK*>: "<x>	World/Sports/Business/ Technology
	DBpedia	The article classified to the category of <*MASK*>: "<x>	Company/School/Artist/ Athlete/ Politician/ Transportation/ Building/ Nature/Village/Animal/Plant/ Album/ Film/Book



(a) Epoch 0(54%). (b) Epoch 1(61%). (c) Epoch 2(63%). (d) Epoch 3(60%). (e) Epoch 4(62%).

Figure 5: Loss histogram of SST-2 with 30% uniform label noise. Clean data and noisy data are marked by green and red respectively. The accuracy is listed in the parentheses. We observe that the loss value can not separate the clean data from the noisy ones. Therefore, the methods loss-value-based methods may not work well in our case.

G WHY LOSS-VALUE-BASED DE-NOISE METHODS DOES NOT WORK IN OUR SITUATION?

We further empirically analyze why the popular loss-value-based methods (Shu et al., 2019; Han et al., 2018) fail to help sample noise-free dataset in our scenario. For this experiment, we manually construct a dataset with a 30% label noise using the training set of SST-2 by randomly flipping the class label. As shown in figure 5, the loss values of the correctly labelled data and the mislabelled data are still clustered together. We conjecture that this is due to the nature of the task: not all tasks demonstrate the phenomenon that noisy data demonstrate higher loss values, which is also mentioned in works related to instance dependent noise learning (Cheng et al., 2020). Therefore, selecting subset based on the loss value is not applicable in our scenario.