

LogLLM: Log-based Anomaly Detection Using Large Language Models

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Abstract—Software systems often record important runtime information in logs to help with troubleshooting. Log-based anomaly detection has become a key research area that aims to identify system issues through log data, ultimately enhancing the reliability of software systems. Traditional deep learning methods often struggle to capture the semantic information embedded in log data, which is typically organized in natural language. In this paper, we propose LogLLM, a log-based anomaly detection framework that leverages large language models (LLMs). LogLLM employs BERT for extracting semantic vectors from log messages, while utilizing Llama, a transformer decoder-based model, for classifying log sequences. Additionally, we introduce a projector to align the vector representation spaces of BERT and Llama, ensuring a cohesive understanding of log semantics. Unlike conventional methods that require log parsers to extract templates, LogLLM preprocesses log messages with regular expressions, streamlining the entire process. Our framework is trained through a novel three-stage procedure designed to enhance performance and adaptability. Experimental results across four public datasets demonstrate that LogLLM outperforms state-of-the-art methods. Even when handling unstable logs, it effectively captures the semantic meaning of log messages and detects anomalies accurately.

Index Terms—System log, anomaly detection, large language model, deep learning, log analysis

I. INTRODUCTION

Ensuring high availability and reliability is crucial for large-scale software-intensive systems [1], [2]. As these systems become more complex and expansive, the occurrence of anomalies becomes unavoidable [3], [4]. Even a minor issue can lead to performance degradation, data integrity problems, and substantial losses in both customers and revenue. Therefore, anomaly detection is vital for maintaining the health and stability of complex software-intensive systems [5].

Software-intensive systems typically produce console logs that record system states and critical runtime events [6]. Engineers can utilize this log data to evaluate system health, identify anomalies, and trace the root causes of issues. However, due to the potentially vast volume of logs, manually analyzing them for anomalies can be both labor-intensive and prone to mistakes [7]. Consequently, log-based anomaly detection has emerged as a key area in automated log analysis, focusing on the automatic identification of system anomalies through log data.

Numerous deep learning-based methods [8]–[22] for log-based anomaly detection have been proposed. These methods typically employ sequential deep learning models such as LSTM [23] and transformers [24]. These methods can be further divided into reconstruction-based methods [8]–[15] and binary classification-based methods [16]–[22]. Reconstruction-based methods involve designing and training a deep neural network to reconstruct input log sequences, with anomalies detected based on reconstruction errors. The underlying principle is that anomalous samples cannot be accurately reconstructed. Binary classification-based methods, on the other hand, involve designing a binary classifier to classify samples as either normal or anomalous. These methods often require labeled anomalies for training purposes. It is recognized that system logs are documented in natural language and contain a significant amount of semantic information. Nevertheless, traditional deep learning-based methods struggle to effectively capture this information.

In recent years, significant advancements have been achieved in LLMs, such as GPT-4 [25], Llama 3 [26], and ChatGLM [27]. These models are characterized by their vast parameter sizes and are pretrained on substantially larger datasets, ranging from several gigabytes to terabytes in size. This extensive pretraining equips them with remarkable language comprehension abilities, enabling superior performance in tasks such as summarization, paraphrasing, and instruction following even in zero-shot scenarios [28]. Existing methods that utilize LLMs for log-based anomaly detection can be categorized into prompt engineering-based [7], [29]–[31] and fine-tuning-based [3], [32]–[40] approaches. Prompt engineering-based methods leverage the zero/few-shot capabilities of LLMs to detect anomalies based solely on the models’ internal knowledge. However, these methods often struggle to customize solutions for specific datasets, leading to suboptimal detection performance. Fine-tuning-based methods integrate LLMs into deep neural networks and tailor them to user-specific datasets. Nevertheless, these methods encounter challenges such as limited semantic understanding, suboptimal LLM utilization (relying solely on LLMs for semantic information extraction), and insufficient consideration of input data format, which can lead to memory overflow.

To tackle the aforementioned challenges, we propose LogLLM, a novel log-based anomaly detection framework that harnesses LLMs. Unlike traditional methods that rely on

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log parsers for template extraction, LogLLM preprocesses log messages using regular expressions, thereby streamlining the entire process. LogLLM, a fine-tuning-based method, utilizes BERT, a transformer encoder-based model, to extract semantic vectors from log messages. Additionally, it employs Llama, a transformer decoder-based model, to classify log sequences. To ensure coherence in log semantics, we introduce a projector that aligns the vector representation spaces of BERT and Llama. Our framework is trained using a novel three-stage procedure designed to enhance both performance and adaptability.

As we know, LLMs frequently face out-of-memory challenges due to their extensive parameter sizes [41]. Directly inputting the entire log sequence (by concatenating log messages into a long string) into Llama can lead to out-of-memory issues and potentially confuse the LLM, making it difficult to focus on key points for distinguishing anomalies. By adopting BERT to summarize each log message, LogLLM effectively mitigates these problems. Compared to other methods, LogLLM fully exploits the capabilities of LLMs for log-based anomaly detection. We conduct experiments across four public datasets, and the results demonstrate that LogLLM outperforms state-of-the-art methods. Even when handling unstable logs, where new log templates frequently emerge due to software evolution, it effectively captures the semantic meaning of log messages and detects anomalies accurately. The ablation study confirms the effectiveness of the three-stage training procedure.

The main contributions of our work are as follows:

- We introduce LogLLM, a novel log-based anomaly detection framework leveraging LLMs. This study marks the first attempt to simultaneously employ transformer encoder-based and decoder-based LLMs, specifically BERT and Llama, for log-based anomaly detection.
- We propose a novel three-stage procedure to optimize the training and coordination of different components within the deep model, enhancing both performance and adaptability.
- We conduct extensive experiments on four publicly available real-world datasets, demonstrating that LogLLM achieves exceptional performance.

II. RELATED WORK

In this section, we explore related work in the field of log-based anomaly detection, with a particular focus on deep learning-based methods. We give special attention to approaches that utilize pretrained LLMs.

A. Traditional Deep Learning for Log-based Anomaly Detection

Many traditional deep learning-based methods for log-based anomaly detection have been proposed. These works can be grouped into two types based on the training paradigm: reconstruction-based methods and binary classification-based methods.

Reconstruction-based methods [8]–[15] involve designing and training a deep neural network to reconstruct input log

sequences. Anomalies are detected based on reconstruction errors. Normal log sequences can be reconstructed with minimal errors, while anomalous log sequences cannot be effectively reconstructed, resulting in significantly higher reconstruction errors. These methods consistently train the deep model on normal data that is free of anomalies, which means they are semi-supervised.

DeepLog [8] adopts LSTM to predict the next log template ID based on past log sequences. Similarly, LogAnomaly [9] predicts the next log template ID based on both sequential and quantitative patterns. Autoencoders (AEs) [10]–[13] and generative adversarial networks (GANs) [14], [15] are widely used in reconstruction-based methods. For example, LogAttn [10] adopts an AE that incorporates a temporal convolutional network (TCN) to capture temporal semantic correlations and a deep neural network (DNN) to capture statistical correlations. Duan et al. [14] use a GAN, where an encoder-decoder framework based on LSTM serves as the generator. Convolutional neural networks (CNNs) are used as the discriminator. The reconstruction error is calculated based on the difference between the input and the output from the generator.

Binary classification-based methods [16]–[22] often employ deep neural networks that output either one or two values. Typically, a single value represents the probability that a sample belongs to the anomalous class, and anomalies are detected by applying a threshold to convert this probability into a binary classification. When two values are output, they represent the probabilities of the sample belonging to the normal and anomalous classes, respectively.

Most methods [16]–[20] typically train deep models in a supervised manner. For example, Zhang et al. [16] propose LayerLog, which integrates word, log, and logseq layers to extract semantic features from log sequences. CNNs are utilized in [17], [18] to develop a binary classifier. LogRobust [19] integrates a pre-trained Word2Vec model, specifically FastText [42], and combines it with TF-IDF weights to learn representation vectors of log templates. These vectors are then fed into an attention-based Bi-LSTM model for anomaly detection. LogGD [20] transforms log sequences into graphs and utilizes a graph transformer neural network that combines graph structure and node semantics for log-based anomaly detection.

Some work [21], [22] involves training binary classifiers in a semi-supervised manner. For example, Trine [21] uses a transformer encoder [24] to encode normal log sequences into vector representations and a generator to produce random fake vector representations. The discriminator, which is composed of a transformer and a multi-layer perceptron (MLP), is trained to distinguish whether the given vector representations are normal log sequences and it is subsequently used to detect anomalies. PLELog [22] tackles the challenge of insufficient labeling by employing probabilistic label estimation and develops an attention-based GRU neural network for anomaly detection.

It is acknowledged that system logs are recorded in natural

Header	Content
1117838978 2005.06.03 R02-M1-N0-C:J12-U11 2005-06-03-15.49.38.026704 R02-M1-N0-C:J12-U11 RAS KERNEL INFO	instruction cache parity error corrected
1117843015 2005.06.03 R21-M1-N6-C:J08-U11 2005-06-03-16.56.55.309974 R21-M1-N6-C:J08-U11 RAS KERNEL INFO	141 double-hummer alignment exceptions
1117848119 2005.06.03 R16-M1-N2-C:J17-U01 2005-06-03-18.21.59.871925 R16-M1-N2-C:J17-U01 RAS KERNEL INFO	CE sym 2, at 0x0b85eee0, mask 0x05
...	...

Fig. 1: An example of a system log.

language and contain a substantial amount of semantic information. However, traditional deep learning-based methods face challenges in capturing this information.

B. LLMs for Log-based Anomaly Detection

Existing LLMs can be categorized into transformer encoder-based models, such as BERT [43], RoBERTa [44], and SpanBERT [45], and transformer decoder-based models, including GPT-4 [25], Llama 3 [26], and ChatGLM [27]. Two prevalent strategies for utilizing LLMs are prompt engineering and fine-tuning.

Prompt engineering-based methods [7], [29]–[31] detect anomalies solely by relying on the internal knowledge of LLMs. These methods typically employ transformer decoder-based models. For instance, Qi et al. [7] employ ChatGPT for zero-shot and few-shot log-based anomaly detection, utilizing prompt templates that integrate the log sequence directly. However, this approach becomes impractical when using a large window size for grouping log messages. Egersdoerfer et al. [30] address this issue by maintaining a summary-based memory, which summarizes the previous log messages, eliminating the need to input the entire log sequence for anomaly detection. RAGLog [31] uses a retrieval augmented generative (RAG) framework [46] to analyze log entries by querying its store of samples of normal log entries. They design prompt templates for LLMs to determine whether a queried log entry is normal or abnormal. Prompt engineering-based methods often struggle to customize solutions for specific datasets, which can lead to suboptimal detection performance in particular datasets.

Fine-tuning-based methods [3], [32]–[40] incorporate LLMs into deep neural networks and customize them to the user’s own dataset. Some methods [32]–[35], although adopting transformer encoder-based LLMs for anomaly detection, do not capture the semantic information within log sequences. For example, LogBERT [32] and LAnoBERT [33] utilize BERT to reconstruct the input sequence of log template IDs (IDs of log string templates) and detect anomalies based on reconstruction errors, disregarding the semantic information. Other methods [3], [36]–[39] use transformer encoder-based LLMs solely for extracting semantic information from log messages and then employ either smaller models [3], [36]–[38] or distance-based comparison [39] for classification. For instance, NeuralLog [3] leverages BERT to extract semantic vectors from raw log messages, which are subsequently used to detect anomalies via a transformer-based classification model. Similarly, RAPID [39] utilizes transformer encoder-based models to extract semantic vectors and performs anomaly

detection by comparing each query log sequence with its nearest document log sequence. Hadadi et al. [40] directly input template sequences parsed from log sequences, into an LLM and fine-tune it to accurately predict sequence labels. However, this method is impractical because each template may be processed into multiple tokens by the LLM’s tokenizer, and a single template sequence can contain numerous log templates. Consequently, an excessive number of tokens can be generated for one template sequence, which LLMs often cannot process due to token (memory) limitations [41].

LogLLM is a fine-tuning-based method that utilizes BERT for extracting semantic vectors from log messages and Llama, a transformer decoder-based model, for log sequence classification. This method aligns the vector representation spaces of BERT and Llama using a projector. By adopting BERT, LogLLM effectively mitigates the out-of-memory issue caused by excessive tokens when directly tokenizing the entire log sequence with Llama’s tokenizer. Compared to other methods, LogLLM fully exploits the capabilities of LLMs for log-based anomaly detection.

III. PRELIMINARIES

To establish the groundwork for subsequent sections, we introduce the **system log**, which records the system’s events and internal states during runtime. A system log contains a list of log messages in chronological order.

Fig. 1 presents a snippet of a raw system log generated by the BGL (the BlueGene/L supercomputer system), with each log message ordered according to the recorded time. These raw log messages are semi-structured texts consisting of a **header** and **content**. The header, determined by the logging framework, includes information such as timestamp, verbosity level (e.g., WARN/INFO), and component [47]. The log content comprises a constant part (keywords that reveal the log template) and a variable part (parameters that carry dynamic runtime information). In this paper, we focus solely on the content of each log message.

The log messages can be grouped into **log sequences** (i.e., series of log messages that record specific execution flows) based on session or fixed/sliding windows [48]. **Session window** partitioning groups log messages according to their session IDs, thereby generating sequences that include the log messages within each session. For example, Fig. 2a illustrates the HDFS [49] logs undergoing the session window grouping process, where the *block_id* serves as the session ID. In contrast, **fixed/sliding window** partitioning groups log messages based on a fixed size (window size), which can be defined

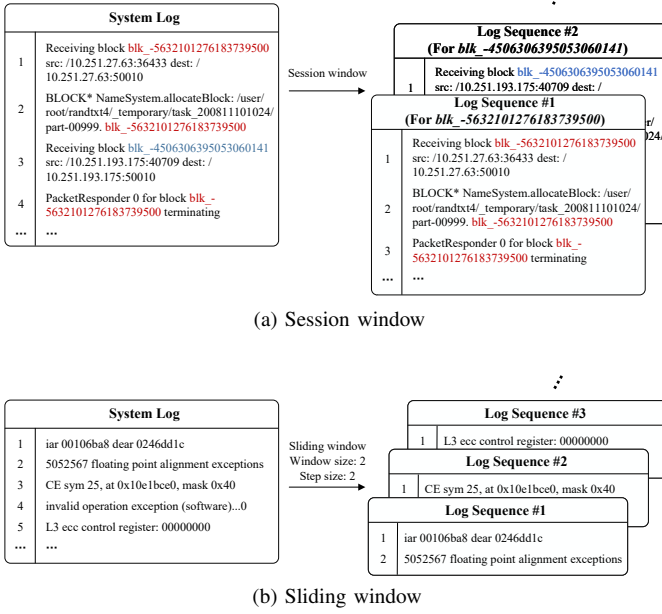


Fig. 2: Illustrative examples of log message partitioning.

by either the time span or the number of log messages. This method creates sequences that capture snapshots of system log messages over time. For example, Fig. 2b illustrates the BGL [50] logs undergoing the sliding window grouping process, with a window size of 2 messages and a step size of 2 messages.

The objective of log-based anomaly detection is to identify anomalous log sequences, facilitating the recognition of potential issues within the system's operational behavior.

IV. METHODOLOGY

In this section, we present our innovative anomaly detection framework, LogLLM. As illustrated in Fig. 3, the log sequence undergoes preprocessing using regular expressions before being fed into a deep neural network that integrates BERT [43], a projector, and Llama 3 [26] for log sequence classification. In the following sections, we will provide detailed insights into log sequence preprocessing, the architecture of the deep model, and the model training procedure.

A. Preprocessing

Considering that the log message content includes variable parameters carrying dynamic runtime information, which is always irrelevant to the anomalies and complicates deep model training, as demonstrated in Section V-F, a technique is needed to identify these parameters and replace them with a constant token. Log parsers, such as Drain [51] and Spell [52], are widely adopted in log-based anomaly detection methods and appear to be a useful technique. However, as noted by Le et al. [3], existing log parsers do not always perform correctly on all log datasets and struggle to handle out-of-vocabulary (OOV) words in new log messages, resulting in a loss of semantic information. When logs are unstable, these parsers become

increasingly ineffective over time, making it difficult to support subsequent anomaly detection.

Thanks to the structured log generation process, the textual format of parameters representing specific objects can be easily identified using regular expressions [53]. Consequently, we replace each variable parameter, such as account, directory path, and IP address, with '<*>'. Despite its simplicity, this technique offers significant performance advantages. Compared with log parsers, this preprocessing technique is more effective and does not require training.

B. Model Architecture

As shown in Fig. 3, our deep model consists of three main components: BERT, a projector, and Llama. Both BERT and Llama are pretrained LLMs. BERT is utilized to extract vector representations of log messages, while Llama is employed to classify the log sequences. The projector serves as a bridge, aligning the vector representation spaces of BERT and Llama. It is important to note that our model incorporates only one instance of BERT and one projector.

1) *BERT*: BERT generates a semantic vector by processing the semantic vector of the classification token ([CLS]) through a linear layer followed by a \tanh activation function. Each log message, once preprocessed, is encoded into a semantic vector using the BERT tokenizer and BERT model. For a preprocessed log sequence, the output of BERT is a sequence of semantic vectors $C = (c_1, c_2, \dots, c_N) \in \mathbb{R}^{N \times d_{BERT}}$, where N represents the length of the log sequence (i.e., the number of log messages) and d_{BERT} is the dimension of each semantic vector (i.e., hidden size). LogLLM utilizes the BERT base model¹, which consists of 12 layers of transformer encoders and 768 hidden units in each transformer. Therefore, d_{BERT} is 768.

2) *Projector*: The projector is a linear layer that maps the semantic vectors $C \in \mathbb{R}^{N \times d_{BERT}}$ to the token embedding vectors accepted by Llama, represented as $E = (e_1, e_2, \dots, e_N) \in \mathbb{R}^{N \times d_{Llama}}$, where d_{Llama} is the hidden size of Llama. The projector is designed to align the vector representation spaces of BERT and Llama.

3) *Llama*: To conduct prompt tuning on Llama, the transformer decoder-based LLM, we generate corresponding textual queries based on embedded log sequences. Specifically, each query consists of three components.

The first component introduces the log sequence, such as "Below is a sequence of system log messages:". The second component comprises the token embeddings E output by the projector. The third component queries whether the sequence is anomalous, asking, for instance, ". Is this sequence normal or anomalous?". The first and third components are fed into the Llama tokenizer and Llama embedding layer sequentially, producing $E_1 \in \mathbb{R}^{A \times d_{Llama}}$ and $E_3 \in \mathbb{R}^{Q \times d_{Llama}}$, where A and Q are the number of tokens produced by tokenizing the first and third components, respectively. Then, the token embeddings of the three components are concatenated,

¹<https://huggingface.co/google-bert/bert-base-uncased>

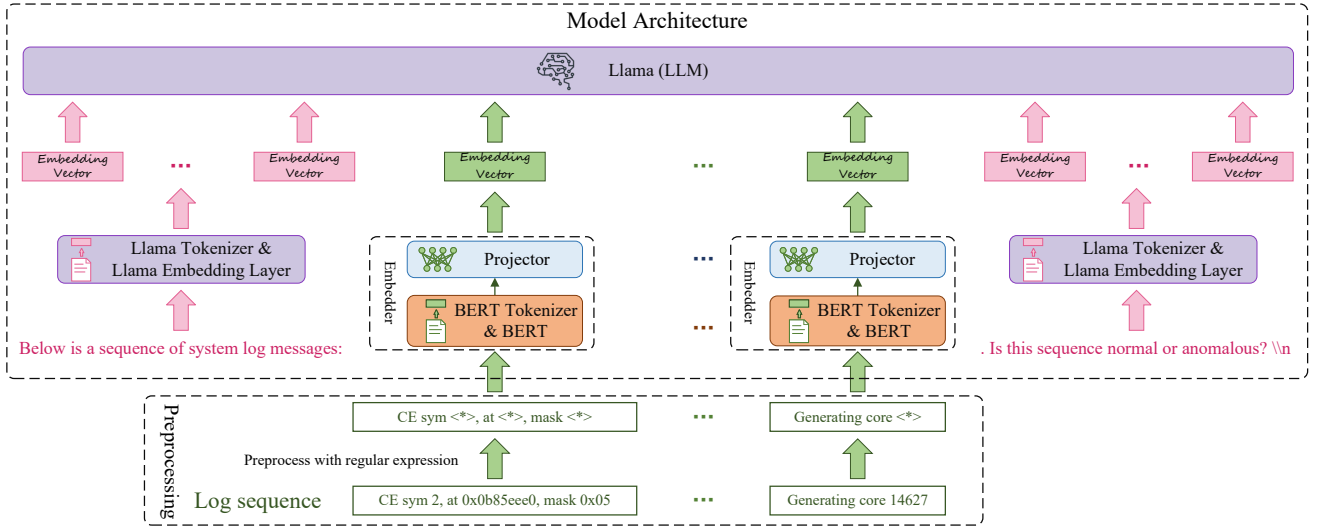


Fig. 3: The framework of LogLLM. Notably, the model includes a single instance of BERT and the projector.

represented as $[E_1||E||E_3] \in \mathbb{R}^{(A+N+Q) \times d_{Llama}}$ and fed into Llama. We utilize Llama 3 8B model², which consists of 32 transformer decoder-like layers and contains 8 billion parameters. Here, d_{Llama} is 4096.

C. Training

1) *Minority Class Oversampling*: LogLLM is a supervised anomaly detection method, which means it needs labeled normal and anomalous samples for training. However, supervised anomaly detection methods often face the challenge of data imbalance, which can lead to biased model training. In an anomaly detection task, there are only two classes: normal and anomalous, and the number of instances in each class is uncertain. To cope with data imbalance, we oversample the class with fewer samples, ensuring that the proportion of the minority class is no less than β . Formally, let the proportion of the minority class be α and $\alpha < \beta$, and the total number of samples be $Sample_num$. To achieve a proportion of β for the minority class, it will be oversampled to the following quantity:

$$\frac{\beta(1-\alpha)}{1-\beta} \times Sample_num \quad (1)$$

This adjustment will make the proportion of the minority class equal to β .

2) *Training Objective*: Our objective is to train the deep model to predict whether a given log sequence is normal or anomalous. We fine-tune the model to respond appropriately: if the sequence is anomalous, it outputs ‘The sequence is anomalous.’; if normal, it outputs ‘The sequence is normal.’. We utilize cross-entropy loss [54] as our loss function.

3) *Training Procedure*: To train our deep model, we follow three main stages.

Stage 1. Fine-tuning Llama to capture the answer template: The first stage involves fine-tuning Llama to capture

the answer template. Specifically, we train Llama to respond to the prompt ‘Is this sequence normal or anomalous?’ with ‘The sequence is anomalous/normal.’. This stage requires only a few data samples.

Stage 2. Training the embedder of log messages: The second stage involves training the embedder of log messages, specifically BERT and the projector. This stage aims to project each log message to the embedding of the most suitable token in Llama, enabling Llama to discern whether the given log sequence is normal or anomalous.

Stage 3. Fine-tuning the entire model: Finally, we fine-tune the entire model to ensure cohesive and accurate performance across all components.

4) *Efficient Fine-Tuning on LLMs*: To reduce the costs involved in fine-tuning LLMs (BERT and Llama) with a substantial number of parameters, we utilize QLoRA [55] to minimize memory usage. QLoRA accomplishes this by backpropagating gradients into a frozen 4-bit quantized model, while maintaining the performance levels achieved during the full 16-bit fine-tuning process.

V. EXPERIMENTS

In this section, we conduct extensive experiments on four real-life logs to investigate the following research questions (RQs):

- **RQ1**: How effective is LogLLM in log-based anomaly detection?
- **RQ2**: How do different preprocessing techniques impact the performance of LogLLM?
- **RQ3**: How does each stage of the three-stage training process influence the performance of LogLLM?
- **RQ4**: How do different levels of minority class oversampling, determined by the hyperparameter β , affect the performance of LogLLM?

LogLLM is coded in Python, and the source code is available at <https://github.com/guanwei49/LogLLM>.

²<https://huggingface.co/meta-llama/Meta-Llama-3-8B>

TABLE I: The statistics of datasets used in the experiments.

	# Log messages	# Log sequences	Training Data			Testing Data		
			# Log sequences	# Anomalies	Anomaly ratio	# Log sequences	# Anomalies	Anomaly ratio
HDFS	11,175,629	575,061	460,048	13,497	2.93%	115,013	3,341	2.90%
BGL	4,747,963	47,135	37,708	4,009	10.63%	9,427	817	8.67%
Liberty	5,000,000	50,000	40,000	34,144	85.36%	10,000	651	6.51%
Thunderbird	10,000,000	99,997	79,997	837	1.05%	20,000	29	0.15%

A. Benchmark Methods

To verify the superiority of the proposed method, we compare LogLLM with five state-of-the-art semi-supervised methods: DeepLog [8], LogAnomaly [9], PLELog [22], FastLogAD [34], and LogBERT [32]. We also compare it with three supervised methods: LogRobust [19], CNN [18] and NeuralLog [3], and one method that does not require training a deep model but needs some normal samples for retrieval: RAPID [39].

Notably, FastLogAD, LogBERT, NeuralLog, and RAPID adopt LLMs for anomaly detection.

B. Experimental Settings

In our experiment, the hyperparameter β , which is described in Section IV-C1, is set to 30%. We use the AdamW optimizer [56] to train the model with a mini-batch size of 16. Unless otherwise specified, the training procedure is configured as follows: In the first stage, only 1,000 samples are involved with a learning rate of $5e-4$. The second and third stages each consist of two epochs with a learning rate of $5e-5$.

For a fair comparison, we configure the hyperparameters for all compared methods according to the values provided in their original articles.

C. Metrics

We evaluate the performance of these methods using the widely adopted *Precision*, *Recall* and F_1 -score. These metrics are calculated as follows:

$$Precision = \frac{TP}{TP + FP} \quad (2)$$

$$Recall = \frac{TP}{TP + FN} \quad (3)$$

$$F_1\text{-score} = \frac{2 * Precision * Recall}{Precision + Recall} \quad (4)$$

, where TP , FN , FP represent true positives, false negatives and false positives respectively.

Precision refers to the percentage of correctly detected anomalies among all anomalies identified by the model, while recall represents the percentage of anomalies that are correctly identified from all real anomalies. The F_1 -score combines these two metrics into a single measure, providing a balanced assessment of the model's performance in detecting anomalies.

D. Dataset

To evaluate our method for log-based anomaly detection, we selected four public datasets [57]: HDFS, BGL, Liberty, and Thunderbird. The details for each dataset are provided below:

HDFS (Hadoop Distributed File System) dataset [49] is generated by running Hadoop-based mapreduce jobs on over 200 Amazon EC2 nodes and contains a total of 11,175,629 log messages. These log messages are grouped into different log windows based on their *block_id*, which reflect program executions in the HDFS, resulting in 575,061 blocks. Among these, 16,838 blocks (2.93%) indicate system anomalies.

BGL (Blue Gene/L) dataset [50] is a supercomputing system log dataset collected from a BlueGene/L supercomputer system at lawrence livermore national labs (LLNL). The dataset contains 4,747,963 log messages, each of which has been manually labeled as either normal or anomalous. There are 348,460 log messages (7.34%) that are labeled as anomalous.

Thunderbird dataset [50] is a publicly accessible collection of log data sourced from the Thunderbird supercomputer at sandia national laboratories (SNL). This dataset consists of both normal and anomalous messages, each of which has been manually categorized. Although the dataset contains over 200 million log messages, we focus on a subset of 10 million continuous log messages for computational efficiency. This subset includes 4,937 anomalous log messages, representing approximately 0.049% of the total.

Liberty dataset [50] comprises system logs from the Liberty supercomputer at sandia national labs (SNL) in Albuquerque. This supercomputer features 512 processors and 944 GB of memory, and the dataset contains over 200 million log messages. For computational efficiency, we sample 5 million consecutive log messages, among which 1,600,525 are identified as anomalous, constituting approximately 32.01% of the total sampled messages.

In the context of HDFS, we adopt a session window strategy, which involves grouping log messages into sequences based on the *block_id* present in each log message. Each session is labeled using ground truth. For other datasets, including BGL, Thunderbird, and Liberty, we utilize a sliding window strategy to group log messages, with a window size of 100 messages and a step size of 100 messages. A log sequence is deemed anomalous if it contains at least one anomalous log message according to the ground truth.

Similar to existing work [8], [9], [19], [22], [34], [39], we split each dataset into a training set and a testing set with a ratio of 8:2 to evaluate the performance of a log-based anomaly

TABLE II: Experimental results on HDFS, BGL, Liberty, and Thunderbird datasets.

Methods	Datasets	Log parser	HDFS			BGL			Liberty			Thunderbird			Avg. F_1
			Prec.	Rec.	F_1	Prec.	Rec.	F_1	Prec.	Rec.	F_1	Prec.	Rec.	F_1	
DeepLog		✓	0.835	0.994	0.908	0.166	0.988	0.285	0.751	0.855	0.800	0.017	0.966	0.033	0.506
LogAnomaly		✓	0.886	0.893	0.966	0.176	0.985	0.299	0.684	0.876	0.768	0.025	0.966	0.050	0.521
PLELog		✓	0.893	0.979	0.934	0.595	0.880	0.710	0.795	0.874	0.832	0.808	0.724	0.764	0.810
FastLogAD		✓	0.721	0.893	0.798	0.167	1.000	0.287	0.151	0.999	0.263	0.008	0.931	0.017	0.341
LogBERT		✓	0.989	0.614	0.758	0.165	0.989	0.283	0.902	0.633	0.744	0.022	0.172	0.039	0.456
LogRobust		✓	0.961	1.000	0.980	0.696	0.968	0.810	0.695	0.979	0.813	0.318	1.000	0.482	0.771
CNN		✓	0.966	1.000	0.982	0.698	0.965	0.810	0.580	0.914	0.709	0.870	0.690	0.769	0.818
NeuralLog		✗	0.971	0.988	0.979	0.792	0.884	0.835	0.875	0.926	0.900	0.794	0.931	0.857	0.893
RAPID		✗	1.000	0.859	0.924	0.874	0.399	0.548	0.911	0.611	0.732	0.200	0.207	0.203	0.602
LogLLM		✗	0.994	1.000	0.997	0.861	0.979	0.916	0.992	0.926	0.958	0.966	0.966	0.966	0.959

detection approach. For the HDFS dataset, we randomly split the log sequences into training and testing data. In contrast, for the BGL, Thunderbird, and Liberty datasets, we adhere to a chronological split [6]. This strategy ensures that all log sequences in the training set precede those in the testing set, reflecting real-world conditions and mitigating potential data leakage from unstable log data.

Table I summarizes the statistics of the datasets used in the experiments.

E. Performance Evaluation (RQ1)

Table II presents the experimental results of various log-based anomaly detection methods on the HDFS, BGL, Liberty, and Thunderbird datasets. The best results are highlighted in bold. We have the following observations:

The proposed LogLLM achieves the highest F_1 -score across all datasets. On average, LogLLM’s F_1 -scores are 6.6% better than the best existing method, NeuralLog, demonstrating its effectiveness in log-based anomaly detection. Despite the adoption of LLMs in FastLogAD, LogBERT, NeuralLog, and RAPID for anomaly detection, their performance remains unsatisfactory. FastLogAD and LogBERT utilize BERT, a transformer encoder-based model, for detecting anomalies based on log sequence reconstruction errors. Their inputs consist of sequences of log template IDs (IDs of log string templates) extracted from log messages via log parsers, lacking semantic information. In contrast, NeuralLog and RAPID utilize transformer encoder-based models to extract semantic vectors from log messages. However, NeuralLog utilizes smaller models, whereas RAPID relies on distance-based comparison for anomaly sequence classification. LogLLM, on the other hand, leverages both BERT for extracting semantic vectors and Llama, a transformer decoder-based LLM, for anomaly detection. The representation spaces of BERT and Llama are aligned via a projector, fully harnessing the potential of LLMs for log-based anomaly detection.

Moreover, LogLLM achieves a balance between precision and recall, indicating that it maintains low false alarm rates and minimizes missed reports. In contrast, methods like FastLogAD are excessively sensitive to anomalies, often resulting in numerous false alarms. For example, on the BGL dataset, despite FastLogAD having a recall of 1, it only achieves

TABLE III: Computational cost.

	Training time (minutes)	Testing time (minutes)
DeepLog	72.17	3.42
LogAnomaly	156.16	7.25
PLELog	315.47	33.59
LogRobust	108.42	2.48
CNN	98.16	2.16
FastLogAD	254.17	0.29
LogBERT	429.04	43.77
NeuralLog	267.46	21.44
RAPID	63.98	38.43
LogLLM	1,065.15	64.48

a precision of 0.167, making it impractical for real-world use. Similarly, methods such as DeepLog, LogAnomaly and LogBERT exhibit similar issues. On the other hand, RAPID is not sensitive enough to anomalies, leading to many undetected anomalies. For instance, on the BGL dataset, RAPID achieves a precision of 0.874 but a recall of only 0.399.

Effect of labeled anomalies (RQ2): As illustrated in Table II, in contrast to methods such as DeepLog, LogAnomaly, FastLogAD, LogBERT, and RAPID, which require clean datasets devoid of anomalies to build anomaly detection models, methods like PLELog, LogRobust, CNN, NeuralLog, and LogLLM demonstrate superior performance. These models are trained using not only normal samples but also labeled anomalies. For instance, these five methods achieve an average F_1 -score above 0.771 across four datasets, whereas others that do not utilize labeled anomalies perform poorly, with an average F_1 -score below 0.602 across four datasets. This demonstrates that incorporating labeled anomalies can provide a significant advantage to anomaly detection methods.

Computational cost: The time consumption of each method is presented in Table III. These results have been averaged across all the datasets.

Although RAPID does not require training a deep model, the extraction and retrieval of vector representations remain time-consuming. In comparison to other methods, FastLogAD requires relatively high training time, but it has the shortest testing time because it uses only the discriminator of the model during testing. As anticipated, while our proposed LogLLM demonstrates the best performance, it also incurs the highest computational cost due to its large number of parameters.

TABLE IV: Effects of different preprocessing techniques on HDFS, BGL, Liberty, and Thunderbird datasets.

	HDFS			BGL			Liberty			Thunderbird			Avg. F ₁
	Prec.	Rec.	F ₁	Prec.	Rec.	F ₁	Prec.	Rec.	F ₁	Prec.	Rec.	F ₁	
Raw	0.994	0.991	0.993	0.943	0.767	0.846	0.911	0.908	0.909	0.806	0.862	0.833	0.895
Template ID	0.995	0.945	0.969	0.775	0.286	0.418	0.994	0.270	0.425	1.000	0.379	0.550	0.591
Template	0.991	1.000	0.995	0.861	0.919	0.889	0.968	0.931	0.949	0.950	0.655	0.776	0.902
RE (LogLLM)	0.994	1.000	0.997	0.861	0.979	0.916	0.992	0.926	0.958	0.966	0.966	0.966	0.959

However, the testing time of LogLLM remains acceptable when compared to other methods that utilize LLMs, such as LogBERT, NeuralLog, and RAPID.

F. Effects of Different Preprocessing Techniques (RQ3)

We evaluate the effectiveness of the different preprocessing techniques. The results are shown in Table IV. In this table, ‘Raw’ indicates that the content of log messages is not preprocessed and is directly input into the proposed deep model. ‘Template’ indicates that sequences of log templates produced by Drain [51], a log parser, are used as input for the proposed deep model. ‘Template ID’ signifies that the IDs of log templates, obtained by Drain, are simply encoded into numeric vectors using an embedding layer instead of BERT. The preprocessing technique ‘Template ID’ renders the model unable to capture the semantic information within log messages. Notably, the parser Drain is applied to the entire dataset, rather than only the training dataset, to avoid performance degradation due to the OOV problem. ‘RE’ indicates that regular expressions, as introduced in Section IV-A, are used for preprocessing log messages.

As anticipated, the preprocessing technique ‘RE’ yields the highest F₁-score across all datasets. Conversely, the preprocessing technique ‘Template ID’ consistently results in the lowest F₁-score across all datasets, averaging 36.8% lower than that of ‘RE’. This can be attributed to the fact that ‘Template ID’ hinders the model’s ability to capture the semantic information within log messages, thereby impairing its capability to detect anomalies from a natural language perspective. The preprocessing techniques ‘Raw’ and ‘Template’ result in relatively good performance, but their F₁-scores are still 6.4% and 5.7% lower than that of ‘RE’, respectively. For the preprocessing technique ‘Raw’, the variable parts (parameters that carry dynamic runtime information) within the content of each log message have little influence on anomaly detection. However, due to their high randomness, they can confuse the model, making it difficult to discern anomalies. For the preprocessing technique ‘Template’, the parser is not always reliable, sometimes incorrectly removing the constant parts or retaining the variable parts, which can lead to information loss or confusion for the model, making it difficult to discern anomalies.

G. Ablation Study of the Training Procedure (RQ4)

We investigate the effect of each training procedure through an ablation study. The results are presented in Table V, where ‘W/O’ denotes ‘without’. We have the following observations:

Skipping any training stage results in a decrease in the F₁-score across all datasets, demonstrating the effectiveness of our three-stage training procedure. It is noteworthy that training without stage 1 leads to the worst performance, with the F₁-score averaged across all datasets decreasing by as much as 29.7%. However, training without stages 1&2 (only adopting training stage 3: fine-tuning the entire model) yields acceptable performance, with only a 3.2% decrease in the average F₁-score. This demonstrates that fine-tuning Llama to capture the answer template (Stage 1) is essential before training the embedder (BERT and projector) of log messages (Stage 2). Without stage 1 (i.e., directly training the embedder), the embedder may be misdirected, resulting in incorrect semantic capture of log messages and model failure. Training without stage 3 yields relatively poor performance, with an average F₁-score decrease of 10.5%. This indicates that sequentially fine-tuning Llama and training the embedder alone is insufficient for the model to capture anomalous patterns; cohesive fine-tuning of the entire model is essential. Training without stages 2 and 1&2 also results in a performance decrease, with average F₁-score reductions of 2.5% and 3.2%, respectively. This demonstrates that individually training the embedder before fine-tuning the entire model can also enhance performance. This stage allows the embedder to generate better semantic vectors of log messages for Llama to discern anomalies.

In summary, our proposed three-stage training procedure is well-suited for our deep model in log-based anomaly detection.

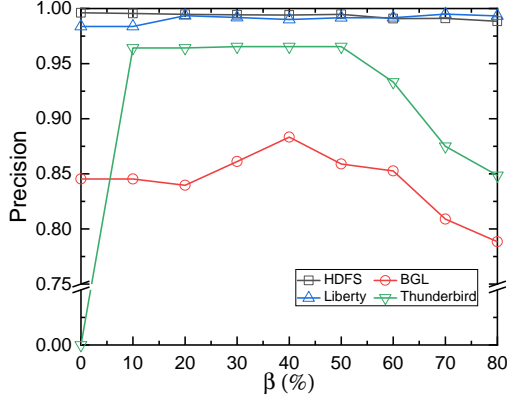
H. Impact of Minority Class Oversampling

Note that normal and anomalous samples in the training dataset are imbalanced, as shown in Table I. For the HDFS, BGL, and Thunderbird datasets, normal samples outnumber anomalous samples. Conversely, in the Liberty dataset, anomalous samples exceed normal samples. As described in Section IV-C1, the hyper-parameter β controls the proportion of the minority class by oversampling to address the data imbalance problem. In this section, we investigate the impact of β by varying its value. Fig. 4 illustrates the performance of LogLLM on the four datasets under different magnitudes of β . When $\beta = 0$, the samples are not oversampled; instead, the original datasets are utilized directly for training.

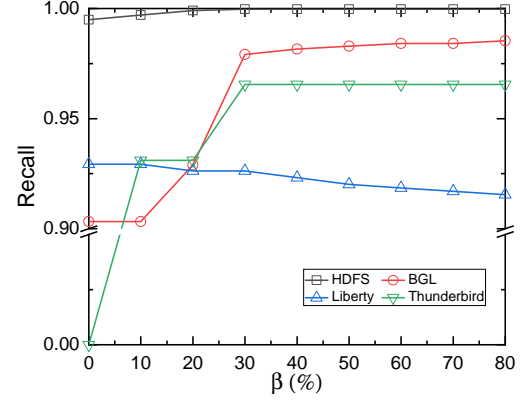
As illustrated in Fig. 4b, for the HDFS, BGL, and Thunderbird datasets, the recall always increases, while for the Liberty dataset, recall decreases as β increases. This can be attributed to the fact that for the HDFS, BGL, and Thunderbird datasets, when β increases, anomalies are oversampled, making the model more prone to identifying samples as anomalies. In

TABLE V: Ablation study of the training procedure on HDFS, BGL, Liberty, and Thunderbird datasets.

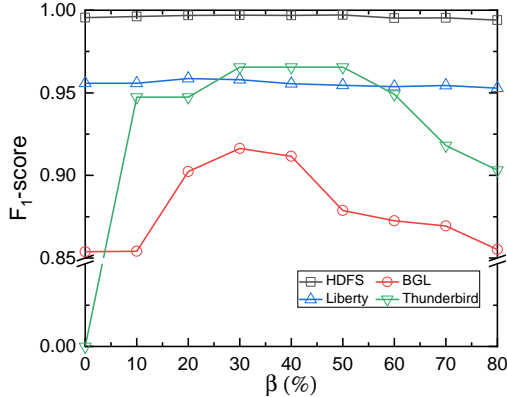
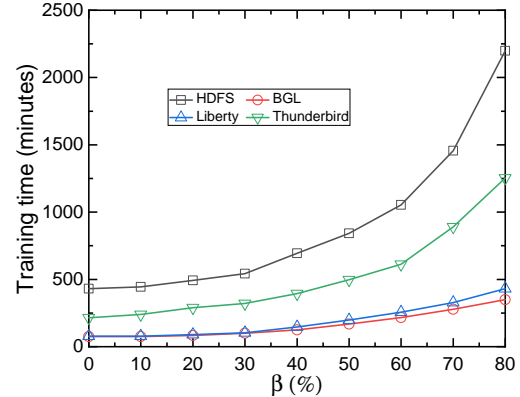
	HDFS			BGL			Liberty			Thunderbird			Avg. F ₁
	Prec.	Rec.	F ₁	Prec.	Rec.	F ₁	Prec.	Rec.	F ₁	Prec.	Rec.	F ₁	
W/O Stage 1	0.991	1.000	0.995	0.578	0.971	0.725	0.685	0.290	0.408	0.381	0.828	0.522	0.662
W/O Stage 2	0.994	1.000	0.997	0.858	0.920	0.888	0.995	0.906	0.949	0.848	0.966	0.903	0.934
W/O Stage 1&2	0.992	1.000	0.996	0.853	0.882	0.868	0.995	0.906	0.949	0.897	0.897	0.897	0.927
W/O Stage 3	0.993	0.999	0.996	0.704	0.776	0.738	1.000	0.684	0.812	0.958	0.793	0.868	0.854
LogLLM	0.994	1.000	0.997	0.861	0.979	0.916	0.992	0.926	0.958	0.966	0.966	0.966	0.959



(a) Precision



(b) Recall


 (c) F₁-score


(d) Training time

Fig. 4: Impact of minority class oversampling.

contrast, for the Liberty dataset, when β increases, normal samples are oversampled, making the model more prone to identifying samples as normal.

As illustrated in Fig. 4c, the trend of the F₁-score is basically the same across all datasets. The F₁-score increases and then decreases as β increases. However, the LogLLM seems not to be sensitive to β ; when β is between 10% and 80%, the variation in the F₁-score is no more than 0.07. Thanks to the substantial semantic knowledge embedded in LLMs, a trained model can effectively learn anomalous patterns and detect anomalies, even when the minority class constitutes only 10% of the dataset. However, LogLLM appears unable to effectively handle extremely imbalanced scenarios. For instance, in the Thunderbird dataset, anomalies constitute only 1.05% of the

samples, causing the trained model to be biased and classify all samples as normal. As a result, precision, recall, and F₁-score are all equal to 0.

Compared to the BGL and Thunderbird datasets, the precision, recall and F₁-score for the HDFS and Liberty datasets exhibit minimal variation with respect to β . This consistency arises from the more distinct patterns between abnormal and normal samples in the HDFS and Liberty datasets, allowing LogLLM to easily differentiate them, regardless of the ratio of normal and abnormal samples.

As anticipated, as β increases, the training time also increases, as shown in Fig. 4d. This relationship arises because a higher β leads to more oversampled data samples, as indicated by equation (1), thereby enlarging the training dataset.

To summarize, minority class oversampling is essential;

however, the value of the hyperparameter β does not significantly impact the performance of LogLLM, making careful selection unnecessary. Moreover, excessively large values of β are undesirable, as they result in prolonged training times. Values between 30% and 50% are deemed acceptable.

VI. CONCLUSION

In this paper, we propose LogLLM, a novel log-based anomaly detection framework that leverages LLMs. LogLLM employs both transformer encoder-based and decoder-based LLMs, specifically BERT and Llama, for log-based anomaly detection. BERT is utilized to extract semantic vectors from log messages, while Llama is used to classify log sequences. To ensure coherence in log semantics, we introduce a projector that aligns the vector representation spaces of BERT and Llama. LogLLM is trained using an innovative three-stage procedure designed to enhance both performance and adaptability. Extensive experiments conducted on four public real-world datasets demonstrate that LogLLM achieves remarkable performance. Subsequent ablation studies further confirm the effectiveness of our three-stage training procedure.

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