

Practical Binary Code Similarity Detection with BERT-based Transferable Similarity Learning

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ABSTRACT

Binary code similarity detection (BCSD) serves as a basis for a wide spectrum of applications, including software plagiarism, malware classification, and known vulnerability discovery. However, the inference of contextual meanings of a binary is challenging due to the absence of semantic information available in source codes. Recent advances leverage the benefits of a deep learning architecture into a better understanding of underlying code semantics and the advantages of the Siamese architecture into better BCSD.

In this paper, we propose BINSHOT, a BERT-based similarity learning architecture that is highly transferable for effective BCSD. We tackle the problem of detecting code similarity with one-shot learning (a special case of few-shot learning). To this end, we adopt a *weighted distance vector* with a *binary cross entropy* as a loss function on top of BERT. With the prototype of BINSHOT, our experimental results demonstrate the effectiveness, transferability, and practicality of BINSHOT, which is robust to detecting the similarity of previously unseen functions. We show that BINSHOT outperforms the previous state-of-the-art approaches for BCSD.

CCS CONCEPTS

• Security and privacy → Software security engineering; Software reverse engineering.

KEYWORDS

Binary Analysis, Similarity Detection, Deep Neural Network

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1 INTRODUCTION

Today, software arguably plays a pivotal role in operating billions of computing systems around us, including desktops, laptops, workstations, mobile phones, cloud servers, and IoT (Internet of Things) devices. Each program comprises a collection of instructions, routines, and data associated with a certain task, most of which (e.g., off-the-shelf applications) are distributed as an executable binary form. Albeit the surge in programs' complexity and size, software development has been evolving in a simplified manner with a myriad of well-designed libraries, toolkits, modules, and frameworks available. While code reuse benefits from high productivity and handy code maintenance, it comes along with unforeseen threats such as copyright infringement [90], the prevalence of malware variants [5], and vulnerable code reproduction [43].

Binary code similarity detection (BCSD) is the task of determining whether a pair of code snippets (*i.e.*, assembly function) is similar when the original source code is unavailable. The task serves as a basis for a wide range of applications, including code clone detection [19, 20, 23, 24, 26, 40, 46, 63, 65, 79, 88, 92, 96, 97, 100], malware detection [1, 6, 8, 44, 53, 55, 98], malware family classification [38, 47, 59], known vulnerability discovery [10, 81, 93], and code patching [29, 39, 94]. However, the inference of contextually underlying meanings from a stripped binary is non-trivial because ① a complex compilation process eliminates lots of semantic information (e.g., variable name, structure, type, class hierarchy) with massive transformations, ② the form of (semantically equivalent) binaries can vary depending on compilers, compiler versions, compiler optimizations, architectures, or even obfuscation techniques, and ③ it is undecidable to prove that two arbitrary programs are functionally equivalent (*i.e.*, Halting Problem [83]).

To tackle a BCSD problem from such dynamic nature of binary code generation, early works adopt static approaches with diverse algorithms, including graph isomorphism detection [3, 25, 101], symbolic execution [30, 63], or data flow analysis [19, 20, 74], which helps extract useful information such as instructions, control flow, and data values. Another direction utilizes dynamic

approaches [9, 26, 45, 47, 66, 67, 73, 89] by observing a binary execution to understand the code semantics better; however, it often suffers from poor scalability and incomplete code coverage.

Meanwhile, with the rise of machine learning (ML) techniques, various ML-based approaches have been proposed [23, 24, 28, 60, 64, 65, 84, 92, 95, 100] in the field of BCSD. Moreover, recent advancements (e.g., deep learning) in the area of natural language processing (NLP) inspire the inference of machine-interpretable code [23, 24, 65, 100], which repeatedly demonstrates noticeable results. For example, InnerEye [100] views an assembly instruction, a basic block, and a function as a word, a sentence, and a paragraph, respectively. Lately, the emergence of the BERT architecture [22] and its descendants [54, 61, 78] assists in better deduction of the underlying context. A handful of approaches [51, 57, 73, 88, 96] leverage BERT into various downstream tasks, including BCSD.

The essence of a BCSD problem with ML-based approaches is to learn a similarity metric from data so that a model appropriately determines the similarity of a (previously unseen) new sample. As the number of semantically equivalent binary codes is limited to learn, learning a similarity metric is a suitable approach (e.g., a Siamese neural network) for an N -way k -shot classification problem (i.e., N classes with k examples of each). A number of prior approaches [10, 57, 60, 64, 65, 73, 84, 88, 92, 95, 96, 100] utilize a Siamese neural network [4, 11], which computes a similarity score with a distance function that represents the proximity of two vectors (e.g., function embeddings). Taking it to the next level, we view a task of identifying semantically analogous code as an N -way *one-shot classification problem* (i.e., one-shot learning), a special case ($k = 1$) of an N -way k -shot classification problem (i.e., few-shot learning in §2). In particular, it fits into a practical scenario that seeks the presence of a particular function in a pre-built database.

In this paper, we propose BINSHOT, a BERT-based transferable similarity learning architecture (with a Siamese neural network) for effective BCSD. Although the concept of BERT and Siamese is common for binary similarity detection, our finding reveals that both a distance function and a loss function within an architecture highly affect the performance of a model. Notably, our main contribution is to suggest to learn a *weighted distance vector* with a *binary cross entropy loss function* (suggested by Koch et al. [50]), while the existing models solely learn a *distance itself* [10, 57, 60, 65, 73, 88, 92, 96, 100]. Leveraging BERT, we take two-phase training: pre-training for building a generic model with assembly code, followed by fine-tuning for building a downstream model for a BCSD task. The adoption of BERT inherently enhances the robustness of a model for *unseen functions* by learning the relationships between an assembly code (i.e., pre-training), adjusting it well into a BCSD task (i.e., fine-tuning). Note that one of the popular loss functions is a contrastive loss [11] used in previous learning-based approaches [10, 57, 60, 65, 92, 100].

We implemented a full-fledged prototype of BINSHOT that consists of four components: ① pre-processor for learning preparation, ② pre-trainer for building a machine code model, ③ fine-tuner for building a code similarity model, and ④ predictor for detecting binary similarity with a given code snippet (i.e., function). We build 1,400 binaries from varying source code, which contains around 1.77 million functions. Our evaluations for both effectiveness and

transferability demonstrate that BINSHOT surpasses previous state-of-the-art models for detecting binary code similarity, including Gemini [92], Asm2Vec [23], PalmTree [57], and DeepSemantic [51]. Further, we set up a realistic scenario that detects vulnerable functions. Surprisingly, previous approaches [23, 51, 57, 92] reveal a quite low accuracy ($< 15\%$) due to large false positives, remaining their practicality questionable. Finally, we visualize how BINSHOT can distinguish a binary function from a (dis)similar one.

The following summarizes the contribution of our paper:

- We propose BINSHOT that learns a weighted distance vector with a binary cross entropy atop the BERT-based Siamese architecture for BCSD.
- We design and implement the prototype of BINSHOT. We have open-sourced BINSHOT¹ to foster the area of BCSD in the future.
- We evaluate BINSHOT to present its effectiveness, transferability, and practicality by comparing it with state-of-the-art baseline models.
- We demonstrate that BINSHOT represents similar embeddings well in a vector space via visualization.

2 BACKGROUND

BERT. BERT [22] is a transformer-based ML architecture that originates from the domain of NLP. The Transformer [86] architecture gains high popularity in text processing tasks with noticeable results. It adopts ① the self-attention mechanism that aims to infer contextual information per each word (considering a position) within the input sentence, and ② the design that allows for parallel processing during training on a large volume of a dataset, which reduces training time over sequential processing like Long Short-Term Memory (LSTM) [37]. The BERT architecture leverages a careful design choice from the Transformer’s encoder (e.g., multi-head self-attention) into various downstream applications with two major phases (i.e., pre-training and fine-tuning). First, the pre-training of BERT aims to capture both token-level and sentence-level contextual information, building a generic model that contains embedding vectors of each token. A final input embedding representation considers a position (e.g., location of a word in a sentence) and a segment (e.g., a sentence that a word belongs to) as well as a token itself. For capturing hidden context from a sentence, pre-training performs two sub-tasks: masked language modeling (MLM) and next sentence prediction (NSP). MLM randomly masks a certain portion of tokens in a given sentence (e.g., 15% in the original BERT scheme), exploiting unlabeled data (i.e., masked positions) to yield labels (i.e., original tokens). The special token, [CLS], is placed at the beginning of every input, where [SEP] represents a token separator so that two sentences can be concatenated as a single input. Meanwhile, NSP predicts if the next sentence pertains to the current one. Note that pre-training does not require a laborious labeling process (i.e., unsupervised learning), creating a generic model to be served as a base knowledge layer to build from. Second, the fine-tuning phase of BERT improves a generic model by retraining weights with another dataset for a specialized user-defined task (i.e., supervised learning), which allows for being adjusted to task-oriented contextual representations. In this paper,

¹<https://github.com/asw0316/binshot>

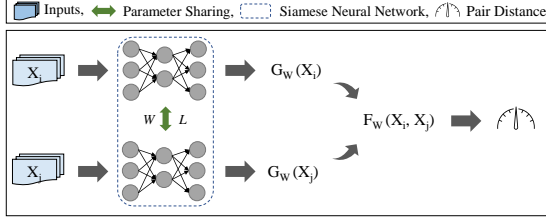


Figure 1: A popular loss function in a Siamese neural network (NN): a contrastive loss (L_c) using a twin NN. G , F , X , and W denotes an output vector, similarity metric, input, and weight, respectively.

we build a pre-trained BERT model for binary code representation and a fine-tuned model for BCSD as a downstream task.

Siamese Neural Network. A Siamese neural network [4] was first introduced for verifying signatures, in which multiple identical sub-networks extract features from multiple inputs while training. The gist of the Siamese neural network is to compute a *distance function* that represents how two feature vectors are close together; that is, a set of similar inputs should be encoded as adjacent as possible, whereas that of dissimilar inputs should be placed as far as possible. Unlike traditional approaches (e.g., support vector machines) that require known labels ahead of training time for a classification problem, the architecture is suitable for which there are a large number of unknown categories with a limited number of datasets at the time of training [49]. More precisely, we can formally define a *similarity metric* (F_W) between two inputs (X_i and X_j) with a distance function (D), where $G_W(X)$ represents an output vector in a neural network that is parameterized by weight (W) as follow:

$$F_W(X_i, X_j) = D(G_W(X_i), G_W(X_j)) \quad (1)$$

The distance function in Equation 1 between two n -dimensional vectors may vary [68], including an L1 norm, L2 norm, or cosine distance. The similarity metric can be learned by seeking W that minimizes a loss function over a training set. With a distance function, a Siamese neural network regards the resulting distances as the degree of two inputs' similarity. A Siamese neural network relies on a pre-defined loss function as well as a distance function that one chooses from. The following exemplifies one of the popular loss functions (Figure 1), contrastive loss (L_c in Equation 2). A contrastive loss minimizes the distance of positive pairs while maximizing the distance of negative pairs. Note that Y represents a label (0 or 1) for the pair of inputs (X_i, X_j).

$$L_c(W, Y, X_i, X_j) = Y \frac{1}{2} (F_W)^2 + (1 - Y) \frac{1}{2} (\max(0, 1 - F_W))^2 \quad (2)$$

Few-shot Learning. Few-shot learning differs from classical supervised learning in that it aims to *learn how to learn* (e.g., two objects are alike) instead of letting a model directly recognize a label (e.g., an object is a dog). The main idea [4, 11, 50, 80] stems from computer vision tasks, which are inspired by a human capability that learns a new object based on previously acquired information with a limited number of instances. In general, classifying N classes with k samples per each category (i.e., few samples) is known as an N -way k -shot classification problem. Simply put, a dataset is divided into two mutually exclusive sets: a support set ($N \times k$) for training and a query set for testing, followed by learning similarity

between feature vectors. A Siamese neural network is one of the few-shot learning enablers, which fits well into BCSD. Ideally, a well-learned model from other function pairs can successfully identify a distance from a given (possibly unseen) function pair with the model.

3 BINARY CODE SIMILARITY DETECTION

Problem Definition and Scope. A BCSD task is defined as identifying the proximity of two or more machine codes (i.e., assembly) when source code is unavailable. The task may vary depending on different aspects of code comparison. For instance, the comparison granularity of a code snippet can be an entire program, function, basic block, or even instruction. One may view the detection task as a code search problem, in which the number of code pieces can be one-to-one, one-to-many, or many-to-many. Furthermore, binary code may hold equivalent semantics with diverse code transformations from different compilers, different compiler options/versions/optimization levels, different architectures, and obfuscations. Meanwhile, it may represent similar semantics with distinct updates from different source code versions or bug fixes (patches). In this work, we deal with detecting similar code snippets whose transformation solely originates from *cross-compiler* and *cross-optimization-levels* for the `x86_64` architecture. We seek a similar binary *function pair* from a prepared function corpus (*one-to-many* setting) in practice.

Open Challenges. The dynamic nature of diversified binary code generation inevitably makes BCSD quite challenging. It is undecidable to prove that two arbitrary programs are functionally and semantically equivalent (i.e., Halting Problem [83]). Note that our methodology is agnostic to other transformations from compiler options or versions; however, we deliberately do not consider the differences in code semantics from cross-source-versions (e.g., updates, bug repair) due to the absence of quantitative metrics for the semantic gap. Another challenge arises from code obfuscation techniques that often blur the original semantics with packing, random code insertion, customized virtual machines, etc.

4 BINSHOT DESIGN

4.1 BINSHOT Overview

Figure 2 illustrates the whole workflow of BINSHOT, which mainly consists of four components as follows:

Pre-processor. With a binary corpus, we prepare a dataset that can be readily fed into a BERT model for training (①). Using a reverse engineering tool, we obtain all disassembled instructions. Next, we convert a naïve instruction into a concise form (Table 4 in Appendix A), building the database of normalized functions (NFs) with normalization rules proposed by DeepSemantic [51].

Pre-trainer. Once all NFs are ready, we build a generic BERT model with pre-training, being able to emit an embedding per function (②). Note that a generic BERT model learns the relationship between instructions, which makes the final model robust against unseen functions. Akin to NLP's pre-trained language models, this model for an assembly language allows for repurposing it to varying downstream tasks.

Fine-tuner. Next, we re-train the pre-trained model (i.e., fine-tuning) to meet our purpose; BCSD (③). To this end, we prepare

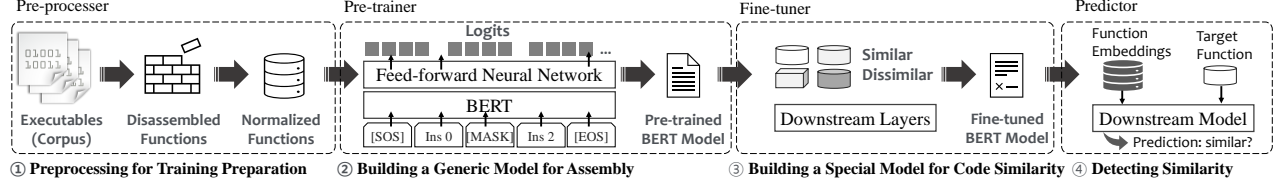


Figure 2: The overall workflow of BinSHOT that consists of four components: ① a pre-processor (§4.2) that generates a dataset in preparation for training, ② a pre-trainer (§4.3) that builds an assembly representation model (i.e., pre-trained BERT), ③ a fine-tuner (§4.4) that constructs a BCSD model (i.e., fine-tuned BERT), and ④ a predictor (§4.5) that judges the similarity of a target function.

another dataset with function pairs and their labels for a BCSD task. The fine-tuned model predicts if a function is analogous to another. **Predictor.** As a final step, using the fine-tuned BERT, we build a database that contains all function vectors of our interest for further comparison (④). A downstream model takes a function pair as an input, seeking any similar function with a series of predictions.

4.2 Preprocessor: Learning Preparation

A pre-processing step encompasses a conversion needed to feed a wide range of collected executable binaries (See Table 1) into a neural network, including disassembly and normalization.

Disassembly Process. We first disassemble every instruction in a code region of each executable with a state-of-the-art reversing tool (e.g., IDA Pro [35]). We generated the whole binary corpus with debugging information available (e.g., obtaining function boundaries) for training a better model with accurate disassembly. Note that we assume a stripped binary for further testing.

Well-balanced Instruction Normalization. Feeding machine instructions as they are into a neural network raises an out-of-vocabulary (OOV) problem because the number of possible tokens (i.e., an opcode, operands, or a combination of both) would be prohibitively huge. For example, a four-byte immediate value or a relative address as an operand could hold $2^{32} - 1$ (i.e., around four billion) different tokens. A large number of OOV may end up incurring the failure of meaningful input embedding generation. In this regard, we adopt a strategy of well-balanced instruction normalization that is introduced by DeepSemantic [51], which strikes a balance between expressing binary code representation that preserves the original semantics while maintaining a reasonable amount of tokens to avoid OOV (Interested readers refer to Appendix A).

4.3 Pre-trainer: Model for Assembly

BinSHOT adopts a BERT-based model (but NSP) that conforms to two-step training; the first one is pre-training (② in Figure 2) that plays a role to train a generic model for assembly codes.

MLM task. We take the identical strategy with the original BERT, replacing 15% of input tokens (instructions) with a mask symbol (i.e., [MASK] token). The parameters of MLM, θ_m , are optimized by solving the following optimization problem:

$$\theta_m = \underset{\theta_m}{\operatorname{argmin}} \sum_{t \in T} p(t|y) \log p(t|\hat{y}) \quad (3)$$

$$\hat{y} = \operatorname{Softmax}(G_m(X)) \quad (4)$$

where t , T , y , and \hat{y} denote a token, a set of tokens, an original token before masking, and a predicted token for MLM, respectively.

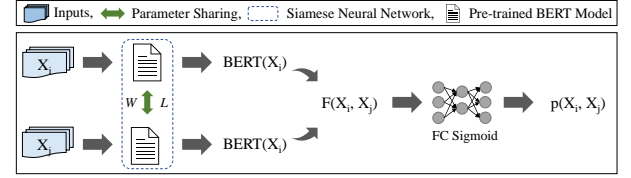


Figure 3: Siamese neural network for building a BCSD model. Our model learns a weighted distance vector from a labeled dataset (i.e., a set of two functions and a label). X , W , L , F , FC , and p represent an input, weights, loss, distance vectors, a fully connected layer, and the probability of code similarity.

$G_m(X)$ represents the output vector of a fully connected layer from an MLM classifier with an input function X . At a high level, MLM learns to predict an appropriate token in place of a masked token, aiding in capturing the context between individual instructions.

Alternatives to an NSP task. We exclude NSP from the original BERT architecture because, unlike a neighboring sentence in NLP, the relationship between functions is determined by a function invocation rather than their locations, rendering the next function prediction (i.e., NSP) pointless. Although we do not directly take a function call into account, well-balanced instruction normalization implicitly deals with a significant `libc` call by defining it as a separate word. Otherwise, the normalization process recognizes either external library calls (e.g., throughout PLT; procedure linkage table, and GOT; global offset table) or internal function calls (e.g., other functions defined within an executable). Besides, it views an indirect call (e.g., `call reg8`) or recursive call (e.g., `call self`) as a distinguishing instruction for better contextual inference.

4.4 Fine-tuner: Model for Code Similarity

Based on a generic BERT model with a large swath of binaries, we define a downstream task (③ in Figure 2); BCSD. To this end, we leverage a Siamese neural network into a classifier, learning a weighted distance from a labeled dataset (i.e., $(NF_1, NF_2, \{0,1\})$ where 1 for a similar pair and 0 for a dissimilar one). Figure 3 illustrates the Siamese architecture for the fine-tuner in BinSHOT. The following equation shows how to compute a distance vector ($F(X_i, X_j)$) between two function embeddings based on the BERT model ($BERT(X)$) where D represents a distance function such as an element-wise absolute error ($k=1$) or a squared error ($k=2$).

$$D(X, Y) = (x_i - y_i)^k, F(X_i, X_j) = D(BERT(X_i), BERT(X_j)) \quad (5)$$

Then, our binary classifier learns a *weighted distance vector* with the following *binary cross entropy loss function*:

$$L = Y \log p(X_i, X_j) + (1 - Y) \log(1 - p(X_i, X_j)) \quad (6)$$

$$p(X_i, X_j) = \sigma(FC(F(X_i, X_j))) \quad (7)$$

where Y is a label for (X_i, X_j) . $FC(X) = WX + b$ represents the output vector of a fully connected layer with weights (W), and σ means a Sigmoid function ($\sigma(z) = \frac{1}{1+e^z}$), ranging from 0 to 1 for the probability of the code similarity with a function pair $(p(X_i, X_j))$.

Loss Function. It is noteworthy mentioning that we carefully choose an appropriate loss function for a BCSD task. One of the common scenarios is to search for a certain function or a series of particular functions of one's interest. Assuming that each function has a single sample, the task of identifying semantically analogous code is aligned with an N -way one-shot classification problem, which is a special case ($k = 1$) of an N -way k -shot classification problem (See §2). In essence, we employ a *weighted distance learning with the Siamese architecture* that has been proposed by one-shot learning [50], which defines a loss function as a binary cross entropy for binary classification. In the same vein, we solve an optimization problem with the loss function (Equation 6), seeking the optimized parameters (θ_d) for a downstream model. Meanwhile, previous learning-based BCSD models [10, 57, 60, 65, 92, 100] often employ a contrastive loss L_c [11]. We empirically confirm that BinSHOT equipped with our loss performs better for the inference of an unseen function (See §6) than other state-of-the-art BCSD models.

4.5 Predictor for BCSD

With the fine-tuned model for BCSD, a predictor (④ in Figure 2) takes a function pair as an input; one as a target function to compare with, and the other from a database. Note that a look-up process could speed up by i) pre-computing function embeddings in the database and ii) inserting unseen function vectors into the database. Once the predictor acquires two function vectors with $BERT(X_i)$ and $BERT(X_j)$, it computes a probability according to Equation 5 and Equation 7. BinSHOT is trained to adjust the output to be 0 (negative) or 1 (positive) as it applies a Sigmoid function for obtaining a final output. Therefore, we set $p = 0.5$ as a threshold to determine if the two functions are similar.

5 IMPLEMENTATION

Static Binary Analysis. We leverage one of the state-of-the-art binary reverse engineering tools, IDA Pro 7.6 [35], into disassembling binaries and extracting fruitful static binary information. We wrote a script with built-in IDAPython APIs [34] that can extract a list of assembly functions, cross references (*i.e.*, call graph), section names, string references, and external library calls, facilitating further instruction normalization. Other binary reverse engineering tools such as angr [2], Ghidra [70], or radare2 [77] would suffice for our static analysis purpose.

BinSHOT Implementation. We develop BinSHOT with PyTorch [76], one of the most popular frameworks for ML. At the heart of BinSHOT, we implement the prototype using BERT [22, 32, 41, 91] and a Siamese neural network [50]. For a distance function described in §2, we adopt an squared error that generates a distance vector as an output because our experiment shows that overall

Table 1: Our binary corpus. We build 1.4K binaries that contain 1.77M functions, obtaining 18K unique tokens after the well-balanced instruction normalization process.

Dataset	Binaries	Functions	Basic blocks	Instructions	Tokens
GNU utilities	1,000	439,036	3,965,532	22,137,920	1,244
SPEC2006	176	407,277	4,661,761	28,307,441	9,631
SPEC2017	120	755,297	9,336,587	52,940,593	11,932
Real-world programs	104	169,065	2,422,651	14,269,468	8,892
Total	1,400	1,770,675	20,386,531	117,655,422	18,449

performance with the squared error was slightly better than that with an absolute error. We heuristically pick the following hyperparameters that demonstrate the best performance: the 256 dimensions for instruction embeddings, 128 hidden layers, eight attention layers and heads (for the Transformer structure), 256 maximum length of tokens, and three token encoder layers. We use the Adam optimizer [48] with a learning rate of 0.0005 and the dropout algorithm [36] for both pre-training and fine-tuning. The dropout rate is 0.2 for token encoder layers and 0.1 for the other layers. We employ a linear learning rate warm-up strategy [62] and a gradient clipping strategy [72] for stable training results. The number of parameters for building the BinSHOT model is 6,815,362. We train BinSHOT for 20 epochs with a batch size of 32.

6 EVALUATION

Prior BCSD studies with ML-based approaches predominately focus on effectiveness (*i.e.*, accuracy, F1 score) and efficiency (*i.e.*, runtime performance). In this paper, we attempt to evaluate BinSHOT in terms of practicality by reasoning dataset generation and usefulness of a result by closely looking into interesting cases as well as previous metrics. To this end, we define two different test sets to compare BinSHOT with baseline models. Additionally, we demonstrate that a group of similar function embedding vectors are indeed close together in a space with a visualization technique (*i.e.*, t-SNE [85]).

Environment. We evaluate BinSHOT on the server equipped with two Intel Xeon Gold 6226R CPUs (with 32 cores in total) running at 2.90 GHz, 256 GB RAM, and two NVIDIA RTX A6000 GPU cards. Note that we had a single GPU card for performance assessment.

Evaluation Metrics. We use the following metrics for BinSHOT: a precision (P), recall (R), F1 score (F), and accuracy (A) where TP , FP , TN , and FN are the number of true positive, false positive, true negative, and false negative cases, respectively.

$$P = \frac{TP}{TP + FP}, R = \frac{TP}{TP + FN}, F = \frac{2 \times P \times R}{P + R}, A = \frac{TP + TN}{TP + TN + FN + FP} \quad (8)$$

6.1 Dataset

Binary Corpus. Table 1 summarizes our corpus for evaluation. We collect varying applications in our corpus: executable binaries from GNU utilities, SPEC2006, SPEC2017, and real-world programs of our choice. GNU utilities include `binutils` (v2.26), `coreutils` (v8.30), `diffutils` (v2.8), and `findutils` (v4.7.0) that have been extensively evaluated in previous works [3, 9, 19–21, 23, 24, 26, 28, 51, 57, 60, 65, 73, 74, 89, 93, 100]. SPEC2006 and SPEC2017 provide a series of standardized CPU-intensive benchmark suites. We also gather 11 real-world programs that

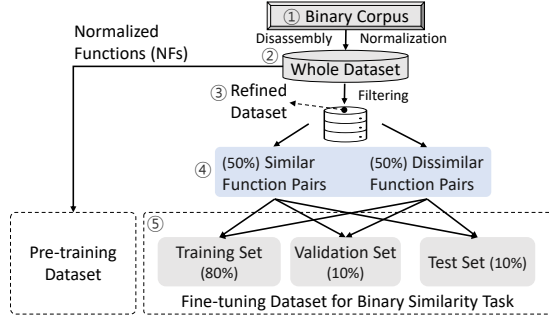


Figure 4: Dataset generation for similarity learning. All normalized functions from the raw binary corpus (①) constitute the whole dataset (②) for pre-training. We refine a dataset (③) by filtering out too small/large functions, followed by generating function pairs (④), splitting them into a training, validation, and test set (⑤).

are available as popular open-source projects from Github, including BusyBox (v1.34.1) [7], Libgmp (v6.2.1) [31], ImageMagick (v7.0.10) [42], Libcurl (v7.78.0) [18], LibTomCrypt (v1.18.2) [58], OpenSSL (v1.1.1f) [71], SQLite (v3.30.1) [82], zlib (v1.2.8) [99], PuTTYgen (v0.76) [75], Nginx (v1.16.1) [69], and vsftpd (v3.0.3) [87]. With two different compilers (*i.e.*, GCC v5.4, Clang v6.0.1) and four different compiler optimization levels (*i.e.*, O0–O3), we generated 1,400 executable binaries as a whole.

Refining Dataset. We refine our dataset (③ in Figure 4) before creating similar and dissimilar function pairs by filtering out certain functions depending on the size of a function (*i.e.*, the number of instructions within). Namely, we set up a threshold of two outliers: too small function where the number of instructions is less than or equal to m , and too large function where that of instructions is greater than n . The rationale behind this decision is that i) too small function may not often return a semantically meaningful result, ii) chances are slim that a target function (*e.g.*, containing a vulnerability) is too trivial, and iii) BERT has a limitation to handle too long sequences (*i.e.*, large function) while training. For our experiment, we set $m = 5$ and $n = 250$ in BINSHOT, which can be adjustable. In our dataset, the proportions of too large functions and too small functions are 4.66% and 16.47%, respectively.

Dataset Generation for Learning. Figure 4 depicts an overview of generating the whole dataset (②) from a binary corpus (①), which can be fed into the BERT architecture. Borrowing the well-balanced instruction normalization strategy [51], the whole 117,655,422 instructions (from 1,770,675 functions) result in 18,449 vocabularies (§4.2). Because each vocabulary is dealt with as a token, we obtain 18,454 tokens, including five special ones for BERT: [SOS]; start of a function, [EOS]; end of a function, [UNK]; unknown token, [MASK]; mask symbol, and [PAD]; padding symbol. Recall that a pre-trainer builds a generic BERT model with the pre-processed dataset (*i.e.*, NFs). Once the instruction normalization step is complete, we create a set of similar and dissimilar function pairs for fine-tuning. We define a function pair to be similar two function names are identical from a binary built with either a different compiler or optimization level. We exclude the cases where a pair of function bodies are identical after instruction normalization because it causes a distance of 0 in the Siamese neural network, which

Table 2: Summary of a distance function, loss function, and architecture for baseline models, BINSHOT, and its variant (*). GNN and PV-DM represent Graph Neural Network and Distributed Memory Model of Paragraph Vectors.

Model	Distance Function	Loss Function	Architecture
Gemini	Cosine distance	Contrastive loss	GNN, Siamese NN
Asm2Vec	Cosine distance	Log probability	PV-DM
PalmTree	Cosine distance	Contrastive loss	BERT, GNN, Siamese NN
DeepSemantic	None	Cross entropy	BERT, Softmax classifier
BINSHOT-CTR*	L2 norm	Contrastive loss	BERT, Siamese NN
BINSHOT	Weighted squared error	Binary cross entropy	BERT, Siamese NN

hinders the training process (*e.g.*, Figure 8 in Appendix A). For example, the function `openat_safer` (from `mkdir`) compiled with `gcc` and `O1` and the one compiled with `clang` and `O2` are similar as long as two function bodies after normalization are disparate. We adopt negative sampling (with the ratio of 1:1) for dissimilar function pairs, selecting different functions from different binaries. In our experiment, we create 5,259,310 function pairs in total (④ in Figure 4). We split the whole pairs into three disjoint groups for training, validation, and test dataset with the ratio of 8:1:1, while maintaining half and half for similar and dissimilar pairs.

OOV. In our setting, there are unique 18,280 tokens in a training set and 16,166 tokens in a test dataset. The 64 tokens were merely discovered in a test set (*i.e.*, missing them in a training set), in which OOV accounts for 0.40% of the whole tokens.

6.2 Effectiveness

In this section, we evaluate the effectiveness of BINSHOT with previous BCSD approaches using deep learning techniques. Table 2 summarizes a distance function, loss function, and architecture for each approach, which largely impacts performances.

Baseline. As a baseline, we assess varying state-of-the-art BCSD models, including Gemini [92], Asm2Vec [23]², PalmTree [57], and DeepSemantic [51]. In the case of PalmTree, we leverage the pre-trained model that is publicly available [56] to build a downstream model with our datasets for comparison. We follow the hyperparameters from the original implementations unless otherwise stated.

BINSHOT Variant. To show the effectiveness of a loss function, we additionally generate a BINSHOT variant, BINSHOT-CTR, which adopts a contrastive loss (Equation 2) with an L2 norm as a distance function (Equation 1).

Similarity Threshold. We choose a threshold for similarity prediction that maximizes an F1 score in the case of Gemini [92], Asm2Vec [23], PalmTree [57], and BINSHOT-CTR (Appendix B).

Test Set Evaluation. Recall that the test set (§6.1) contains the same rate of similar and dissimilar function pairs. Figure 5 demonstrates the effectiveness of BINSHOT, compared with four baseline models (Gemini [92], Asm2Vec [23], PalmTree [57], DeepSemantic [51]) and the BINSHOT variant model (BINSHOT-CTR). We measure an accuracy, precision, recall, and F1 score with i) the whole dataset and ii) the datasets that are separated with all 36 combinations across different compilers and optimization levels (*e.g.*, (gcc-O0, gcc-O0), (gcc-O0, clang-O0), ..., (clang-O3, clang-O3)). Note

²As the original implementation [23] runs on the Windows platform, we adopt a version from <https://github.com/oalieno/asm2vec-pytorch> for handy comparison.

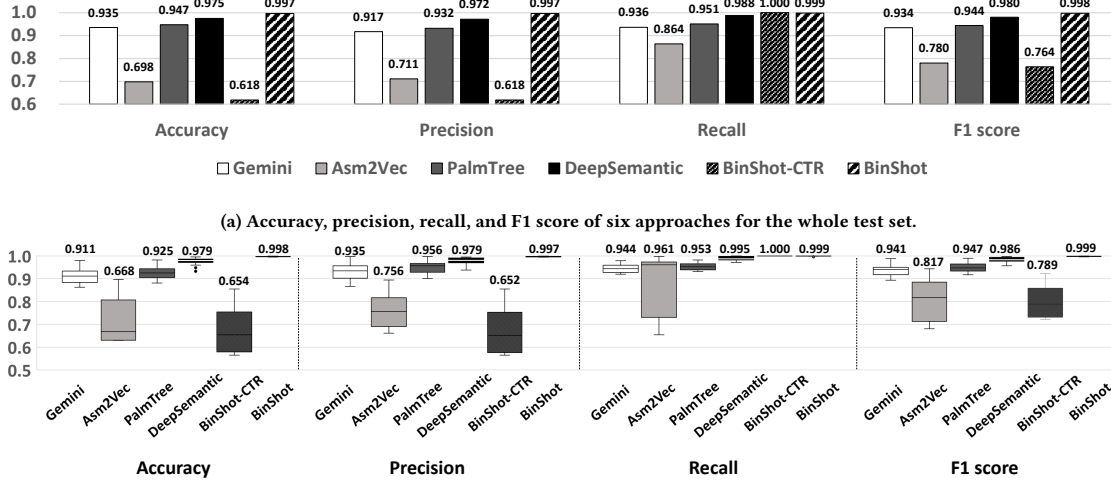


Figure 5: Results of BCSD comparison with the test set. BINSHOT surpasses the others with the lowest variations in accuracy and F1 score.

that the latter dataset is designed for a better understanding of the impact of different configurations (*i.e.*, cross-compilers, cross-optimization-levels) to deduce code similarity. Figure 5a clearly shows that BINSHOT outperforms all other state-of-the-art models for BCSD. Likewise, Figure 5b supports that the performance of BINSHOT stays stable with a low variance regardless of any combination of a compiler and optimization level. We hypothesize that learning a weighted distance helps BINSHOT outperform other models because BINSHOT can understand a relationship among all elements of distance vectors, rendering a sophisticated inference feasible. Meanwhile, other models oversimplify a relationship between the two functions based on a scalar value (*i.e.*, distance from feature vectors of them). It is also noted that the performance gap between BINSHOT and BINSHOT-CTR arises from different distance functions rather than loss functions.

6.3 Transferability

This section delineates empirical results of model transferability; specifically, we raise the following research questions: ① how well is the model learned from a dataset X capable of inferring binary similarity in another dataset Y ? and ② which state-of-the-art model performs the best? The higher transferability means that a model is more generalizable or scalable. Note that our transferability experiment attempts to answer that a certain model could be generalizable when applying it to a completely different binary group (rather than a compartmentalization of train, validation, test) in practice.

Experimental Setup. We conduct another experiment that utilizes a binary corpus from SPEC2006 and SPEC2017 (Table 1), building two fine-tuned models with BINSHOT because they contain the largest number of functions that could be further generalizable. Likewise, using Gemini [92], Asm2Vec [23], PlamTree [57], DeepSemantic [51], and BINSHOT-CTR, we build twelve different models with the same dataset (*i.e.*, SPEC2006, SPEC2017). Then, we have each model infer similarity with unseen datasets (*i.e.*, GNU utilities,

real-world programs). Figure 6 briefly shows the results of inference across different models, including accuracy, precision, recall, and F1 score. As seen in both Figure 6a and Figure 6b, we observe that BINSHOT mostly achieves better performance than others but GNU utilities. Namely, the accuracy and F1 score with the BINSHOT model are higher than those with four baseline models and the BINSHOT variant; for example, the F1 score for real-world programs (rightmost bar in Figure 6b) when applying transfer learning from SPEC2017 indicates the best performance of all.

Results. We obtain the following insights with our experimental outcomes: ① a fine-tuned model with BINSHOT could be applicable to other (unseen) datasets in general, indicating that a weighted distance learning with a Siamese neural network appropriately works as intended, ② training and test set have evenly distributed based on Figure 6a and Figure 6b that are similar to Figure 5b, and ③ functions from SPEC2006 do not have largely those from SPEC2017 in common because the mutual inferences (*e.g.*, SPEC2006-based model toward SPEC2017 inferences, SPEC2017-based model toward SPEC2006 inferences) do not have much difference from the ones for real-world programs. Last but not least, BINSHOT shows relatively poor performance on GNU utilities. With a careful investigation, we found that GNU utilities have quite a few sharing functions across different binaries. This is because, `coreutils` have a static library (*i.e.*, `libc.so.6`) in common when compiling various utility programs, which inherently contain identical (normalized) functions in multiple binaries (See Appendix D). Note that our finding is aligned with the observation from Koo et al. [52].

6.4 Vulnerable Function Detection

In this section, we set up a realistic scenario that detects a vulnerable function in a binary to demonstrate the practicality of BINSHOT.

Scenario Setup. Table 3 displays three programs that contain nine vulnerable functions along with six common vulnerabilities and exposures (CVEs). Each program has eight variants generated by

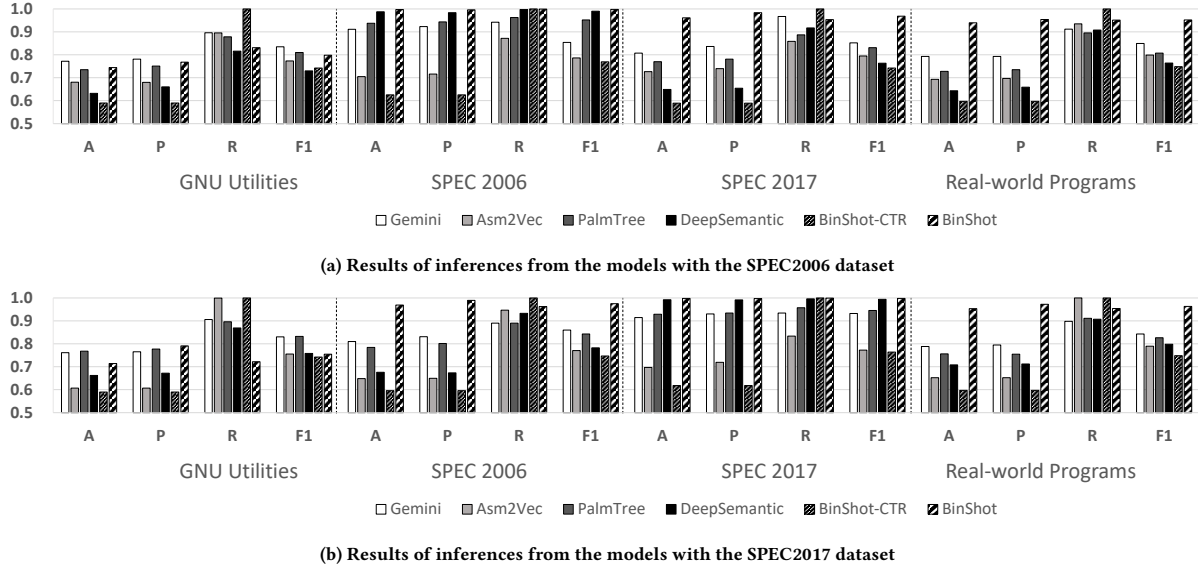


Figure 6: Results of transferability experiments. As expected, the inferences to the same dataset (e.g., SPEC2006 \rightarrow SPEC2006, SPEC2017 \rightarrow SPEC2017) are the highest values across all metrics. Empirically, BINSHOT demonstrates the best generalizable capability when applying its model to other datasets. We explain why BINSHOT shows poor performance on GNU utilities in §6.3.

Table 3: Results of detecting vulnerable functions with BINSHOT. An asterisk (*) indicates that our model includes a program (but a different version) during training. Each symbol of \checkmark and \times denotes detection success and failure, while - denotes a case that a reversing tool fails to discover a function boundary. BINSHOT achieves the best performance in the accuracy (A) and recall (R) while others show the poor accuracy.

Program	CVE	Vulnerable function	Gemini O0-O3	A/R	Asm2Vec O0-O3	A/R	PalmTree O0-O3	A/R	DeepSemantic O0-O3	A/R	BinShot-CTR O0-O3	A/R	BinShot O0-O3	A/R
OpenSSL v1.0.1e*	2014-0160 [13]	tls1_process_heartbeat	$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$	
	2014-0221 [14]	dtls1_process_heartbeat	$\checkmark\checkmark\checkmark\checkmark$	0.0033/	$\checkmark\checkmark\checkmark\checkmark$	0.1179/	$\checkmark\checkmark\checkmark\checkmark$	0.0140/	$\checkmark\checkmark\checkmark\checkmark$	0.3656/	$\checkmark\checkmark\checkmark\checkmark$	0.0033/	$\checkmark\checkmark\checkmark\checkmark$	0.9009/
	2014-3508 [15]	dtls1_get_message_fragment	$\checkmark\checkmark\checkmark\checkmark$	1.0000	$\checkmark\checkmark\checkmark\checkmark$	1.0000	$\checkmark\checkmark\checkmark\checkmark$	1.0000	$\checkmark\checkmark\checkmark\checkmark$	0.6000	$\checkmark\checkmark\checkmark\checkmark$	1.0000	$\checkmark\checkmark\checkmark\checkmark$	1.0000
	2015-1791 [17]	OBJ_obj2txt	$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$	
NTP v4.2.7p10	2014-9295 [16]	ssl3_get_new_session_ticket	$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$	
		crypto_recv	$\checkmark\checkmark\checkmark\checkmark$	0.0055/	$\checkmark\checkmark\checkmark\checkmark$	0.1588/	$\checkmark\checkmark\checkmark\checkmark$	0.0083/	$\checkmark\checkmark\checkmark\checkmark$	0.4505/	$\checkmark\checkmark\checkmark\checkmark$	0.0064/	$\checkmark\checkmark\checkmark\checkmark$	0.7940/
		ctl_putdata	$\checkmark\checkmark\checkmark\checkmark$	1.0000	$\checkmark\checkmark\checkmark\checkmark$	1.0000	$\checkmark\checkmark\checkmark\checkmark$	1.0000	$\checkmark\checkmark\checkmark\checkmark$	1.0000	$\checkmark\checkmark\checkmark\checkmark$	1.0000	$\checkmark\checkmark\checkmark\checkmark$	1.0000
libav v0.8.3	2012-2776 [12]	configure	$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$		$\checkmark\checkmark\checkmark\checkmark$	
		decode_cell_data	$\checkmark\checkmark\checkmark\checkmark$	0.0007/	$\checkmark\checkmark\checkmark\checkmark$	0.1215/	$\checkmark\checkmark\checkmark\checkmark$	0.0065/	$\checkmark\checkmark\checkmark\checkmark$	0.0003/	$\checkmark\checkmark\checkmark\checkmark$	0.0007/	$\checkmark\checkmark\checkmark\checkmark$	0.9497/
				1.0000		1.0000		1.0000		0.5000		1.0000		1.0000

two different compilers (i.e., GCC v5.4, Clang v6.0.1) and four different compiler optimization levels (i.e., O0–O3). We arrange the following three assumptions close to a real setting: ① the database of vulnerable function embeddings (compiled by GCC) of our interest has been prepared; ② the query binary is stripped, and compiled with Clang; ③ one attempts to find a vulnerable function in a query binary. Note that previous approaches [9, 10, 21, 23, 26–28, 60, 65, 73, 74, 92, 93, 95, 100] solely query a function to determine if it contains a vulnerability. However, querying a vulnerable function could suffer from accuracy in case of a number of false positive responses (e.g., say all functions are vulnerable). Instead, we allow one to find all vulnerable functions by querying an entire binary itself for a precise result. Moreover, a single CVE may entail multiple functions in practice.

Evaluation Metric. In the above scenario, similar function pairs are much rarer than dissimilar ones. Unavoidably, this imbalance may distort a few metrics even for a highly accurate model, such as a recall and F1 score. Suppose that we have S positive samples and D negative samples, and a model reaches up to $TP = 0.99 \times S$

and $FP = 0.01 \times D$ where $S = TP + FN$ and $D = TN + FP$. Also, assume that $S \approx 0.003 \times D$. Then, the precision, recall, and F1 score are approximately 0.23, 0.99, and 0.37, respectively. As shown, a large volume of negative samples can distort a precision and F1 score even for an accurate model, so we merely include accuracy and recall for the evaluation with a query binary.

Results. We assess four baselines, BINSHOT and BINSHOT-CTR with 12 query binaries from three programs compiled with Clang O0–O3. Table 3 summarizes the results of detecting a vulnerable function along with functions in our database. Note that we rule out a few vulnerable functions (e.g., `crypto_recv`, `ctl_putdata`-O3, `configure`-O1) because a reversing tool (i.e., IDA [35]) failed to recognize their boundaries in a stripped binary. Interestingly, with the thresholds in §6.2, all models but DeepSemantic [51] discover the whole vulnerable functions in the query binaries. However, only BINSHOT achieves the high accuracy (i.e., 88.2% on average) while all the others show the quite poor accuracy (i.e., less than 50%), which remains their effectiveness questionable when applying them to a real scenario in practice. This is mainly because even a

single false positive (of all comparisons in the database) returns the result as a vulnerable function, which decreases the overall accuracy. Besides, we investigate the case of NTP in Table 3; the boundary of a function was different (incorrect) from the ground truth, resulting in the relatively poor accuracy (79.4%).

6.5 Function Embedding Visualization

One of the popular means to comprehend a classification model on vast amounts of data is through visualization. Because our model relies on binary classification, it requires checking if the embeddings for a similar function pair are close enough while those of a dissimilar one is sufficiently distant. However, representing each vector in a high dimensional space (e.g., 128 dimensions in our experiment) is difficult. We utilize a t-distributed Stochastic Neighbor Embedding (t-SNE) method [85] that offers non-linear dimensionality reduction where similar data are pointed close together in a lower-dimensional space. As in Figure 7, we select five different functions that have been wrongly classified (i.e., false negative) by baseline models in §6.2, which BINSHOT has correctly classified (i.e., true positive). Note that Figure 7 shows eight different embeddings per assembly function (with a unique symbol) because each function has been compiled with a combination of two compilers and four optimization levels. Hence, the vectors representing similar functions are expected to be located nearby. Figure 7 intuitively visualizes the vectors representing similar functions generated by BINSHOT, which are indeed well clustered together. Interestingly, visualized functions other than `hmac_key` (green X mark) have two disparate groups: one comes from `gcc`, and the other from `clang`.

6.6 Runtime Efficiency

In this section, we conduct two experiments to assess runtime efficiencies of BINSHOT and other baseline models for inferring binary similarity (i.e., binary classification of a given function pair). First, we sampled 16,595 function pairs (0.28%; 99% confidence level) from all 5,884,690 pairs that include training, validation, and test sets (§6.1). As a result, Gemini [92], Asm2Vec [23], PalmTree [57], DeepSemantic [51], BINSHOT-CTR, and BINSHOT took 0.10, 81.94, 1.33, 1.34, 1.30, and 1.32 ms (millisecond) per each function pair, respectively. Other than Gemini (the fastest run) and Asm2Vec (the slowest run), all the others are similar. Next, we assume the scenario (§4.5) where one attempts to seek if any function in a target binary has a similar one in a database that contains 100 function embeddings of our interest. We pre-build the database that stores a series of (NF, NF embedding) as a (key, value) pair for a quick look-up. Then, we collect 823 functions (after refinement as §6.1) from the OpenSSL library as a target. With the above settings, we measure the running time for both function embedding generation (i.e., 823) and similarity inferences (i.e., $82,300 = 100 \times 823$) with five state-of-the-art approaches, including BINSHOT. It is noted that generating embeddings dominates runtime overheads over comparisons by look-ups. As a result, Gemini [92], Asm2Vec [23], PalmTree [57], DeepSemantic [51], BINSHOT-CTR, and BINSHOT took 1.16, 6,743.66, 29.03, 1.51, 1.45, and 1.54 seconds, respectively. While Gemini [92] ranks first, BINSHOT shows a comparable efficiency.

7 RELATED WORK

The related work in the domain of BCSD is vast [33]. We classify prior work into three categories: static [1, 3, 19–21, 25, 27, 30, 46, 55, 63, 74, 93, 101], dynamic [9, 26, 45, 47, 66, 67, 73, 89], and ML-based [10, 23, 24, 28, 51, 57, 60, 64, 65, 73, 84, 92, 95, 96, 100] approaches.

Static Approaches. In the era of non-ML techniques, the main static approaches in the field of BCSD utilize graph isomorphism detection [3, 25, 101], symbolic execution [30, 63], data flow analysis [19, 20, 74], or other techniques [1, 21, 27, 46, 55, 93]. BinDiff [25, 101] uses graph isomorphism on both call graph and control flow graph (CFG), and later BinSlayer [3] improves BinDiff by augmenting the Hungarian algorithm for bi-partite graph matching. BinHunt [30] and CoP [63] employ static symbolic execution to understand the semantics of binaries. In particular, BinHunt utilizes theorem proving for extracting semantics of binaries, whereas CoP searches the longest common sub-sequence to compute the similarity. Lee et al. [55] determines the similarity of a pair target with both the structural information of a call graph and the N-gram of instruction mnemonics. Tracelet [21] divides the CFG of a function into a fixed length of partial traces of an execution to measure similarity with those traces. Pewny et al. [74] propose a tool that collects input/output (I/O) pairs by providing random inputs to a code snippet. With these I/O pairs, it obtains a hash value that represents a basic block, followed by performing graph matching with the represented values. OpSeq [1] generates the signature of Android malware by analyzing the sequence of normalized opcodes in a sensitive functional module. discovRE [27] introduces a fast similarity comparison method by filtering numeric and structural features from pre-generated features before function matching. ESH [19] and GitZ [20] decompose a target code into smaller fragments via data flow analysis, applying statistical reasoning for further BCSD. BinXary [93] analyzes the signature of a patch by comparing a vulnerable program with a patched program. Meanwhile, BinKit [46] releases the first large-scale public benchmark that allows one to reproduce a BCSD task along with its tool, KitNib [46] for ground truth building.

Dynamic Approaches. Dynamic approaches for BCSD aim to analyze the semantics of binaries by running executables [9, 26, 45, 47, 66, 67, 73, 89]. Varying techniques have been introduced, such as comparing I/O pairs [9, 26, 45, 89], dynamic symbolic execution [66, 67], and learning semantics of execution paths with a neural network [73]. BLEX [26] executes two target functions with randomly sampled input values to compare their behaviors provoked by the inputs. BinSim [67] utilizes system calls or API calls to slice out corresponding code segments and then check their equivalence with symbolic execution. Kim et al. [47] propose a similarity computation based on function matching with both static analysis (e.g., CFG, N-gram) and dynamic analysis (e.g., instruction traces). TREX [73] employs a neural network model, training with diverse execution traces and assembly codes. However, dynamic approaches require a time-consuming and cumbersome task to execute binaries multiple times, limiting them to be scalable.

ML-based Static Approaches. Over the last decade, as the ML field has been remarkably advanced, applying ML-based techniques

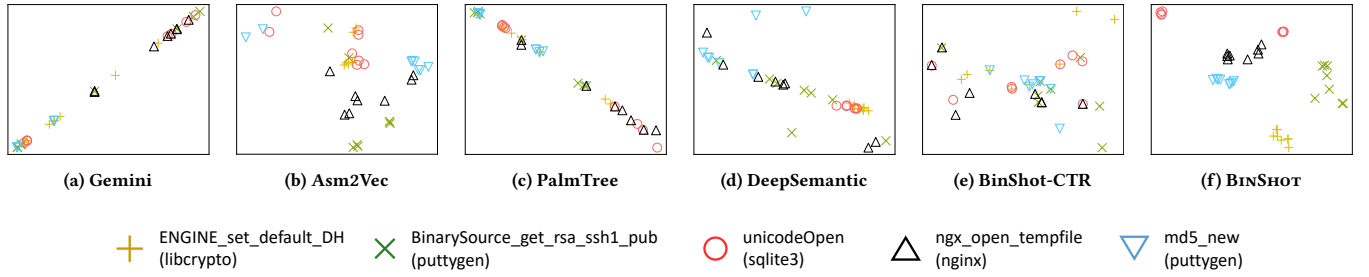


Figure 7: t-SNE visualization [85] of six different models in a two-dimensional space. Each symbol (e.g., +, x, o) denotes five function embeddings where each function has eight similar versions (i.e., functions with two compilers and four optimization levels). BINSHOT has the clearest boundary so that similar functions can group together.

to BCSD [10, 23, 24, 28, 60, 64, 65, 84, 92, 95, 100] has become common. To learn the features of a function from a CFG, Genius [28] employs a genetic algorithm and spectral clustering. On the other hand, Gemini [92] and VulSeeker [10] employ a graph embedding network-based Siamese architecture. Meanwhile, Asteria [95] utilizes a target function’s abstract syntax tree (AST) from decompilation, followed by training a Tree-LSTM-based model based on a Siamese architecture. With the model and a set of callees from the target, Asteria obtains a similarity score. α Diff [60] takes another approach that uses raw bytes of functions to train a convolution neural network-based Siamese architecture. Recently, advances in NLP techniques have triggered applications [23, 24, 65, 100] in the computer-language domain that leverage various techniques into training assembly language. Asm2Vec [23] and DeepBinDiff [24] conduct unsupervised learning by training the context of instructions. InnerEye [100] and SAFE [65] employ an NLP-based Siamese network. The closest work to BINSHOT would be Luo et al. [64] and BinDiff_{NN} [84], which takes an approach of learning a weighted distance vector. However, Luo et al. [64] manually extract features for function embeddings, whereas BinDiff_{NN} [84] employs an attention-based neural network. Moreover, unlike ours, they do not thoroughly discuss the difference between their Siamese architectures with previous works.

BERT Applications. With the emergence of BERT [22], there is a prominent research trend in the field of NLP with transformer-based language models [54, 61, 78]. The popularity of BERT penetrates the domain of binary code analysis by building a representative assembly language model [51, 57, 73, 88, 96]. Yu et al. [96], TREX [73], and jTrans [88] fully focus on BCSD, whereas others [51, 57] utilize a BERT-based model for various downstream tasks. Yu et al. [96] obtain a pre-trained BERT model with the information extracted from a CFG, generating semantic-aware token embeddings and block embeddings, followed by predicting if two binaries are similar. TREX [73] employs MLM to learn dynamic values with micro-traces (a form of under-constrained dynamic traces) of a function and then fine-tune the downstream model for a binary function similarity task. jTrans [88] proposes modified BERT to represent jump instructions to be aware of their jump target. The authors use a triplet loss [80], another popular loss function in Siamese neural network, to train their downstream model. Meanwhile, DeepSemantic [51] and PalmTree [57] apply a generic model for assembly language to other tasks. DeepSemantic [51] demonstrates two downstream

tasks: BCSD and classification for a compiler or optimization level. Likewise, PalmTree [57] applies a generic model to five downstream tasks: outlier detection, basic block search, BCSD, function type signature inference, and value set analysis. We adopt a BERT-based model for BINSHOT; however, we focus more on how to train a Siamese neural network for better BCSD.

8 CONCLUSION

In this paper, we propose BINSHOT that learns a weighted distance vector with a BERT-based Siamese architecture for binary code similarity detection. We adopt BERT to be able to learn the semantics of an assembly language and harness a binary cross entropy as a loss function. We implemented the prototype of BINSHOT, which shows that BINSHOT is more robust than existing state-of-the-art models for BCSD. Our experimental results show that the performance of BINSHOT surpasses that of the cutting-edge approaches, demonstrating its effectiveness and practicality.

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A NORMALIZED FUNCTIONS

Table 4 shows the primary rules for processing instruction normalization suggested by [51], which apply an operand that represents an immediate, a register, or a pointer. After the normalization, two

different functions may be mapped into the same instruction sequence as shown in Figure 8. Note that we exclude such cases for stable training.

Table 4: Illustrative rules on an operand for the well-balanced instruction normalization [51] and examples accordingly. [I], [R], and [P] represent a category for an immediate, register, and pointer.

Rule	Notation	Example
[I] libc library call	libc[name]	call_libcprintf
[I] recursive call	self	call_self
[I] call within a binary	innerfunc	call_innerfunc
[I] call out of a binary	externfunc	call_externfunc
[I] jump to a destination	jmpdst	jmp_jmpdst
[I] referring a string	dispstr	mov_reg4_dispstr
[I] referring a static variable	dispbss	mov_reg8_dispbss
[I] referring non-string data	dispdata	movabs_reg8_dispdata
[I] other immediates	immval	sar_reg8_immval
[R] register size	reg[1 2 4 8]	rax → reg8, ebx → reg4
[R] stack register	rsp	rsp → sp8
[R] base register	rbp	rbp → bp8
[R] instruction register	rip	rip → ip8
[P] direct pointer	[byte word dword qword]ptr	mov_qwordptr [reg8-8]_reg8
[P] indirect pointer	[base_index*scale +displacement]	or_dwordptr [reg8+disp]+immval

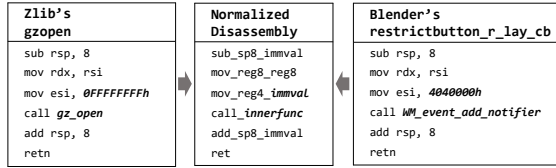


Figure 8: Example of two identical functions after normalization. Here the function `gzopen` from `Zlib` and `restrictbutton_r_lay_cb` from `Blender` embody the same sequence of tokens. Both are compiled with `gcc` with `-O1`. We exclude this case from our dissimilar function pair set.

B MODEL THRESHOLDS

A different model adopts its own distance function such as a cosine distance or L2 norm (Table 2). Moreover, a model takes its own similarity threshold of a computed distance (or probability) to determine the similarity of a given pair. For fair comparisons, we choose a similarity threshold that maximizes an F1 score per baseline approach. As an example, Gemini [92] utilizes a cosine distance that ranges from -1 to 1 , resulting in a drastic change in F1 scores. Figure 9 depicts that a threshold of 0.383 maximizes Gemini’s performance. A too high threshold lowers a prediction of positive samples, resulting in the recall (and F1) decrease accordingly. In the same vein, we choose the thresholds of 0.037 and 0.394 for `Asm2Vec` [23] and `PalmTree` [57]. `BINSHOT-CTR` utilizes the L2 norm as a distance function, having a threshold of 0.485. It is worth noting that a threshold could vary empirically depending on a distance function, loss function, and architecture across different approaches.

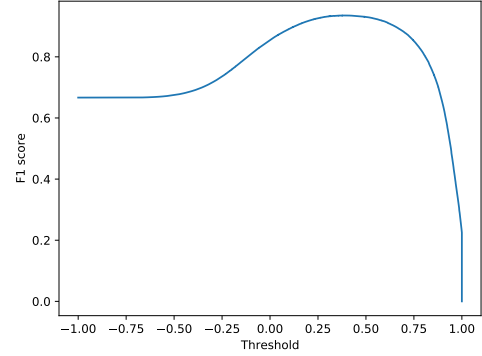


Figure 9: F1 scores by similarity thresholds with the Gemini model (§6.2). The cosine distance threshold of 0.383 maximizes an F1 score.

Table 5: Results of BCSD for large functions with `BINSHOT`.

Accuracy	Precision	Recall	F1 score
0.978	0.995	0.966	0.980

C LARGE FUNCTION EVALUATION

Recall that we exclude large functions (4.66%) when training the current model for `BINSHOT`. We conduct an additional experiment to demonstrate the capability of `BINSHOT` even for such large functions without training them at all. We adopt a naïve approach that truncates the number of tokens when exceeding the limit that BERT can take as an input. Table 5 shows accuracy, precision, recall, and F1 score, which shows little performance degradation.

D CASE STUDY

We analyze several cases that make BCSD challenging, which has been discussed in Appendix E.

```

1 static void emDM_drawEdges(DerivedMesh *dm,
2 int UNUSED(drawLooseEdges),
3 int UNUSED(drawAllEdges))
4 {
5     emDM_drawMappedEdges(dm, NULL, NULL);
6 }

```

Listing 1: Example of a function inlining. `emDM_drawMappedEdges` is inlined at the optimization level 3.

(Case 1) False Negative: Function Inlining. The code snippet in Listing 1 shows the definition of the function, `emDM_drawEdges`, in the `blender_r` binary from the SPEC2017 suite. As it contains a single function call, a modern compiler often embeds (copies) it into another function (*i.e.*, function inlining) as part of optimization to eliminate a call-linkage overhead like a function prologue or epilogue. For instance, `emDM_drawEdges-00` (*i.e.*, compiled with the optimization level of `-O0`) contains a single call with 13 instructions, whereas `emDM_drawEdges-03` (*i.e.*, compiled with the optimization level of `-O3`) contains seven calls with 56 instructions because the compiler inserts `emDM_drawMappedEdges` into `emDM_drawEdges`. As a label for ground truth is based on a function symbol name (from binary debugging information) irrespective of such an inlining optimization, our dataset may erroneously claim

that `emDM_drawEdges-00` and `emDM_drawEdges-03` are a similar function pair. Strictly speaking, this case must be regarded as a true negative case because those functions are contextually not identical.

(Case 2) False Positive: Mangled Names. In our dataset, the function named `_M_get_Tp_allocator` at `ld.gold` (from `binutils`) and the one at `parest_r` (from SPEC 2017) turn out to be identical because both originate from the same member function in the standard template library (STL). In this case, the label marks “dissimilar” due to different namespaces, leading to a false positive, although the decision must be correct. In general, polymorphic techniques (for inheritance), such as function overloading and overriding, make a decision more complicated because it is challenging to be aware of one’s intention; e.g., the implementation of an overridden function may or may not be different.

(Case 3) False Positive: Identical Functions in Different Binaries. Another interesting case arises from a traditional linking process. It is possible to have literally identical functions (except adjustable fixups for relocation) across different executable binaries when there is a statically shared library in common during compilation. The static library (e.g., shared objects with an `.so` file extension in a *NIX system) holds a number of object files, each of which contains one or more functions within. If a binary borrows any function in a certain object file, a linker consolidates all (binary) functions in that object file by default. Those functions would preserve exactly the same function bodies across other binaries that import an arbitrary function in that object file because an offset (e.g., relative address to call or jump) as an operand would be ignored during instruction normalization. A good example would be the case of GNU utilities; e.g., `quotearg_style_mem` is present at both `find` (from `findutils`) and `stat` (from `coreutils`). With the current labeling scheme, they are a dissimilar function pair; however, the truth is that they should be served as similar because those functions stem from the same source code.

E DISCUSSIONS AND LIMITATIONS

In this section, we discuss future work and limitations of our work.

Mangled Names. Name mangling (*i.e.*, name decoration) is a technique that allows one to employ unique entity names (e.g., function name), which has been widely adopted by modern programming languages. Simply put, one can declare multiple entity identifiers using a different namespace (with a structure, class, or module) or function overloading. Then, a compiler internally creates a distinguishing name that utilizes class hierarchy, arguments, and type information. Since the current labeling process endorses the original mangled names, it may give rise to incorrect labels (See Appendix D).

Code Obfuscation and Other Code Constructs. `BINSHOT` mainly focuses on BCSD where obfuscation techniques have not been applied. `Asm2Vec` [23] and Luo et al. [63] introduce a technique for obfuscation-resilient binary code similarity comparison. `InnerEye` [100] proposes a similar function detection technique across different architectures (e.g., Intel and ARM instruction set architecture). `DeepBinDiff` [24] seeks similar functions across different versions of source code. Although the current form of `BINSHOT`

may not be directly applicable to obfuscated binaries or other code constructs, we plan to expand `BINSHOT` in the future.

Function Inlining. Function inlining is one of the well-known compiler optimization techniques³ which aim to reduce the runtime overheads that come from entering and exiting a function. Oftentimes, an inlining process involves either a caller or callee becoming part of another, leading to drastic changes in resulting assembly; e.g., an inlined function disappears while an inlining function includes an additional functionality with the original name. This might be problematic for labeling with a function name because semantically similar functions could be classified as dissimilar. Previous approaches [9, 23, 40] propose a selective callee expansion technique to handle it. We hypothesize that the impact of function inlining seems limited for a BCSD task considering the performance of `BINSHOT`. Interested readers refer to our case study in Appendix D.

Rarely Appeared Instructions. A pre-training model may encounter rarely appeared instructions, which results in the embedding of those instructions that could stay close to randomly initialized values. On the one hand, one can increase a pre-training dataset to relax the issue of hardly-updated instructions; however, further investigation is needed. On the other hand, it is possible to leverage the presence of a particular instruction as a birthmark to BCSD because it could be the unique property of a code snippet.

³A programming language like C++ offers an `inline` specifier as a keyword on demand; however, a compiler fully controls an inlining operation.