

Supervised Learning over Test Executions as a Test Oracle

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ABSTRACT

The challenge of automatically determining the correctness of test executions is referred to as the *test oracle problem* and is a key remaining issue for automated testing. The paper aims at solving the test oracle problem in a scalable and accurate way. To achieve this, we use supervised learning over test execution traces. We label a small fraction of the execution traces with their verdict of pass or fail. We use the labelled traces to train a neural network (NN) model to learn to distinguish runtime patterns for passing versus failing executions for a given program.

We evaluate our approach using case studies from different application domains - 1. Module from Ethereum Blockchain, 2. Module from PyTorch deep learning framework, 3. Microsoft SEAL encryption library components and 4. Sed stream editor. We found the classification models for all subject programs resulted in high precision, recall and specificity, averaging to 89%, 88% and 92% respectively, while only training with an average 15% of the total traces. Our experiments show that the proposed NN model is promising as a test oracle and is able to learn runtime patterns to distinguish test executions for systems and tests from different application domains.

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1 INTRODUCTION

As the scale and complexity of software increases, the number of tests needed for effective validation becomes extremely

large, slowing down development, hindering programmer productivity, and ultimately making development costly [9]. To make testing faster, cheaper and more reliable, it is desirable to automate as much of the process as possible.

Over the past decades, researchers have made remarkable progress in automatically generating effective test inputs [12, 16]. Automated test input generation tools, however, generate substantially more tests than manual approaches. This becomes an issue when determining the correctness of test executions, a procedure referred to as the *test oracle*, that is still largely manual, relying on developer expertise. Recent surveys on the test oracle problem [11, 31, 35] show that automated oracles based on formal specifications, metamorphic relations [34] and independent program versions are not widely applicable and difficult to use in practice. In this paper, we seek to address the test oracle problem. More specifically, for a system with a large set of test inputs, that are automatically and/or manually generated, we ask, “*Is there a widely applicable technique that automates the classification of test executions as pass/fail ?*”

Key Idea. We explore supervised machine learning to infer a test oracle from labelled execution traces of a given system. In particular, we use neural networks (NNs), well suited to learning complex functions and classifying patterns, to design the test oracles. Our technique is widely applicable and easy to use, as it only requires execution traces gathered from running tests through the program under test (PUT) to design the oracle. This is shown in Figure 1 where a small fraction of the gathered execution traces labelled with pass/fail (shown in light gray) is used to train the NN model which is then used to automatically classify the remaining unseen execution traces (colored dark gray).

Previous work exploring the use of NNs for test oracles has been in a restricted context – applied to very small programs with primitive data types, and only considering their inputs and outputs [28, 40]. Information in execution traces which we believe is useful for test oracles has not been considered by existing NN-based approaches. Other bodies of work in program analysis have used NNs to predict method or variable names and detecting name-based bug patterns [7, 38] relying on static program information, namely, embeddings of the Abstract Syntax Tree (AST) or source code. Our proposed approach is the first attempt at using *dynamic execution trace information in NN models for classifying test executions*.

Our approach for inferring a test oracle has the following steps,

- (1) Instrument a program to gather execution traces as sequences of method invocations.
- (2) Label a small fraction of the traces with their classification decision.

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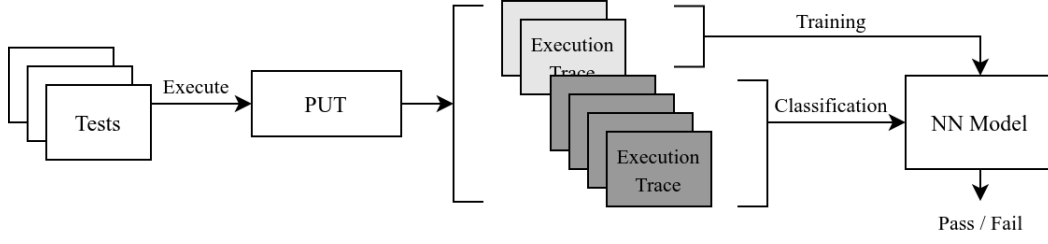


Figure 1: Key idea in our approach.

- (3) Design a NN component that embeds the execution traces to fixed length vectors.
- (4) Design a NN component that uses the line-by-line trace information to classify traces as pass or fail.
- (5) Train a NN model that combines the above components and evaluate it on unseen execution traces for that program.

The novel contributions in this paper are in Steps 3, 4 and 5. Execution traces from a program vary widely in their length and information. We propose a technique to encode and summarise the information in a trace to a fixed length vector that can be handled by a NN. We then design and train a NN to serve as a test oracle.

Labelled execution traces. Given a PUT and a test suite, we gather execution traces corresponding to each of the test inputs in the test suite with our instrumentation framework. Effectively learning a NN classifier for a PUT that distinguishes correct from incorrect executions requires labelled data with both passing and failing examples of traces. We require a small fraction of the overall execution traces to be labelled, which is likely to be a manual process. As a result, our proposed approach for test oracle is *not* fully automated. We hypothesize that the time invested in labelling a small proportion of the traces is justified with respect to the benefit gained in automatically classifying the remaining majority of traces. In contrast, with no classifier, the developer would have had to specify expected output for all the tests, which is clearly more time consuming than the small proportion of tests we need labelled.

NN Architecture. An execution trace in our approach comprises multiple lines, with each line containing information on a method invocation. Our architecture for encoding and classifying an execution trace uses multiple components: (1) Value encoder for encoding values within the trace line to a distributed vector representation, (2) Trace encoder encoding trace lines within a variable-length trace to a single vector, and (3) Trace Classifier that accepts the trace representation and classifies the trace. The components in our architecture is made up of LSTMs, one-hot encoders, and a multi-layer perceptron.

Case Studies. We evaluate our approach using 4 subject programs and tests from different application domains - a single module from Ethereum project [2], a module from Pytorch [36], one component within Microsoft SEAL encryption library [39] and a Linux stream editor [1]. One of the 4 subject programs were accompanied by both passing and

failing tests that we could directly use in our experiment. The remaining three programs were only accompanied by passing tests. We treated these programs as reference programs. We then generated PUTs by artificially seeding faults into them. We generated traces through the PUTs using the existing tests, labelling the traces as passing or failing based on comparisons with traces from the reference program. We trained a NN model for each PUT using a fraction of the labelled traces. We found our approach for designing a NN classification model was effective for programs from different domains. We achieved high accuracies in detecting both failing and passing traces, with an average precision of 89% and recall of 88%. Only a small fraction of the overall traces (average 15%) needed to be labelled for training the classification models. In summary, the paper makes the following contributions:

- Given a PUT and its test inputs, we provide a framework that instruments the PUT and gathers test execution traces as sequences of method invocations.
- A NN component for encoding variable-sized execution traces into fixed length vectors.
- A NN for classifying the execution traces as pass or fail.
- We provide empirical evidence that this approach yields effective test oracles for programs and tests from different application domains.

2 BACKGROUND

When a test oracle observes a test execution, it returns a test verdict, which is either pass or fail, depending on whether the observations match expected behaviour. A test execution is execution of the PUT with a test input. The importance of oracles as an integral part of the testing process has been a key topic of research for over three decades. We distinguish four different kinds of test oracles, based on the survey by Barr et al. in 2015 [11]. The most common form of test oracle is a *specified oracle*, one that judges behavioural aspects of the system under test with respect to formal specifications. Although formal specifications are effective in identifying failures, defining and maintaining such specifications is expensive and also relatively rare in practice. *Implicit* test oracles require no domain knowledge and are easy to obtain at no cost. However, they are limited in their scope as they are only able to reveal particular anomalies like buffer overflows, segmentation faults, deadlocks. *Derived* test oracles use documentations or system executions, to judge a system's behaviour, when specified test oracles are unavailable. However,

derived test oracles, like metamorphic relations and inferring invariants, is either not automated or it is inaccurate and irrelevant making it challenging to use.

For many systems and much of testing as currently practised in industry, the tester does not have the luxury of formal specifications or assertions or even automated partial oracles [21, 22]. Statistical analysis and machine learning techniques provide a useful alternative for understanding software behaviour using data gathered from a large set of test executions.

2.1 Machine Learning for Software Testing

Briand et al. [14], in 2008, presented a comprehensive overview of existing techniques that apply machine learning for addressing testing challenges. Among these, the closest related work is that of Bowering et al. in 2004 [13]. They proposed an active learning approach to build a classifier of program behaviours using a frequency profile of single events in the execution trace. Evaluation of their approach was conducted over one small program whose specific structure was well suited to their technique. Machine learning techniques have also been used in fault detection. Brun and Ernst, in 2004 [15], explored the use of support vector machines and decision trees to rank program properties, provided by the user, that are likely to indicate errors in the program. Podgurski et al., in 2003 [37], use clustering over function call profiles to determine which failure reports are likely to be manifestations of an underlying error. A training step determines which features are of interest by evaluating those that enable a model to distinguish failures from non-failures. The technique does not consider passing runs. In their experiments, most clusters contain failures resulting from a single error.

More recently, Almaghairbe et al. [6] proposed an unsupervised learning technique to classify unlabelled execution traces of simple programs. They gather two kinds of execution traces, one with only inputs and outputs, and another that includes the sequence of method entry and exit points, with only method names. Arguments and return values are not used. They use agglomerative hierarchical clustering algorithms to build an automated test oracle, assuming passing traces are grouped into large, dense clusters and failing traces into many small clusters. They evaluate their technique on 3 programs from the SIR repository [19]. The proposed approach has several limitations. They only support programs with strings as inputs. They do not consider correct classification of passing traces. The accuracy achieved by the technique is not high, classifying approximately 60% of the failures. Additionally, fraction of outputs that need to be examined by the developer is around 40% of the total tests, which is considerably higher than the labelled data used in our approach. We objectively compared the accuracy achieved by the hierarchical clustering technique against our approach using 5 PUTs, discussed in Section 5. We found our approach achieves significantly higher accuracy in classifying program executions across all case studies.

Existing work using execution traces for bug detection has primarily been based on clustering techniques. Neural networks, especially with deep learning, have been very successful for complex classification problems in other domains like natural language processing, speech recognition, computer vision. There is limited work exploring their benefits for software testing problems.

Neural Networks for Test Oracles. NNs were first used by Vanmali et al. [40] in 2002 to simulate behaviour of simple programs using their previous version, and applied this model to regression testing of unchanged functionalities. Aggarwal et al. [3] and Jin et al. [28] applied the same approach to test a triangle classification program, that computes the relationship among three edge inputs to determine the type of triangle. The few existing approaches using NNs have been applied to simple programs having small I/O domains. The following challenges have not been addressed in existing work,

1. Training with test execution data and their vector representation – Existing work only considers program inputs and outputs that are of primitive data types (integers, doubles, characters). Test data for real programs often use complex data structures and data types defined in libraries. There is a need for techniques that encode such data. In addition, existing work has not attempted to use program execution information in NNs to classify tests. Achieving this will require novel techniques for encoding execution traces and designing a NN that can learn from them.
2. Test oracles for industrial case studies - Realistic programs with complex behaviours and input data structures has not been previously explored.
3. Effort for generating labelled training data - Training data in existing work has been over simple programs, like the triangle classification program, where labelling the tests was straightforward. Availability of labelled data that includes failing tests has not been previously discussed. Additionally, the proportion of labelled data needed for training and its effect on model prediction accuracy has not been systematically explored.

Deep Learning for Software Testing. The performance of neural networks as classifiers was boosted with the birth of deep learning in 2006 [23]. Deep learning methods have *not* been explored extensively for software testing, and in particular for the test oracle problem. Recently, a few techniques have been proposed for automatic pattern-based bug detection. For example, Pradel et al. [38] proposed a deep learning-based static analysis for automatic name-based bug detection and Allamanis et al. [4] used graph-based neural static analysis for detecting variable misuse bugs. In addition to these techniques, several other deep learning methods for statically representing code have been developed [5, 8]. We do not discuss these further since we are interested in execution trace classification and in NNs that use dynamic trace information rather than a static view of the code.

Embedding Execution Traces for Neural Networks. One of the main contributions in this paper is an approach for

embedding information in execution traces as a fixed length vector to be fed into the neural network. There is limited work in using representations of execution traces. Wang et al. [41] proposed embeddings of execution traces in 2017. They use execution traces captured as a sequence of variable values at different program points. A program point is when a variable gets updated. Their approach uses recurrent NNs to summarise the information in the execution trace. Embedding of the traces is applied to an existing program repair tool. The work presented by Wang et al. has several limitations

- 1. Capturing execution traces as sequences of updates to every variable in the program has an extremely high overhead and will not scale to large programs. The paper does not describe how the execution traces are captured, they simply assume they have them.
- 2. The approach does not discuss how variables of complex data types such as structs, arrays, pointers, objects are encoded. It is not clear if the traces only capture updates to user-defined variables, or if system variables are also taken into account.
- 3. The evaluation uses three simple, small programs (eg. counting parentheses in a string) from students in an introductory programming course. The complexity and scale of real programs is not assessed in their experiments. Their technique for capturing and directly embedding traces as sequences of updates to every variable is infeasible in real programs. Our approach captures and embeds traces as sequences of method invocations and updates to global variables, which scales better than tracking every program variable. We have implemented our instrumentation in the LLVM compiler framework that is language agnostic and scales to industry-sized programs. We support all types of variables and objects, including system defined variables.

3 APPROACH

Our approach for building an automated test oracle for classifying execution traces has the following steps,

- Step 1:** Instrument the PUT to gather traces when executing the test inputs.
- Step 2:** Preprocess the traces to prune unnecessary information.
- Step 3:** Encode the preprocessed traces into vectors that can be accepted by the neural network.
- Step 4:** Design a NN model that takes as input an encoded trace, and outputs a verdict of pass or fail for that trace.

Figure 2a illustrates the steps in our approach, with the bottom half of the figure depicting steps 3 and 4 for any given preprocessed trace from step 2. We discuss each of the steps in the rest of this Section.

3.1 Instrument and Gather Traces

For every test input executed through the PUT, we aim to collect an execution trace as a sequence of method invocations, where we capture the name of the method being called, values and data types of parameters, return values and their types, and, finally, the name of the parent method in the call graph. We find gathering further information, eg. updates to

local variables within each method, incurs a significant overhead and is difficult to scale to large programs. To gather this information we use the middleware of LLVM [32] and instrument the intermediate representation (IR) of programs. This allows our implementation to be language-agnostic. LLVM provides front-end support for multiple programming languages, such as C/C++, CUDA, Haskell, Swift, Rust among others, along with numerous libraries for optimisation and code generation.

To perform the instrumentation, we traverse the PUT, visiting each method. Every time a method invocation is identified, code is injected to trace the caller-callee pair, the arguments and the return values. At the end of the program, code is inserted to write the trace information to the output.

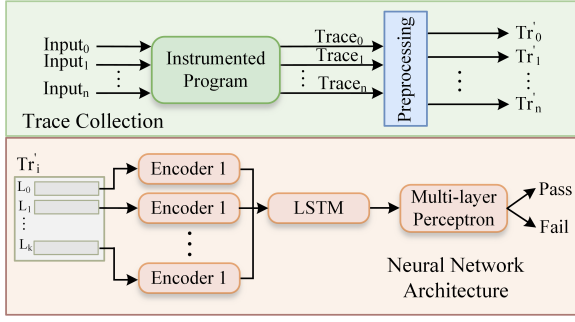
Each trace contains a sequence of method invocations. This sequence comprises multiple lines, each line being a tuple (n_p, n_c, r, a) that represents a single method invocation within it having:

- The names of the caller (parent) n_p and called n_c functions.
- Return values r of the call, if any.
- Arguments passed a , if any.

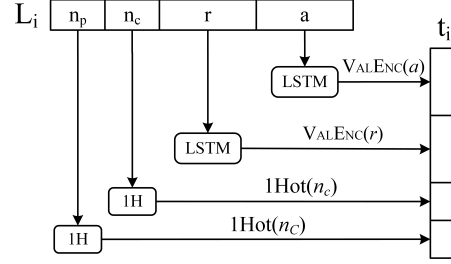
The order of trace lines or method invocations is the order in which the methods complete and return to the calling point. We support all variable types including primitive types (such as `int`, `float`, `char`, `bool`), composite data types (such as structs, classes, arrays) defined by a user or library, and pointers for return and argument values. Structs and classes are associated with a sequence of values for their internal fields. We instrument these data structures in a depth first fashion, until all primitive types are traced. For pointers, we monitor the values they refer to.

3.2 Training Set

We execute the instrumented program with each test input in the test suite to gather a set of traces. A subset of the traces is labelled and used in training the classification model. To label the traces as pass or fail, we compare actual outputs through the PUT with expected outputs provided by a reference program or the specifications. Section 4.1 discusses how we label traces for the subject programs in our experiment. It is worth noting that in our approach, the developer will only need to provide expected outputs for a *small proportion of tests rather than the whole test suite*. In the absence of expected output in tests, how will tests be labelled is a common question. Answering this question will depend on what is currently being done by the developer or organisation for classifying tests as pass or fail. Our approach will entail applying the same practice to labelling, albeit to a significantly smaller proportion of tests. To avoid data leakage in our experiment in Section 4, we ensure that expected output is removed from the traces. We also remove exceptions, assertions and any other information in the program or test code that may act as a test oracle. This is further discussed in Section 4.2.



(a) Gathering traces, encoding them, and using NNs to classify them.



(b) Encoder 1 representing a single line in a trace as a vector containing function caller, callee names, arguments and return values.

Figure 2: High-level architecture of our approach and Encoder 1 description.

3.3 Preprocessing

The execution traces gathered with our approach include information on methods declared in external libraries, called during the linking phase. To keep the length of the traces tractable and relevant, we preprocess the traces to only keep trace lines for methods that are defined within the module, and remove trace lines for declared functions that are not defined, but simply linked to later.

For method invocations within loops, a new trace line is created for each invocation of the same method within the loop. For loops with large numbers of iterations, this can lead to redundancy when the method is invoked with similar arguments and return values. We address this potential redundancy issue by applying average pooling to trace lines with identical caller-callee methods within loops.

3.4 Neural Network Model

In this step, we perform the crucial task of designing a neural network that learns to classify the pre-processed traces as passing or failing. Shape and size of the input traces vary widely, and this presents a challenge when designing a NN that accepts fixed length vectors summarizing the traces. To address this, our network comprises three components that are trained jointly and end-to-end: 1. a VALENC that encodes values (such as the values of arguments and return values) into D_V -dimensional distributed vector representations, shown within **Encoder 1** in Figure 2b, 2. a TRENC that encodes variable-sized traces into a single D_T -dimensional vector, shown as LSTM in Figure 2a, and finally, 3. a TRACE-CLASSIFIER that accepts the trace representation for state and predicts whether the trace is passing or failing. The **Multi-layer Perceptron** in Figure 2a represents the TRACE-CLASSIFIER. We describe each component in detail in the rest of this section.

Encoding Values Values within the trace provide useful indications about classifying a trace. However, values — such as ints, structs, and floats — vary widely in shape and size. We, therefore, design models that can summarize variable-sized sequences into fixed-length representations. In the machine learning literature, we predominantly find three

kinds of models that can achieve this: recurrent neural networks (RNNs), 1D convolutional neural networks (CNN) and transformers. In this work, we employ LSTMs [24] — a commonly used flavour of RNNs. Testing other models is left as future work. At a high-level RNNs are recurrent functions that accept a vector \mathbf{h}_t of the current state and an input vector \mathbf{x}_t and compute a new state vector $\mathbf{h}_{t+1} = RNN(\mathbf{x}_t, \mathbf{h}_t)$ which “summarizes” the sequence of inputs up to time t . A special initial state \mathbf{h}_0 is used at $t = 0$.

To encode a value v , we decompose it into a sequence of primitives $v = [p_0, p_1, \dots]$ (integers, floats, characters, etc.). Each primitive p_i is then represented as a binary vector $\mathbf{b}_i = e(p_i)$ containing its bit representation padded to the largest primitive data type of the task. For example, if `int64` is the largest primitive then all \mathbf{b}_i s have dimensionality of 64. This allows us to represent all values (integers, floats, strings, structs, pointers, etc.) as a unified sequence of binary vectors. We encode v into a D_V -dimensional vector by computing

$$\text{VALENC}(v) = \text{LSTM}_v(e(p_L)_L, \text{VALENC}([p_0, p_1, \dots, p_{L-1}])),$$

where LSTM_v is the LSTM that sequentially encodes the \mathbf{b}_i s. Note that we use the same VALENC for encoding arguments and return values, as seen in Figure 2b. The intuition behind this approach is that the bits of each primitive can contain valuable information. For example, the bits corresponding to the exponent range of a float can provide information about the order of magnitude of the represented number, which in turn may be able to discriminate between passing and failing traces.

Representing a Single Trace Line Armed with a neural network component that encodes values, we can now represent a single line (n_p, n_c, r, a) of the trace. To do this, we use VALENC to encode the arguments a and the return value r . We concatenate these representations along with one-hot representations of the caller and callee identities, as shown in Figure 2b. Specifically, the vector encoding \mathbf{t}_i of the i th trace line is the concatenation

$$\mathbf{t}_i = [\text{VALENC}(a), \text{VALENC}(r), \text{1HOT}(n_p), \text{1HOT}(n_c)],$$

where 1HOT is a function that takes as input the names of the parent or called methods and returns a one-hot vector that

uniquely encodes that method name. For methods that are rare (appear fewer than k_{min} times) in our data, 1HOT collapses them to a single special Unknown (UNK) name. This is similar to other machine learning and natural language processing models and reduces sparsity often improving generalization. The resulting vector \mathbf{t}_i has size $2D_V + 2k$ where k is the size of each one-hot vector.

Encoding Traces Now that we have built a neural network component that encodes single lines within a trace, we design TRENC that accepts a sequence of trace line representations $\mathbf{t}_0 \dots \mathbf{t}_N$ and summarizes them into a single D_T -dimensional vector. We use an LSTM with a hidden size D_T , and thus

$$\text{TRENC}(\mathbf{t}_0 \dots \mathbf{t}_N) = \text{LSTM}_{tr}(\mathbf{t}_N, \text{TRENC}(\mathbf{t}_0 \dots \mathbf{t}_{N-1})),$$

where $\text{LSTM}_{tr}()$ is an LSTM network that summarizes the trace line representations.

Classifying Traces With the neural network components described so far we have managed to encode traces into fixed length vector representations. The final step is to use those computed representations to make a classification decision. We treat failing traces as the positive class and passing traces as the negative class since detecting failing runs is of more interest in testing. We compute the probability that a trace is failing as

$$P(\text{fail}) = \text{TRACECLASSIFIER}([\text{TRENC}(\mathbf{t}_0 \dots \mathbf{t}_N)]),$$

where the input of TRACECLASSIFIER is the output vector of TRENC. Our implementation of TRACECLASSIFIER is a multilayer perceptron (MLP) with sigmoid non-linearities and a single output, which can be viewed as the probability that the trace is a failing trace. It follows that $P(\text{pass}) = 1 - P(\text{fail})$.

Training and Implementation Details We train our network end-to-end in a supervised fashion, minimizing the binary cross entropy loss. All network parameters (parameters of LSTM_v and LSTM_{tr} and parameters of the MLP) are initialized with random noise. For all the runs on our network we use $D_V = 128$, $D_T = 256$. The TRACECLASSIFIER is an MLP with 3 hidden layers of size 256, 128 and 64. We use the Adam optimizer [30] with a learning rate of $10e - 5$.

For our subject programs, we find the aforementioned feature values to be optimal for performance and training time, after having experimented with other NN architectures, varying the D_V , D_T sizes, and the hidden layers in the MLP. We explored increasing D_V to 256, 512, D_T to 512, 1024 and size of hidden layers to 512 and 1024.

To handle class imbalance in datasets, we explicitly counteract the imbalance in the loss function by down-weighting the samples within the most popular class such that samples of both class participate equally within this function.

Our implementation of the proposed approach is available at <https://github.com/fivosts/Learning-over-test-executions>.

4 EXPERIMENT

In our experiment, we evaluate the feasibility and accuracy of the NN architecture proposed in Section 3 to classify

execution traces for 4 subject programs and their associated test suites. We investigate the following questions regarding feasibility and effectiveness:

Q1. Precision, Recall and Specificity: *What is the precision, recall and specificity achieved over the subject programs?*

To answer this question, we use our tool to instrument the source code to record execution traces as sequences of method invocations, arguments and return values. A small fraction of the execution traces are labelled (*training set*) and fed to our framework to infer a classification model. We then evaluate precision, recall and specificity achieved by the model over unseen execution traces (*test set*) for that program. The test set includes both passing and failing test executions. We use *Monte Carlo cross-validation*, creating random splits of the dataset into training and test data. We created 15 such random splits and averaged precision, recall and specificity computed over them. In our experiments, we do not use a validation set to tune the hyper-parameters in the NN model.

Q2. Size of training set: *How does size of the training set affect precision and recall of the classification model?*

For each program, we vary the size of training set from 5% to 30% of the overall execution traces and observe its effect on precision and recall achieved.

Q3. Comparison against state of art: *How does the precision, recall and specificity achieved by our technique compare against agglomerative hierarchical clustering, proposed by Almaghairbe et al. [6] in 2017?*

We choose to compare against the hierarchical clustering work as it is the most relevant and recent in classifying execution traces. Traces used in their work are sequences of method invocations, similar to our approach. Other test oracle work that use NNs is not used in the comparison as they do not work over execution traces, and are limited in their applicability to programs with numerical input and output which is not the case for programs in our experiment.

All experiments are performed on a single machine with 4 Intel i5-6500 CPU cores, Nvidia RTX 2060 GPU, 16GB of memory.

4.1 Labelling Traces

All our subject programs are open source, and most of them were only accompanied by passing tests. This is not uncommon as most released versions of programs are correct for the given tests. We take these correct programs to be reference implementations. To enable evaluation of our approach that distinguishes correct versus incorrect executions, we need subject programs with bugs. We, therefore, generate PUTs by automatically mutating the reference implementation using common mutation operators [27] listed below,

- (1) Arithmetic operator replacement applied to $\{+, -, *, /, --, ++\}$.
- (2) Logical connector replacement applied to $\{\&\&, ||, !\}$.
- (3) Bitwise operator replacement applied to $\{\&, |, \wedge, <, <<, >, >>\}$.

- (4) Assignment operator replacement applied to $\{+ =, - =, * =, / =, \% =, < < =, > > =, \& =, | =, \wedge =\}$.

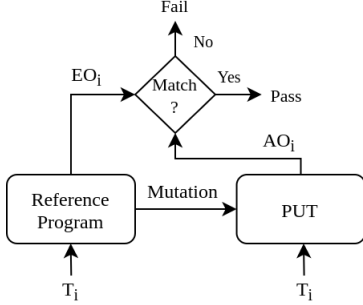


Figure 3: Labelling test executions by matching actual and expected behavior.

A PUT is generated by seeding a single fault into the reference implementation at a random location using one of the above mutation operators. We used an independent open source mutation tool¹ to generate PUTs from a given reference program. Figure 3 shows a PUT generated by seeding a single fault into a reference program. As seen in Figure 3, we run each test, T_i , in the test suite, through both the reference program and PUT, and label the trace as *passing* if the expected output, EO_i , from the reference matches the actual output, AO_i , from the PUT. If they do not match, the trace is labelled as *failing*. We rejected PUTs from mutations that did not result in any failing traces (outputs always match with the reference). This avoids the problem of equivalent mutants. All the PUTs in our experiment had both passing and failing traces.

4.2 Subject Programs

We chose subject programs from different domains to assess applicability of our approach, namely from the blockchain, deep learning, encryption and text editing domains. A description of the programs and associated tests is as follows.

1. Ethereum [2] is an open-source platform based on blockchain technology, which supports smart contracts. Within it, we evaluate our approach over the **Difficulty** module that calculates the mining difficulty of a block, in relation to different versions (eras) of the cryptocurrency (Byzantium, Homestead, Constantinople etc.). The calculation is based on five fields of an **Ethereum** block, specified in the test input.

Tests. We use the default test inputs provided by Ethereum’s master test suite for the **Difficulty** module. We test this module for the Byzantium era of the cryptocurrency (version 3.0). The test suite contains 2254 *automatically* generated test inputs. Each test input contains one hex field for the test input of the difficulty formula and another hex field for the expected output of the program. All the test inputs provided with the module are passing tests with the actual output equal to the expected output. As a result, we use the provided module as a reference implementation. As described in

Section 4.1, we seed faults into the reference implementation to generate PUTs, each containing a single mutation. For the difficulty module, we generate 2 PUTs – 1. Ethereum-SE with a seeded fault in the core functionality of the difficulty module, and 2. Ethereum-CD with a fault seeded in one of the functions that is external to the core function but appears in the call graph of the module. The balance between passing and failing tests varies between the two PUTs, Ethereum-CD being perfectly balanced and Ethereum-SE being slightly imbalanced (828 failing and 1426 passing tests).

2. Pytorch [36] is an optimized tensor library for deep learning, widely used in research. In our experiment, we evaluate our model over the **intrusive_ptr** class, which implements a pointer type with an embedded reference count. We chose this class because it had a sizeable number of tests (other modules had < 20 published tests).

Tests. Implementation of the class is accompanied by 638 tests, all of which are passing. We, thus, use this as the reference implementation. As with **Ethereum**, we apply mutations to the **intrusive_ptr** implementation to generate a single PUT. Upon comparison with the reference, 318 of the existing tests are labelled passing through the PUT and 320 as failing.

3. Microsoft SEAL [39] is an open-source encryption library. In our experiment, we study one component within Microsoft SEAL, the **Encryptor** module, which is accompanied by tests. This component is responsible for performing data encryption.

Tests. The **Encryptor** component is accompanied by 133 tests. The provided tests were all passing tests, with matching expected and actual output. As with previous programs, we generate a PUT by mutating the original implementation. On the PUT, 11 tests fail and 122 pass.

4. Sed [1] is a Linux stream editor that performs text transformations on an input stream.

Tests. We use the fifth version of **Sed** available in the SIR repository [19]. This version is accompanied by 370 tests, of which 352 are passing and 18 are failing. The failing tests point to real faults in this version. Since the implementation was accompanied by both passing and failing, we used it as the PUT. We did *not* seed faults to generate the PUT.

Checks to avoid data leakage. We ensure no test oracle data is leaked into traces. We remove expected outputs, assertions, exceptions, test names and any other information that may act directly or indirectly as a test oracle. For example, Ethereum uses **BOOST** testing framework to deploy its unit tests. We remove expected outputs and assertions in the test code that compare actual with the expected output e.g. **BOOST_CHECK_EQUAL**.

For PUTs generated by seeding faults into the reference implementation, we only use one PUT for each reference implementation except in the case of Ethereum where we generated two PUTs, since faults were seeded in different files. Generating more PUTs for each reference implementation would be easy to do. However, we found our results across

¹<https://github.com/chao-peng/mutec>

PUTs for a given reference program only varied slightly. As a result, we only report results over one to two PUTs for each reference implementation.

4.3 Performance Measurement

For each PUT, we evaluate performance of the classification model over unseen execution traces. As mentioned in Section 3.4, we use positive labels for failing traces and negative labels for passing. We measure

- (1) *Precision* as the ratio of number of traces correctly classified as “fail” (TP) to the total number of traces labelled as “fail” by the model (TP + FP).
- (2) *Recall* as the ratio of failing traces that were correctly identified (TP/(TP + FN)).
- (3) *Specificity* or true negative rate (TNR) as the ratio of passing traces that were correctly identified (TN/(TN + FP)).

TP, FP, TN, FN represent true positive, false positive, true negative and false negative, respectively.

4.4 Hierarchical Clustering

In research question 3 in our experiment, we compare the classification accuracy of our approach against agglomerative hierarchical clustering proposed by Almaghairbe et al. [6]. Their technique also considers execution traces as sequences of method calls, but only encoding callee names. Caller names, return values and arguments are discarded. We attempted to add the discarded information, but found the technique was unable to scale to large number of traces due to both memory limitations and a time complexity of $\mathcal{O}(n^3)$ where n is the number of traces. For setting clustering parameters for each subject program, we evaluate different types of linkage (**single**, **average**, **complete**) and a range of different cluster counts (as a percentage of the total number of tests): 1, 5, 10, 20 and 25%. We use Euclidean distance as the distance measure for clustering. For each program, we report the best clustering results achieved over all parameter settings.

5 RESULTS AND ANALYSIS

In this section, we present and discuss our results in the context of the research questions presented in Section 4.

5.1 Q1. Precision, Recall and Specificity

Table 1 shows the precision, recall and specificity achieved by the classification models in our approach for the different PUTs. Results with the hierarchical clustering approach by Almaghairbe et al. [6] are also presented in Table 1 for comparison, but this is discussed in Q3 in Section 5.3. The column showing % of traces used in training varies across programs, we show the lowest percentage that is needed to achieve near maximal precision and recall.

The classification models for all 5 PUTs achieve more than 75% precision and recall, with an average of 89% and 88%, respectively. Our technique works particularly well for Pytorch and Sed, achieving $\geq 94\%$. This implies that the

number of false positives in the classification is very low and a large majority of the failing traces are correctly identified.

The classification models for all PUTs also achieve high specificity ($\geq 79\%$, average 92%). This implies that the NN models are able to learn runtime patterns that distinguish not only failing executions, but also passing executions with a high degree of accuracy. These results are unprecedented as we are not aware of any technique in the literature that can classify both passing and failing executions at this level of accuracy.

Analysis. To understand the results in Table 1, for each of the PUTs, we inspected and compared passing and failing traces using a combination of longest common subsequence, syntactic diffs, and manual inspection. We also performed *ablation* – systematically removing information (one parameter at a time) from the traces, training new classification models with the modified traces and observing their effect on precision, recall and specificity (TNR). In our experiments, we systematically remove the following parameters from the original traces – function call names, arguments, and return values. Table 2 shows the results from our ablation study. We discuss results for each of the programs in the following paragraphs.

Over SEAL Encryptor, our approach achieves 75% precision, 86% recall and 98% specificity when trained with 30% of the traces. Encryptor requires a higher fraction of traces for training when compared to other PUTs, as the number of failing traces is very small ($= 11$), unlike other programs. Although we handle imbalance in datasets by weighting samples in the loss function, the NN still needs some representatives of the failing class during training. Using 10% of the traces in training, will only provide one example of failing trace (10% of 11) which is not enough for the NN model to learn to distinguish failing versus passing behaviour. Training using 30% of the traces includes 3 failing traces which allows the NN to achieve 75% precision. High precision with only 3 failing traces is because all the failing traces for this program have the same call sequence, which is sufficiently different from passing traces. Passing traces do not all have the same sequence. However, due to the availability of a larger set of passing traces (training with 30% is 40 passing traces), the NN is able to identify the different method call patterns in passing traces accurately (98% specificity). The ablation study in Table 2 shows that all the parameters contribute to model performance as removing them has a detrimental effect.

For PyTorch, we achieve 99% precision, 98% recall and 99% specificity when trained with 10% of the traces. The dataset for PyTorch PUT is balanced (318 passing and 320 failing). 10% of the traces during training provides sufficient examples from both passing and failing classes for the NN to learn to distinguish them. We find the reason for the superior performance of our model over PyTorch is because all failing traces have significantly fewer trace lines than passing traces. The consistent difference in length of traces between the two classes allows the NN to easily distinguish them. The ablation

PUT	Lines of Code	% Traces for training	Total # Traces	Our Approach			Hierarchical Clustering [6]		
				Precision	Recall	TNR	Precision	Recall	TNR
Ethereum-CD	55927	15	2254	0.80	0.82	0.79	1.0	0.49	1.0
Ethereum-SE	55927	15	2254	0.99	0.82	0.86	1.0	0.25	1.0
Pytorch	21090	10	638	0.99	0.98	0.99	0.48	1.0	0.16
SEAL Encryptor	25967	30	132	0.75	0.86	0.98	0.16	0.36	0.83
Sed	4492	10	370	0.94	0.94	0.99	0.35	0.63	0.86

Table 1: Precision, Recall and True Negative rate (TNR) using our approach and hierarchical clustering.

study in Table 2 shows arguments in traces matter for model performance, while method names and return values are irrelevant.

With Sed, our model achieves 94% precision and recall, and 99% specificity using 10% of the traces in training. The dataset for Sed is unbalanced, with only 18 failing and 352 passing. 10% of the traces in training uses 2 failing tests and 35 passing tests. Given the extremely small sample of failing tests, it is surprising that the model classifies and identifies failing traces with such high precision and recall. To understand this, we examined both the passing and failing trace lines. We find the length of passing and failing traces is similar. All failing traces, however, have a call to a function, `getChar`, towards the end of the trace. This function call is absent in passing traces. We believe associating this function call to failing traces may have helped the performance of the NN. The ablation study in Table 2 shows all the parameters considered in our traces are important for model performance.

For Ethereum-CD, our model achieves 80% precision, 82% recall and 79% specificity when trained with 15% of the traces - 169 passing and 169 failing. Ethereum-CD was generated from the reference implementation using an arithmetic operator mutation in a function deeply embedded in the call graph for the difficulty module. Differences between failing and passing traces are not apparent, and analysing longest common subsequence, syntactic diff and manual inspections did not reveal any characteristic feature for failing or passing traces. We believe the model performance of around 80% precision, recall and specificity is due to the similarity between passing and failing traces and the esoteric nature of the mutation. Ablation study for this program reveals that all features in the traces slightly impact model performance.

For Ethereum-SE, our model achieves 99% precision, 82% recall and 86% specificity with 15% traces in training - 214 failing and 124 passing. Unlike Ethereum-CD, mutation to generate Ethereum-SE was in the core functionality. Failing traces when compared to passing traces had differences towards the end of the trace which is easily distinguished by the NN. Curiously, removing return values in the ablation study, increases recall and specificity. This may be because the model was previously overfitting to return values in traces which may not have been relevant to the classification.

Summary. Overall, we find NN models for all our PUTs perform well as a test oracle, achieving an average of 89% precision, 88% recall and 92% specificity. The NN models perform exceptionally well for programs whose traces have characteristic distinguishing features between passing and failing executions, such as differences in trace lengths or

presence of certain function call patterns. In the absence of such features, NNs can still do well if it has enough training samples, as in Ethereum-CD. We also find our approach can cope effectively with unbalanced datasets – three of the five programs in our experiment have unbalanced passing and failing traces.

PUT	Omitted Info.	P	R	TNR
Ethereum-CD	Function names	0.63	0.64	0.62
	Return values	0.68	0.87	0.60
	Arguments	0.54	0.78	0.35
Ethereum-SE	Function names	0.96	0.84	0.35
	Return values	0.99	0.97	0.93
	Arguments	0.96	0.84	0.33
Pytorch	Function names	0.99	1.0	1.0
	Return values	0.99	0.99	0.99
	Arguments	0.51	0.99	0.04
Seal Encryptor	Function names	0.53	0.87	0.92
	Return values	0.46	0.99	0.90
	Arguments	0.28	0.88	0.76
Sed	Function names	0.19	0.72	0.24
	Return values	0.48	0.52	0.85
	Arguments	0.30	0.40	0.73

Table 2: Precision (P), Recall (R) and Specificity (TNR) for each PUT omitting certain trace information.

5.2 Q2. Size of training set

Figure 4 shows precision and recall achieved by our approach with different training set sizes. The fraction of traces needed in training to achieve near maximal performance was 10% to 30% across the PUTs. Excluding SEAL Encryptor, all the other programs only needed to be trained over 15% of the traces to achieve near maximal performance. SEAL encryptor had very few failing traces, requiring a larger fraction of traces to get sufficient representation of failing classes during training. As seen in the plots in Figure 4, increasing the % of traces used in training does not increase precision and recall for all PUTs. For instance, Pytorch and Sed observe a dramatic increase in precision and recall when going from 5 to 10% traces in training. Performance, however, stagnates after that point with increasing traces. With Ethereum-CD and Ethereum-SE, precision or recall becomes worse after 20% traces. This maybe because the model is overfitting to the training traces.

It is also worth noting that the absolute size of our training set varies across subject programs. We find our approach works with training sets with as few as 3 failing traces to as many as 214. The range of passing tests in training was between 31 and 169.

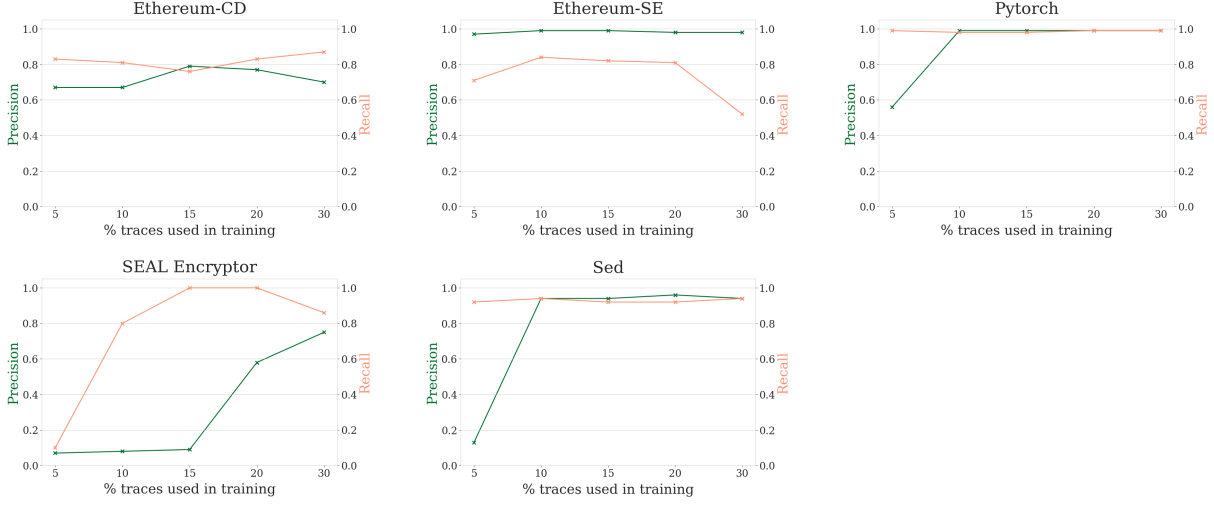


Figure 4: Precision and recall achieved by classification model over each PUT.

5.3 Q3. Comparison against state of art

Table 1 presents precision, recall, and specificity (TNR) achieved by the agglomerative hierarchical clustering proposed by Almaghairbe et al. [6] on each of the PUTs. Comparing the precision, recall and TNR of our approach versus hierarchical clustering, we find our approach clearly outperforms the clustering approach on all but the Ethereum-CD PUT. This is because the hierarchical clustering assumption does not hold for these programs. According to this assumption, passing traces tend to be grouped in a few big clusters and failing traces are grouped into many small clusters. However, for these programs, passing traces tend to be grouped in many small clusters based on their call sequence pattern, making it hard to distinguish them from failing traces by simply comparing cluster sizes.

With Ethereum-CD, the hierarchical clustering approach achieves precision and specificity of 100% and a recall of 49%. This is achieved with complete-linkage clustering, Euclidean distance and a cluster count equal to 10% of total traces. In contrast our approach achieves a precision of 80%, recall of 82% and specificity of 79%. To enable better comparison, we plot the precision-recall curve of the NN model in Figure 5 for Ethereum-CD, using 15% of the traces in training.

This curve shows the precision and recall of our trained model with respect to different values of the classification threshold. It is clear from the plot that for the same value of recall (49%), hierarchical clustering performs marginally better than our approach - 100% versus 99%. Hierarchical clustering works well over the Ethereum-CD PUT because the traces are clustered into just one big passing cluster and one failing cluster. Lack of cluster fragmentation improved accuracy of the hierarchical clustering approach. Nevertheless, our model achieves comparable performance for such traces. In addition, our model allows trade off between precision and recall by changing the classification threshold which may

be driven by requirements or priorities of the use case. This tradeoff is not possible with the clustering approach.

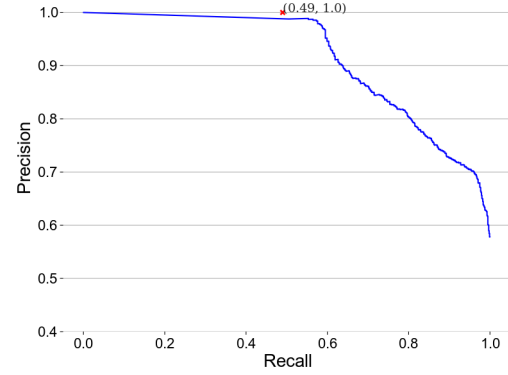


Figure 5: Precision-Recall curve for Ethereum-CD.

5.4 Threats to Validity

We see three threats to validity of our experiment based on the selection of subject programs and associated tests.

First, PUTs for 3 out of the 4 subject programs in our experiment were generated by seeding faults into a reference implementation. A reference implementation with only passing tests is not suitable for evaluating our approach. To address this, we generated a faulty implementation and ran the original tests through the PUT to gather both passing and failing traces. It is possible using real faults in place of seeded faults may lead to different results. However, Andrews et al. have shown the use of seeded faults leads to conclusions similar to those obtained using real faults [10, 26]. For one of the subject programs, Sed, we did not artificially seed faults, but instead used the existing implementation as it was accompanied by both passing and failing tests.

Second, the number of tests that accompanied our subject programs was not very large, ranging from 132 to 2254 tests. The NN models in our experiments produced good performance with small to medium sized test suites that may be automatically or manually generated. Our approach is constrained by the amount of training data and not by the size of the test suite. As a result for programs accompanied by large test suites, the NN model will need a larger training set (fraction of traces to be used in training might still be 15%). Nevertheless, the labelling effort for a fraction of the tests in our approach is still less than the current practise of labelling all the tests.

Finally, we conducted our study on subject programs from 4 different application domains which is not representative of all application domains. Given that our approach has no domain specific constraints, we believe it will be widely applicable.

6 CONCLUSION

In this paper, we propose a novel approach for designing a test oracle as a NN model, learning from execution traces of a given program. We have implemented an end to end framework for automating the steps in our approach, (1) Gathering execution traces as sequences of method invocations, (2) Encoding variable length execution traces into a fixed length vector, (3) Designing a NN model that uses the trace information to classify the trace as pass or fail.

We evaluated the approach using 5 realistic PUTs and tests. We found the classification model for each PUT was effective in classifying passing and failing executions, achieving an average of 89% precision, 88% recall and 92% specificity while only training with an average 15% of the total traces. We outperform the hierarchical clustering technique proposed in recent literature by a large margin of accuracy for 4 out of the 5 PUTs, and achieved comparable performance for the other PUT.

Practical use. Our approach can be applied out of the box for classifying tests for any software that can be compiled to LLVM IR. We gather execution traces for test inputs automatically, and require a small fraction of the traces to be labelled with their pass or fail outcomes (average 15% in our experiments). The remaining traces will then be classified automatically. Our approach is promising with high accuracy and has clear benefits over current industry practices where developers label *all* the tests. Our future work will focus on methods to improve the classification accuracy while reducing the training data requirement using techniques like transfer learning.

REFERENCES

- [1] Sed, linux stream editor. <https://linux.die.net/man/1/sed>, 2009.
- [2] *Ethereum Project (release 3.5)*, 2019. <https://github.com/ethereum/aeth>.
- [3] Aggarwal et al. A neural net based approach to test oracle. *ACM SIGSOFT Software Engineering Notes*, 29(3):1–6, 2004.
- [4] Miltiadis Allamanis, Marc Brockschmidt, and Mahmoud Khademi. Learning to represent programs with graphs. In *ICLR*, 2018.
- [5] Miltiadis Allamanis, Hao Peng, and Charles Sutton. A Convolutional Attention Network for Extreme Summarization of Source Code. In *ICML*, 2016.
- [6] Rafiq Almaghairbe and Marc Roper. Separating passing and failing test executions by clustering anomalies. *Software Quality Journal*, 25(3):803–840, 2017.
- [7] Uri Alon et al. code2vec: Learning distributed representations of code. *arXiv preprint arXiv:1803.09473*, 2018.
- [8] Uri Alon, Omer Levy, and Eran Yahav. code2seq: Generating sequences from structured representations of code. *arXiv preprint arXiv:1808.01400*, 2018.
- [9] Paul Ammann and Jeff Offutt. *Introduction to software testing*. Cambridge Univ. Press, 2016.
- [10] James H Andrews, Lionel C Briand, Yvan Labiche, and Akbar Siami Namin. Using mutation analysis for assessing and comparing testing coverage criteria. *IEEE Transactions on Software Engineering*, 32(8):608–624, 2006.
- [11] Earl Barr et al. The oracle problem in software testing: A survey. *IEEE TSE*, 41(5):507–525, 2015.
- [12] Antonia Bertolino. Software testing research: Achievements, challenges, dreams. In *Future of Software Engineering*, pages 85–103. IEEE Computer Society, 2007.
- [13] James Bowring et al. Active learning for automatic classification of software behavior. In *ACM SIGSOFT Software Engineering Notes*, pages 195–205, 2004.
- [14] Lionel C Briand. Novel applications of machine learning in software testing. In *QISIC'08*, pages 3–10. IEEE, 2008.
- [15] Yuriy Brun and Michael D Ernst. Finding latent code errors via machine learning over program executions. In *Proceedings of the 26th ICSE*, pages 480–490, 2004.
- [16] TY Chen et al. An orchestrated survey on automated software test case generation. *Journal of Systems and Software*, 2013.
- [17] I. Chung. A static approach to automated test data generation in the presence of pointers. In *ISCIS*, 2004.
- [18] Insang Chung and James M. Bieman. Generating input data structures for automated program testing. *Software Testing, Verification & Reliability*, 19:3–36, 2009.
- [19] Hyunsook Do, Sebastian Elbaum, and Gregg Rothermel. Supporting controlled experimentation with testing techniques: An infrastructure and its potential impact. *Empirical Software Engineering*, 10(4):405–435, 2005.
- [20] Emanuel S. Grant and Smruti Priyambada Nanda. A review of applications of formal specification in safety-critical system development. In *Proceedings of the 2020 the 4th International Conference on Compute and Data Analysis, ICCDA 2020*, page 208–215, 2020.
- [21] Robert M Hierons. Verdict functions in testing with a fault domain or test hypotheses. *ACM TOSEM*, 18(4):14, 2009.
- [22] Robert M Hierons. Oracles for distributed testing. *IEEE TSE*, 38(3):629–641, 2012.
- [23] Geoffrey Hinton et al. A fast learning algorithm for deep belief nets. *Neural computation*, 18(7):1527–1554, 2006.
- [24] Sepp Hochreiter and Jürgen Schmidhuber. Long short-term memory. *Neural computation*, 9(8):1735–1780, 1997.
- [25] R. Huang, X. Xie, T. Y. Chen, and Y. Lu. Adaptive random test case generation for combinatorial testing. In *2012 IEEE 36th Annual Computer Software and Applications Conference*, pages 52–61, 2012.
- [26] Hyunsook Do and G. Rothermel. On the use of mutation faults in empirical assessments of test case prioritization techniques. *IEEE Transactions on Software Engineering*, 32(9):733–752, 2006.
- [27] Yue Jia and Mark Harman. An analysis and survey of the development of mutation testing. *IEEE transactions on software engineering*, 37(5):649–678, 2011.
- [28] Hu Jin et al. Artificial neural network for automatic test oracles generation. In *Proceedings of CSSE*, volume 2, pages 727–730. IEEE, 2008.
- [29] Young Gon Kim, Hyoung Seok Hong, Doo-Hwan Bae, and Sung Deok Cha. Test cases generation from uml state diagrams. *IEE Proceedings-Software*, 146(1):187–192, August 1999.
- [30] Diederik P. Kingma and Jimmy Ba. Adam: A method for stochastic optimization. In *3rd International Conference for Learning Representations*, 2015.
- [31] William Langdon et al. Inferring automatic test oracles. In *Proceedings of the 10th SBST*, pages 5–6, 2017.
- [32] Chris Lattner. LLVM: An Infrastructure for Multi-Stage Optimization. Master's thesis, Computer Science Dept., University of Illinois at Urbana-Champaign, Urbana, IL, Dec 2002. See <http://llvm.cs.uiuc.edu>.
- [33] R. Lipka, T. Potuák, P. Brada, P. Hnetyanka, and J. Vinárek. A method for semi-automated generation of test scenarios based

- on use cases. In *2015 41st Euromicro Conference on Software Engineering and Advanced Applications*, pages 241–244, 2015.
- [34] H. Liu, F. Kuo, D. Towey, and T. Y. Chen. How effectively does metamorphic testing alleviate the oracle problem? *IEEE Transactions on Software Engineering*, 40(1):4–22, 2014.
- [35] Paulo Augusto Nardi and Eduardo Damasceno. A survey on test oracles. *Advances in Theoretical and Applied Informatics*, 1(2):50–59, 2015.
- [36] Adam Paszke and Soumith Chintala. Pytorch, 2017.
- [37] Andy Podgurski et al. Automated support for classifying software failure reports. In *Proceedings of 25th ICSE 2003.*, pages 465–475. IEEE, 2003.
- [38] Michael Pradel and Koushik Sen. Deepbugs: a learning approach to name-based bug detection. *Proceedings of the ACM on Programming Languages*, 2(OOPSLA):147, 2018.
- [39] Microsoft SEAL (release 3.2). <https://github.com/Microsoft/SEAL>, 2019. Microsoft Research, Redmond, WA.
- [40] Meenakshi Vannali et al. Using a neural network in the software testing process. *International Journal of Intelligent Systems*, 17(1):45–62, 2002.
- [41] Ke Wang, Rishabh Singh, and Zhendong Su. Dynamic neural program embedding for program repair. *ICLR*, 2018.