

Neural Exception Handling Recommender for Code Snippets

Anonymous Author(s)

ABSTRACT

With practical code reuse, the code fragments from developer forums often migrate to applications. Owing to the incomplete nature of such fragments, they often lack the details on exception handling. The adaptation for exception handling to the codebase is not trivial as developers must learn and memorize what API methods could cause exceptions and what exceptions need to be handled. We propose NEUREX, an exception handling recommender that learns from complete code, and accepts a given Java code snippet and recommends 1) if a try-catch block is needed, 2) what statements need to be placed in a try-catch block, and 3) what exception types need to be caught in the catch clause. Inspired by the sequence chunking techniques in natural language processing, we design NEUREX via a multi-tasking model with the fine-tuning of the large language model CodeBERT for the three above exception handling recommending tasks. Via the large language model, we enable NEUREX to learn the surrounding context, leading to better learning the identities of the APIs, and the relations between the statements and the corresponding exception types needed to be handled.

Our empirical evaluation on a real-world dataset shows that NEUREX achieves a high accuracy of **98.3%** and improves relatively by **56%** over the state-of-the-art approach in try-catch block necessity checking. Moreover, it can correctly decide both the need of try-catch block(s) and the statements to be placed in such blocks in **79.4%** of the cases, an improvement of **62X** over the baseline. Importantly, with an accuracy of **71.5%** (an improvement of **146X** over the baseline), NEUREX correctly recommend exception handling in all three tasks. Our extrinsic evaluation also shows that with its recommendations, NEUREX improves by **YY.Y%** in F-score over the existing approach in detecting exception-related bugs.

1 INTRODUCTION

The online question and answering (Q&A) forums, e.g., StackOverflow (S/O) provide important resources for developers to learn how to use software libraries and frameworks. While the code snippets in an S/O answer are good starting points, they are often incomplete with several missing details, even with ambiguous references, etc. Zhang *et al.* [16] have conducted a large-scale empirical study on the nature and extent of manual adaptations of the S/O code snippets by developers into their Github repositories. They reported that the adaptations from S/O code examples to their Github counterpart projects are prevalent. They qualitatively inspected all the adaptation cases and classified them into 24 different adaptation types. They highlighted several adaptation types including *type conversion*, *handling potential exceptions*, and *adding if checks* [16]. Among them, adding a try-catch block to wrap the code snippet and listing the handled exceptions in the catch clause are frequently performed, yet not automated by existing tools.

The adaptation process for exception handling is not trivial as Nguyen *et al.* [10] have reported that it is challenging for developers to learn and memorize what API methods could cause exceptions and what exceptions need to be handled. Kechagia *et al.* [7] found

that 19% of the crashes in Android applications could have been caused by insufficient documented exceptions in Android APIs. Thus, it is desirable to have an automated tool to recommend proper exception handling for the adaptation of online code snippets.

There exist several approaches to automatic recommendation of exception handling [2–4, 10, 13, 17]. They can be classified into four categories. The first category of approaches relies on a few *heuristics* on exception types, API calls, and variable types to recommend exception handling code [3]. These heuristic-based approaches do not always work in all cases. The second category of approaches utilized *exception handling policies*, which are enforced in all cases [4, 9]. However, the policies need to be pre-defined and encoded within the recommending tools. This is not an ideal solution considering the fast evolution of software libraries. To enable more flexibility than policy enforcement, the third category leverages *mining algorithms* that derive similar exception handling for two similar code fragments [13]. While avoiding hard-coding of the rules, these mining approaches suffer the issue of how much similar for two fragments to be considered as having similar exception handling. For the mining approaches, deterministically setting a threshold for frequent occurrences is also challenging.

To provide more flexibility in code matching, the fourth category follows *information retrieval* (IR) [10]. XRank [10] takes as input source code and recommends a ranked list of API method calls in the code that are potentially involved in the exceptions in a catch-try block. XHand [10] recommends the exception handling code in a catch block for a given code. Both use a fuzzy set technique to compute the associations between the API calls (e.g., `newBufferedReader`) and the exceptions (e.g., `IOException`).

While the IR-based approach achieves higher accuracy than the others [10], it has key limitations. First, it is not trivial to **pre-define a threshold** for feature matching for a retrieval of an exception type or an API element. The effectiveness of those IR techniques depends much on the correct value of such pre-defined threshold. Second, the IR-based techniques rely on the lexical values of the code tokens and API elements, whose names can be *ambiguous* in an incomplete code snippet. For example, the `Document` class in `org.w3c.dom` of the W3C library has the same simple name as the `Document` class in `com.google.gwt.dom.client` of Google Web Toolkit library (GWT). An API method to open/write/read a `Document` in the W3C library might need to catch a different set of exceptions than the one in GWT. Those IR-based techniques are not sufficiently flexible to handle such **ambiguous names**. Third, the IR techniques *do not consider the context of surrounding code*, thus, cannot leverage the *dependencies* among API elements to resolve the ambiguity of the names of the APIs and exceptions in an incomplete snippet.

In this paper, we propose NEUREX, a learning-based exception handling recommender, which accepts a given Java code snippet and recommends 1) *whether a try-catch block is needed for the snippet* (XBLOCK), 2) *what statements need to be placed in a try-catch block* (XSTATE) and 3) *what exception types need to be caught in the catch clause* (XTYPE). We find a motivation for such a data-driven,

learning-based approach from the previous studies reporting that exception handling for the API elements is frequently repeated across different projects [13, 18]. The rationale is that the designers of a software library have the intents for users to use certain API elements with corresponding exception types. Thus, we design NEUREX to learn from the statements in try-catch blocks and the exception types retrieved from *complete source code* in a large code corpus, and derive the above exception handling suggestions for the (*partial*) *code snippet* under study.

We leverage and fine-tune the large language model CodeBert [?] to capture the surrounding context with the dependencies among the API elements. Capturing such contextual information and the dependencies enable NEUREX to realize the idea “*Tell Me Your Friends, I’ll Tell You Who You Are*” to learn the identities of the API elements in a given (in)complete code, leading to better learning in XBLOCK, XSTATE and XTYPE. Inspired by sequence chunking in natural language processing (NLP), we formulate our problem as detecting one or multiple chunks of consecutive statements that need try-catch blocks. NEUREX also has the three tasks in a *multi-tasking* mechanism to enable the mutual impact among the learning, leading to better performance in all three tasks.

Our aforementioned idea gives NEUREX three advantages over the state-of-the-art IR approach. First, with the learning-based approach, NEUREX does not rely on a pre-defined threshold for explicit feature matching for the retrieval of the API elements or exception types. Second, instead of learning only the associations between the API elements and corresponding exception types, NEUREX has advantages in both predicting and training. During predicting, for a given incomplete code, the context enables NEUREX to *learn the identities of the API elements via the dependencies/relations* among them in the context, thus, avoiding the name ambiguity. Let us call it *dependency context*. During training, the complete code enables the identifications (i.e., the fully-qualified names) of the API elements. Third, the context of surrounding code also helps the model implicitly learn the important features to connect between the API elements and the corresponding exception types.

We have conducted several experiments to evaluate NEUREX. We have collected a large dataset of 5,726 projects from Github, with 19,379 code snippets that contain try-catch blocks. The result shows that NEUREX achieves a high accuracy of **98.3%** and improves relatively by **56%** over the state-of-the-art approach in try-catch block necessity checking. Moreover, it can correctly decide both the need of try-catch block(s) and the statements to be placed in such blocks in **79.4%** of the cases, an improvement of **62X** over the baseline. Importantly, with an accuracy of **71.5%** (an improvement of **146X** over the baseline), NEUREX correctly recommend exception handling in all three tasks. Our extrinsic evaluation also shows that with its recommendations, NEUREX improves by **YY.Y%** in F-score over the existing approach in detecting exception-related bugs.

In brief, this paper makes the following major contributions:

1. **[Neural Network-based Automated Exception Handling Recommendation]**. NEUREX is the first neural network approach to automated exception handling recommendation in three above tasks. NEUREX works for either complete or incomplete code.
2. **[Multi-tasking among three Exception Handling Recommendations]** We formulate the problem as sequence chunking with a multi-tasking mechanism to learn for three above tasks.

```

1 public static void addLibraryPath(String pathToAdd) throws Exception {
2     final Field usrPathsField =
3         ClassLoader.class.getDeclaredField("usr_paths");
4     usrPathsField.setAccessible(true);
5
6     //get array of paths
7     final String[] paths = (String[])usrPathsField.get(null);
8
9     //check if the path to add is already present
10    for(String path : paths) {
11        if(path.equals(pathToAdd)) {
12            return;
13        }
14    }
15
16    //add the new path
17    final String[] newPaths = Arrays.copyOf(paths, paths.length + 1);
18    newPaths[newPaths.length-1] = pathToAdd;
19    usrPathsField.set(null, newPaths);
20 }

```

Figure 1: StackOverflow post #15409223 on adding new paths for native libraries at runtime in Java

3. **[Empirical Evaluation]**. Our extensive evaluation shows NEUREX’s high accuracy in exception handling recommendation as well as in exception-related bug detection. Data and code is available at [5].

2 MOTIVATION

2.1 Motivating Examples

Let us use a few real-world examples to explain the problem and motivate our approach. Figure 1 displays a code snippet in an answer to the StackOverflow (S/O) question 15409223 on how to “*add new paths for native libraries at runtime in Java*”. The code snippet serves as an illustration in the S/O post, thus, does not contain all the details on what exceptions that need to be handled. It contains only a throw of a generic Exception in the method header (addLibraryPath). From Zhang *et al.*’s study [16], this code snippet was adopted by developers into their Github project named *armint* (Figure 2). *armint*’s developers handle in a try-catch block several exceptions caused by `java.lang.Class.getDeclaredField(...)` (line 7) according to JDK’s documentation, e.g., `NoSuchFieldException`, `SecurityException`, `IllegalArgumentException`, and `IllegalAccessException` (line 24, Figure 2).

The manual adaptation on exception handling by inserting a try-catch block is quite popular, yet not automated by any tools [16]. Such manual adaptation for a code snippet could lead to exception-related bugs, which could cause serious issues including crashes or unstable states. It is not trivial for developers to memorize what API methods could cause exceptions and what exceptions need to be handled [10]. Thus, it is desirable to have an automated tool to recommend proper exception handling in order to adapt the incomplete code snippets. Such a tool could recommend if a try-catch block is needed for the snippet, what lines need to be included in that block, and what exception types need to be handled.

OBSERVATION 1 (Exception Handling Recommendation). *Automated recommendation to handle exceptions is desirable to assist developers in adapting incomplete code snippets into their codebases.*

As explained in Section 1, four categories of automated approaches have been proposed to recommend exception handling [2–4, 10, 13]. While early approaches were not effective in all cases

```

1  /** ...
2  * taken from http://stackoverflow.com/questions/15409223/
3  * adding-new-paths-for-native-libraries-at-runtime-in-java
4  */
5  private static void addLibraryPath(String pathToAdd) {
6      try {
7          final Field usrPathsField =
8              ClassLoader.class.getDeclaredField("usr_paths");
9          usrPathsField.setAccessible(true);
10
11         // get array of paths
12         final String[] paths = (String[]) usrPathsField.get(null);
13
14         // check if the path to add is already present
15         for (String path : paths) {
16             if (path.equals(pathToAdd)) {
17                 return;
18             }
19         }
20
21         // add the new path
22         final String[] newPaths = Arrays.copyOf(paths, paths.length + 1);
23         newPaths[newPaths.length - 1] = pathToAdd;
24         usrPathsField.set(null, newPaths);
25     } catch (NoSuchFieldException | SecurityException |
26             IllegalArgumentException | IllegalAccessException e) {
27         throw new RuntimeException(e);
28     }
29 }

```

Figure 2: GitHub project armint adapts SO post in Figure 1

due to their *heuristics* [3], the *exception policies* are too strict in enforcing them, yet requires the rules to be encoded in the tools [4, 9]. The state-of-the-art *information retrieval*-based approaches (e.g., XRank/Xhand [10]) have been shown to outperform the existing approaches including the *mining approaches* [13] (which suffers the issue of setting a threshold for frequent occurrences).

However, the state-of-the-art, IR-based approaches [10] have the limitations. First, it is not trivial to pre-define a threshold for feature matching for a retrieval, e.g., the threshold to determine the associations between an API call (e.g., `getDeclaredField`) and an exception type (e.g., `NoSuchFieldException`). Thus, the pre-defined threshold affects much their effectiveness. Second, relying on the lexical values of API elements' names, they suffer the issue of ambiguous names of the APIs or exceptions in an incomplete code snippet (e.g., the API method `get` at line 6 of Figure 1 occurs in multiple libraries), which might not be parseable for fully-qualified name resolution. Thus, this reduces effectiveness. Finally, they consider only the associations between an API method and an exception type, and discard the surrounding context. For example, they compute the association between the names of the API call (e.g., `getDeclaredField`) and the exceptions to be handled (e.g., `NoSuchFieldException`, `SecurityException`, etc.). Without the context, it is challenging to decide the identities of the APIs and exceptions via only simple names.

Now, consider the complete code example in Figure 3 from the Github project named *quarkus*. While there are differences between the complete code in Figure 3 and the adapted code in Figure 2, the lists of the handled exceptions are the same (line 8 in Figure 3 and line 24 in Figure 2) due to the presence of the API call to `getDeclaredField` in both code. This is expected because the designers of the JDK library have the intent for developers to use the API method `getDeclaredField` within a try-catch block and to handle the list of exceptions as in line 8 of Figure 3. Thus, to adapt the incomplete code snippet in Figure 1, one could learn from the public code repositories to properly handle the exceptions.

```

1 public Object readField(Class<?> clazz, String name, Object instance) {
2     try {
3         Field field = clazz.getDeclaredField(name);
4         if (!field.isAccessible()) {
5             field.setAccessible(true);
6         }
7         return field.get(instance);
8     } catch (NoSuchFieldException | SecurityException |
9             IllegalArgumentException | IllegalAccessException e) {
10         throw new RuntimeException("Cannot read field value: " + clazz.getName()
11             + "#" + name, e);
12     }
13 }

```

Figure 3: Project quarkus with same exception handling

```

1 Charset charset = Charset.forName("US-ASCII");
2 try {
3     BufferedReader reader = Files.newBufferedReader(file, charset);
4     String line = null;
5     while ((line = reader.readLine()) != null) {
6         System.out.println(line);
7     }
8 } catch (IOException x) {
9     System.err.format("IOException: %s\n", x);
10 }

```

Figure 4: Using `newBufferedReader` to read from a file

OBSERVATION 2 (Regularity of Exception Handling). *Finding the patterns from complete code in existing code corpora could be a good strategy to learn to properly handle the exceptions in adapting an (incomplete) code snippet into a codebase.*

OBSERVATION 3 (Relations between API methods and Exceptions). *The presence of certain API elements helps decide the exceptions that need to be handled.*

For example, the relation between `java.lang.Class.getDeclaredField` and the exceptions `NoSuchFieldException`, `SecurityException`, `IllegalArgumentException`, and `IllegalAccessException` can be learned from the code corpora. Thus, a model can learn to recommend those exceptions for an incomplete code snippet involving `getDeclaredField`.

OBSERVATION 4 (Surrounding Context help resolve name ambiguity). *The surrounding code context can help resolve the ambiguity of the names of those elements in incomplete code snippets.*

For an incomplete code snippet, as explained earlier, the simple names of the API elements (methods, fields, classes) could be ambiguous. However, if a model can learn from the complete code the fully-qualified names of the API elements, the surrounding context consisting of those API elements and their program dependencies can help a model decide the correct identities of the API elements, leading to correct prediction of the handled exceptions.

In Figure 1, to derive the identities of `Field` (line 2), `getDeclaredField` (line 2), `setAccessible` (line 3), `get` (line 6), etc., a model could rely on the dependencies among them in the surrounding context. For example, the return type of `getDeclaredField` is `Field` (thanks to line 2), which has an API method named `setAccessible` (thanks to line 3) and another API method named `get` (thanks to line 6). Considering all those dependencies among the API elements in the context and with the knowledge learned from the complete code, a model could decide that in the code snippet, the identity of `Field` is `java.lang.Class.Field`, that of `setAccessible` is `java.lang.Class.Field.setAccessible`, and that of `get` at line 6 is `java.lang.Class.Field.get`.

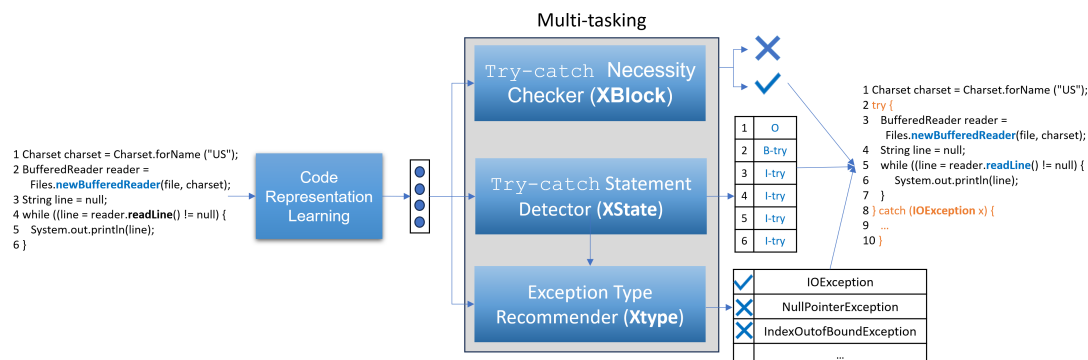


Figure 5: NEUREX: Architecture Overview

The rationale is that a model could see such dependencies among those API elements before in a complete code in training.

For the list of statements in an incomplete code, not all of them needs to be wrapped around in a try-catch block. For example, considering the example of using `newBufferedReader` in Figure 4. While the API call `java.nio.file.newBufferedReader` needs to be within a try-catch block, the statement at line 1 to retrieve the character set does not. Moreover, the statement at line 5 with the API call to `readLine` needs to be wrapped in a try-catch block as well.

OBSERVATION 5 (Learn to decide what statements to be in a Try-Catch block). *A model can learn from the code corpora what statements need to be placed within a try-catch block or not.*

2.2 Key Ideas

We introduce NEUREX with the following three functionality for exception handling recommendation: given a Java code snippet, it will 1) predict if a `try-catch` block is required (XBLOCK), 2) point out which statements in the code snippet need to be placed in a `try-catch` block (XSTATE), and 3) suggest what exceptions need to be caught in the catch clause (XTYPE). Following the above Observations, we design NEUREX with the following key ideas:

2.2.1 [Key Idea 1] Neural Network-based approach to Exception Handling Recommendation by Learning from Complete Code. Instead of deterministically deriving the exceptions to be handled for a given (incomplete) code snippet, following Observation 2, we design a deep learning model (DL) to learn to properly handle the exceptions in the three above tasks. By learning from the try-catch blocks of the complete code in the open-source projects in the training process, our DL model can help the adaptation tasks.

2.2.2 [Key Idea 2] Leveraging Context to avoid name ambiguity and Learning the Relations between API elements and Exception types. Instead of learning only the associations between an API element and exception types as in IR-based approaches, we leverage as the context the complete code in the training corpus, which are parsable and provide the identities (i.e., FQNs) of the API elements. In predicting for a code snippet, NEUREX will also leverage the context and dependencies among the API elements to learn their identities (see Observation 4). Importantly, that leads to the learning of the relations between the key API elements in the context and the handled exception types (Observation 3).

2.2.3 [Key Idea 3] Leveraging Sequence Chunking with a Large Language Model and Multi-tasking. Inspired by the sequence chunking techniques [1] in NLP, we formulate our problem as identifying one or multiple chunks of consecutive statements that need to be placed within try-catch blocks. We leverage and fine-tune the large language model CodeBERT [6] to learn the relations among statements with the API elements. We also leverage the multi-tasking framework for all three tasks XBLOCK, XSTATE, and XTYPE because the learning for one task can benefit for another task and vice versa.

3 NEUREX OVERVIEW

Figure 5 displays the overview architecture of NEUREX. Generally, it has three main components dedicated to the three tasks: for a given (in)complete code snippet, 1) XBLOCK aims to check the necessity of try-catch blocks, 2) XSTATE aims to detect which statements need to be in a try-catch block, and 3) XTYPE aims to detect the exception types need to be caught in the catch clauses. We support the detection of one or multiple try-catch blocks if any.

During training, the code snippets with `try-catch` blocks are used as the positive samples and the ones without them as the negative samples. For a positive sample, the statements inside the `try` blocks and the exception types in the `catch` clauses are used as the labels for training. The negative samples are labeled as not needing a `try-catch` block. In prediction, NEUREX accepts as input any incomplete or complete code snippet without a `try-catch` block, and predicts the results for those tasks. The predicted results from `XSTATE` and `XTYPE` are considered only when `XBLOCK` predicts `Yes`, i.e., a need of a `try-catch` block for the given code snippet.

The input code is used as the input of a large language model to act as the code representation learning model to produce the vector representations for the (sub)tokens and statements in the source code. We use CodeBERT [6] as it is capable of producing embeddings that capture both the syntactic and semantic information.

The vectors are used as the inputs for three components. The prediction is made on the vectors that are attained by composing the embeddings of individual (sub)tokens into the ones for a statement and for a block of statements. First, XBLOCK is modeled as a binary classifier on deciding whether the input code needs at least one `try-catch` block. Second, inspired by the sequence chunking techniques [1] in NLP, we model the second task, XSTATE, as



Figure 6: Try-catch Necessity Checker (XBLOCK)

learning to tag/label each statement in the code snippet with either 0 (i.e., the statement is outside of a try-catch block), B-try (i.e., it is the beginning of a try-catch block), or I-try (i.e., it is inside of such a block). During training, the statements within or outside of the try-catch blocks enable us to build the tags/labels for them.

The last task, XTYPE, is modeled as a set of binary classifiers, each is responsible for deciding whether an exception type of interest needs to be caught in the catch clause. An *Yes* outcome indicates the need to catch a specific exception type of interest in the set of libraries under consideration. An *No* outcome indicates otherwise. During training, the exception types for each try-catch block in the positive samples are used as labels. During prediction, for each predicted block from XSTATE (starting from a statement with B-try to the last respective I-try), XTYPE uses the embeddings for those statements to predict the corresponding exception types. Finally, from the results in all three tasks, NEUREX forms the final output.

4 XBLOCK: TRY-CATCH NECESSITY CHECKER

Given an input code snippet, we first split it into the statements. Each statement is then tokenized into sub-tokens using the CodeBERT tokenizer. We use a special separator token [SEP] to concatenate the tokenized statements, and add a [CLS] token at the beginning. As in CodeBERT, we take the [CLS] token to be the representation of the entire code snippet.

We fine-tune a CodeBERT (MLM) for this problem. Given the good performance of CodeBERT on many code-related downstream tasks (<https://github.com/microsoft/CodeXGLUE>), we expect it to be able to learn the correlation between important code tokens that would signal the need of exception handling. Importantly, by providing the code snippet, we expect to leverage the code context in which the API elements are used with regard to one another. For example, in Figure 5, CodeBERT is expected to learn that the APIs `newBufferedReader` of the class `Files` and `readLine` of the class `BufferedReader` are used often together in API usages and they require `IOException`. For the input incomplete code snippet, CodeBERT is expected to learn such relations/connections to avoid name ambiguity and to connect them with the exception types.

During training, as we use exactly one CodeBERT, all three modules (Sections 5 and ??) contribute to the signal for updating the



Figure 7: Try-catch Statement Detector (XSTATE)

CodeBERT parameters. In XBLOCK, we feed the vector representation of the [CLS] token to a linear layer (Feed-forward neural network - FFNN) and use a softmax function to learn the decision as to whether the input code needs to handle any exceptions.

5 XSTATE: TRY-CATCH STATEMENT DETECTOR

The goal of XSTATE (Figure 7) is to decide if a statement in the given code snippet needs to be in a try-catch block or not. For code representation learning, we use one single CodeBERT [6] model as in XBLOCK (see Figure 6) to produce the embedding for code (sub)-tokens. For the input code, each [SEP] token represents the statement preceding it. Note that semicolon would not be as consistent as our explicit separator, because some statements might not end with a semicolon. A semicolon also could appear inside string literals and for-loop conditions.

The advantage in using CodeBERT on the entire code snippet has two folds. First, as in Key idea 2, the context of the entire code facilitates our model to learn the identities of the API elements, thus, making the connections between the APIs and the presence of try-catch blocks. For example, `write` in the statement 1 could be determined to belong to `OutputStream` in `JDK`. Thus, that leads to better learning to place that statement inside a try-catch block. Second, we expect that CodeBERT would learn *the data and control dependencies among the consecutive statements* separated by the special tokens [SEP]. Those dependencies would help the model better decide whether some consecutive statements need to be placed together in a try-catch block. For example, in Figure 5, the statements at lines 2–5 have data dependencies, thus, they should be in the same try-catch block.

We take the embedding produced by CodeBERT for each [SEP] token as the statement embedding and feed it to a layer with Feed-forward neural network (FFNN). We then use a softmax function to learn to label each corresponding statement with one of three tags: 0 tag means that the statement is outside of any try-catch blocks; B-try tag means that the statement begins a try-catch block; and I-try tag means that the statement is inside a try-catch block and is not the first line of that block. For example, in Figure 7, the embedding computed by CodeBERT for the first [SEP], which represents the

statement `out.write(...)`, is classified by the first FFNN+Softmax layer into the B-Try category/label because it is the first statement of a try-catch block. However, the embedding for the second [SEP], representing `print(node.getBody(...))`, is labeled as I-Try because it is the second statement of the try-catch block. Finally, the embedding of the third [SEP], is labeled as 0 because the statement `return null;` does not need to be in the try-catch block. With this tag encoding, we can support multiple try-catch blocks in which the statement with the B-Try tag is the start of a try-catch block and the statement with the last respective I-Try tag is the end of that block. A new block will be formed with another statement having a B-Try tag.

During training, the labels for all the statements are known from the code. During prediction, our model will assign the labels to the statements, from which we can derive the try-catch blocks and what statements belonging to each block.

6 XTYPE: EXCEPTION TYPE RECOMMENDER

XTYPE uses the same CodeBERT that is shared among other modules. We expect CodeBERT to learn the relation between statements in the same try-block, as well as the relation between the try-block and the corresponding exceptions that need to be caught.

For each try block, we first take the vector outputs of [SEP] tokens, from CodeBERT, that correspond to statements in the try block. Then, we add them together to get the vector representation of the try block, before feeding it into a linear layer and use a sigmoid function to do binary classification for the most common exceptions that are in the library. If we included more libraries for the study, the classification head will likely need to change to a different one.

During training, we know all the tags associated with every line in the input code snippet, so we know how to connect them, while during prediction, the model uses tags predicted in XSTATE in order to make the connection.

7 EMPIRICAL EVALUATION

7.1 Research Questions

We conducted several experiments to evaluate NEUREX. We seek to answer the following questions:

RQ1. [Effectiveness on Try-Catch Necessity Checking] How accurate is NEUREX in predicting whether a given code snippet needs to have a try-catch block?

RQ2. [Effectiveness on Try-Catch Statement Detection]. How accurate is NEUREX in predicting which statements in a given code snippet needs to be placed in a try-catch block?

RQ3. [Effectiveness on Exception Type Recommendation]. How accurate is NEUREX in recommending what exception types need to be handled in the catch clause of a try-catch block?

RQ4. [Ablation Study]. How do various components in NEUREX affect its performance?

RQ5. [Extrinsic Evaluation on Exception-related Bug Detection]. How well does NEUREX detect exception-related bugs?

7.2 Empirical Methodology

7.2.1 Datasets. We conducted experiments on two datasets: 1) *Github dataset* for intrinsic evaluation on exception handling recommendation tasks (XBLOCK, XSTATE, XTYPE), and 2) *FuzzyCatch* dataset [10] for extrinsic evaluation on exception-related bug detection. We collected the Github dataset as follows. We first chose in Github 5,726 Java projects with the highest ratings that use the following libraries: jodatime, JDK, Android, xstream, GWT, and Hibernate. These are the well-established libraries that have been used in several prior research on the topics related to APIs [12, 14]. We then selected the methods with at least one try-catch block. If there is one try-catch block, we take the body of the method as the code snippet. If there are multiple try-catch blocks in a method, we split the method into multiple code snippets by checking the above and below statements, one by one, starting from the closest one for each try-catch block, to verify if the statement is included in the other block. If not, we put it in the current code snippet. If yes, we finish the current one. In total, we have 19,379 code snippets containing one try-catch block as positive samples. We also randomly selected from the same Github projects the same amount of code snippets that do not have any try-catch block as the negative samples.

For extrinsic evaluation, we used FuzzyCatch dataset, provided by the authors of XRank/XHand [10], which contains 608 samples of methods with exception-related bugs (missing try-catch blocks or missing catching some exceptions). We also randomly selected from the projects in FuzzyCatch dataset the same amount of code snippets with no exception-related bugs as the negative samples.

7.2.2 RQ1. Effectiveness on Try-Catch Necessity Checking

Baselines. We compared XBLOCK against XRank [10] (XRank is part of FuzzyCatch tool). XRank computed the exception risk score for each API call. If one score of a call in the snippet is higher than a threshold, it is considered as needing a try-catch block.

Procedure. We used the Github dataset and randomly split both the positive and negative sets into 80%, 10%, and 10% of the code snippets for training, tuning, and testing.

Tuning. We tuned NEUREX with autoML [8] for the following key hyper-parameters to have the best performance: (1) Epoch size (50, 100, 150); (2) Batch size (32, 64, 128); (3) Learning rate (0.001, 0.003, 0.005); (4) Vector length of feature embeddings and its output (64, 128, 256); (5) Number of R-GCN layers (4, 6, 8).

Metrics. We use **Recall**, **Precision**, and **F-score** to evaluate the performance of the approaches. They are calculated as $Recall = \frac{TP}{TP+FN}$, $Precision = \frac{TP}{TP+FP}$, $F\text{-score} = \frac{2*Recall*Precision}{Recall+Precision}$. TP: true positive, FN: false negative, and FP: false positive.

7.2.3 RQ2. Effectiveness on Try-Catch Statement Detection

Baselines. None. FuzzyCatch (XRank/XHand) does not have this.

Procedure. We processed the Github dataset for this experiment as follows. For the snippets that need try-catch, but were predicted as not, we consider them as incorrect because the resulting statements predicted from XSTATE do not make sense for incorrect XBLOCK's detection. The snippets that do not need try-catch, but were predicted as yes, we also consider them as incorrect for the same reason. Thus, for the evaluation of XSTATE, we used the set of code snippets that XBLOCK predicted correctly as needing a try-catch block. We used the same data splitting scheme with 80%, 10%, and 10% for

training, tuning, and testing as in RQ1. Each code snippet in the testing set and the trained R-GCN model in XBLOCK are the input of the GNNExplainer model in XSTATE in this experiment.

Tuning. We used the same parameters as in GNNExplainer [15]. It also has a parameter on the limit of the number N of the nodes in the explanation sub-graph. We varied N from 1 to 10. The average number of statements in a try-catch block in Github dataset is 5.9.

Metrics. If XSTATE predicts for a statement correctly if it is in a try-catch block or not, we count it as a correct case. Otherwise, it is an incorrect one. **Accuracy** is defined as the ratio between the number of correct statements over the total number of statements.

7.2.4 RQ3. Effectiveness on Exception Type Recommendation

Baselines. None. XRank/Xhand do not support this feature.

Procedure. We processed the Github dataset for this experiment in the same manner as in RQ2 because the result of XTYPE (i.e., what exception types need to be in the catch clause) makes sense only when one knows that the given code snippet needs to have a try-catch block. Thus, for the evaluation of XTYPE, we used the set of code snippets that XBLOCK predicted correctly as needing a try-catch block. We used the same splitting as RQ2. The exception types in the catch clauses are used as the labels.

Tuning. We tuned NEUREX with autoML [8] for the key hyper-parameters to have the best performance as in RQ1 including epoch size, batch size, learning rate, vector length, and R-GCN layers.

Metrics. Let us use E and P to denote the set of the exception types in the oracle and the set of predicted ones for one code snippet in the testing set. We aim to measure 1) how precise NEUREX predicts the exception types (**Precision**), i.e., how accurate the predicted types in P , and 2) how much NEUREX can cover in its prediction with respect to the oracle (**Recall**), i.e., how much of E that the predicted set P can cover. Toward measuring Precision and Recall, we define **Hit- n** as the number of the cases in which the predicted set P contains *at least* n correct exception types, i.e., P and E overlaps *at least* n exception types regardless of the sizes of both sets.

In Github dataset, more than 98.1% of the code snippets have 1–3 exception types in a catch clause. Thus, we compute Hit- n , Precision, and Recall for the size of E ($|E|$) from 1–3 and 3+, and for the size of P ($|P|$) from 1–3 and 3+. When computing Recall, we use the set E as the basis. Recall at a size N_E of E is computed as the ratio between Hit- n at that size and the total number of cases with that size N_E . We compute Recall for all $N_E = 1-3$, and 3+, and $n=1-N_E$. We also define **Hit-All $_{Rec}$** as Hit- n when the number n of overlapping exception types is equal to $|E|$, i.e., all exception types in the oracle set for a code snippet are covered. When computing Precision, we use the set P as the basis. Precision at a size N_P of P is computed as the ratio between Hit- n at that size and the total number of cases with that size N_P . We compute Precision for all $N_P = 1-3$, and $n=1-N_P$. We also define **Hit-All $_{Prec}$** as Hit- n when the number n of overlapping exception types is equal to $|P|$, i.e., all predicted types in the predicted set P for a snippet are correct.

7.2.5 RQ4. Ablation Study. In this experiment, we aim to evaluate the impact on the performance of the key features: sequences of code tokens and Abstract Syntax Tree. We removed one key feature at a time and compared the performance with the original model to evaluate its impact. We used the same evaluation metrics as in the

Table 1: Try-Catch Necessity Checking Comparison (RQ1)

	Github Dataset	
	NEUREX	XRank [10]
Recall	0.79	0.81
Precision	0.68	0.53
F-score	0.73	0.63

previous experiments. Because our model is designed with R-GCN, we cannot remove it to evaluate the impact of dependencies.

7.2.6 RQ5. Extrinsic Evaluation on Exception-related Bug Detection . Baselines. FuzzyCatch [10] leverages XRank to detect the exception-related bugs, which are the code snippets that were supposed to handle exceptions, but missed try-catch blocks and/or exceptions.

Procedure. We trained NEUREX on the Github dataset and detected the exception-related bugs in FuzzyCatch bug dataset.

Metrics. We compared the result against the oracle in FuzzyCatch dataset. If a model correctly detects a (non)buggy snippet (missing a try-catch block or exceptions), we consider it as correct. Otherwise, it is a miss. We use **Recall**, **Precision**, and **F-score** as in RQ1.

8 EMPIRICAL RESULTS

8.1 Comparison on Try-Catch Necessity Checking Effectiveness (RQ1)

As seen in Table 1, NEUREX achieves high performance across two datasets. With a Precision of 68%, it can decide correctly 2 out of 3 cases if a code snippet needs a try-catch block or not. With a Recall of 79%, NEUREX covers 4 out of 5 cases that needs to be placed in a try-catch block. Users just need to find 1 out of 5 cases. As a result, it achieves a high F-score of 0.73. In comparison, NEUREX improves relatively over XRank 28.3% in Precision and 12.3% in F-score.

Examining the result, we reported the following. First, if the association score of *only one API method* in the snippet and *one exception* is higher than a threshold, XRank decides that a try-catch block is needed. Thus, it often tends to output “Yes”. *Its recall is slightly better, but precision is just marginally better than a coin toss (0.53) in our balanced dataset. That leads to lower F-score than NEUREX.* Second, the decisions on the necessity of a try-catch block or the exception types depend on the pre-defined thresholds in XRank on those association scores. Thus, those pre-defined thresholds might not be suitable across the libraries. Third, for the incomplete code snippets in which the names of the API methods in different packages or libraries are the same (e.g., `toString` or `getText` in various JDK packages), XRank cannot distinguish them and use one entry in the dictionary for them due to its IR approach. In contrast, unlike XRank which considers only the API method calls in a try-catch block, NEUREX considers the code in the block as the context to learn the program dependencies/relations among the names of those API elements. That is, it leverages the relations among the names of API elements to learn their identities, thus, deciding better the need of try-catch blocks and the corresponding exception types.

Take as an example a code snippet (not shown) in our dataset with the presence of `getText`. This name is popular with a very large number of API method candidates. However, considering the relation between `css` and `getText` in the code `...css().getText()`, the

Table 2: Try-Catch Statement Detection Effectiveness (RQ2)

	Accuracy									
	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10
NEUREX	0.42	0.47	0.59	0.66	0.71	0.74	0.76	0.77	0.78	0.79

N_x is number of nodes in the explanation sub-graph (try-catch block)

```

1 int ret = -1;
2 try {
3     FileInputStream fin = new FileInputStream(path);
4     int length = fin.available();
5     byte[] buf = new byte[length];
6     fin.read(buf);
7     ret = loadFromBuffer(buf);
8     fin.close();
9 } catch (FileNotFoundException e) {
10     Log.e(TAG, "error:" + e);
11     e.printStackTrace();
12 } catch (IOException e) {
13     Log.e(TAG, "error:" + e);
14     e.printStackTrace();
15 }
16 return ret;

```

Highlighted statements with highest scores contain three crucial API method calls relevant to the exception types at lines 9 and 12.

Figure 8: Correct Exception Handling Suggestion by NEUREX

number of candidates for `getText` is only 4. Finally, considering the return value of `getText` as an argument of `setInnerText(...)` in the code 'setInnerText(...css().getText())', only one candidate is remained: `com.google.gwt.resources.client.CssResource.getText()`. Thus, those relations actually help identify the API elements, leading to better decision in NEUREX on the try-catch block and exception types. Because it has not seen any try-catch block involving `com....getText()` and those related ones, NEUREX decides that the code snippet does not need a try-catch block. In contrast, XRank considers only the *pairwise* associate scores between an *individual API method call* and the exception types in a catch clause. It disregards those above relations/dependencies among the API names. Thus, it might misunderstand that `getText` needs a try-catch due to the co-occurrences of other API elements that need one. That is, without the dependencies, XRank might make incorrect identification of the API elements via their names, leading to incorrect exception recommendation.

8.2 Try-Catch Statement Detection (RQ2)

Table 2 displays the result on detecting the statements that need to be placed in a try-catch block. N_x is a parameter in GNNExplainer that defines the number of nodes in the explanation graph \mathcal{G}_C , i.e., the number of statements to be placed in the try-catch block. As the number of nodes (statements) in \mathcal{G}_C increases, the number of correct statements covered also increases, thus, accuracy increases. However, as the number of statements increases higher than 5, accuracy increases more slowly. In our dataset, the average size of a try-catch block is 5.9 statements. As seen, the accuracy as $N_x=6$ is 74%. That is, by pointing out 6 statements on average, NEUREX can correctly suggest 74% of the total number of statements in the dataset that need to be placed in try-catch blocks. That is, it points out correctly 4.5 out of 6 statements to be in a try-catch block. For the statements that do not need to be placed in a try-catch block, NEUREX predicts correctly with 63% accuracy (not shown).

Table 3: Detailed Results on Different Numbers of Exception Types in a catch clause in Oracle Set (RQ3) (Recall)

# Ex. Types in catch clause in Oracle Set	Metrics	Accuracy
1 (1,385 instances)	Hit-1	918 (66%)
2 (98 instances)	Hit-1	75 (77%)
	Hit-2	41 (42%)
3 (18 instances)	Hit-1	12 (67%)
	Hit-2	5 (28%)
	Hit-3	3 (17%)
3+ (30 instances)	Hit-1	18 (60%)
	Hit-2	10 (33%)
	Hit-3	4 (13%)
	Hit-All _{Rec}	962 (63%)

The sum of the percentages in each row section is not 100% because Hit-1 contains Hit-2, which contains Hit-3, and so on. Hit- n : number of overlap between the predicted set and the oracle set is at least n exception types.

Example. Figure 8 displays an example that NEUREX made correct suggestions. **First**, it made a correct suggestion on the need of a try-catch block for the code at lines 1–8, 16. **Second**, GNNExplainer pointed out that XBLOCK used all the statements at lines 3–8 for such correct prediction. As a consequence, NEUREX correctly suggests to place lines 3–8 into a try-catch block. Note that, it also correctly pointed out that lines 1 and 16 do not need to be inside the try-catch block. **Third**, GNNExplainer gives three statements at lines 3, 6, and 8 highest scores. We can see that those lines contain three crucial API method calls: 1) `FileInputStream`, 2) `read`, and 3) `close`. **Fourth**, those three lines have data and control dependencies, which could help the model learn the identities of the API elements via their names `FileInputStream`, `read`, and `close`, despite that the code snippet does not have the fully-qualified names for those API elements. This confirms the need of integrating *program dependencies* in our solution. **Finally**, NEUREX was also able to learn from the training corpus that those names refer to those API elements, which often correspond to the following exception types: 1) `FileInputStream` with `FileNotFoundException`, and 2) `FileInputStream.read` and `FileInputStream.close` with `IOException`.

8.3 Exception Type Recommendation (RQ3)

8.3.1 Recall on Exception Type Recommendation. Table 3 displays the *Recall* result on how well NEUREX covers on the actual exception types in the catch clauses in the oracle. The result is with respect to the instances (code snippets) in the dataset with different numbers K of exception types in the catch clauses: $K =$ the number of exception types in a catch clause in the oracle = 1, 2, 3, 3+. For example, in the oracle, there are 98 instances with 2 exception types in a catch clause. NEUREX's predicted set correctly contains all 2 exception types for 41 instances (42%) (Hit-All_{Rec}). The predicted set contains *at least 1 out of 2* exception types for 75 instances (77%).

There are 1,385 instances (90.5%) over 1,531 total instances with a single exception type in the catch clause in the oracle in the testing dataset. NEUREX covers correctly the exception type in 918 (66%) of the instances. There are 98 instances with two exception types in the oracle and it correctly suggests both types in 41 cases (42%).

Note that Hit-All_{Rec} = Hit- n when n (the number of overlaps between the predicted and oracle sets) = K (the number of exception types). For $K=1..3$, which is a total of 1,501 instances (98.1%),

Table 4: Detailed Results on Different Numbers of Exception Types in a catch clause in Predicted Set (RQ3) (Precision)

# Ex. Types in catch clause in Predicted Set	Metrics	Accuracy
1 (1,154 instances)	Hit-1	442 (38%)
2 (294 instances)	Hit-1	90 (31%)
	Hit-2	61 (21%)
3 (83 instances)	Hit-1	27 (33%)
	Hit-2	23 (28%)
	Hit-3	6 (7%)
	Hit-All _{Prec}	509 (33%)

The sum of the percentages in each row section is not 100% because Hit-1 contains Hit-2, which contains Hit-3, and so on. Hit- n : number of overlap between the predicted set and the oracle set is at least n exception types.

Table 5: Impact of Different Features on XBLOCK (RQ4)

	NEUREX w/o SOT	NEUREX w/o AST	NEUREX
Recall	0.69	0.71	0.79
Precision	0.64	0.57	0.68
F-score	0.66	0.63	0.73

SOT: Sequence of tokens; AST: Abstract Syntax Tree

NEUREX covers all the exception types (Hit-All_{Rec}) in 962 instances (63%) in the testing dataset. That is, developers do not have to search for other exception types in 63% of the cases. Thus, it achieves high Hit-All_{Rec} in 98.1% of the entire dataset.

8.3.2 Precision on Exception Type Recommendation. Table 4 shows the *Precision* result, which is shown with respect to different numbers K of *predicted exception types* in the catch clauses. For example, as seen in Table 4, there are a total of 294 instances (code snippets) in which NEUREX predicted two exception types in a try-catch block. Among them, with Hit-1=31%, there are 90 instances in which at least one predicted exception type is correct. With Hit-2=21%, there are 61 instances in which both the predicted exception types are correct (some types might be missing). Producing the exact-matched sets (Hit-All) for all exception types when $K \geq 3$ is still challenging, however, those cases are only 1.9% in the entire dataset. We do not have the row for 3+ because in our dataset, 98.1% of the cases have ≤ 3 exception types, thus, we set 3 as the limit of the number of exception types for XTYPE.

Importantly, Hit-All_{Prec} = Hit- n when n (the number of overlaps between the predicted and oracle sets) = k (the number of exception types predicted by NEUREX). For $k=1..3$, which is a total of 1,531 instances (98.1%), **NEUREX predicts correctly all the exception types (Hit-All_{Prec}) in 509 instances (33%)**. That is, in 509 instances (i.e., 33%), all the predicted exception types are actually the correct ones. Developers do not have to delete any exception types in a predicted set, thus, NEUREX can save their efforts.

8.4 Ablation Study (RQ4)

8.4.1 Impact of Different Features on Try-Catch Necessity Checking (XBLOCK). Table 5 displays the results when we removed the two key features in NEUREX and measured XBLOCK’s performance. As seen, without the sequences of code (lexical tokens) for each statement, Recall, Precision, and F-score decrease 12.7%, 5.9%, and 9.6%, respectively. Without considering the AST structure, Recall,

Table 6: Impact of Different Features on XSTATE (RQ4)

	NEUREX w/o SOT	NEUREX w/o AST	NEUREX
Accuracy	0.75	0.73	0.74

SOT: Sequence of tokens; AST: Abstract Syntax Tree

Table 7: Impact of Different Features on XTYPE (Recall)

# ET in Try-Catch Block in Oracle	Metrics	NEUREX w/o SOT	NEUREX w/o AST	NEUREX
1 (1,385 instances)	Hit-1	833 (60%)	791 (57%)	918 (66%)
2 (98 instances)	Hit-1	69 (70%)	66 (67%)	75 (77%)
	Hit-2	39 (40%)	37 (38%)	41 (42%)
3 (18 instances)	Hit-1	10 (56%)	11 (61%)	12 (67%)
	Hit-2	4 (22%)	4 (22%)	5 (28%)
	Hit-3	2 (11%)	3 (17%)	3 (17%)
3+ (30 instances)	Hit-1	16 (53%)	15 (50%)	18 (60%)
	Hit-2	9 (30%)	8 (27%)	10 (33%)
	Hit-3	3 (10%)	2 (7%)	4 (13%)

ET: Exception types; SOT: Sequence of tokens; AST: Abstract Syntax Tree

Table 8: Impact of Different Features on XTYPE (Precision)

# ET in Predicted Try-Catch Block	Metrics	NEUREX w/o SOT	NEUREX w/o AST	NEUREX
1 (1,154 instances)	Hit-1	357 (31%)	309 (27%)	442 (38%)
2 (294 instances)	Hit-1	83 (28%)	78 (27%)	90 (31%)
	Hit-2	57 (19%)	51 (17%)	61 (21%)
3 (83 instances)	Hit-1	24 (29%)	21 (25%)	27 (33%)
	Hit-2	19 (23%)	18 (22%)	23 (28%)
	Hit-3	6 (7%)	4 (5%)	6 (7%)

ET: Exception types; SOT: Sequence of tokens; AST: Abstract Syntax Tree

Table 9: Exception-Related Bug Detection (RQ5)

	FuzzyCatch Dataset	
	NEUREX	FuzzyCatch [10]
Recall	0.75	0.76
Precision	0.62	0.54
F-score	0.68	0.62

Precision, and F-score also decrease even further with 10.1%, 16.2%, and 13.7%, respectively. In other words, *the code structure has a higher contribution than the lexical values of code tokens*.

8.4.2 Impact of Different Features on Try-Catch Statement Detection (XSTATE). We used six as the limit on the number of nodes in the explanation sub-graph in which NEUREX achieves 0.74 of Accuracy. Note: the average number of the statements in a try-catch block in our dataset is 5.9. As seen, the result in Table 6 is consistent with Table 5, as AST contributes slightly more than code sequences.

8.4.3 Impact of Different Features on Exception Type Recommendation (XTYPE). Tables 7 and 8 display the results. As seen, the impact result is consistent with those in Tables 5 and 6. Thus, code structure has slightly higher impact than code sequence.

8.5 Exception-Related Bug Detection (RQ5)

Has seen in Table 9, NEUREX can be used to detect well real-world exception-related bugs in which a code snippet needs but did not have a try-catch block or miss some exceptions. In comparison,

```

1 public void onCreate(Bundle state) {
2     requestWindowFeature(Window.FEATURE_NO_TITLE);
3     + try {
4         final WindowManager.LayoutParams attrs = getWindow().getAttributes();
5         final Class<?> cls = attrs.getClass();
6         final Field fld = cls.getField("buttonBrightness");
7         if (fld != null && "float".equals(fld.getType().toString())) {
8             fld.setFloat(attrs, 0);
9         }
10    + } catch (NoSuchFieldException e) {
11    + } catch (IllegalAccessException e) {
12    + } ...
13 }

```

Figure 9: Exception-related Bug #106 in FuzzyCatch dataset (missing try-catch) (detected by NEUREX)

NEUREX improves relatively over FuzzyCatch [10] 14.8% in Precision and 9.8% in F-score. While the recall values between two models are almost the same, FuzzyCatch has lower precision. It tends to predict “Yes” (buggy) for all code snippets. That is because if there is an association score between *only* one API method call in the code snippet and one exception type higher than the threshold, it will decide that the snippet is buggy. Figure 9 shows a bug detected by NEUREX, and its fix (adding a try-catch block). All buggy code and fixes are available in FuzzyCatch’s repository: ebrand.ly/ExDataset.

Limitations and Threats to Validity. First, NEUREX can not handle the code with multiple try-catch blocks. Second, it cannot generate new exception types that were not in the training corpus. Third, it does not support the generation of exception handling code inside the body of catch. Finally, NEUREX needs training data, thus, does not work for a new library without any API usage yet.

Our solution is specifically for Java. Our collected data might not be representative. However, we use well-established open-source projects with well-known libraries.

9 RELATED WORK

The automated approaches to recommend exception handling can be classified into four categories as presented in Section 1. The closest work to NEUREX is the state-of-the-art *information retrieval* (IR) approaches [10], which provides more flexibility than the others. XRank [10] recommends a ranked list of API calls that might need exception handling and XHand [10] recommends exception handling code. Both leverages fuzzy set theory to compute the associations between API method calls and the exception types. This direction has three key limitations. First, one needs to pre-define a threshold for feature matching for the retrieval of API elements or exception types. Second, the IR techniques are not flexible as the ML approaches because they use the lexical values of API simple names. Thus, they suffer the ambiguity in the names of API elements in incomplete code snippets. Lastly, XRank/XHand considers only pairwise associations between the API method calls and exceptions. It disregards the surrounding code context and the dependencies/relations. XRank/XHand simply uses Groum [11], a dependency graph among API elements, to collect the API calls, but did not use dependencies in computing the association scores.

In addition to exception handling recommendation research, ThEx [17] predict which exception(s) shall be thrown under a given programming context. ThEx learns a classification model from existing thrown exceptions in different contexts.

10 CONCLUSION

NEUREX is the first neural-network model to automated exception handling recommendation in three tasks for (in)complete code. It is designed to capture the basic insights to overcome key limitations of the state-of-the-art IR approaches. With the learning-based approach, it does not rely on a pre-defined threshold for explicit feature matching. The dependencies and context help NEUREX learn the identities of API elements to avoid name ambiguity and to learn their relations with the exception types. Our evaluation shows that NEUREX improves over the state-of-the-art approaches in both intrinsic task and extrinsic one in exception-related bug detection.

REFERENCES

[1] [n. d.].

[2] Eiji Adachi Barbosa and Alessandro Garcia. 2018. Global-Aware Recommendations for Repairing Violations in Exception Handling. *IEEE Transactions on Software Engineering* 44, 9 (2018), 855–873. <https://doi.org/10.1109/TSE.2017.2716925>

[3] Eiji Adachi Barbosa, Alessandro Garcia, and Mira Mezini. 2012. Heuristic Strategies for Recommendation of Exception Handling Code. In *2012 26th Brazilian Symposium on Software Engineering*. 171–180. <https://doi.org/10.1109/SBES.2012.22>

[4] Eiji Adachi Barbosa, Alessandro Garcia, Martin P. Robillard, and Benjamin Jakobus. 2016. Enforcing Exception Handling Policies with a Domain-Specific Language. *IEEE Transactions on Software Engineering* 42, 6 (2016), 559–584. <https://doi.org/10.1109/TSE.2015.2506164>

[5] DeepEx [n. d.]. DeepEx. https://github.com/trycatchresearch/try_catch_research.

[6] Zhangyin Feng, Daya Guo, Duyu Tang, Nan Duan, Xiaocheng Feng, Ming Gong, Linjun Shou, Bing Qin, Ting Liu, Daxin Jiang, and Ming Zhou. 2020. CodeBERT: A Pre-Trained Model for Programming and Natural Languages. In *Findings of the Association for Computational Linguistics: EMNLP 2020, Online Event, 16-20 November 2020 (Findings of ACL, Vol. EMNLP 2020)*, Trevor Cohn, Yulan He, and Yang Liu (Eds.). Association for Computational Linguistics, 1536–1547. <https://doi.org/10.18653/v1/2020.findings-emnlp.139>

[7] Maria Kechagia and Diomidis Spinellis. 2014. Undocumented and Unchecked: Exceptions That Spell Trouble. In *Proceedings of the 11th Working Conference on Mining Software Repositories (Hyderabad, India) (MSR 2014)*. Association for Computing Machinery, New York, NY, USA, 312–315. <https://doi.org/10.1145/2597073.2597089>

[8] Microsoft. [n. d.]. Neural Network Intelligence. <https://github.com/microsoft/nni>. Last Accessed August 28th, 2020.

[9] Taiza Montenegro, Hugo Melo, Roberta Coelho, and Eiji Barbosa. 2018. Improving developers awareness of the exception handling policy. In *2018 IEEE 25th International Conference on Software Analysis, Evolution and Reengineering (SANER)*. 413–422. <https://doi.org/10.1109/SANER.2018.8330228>

[10] Tam Nguyen, Phong Vu, and Tung Nguyen. 2020. Code Recommendation for Exception Handling. In *Proceedings of the 28th ACM Joint Meeting on European Software Engineering Conference and Symposium on the Foundations of Software Engineering (Virtual Event, USA) (ESEC/FSE 2020)*. Association for Computing Machinery, New York, NY, USA, 1027–1038. <https://doi.org/10.1145/3368089.3409690>

[11] Tung Thanh Nguyen, Hoan Anh Nguyen, Nam H. Pham, Jafar M. Al-Kofahi, and Tien N. Nguyen. 2009. Graph-based Mining of Multiple Object Usage Patterns. In *Proceedings of Conference on the Foundations of Software Engineering (ESEC/FSE '09)*. ACM, 383–392.

[12] Hung Phan, Hoan Anh Nguyen, Ngoc M. Tran, Linh H. Truong, Anh Tuan Nguyen, and Tien N. Nguyen. 2018. Statistical Learning of API Fully Qualified Names in Code Snippets of Online Forums. In *Proceedings of the 40th International Conference on Software Engineering (ICSE '18)*. Association for Computing Machinery, New York, NY, USA, 632–642. <https://doi.org/10.1145/3180155.3180230>

[13] Mohammad Masudur Rahman and Chanchal K. Roy. 2014. On the Use of Context in Recommending Exception Handling Code Examples. In *2014 IEEE 14th International Working Conference on Source Code Analysis and Manipulation*. 285–294. <https://doi.org/10.1109/SCAM.2014.15>

[14] Siddharth Subramanian, Laura Inozemtseva, and Reid Holmes. 2014. Live API Documentation. In *Proceedings of the 36th International Conference on Software Engineering (Hyderabad, India) (ICSE '14)*. ACM, 643–652. <https://doi.org/10.1145/2568225.2568313>

[15] Zhitao Ying, Dylan Bourgeois, Jiaxuan You, Marinka Zitnik, and Jure Leskovec. 2019. GNNExplainer: Generating Explanations for Graph Neural Networks. In *Advances in Neural Information Processing Systems 32*, H. Wallach, H. Larochelle, A. Beygelzimer, F. d'Alché-Buc, E. Fox, and R. Garnett (Eds.). Curran Associates, Inc., 9244–9255.

[16] Tianyi Zhang, Di Yang, Crista Lopes, and Miryung Kim. 2019. Analyzing and Supporting Adaptation of Online Code Examples. In *Proceedings of the 41st International Conference on Software Engineering (ICSE '19)*. IEEE Press, 316–327. <https://doi.org/10.1109/ICSE.2019.00046>

[17] Hao Zhong. 2023. Which Exception Shall We Throw?. In *Proceedings of the 37th IEEE/ACM International Conference on Automated Software Engineering (ASE '22)*. Association for Computing Machinery, New York, NY, USA, Article 116, 12 pages. <https://doi.org/10.1145/3551349.3556895>

[18] Hao Zhong and Hong Mei. 2018. Mining repair model for exception-related bug. *Journal of Systems and Software* 141 (2018), 16–31. <https://doi.org/10.1016/j.jss.2018.03.046>