

Unified Pre-training for Program Understanding and Generation

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Abstract

Code summarization and generation empower conversion between programming language (PL) and natural language (NL), while code translation avails the migration of legacy code from one PL to another. This paper introduces PLBART, a sequence-to-sequence model capable of performing a broad spectrum of program and language understanding and generation tasks. PLBART is pre-trained on an extensive collection of Java and Python functions and associated NL text via denoising autoencoding. Experiments on language generation tasks, including code summarization, generation, translation in seven programming languages show that PLBART outperforms or rivals state-of-the-art models. Moreover, experiments on discriminative tasks, *e.g.*, program repair, clone detection, and vulnerable code detection demonstrate PLBART’s effectiveness in program understanding. Furthermore, analysis reveals that PLBART learns program syntax, style (*e.g.*, identifier naming convention), logical flow (*e.g.*, `if` block inside an `else` block is equivalent to `else if` block) that are crucial to program semantics and thus excels even with limited annotations.

1 Introduction

Engineers and developers write software programs in a programming language (PL) like Java, Python, etc., and often use natural language (NL) to communicate them. Use of NL ranges from writing documentation, commit messages, bug reports to seeking help in different forums (*e.g.*, Stack Overflow), etc. Automating different software engineering applications, such as source code summarization, generation, and translation, heavily rely on the understanding of PL and NL—we collectively refer them as PLUG (stands for, Program and Language Understanding and Generation) applications

Program snippet in Python

```
1 def sort_list(uns):
2     return sorted(uns, key=lambda x:x[0])
```

Program snippet in Java

```
1 static Tuple[] sortArray(Tuple[] uns){
2     return Arrays.sort(
3         uns, new Comparator<Tuple>() {
4             public int compare(
5                 Tuple o1, Tuple o2) {
6                 return o1.get(0) == o2.get(0);
7             }
8         });
9 }
```

Summary: sort a list of tuples by first element

Figure 1: An example motivating the need of program understanding for code translation (between programming languages), and code summarization.

or tasks. Note that the use of NL in software development is quite different than colloquially written and spoken language. For example, NL in software development often contains domain-specific jargon, *e.g.*, when software engineers use *Code Smell*¹, it means a potential problem in code (something other than *Smell* in regular English language).

In this work, our goal is to develop a general-purpose model that can be used in various PLUG applications. Recent advancements in deep learning and the availability of large-scale PL and developers’ NL data ushered in the automation of PLUG applications. One important aspect of PLUG applications is that they demand a profound understanding of program syntax and semantics and mutual dependencies between PL and NL. For example, Figure 1 shows two implementations of the same algorithm (sorting) in two PL and corresponding NL summary. An automatic translation tool must understand that function `sorted` in Python acts similar to `Arrays.sort` in Java and the `lambda` operation in Python is equivalent to instantiating a

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¹https://en.wikipedia.org/wiki/Code_smell

Comparator object in Java. Similarly, a tool that summarizes either of these code must understand that `x[0]` in Python or `Tuple.get(0)` in Java refers to the first element in the tuple list.

Most of the available data in PL and NL are unlabeled and cannot be trivially used to acquire PLUG task-specific supervision. However, PLUG tasks have a common prerequisite — understanding PL and NL syntax and semantics. Leveraging unlabelled data to pretrain a model to learn PL and NL representation can be transferred across PLUG tasks. This approach reduces the requirement of having large-scale annotations for task-specific fine-tuning. In recent years we have seen a colossal effort to pretrain models on a massive amount of unlabeled data (*e.g.*, text, images, videos) (Devlin et al., 2019; Liu et al., 2019; Conneau and Lample, 2019; Conneau et al., 2020; Li et al., 2019; Sun et al., 2019) to transfer representation encoders across a wide variety of applications. There are a few research effort in learning general purpose PL-NL representation encoders, such as CodeBERT (Feng et al., 2020) and GraphCodeBERT (Guo et al., 2020) that are pretrained on a *small-scale* bimodal data (code-text pairs). Such models have been found effective for PLUG tasks, including code search, code completion, etc.

Language generation tasks such as code summarization is modeled as sequence-to-sequence learning, where an encoder learns to encode the input code and a decoder generates the target summary. Despite the effectiveness of existing methods, they do not have a pretrained decoder for language generation. Therefore, they still require a large amount of parallel data to train the decoder. To overcome this limitation, Lewis et al. (2020) proposed denoising sequence-to-sequence pre-training where a Transformer (Vaswani et al., 2017) learns to reconstruct an original text that is corrupted using an arbitrary noise function. Very recently, Lachaux et al. (2020) studied denoising pre-training using a large-scale source code collection aiming at unsupervised program translation and found the approach useful. This raises a natural question, *can we unify pre-training for programming and natural language?* Presumably, to facilitate such pre-training, we need unlabeled NL text that is relevant to software development. Note that unlike other bimodal scenarios (*e.g.*, vision and language), PL and associated NL text share the same alphabet or uses anchor tokens (*e.g.*, “sort”, “list”, “tuple” as shown in Figure 1)

| | Java | Python | NL |
|-----------------------|--------|--------|-------|
| All Size | 352 GB | 224 GB | 79 GB |
| All - Nb of tokens | 36.4 B | 28 B | 6.7 B |
| All - Nb of documents | 470 M | 210 M | 47 M |

Table 1: Statistics of the data used to pre-train PLBART. “Nb of documents” refers to #functions in Java and Python collected from Github, and #posts in natural language (NL) from StackOverflow.

that can help to learn alignment between semantic spaces across languages.

We introduce PLBART (Program and Language BART), a bidirectional and autoregressive transformer pre-trained on unlabeled data across PL and NL to learn multilingual representations applicable to a broad spectrum of PLUG applications. We evaluate PLBART on code summarization, generation, translation, program repair, clone detection, and vulnerability detection tasks. Experiment results show that PLBART outperforms or rivals state-of-the-art methods, *e.g.*, CodeBERT and GraphCodeBERT, demonstrating its promise on program understanding and generation. We perform a thorough analysis to demonstrate that PLBART learns program syntax, logical data flow that is indispensable to program semantics, and excels even when limited annotations are available. We release our code² to foster future research.

2 PLBART

PLBART uses denoising sequence-to-sequence pre-training to utilize unlabeled data in PL and NL. Such pre-training lets PLBART reason about language syntax and semantics. At the same time, PLBART learns to generate language coherently.

2.1 Denoising Pre-training

Data & pre-processing We pre-train PLBART on a large-collection of Java and Python functions and natural language descriptions from Github and StackOverflow, respectively. We download all the GitHub repositories associated with Java and Python languages available on Google BigQuery.³ We extract the Java and Python functions following the pre-processing pipeline from Lachaux et al. (2020). We collect the StackOverflow posts (include both questions and answers, exclude code snippets) by downloading the data dump (date: 7th

²<https://github.com/wasiahmad/PLBART>

³<https://console.cloud.google.com/marketplace/details/github/github-repos>

| PLBART Encoder Input | PLBART Decoder Output |
|---|--|
| Check if __ number is a Fibonacci __ ? __ addThreeNumbers (x , y , z) : NEW_LINE INDENT return x + __ public static main (String args []) { date = new Date () ; System . out __ (String . format (" Current Date / Time : % tc " , __)) ; } | <En> Check if a given number is a Fibonacci number ? <python> def addThreeNumbers (x , y) : NEW_LINE INDENT return x + y + z <java> public static void main (String args []) { Date date = new Date () ; System . out . printf (String . format (" Current Date / Time : % tc " , date)) ; } |

Table 2: Example encoder inputs and decoder outputs during denoising pre-training of PLBART.

September 2020) from stackexchange.⁴ Statistics of the pre-training dataset are presented in Table 1. We tokenize all the data with a sentencepiece model (Kudo and Richardson, 2018) learned on 1/5'th of the pre-training data. We train sentencepiece to learn 50,000 subword tokens.

One key challenge to aggregate data from different modalities is that some modalities may have more data, such as we have 14 times more data in PL than NL. Therefore, we mix and up/down sample the data following Conneau and Lample (2019) to alleviate the bias towards PL. We sample instances for pre-training according to a multinomial distribution with probabilities (q_1, q_2, \dots, q_N) :

$$q_i = \frac{1}{p_i} \cdot \frac{p_i^\alpha}{\sum_{j=1}^N p_j^\alpha}, p_i = \frac{n_i}{\sum_{j=1}^N n_j},$$

where N is the total number of languages and n_i is the total number of instances in language i . We set the smoothing parameter α to 0.3.

Architecture PLBART follows the same architecture as BART_{base} (Lewis et al., 2020), it uses the sequence-to-sequence Transformer architecture (Vaswani et al., 2017), with 6 layers of encoder and 6 layers of decoder with model dimension of 768 and 12 heads ($\sim 140M$ parameters). The only exception is, we include an additional layer-normalization layer on top of both the encoder and decoder following Liu et al. (2020), which is found to stabilize training with FP16 precision.

Noise function, f In denoising autoencoding, a model learns to reconstruct an input text that is corrupted by a noise function. Reconstruction of the original input requires the model to learn language syntax and semantics. In this work, we use three noising strategies: token masking, token deletion, and token infilling (Lewis et al., 2020). According to the first two strategies, random tokens are sampled and replaced with a mask token or deleted from the input sequence. In token infilling, a number of text spans are sampled and replaced

with a *single* mask token. The span lengths are drawn from a Poisson distribution ($\lambda = 3.5$). We mask 35% of the tokens in each instance.

Input/Output Format The input to the encoder is a noisy text sequence, while the input to the decoder is the original text with one position offset. A language id symbol (e.g., <java>, <python>) is pre-pended to the decoder input to predict the sequence. We provide a few examples in Table 2. The input instances are truncated if they exceed a maximum sequence length of 512.

Learning PLBART is pre-trained on N languages (in our case, $N=3$), where each language N_i has a collection of unlabeled instances $\mathcal{D}_i = \{x_1, \dots, x_{n_i}\}$. Each instance is corrupted using the noise function f and we train PLBART to predict the original instance x from $f(x)$. Formally, PLBART is trained to maximize \mathcal{L}_θ :

$$\mathcal{L}_\theta = \sum_{i=1}^N \sum_{j=1}^{n_i} \log P(x_j | f(x_j); \theta)$$

where PLBART outputs the distribution P .⁵

Optimization We train PLBART on 8 Nvidia GeForce RTX 2080 Ti GPUs for 100K steps. The effective batch size is maintained at 2048 instances. We use Adam ($\epsilon = 1e-6$, $\beta_2 = 0.98$) with a linear learning rate decay schedule for optimization. We started the training with dropout 0.1 and reduced it to 0.05 at 50K steps and 0 at 80K steps. This is done to help the model better fit the data (Liu et al., 2020). The total training time was approximately 276 hours (11.5 days). All experiments are done using the Fairseq library (Ott et al., 2019).

2.2 Fine-tuning PLBART

We fine-tune PLBART for two broad categories of downstream applications.

Sequence Generation PLBART has an encoder-decoder architecture where the decoder is capable of generating target sequences autoregressively.

⁴<https://archive.org/download/stackexchange>

⁵Following the standard sequence-to-sequence decoding.

| | PLBART Encoder Input | PLBART Decoder Input |
|---|--|---|
| S | <code>def maximum (a , b , c) : NEW_LINE INDENT return max ([a , b , c])</code> | <code><En> Find the maximum of three numbers</code> |
| G | Find the maximum of three numbers | <code><java> public int maximum (int a , int b , int c) { return Math . max (a , Math . max (b , c)) }</code> |
| T | <code>public int maximum (int a , int b , int c) { return Math . max (a , Math . max (b , c)) }</code> | <code><python> def maximum (a , b , c) : NEW_LINE INDENT return max ([a , b , c])</code> |

Table 3: Example inputs to the encoder and decoder for fine-tuning PLBART on sequence generation tasks: source code summarization (S), generation (G), and translation (T).

Therefore, we can directly fine-tune PLBART on sequence generation tasks, such as code summarization, generation, and translation. Unlike denoising pre-training, the source sequence is given as input to the encoder during fine-tuning, and the decoder generates the target sequence. The source and target sequence can be a piece of code or text sequence. In Table 3, we show a few examples of input and output to and for PLBART for different generation tasks. Note that PLBART appends a list of language ids to its vocabulary such that it can generate sequences in unseen languages, languages other than Java, Python, and English.

Sequence Classification We fine-tune PLBART on sequence classification tasks following Lewis et al. (2020). The input sequence is fed into both the encoder and decoder. For a pair of inputs, we concatenate them but insert a special token (“</s>”) between them. A special token is added at the end of the input sequence. This last token’s representation from the final decoder layer is fed into a linear classifier for prediction.

Optimization We fine-tune PLBART for a maximum of 100K steps on downstream tasks with 2500 warm-up steps. We set the maximum learning rate and dropout rate to $3e-5$ and 0.1, respectively. The final models are selected based on the validation BLEU (in generation task) or accuracy (in classification tasks). Fine-tuning PLBART is carried out in one Nvidia GeForce RTX 2080 Ti GPU.

3 Experiment Setup

To understand PLBART’s performance in a broader context, we evaluate PLBART on several tasks. Our evaluation focuses on assessing PLBART’s ability to capture rich semantics in source code and associated natural language text.

3.1 Evaluation Tasks

We divide the evaluation tasks into four categories. The evaluation task datasets are summarized in

Table 4. We use CodeXGLUE (Lu et al., 2021) provided public dataset and corresponding train-validation-test splits for all the tasks.

Code Summarization refers to the task of generating a natural language (NL) summary from a piece of code. We fine-tune PLBART on summarizing source code written in six different programming languages (PL), namely, Ruby, Javascript, Go, Python, Java, and PHP.

Code Generation refers to the task of generating a code (in a target PL) from its NL description. We fine-tune PLBART on the Concode dataset (Iyer et al., 2018), where the input is a text describing class member functions in Java and class environment, the output is the target function.

Code Translation requires a model to generate an equivalent code in the target PL from the input code written in the source PL. Note that the source and target PL can be the same. Hence, we consider two types of tasks in this category.

The first task is a typical PL translation task, translating a code *i.e.*, from Java code to C#, and vice versa. In this task, the semantic meaning of the translated code should exactly match the input code. Thus, this task evaluates PLBART’s understanding of program semantics and syntax across PL. The second task we consider is program repair. In this task, the input is a buggy code, and the output is a modified version of the same code which fixes the bug. This task helps us understand PLBART’s ability to understand code semantics and apply semantic changes in the code.

Code Classification aims at predicting the target label given a single or a pair of source code. We evaluate PLBART on two classification tasks. The first task is clone detection, where given a pair of code, the goal is to determine whether they are clone of each other (similar to paraphrasing in NLP). The second task is detecting whether a piece of code is vulnerable. This task help us gauging

| Task | Dataset | Language | Train | Valid | Test |
|----------------|---|------------------------|---------|--------|---------|
| Summarizaion | Husain et al. (2019) | Ruby | 24,927 | 1,400 | 1,261 |
| | | Javascript | 58,025 | 3,885 | 3,291 |
| | | Go | 167,288 | 7,325 | 8,122 |
| | | Python | 251,820 | 13,914 | 14,918 |
| | | Java | 164,923 | 5,183 | 10,955 |
| | | PHP | 241,241 | 12,982 | 14,014 |
| Generation | Iyer et al. (2018) | NL to Java | 100,000 | 2,000 | 2,000 |
| Translation | Code-Code (Lu et al., 2021) | Java to C# | 10,300 | 500 | 1,000 |
| | | C# to Java | 10,300 | 500 | 1,000 |
| | Program Repair (Tufano et al., 2019) | Java _{small} | 46,680 | 5,835 | 5,835 |
| | | Java _{medium} | 52,364 | 6,545 | 6,545 |
| Classification | Vulnerability Detection (Zhou et al., 2019) | C/C++ | 21,854 | 2,732 | 2,732 |
| | Clone Detection (Wang et al., 2020) | Java | 100,000 | 10,000 | 415,416 |

Table 4: Statistics of the evaluation task datasets.

PLBART’s effectiveness in program understanding in an unseen PL since the code examples in this task are written in C/C++.

3.2 Evaluation Metrics

BLEU computes the n-gram overlap between a generated sequence and a collection of references. We use corpus level BLEU (Papineni et al., 2002) score for all the generation tasks, except code summarization where we use smoothed BLEU-4 score (Lin and Och, 2004) following Feng et al. (2020).

CodeBLEU is a metric for measuring the quality of the synthesized code (Ren et al., 2020). Unlike BLEU, CodeBLEU also considers grammatical and logical correctness based on the abstract syntax tree and the data-flow structure.

Exact Match (EM) evaluates if a generated sequence exactly matches the reference.

3.3 Baseline Methods

We compare PLBART with several state-of-the-art models and broadly divide them into two categories. First, the models that are trained on the evaluation tasks from scratch, and second, the models that are pre-trained on unlabeled corpora and then fine-tuned on the evaluation tasks.

3.3.1 Training from Scratch

- **Seq2Seq** is an LSTM based Seq2Seq model with attention mechanism (Luong et al., 2015). Vocabulary is constructed using byte-pair encoding.
- **Transformer** (Vaswani et al., 2017) is the base architecture of PLBART and other pre-trained mod-

els. Transformer baseline has the same number of parameters as PLBART. Hence, a comparison with this baseline demonstrates the direct usefulness of pre-training PLBART.

3.3.2 Pre-trained Models

As described in section 2, PLBART consists of an encoder and autoregressive decoder. We compare PLBART on two categories of pre-trained models. First, the encoder-only models (*e.g.*, RoBERTa, CodeBERT, and GraphCodeBERT) that are combined with a randomly initialized decoder for task-specific fine-tuning. The second category of baselines include decoder-only models (CodeGPT) that can perform generation autoregressively.

- **RoBERTa, RoBERTa (code)** are RoBERTa (Liu et al., 2019) model variants. While RoBERTa is pre-trained on natural language, RoBERTa (code) is pre-trained on source code from CodeSearchNet (Husain et al., 2019).
- **CodeBERT** (Feng et al., 2020) combines masked language modeling (MLM) (Devlin et al., 2019) with replaced token detection objective (Clark et al., 2020) to pretrain a Transformer encoder.
- **GraphCodeBERT** (Guo et al., 2020) is a concurrent work with this research which improved CodeBERT by modeling the data flow edges between code tokens. We report GraphCodeBERT’s performance directly from the paper since their implementation is not publicly available yet.
- **GPT-2, CodeGPT-2, and CodeGPT-adapted** are GPT-style models. While GPT-2 (Radford et al.,

2019) is pretrained on NL corpora, CodeGPT-2 and CodeGPT-adapted are pretrained on CodeSearch-Net (Lu et al., 2021). Note that, CodeGPT-adapted starts from the GPT-2 checkpoint for pre-training.

4 Results & Analysis

We aim to address the following questions.

1. Does PLBART learn strong program and language representations from unlabeled data?
2. Does PLBART learn program characteristics, e.g., syntax, style, and logical data flow?
3. How does PLBART perform in an unseen language with limited annotations?

4.1 Code Summarization

Table 5 shows the result of code summarization. PLBART outperforms the baseline methods in five out of the six programming languages with an overall average improvement of 0.49 BLEU-4 over CodeBERT. The highest improvement ($\sim 16\%$) is in the Ruby language, which has the smallest amount of training examples. Unlike CodeBERT, PLBART is not pretrained on the Ruby language; however, the significant performance improvement indicates that PLBART learns better generic program semantics. Moreover, compared to the Transformer baseline, PLBART improves with an average of 2.76 BLEU-4, and we credit this improvement to the pre-training step.

4.2 Code Generation

Table 6 shows the evaluation result on code generation from NL description. PLBART outperforms all the baselines in terms of BLEU and CodeBLEU. While CodeGPT-adapted (Lu et al., 2021) achieves the best Exact Matches(EM), PLBART outperforms CodeGPT-adapted by a large margin in terms of CodeBLEU. It is also noteworthy that, in all the baselines, CodeBLEU is lower than the BLEU score. This result implies that PLBART can generate *significantly more* syntactically and logically correct code than all the baselines.

Figure 2 shows an example of code generated by PLBART which does not exactly match the reference. As we can see the reference code clears the buffer by setting the `bufferSize` to 0, PLBART does the same by setting `buffer` to `null`. Since, `buffer` is a byte array (mentioned in the input text), setting it to `null` does not violate program semantics. To study whether PLBART learns code syntax and logical flow during pre-

Input text: returns the count to which the specified key is mapped in this frequency counter , or 0 if the map contains no mapping for this key .

| Reference Code | Generated Code |
|---|--|
| <pre> 1 Integer function (T arg0) { 2 Integer loc0 = counter.get(arg0); 3 if (loc0 == null) { 4 return 0 ; 5 } 6 return loc0; 7 }</pre> | <pre> 1 int function (T arg0) { 2 Integer loc0 = counter.get(arg0); 3 if (loc0 == null) { 4 return 0 ; 5 } 6 else { 7 return loc0; 8 } 9 }</pre> |

Figure 2: An example of generated code by PLBART that is syntactically and semantically valid, but does not match the reference.

training or fine-tuning, we perform an ablation study where we use subset of the training examples (10K, 20K, and 50K) to finetune PLBART in this task. As table 6 shows, with only 10K examples, PLBART outperforms all baselines in terms of CodeBLUE. This ablation indicates that PLBART learns program syntax and data flow during pre-training and performs effectively on downstream tasks even with small number of examples.

As shown in prior works (Yin and Neubig, 2017; Chakraborty et al., 2020), generating syntactically and logically correct code has been a big challenge in program generation. We conjecture that PLBART’s large scale denoising autoencoding pre-training help understand program logic and generate syntactically and logically valid code.

4.3 Code Translation

We present the evaluation results in Table Table 7. PLBART outperforms all the baselines *w.r.t.* EM, BLEU and CodeBLEU. PLBART improves over CodeBERT by 9.5% and 10.5% when translating from Java to C# and C# to Java, respectively. Although PLBART is not pretrained on C#, there is a large syntactic and semantic similarity between Java and C#, and thus PLBART is able to understand C# language syntax and semantics. However, such similarities are non-trivial, making the Naive copy and PBSMT perform very poorly.

| Methods | Ruby | Javascript | Go | Python | Java | PHP | Overall |
|-------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Seq2Seq | 9.64 | 10.21 | 13.98 | 15.93 | 15.09 | 21.08 | 14.32 |
| Transformer | 11.18 | 11.59 | 16.38 | 15.81 | 16.26 | 22.12 | 15.56 |
| RoBERTa | 11.17 | 11.90 | 17.72 | 18.14 | 16.47 | 24.02 | 16.57 |
| CodeBERT | 12.16 | 14.90 | 18.07 | 19.06 | 17.65 | 25.16 | 17.83 |
| PLBART | 14.11 | 15.56 | 18.91 | 19.30 | 18.45 | 23.58 | 18.32 |

Table 5: Results on source code summarization, evaluated with smoothed BLEU-4 score. The baseline results are reported from Feng et al. (2020).

| Methods | EM | BLEU | CodeBLEU |
|-----------------------|--------------|--------------|--------------|
| Seq2Seq | 3.05 | 21.31 | 17.61 |
| Guo et al. (2019) | 10.05 | 24.40 | 20.99 |
| Iyer et al. (2019) | 12.20 | 26.60 | - |
| GPT-2 | 17.35 | 25.37 | 22.79 |
| CodeGPT-2 | 18.25 | 28.69 | 25.69 |
| CodeGPT-adapted | 20.10 | 32.79 | 27.74 |
| PLBART | 18.75 | 36.69 | 38.52 |
| PLBART _{10K} | 17.25 | 31.40 | 33.32 |
| PLBART _{20K} | 18.45 | 34.00 | 35.75 |
| PLBART _{50K} | 17.70 | 35.02 | 37.11 |

Table 6: Results on text-to-code generation task using the CONCODE dataset (Iyer et al., 2018).

Figure 3 shows an example where PLBART’s generated C# code does not exactly match the reference; however, they are semantically equivalent. In the reference, the `else` block (line 4-9) is equivalent to the `else if` block (line 4-7) in the generated code. In addition, `start` is generated as function parameter and used in the function body, equivalent to `start_1` in the reference code. This further corroborates the syntactic understanding of PLBART and its ability to reason about the data flow in source code. We present more qualitative examples in Appendix.

In the program repair task, both the input and the output are in the same language. While the input is a buggy code, the output should be the target bug-free code. Thus in this task, the exact match is the critical metric. Nevertheless, as shown in table 8, PLBART can generate 17.13%, and 74.03% more correct bug fixes than CodeBERT in *Java_{small}* and *Java_{medium}* datasets, respectively. On the other hand, PLBART performs comparably to GraphCodeBERT that uses structure-aware pre-training to learn program syntax and semantics.

4.4 Classification

In both clone detection and the vulnerability detection tasks, PLBART outperforms CodeBERT. We present the results in Table 9. In the vulnerability detection task, code semantics is the most critical

| Reference Code : C# | |
|---------------------|---|
| 1 | <code>public bool find(int start_1) {</code> |
| 2 | <code> findPos = start_1;</code> |
| 3 | <code> ...</code> |
| 4 | <code> else{</code> |
| 5 | <code> if (findPos >= _regionEnd) {</code> |
| 6 | <code> matchFound = false;</code> |
| 7 | <code> return false;</code> |
| 8 | <code> }</code> |
| 9 | <code> }</code> |
| 10 | <code> ...</code> |
| 11 | <code>}</code> |
| Generated Code : C# | |
| 1 | <code>public bool find(int start) {</code> |
| 2 | <code> findPos = start;</code> |
| 3 | <code> ...</code> |
| 4 | <code> else if (findPos >= _regionEnd) {</code> |
| 5 | <code> matchFound = false;</code> |
| 6 | <code> return false;</code> |
| 7 | <code> }</code> |
| 8 | <code> ...</code> |
| 9 | <code>}</code> |

Figure 3: Example C# code generated by PLBART that does not exactly match the reference code.

feature (Chakraborty et al., 2020). Since PLBART is not pretrained on C/C++ language, its improved performance compared to the Transformer baseline is the testament that PLBART can identify semantics beyond the language syntax’s specifics. Moreover, PLBART’s improved performances over CodeBERT and GraphCodeBERT confirms its effectiveness in program understanding in addition to its generation ability.

We want to acknowledge that, neither PLBART, nor CodeBERT is the state-of-the-art in vulnerability detection, as graph based models perform best in this task. In this evaluation, our goal is to study how well PLBART understands program semantics in an unseen language for a different type of task (other than generation, *i.e.*, classification).

5 Related Work

Pre-training for Language Understanding and Generation Transformer (Vaswani et al., 2017), a sequence-to-sequence architecture that includes

| Methods | Java to C# | | | C# to Java | | |
|----------------|--------------|--------------|--------------|--------------|--------------|--------------|
| | BLEU | EM | CodeBLEU | BLEU | EM | CodeBLEU |
| Naive Copy | 18.54 | 0 | 34.20 | 18.69 | 0 | 43.04 |
| PBSMT | 43.53 | 12.50 | 42.71 | 40.06 | 16.10 | 43.48 |
| Transformer | 55.84 | 33.00 | 63.74 | 50.47 | 37.90 | 61.59 |
| RoBERTa (code) | 77.46 | 56.10 | 83.07 | 71.99 | 57.90 | 80.18 |
| CodeBERT | 79.92 | 59.00 | 85.10 | 72.14 | 58.80 | 79.41 |
| GraphCodeBERT | 80.58 | 59.40 | - | 72.64 | 58.80 | - |
| PLBART | 83.02 | 64.60 | 87.92 | 78.35 | 65.00 | 85.27 |

Table 7: Results on source code translation using Java and C# language dataset introduced in (Lu et al., 2021). PBSMT refers to phrase-based statistical machine translation where the default settings of Moses decoder (Koehn et al., 2007) is used. The training data is tokenized using the RoBERTa (Liu et al., 2019) tokenizer.

| Methods | Small | | Medium | |
|---------------|--------------|--------------|-------------|--------------|
| | EM | BLEU | EM | BLEU |
| Naive Copy | 0 | 78.06 | 0 | 90.91 |
| Seq2Seq | 10.00 | 76.76 | 2.50 | 72.08 |
| Transformer | 14.70 | 77.21 | 3.70 | 89.25 |
| CodeBERT | 16.40 | 77.42 | 5.16 | 91.07 |
| GraphCodeBERT | 17.30 | 80.58 | 9.10 | 72.64 |
| PLBART | 19.21 | 77.02 | 8.98 | 88.50 |

Table 8: Results on program repair (in Java).

| Tasks | Vulnerability Detection | Clone Detection |
|---------------|-------------------------|-----------------|
| Transformer | 61.64 | - |
| CodeBERT | 62.08 | 96.5 |
| GraphCodeBERT | - | 97.1 |
| PLBART | 63.18 | 97.2 |

Table 9: Results on the vulnerable code detection (accuracy) and clone detection (F1 score) tasks.

an encoder and decoder, has shown tremendous promise in natural language processing (NLP), computer vision, software engineering, and more. Devlin et al. (2019) first proposed to pre-train a large Transformer architecture, called BERT to learn representations of natural language using large-scale unlabeled data in a self-supervised fashion. Later, BERT’s task-independent pre-training approach is rigorously studied (Devlin et al., 2019; Liu et al., 2019; Solaiman et al., 2019; Feng et al., 2020; Sun et al., 2019; Li et al., 2020). While BERT type models have shown effectiveness in learning contextualized representation, it is not very useful in generation tasks. GPT (Radford et al., 2018) style models improve upon BERT for generative tasks with autoregressive pre-training; however, they are not bidirectional as BERT. Lewis et al. (2020) introduced BART, a denoising autoencoder that uses a bidirectional encoder and an autoregressive decoder. Similar to BART, PLBART

uses denoising pre-training to cope with generative tasks and learns multilingual representations of programming and natural language jointly.

Deep Learning in Software Engineering There is a growing interest in automating software engineering (SE) using deep learning in the last few years. Vast sources of code in open source repositories and forums make deep learning feasible for SE tasks. Code Summarization (Movshovitz-Attias and Cohen, 2013; Allamanis et al., 2016; Iyer et al., 2016; Alon et al., 2019a; Hu et al., 2018; Harer et al., 2019; Ahmad et al., 2020), Bug Detection (Ray et al., 2016; Li et al., 2018b; Russell et al., 2018; Zhou et al., 2019; Chakraborty et al., 2020), Program Repair (Chen et al., 2019; Chakraborty et al., 2020; Lutellier et al., 2020), Code Translation (Chen et al., 2018; Drissi et al., 2018; Xu et al., 2020), Clone Detection (Zhang et al., 2019; Yu et al., 2019; Wang et al., 2020), Code completion (Li et al., 2018a; Hellendoorn and Devanbu, 2017) are some of the tasks that are addressed with deep neural solution. While most of the prior approaches use task-specific representation learning, a few works (Alon et al., 2019b; Feng et al., 2020; Guo et al., 2020; Lachaux et al., 2020; Clement et al., 2020) attempted to learn transferable representations in an unsupervised fashion. However, unlike prior works, we jointly pre-train PLBART to learn program and language representations.

6 Conclusion

In this paper, we present PLBART, a sizeable pre-trained model that can perform program and language understanding and generation tasks. PLBART achieved state-of-the-art performance on various downstream software engineering tasks. We show that due to pre-training, PLBART excels in identifying crucial program characteristics, such

as data flow. In the future, we want to explore ways to fine-tune PLBART jointly on all the tasks.

Broader Impact

Automation in software engineering is paramount in increasing programmers' productivity. A reduced workload of tedious works at the part of developers' daily routine would give them more time to solve significant problems for society's wellbeing. There are numerous program-and-language applications in the software development lifecycle, such as code documentation/summarization, code synthesis, translating code across languages, etc that can be automated to facilitate software engineering. The availability of large-scale data (thanks to open source repositories, forums, and millions of contributors worldwide) opens up the opportunity to solve many of those problems in a data-driven fashion. PLBART aims at program-and-language applications that demand a complete syntactic and semantic understanding of source code and associated textual data. For the tasks we have shown evaluation, PLBART will serve as a solid and replicable baseline to guide future research. We also believe our work could be an excellent starting point for future works aim at solving a variety of software engineering problems.

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| Hyper-parameter | RoBERTa* | CodeGPT-2 | CodeBERT | GraphCodeBERT | PLBART |
|-----------------|----------|-----------|----------|---------------|--------|
| vocab size | 50,265 | 50,001 | 50,265 | - | 50,004 |
| n_positions | 514 | 1024 | 514 | 256 | 1024 |
| model size | 768 | 768 | 768 | 768 | 768 |
| # layers | 12 | 12 | 12 | 12 | 6 |
| # heads | 12 | 12 | 12 | 12 | 12 |
| d _{ff} | 3072 | 3072 | 3072 | - | 3072 |
| dropout | 0.1 | 0.1 | 0.1 | - | 0.1 |
| optimizer | Adam | Adam | Adam | Adam | Adam |
| learning rate | 5e-5 | 5e-5 | 5e-5 | 1e-4 | 5e-5 |
| batch size | 32 | 32 | 32 | 64 | 32 |

Table 10: Details of the hyper-parameters used during fine-tuning for sequence generation tasks. * indicates pre-trained from scratch using source code-text pairs.

Example 1 : get the msg value.

| Reference Code | Generated Code |
|---|--|
| <pre>1 String function() { 2 return msg; 3 }</pre> | <pre>1 String function() { 2 return this.msg; 3 }</pre> |

Example 2 : returns the instance of the singleton .

| Reference Code | Generated Code |
|--|---|
| <pre>1 IConfigurationFactory function() { 2 return SINGLETON; 3 }</pre> | <pre>1 IConfigurationFactory function() { 2 if (SINGLETON == null) { 3 SINGLETON = new SINGLETON(); 4 } 5 return SINGLETON; 6 }</pre> |

Example 3 : convert the reader into an inputstream .

| Reference Code | Generated Code |
|---|---|
| <pre>1 InputStream function () { 2 return new ReaderInputStream(reader); 3 }</pre> | <pre>1 InputStream function () { 2 return reader.getInputStream(); 3 }</pre> |

Example 4 : setter for a property . if the property already exists , the value will be overridden .

| Reference Code | Generated Code |
|--|---|
| <pre>1 void function (2 final String arg0, 3 final String arg1) { 4 properties.setProperty (5 arg0, arg1) ; 6 }</pre> | <pre>1 void function (2 String arg0, 3 String arg1) { 4 properties.put (5 arg0, arg1) ; 6 }</pre> |

Example 5 : clear the buffer .

| Reference Code | Generated Code |
|---|---|
| <pre>1 void function() { 2 bufferSize = 0; 3 }</pre> | <pre>1 void function() { 2 buffer = null; 3 }</pre> |

Figure 4: Text to code generation examples using PLBART, where generated code does not exactly match the reference.

Example 1 : ✓

Input Code : C#

```
1 public int GetCells() {
2     int size = 0;
3     foreach (char c in cells.Keys) {
4         Cell e = At(c);
5         if (e.cmd >= 0 || e.@ref >= 0) {
6             size++;
7         }
8     }
9     return size;
10 }
```

Generated Code : Java

```
1 public int getCells() {
2     Iterator<Character> i =
3         cells.keySet().iterator();
4     int size = 0;
5     for (; i.hasNext(); ) {
6         Character c = i.next();
7         Cell e = at(c);
8         if (e.cmd >= 0 || e.ref >= 0) {
9             size++;
10        }
11    }
12    return size;
13 }
```

Example 2 : ✓

Input Code : C#

```
1 public override Cell Merge(
2     Cell m, Cell e) {
3     if (m.cmd == e.cmd && m.@ref ==
4         e.@ref && m.skip == e.skip) {
5         Cell c = new Cell(m);
6         c.cnt += e.cnt;
7         return c;
8     }
9     else {
10        return null;
11    }
12 }
```

Generated Code : Java

```
1 public Cell merge(Cell m, Cell e) {
2     if (m.cmd == e.cmd &&
3         m.ref == e.ref &&
4         m.skip == e.skip) {
5         Cell c = new Cell(m);
6         c.cnt += e.cnt;
7         return c;
8     }
9     else {
10        return null;
11    }
12 }
```

Example 3 : ✓

Input Code : Java

```
1 @Override public List<E> subList(
2     int start, int end) {
3     synchronized (mutex) {
4         return new
5             SynchronizedRandomAccessList
6             <E>(
7                 list.subList(start, end),
8                 mutex);
9     }
10 }
```

Generated Code : C#

```
1 public override java.util.List<E>
2     SubList(int start, int end) {
3     lock (mutex) {
4         return new java.util.Collections.
5             SynchronizedRandomAccessList<E>(
6                 list.subList(start, end),
7                 mutex
8             );
9     }
10 }
```

Example 4 : ✓

Input Code : Java

```
1 public
2     PersianNormalizationFilterFactory(
3         Map<String,String> args) {
4     super(args);
5     if (!args.isEmpty()) {
6         throw
7             new IllegalArgumentException(
8                 "Unknown parameters: "
9                 + args);
10    }
11 }
```

Generated Code : C#

```
1 public
2     PersianNormalizationFilterFactory(
3         IDictionary<string, string> args)
4         : base(args) {
5     if (args.Count > 0) {
6         throw new System.ArgumentException(
7             "Unknown parameters: "
8             + args
9         );
10    }
11 }
```

Figure 5: Qualitative examples on source code translation between Java and C# using PLBART.