Multilingual Code Snippets Training for Program Translation

Ming Zhu\textsuperscript{1}, Karthik Suresh\textsuperscript{1}, Chandan K. Reddy\textsuperscript{1}

\textsuperscript{1}Department of Computer Science, Virginia Tech, Arlington VA - 22203.
mingzhu@vt.edu

Abstract

Program translation aims to translate source code from one programming language to another. It is particularly useful in applications such as multiple-platform adaptation and legacy code migration. Traditional rule-based program translation methods usually rely on meticulous manual rule-crafting, which is costly both in terms of time and effort. Recently, neural network based methods have been developed to address this problem. However, the absence of high-quality parallel code data is one of the main bottlenecks which impedes the development of program translation models. In this paper, we introduce CoST, a new multilingual Code Snippet Translation dataset that contains parallel data from 7 commonly used programming languages. The dataset is parallel at the level of code snippets, which provides much more fine-grained alignments between different languages than the existing translation datasets. We also propose a new program translation model that leverages cross-lingual snippet denoising auto-encoding and Multilingual Snippet Translation (MuST) pre-training. Extensive experiments show that the multilingual snippet training is effective in improving program translation performance, especially for low-resource languages. Moreover, our training method shows good generalizability and consistently improves the translation performance of a number of baseline models. The proposed model outperforms the baselines on both snippet-level and program-level translation, and achieves state-of-the-art performance on CodeXGLUE translation task.

Introduction

Program Translation is the problem of converting source code from one programming language to another. Different from computer compilers which translate high-level programming languages to lower-level machine code, it mainly focuses on translation between high-level programming languages. Efficient and accurate program translation is of enormous value in a variety of scenarios, such as: 1) Migrating legacy code to another language. For instance, many industries spend several hundreds of millions of dollars to convert code written in older programming languages (such as FORTRAN and COBOL) to newer ones (such as Java and C++) (Roziere et al. 2020a). 2) Adapting software to different operating systems and platforms. For instance, for an Android application to run on iOS and Web browsers, it needs to be re-developed in Objective-C and Javascript. Traditional rule-based program translation usually relies on meticulous manual rule-crafting, which requires expertise in both programming languages, and requires an enormous amount of time and resources.

In recent years, deep learning based methods have been employed to address this problem. The success of transformer-based models (Vaswani et al. 2017) in natural language processing (NLP) has motivated researchers to utilize them for programming languages. A few recent works based on neural machine translation (NMT) have been applied to this task and achieved some impressive results (Roziere et al. 2020a; Ahmad et al. 2021). One of the important requirements for NMT models is the availability of high-quality parallel data for model training. Such data is even more critical for the program translation problem since it requires the generated code to be logically precise as well. However, existing code translation datasets have significant limitations. Most of the commonly used datasets (Lu et al. 2021; Chen, Liu, and Song 2018; Nguyen, Nguyen, and Nguyen 2015; Karaivanov, Raychev, and Vechev 2014; Nguyen, Nguyen, and Nguyen 2013) only contain two languages (Java and C#), and the alignment comes from mining similar function names from open source projects. Github has a huge number of open-source repositories in several languages. However, the data is not parallel and can not be used for supervised translation. Project CodeNet (Puri et al. 2021) and Google Code Jam\textsuperscript{1} datasets contain solutions submitted to coding problems in multiple programming languages. However, given that the alignment comes from solutions to the same problems, they are aligned based on the task level. Since programs that solve the same problem can have a high diversity in terms of variable names, method design and logical flow, these datasets are not ideal to train program translation models. This especially becomes a bottleneck in case of low resource languages, since models for those languages cannot be trained using limited data with high multiformality.

The scarcity of high quality parallel data has become a bottleneck in program translation research. In this paper, we introduce CoST, a new dataset that consists of paral-

\textsuperscript{1}https://codingcompetitions.withgoogle.com/codejam/archive
Figure 1: An example of a program and code snippets in different languages from CoST dataset. Each column is one program (truncated) in a specific language. Each cell is one snippet. The snippets are aligned by matching the code comments in different languages. We only show 4 languages due to space constraints. All the remaining languages are shown in the Appendix.

<table>
<thead>
<tr>
<th>JavaScript</th>
<th>Python</th>
<th>PHP</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>import java.io.*; class GFG { // Function to check whether a number is divisible by 7 static boolean isDivisibleBy7(int num) { // If number is negative, // make it positive if (num &lt; 0) { return isDivisibleBy7(-num); } // If number is negative, // make it positive if (num &lt; 0) { return isDivisibleBy7(-num); } // Base cases if (num == 0</td>
<td></td>
<td>num == 7) return true; if (num % 10) return false; // If function is positive, // make it positive if (num % 10) return false; // Recur for (num / 10 - 2 * num % 10) return isDivisibleBy7(...); } }</td>
<td></td>
</tr>
<tr>
<td># Function to check whether a number is divisible by 7 function isDivisibleBy7($num) { // If number is negative, // make it positive if ($num &lt; 0) { return isDivisibleBy7(-$num); } // Base cases if ($num == 0</td>
<td></td>
<td>$num == 7) return true; if ($num &lt; 10) return false; // Recur for ($num / 10 - 2 * $num % 10) return isDivisibleBy7(...); }</td>
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<td>#include &lt;stdio.h&gt; // Function to check whether a number is divisible by 7 int isDivisibleBy7(int num) { // If number is negative, // make it positive if (num &lt; 0) { return isDivisibleBy7(-num); } // Base cases if (num == 0</td>
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<td></td>
</tr>
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</table>

We introduce CoST, a new dataset that consists of both snippet-level and program-level parallel data from 7 programming languages. Our dataset can be used to train program translation models for up to 42 programming language pairs.

We provide a new benchmark to evaluate program translation model on 42 programming language pairs. Extensive experiments demonstrate that models which achieve the best performance on some languages can do much worse on certain other languages.

We propose a multilingual program translation model that leverages the similarity between different programming languages and the snippet level alignment of the dataset. The proposed model outperforms a number of baseline models and achieves state-of-the-art performance on CodeXGLUE translation task.

The MuST training method in our model has good generalizability and consistently improves the performance of several other models on program translation.

Related Work

Methods: One line of work has directly applied recent advances in natural language processing (NLP) to the programming language domain. Inspired by the success of natural language pre-training, CodeBERT (Feng et al. 2020) pre-trained a BERT (Kenton and Toutanova 2019) based encoder on the source code, and then added a decoder to perform end-to-end training on program translation. PLBART (Ahmad et al. 2021) utilized an existing natural language translation model, BART (Lewis et al. 2020), and also pre-trained it with source code. Transcoder (Roziere et al. 2020a) combined cross-lingual masked language modeling (Lample and Conneau 2019), denoising auto-encoding and back-translation, and applied them in a source code setting. Another line of work incorporates the intrinsic features of programming languages to improve translation performance. (Chen, Liu, and Song 2018) modeled this problem as translating a source tree into a target tree. GraphCodeBERT(Guo et al. 2020) improved upon CodeBERT (Feng et al. 2020) by adding data-flow graph extracted from source code, improving the model’s understanding of the code structure. Some other works (Rabinovich, Stern, and Klein 2017; Yin and Neubig 2017; Brockschmidt et al. 2018) also make use of abstract syntax tree (AST) derived from the code. DOBF (Roziere et al. 2021) added a de-obfuscation objective to the
Datasets: Many preceding works (Lu et al. 2021; Chen, Liu, and Song 2018; Nguyen, Nguyen, and Nguyen 2015; Karaivanov, Raychev, and Vechev 2014; Nguyen, Nguyen, and Nguyen 2013) consist of parallel Java-C# code from various open source projects. CodeNet (Puri et al. 2021) and Google CodeJam (GCJ) datasets contain code samples from multiple languages resulting in vastly different program structures, and misaligned cells. To remedy this, we manually verified the code to identify different instances of non-compliance, and either modify the alignment or discard the example in extreme cases. Few of the URLs scraped from different pages sometimes pointed to the same program, thus resulting in duplicate files. A duplication detection program was used to identify these duplicates and remove them.

Dataset Comparisons and Characteristics
As shown in Table 1, many of the existing source code translation datasets such as (Lu et al. 2021; Chen, Liu, and Song 2018) consisting of pairwise samples at the method level collect their samples from very similar publicly available repositories. However, they only have parallel data in two languages; Java and C#. Moreover, their mapping is at the method level, and there are relatively fewer number of method pairs available. Other datasets such as Google Code Jam (GCJ) and CodeNet (Puri et al. 2021) have an abundance of problem statements along with their solutions and span a wide range of languages. However, these datasets suffer from quality issues. For instance, in CodeNet, only about half of the problems are rated by the online judges to be an accepted solution to the problem. This makes less than half of the dataset as wrong solutions and deems these erroneous samples unsuitable for the translation task. In contrast, our dataset contains programs which have been manually verified to ensure correctness at program and snippet levels, thereby resulting in higher quality and less noise.

A major drawback of the existing datasets is that the samples are aligned at program level, which means less supervi-
sion. Since program level alignment is based on programs doing similar tasks and achieving similar results on test cases, there is a significant amount of variation between the programs in multiple languages, due to differences in terms of method and variable names, as well as the logic flow. The granularity in our case is at the snippet level, which provides more supervision in contrast to the method level or program level mapping that exists in previous datasets. Moreover, the code snippets in our dataset are consistent in terms of variable and method names, and the programs in each language follow similar logic flow.

The Proposed Method

Problem Formulation

Consider $L = \{l_1, \ldots, l_k\}$ as the set of all languages, where $l_i$ denotes a programming language. Given a program $X$ in language $l_i$, the objective of program translation is to generate a program $Y$ in the target language $l_j$. We represent a program containing $m$ snippets as $X = \{x_1, \ldots, x_m\}$, where $x_i = (x_{i1}, \ldots, x_{in})$ denotes a snippet with $n$ tokens. We further denote the monolingual snippet dataset in language $l_i$ as $D_{l_i}^{mono}$, and the bilingual snippet dataset for languages $l_i$ and $l_j$ as $D_{l_i,l_j}^{bi}$. We represent a program containing $m$ snippets as $Y = \{y_1, \ldots, y_m\}$, where $y_i = (y_{i1}, \ldots, y_{in})$ denotes a snippet with $n$ tokens. We further denote the monolingual snippet dataset in language $l_i$ as $D_{l_i}^{mono}$, and the bilingual snippet dataset for languages $l_i$ and $l_j$ as $D_{l_i,l_j}^{bi}$.

Model Architecture

Given the sequence-to-sequence nature of the program translation problem, our model draws inspiration from the Transformer model (Vaswani et al. 2017), which has been shown to have state-of-the-art performance on many language generation tasks. The encoder-decoder based transformer model serves as the base model for our translation task. The model consists of an encoder $E$ and a decoder $G$ with parameters $\theta_E$ and $\theta_G$, respectively, that are augmented to support code from multiple languages. This is done by using a unique identifier $\alpha_i$ for each language. Given the input token embeddings $\mathbf{x} = (x_1, \ldots, x_n)$, we add the language identifier to each token, such that $(x_i + \alpha_{l_i}, \ldots, x_n + \alpha_{l_i})$ serves as the input to the encoder. The encoder representations $\mathbf{z} = E(\mathbf{x}, \alpha_{l_i})$ are then fed to the decoder along with the target language identifier $\alpha_{l_j}$ to generate output snippet tokens $\mathbf{y} = G(\mathbf{z}, \alpha_{l_j})$.

Model Initialization

We initialize the model parameters with the pre-trained weights of the DOBF model (Roziere et al. 2021). DOBF is a Transformer-based model trained with masked language modeling (MLM) and code deobfuscation objectives on Python and Java files from GitHub public dataset available on Google BigQuery. The MLM objective helps the model to learn representations by leveraging the left and right contexts. The deobfuscation objective guides the model to recover the original class, function and variable names from obfuscated code, which is a more difficult task and requires a deeper understanding of the code, thereby providing a better learning signal to the model. By initializing our model with the weights of a sequence-to-sequence model pre-trained on source code, we can leverage its knowledge about the syntax and structure of the specific programming languages.

Cross-lingual Snippet Denoising Auto-Encoding

To train the model to do translation on different language pairs, we first need to make the model familiar with all the 7 languages. Although the model is initialized with pre-trained weights from DOBF, the weights were learned from only two languages, Python and Java. Therefore, the model has no knowledge about other languages (C++, C#, Javascript, PHP, C). To address this issue, we first train the model with Denoising Auto-Encoding (DAE) objective (Lample et al. 2018) on snippets from all the languages. There are several advantages of this pre-training task. First, the sequence-to-sequence nature of DAE enables the model to decode all the languages, which is necessary for the translation task. Second, by sharing the same encoder and decoder across all the languages, all the languages are mapped into the same latent space. This helps the model to learn the similarities between different languages, which can be useful in the translation of low-resource languages. Third, the DAE only requires monolingual data, which is much more accessible than pairwise data. We use the same set of noise functions as TransCoder (Roziere et al. 2020a), which includes random word shuffle, random word dropout and random span masking. Considering $C$ as the noise model (non-learnable is this case), and $\mathbf{x}$ as the input sampled from $D_{l_i}^{mono}$, the DAE objective can be written as:

$$
L_{DAE}(\theta_E, \theta_G) = \sum_{l_i \in L} \mathbb{E}_{x \sim D_{l_i}^{mono}, \mathbf{x} \sim C(\mathbf{x})} [-\log p_G(\mathbf{y}|E(\mathbf{x}, \alpha_{l_i}), \alpha_{l_i})]
$$

(1)

Multilingual Snippet Translation (MuST)

In many language generation tasks, the performance goes down significantly as the length of input sequences increases. This is a common problem in sequence-to-sequence models due to the difficulty of capturing long-distance dependency. Since source code programs usually contain at least tens of lines, achieving acceptable performance from translation models can be challenging. In order to alleviate this problem, we use code snippets translation as a pre-training method to improve the accuracy of program translation. The code snippets are much shorter than programs, thus they provide a fine-grained supervision to the translation model, and can help to address the problem of reduced performance for longer inputs.

Another problem encountered by many models is that program translation datasets are usually not balanced in size for all the languages. Some languages may have much less parallel data than others. For example, in CoST dataset, there are 13k snippet pairs for Java and C++, but only 700 pairs for C and PHP. Less parallel training data can significantly affect the translation performance on low-resource languages. Therefore, in addition to snippet translation, we propose to leverage the multilingual training to improve the performance on low-resource languages. In CoST dataset, one code snippet may have corresponding snippets in multiple languages. Moreover, some languages are naturally similar in syntax, such as C++, Java and C, Java and C#. This motivates us to use other languages to improve the translation of low resource languages, e.g. using C++-PHP and
Figure 2: The training paradigm of the proposed Multilingual Snippet Training for Program Translation (MuST-PT) model. We first train the model with cross-lingual snippet denoising auto-encoding, which helps the model to learn the similarity between different languages. Then we apply multi-lingual snippet translation (MuST) training to leverage the snippet-level alignment to increase the accuracy of program-level translation. The MuST training also helps to improve the performance on low-resource languages. Finally, we fine-tune the model on program translation task to bridge the distribution gap between snippet and program data.

\[
L_M(\theta_E, \theta_G) = \sum_{l_i,v_j \in L} \mathbb{E}_{(x,y) \sim D_{l_i,v_j}} [-\log p_G(y \mid E(x, \alpha_{l_i}, \alpha_{v_j}))]
\]

\[
L = L_M + \lambda L_{DAE}
\]

The overall training objective of our model is given above. Here, \(\lambda\) is a hyperparameter that represents the weight of DAE loss. After the cross-lingual snippet DAE and MuST pre-training, the model is capable of translating code snippets across all the 42 language pairs. However, because of the difference in length between code snippets and programs, the model cannot directly be used for program translation. Therefore, we further fine-tune the model on the program pairs from our dataset. We adopt similar multilingual training strategy on the program-level pairwise data. The overall training process is illustrated in Fig. 2. We refer to the model as MuST-PT, which is short for the Multilingual Snippet Training for Program Translation model.

**Experiments**

**Implementation Details**

In our model, the encoder and decoder consist of 12 and 6 transformer layers, respectively. The transformer units have a model dimension of 768, and 12 attention heads. The weight of the cross-lingual snippet DAE objective \(\lambda\) was set to 1.0 in the beginning, and decayed to 0.1 linearly in 30K steps, and then to 0 in 100K steps. The DOBF model we used for initializing our model is dobf_plus_denoising.pth, which can be found on the their repository on GitHub. Most of the settings during training were the same as DOBF (Roziere et al. 2021). Float 16 operations were used to speed up the training. The model was trained using Adam optimizer (Kingma and Ba 2014) with a learning rate of 0.0001, and the same learning rate scheduler was used from the Transformer (Vaswani et al. 2017). We used a batch size of 128 on all the 42 language pairs. The batches of different languages pairs were sent to the model alternatively during training. The model was trained with 4 RTX 8000 GPUs with 48GB memory on each GPU.

**Datasets**

The datasets used for the experimental evaluation are below:

- **CoST Snippets Dataset** We used the monolingual snippets to do the cross-lingual snippet DAE training, and the pairwise snippets to do the multilingual snippet translation (MuST) training. The train-validation-test data is split at the problem level, to ensure no overlapping snippets between the splits in any of the languages. The statistics of the split in each language can be found in the Appendix.

- **CoST Programs Dataset** We used the pairwise program data to fine-tune the model for program translation.

- **CodeXGLUE Translation Dataset** CodeXGLUE stands for General Language Understanding Evaluation bench-
Table 3: Results on the CodeXGLUE translation task. Our model achieves state-of-the-art performance on BLEU score of C#-Java and both BLEU and CodeBLEU on Java-C#.

<table>
<thead>
<tr>
<th>Method</th>
<th>BLEU</th>
<th>CodeBLEU</th>
<th>BLEU</th>
<th>CodeBLEU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naive copy</td>
<td>18.54</td>
<td>-</td>
<td>18.69</td>
<td>-</td>
</tr>
<tr>
<td>PBSMT</td>
<td>43.53</td>
<td>42.71</td>
<td>40.06</td>
<td>43.48</td>
</tr>
<tr>
<td>Transformer</td>
<td>55.84</td>
<td>63.74</td>
<td>50.47</td>
<td>61.59</td>
</tr>
<tr>
<td>RoBERTa(code)</td>
<td>77.46</td>
<td>83.07</td>
<td>71.99</td>
<td>80.18</td>
</tr>
<tr>
<td>CodeBERT</td>
<td>79.92</td>
<td>85.1</td>
<td>72.14</td>
<td>79.41</td>
</tr>
<tr>
<td>GraphCodeBERT</td>
<td>80.58</td>
<td>-</td>
<td>72.64</td>
<td>-</td>
</tr>
<tr>
<td>PLBART</td>
<td>83.02</td>
<td>87.92</td>
<td>78.35</td>
<td>85.27</td>
</tr>
<tr>
<td>MuST-PT</td>
<td>87.37</td>
<td>86.82</td>
<td>85.25</td>
<td>86.09</td>
</tr>
</tbody>
</table>

Evaluation Metrics
- **BLEU** Given an input code sample, we use BLEU (Papineni et al. 2002) score to evaluate the n-gram overlap between the generated and the ground-truth target code.
- **CodeBLEU** CodeBLEU (Ren et al. 2020) is designed for automatic evaluation of code synthesis. Besides n-gram match as in BLEU, it also evaluates the code syntax via abstract syntax trees (AST) and code semantics via data-flow.

Baseline Methods
- **Naive Copy** Naive Copy (Lu et al. 2021) directly copies the input source code as the translation output. This baseline shows how similar two programming languages are.
- **Transformer** The sequence-to-sequence transformer model (Vaswani et al. 2017) was originally designed for translation problem. We use it as a baseline to see how well a transformer model performs without any pre-training on source code corpus.
- **CodeBERT** CodeBERT (Feng et al. 2020) uses the BERT architecture pre-trained on source code corpus.
- **DOBF** DOBF (Roziere et al. 2021) is the model from which the weights are used to initialize our model. It is pre-trained on Java and Python.
- **TransCoder** TransCoder (Roziere et al. 2020b) is an unsupervised program translation model pre-trained on Java, Python, and C++. We did not include TransCoder in Table 4 because it does not support input languages other than the ones it was pre-trained on (performance not increasing through training).

Because of the limited space, we did not include some baselines (PLBART, GraphCodeBERT, RoBERTa(code)(Liu et al. 2019), PBSMT(Zens, Och, and Ney 2002)) from CodeXGLUE translation task in other experiments.

Results Analysis
**Translation Performance on Snippets** Table 4 shows the translation performance of our model and the baseline models on all the 42 language pairs. Every model is evaluated on both the snippets dataset and the program dataset. The left part of table shows BLEU score of each model on the snippets dataset. We can see that our model outperforms the baseline models, with significant performance gains on low resource languages like PHP and C. This shows that the multilingual training in both DAE and MuST is helpful in improving low-resource language translation.

**Translation Performance on Programs** The right part of Table 4 shows BLEU score of each model on the program dataset. We can see that almost all the baseline models have much worse performance on program than snippets. This can be attributed to the more challenging nature of program-level translation due to longer sequence length compared to snippets, and less training data than snippet level. However, our model’s performance does not drop much on program-level compared to snippet level. This shows that the MuST pre-training improves the program translation performance.

**Generalizability of MuST Training** We combine some of the baselines with MuST training to see if the method is generalizable to more models. Table 5 shows the results of each baseline before and after MuST training. We can see that all the three baselines got significant improvement after MuST training, indicating that MuST is not only effective in our model setting, but also benefits other models. This demonstrates that MuST has good generalizability and can potentially benefit other program translation models.

**Conclusion and Future Work**
Scarcity of high quality parallel data has become the bottleneck of program translation research. In this paper, we introduced a new multilingual code translation dataset CoST, with snippet-level parallel data across 7 programming languages. Our dataset provides fine-grained supervision for the translation of 42 language pairs. We also propose a new program translation model that leverages cross-lingual snippet denoising auto-encoding(DAE) and multilingual snippet translation(MuST) pre-training. Extensive experiments shows that DAE and MuST are effective in improving program translation performance, especially for low-resource languages. We also achieved state-of-the-art performance on CodeXGLUE translation task. The MuST training also shows good generalizability and improves the translation performance of a number of baseline models. The new dataset we present can potentially be used for tasks other than translation, such as code summarization, comment generation, and text-to-code generation. The MuST can also potentially improve the performance on these new tasks. We will leave them for future work.
Table 5: Multilingual Snippet Translation (MuST) training consistently improves the performance (measured by BLEU scores) of the baseline models on the CoST program translation dataset. This shows that MuST pre-training method can be generalized to other models and benefit their translation performance.
Acknowledgments

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References


