Mining API Mapping for Language Migration

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ABSTRACT

Since the inception of programming languages, researchers and practitioners developed various languages such as Java and C#. To address business requirements and to survive in competing markets, companies often have to develop different versions of their projects in different languages. Migrating projects from one language to another language (such as from Java to C#) manually is a tedious and error-prone task. In contrast, automatic translation of projects from one language to another requires the knowledge of how Application Programming Interfaces (API) of one language are mapped with the APIs of the other language. In this paper, we propose a novel approach that mines API mapping relations using the API client code. Our approach accepts a set of projects with versions in two languages and mines API mapping relations based on how APIs are used by the two versions. These mined API mapping relations assist in translation of projects from one language to another. Based on our approach, we implemented a tool, called MAM (**M**ining **A**PI **M**apping), and conducted two evaluations to show the effectiveness of our approach. The results show that our approach mines 26,369 mapping relations of APIs between Java and C# with 83.2% accuracy. The results also show that mined API mapping relations reduce 54.4% compilation errors in translated projects of the Java2CSharp tool as our mappings include relations that do not exist in language migration tools such as Java2CSharp.

1. INTRODUCTION

A programming language serves as a means for instructing computers to achieve a programming task at hand. Since their inception, various programming languages came into existence due to reasons such as existence of many platforms or requirements for different programming styles. The HOPL[1] website lists 8,512 different programming languages. To address business requirements and to survive in competing markets, companies often have to develop different versions of their projects in different languages. For example, many well-known projects such as Lucene[2], Db4o[3], and WordNet[4] provide multiple versions in different languages. There are instances where companies incurred huge losses due to lack of multiple versions of their projects. For example, Terekhov and Verhoef [10] stated that at least three companies went bankrupt and another company lost 50 million dollars due to failed language migration projects.

For some open source projects, although companies do not offically provide multiple versions, external programmers often create their versions in different languages. For example, WordNet does not provide a C# version. However, Simpson and Crowe developed a C# version of WordNet.Net[5]. Another example is iText[6], which provides Java version only. Kazuya developed a C# version of iText.Net[7]. As described by Jones [6], about one-third of the existing projects have multiple versions in different languages.

Migrating projects from one language to another language (such as from Java to C#) manually is a tedious and error-prone task. A natural way to address this issue is to develop a translation tool that can automatically translate projects from one language to another. However, it is challenging to develop such a translation tool as the translation tool should have knowledge of how one programming language is mapped to the other language. In literature, there exist approaches [3,7,16] that address the problem of language migration partially. These approaches address the problem of language migration partially, because these approaches expect programmers to describe how one language is mapped to another language. Based on the mappings provided as input, these existing approaches translate projects from one language to another. As programming languages provide a large number of Application Programming Interfaces (API), writing these rules manually for all APIs is tedious and error-prone. As a result, existing approaches [3, 7, 16] support only a subset of APIs or even ignore the mapping relations of APIs. Such a limitation causes many compilation errors in migrated projects and limits their usage in practice.

In this paper, we propose a novel approach that automatically captures how APIs of one language are mapped to the APIs of another language. We refer this mapping as *mapping relations of APIs*. There are two possible alternatives for capturing mapping relations of APIs. First, capture mapping relations based on API implementations. Second, mine mapping relations based on API usages in the client code. In our approach, we use the second alternative rather than the first alternative for three major reasons: (1)

[1]`http://hopl.murdoch.edu.au`

[2]`http://lucene.apache.org/`

[3]`http://www.db4o.com/`

[4]`http://wordnet.princeton.edu/`

[5]`http://opensource.ebswift.com/WordNet.Net/`

[6]`http://www.lowagie.com/iText/`

[7]`http://www.ujihara.jp/iTextdotNET/en/`

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Often API implementations such as implementations of C# base class libraries are not available. (2) Capturing relations based on API implementations often can have relatively low confidence than mining mapping relations based on API usages. The reason is that API implementations have only one call site for the analysis, whereas API usages can have many call sites for mining; providing relatively high confidence on mapped relations. (3) Mapping relations of APIs are more complex and cannot be captured solely based on the information available in the API implementations. We next show why it is not possible to capture mapping relations based on the information available in API implementations using two illustrative examples.

Consider the following two API methods in Java and C#:

m_1 in Java: BigDecimal java.math.BigDecimal.multiply (BigDecimal p_1^1)

m_2 in C#: Decimal System.Decimal.Multiply (Decimal p_1^2, Decimal p_2^2)

Here, m_1 has a receiver, say v_1^1, of type `BigDecimal` and has one parameter p_1^1, and m_2 has two parameters p_1^2 and p_2^2. Based on the definitions of these inputs, v_1^1 is mapped to p_1^2, and p_1^1 is mapped to p_2^2. This preceding example shows the complexities involved in mapping parameters of an API method in one language with an API method in the other language. We next provide a more complex example where an API method of one language is mapped to more than one API method in the other language. Consider the following two API methods:

m_3 in Java: E java.util.LinkedList.removeLast()

m_4 in C#: void System.Collections.Generic.LinkedList.RemoveLast()

Although the method names of m_3 and m_4 are the same, m_3 in Java cannot be directly mapped with m_4 in C#. The reason is that m_3 in Java returns the last element removed from the list, whereas m_4 does not return any element. Therefore, m_3 is mapped to two API methods m_4 and m_5 (shown below) in C#. The API method m_5 returns the last element and should be called before calling m_4.

m_5 in C#: void System.Collections.Generic.LinkedList.Last()

This example shows that an API method of one language is mapped to multiple API methods of the other language. Therefore, capturing API mapping relationships based on API implementations is often not possible. We next describe our approach that mines mapping relations using the API client code.

Our approach accepts existing projects such as Lucene that have both Java and C# versions, and mines mapping relations of APIs. We refer these existing projects as client code using the APIs of two languages. First, our approach aligns classes and methods of the two versions by using a matching algorithm based on similarities in the names of classes and methods. Aligning client code based on names of classes and methods is based on our observation of how existing projects such as rasp[8] are migrated from one language to another. We observed that while migrating rasp project from Java to C#, programmers first rename source files from Java to C# and systematically address the compilation errors by replacing Java APIs with C# APIs. During this procedure, names of classes, methods, fields of classes, or local variables in methods often remain the same between the two versions. Therefore, we use name similarities for aligning client code of the two versions. Second, our approach maps API classes of one language with the other language by matching the names of fields of classes and local variables of methods in the client code. Finally, our approach maps API methods of one language with the other language. Mapping API methods is challenging as one API method of one language can be mapped to multiple API methods of the other language (as shown in our preceding example). To address this challenge, we construct a graph, referred as *API transformation graph* (ATG), for aligned

[8]`http://sourceforge.net/projects/r-asp/`

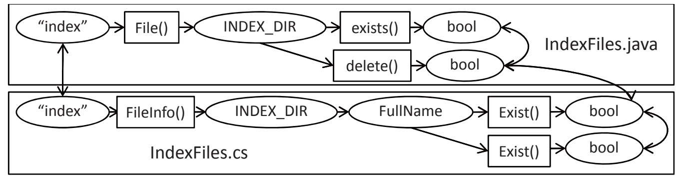


Figure 1: API methods connected by inputs and outputs

methods of the client code in both languages. These ATGs precisely capture inputs and outputs of API methods, and help mine relationships API methods. (@Hao, could you please revise this preceding sentence and put more details)

This paper makes the following major contributions:

- A first approach that mines mapping relations of APIs between different languages using API client code. Our approach addresses an important and yet challenging problem that is not addressed by previous work on language migration.
- A technique to build and compare API transformation graphs (ATG). ATGs describe data dependencies among inputs and outputs of API methods. Our approach uses these ATGs to mine complex many-to-many mapping relations between API methods.
- A tool named MAM based on our approach and two evaluations on 15 projects with both Java and C# versions. These projects include 18,568 classes and 109,850 methods. The results show that our approach mines 26,369 mapping relations of APIs with 83.2% accuracies and the mined API mapping relations reduce 55.4% of compilation errors during translation projects from Java to C#.

The remainder of this paper is organized as follows. Section 2 illustrates our approach using an example. Section 3 presents definitions. Section 4 presents our approach. Section 5 presents our evaluations. Section 6 discusses issues of our approach. Section 7 presents related work. Finally, Section 8 concludes.

2. EXAMPLE

We next use an example to illustrate challenges involved in mining API mapping. Consider that a programmer needs to migrate a Java code example (shown in Figure 2) to C# using a translation tool. This code example accepts a `string` input that represents name of a file or directory and returns a `boolean` value that describes whether the file or directory exists. To achieve this functionality, the code example declares a local variable, called `file`, of type `java.io.File` and calls the `exists` method. We consider the local variable `file` as a receiver object for the `exists` method.

To translate this code example into C#, the translation tool needs to know mapping relations of API classes. For example, the translation tool needs to know the mapped API class for `java.io.File` in C# to translate the variable `file` to C#. In addition, the translation tool needs to know the mapped API methods of `exists`. Furthermore, the translated code should be able to accept the same input "`test`" and produce the same output as the Java code example.

As APIs are often large in size, existing translation tools [] (@Hao: Please add citations) often support only a subset of mapping relations of used APIs. The reason for supporting only a subset of mapping relations is that the mapping relations are written manually in these translation tools. Therefore, the translation tool cannot translate this Java code example, if the mapping relation for the `java.io.File` does not exist. To address this issue, a few

```
1  File file = new File("test");
2    if(file.exists()){...}
```

Figure 2: A code example for language migration.

```
                 IndexFiles.java
3 public class IndexFiles {
4   static final File INDEX_DIR = new File("index");
5   public static void main(String[] args) {
      ...
6     if (INDEX_DIR.exists()) {...}
      ...
7       INDEX_DIR.delete();
    }
  }
                 IndexFiles.cs
8 class IndexFiles{
9   internal static readonly System.IO.FileInfo INDEX_DIR
          = new System.IO.FileInfo("index");
10   public static void  Main(System.String[] args){
      ...
11     bool tmpBool;
12     if (System.IO.File.Exists(INDEX_DIR.FullName))
13       tmpBool = true;
14    else
15       tmpBool = System.IO.Directory
                       .Exists(INDEX_DIR.FullName);
      ...
    }
 }
```

Figure 3: Two versions (Java and C#) of client code.

translation other tools [] (@Hao, please add citations) provide extensions for the programmer to write customized rules for translation. However, to write customized rules, programmer needs to have knowledge about both the languages. Furthermore, writing these customized rules manually for all APIs is tedious and error-prone.

To address these preceding issues and to generate the rules for translation, we propose a novel approach that automatically mines mapping relations of APIs. Our approach uses existing projects such as Lucene that have both Java and C# versions, and mines mapping relations of APIs. One would argue that given projects such as Lucene with both Java and C# versions, a programmer can manually learn these mapping relations easily. We next explain why it is not straightforward to learn these mapping relations of APIs and how our approach addresses these challenges.

First, our approach aligns classes and methods of the two versions by using a matching algorithm based on similarities in the names of classes and methods between the two versions. For example, our approach aligns `IndexFiles.java` with the `IndexFiles.cs` (shown in Figure 3) as the names of their classes and methods are similar. Although it appears trivial, It is tedious task for the programmer to align the classes manually as both versions can have large number of classes and methods. For example, Lucene includes more than 1,000 classes.

Even after the programmer successfully finds out the two aligned files, it is still non-trivial to learn mapping relations of APIs. The programmer first needs to map inputs of the three code snippets. In particular, by comparing Line 1 with Line 4, the programmer knows that `index` is the name for a file or a directory. Consequently, the programmer analyzes how `index` in Line 4 (Java code) and `index` in Line 9 (C# code) are used in the two source files for API mapping of interest so that boolean values are produced for the functionality. To achieve so, the programmer may need to analyze inputs and outputs of each API method. Figure 1 shows API methods connected by inputs and outputs for the preceding two files. In particular, a box denotes an API method, and an ellipse denotes either an input or an output. The strategy of analyzing inputs and outputs helps find out an API method like `System.IO.Directory.Exists()`. This API method is called in an assignment statement, whereas three other related API methods are called in infix expressions of

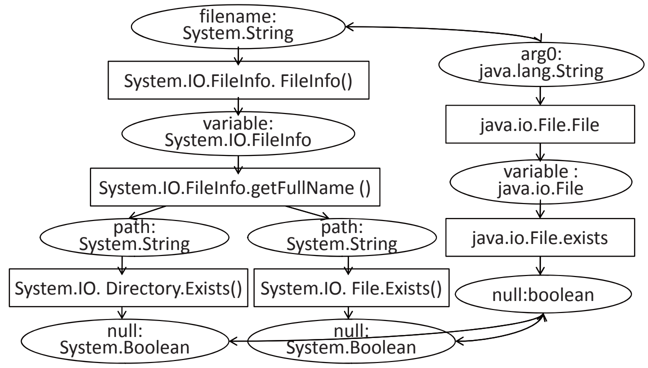


Figure 4: API mapping

if-statements. If the programmer relies on call-site structures only, the programmer can miss the API method as its call-site structure is quite different. To match outputs, the programmer must know the mapping relations of classes. For this example, the programmer should know the mapping relation between `boolean` in Java and `System.Boolean`. After the inputs and outputs are mapped, the programmer needs to further match functionalities. For this example, the `delete()` branch of Figure 1 implements a different functionality as indicated by its name, and thus this branch is not mapped with other branches.

The programmer learns mapping relations of APIs from the preceding analysis. However, the analysis is not accurate enough. In particular, Figure 1 does not consider parameters and fails to provide useful information if two API methods have different parameter orders. For this example, as shown in Line 6, the input of `java.io.File.exist()` is a variable, but the inputs of `System.IO.Directory.Exist()` and `System.IO.File.Exist()` are both their parameters as shown in Line 12 and Line 15. The preceding analysis does not consider parameters yet.

In this paper, we propose a novel approach that mines API mapping automatically. Figure 4 show the mined mapping relation of APIs from the preceding two source files. In this figure, a box denotes an API method. Here, our approach uses `getFullName()` to denote the field access of `FullName`. An ellipse denotes a parameter, a variable, or a return value. Each ellipse is named as "*name:type*". Here, our approach uses "variable" for accesses of variables, "null" for return values, and parameter names for parameters.

The mined API mapping has matched inputs, outputs, and how inputs and outputs are connected. Consequently, with the mined API mapping, a translation tool can automatically translate the preceding code snippet into C# as follows:

In summary, for this example, we find that a programmer needs to take tedious and error-prone efforts to find and to analyze source files from two versions of a project for API mapping. We next present our approach to mine API mapping automatically.

3. DEFINITIONS

We next present definitions of terms used in the rest of the paper.

API: An Application Programming Interface (API) [8] is a set of classes and methods provided by frameworks or libraries.

API library: An API library refers to a framework or library that provides reusable API classes and methods.

Client code: Client code refers to the application code that reuses or extends API classes and methods provided by API libraries. The definitions of API library and Client code are relative to each

```
FileInfo file = new FileInfo("test");
 if(System.IO.File.Exist(file.FullName)||
   System.IO.Directory.Exists(file.FullName)){...}
```

Figure 5: A translated code snippet from Java to C#.

other. For example, Lucene uses J2SE[9] as an API library, whereas Nutch[10] uses Lucene as an API library. Therefore, we consider Lucene as Client code and API library for the J2SE API library and Nutch, respectively. In general, for Client code, source files of API libraries are often not available.

Mapping relation: A mapping relation refers to a replaceable relation among entities such as API classes or methods defined by two different languages. For example, consider two languages L_1 and L_2, and two entities e_1 and e_2 in languages L_1 and L_2, respectively. We define a mapping relation between the entities e_1 and e_2, if e_1 of the Language L_1 can be translated to e_2 of the Language L_2 without introducing new defects in the translated code.

Mapping relation of API classes: We define a mapping relation between two API classes c_1 and c_2 of languages L_1 and L_2, respectively, if the API class c_1 of L_1 is translated to the API class c_2 of L_2 without introducing new defects in the translated code. Our mapping relation of API classes is many-to-many. For example, the `java.util.ArrayList` class of Java is mapped to either `System.Collections.ArrayList` **or** `System.Collections.Generic.List` of C#, whereas the `java.lang.System` class of Java is mapped to `System.DataTime` **and** `System.Environment` of C# based on how client code uses these classes. In particular, when client code uses APIs to get the current time, `java.lang.System` is mapped with `System.DataTime`. At the same time, when client code uses APIs to get environment settings, `java.lang.System` is mapped with `System.Environment`.

Furthermore, mapped API classes may have different behaviors. For example, `java.lang.String` of Java is mapped to `System.String` of C#. However, `System.String` has an API method `insert()`, which does not exist in `java.lang.String`.

Mapping relation of API methods: We define a mapping relation between two API methods m_1 and m_2 of languages L_1 and L_2, respectively, if m_1 is translated to m_2 without introducing defects in the translated code.

Both the mapping relations of API classes and methods are required for achieving language translation. In particular, mapping relation of API classes is required to translate variables such as `file` in Figure 2. Similarly, mapping relation of API methods is required to translate API methods such as `exist()` in Figure 2. When an API method is translated from one language to another, the translated method accepts the same parameters (both variables and constants) and implement the same functionality as the original method.

Merged API method: A merged API method of L_1 refers to an API method that is created by merging two other API methods of L_1. For example, consider two API methods m_1 and m_2 defined in classes C_1 and C_2 of L_1, respectively, with the following signatures:

m_1 `signature:` o_1 $C_1.m_1(inp_1^1,\ inp_2^1,\ \ldots,\ inp_m^1)$
m_2 `signature:` o_2 $C_2.m_2(inp_1^2,\ inp_2^2,\ \ldots,\ inp_n^2)$

We merge methods m_1 and m_2 to create a new merged API method m_{new} if the output o_1 of m_1 is used either as a receiver object or a parameter for m_2 (i.e., $o_1 == C_2$ or $o_1 == inp_i^2$) in Client code. The signature of the new merged API method m_{new} is shown below:

m_{new} `signature:` o_2 $m_{new}(inp_1^1,\ inp_2^1,\ \ldots,\ inp_m^1, inp_1^2,\ inp_2^2,\ \ldots,\ inp_n^2)$

[9] http://java.sun.com/j2se/1.5.0/
[10] http://lucene.apache.org/nutch/

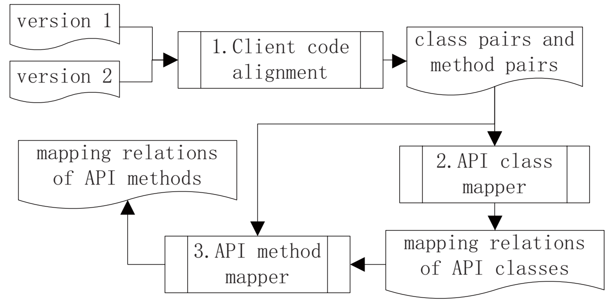


Figure 6: Overview of our approach

We next present an example for a merged API method using the illustrative code example shown in Section 2. For the code snippet shown in Figure 2, consider the `file` variable, which is a return variable for the constructor and a receiver object for the `exist()` method. As the output of one API method is passed as receiver object of another API method, we can combine these two methods to create a new merged API method m_{new}. Figure 4 shows the m_{new} method `boolean File.exists(string)`. The m_{new} method accepts a `string` parameter that represents a file name and returns a boolean value that describes whether a file exists or not.

A merged API method can be further merged with other API methods or other merged API methods. For simplicity, we use API method to refer to both API method and merged API method in the rest of the paper.

4. APPROACH

Our approach accepts a set of projects as data sources and mines API mapping between two different languages L_1 and L_2. As mined API mapping describes mapping relations of APIs between the two languages, this mapping is useful for language migration between the two languages. For each project used as a data source, our approach requires atleast two versions of the project (one version in L_1 and the other version in L_2). Figure 6 shows the overview of our approach.

First, our approach aligns client code in languages L_1 and L_2 so that the aligned source files implement similar functionalities (Section 4.1). Second, our approach mines mapping relations of API classes (Section 4.3). Finally, our approach mines mapping relations of API methods (Section 4.3) defined by the mapped API classes.

4.1 Aligning Client Code

Initially, our approach accepts two versions of a project (one version in L_1 and the other version in L_2) and aligns classes and methods of the two versions. Aligned classes or methods between the two versions implement a similar functionality. As they implement a similar functionality, APIs used by these classes or methods can be replaceable.

To align classes and methods of the two versions, our approach uses name similarities between entities (such as class names or method names) defined by the two versions of the project. In our approach, we have two different kinds of entity names: entity names defined by the two versions of the project and entity names of third-party libraries used by the two versions of the project. The first kind often comes from the same programmer or the same team, or programmers may refer to existing versions for naming entities such as classes, methods, and variables. Therefore, name similarity is often reliable to distinguish functionalities of the first kind compared to the second kind. Our approach uses Simmetrics[11] to calculate

[11] http://sourceforge.net/projects/simmetrics/

Algorithm 1: Align Classes Algorithm

```
Input: C is the classes of a language; C' is the classes of another
       language
Output: P is aligned pairs of classes
begin
    M ← findCandidateClassPairs(C, C')
    while M.size > 0 do
        if M.size > 1 then
            M ← refineByPackageNames(M)
        if M.size == 1 then
            P.add(M)
            C.remove(M[0].c)
            C'.remove(M[0].c')
        M ← findCandidateClassPairs(C, C')
end
```

name similarities.

Algorithm 1 shows how our approach aligns client code classes. The first step is to find candidate class pairs by names. For two sets of classes (C and C'), the algorithm returns candidate class pairs (M) with a similarity greater than a given threshold, referred to as *SIM_THRESHOLD*. As some projects may have many classes with the same name, M may contain more than one matching pair for a class in a version. To align those classes, our algorithm uses package names of these classes to refine M and returns only one matching pair with the maximum similarity[12].

In each aligned class pair, our approach further aligns methods within the class pair. The algorithm for methods is similar to the algorithm for classes but relies on other criteria such as the number of parameters and names of parameters to refine candidate method pairs. These candidates may contain more than one method pair due to overloading. For the example shown in Section 2, our approach correctly aligns the class `IndexFiles` and the method `main` in Java to the class `IndexFiles` and the method `Main` in C# as their names are quite similar.

4.2 Mapping API classes

In this step, our approach mines mapping relations of API classes. As defined in Section 3, mapping relations of API classes are used to translate variables. Consequently, our approach mines mapping relations of API classes based on how aligned client code declares variables such as fields of aligned classes, parameters of aligned methods and local variables of aligned methods. In particular, for each aligned class pair $\langle c_1, c_2\rangle$, our approach analyzes each field pair $\langle f_1, f_2\rangle$ and considers $\langle f_1.type, f_2.type\rangle$ as one mined mapping relation of API classes when the similarity between $f_1.name$ and $f_2.name$ is greater than *SIM_THRESHOLD*. Similarly, for each aligned method pair $\langle m_1, m_2\rangle$, our approach analyzes each local variable pair $\langle var_1, var_2\rangle$ and considers $\langle var_1.type, var_2.type\rangle$ as one mined mapping relation of API classes when the similarity between $var_1.name$ and $var_2.name$ is greater than a threshold. Also, our approach analyzes each parameter pair $\langle para_1, para_2\rangle$ of m_1 and m_2, and our approach considers $\langle para_1.type, para_2.type\rangle$ as one mined mapping relation of API classes when the similarity between $para_1.name$ and $para_2.name$ is greater than *SIM_THRESHOLD*.

For the example shown in Section 2, our approach mines the mapping relation between `java.io.File` and `System.IO.FileInfo` based on the matched fields of Lines 4 and 9 (Figure 3). The mapping relation of API classes helps translate the variable declared in Line 1 (Figure 2) to the variable declared in Line 16 (Figure 5).

4.3 Mapping API methods

[12] For C#, we refer to namespace names for package names.

In this step, our approach mines mapping relations of API methods. This step has two major sub-steps. First, our approach builds a graph, referred as API transformation graph, for each client code method. Second, our approach compares the two graphs of each paired client code methods for mining mapping relations of API methods.

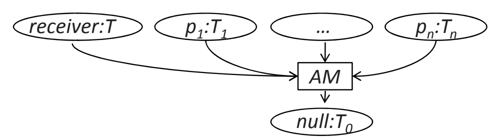
4.3.1 API transformation graph

We propose API transformation graphs (ATG) to help deal with the two challenges of mining API mapping listed in Section 1. An API transformation graph of a client code method m is a directed graph $G\langle N_{data}, N_m, E\rangle$. N_{data} is a set of the fields F of m's declaring class, local variables V of m, parameters P_1 of m, parameters P_2 of methods called by m, and return values R of all methods. N_m is a set of methods called by m. E is a set of directed edges. An edge $d_1 \rightarrow d_2$ from a datum $d_1 \in N_{data}$ to a datum $d_2 \in N_{data}$ denotes the data dependency from d_1 to d_2. An edge $d_1 \rightarrow m_1$ from a datum $d_1 \in N_{data}$ to a method $m_1 \in N_m$ denotes d_1 is a parameter or a related variable of m_1. An edge $m_1 \rightarrow d_1$ from a method $m_1 \in N_m$ to a datum $d_1 \in N_{data}$ denotes d_1 is the return value of m_1.

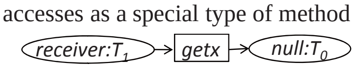
4.3.2 Building API transformation graphs

Our approach builds an ATG for each method m. ATG includes information such as inputs and outputs for each client code method. In particular, for each method m, our approach first builds subgraph for its variables, API methods, and field accesses according to the following rules:

1. $\forall\ f \in F \cup V \cup P_1$, our approach adds a node to the built ATG. The reason for considering these variables such as fields in declaring class or local variables in method m used in client code is that these variables are useful to analyze data dependencies among API methods.
2. $\forall$ API methods of the form "$T_0\ T.AM(T_1 p_1, \ldots, T_n p_n)$" called by method m, our approach adds receiver (of type T) and parameter nodes to the built ATG as shown below. Our approach does not add receiver node for static API methods.

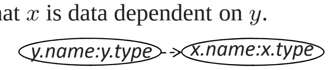


3. $\forall\ f \in F \cup V$, if f is a non-primitive variable of type T_1 and a field x of T_1 is accessed as $f.x$, our approach adds nodes to the built ATG as shown below. As Java often uses getters and setters whereas C# often use field accesses, our approach treats field accesses as a special type of method calls.



Our approach adds additional edges to the built ATG (and sub-graphs inside ATG) representing data dependencies among built sub-graphs. We use the following rules for adding additional edges to the built ATG.

1. $\forall$ statements of the form $x = y$, where $x \in F \cup V \wedge y \in F \cup V$, our approach adds an edge from y to x. This edge represents that x is data dependent on y.



2. $\forall$ statements of the form $x = AM()$, where $x \in F \cup V$, our approach adds an edge from AM to x if the return value of AM is assigned to x. This edge represents that x is data dependent on the return value of AM.

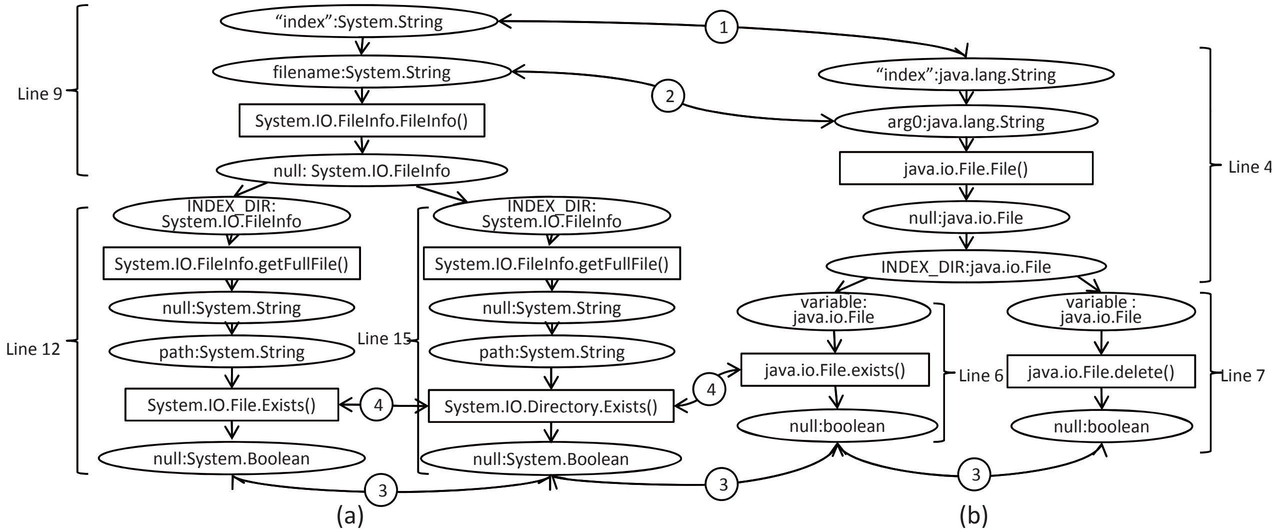
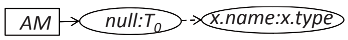
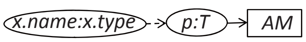


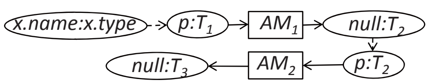
Figure 7: Built ATGs and the main steps of comparing ATGs



3. $\forall$ API methods $AM(x)$ called by method m, our approach adds an edge from x to the parameter node of AM. This edge represents that the parameter of AM is data dependent on x.

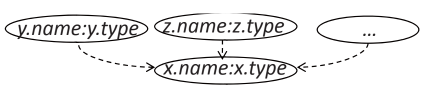


4. $\forall$ statements of the form $m_2(m_1(x))$, our approach adds an edge from the return value node of m_1 to the parameter node of m_2 parameter node. This edge represents that the parameter of m_2 is data dependent on the return value of m_1.



5. $\forall$ statements of the form $x.m()$, our approach adds an edge from x to m as x is the receiver object of m. This edge represents that the receiver object of m is data dependent on x.

6. $\forall$ statements of the form $x = y\ op\ z\ op\ \ldots, op \in \{+, -, *, /\}$, our approach adds edges from y, z, and others to x, as these variables are connected by binary operations and the return value is assigned to x. The edge denotes the data dependency from y, z, and other variables to x. For simplicity, our approach ignores *op* info. We discuss the issue in Section 6.



For each method m in the client code, our approach applies preceding rules for each statement from the beginning to the end of m. Within each statement, our approach applies these rules based on their nesting depth in the abstract syntax tree. For example, for the statements of the form $m_2(m_1(x))$, our approach first applies these rules on m_1 and then on m_2.

Figures 7a and 7b show partial ATGs for C# (`IndexFiles.cs`) and Java (`IndexFiles.java`) code examples shown in Figure 3, respectively. Figure 7 also shows corresponding line numbers of each sub-graph. Our approach applies Rules 2 and 6 for Lines 4 and 9 (Figure 3) to build corresponding sub-graphs in the ATG. For Lines 6 and 7 (Figure 3), our approach applies Rules 2 and 8 to build corresponding sub-graphs in the ATG. For Lines 12 and 15 (Figure 3), our approach applies Rule 2, 3, and 6 to build corresponding sub-graphs.

Algorithm 2: ATG Comparison Algorithm

Input: G is the ATG of a method (m); G' is the ATG of m's mapped method.
Output: S is a set of mapping relations for API methods

begin
- $P \leftarrow findVarPairs(m, m')$
- **for** *Pair p in P* **do**
  - $SM \leftarrow G.nextMethods(p.sharp)$
  - $JM \leftarrow G.nextMethods(p.java)$
  - $\Delta S = mapping(SM, JM)$
  - **while** $\Delta S \neq \phi | \Delta SM \neq \phi | \Delta JM \neq \phi$ **do**
    - $S.addAll(\Delta S)$
    - **for** *Method sm in SM* **do**
      - **if** $sm.isMapped$ **then**
        - $SM.replace(sm, sm.nextMethod())$
      - **else**
        - $SM.replace(sm, sm.mergeNextMethod())$
    - **for** *Method jm in JM* **do**
      - **if** $jm.isMapped$ **then**
        - $JM.replace(jm, jm.nextMethod())$
      - **else**
        - $JM.replace(jm, Jm.mergeNextMethod())$
    - $\Delta S = mapping(SM, JM)$

end

4.3.3 Comparing API transformation graphs

The second sub-step compares each pair of built ATGs for mining mapping relations of API methods. Our mapped API methods satisfy three criteria: (1) Mapped API methods implement the same functionality. (2) Mapping relation describes the relation between parameters of mapped API methods. (3) Mapping relation describes the relation between return values of mapped API methods. The two mapped API methods in two different languages satisfying the preceding three criteria are replaceable in the client code. Therefore, these mapped API methods assist for migrating client code from one language to another.

Algorithm 2 presents major steps of comparing ATGs for mining mapping relations of API methods. Consider two methods m and m' of two different languages L and L', respectively, in the client code. Consider that the associated ATGs of m and m' are compared to mine mapping relations of API methods. First, our algorithm finds matching variables $\in F$, V, and P_1 in m and m'. Our algorithm maps two variables v and v' of methods m and m', respectively, if the similarity measure on their names is greater than *SIM_THRESHOLD*. For constants in m and m', our algorithm maps those two constants, if they have exactly the same value. Our algorithm uses these variable and constant mappings to compute mappings between API methods that use these variables and constants. Our algorithm uses the following criteria for mapping two API methods jm and sm.

Matching entities: The first criterion is based on entities such as receiver variable or parameters of jm and sm to map jm and sm. We map jm with sm, if the receiver variable of API method jm is mapped to the receiver variable of sm, and there is a one-to-one mapping between parameters of jm and sm.

Matching functionalities: The second criterion is based on functionalities of jm and sm. We consider that jm and sm implement the same functionality, if the similarity measure between the name of jm and the name of sm is greater than *SIM_THRESHOLD*.

Matching outputs: The third criterion is based on the return values of jm and sm. Consider the return values of jm and sm as r_1 and r_2, respectively. We map jm with sm, if the type of r_1 is mapped with the type of r_2 in mapping API classes relationship.

Our algorithm first attempts to map first API method jm in m with the first API method sm in m'. If our algorithm successfully maps jm with sm, our algorithm moves to the next available API methods in m and m' of the client code. If our algorithm does not able to map jm with sm, our algorithm merges sm and jm with their next available API methods in the corresponding ATGs, respectively, and attempts to map merged API methods. For two merged API methods, our algorithm uses the maximum similarity of method names between jm and sm as a similarity measure for matching their functionalities. With each iteration, sm or jm or the mapping relation (represented as S) in the algorithm changes. Therefore, we repeat our algorithm till S, sm, and jm do not change anymore.

We next explain our algorithm using the illustrative example shown in Figure 7. The numbers shown in circles represent the major steps in our algorithm for mining mapping relations of API methods. We next explain each step in detail.

S1: mapping parameters, fields, local variables, and constants. Given two ATGs of each method pair $\langle m, m' \rangle$, this step maps variables such as parameters, fields, and local variables by comparing their names and maps constants by comparing their values. As shown in Figure 7, Step 1 maps two constants as both the constants have the same value `index`.

S2: mapping inputs of API methods. Step 2 mines mapping relations of API methods using variable and constant mapping relations. Initially, this step identifies first API methods in the two ATGs and tries to map their parameters and receiver objects of the two API methods. In our current example, this step maps the parameter `filename` to the parameter `arg0` as these parameters are of the same type and their associated constants are mapped.

S3: mapping outputs of API methods. In contrast to Step 2 that maps parameters, Step 3 maps return values of API methods. In this step, if our approach is not able to map return values, our approach merges the next API method and then attempts to map return values of merged API methods. In our current example shown in Figure 7, return value of `System.IO.FileInfo.FileInfo()` cannot be mapped to the return value of `java.io.File.File()`.

Project	Source	Java version		C# version	
		#C	*#M*	*#C*	*#M*
neodatis	SourceForge	1298	9040	464	3983
db4o	SourceForge	3047	17449	3051	15430
numerics4j	SourceForge	145	973	87	515
fpml	SourceForge	143	879	144	1103
PDFClown	SourceForge	297	2239	290	1393
OpenFSM	SourceForge	35	179	36	140
binaryNotes	SourceForge	178	1590	197	1047
lucene	Apache	1298	9040	464	3015
logging	Apache	196	1572	308	1474
hibernate	hibernate	3211	25798	856	2538
rasp	SourceForge	320	1819	557	1893
llrp	SourceForge	257	3833	222	978
simmetrics	SourceForge	107	581	63	325
aligner	SourceForge	41	232	18	50
fit	SourceForge	95	461	43	281
Total		11668	75685	6900	34165

Table 1: Subjects

Therefore, our approach merges next API methods in the ATG till the `Exists` API method, as the return values (shown as `Boolean`) match only after the `Exists` API method. Figure 7 shows Step 3 along with the matching return values.

S4: mapping functionalities. After our approach maps parameters and return values, this step further maps functionalities of those merged API methods. Given two merged API methods with mapped parameters and return values, this step uses the similarity measure based of their method names as a criterion for matching their functionalities. In the preceding example, this step maps the two merged API methods shown in Figure 7a to the merged API methods of the `java.io.File.exist()` as all three merged API methods include the method named `exist`.

Our approach applies preceding steps on ATGs (as shown in Figures 7a and 7b) and mines mapping relations. An example mapping relation from the preceding ATGs is shown in Figure 4.

5. EVALUATIONS

We implemented a tool named MAM based on our approach and conducted two evaluations on the tool. Our evaluations focus on two research questions as follows:

1. How effective can our approach mine various mapping relations of APIs (Section 5.1)?
2. How much benefit can the mined mapping relations of APIs offer in aiding language migration (Section 5.2)?

We choose 15 open source projects that have both Java versions and C# versions as the subjects of our evaluations, and Table 1 show these subjects. Column "Project" lists names of subjects. Column "Source" lists sources of these subjects. These subjects come from famous open source societies such as SourgeForge[13], Apache[14], and hibernate[15]. Columns "Java version" and "C# version" list the two versions from each subject. All these used versions are the latest versions at the time of writing. For these two columns, subcolumn "*#C*" lists numbers of classes, and sub-column "*#M*" lists numbers of methods. We notice that Java versions are much larger than C# versions totally. We investigate these projects and find two factors as follows. One is that Java versions of some projects are more update-to-date. For example, the latest Java version of *numericas4j* is 1.3 whereas the latest C# version is 1.2. The other factor is that some projects are migrating from Java to C# in progress. For

[13]`http://www.sf.net`
[14]`http://www.apache.org/`
[15]`http://www.hibernate.org/`

example, the website[16] of *neodatis* states that *neodatis* is a project in Java and is being ported to C#. This observation further confirms the usefulness of our approach as our approach aids migrating from one language to other languages. Totally, these projects have 18,568 classes and 109,850 methods.

We conducted all the evaluations on a PC with an Intel Qual CPU @ 2.83GHz and 1.98M memory running Windows XP.

5.1 Mining API mapping

To evaluate the first research question, we use 10 projects from Table 1 as the subjects for mining API mapping.

Aligning client code. We first use our approach to align client code. The threshold is set to 0.6 based on our initial experience. We choose a relatively low threshold so that our approach can take into account as much client code as possible.

Table 2 shows the results of this step. For column "Aligned", sub-column "*# C*" lists numbers of aligned classes, and sub-column "*# M*" lists numbers of aligned methods. For each project of Column "C# version" and Column "Java version", sub-column "*%C*" lists the percentage of the aligned classes among total classes of corresponding versions. Sub-column "*%M*" lists the percentage of the aligned methods among total methods of corresponding versions. Row "Total" of the two sub-columns lists the percentage of aligned methods/classes among the total methods/classes as shown in Table 1. We find that the results of Table 2 fall into three categories. This first category includes *db4o*, *fpml*, *PDFClown*, *OpenFSM*, and *binaryNotes*. There, our approach achieves relatively high percentages for both Java versions and C# versions. For each of the five project, "*%M*" is relatively smaller than "*%C*" since methods of those unaligned classes cannot be aligned and thus are counted as unaligned[17]. The second category includes *neodatis*, *numerics4j*, and *lucene*. There, our approach aligns C# versions well but does not align Java versions so well. We find that *neodatis* and *lucene* are migrating from Java to C# in progress and the Java version of *numerics4j* is more update-to-date than its C# version. As a result, some Java classes or methods do not have corresponding implementations in C# versions in these projects and thus are left unmapped. The third category includes *logging* and *hibernate*. There, our approach does not align classes and methods of the two projects well. Although both of the two projects seem to be migrated from existing Java versions, the programmers of the two projects often do not refer to names of existing Java versions for naming entities. For each of the two projects, the percentage of aligned classes is relatively high, and the percentage of aligned methods is relatively low. We find that even if our approach aligns a wrong class pair, our approach does not align methods within the wrong pair as the method names of a wrong pair are quite different. The result suggests that we can take method names into account when aligning classes in future work.

For all these projects, our approach does not align all classes and all methods. We find another two factors besides the factor of different entities naming across languages. First, one functionality may be implemented as a single class in one language version and is implemented as multiple classes in the other language version. Second, a Java version and a C# version sometimes may have quite different functionalities. We discuss these issues in Section 6.

In summary, as shown by Row "Average", our approach aligns most classes and methods on average. The result confirms that many programmers refer to existing versions of another language

[16] http://wiki.neodatis.org/

[17] Another factor lies in that Java versions usually have many getters and setters and these getters and setters often do not have corresponding methods in C# versions.

Project	Java version		C# version		Aligned	
	%C	*%M*	*%C*	*%M*	*#C*	*#M*
db4o	87.8%	65.5%	87.6%	74.1%	2674	11433
fpml	93.7%	70.5%	93.5%	56.2%	134	620
PDFClown	86.5%	51.0%	88.6%	82.1%	257	1143
OpenFSM	97.1%	72.1%	94.4%	92.1%	34	129
binaryNotes	98.9%	61.1%	89.3%	92.7%	176	971
neodatis	44.7%	54.8%	100.0%	93.6%	408	3728
numerics4j	57.2%	48.6%	95.4%	89.9%	75	174
lucene	34.9%	26.6%	97.6%	79.8%	453	2406
logging	91.8%	18.1%	58.4%	19.3%	180	285
hibernate	26.4%	1.2%	99.1%	12.6%	848	319
Average	53.2%	30.8%	88.8%	69.2%	524	2121

Table 2: Results of Aligning client code

Project	Class		Method	
	Num.	*Acc.*	*Num.*	*Acc.*
db4o	3155	83.3%	10787	90.0%
fpml	199	83.3%	508	83.3%
PDFClown	539	96.7%	514	100.0%
OpenFSM	64	86.7%	139	73.3%
binaryNotes	287	90.0%	671	90.0%
neodatis	526	96.7%	3517	100.0%
numerics4j	97	83.3%	429	83.3%
lucene	718	90.0%	2725	90.0%
logging	305	73.3%	56	90.0%
hibernate	1126	66.7%	7	13.3%
Average	702	85.0%	1936	81.3%

Table 3: Results of mining API mapping

to name entities of a version under development.

Mining API mapping. We then use our approach to mine mapping relations of API classes and API methods.

Table 3 shows the results of this step. For Columns "Class" and "Method", sub-column "*Num.*" lists numbers of mined mapping relations. The numbers of mined API mapping are largely proportional to the sizes of projects as shown in Table 1 except *logging* and *hibernate*. As classes and methods of these two projects are not quite well aligned, our approach does not mine many mapping relations of APIs from the two projects. For the remaining projects, our approach mines many mapping relations of API classes and API methods. Sub-column "*Acc.*" lists accuracies of the top 30 mined API mapping (*i.e.*, percentages of correct mapping relations). For mined API mapping from each project, we manually inspect top 30 mined mapping relations of APIs and classify them as correct or incorrect based on programming experiences. We find that our approach achieves high accuracies except *hibernate*. Although our approach does not align *logging* quite well either, the accuracies of API mapping from *logging* are still relatively high. To mine API mapping of classes, our approach requires that names of classes, methods, and variables are all similar. To mine API mapping of methods, our approach requires that two built API transformation graphs are similar. The two requirements are relatively strict. As a result, if the first step does not align client code quite well, our approach misses some mapping relations of APIs but does not introduce many false mapping relations. In other words, our approach is robust to mine accurate API mapping.

In summary, our approach mines a large number of mapping relations of APIs totally. These mined mapping relations are accurate and cover various libraries.

Comparing with manually built API mapping. Some translation tools such as Java2CSharp[18] have manually built files that describe mapping relations of APIs. For example, one item from the mapping files of Java2CSharp is as follows:

[18] http://j2cstranslator.wiki.sourceforge.net

Package	Class			Method		
	P	***R***	***F***	***P***	***R***	***F***
java.io	78.6%	26.8%	52.7%	93.1%	53.2%	73.1%
java.lang	82.6%	27.9%	55.3%	93.8%	25.4%	59.6%
java.math	50.0%	50.0%	50.0%	66.7%	15.4%	41.0%
java.net	100.0%	12.5%	56.3%	100.0%	25.0%	62.5%
java.sql	100.0%	33.3%	66.7%	100.0%	15.4%	57.7%
java.text	50.0%	10.0%	30.0%	50.0%	16.7%	33.3%
java.util	56.0%	25.5%	40.7%	65.8%	12.6%	39.2%
junit	100.0%	50.0%	75.0%	92.3%	88.9%	90.6%
orw.w3c	42.9%	33.3%	38.1%	41.2%	25.0%	33.1%
Average	68.8%	26.4%	47.6%	84.6%	28.7%	56.7%

Table 4: Results of comparing results

```
package java.math :: System {
  class java.math.BigDecimal :: System:Decimal {
    method multiply(BigDecimal)
       { pattern =  Decimal.Multiply(@0, @1); }
  }
}
```

This item describes mapping relations between `java.math.BigDecimal.multiply()` and `System.Decimal.Multiply()`. The pattern string describes mapping relations of inputs. In particular, "`@0`" denotes the receiver, and "`@1`" denotes the first parameter. Based on this item, Java2CSharp translates the following code snippet from Java to C# as follows:

```
BigDecimal m = new BigDecimal(1);
BigDecimal n = new BigDecimal(2);
BigDecimal result = m.multiply(n);
->
Decimal m = new Decimal(1);
Decimal n = new Decimal(2);
Decimal result = Decimal.Multiply(m,n);
```

To compare with manually built mapping files of Java2CSharp, we translate our mined API mapping with the following strategy. First, for each Java class, we translate its mapping relations of classes with the highest supports into mapping files as relations of packages and classes. Second, for each Java method, we translate its mapping relations of methods with the highest supports into mapping files as relations of methods with pattern strings. For 1-to-1 mapping relations of methods, this step is automatic as mined mapping relations describe mapping relations of corresponding methods and inputs. For many-to-many mapping relations of methods, this step is manual as mined mapping relations do not include adequate details such as how to deal with multiple outputs. We further discuss this issue in Section 6.

The mapping files of Java2CSharp cover 13 packages defined by J2SE and 2 packages defined by JUnit[19], and we treat these mapping files as a golden standard. We find 9 packages overlapping between the mined mapping files and the mapping files of Java2CSharp. We compare mapping relations of APIs within these mapping packages, and Table 4 shows the results. Column "Class" lists the results of comparing API classes. Column "Method" lists the results of comparing API methods. For their sub-columns, sub-column "*P*" denotes precision. Sub-column "*R*" denotes recall. Sub-column "*F*" denotes F-score. *Precision*, *Recall*, and *F-score* are defined as follows:

$$Precison = \frac{true\ positives}{true\ positives + false\ positives} \quad (1)$$

$$Recall = \frac{true\ positives}{true\ positives + false\ negatives} \quad (2)$$

$$F\!-\!score = \frac{2 \times Precision \times Recall}{Precision + Recall} \quad (3)$$

In the preceding formulae, true positives represent those mapping relations that exist in both the mined API mapping and the golden standard; false positives represent those transitions that exist in the mined API mapping but not in the golden standard; false negatives represent those transitions that exist in the golden standard but not in the mined API mapping. From the results of Table 4, our approach achieves a relatively high precision and a relatively low recall. We further investigate the differences, and we find three main causing impact factors. First, the mined mapping files contain correct items that do not exist in the mapping files of Java2CSharp. For example, the mined mapping files contain a mapping relation between `org.w3c.dom.Attr` and `System.Xml.XmlAttribute`, and the mapping relation does not exist in the mapping files of Java2CSharp. As these items are counted as false positives, this impact factor reduces the precisions. Second, although we use 10 large projects as subjects to mine API mapping, these projects do not cover mapping relations of all API classes and all API methods. Consequently, our approach does not mine mapping relations of the entire API classes and the entire API methods. Although as shown in Table 3 our approach mines many mapping relations, these mapping relations cover many libraries. When we limit mapping relations to the packages as shown in Table 4, the mined mapping relations are actually not so many as expected. On the contrary, the mapping files of Java2CSharp are more detailed as they are manually built. This impact factor reduces the recalls. Third, some API classes and API methods between Java and C# have different behaviors. To hide these behaviors from client code, Java2CSharp maps these classes and methods to its implemented classes and methods. For example, Java2CSharp maps `java.util.Set` to `ILOG.J2CsMapping.Collections.ISet`. Our approach did not mine these mapping relations since the subjects in Table 1 do not use Java2CSharp's own implemented classes and methods. This impact factor reduces both the precisions and the recalls.

In summary, compared with the mapping files of Java2CSharp, our mined mapping files show a relatively high precisions and relatively low recalls. The relatively high precisions show that our mined mapping relations are accurate and contain some mapping relations that are not covered by Java2CSharp. The relatively low recalls show that we need improvements such as introducing more subject projects to cover detailed API mapping.

5.2 Aiding Language Migration

To evaluate the second research question, we feed the mined API mapping to the Java2CSharp tool and investigate whether these mined API mapping can improve the tool's effectiveness. We choose this tool because this tool is a relatively mature project at ILOG[20] (now a part of IBM) and supports the extension of user-defined mapping relations of APIs.

We use Java2CSharp to translate five projects listed in Table 1 from Java to C#, and Table 5 shows the results. For each translated C# project, Column "No MF" lists results without mapping files. Column "MF" lists results with the mapping files of Java2CSharp. Column "Ext. MF" lists results with mapping files that combine mined API mapping with the existing mapping files of Java2CSharp. Sub-column "*E*" lists numbers of compilation errors. Sub-column

Projects	No MF		MF		Ext. MF			
	E	***B***	***E***	***B***	***E***	***%E***	***B***	***%B***
rasp	973	159	708	123	627	11.4%	93	24.4%
llrp	2328	122	1540	114	269	82.5%	42	63.2%
simmetrics	217	13	12	0	6	50.0%	0	0%
aligner	368	34	289	0	262	9.3%	0	0%
fit	177	29	27	0	20	25.9%	0	0%
Total	4063	491	2576	237	1174	54.4%	135	43.0%

Table 5: Compilation errors

[19] http://www.junit.org/

[20] http://www.ilog.com/

"*B*" lists numbers of found bugs. For each project, we find out those overlapping files between translated files and existing C# files and manually inspect the top 5 largest files by comparing existing C# files for API related bugs. Sub-columns "*%E*" and "*%B*" list percentages of improvements over the mapping files of Java2CSharp. Totally, mined API mapping helps further reduces 54.4% compilation errors and 43.0% found bugs. As the five projects use different libraries, the numbers of translated projects are different. In particular, *simmetrics* and *fit* use API classes of J2SE that are covered by mapping files. Consequently, the translated projects of *simmetrics* and *fit* have few errors and bugs. The *aligner* project also mainly uses J2SE, but it uses many API classes and methods from `java.awt` for its GUI. The mapping files of Java2CSharp cover only 1 class of `java.awt`, so the translated project has many errors. As the existing C# version of *aligner* does not have GUI, we do not compare those buggy translated GUI files and we do not find any bugs. The mined files map `java.awt` to `System.Windows.Forms` and thus reduce compilation errors. However, the result is not significant as many classes of the two packages are still not mapped. For *rasp* and *llrp*, they both use various libraries besides J2SE. Consequently, the translated projects have both many errors and bugs. In particular, *llrp* uses log4j[21] and jdom[22], and the mined mapping files contain mapping relations of the two libraries. As a result, the mined API mapping helps reduce compilation errors and bugs significantly. For *rasp*, it uses some libraries such as Neethi[23] and WSS4J[24]. Sine the used subjects for mining and thus our mined API mapping do not cover the two libraries, the translated project of *rasp* contains many "*U*" and "*T*" errors.

In summary, the mined API mapping improves existing language translation tools such as Java2CSharp. In particular, the mined API mapping helps effectively reduce "*U*" and "*T*" errors in the translated projects.

5.3 Threats to Validity

The threat to external validity includes the representativeness of the subjects in true practice. TO... For space These threats could be reduced by more experiments on wider types of subjects in future work. The threats to internal validity are instrumentation effects that can bias our results. Faults in our prototype, the Daikon front end, and the RECON instrumenter might cause such effects. To reduce these threats, we manually inspected the spectra differences on a dozen of traces for each program subject. One threat to construct validity is that our experiment makes use of the data traces collected during executions, hoping that these precisely capture the internal program states for each execution point.

6. DISCUSSION AND FUTURE WORK

In this section, we discuss related issues of our approach.

Aligning client code of similar functionalities. As shown in Table 2, our approach sometimes fails to align client code. For some considerations, programmers may implement one functionality as one class or one method in one language version but implement the same functionality as multiple classes or methods in another language version. One feasible way to align these functionalities is to analyze them dynamically. For example, Jiang and Su [5] propose an approach to mine code snippets of similar functionalities. We plan to develop a dynamic technique for those unmatched classes or methods in our future work.

[21]`http://logging.apache.org/log4j/`
[22]`http://www.jdom.org/`
[23]`http://ws.apache.org/commons/neethi/`
[24]`http://ws.apache.org/wss4j/`

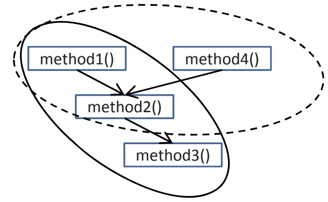


Figure 8: Merging technique

Mining richer API mapping. As shown in Table 4, although we use 10 large projects as subjects, our evaluation does not achieve high recalls for J2SE. For a given library, these projects still do not provide adequate source files for mining. Our previous work [11, 12] show that it is feasible to use the internet-scale code available on the web as subjects for mining with the help of code search engines such as Google code search[25]. In future work, we plan to leverage such search engines to mine richer API mapping.

Ranking mined mapping relations. When comparing with the built mapping files of Java2CSharp, we choose mined mapping relations of APIs with the highest supports as generated mapping files. However, in some cases, the API mapping with the highest support is not necessarily the best choice. For example, `java.util.ArrayList` is mapped to `System.Collections.ArrayList` based on support values. The Java class supports generic programming, whereas the C# class does not. Consequently, the Java class seems to be better mapped to `System.Collections.Generic.List` as this C# class also supports generic programming. We plan to develop ranking techniques to address this issue in future work.

Mining more many-to-many mapping relations of API methods. A majority of mined mapping relations of API methods describe one-to-one relations. Algorithm 2 merges the next API method with a forward strategy. For the example shown in Figure 8, if the algorithm merges `method1()` and `method2()` but fails to find a match, the algorithm tries to merge `method3()`. In some cases, a match can be found if the algorithm merges `method4()` instead of `method3()`. We plan to improve the algorithm to mine more many-to-many relations in future work.

Migrating many-to-many mapping relations of API methods. A mined many-to-many mapping of API methods may have multiple outputs and complicated internal data processes. Our defined API transformation graphs help find out all essential API methods. However a graph does not describe adequate details to support automatic translation. For example, we need to manually add an *or* operator for the two outputs of the API mapping shown in Figure 4. We plan to add more details to help automate migration with many-to-many mapping relations in future work.

Migrating unmapped APIs. Our approach mines API mapping of methods that have mapped inputs, mapped outputs, and similar functionalities. Consequently, mined API mapping can be migrated automatically. However, some APIs between two languages cannot satisfy all the three criteria. For these APIs, if outputs are unmapped, our approach can simply ignore outputs when outputs are not used in client code. If inputs or functionalities are unmapped, we plan to develop techniques that analyze how two versions of a project deal with a similar unmapped API problem for some reusable code snippets in future work.

7. RELATED WORK

Our approach is related to previous work on language migration and library migration.

Language migration. To reduce effort of language migration [9],

[25]`http://www.google.com/codesearch`

researchers propose various approaches to automate the process [3, 7,13,14,16]. Most of these approaches focus the syntax differences bewteen languages. For example, Deursen *et al.* [13] propose an approach to identify objects in legacy code, and the results are useful to deal with differences between object-oriented and procedural languages. As shown by El-Ramly *et al.* [2]'s experience report, existing approaches and tools support only a subset of APIs, and consequently it becomes an important and yet challenging task to automate API transformation. Our approach mines API mapping between languages to aid language migration, addressing a significant problem unaddressed by the previous approaches and complementing these approaches.

Library migration. With evolution of libraries, some APIs may become incompatible across library versions. To deal with the problem, some approaches have been proposed. In particular, Henkel and Diwan [4] propose an approach that captures and replays API refactoring actions to keep client code updated. Xing and Stroulia [15] propose an approach that recognizes the changes of APIs by comparing the differences of two versions of libraries. Balaban *et al.* [1] propose an approach to help translate client code when mapping relations of libraries are available. Different from these approaches, our approach focuses on mapping relations of APIs among different languages. In addition, as our approach uses API transformation graphs to mine mapping relations of APIs, our approach helps mine mapping relations for those API methods whose input orders are changed or whose functionalities are split into several methods if our approach is applied in library migration.

8. CONCLUSION

Mapping relations of APIs are quite useful to language migration but are difficult to obtain due to various factors. In this paper, we propose an approach to mine mapping relations of APIs from existing different versions of a project automatically. We conducted evaluations on our approach. The results show that our approach mines various API mapping between Java and C#, and API mapping improves existing language translators such as Java2CSharp.

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