A General Framework to Identify Software Components from Execution Data

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Abstract: Restructuring an object-oriented software system into a component-based one allows for a better understanding of the software system and facilitates its future maintenance. A component-based architecture structures a software system in terms of components and interactions where each component refers to a set of classes. In reverse engineering, identifying components is crucial and challenging for recovering the component-based architecture. In this paper, we propose a general framework to facilitate the identification of components from software execution data. This framework is instantiated for various community detection algorithms, e.g., the Newman's spectral algorithm, Louvain algorithm, and smart local moving algorithm. The proposed framework has been implemented in the open source (Pro)cess (M)ining toolkit ProM. Using a set of software execution data containing around 1.000.000 method calls generated from four real-life software systems, we evaluated the quality of components identified by different community detection algorithms. The empirical evaluation results demonstrate that our approach can identify components with high quality, and the identified components can be further used to facilitate future software architecture recovery tasks.

1 INTRODUCTION

The maintenance and evolution of software systems have become a research focus in software engineering community (Mancoridis et al., 1999). Architectures of these systems can be used as guidance to help understand and facilitate the future maintenance (Liu et al., 2018d). However, complete and up-to-date software architecture descriptions rarely exist (Lindvall and Muthig, 2008). Software architectures that normally include components and interactions can be reconstructed from low-level data, such as source code, and execution data.

During the execution of software systems, tremendous amounts of execution data can be recorded. By exploiting these data, one can reconstruct a software architecture. To this end, we need to identify components from the execution data. For object-oriented software systems, a component is extracted as a set of classes that provide a number of functions for other components. In this paper, we propose a general framework to identify components from software execution data by applying various community detection algorithms. Community detection is one of the most useful techniques for complex networks analysis with an aim to identify communities. A software system can be viewed as a complex network of classes, in which the component identification problem can be naturally regarded as the community detection problem with modularity maximization.

More concretely, we first construct a class interaction graph by exploiting the software execution data that provides rich information on how classes interact with each other. Then, different community detection algorithms are applied to partition the class interaction graph into a set of sub-graphs. Classes that are grouped in the same sub-graph form a component. Next, a set of quality criteria are defined to evaluate the quality of the identified components from different perspectives. Our framework definition is generic and can be instantiated and extended to support various community detection algorithms. To validate the proposed approach, we developed two plug-ins in the ProM toolkit 1, which support both the identification and the evaluation process.

The main contributions of this paper include:

- a general framework to support the identification and quality evaluation of components from software execution data and its instantiation by five community detection algorithms. Different from

\(^1\)http://www.promtools.org/
existing graph partitioning-based algorithms, our approach does not require users to specify the number of clusters in advance; and

- two plug-ins in the ProM toolkit. This allows other researchers reproducing our experiments and comparing their approaches.

Section 2 presents some related work. Section 3 defines preliminaries. Section 4 presents the main approach. Section 5 introduces the tool support. In Section 6, we present the experimental evaluation. Finally, Section 7 concludes the paper.

2 RELATED WORK

Generally speaking, the identification of components can be achieved by clustering classes. Table 1 summarizes some typical component identification approaches for object-oriented software systems by considering the required type of input (i.e., source code, development documents, execution data), the type of identification techniques (e.g., graph clustering/partition, genetic algorithm, etc.), the parameter settings, and tool support availability. Note that ✓/✗ means that the tool is introduced in the paper but is not available online or does not work any more.

According to Table 1, these approaches are classified into three categories based on their required input artifacts: (1) development documents-based approaches that take the sequence diagram, class diagram and use case diagram as input; (2) source code-based approaches that take the source code as input and consider structural connections among classes; and (3) execution data-based approaches that take software execution data as input. The output of these approaches are component configurations, i.e., how classes are grouped to form components. Our work fits into the third category.

Because software development documents are typical either incomplete or out-of-date, the applicability of the development documents-based approaches is quite limited. For components, the idea is to group together classes that contribute to the same function. Source code-based approaches use the dependencies among classes that are extracted from the source code by static analysis techniques. However, classes in the source code may have in some cases a wider scope than the functional scope. In addition, they are not applicable anymore if the source code is not available (e.g., in case of legacy software systems). Another way to determine which class contributes to which function (component) is to execute the software system with individual functions. The execution data-based approaches help limit the analysis of dependency only to the space covered by the application execution. However, existing execution data-based approaches suffer from the following limitations that may restrict the applicability:

- Requirement for User Input Parameters. Existing approaches require users to specify a group of parameters (e.g., the number/size of components) as input. However, a reasonable parameter setting is very difficult for users that are not familiar with the approach. If parameters are not set properly, the underlying approaches may perform badly.

- Lack of a Clearly Defined Systematic Methodology. A systematic methodology defines clearly the required input, the techniques, the resulted output and the evaluation criteria of the approach to solve a general research challenge. Existing execution data-based approaches do not explicitly define such a complete methodology. This limits the applicability and extensibility of existing approaches in the large.

- Lack of Tool Support. The usability of an approach heavily relies on its tool availability. Existing dynamic component identification approaches do not provide usable tools that implement their techniques. This unavailability prohibits other researchers to reproduce the experiment and compare their approaches.

3 PRELIMINARIES

Let \( \mathcal{M} \) be the method call universe, \( \mathcal{N} \) be the method universe, \( \mathcal{C} \) be the universe of classes, \( \mathcal{O} \) be the object universe where objects are instances of classes. To relate these universes, we introduce the following notations: For any \( m \in \mathcal{M}, m \in \mathcal{N} \) is the method of which \( m \) is an instance. For any \( o \in \mathcal{O}, o \in \mathcal{C} \) is the class of \( o \).

A method call is the basic unit of software execution data (Liu et al., 2016; Liu et al., 2018d; Liu et al., 2018a; Liu et al., 2018c; Liu et al., 2018b; Leemans and Liu, 2017; Qi et al., 2018). The method call and its attributes are defined as follows:

**Definition 1. (Method Call, Attribute)** For any \( m \in \mathcal{M} \), the following standard attributes are defined:

- \( \eta : \mathcal{M} \rightarrow \mathcal{O} \) is a mapping from method calls to objects such that for each method call \( m \in \mathcal{M} \), \( \eta(m) \) is the object containing the instance of the method \( m \).

- \( c : \mathcal{M} \rightarrow \mathcal{M} \cup \{ \bot \} \) is the calling relation among method calls. For any \( m_i, m_j \in \mathcal{M} \), \( c(m_i) = m_j \)
4 COMPONENT IDENTIFICATION

The input of our approach is software execution data, which can be obtained by instrumenting and monitoring software execution. In Section 4.1, we first give an overview of the identification framework. Then, we present the instantiation of the framework with details in Sections 4.2-4.4.

4.1 Approach Overview

An approach overview is described in the following:

- **Class Interaction Graph Construction.** Starting from the software execution data, we construct a class interaction graph (CIG) where a node represents a class and an edge represents a calling relation among the two classes.

- **Component Identification.** By taking the constructed CIG as input, we partition it into a set of sub-graphs using existing community detection algorithms. Classes that are grouped in the same sub-graph form components.

- **Quality Evaluation of the Identified Components.** After identifying a set of components, we evaluate the quality of the identified components against the original CIG.

4.2 Class Interaction Graph Construction

Given the software execution data, we first construct the CIG according to the following definition.

**Definition 3.** (Class Interaction Graph) Let SD be the execution data of a piece of software. G = (V, E) is defined as the Class Interaction Graph (CIG) of SD such that:

\[ V = \{ v \in SD | m \in SD : \eta(m) = v \lor \eta(c(m)) = v \} \]

\[ E = \{ (v_i, v_j) \in V \times V | m \in SD : \eta(m) = v_i \land \eta(c(m)) = v_j \} \]

According to Definition 3, a CIG contains (1) a set of classes, i.e., vertices; and (2) a set of calling relations among them, i.e., edges. Note that the calling relations among classes are obtained from method calls, e.g., if \( m_1 \) calls \( m_2 \) we have a calling relation saying the class of \( m_1 \) calls the class of \( m_2 \). Different from existing software call graphs that are defined on top of the method calling relation in the source code (Qu et al., 2015), the CIG id defined on the class calling relations from the execution data.

4.3 Component Identification

After constructing a CIG, we introduce how to identify components out of the CIG. Essentially, the component identification is a division of the vertices of CIG into a finite set of non-overlapping groups as defined in the following:

**Definition 4.** (Component Identification) Let SD be the software execution data and G = (V, E) be its CIG. CS \( \subseteq \mathcal{P}(V) \) is defined as the identified component set based on certain approach such that:

- \( \bigcup_{C \in CS} C = V \); and

<table>
<thead>
<tr>
<th>Reference</th>
<th>Required Input Artifacts</th>
<th>Techniques</th>
<th>Parameter Requirement</th>
<th>Tool Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Lee et al., 2001)</td>
<td>development documents</td>
<td>graph clustering</td>
<td>✓</td>
<td>\x</td>
</tr>
<tr>
<td>(Kim and Chang, 2004)</td>
<td>development documents</td>
<td>use case clustering</td>
<td>✓</td>
<td>\✓/\x</td>
</tr>
<tr>
<td>(Hasheminejad and Jalili, 2015)</td>
<td>development documents</td>
<td>evolutionary algorithm</td>
<td>✓</td>
<td>\x</td>
</tr>
<tr>
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<td>source code</td>
<td>class relation clustering</td>
<td>✓</td>
<td>\✓/\x</td>
</tr>
<tr>
<td>(Kebir et al., 2012)</td>
<td>source code</td>
<td>hierarchical clustering</td>
<td>✓</td>
<td>\x</td>
</tr>
<tr>
<td>(Cui and Chae, 2011)</td>
<td>source code</td>
<td>hierarchical clustering</td>
<td>✓</td>
<td>\✓/\x</td>
</tr>
<tr>
<td>(Luo et al., 2004)</td>
<td>source code</td>
<td>graph clustering</td>
<td>✓</td>
<td>\x</td>
</tr>
<tr>
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<td>source code</td>
<td>hyper-graph clustering</td>
<td>✓</td>
<td>\x</td>
</tr>
<tr>
<td>(Mancoridis et al., 1999)</td>
<td>source code</td>
<td>graph partition</td>
<td>✓</td>
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</tr>
<tr>
<td>(Qin et al., 2009)</td>
<td>execution data</td>
<td>concept lattices</td>
<td>✓</td>
<td>\x</td>
</tr>
<tr>
<td>(Allier et al., 2009)</td>
<td>execution data</td>
<td>genetic algorithm</td>
<td>✓</td>
<td>\x</td>
</tr>
<tr>
<td>(Allier et al., 2010)</td>
<td>execution data</td>
<td>genetic algorithm</td>
<td>✓</td>
<td>\x</td>
</tr>
</tbody>
</table>

means that \( m_i \) is called by \( m_j \), and we name \( m_i \) as the callee and \( m_j \) as the caller. For \( m \in MD \), if \( c(m) = \perp \), then \( m \) is a main method.
In the following, we instantiate the component identification framework by five state-of-the-art community detection algorithms: (1) the Newman’s spectral algorithm (Newman, 2006) and its MVM refinement (Schaffter, 2014); (2) Louvain algorithm (Blondel et al., 2008) and multi-level refinement (Rotta and Noack, 2011); and (3) Smart local moving algorithm (Waltman and Van Eck, 2013).

1) **Newman’s spectral algorithm and moving vertex method refinement.** Newman’s spectral algorithm aims to determine whether there exists any natural division of the vertices in a graph/network into nonoverlapping groups/modules, where these groups/modules may be of any size. This is addressed by defining a quantity called modularity \( Q \) to evaluate the division of a set of vertices into modules. \( Q \) is defined as follows: \( Q = F_e - E_F \) where \( F_e \) represents fraction of edges falling within modules and \( E_F \) represents expected fraction of such edges in randomized graphs.

To further improve the quality of group structures inferred using the Newman’s spectral algorithm, a refinement technique, called Moving Vertex Method (MVM) is introduced in (Schaffter, 2014). MVM works independently on top of the detection results obtained by the Newman’s spectral algorithm. It tries to move nodes from one community to another community and checks the effect of the modification on \( Q \). The modification that leads to the largest increase in \( Q \) is accepted. For more explanations of the MVM technique refinement, the reader is referred to (Newman, 2006) and (Schaffter, 2014).

2) **Louvain algorithm and multi-level refinement.** The Louvain algorithm starts with each node in a network belonging to its own community, i.e., each component consists of one node only. Then, the algorithm uses the **local moving heuristic** to obtain an improved community structure. The idea of **local moving heuristic** is to repeatedly move individual nodes from one community to another in such a way that each node movement results in a modularity increase. Hence, individual nodes are moved from one community to another until no further increase in modularity can be achieved. At this point, a reduced network where each node refers to a community in the original network is constructed. The Louvain algorithm proceeds by assigning each node in the reduced network to its own singleton community. Next, the local moving heuristic is applied to the reduced network in the same way as was done for the original network. The algorithm continues until a network is obtained that cannot be reduced further. An extension of the Louvain algorithm with multi-level refinement is introduced in (Rotta and Noack, 2011). The refinement improves solutions found by the Louvain algorithm in such a way that they become locally optimal with respect to individual node movements.

3) **Smart local moving algorithm.** The smart local moving (SLM) algorithm starts with each node in a network being its own community and it iterates over all communities in the present community structure. For each community, a sub-network is constructed which is a copy of the original network that includes only the nodes belonging to a specific community of interest. The SLM algorithm then uses the local moving heuristic to identify communities in the sub-network. Each node in the sub-network is first assigned to its own singleton community, and then local moving heuristic is applied. After a community structure has been obtained for each sub-network, the SLM algorithm constructs a reduced network. In the reduced network, each node corresponds to a community in one of the sub-networks. The SLM algorithm then performs an initial assignment of the nodes to communities in the reduced network in such a way that nodes corresponding to communities in the same sub-network are assigned to the same community. The previous steps start over again for the reduced network until a network is obtained that cannot be reduced any more.

### 4.4 Quality Metrics

This section introduces a group of quality metrics to help evaluate the components identified by different community detection techniques.

1) **Size and Counting.**

To give a general overview of the identified components, we first introduce the following metrics:

- The number of identified components (NoC) from the execution data of a software system.
- The average size of identified components (AoC), i.e., the average number of classes that each component involves.
- The ratio of single class components (RSC). RSC means the number of classes in single class components divided by the total number of classes.
- The ratio of largest component (RLC). RLC represents the number of classes in the largest component divided by the total number of classes.
• The ratio of intermediate components (RIC). RIC represents the number of classes in the intermediate components divided by the total number of classes. Note that RICs refer to components that neither contains one class nor be the largest ones.

According to (Cui and Chae, 2011), components with very large number of classes (high RLC) or very small number of classes (high RSC) cannot be regarded as good components. An ideal distribution is a normal distribution where quite many components have reasonable size (high RIC). Hence, we should try to avoid the case of too many single class components as well as a single very large one.

2) Coupling. In component-based software systems, coupling represents how tightly one component interacts with the others. The coupling metric between two components is defined as the ratio of the number of edges connecting them to the maximal number of edges that connect all their vertices.

Let $G = (V, E)$ be a CIG and $CS$ be the identified components. For any $C_1, C_2 \in CS$, we have:

$$coup(C_1, C_2) = \frac{|CouEdge(C_1, C_2)|}{|E_1| \times |E_2|}$$

(1)

where $CouEdge = E \cap ((C_1 \times C_2) \cup (C_2 \times C_1))$ represents the set of edges that connecting components $C_1$ and $C_2$. Then, the coupling metric of all components is defined as follows:

$$Coupling(CS) = \frac{\sum_{1 \leq i \leq j \leq |CS|} coup(C_i, C_j)}{|CS| \times (|CS| - 1)}$$

(2)

3) Cohesion. In component-based software systems, cohesion represents how tightly classes in the same component are associated. The cohesion metric of a component is defined as the ratio of the number of its edges to the maximal number of edges that can connect all its vertices (the number of edges in the complete graph on the set of vertices).

For any $C \in CS$, its cohesion metric is defined as:

$$cohes(C) = \frac{|CohEdge(C)|}{|C| \times (|C| - 1)}$$

(3)

where $CohEdge(C) = E \cap (C \times C)$ represents the set of edges that are contained in $C$. Then, the cohesion metric of all components is defined as follows:

$$Cohesion(CS) = \frac{\sum_{C \in CS} cohes(C)}{|CS|}$$

(4)

4) Modularity Quality. The cohesion and coupling metrics measure the quality of the identification results from two opposite perspectives. A well-organized component-based architecture should be highly cohesive and loosely coupled.

Table 2: Number and Size of Identified Components.

<table>
<thead>
<tr>
<th></th>
<th>JHotDraw 5.1</th>
<th>JGraphx 3.5.1</th>
<th>XGraph 3.5.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSA</td>
<td>20</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>NSA-R</td>
<td>3</td>
<td>22</td>
<td>1</td>
</tr>
<tr>
<td>SLA</td>
<td>5</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>SLA-R</td>
<td>5</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>Base</td>
<td>5</td>
<td>13</td>
<td>3</td>
</tr>
</tbody>
</table>

Modularity Quality (MQ) aims to reward the creation of highly cohesive components and to penalize excessive coupling among them. It is formally defined as follows:

$$MQ(CS) = Cohesion(CS) - Coupling(CS)$$

(5)

$MQ$ lies in the $[-1, 1]$ interval and a higher $MQ$ value normally means a better architecture quality.

5 IMPLEMENTATION IN PROM

The open-source (Pro)cess (M)ining framework ProM 6 provides a completely plugable environment for process mining and related topics. It can be extended by adding plug-ins, and currently, more than 1600 plug-ins are included.

The component identification and quality evaluation approaches have been implemented as two plug-ins in our ProM 6 package. The first one, called Integrated Component Identification Framework, takes as input the software execution data, and returns the component configuration file that describes which classes belong to which components. Note that this plugin currently supports all community detection algorithms introduced in Section 4.3. The second plugin, called Quality Measure of Component Identification, takes (1) the software execution data and (2) component configuration as input, and returns the quality metrics (e.g., size and modularity values) of the identification component configuration. All experimental results in the following discussions are based on these two tools.

6 EXPERIMENTAL EVALUATION

Then, we evaluate our approaches using four open-source software systems.

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<td>13</td>
<td>5</td>
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<tr>
<td>SLA-R</td>
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Note:


6.1 Subject Software Systems and Execution Data

For our experiments, we use the execution data that are collected from four open-source software systems. More specifically, Lexi 0.1.1 is a Java-based open-source word processor. Its main function is to create documents, edit texts, save files, etc. The format exported files are compatible with Microsoft word. JHotDraw 5.1 is a GUI framework for technical and structured 2D Graphics. Its design relies heavily on some well-known GoF design patterns. JUnit 3.7 is a simple framework to write repeatable tests for java programs. It is an instance of the xUnit architecture for unit testing frameworks. JGraphx 3.5.1 is an open-source family of libraries that provide features aimed at applications that display interactive diagrams and graphs.

Note that the execution data of Lexi 0.1.1, JGraphx 3.5.1, and JHotDraw 5.1 are collected by monitoring typical execution scenarios of the software systems. For example, a typical scenario of the JHotDraw 5.1 is: launch JHotDraw, draw two rectangles, select and align the two rectangles, color them as blue, and close JHotDraw. For the JUnit 3.7, we execute the operation of the project test suite with 259 independent tests provided in the MapperXML release. Table 3 shows the detailed statistics of the data execution, including the number of packages/classes/methods that are loaded during execution and the number of method calls analyzed.

Table 3: Statistics of Subject Software Execution Data.

<table>
<thead>
<tr>
<th>Software</th>
<th>#Packages</th>
<th>#Classes</th>
<th>#Methods</th>
<th>#Method Calls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lexi 0.1.1</td>
<td>5</td>
<td>68</td>
<td>263</td>
<td>20344</td>
</tr>
<tr>
<td>JHotDraw 5.1</td>
<td>7</td>
<td>93</td>
<td>549</td>
<td>583423</td>
</tr>
<tr>
<td>JUnit 3.7</td>
<td>9</td>
<td>47</td>
<td>213</td>
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<tr>
<td>JGraphx 3.5.1</td>
<td>9</td>
<td>62</td>
<td>695</td>
<td>74842</td>
</tr>
</tbody>
</table>

6.2 Identification Approaches

Five component identification approaches are evaluated with respect to a baseline. The first approach identifies components by the Newman’s spectral algorithm (denoted as NSA). The second approach identifies components by Newman’s spectral algorithm with MVM refinement (denoted as NSA-R). The third one creates a component based on smart local moving algorithm (denoted as SLM). The forth approach identifies components by the Louvain algorithm (denoted as LA). Finally, the last one identifies components by the Louvain algorithm with multi-level refinement (denoted as LA-R).

To evaluate the quality of identified components, we compare them with a baseline. The packages that are defined in the source code are assumed as components manually classified by software developers in the design stage, and are used as the baseline in the following experiments.

6.3 Evaluation Results

In this section, we evaluate the quality of the components identified by different approaches as well as the baseline. More specifically, we first identify components for the four software systems using NSA, NSA-R, SLM, LA and LA-R. Afterwards, the quality of components is measured and compared in terms of size and modularity metrics that are defined in Section 4.4. In addition, the time performance of different approaches are also compared.

The number of identified components (NoC) and the average size of components (AoC) for the four open-source software systems based on NSA, NSA-R, SLM, LA and LA-R are shown in Table 2. Note that the AoC value decreases as the NoC value increases for each software system. This is because the AoC is computed as the total number of classes divided by NoC. In general, the NoC/AoC values of NSA-R, SLM, LA and LA-R are similar with the baseline while the NoC/AoC value of NSA is much higher than others, i.e., too much components are identified by NSA for each software system.

Fig. 1 shows the size metric evaluation results for Lexi 0.1.1, JHotDraw 5.1, JUnit 3.7 and JGraphx 3.5.1 based on NSA, NSA-R, SLM, LA, LA-R, and the
baseline. Normally, a higher RIC (or low RSC and RLC) value indicates that the identified components are more well-organized than those with lower RIC (or high RSC and RLC) values. Generally speaking, the RIC values of SLM, LA and LA-R are much higher than those of NSA and NSA-R as well as the baseline. As for the SLM, LA and LA-R, they have almost the same results. This can be explained by the fact that all these three approaches are based on the local moving heuristic. Different from this general conclusion, there are some exceptions. Considering for example the JGraphx 3.5.1. The RIC value of the baseline is much higher than those of SLM, LA and LA-R. This indicates that the package structure of the JGraphx 3.5.1 is better-organized than those of other software.

Fig. 2 shows the evaluation results in terms of the MQ for the four software systems. This metric measures the quality of the identified components from an architectural point of view. A higher MQ value normally indicates that the identified components lead to a better software architecture quality than those with lower MQ values. Generally speaking, the MQ values of SLM, LA and LA-R are much higher than those of NSA and NSA-R as well as the baseline. In addition, NSA-R always performs better than NSA for the four software systems. The rationale behind is that NSA-R refines the results of NSA with the aim to improve the overall modularity.

Fig. 3 shows the time performance comparison results in terms of milliseconds for the four software systems. An approach with a lower performance value indicates that it is more efficient than that with a higher value. Generally speaking, SLM, LA and LA-R are more efficient than NSA and NSA-R according to Fig. 3. As for LA and LA-R, LA is always more efficient than LA-R because LA-R requires a further refinement step on top of the results of LA.

In summary, compared with NSA, NSA-R, SLM and LA, LA-R can efficiently (from a performance point of view) identify components with high MQ values, which can help reconstruct the software architecture with better quality. Based on the experimental evaluation, we recommend to apply the LA-R to identify components for architecture recovery from software execution data.

7 CONCLUSION

By exploiting tremendous amounts of software execution data, we can identify a set of components for a given software system. Our proposed approaches have been implemented in the ProM toolkit and its advantage and usability were demonstrated by applying them to a set of software execution data generated from four different real-life software systems.

This paper provides a concrete step to reconstruct the architecture from software execution data by identifying a set of components. If the execution data does not cover certain part of the software, our approach fails to identify interaction between classes. In this scenario, combination of the static analysis techniques (i.e., source code) and dynamic analysis techniques (i.e., execution data) is desired. Another future challenge is to discover how components interact with each other via interfaces as well as reconstructing the overall software architecture. In addition, we will conduct an empirical evaluation to compare the quality of the recovered architectural models using different component identification techniques (e.g., (Allier et al., 2009; Qin et al., 2009)) and interface identification techniques (e.g., (Liu et al., 2018a)).
REFERENCES


