Visualizing Dynamic Data-Flow Analysis of Object-Oriented Programs Based on the Language Server Protocol

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Abstract: Although studies emphasized the effectiveness of analyzing data-flow coverage as opposed to branch coverage in the area of testing, there is still a lack of appropriate tools. We propose an approach to visualize data flows of programs within code editors based on the Language Server Protocol (LSP). For this purpose, we define extensions of the LSP to increase usability in the given application. Furthermore, we present a prototype with implementations of a language server as well as the two language clients IntelliJ IDEA and Visual Studio Code. Moreover, we outline how the different components can interact effectively based on the LSP to enable the analysis and visualization of data-flows. We evaluate our prototype based on various benchmarks.

1 INTRODUCTION

Data-flow analysis determines the flow of definitions and usages throughout a program and was originally developed for compiler optimization (Allen and Cocke, 1976). In the last four decades, continuous research has been focused on this topic (Su et al., 2017). It has been applied to areas such as testing or test case generation where studies have shown that the data-flow-based coverage criteria are more effective than the control-flow-based criteria such as branch coverage (Frankl and Weiss, 1993; Hutchins et al., 1994). Hence, evaluating and generating test cases with respect to the data-flow coverage is desirable (Troost and Kuchen, 2022).

Due to the lack of appropriate tools for precisely tracking the data flow of a program, a prototype called Dacite (DAta-flow Coverage for Imperative TEsting) was developed. It dynamically identifies the reachable data flows of a given Java program and considers typical challenges such as aliasing and interprocedural data flows (Troost and Kuchen, 2022).

To facilitate the comprehensibility of the identified data flow, a graphical visualization of the output of Dacite is needed. In order to provide direct feedback for the considered test cases and the program, an integration of the visualization into the development environment is preferable. However, because of market segmentation there does not exist one mainly used environment but a variety of development environments that are utilized by different users (e.g., Visual Studio Code vs. IntelliJ). To reduce the implementation costs for developing the Dacite integration and visualization for every major Integrated Development Environment (IDE) separately, the LSP (Microsoft Corporation, 2022b) is an approach to extract functionality from the editor into a separate component named *language server*. This way, a centralized implementation of common features can be reused for different editors. In this context, editors are referred to as *language clients* (Rask et al., 2021).

This paper introduces a graphical visualization of the data flow and, thus, extends our original work on Dacite (Troost and Kuchen, 2022). The main contributions are:

- designing an *approach for visualizing data flows* within code editors,
- designing a *protocol* based on the LSP suited for the communication between a language server and client for the purpose of analyzing and visualizing data flows,
- developing a *language server* to make the core functionalities of Dacite as well as features related to the visualization centrally available for language clients,

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- developing integrations for the *language clients* IntelliJ IDEA[1] and Visual Studio Code[2].

The remainder of this paper is structured as follows. In Section 2, the data-flow analysis approach of Dacite is explained. Section 3 illustrates the system design of the prototype necessary for the graphical visualization of the data flow. Afterward, Section 4 describes the LSP. Therefore, it first explains the concept of the LSP approach, which language features can be utilized, and how it can be extended for the data-flow visualization. Next, Section 5 describes the prototype implementation for the language server and two exemplary IDE integrations. In Section 6, the results are evaluated and validated given benchmarks examples. Section 7 summarizes the related work concerning data flow and coverage visualization. Section 8 concludes the results of this paper.

2 DATA-FLOW ANALYSIS APPROACH

The concept of data flow considers the definition and usage of data throughout the program. This information can be represented by assigning definitions and their corresponding usages to definition-usage chains (DUCs), which can be defined as follows:

$$\begin{gathered}\text{let } X \text{ be a variable and } S, S', S'' \text{ instructions}\\ \mathit{def}(S) := \{\, X \mid S \text{ writes to } X \,\}\\ \mathit{use}(S) := \{\, X \mid S \text{ reads from } X \,\}\end{gathered}$$

If $X \in \mathit{def}(S) \;\cup\; \mathit{use}(S')$ and $X \notin \mathit{def}(S'')$ for each S'' on any path from S to S', (X, S, S') forms a *definition-usage chain* (Troost and Kuchen, 2022).

As already stated in the introduction, Dacite dynamically identifies reachable data flows of a given Java Program and its JUnit tests. By using the dynamic approach of identifying the DUCs during the execution, limitations of a static analysis such as identifying unreachable DUCs or using techniques like overapproximation to detect variable aliases are prevented (Denaro et al., 2014). Because the DUCs are tracked during the execution, only those DUCs can be identified that are covered by the given JUnit tests. This information is essential when comparing JUnit tests. For instance, in combination with our existing test-case generator (Winkelmann et al., 2022), which produces one test-case for every path through the classes under test, it can be used to reduce this set of test-cases to an (almost) minimal set ensuring data-flow coverage.

[1]https://www.jetbrains.com/idea

[2]https://code.visualstudio.com

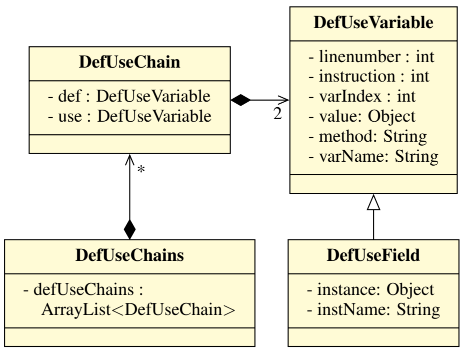


Figure 1: An overview of the DUCs implementation of Dacite (methods omitted for the sake of clarity).

The dynamic analysis of Dacite is based on the Java Virtual Machine (JVM) bytecode and Java instrumentation with the open-source framework ASM[3]. This allows modifying the existing classes of the program on bytecode level before they are loaded into the JVM. More precisely, methods tracking the definition and usage of variables in the program are automatically added to the program code to be able to access this information during the execution. These methods are then called during the execution and pass the information to the analyzer class which is responsible for collecting and analyzing this information in order to derive the passed DUCs (Troost and Kuchen, 2022).

To define the information necessary for the data flow analysis, Figure 1 illustrates the representation of the DUCs in Dacite. A DUC is implemented by the class `DefUseChain` and consists of a `DefUseVariable` instance for the definition and one for the usage. Each instance of this variable has a list of attributes. In order to allocate a usage to its definition, the corresponding variable or element has to be uniquely identified. As the variable index, i.e. the index of the entry in the variable table, is reused due to compiler optimization, the method name and instruction number are additionally utilized to assign definitions and usages. Moreover, to enable users to relate the data flow to their program code, the corresponding variable name and line number are stored for each definition and usage. The class `DefUseField` represents a special form of a definition or usage for an object field or an array element. Therefore, a reference to the related object or array has to be additionally stored (Troost and Kuchen, 2022).

[3]https://asm.ow2.io

3 SYSTEM DESIGN

Before describing the development of the prototype and the LSP in detail, this section aims at explaining general design decisions for the implementation of the visualization.

As stated in Section 1, the data-flow visualization should be shown in programming editors to provide direct feedback for the considered test cases and the program during development. However, as there exist alternative popular IDEs, one would have to implement a Dacite integration for every major IDE to reach the majority of programmers (Rask et al., 2021). LSP is one way to reduce this implementation effort by decoupling the language features functionality from the editor. When given m languages and n editors, without LSP $m*n$ implementations have to be made. But by decoupling the common features into a separate component, called *language server*, they can be reused for different editors. Additionally, by implementing a standardized LSP client endpoint for every editor, referred to as *language client*, these can be reused for different language servers as well. Consequently, the previously mentioned problem of $m*n$ implementations is reduced by LSP to $m+n$ implementations (Rask et al., 2021). Although LSP was originally developed to support the integration of programming languages such as Java or C++, adoptions have emerged for functionalities that are typically not found for programming languages, e.g., in the context of model checking or theorem proving (Rask et al., 2021).

Hence, the Language Server Protocol (LSP) can also be utilized in this scenario to reduce the overhead of implementing a separate Dacite integration for every major IDE. Consequently, different components are necessary for the integration of Dacite into an IDE via the LSP. Namely, next to the Dacite core which is executing the dynamic data-flow analysis (cf. Section 2), a language server and an IDE plugin which serves as the language client endpoint are needed. These components are depicted in Figure 2. The language server aims to extract all IDE independent functionalities such as triggering the execution of Dacite and transforming the data for the visualization while the IDE client communicates via LSP with the language server and visualizes the data for the user.

After explaining the system architecture, the visualization and the necessary information for this purpose need to be defined. To be able to comprehensibly visualize the data-flow information as described in Section 2, three types of visualizations are necessary.

First, to be able to start the Dacite analysis, the user needs some form of interaction with the editor.

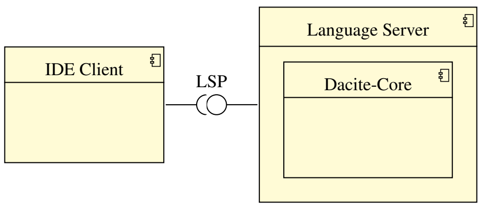


Figure 2: Dacite components for IDE integration via LSP.

This can be done in form of a button for a JUnit test or a link that can be clicked.

Second, the list of identified DUCs needs to be shown to the user to give an overview of how many and what kind of DUCs where detected. Thereby, the data is assorted in a tree-like structure to the corresponding classes, methods, and variables of the program to allow users to view all DUCs, e.g., for a specific variable. When relating a DUC to its variable, method, and class, one has to consider DUCs that go over the boundary of one method or class, e.g., the definition is in one method and through passing this variable as a parameter the usage is in another method. Hence, the mentioned structure always relates the DUCs according to their definitions. Figure 3 displays an example of this structure. Additionally, each level should be expandable to avoid overwhelming the user with all information at once. This is especially relevant for large programs with many classes, methods, and variables respectively. For each level that does not correspond to a DUC, next to the name of the class, method, or variable the number of subordinate DUCs is displayed. This gives an overview of the distribution of the identified DUCs even when levels are minimized. Moreover, for each DUC the corresponding line numbers of the definition and usage are displayed for identification within the source code. If the variable usage is located in a different class or method, the location name is displayed as well. The list of DUCs is generated by the Dacite core analysis (cf. Figure 1). The transformation to the tree-like structure like in Figure 3 can be decoupled by the language server as this has to be performed for every IDE and the result transferred to the IDE client which displays it for the user.

The third type of visualization is the code highlighting in the editor in form of source code annotations. It enhances the comprehensibility of the data flow as it enables the user to directly relate the information of the list of DUCs to the source code of the program. Because these annotations can become convoluted for large programs with many DUCs, users should be able to enable and disable it based on the list of DUCs. So depending on the use case, users can highlight all identified DUCs, all DUCs for a specific

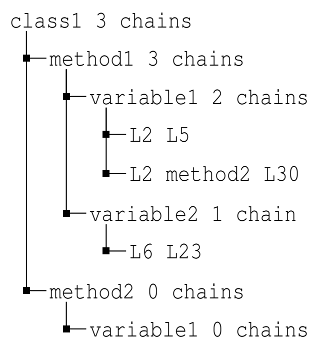


Figure 3: An exemplary tree-like structure for visualizing the list of DUCs.

variable, or a single DUC. This requires user interaction with the IDE for which the IDE client registers the interaction and the language server determines the position to-be-highlighted by the IDE. Moreover, to make the code highlighting more understandable, coloring should be added to be able to differentiate the data flow of variables, e.g, by coloring all DUCs of variable `a` in a different color than variable `b`.

4 PROTOCOL DESIGN

In this section, more details of the protocol designed to enable communication between the different components are discussed. Based on a description of the remote procedure call protocol JSON-RPC (JSON-RPC Working Group, 2013) in Section 4.1, Section 4.2 discusses relevant protocol messages specified in the LSP. Finally, Section 4.3 outlines extensions of the LSP used within this work.

4.1 JSON-RPC

JSON-RPC is a remote procedure call protocol based on the data interchange format JavaScript Object Notation (JSON) (T. Bray, 2013). In this work, remote procedure calls are done between the language client and server which are separate processes exchanging messages based on standard input and standard output. All messages sent are JSON objects containing different attributes based on their type. Subsequently, more details about the main object types are discussed (JSON-RPC Working Group, 2013).

Request Object. A remote procedure call is initiated by sending a *request object*. An example can be seen in Listing 1. Besides specifying the protocol version, an identifier is introduced which later is used to correlate the request and response objects (cf. Listing 2). Additionally, the method to be invoked and corresponding parameters are specified.

```
{
  "jsonrpc": "2.0",
  "id": 1,
  "method": "add",
  "params": [1, 2]
}
```

Listing 1: Exemplary JSON-RPC Request Object.

```
{
  "jsonrpc": "2.0",
  "id": 1,
  "result": 3
}
```

Listing 2: Exemplary JSON-RPC Response Object.

A *notification* is a specialized request object for which no response object is expected. Hence, no identifier is specified in notifications.

Response Object. In Listing 2, an exemplary *response object* is shown. Similar to request objects, the protocol version and an identifier must be specified. Furthermore, the result of the request with a matching identifier is provided. In case of errors, additional information is encoded in response objects (e.g., error type and description).

The `params` attribute of request objects as well as the `result` attribute of response objects can be arbitrarily complex JSON values. Consequently, besides primitive values such as numbers or strings, objects and arrays are also allowed.

4.2 Language Server Protocol

The LSP is a protocol specifying messages intended for the communication between a language client (e.g., an IDE) and a language server providing a centralized implementation of common features. It is based on the JSON-RPC and, thus, uses JSON objects to encode messages. Subsequently, message types relevant to this work are outlined (Microsoft Corporation, 2022b). In all code examples, the attributes `jsonrpc` and `id` explained in the previous subsection and expected by JSON-RPC are omitted for the sake of clarity.

Lifecycle. Communication is initiated at the client by starting the server process and sending an `initialize` request to the server. One main information exchanged during the initialization phase is the capabilities. With these, the client and server specify which protocol features they support such that the subsequent communication is tailored to the features implemented by both.

In addition to starting the server, it is also the client's responsibility to shut down the server. For this purpose, the client can use the `shutdown` request to

```
{
  "method": "textDocument/didOpen",
  "params": {
    "textDocument": {
      "uri": "file:///src/Demo.java",
      "text": "public class Demo {...}"
    }
  }
}
```

Listing 3: Exemplary notification for an opened text document (simplified).

```
1 {
2   "method": "textDocument/codeLens",
3   "params": {
4     "textDocument": {
5       "uri": "file:///src/Demo.java"
6     }
7   }
8 }
```

Listing 4: Exemplary code lens request (simplified).

ask the server to stop responding to regular requests. After that, the server process will exit once an `exit` request has been received.

Synchronization. To provide features such as information about code annotations as described in Section 3 to the client, the server needs to be synchronized with the client. This is done based on dedicated notification messages. An exemplary notification that is sent from the client to the server once a text document has been opened can be seen in Listing 3. By providing the file's Uniform Resource Identifier (URI) as well as its content, the server can cache a virtual file structure in order to perform, e.g., code analysis.

Analogously to the presented notification for opened documents, there are notifications once a document was changed or closed. Both are used by the server to update or clean up the virtual file structure, respectively.

Command Execution. The server can hint the client at positions in the source code from where command executions can be done (e.g., executing the main method or a test case). The client can use this information and display the execution option within the editor (e.g., by displaying an executable link or a button on the side). In LSP, such hints are named code lenses.

A client can request code lenses by sending a corresponding request to the server (cf. Listing 4). Within this request, the URI to the file of interest has to be specified. Correspondingly, the server calculates code lenses only for the given file.

As a response, the server provides an array of code lenses. In Listing 5, an example is provided. A code

```
1  {
2    "response": [{
3      "range": {
4        "start":
5          {"line": 7, "character": 10},
6        "end":
7          {"line": 7, "character": 15}
8      }
9      "command": {
10       "title": "Run Analysis",
11       "command": "dacite.analyze",
12       "arguments": [
13         "file:///src/Demo.java"
14       ]
15     }
16   }]
17 }
```

Listing 5: Exemplary code lens response (simplified).

```
{
  "response": [{
    "position":
      {"line": 2, "character": 7},
    "label": "Def"
  }]
}
```

Listing 6: Exemplary inlay hint response (simplified).

lens is defined by specifying the range in the text document to which it applies. Additionally, information about the command is given including a title to show in the IDE's user interface, a command identifier as well as arguments needed for command execution. The example in Listing 5 contains a command used to trigger the execution of Dacite's dynamic analysis.

Once a command is triggered from within the IDE, a corresponding `executeCommand` request is sent to the server including the command's identifier as well as required arguments. After finishing the execution, the server responds with a result. This result can be any arbitrary JSON value.

Code Annotations. Annotations rendered in place with the source code are named inlay hints in the LSP. A client can obtain such hints using an `inlayHint` request specifying the `textDocument` (cf. lines 4 ff of Listing 4) and `range` (cf. lines 3 ff of Listing 5) of interest.

As a response, the server sends back an array of inlay hints. An example is shown in Listing 6. Based on this specification, the editor would render the label "Def" at the given editor position.

4.3 Protocol Extensions

In addition to standard protocol messages presented previously, this subsection deals with protocol extensions used in this work that enabled realizing selected aspects of the designed visualization types as specified in Section 3. First, we introduce an extension named tree view protocol. Then, we outline how decorations for inlay hints are exchanged between the client and server. Of course, such extended message types are not supported by default in clients compatible with the LSP. However, the standard protocol messages are supported by all language clients and, thus, ensure basic functionality.

Tree View Protocol. The tree view protocol (Metals, 2022) specifies protocol messages enabling the client to render tree views. In this work, tree views are used to provide an overview of identified DUCs (cf. Figure 3). Although not part of the LSP standard at the time of writing, there exist implementations for the tree view protocol at the server as well as the client side making the adoption into this work easier (Metals, 2022).

Entries within tree views are named *tree view nodes*. Every node can be identified using a node URI and may have child nodes. Additionally, a *tree view command* can be associated with a node enabling the client to perform actions based on user interactions with the node. In the following, two message types of the tree view protocol (Metals, 2022) which are relevant to this work are presented.

First, clients can request tree view nodes belonging to a given parent node by sending a `treeViewChildren` request to the server. The parent for which child nodes are requested is specified using its node URI. In order to request a root node, the node URI is left empty. The server responds with a list of tree view nodes. Subsequently, the client requests the children of all newly obtained nodes. An example is given in Listing 7. For displaying purposes, each node can be assigned a label and an icon. Furthermore, it can be specified whether the node should be expanded or collapsed by default. Lastly, the `command` attribute is used to specify tree view commands which work analogously to commands defined in the LSP (cf. lines 9 ff of Listing 5).

Second, clients can request the parent's node URI of a particular node by sending a `treeViewParent` request to the server.

Inlay Hint Decorations. By default, inlay hints cannot be styled. However, to visualize multiple DUCs a coloring greatly improves usability. Hence, this work defines an extension to the `inlayHint` request. By sending an `inlayHintDecoration` request specifying the position of a particular inlay hint of interest, a client can obtain styling information. This includes the text color and font style. An example of the server's response is shown in Listing 8.

```
{
  "response": {[{
    "nodeUri": "HelloWorld.method",
    "label": "Method",
    "command": { ... },
    "icon": "method",
    "collapseState": "expanded"
  }]}
}
```

Listing 7: Exemplary tree view children response containing one child (simplified).

```
{
  "response": {{
    "color": [255, 0, 0, 255],
    "fontStyle": "Serif"
  }}
}
```

Listing 8: Exemplary inlay hint decoration response (simplified).

5 PROTOTYPE DEVELOPMENT

Given the system architecture and visualization approach (cf. Section 3) as well as the protocol design (cf. Section 4) presented previously, this section outlines more details on the development of the different system components. First, Subsection 5.1 elaborates on the general interaction of the components. Then, Subsections 5.2 and 5.3 provide more details on the server and client implementations, respectively. Further information on the implementation of the Dacite core library can be found in (Troost and Kuchen, 2022). All source code for the prototype is available on GitHub[4].

5.1 Component Interaction

As explained in Section 3, the prototype consists of three components interacting with each other (language server, language client, and Dacite core). Figure 4 illustrates this communication based on the user interaction with the IDE. The LSP lifecycle and synchronization messages between the client and server (e.g., the initialization upon the start of the IDE) are omitted for the sake of clarity. Whenever the user opens a Java file in the IDE, the language client sends a `codeLens` request to the language server which analyzes whether the corresponding file contains a JUnit[5] test. If this is the case, a code lens is returned containing a position for which it is displayed as an interaction for the user (e.g., in form of an executable

[4]https://github.com/dacite-defuse/DynamicDefUse
[5]https://junit.org

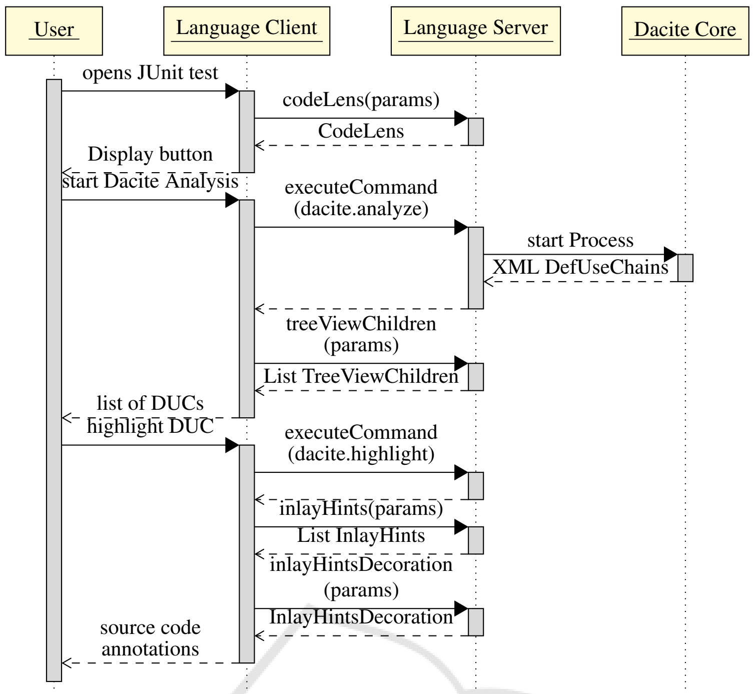


Figure 4: Sequence diagram illustrating the interaction between the user and the components, the client, the language server, and Dacite core.

link or button). When the user utilizes this interaction (e.g., by pressing the button), the client sends an `executeCommand` request for the Dacite analysis to the language server. This triggers the instrumentation and analysis process of Dacite core for the JUnit test case and the corresponding class files (Troost and Kuchen, 2022). It returns an XML file containing all identified DUCs as `DefUseChains` (cf. Figure 1). This output is stored and transformed by the language server to account for the tree-like structure grouping all chains based on their class, method, and variable. This way, when the client requests the tree view children for the root node afterward, the language server returns subsequently the grouped DUCs as tree nodes. These are displayed by the client to the user.

Thereafter, the user has the possibility to interact with the visualized list of DUCs, e.g., by clicking on an entry or checking a box to enable the source code annotations for all related DUCs. For instance, when clicking on the method, all related DUCs which were defined in this method are highlighted. When the user triggers the source code annotations, the client sends an `executeCommand` request to the language server specifying which entry was clicked. The language server internally saves this information, so that when the client sends the `inlayHints` request for the document subsequently the language server returns the position of all DUCs which should be annotated. After the request for inlay hints, the client requests for each inlay hint the corresponding decoration including the color and font style. With this information, the annotations are rendered within the source code.

In addition to the three mentioned components, common implementations related to the extension of the LSP have been extracted into a library that is used by both the language server as well as the client implementation for IntelliJ IDEA. All components are combined within a multi-project Gradle[6] build.

5.2 Language Server

The language server was implemented in Java based on the `lsp4j`[7] library providing Java bindings for the LSP. This way, the work needed for realizing standard protocol messages could be reduced to implementing appropriate interfaces. Additionally, custom interfaces were registered to account for the required LSP extensions mentioned previously. All details needed to enable the communication based on the JSON-RPC protocol are handled by the `lsp4j` library (e.g., serializing and deserializing JSON). The following paragraphs highlight selected aspects of the language server implementation.

As mentioned in the previous subsection, the language server obtains analysis results from Dacite

[6]https://gradle.org
[7]https://github.com/eclipse/lsp4j

]

core. This includes starting a new Java process, instrumenting the to-be-analyzed code by using a Java agent and running the given JUnit test case. However, to be able to access the code, the server has to make the classes of the project that should be analyzed available. Hence, the server collects directories with `*.class` files as well as `*.jar` files and adds these to the class path of the new Java process.

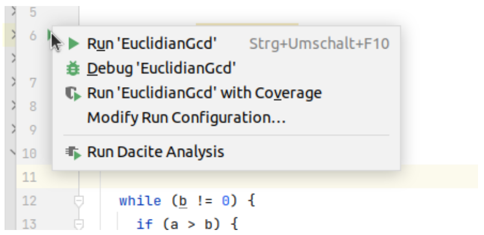
Furthermore, the language server combines the analysis result delivered by Dacite core with information extracted from parsing the source code. This is necessary to identify exact positions for the inlay hints. From the dynamic analysis only line numbers are provided but not column numbers which are necessary to distinguish elements in one line. The language server overcomes this limitation by exploring the Abstract Syntax Tree (AST) corresponding to the source code. The AST is obtained by using the `JavaParser`[8] library. Each element in the AST can be tracked back to its exact position in the source code including line and column numbers. Hence, in order to find the position of an inlay hint corresponding to a variable definition or usage, the server identifies the AST node corresponding to the variable in the specific line. Then, the column number can be obtained as an property of the AST node.

`JavaParser` is also used to identify JUnit test cases representing starting points for the Dacite analyzer. For all identified tests, the server returns appropriate code lenses.

5.3 Language Client

This section elaborates on the implementation of the language client. By adhering to as many existing LSP message types as possible, the effort to implement the language client is minimized for IDEs that support the LSP. In this case, the functionality of sending and receiving these messages to and from the server and displaying the information to the user is already implemented and ready to use. However, custom extensions of LSP and their visualization still need to be implemented for the client. Subsection 5.3.1 describes the integration of LSP and the implementation of necessary message types for the IDE IntelliJ IDEA. To showcase the adaptability to other IDEs, Subsection 5.3.2 describes the integration of the Dacite visualization to Visual Studio Code (VS Code) with minimal effort by utilizing the standard LSP.

[8]https://javaparser.org



```
while (b != 0) {
    if (a > b) {
```

Figure 5: Exemplary screenshot on how the Dacite trigger is added as run line marker for JUnit Tests in IntelliJ.

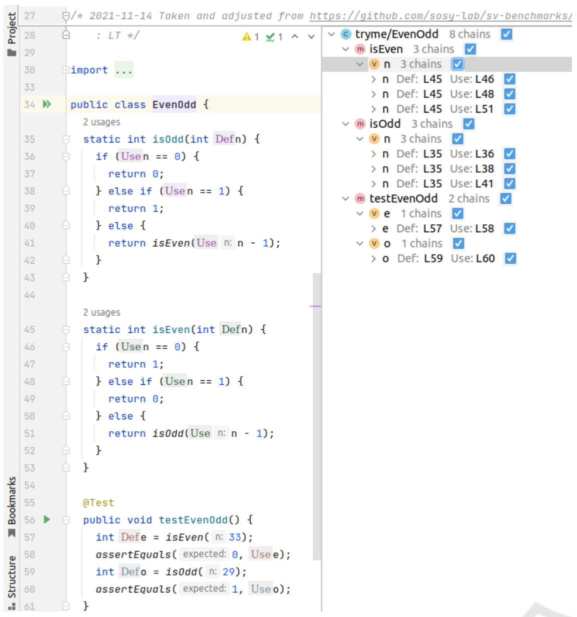
5.3.1 IntelliJ IDEA

As LSP has emerged in recent years, many IDEs such as IntelliJ do not support LSP per default. However, additional plugins or libraries have been developed which provide the standard LSP functionality of communicating and synchronizing with the server. For IntelliJ there exists the client library `lsp4intellij`[9] which provides this language server support. By adding this library to a custom IntelliJ plugin implemented in Java and specifying the path to the language server binary, the basic functionality of communicating with the server is available, e.g, for synchronization. The library also enables easy integration of protocol extensions by providing the interface `LSPExtensionManager` which allows overriding existing messages or adding new ones for the communication with the server. To add the protocol extension for the tree view protocol and the inlay hint decorations for the client and server consistently, two interfaces, `DaciteTreeViewService` and `DaciteExtendedTextDocumentService` respectively, were defined specifying the requests with their parameters and return types as shown in Section 4.3.

To visualize the information received from the language server in adherence to the IntelliJ scheme three parts need to be implemented (cf. Figure 4). First, the possibility to trigger the Dacite analysis needs to be displayed to the user. This information is given to the client in form of a `CodeLens` containing an exact position within the source code where this should be displayed if the opened file contains a JUnit test case. For this position, similar to other run configurations, a run line marker is added in the IntelliJ editor on the side (cf. Figure 5).

Second, the tree-like structure of DUCs has to be displayed (cf. Figure 3). This is possible with the internal IntelliJ class `Tree`. After executing the Dacite command, a new tool window is opened in the editor with the corresponding tree. To highlight the important information and allow a differentiation of the types of information more clearly, each level is ren-

[9]https://github.com/ballerina-platform/lsp4intellij



```
27 /* 2021-11-14 Taken and adjusted from https://github.com/sosy-lab/sv-benchmarks/
28      : LT */
29
30 import ...
33
34 public class EvenOdd {
     2 usages
35   static int isOdd(int Defn) {
36     if (Usen == 0) {
37       return 0;
38     } else if (Usen == 1) {
39       return 1;
40     } else {
41       return isEven(Use n: n - 1);
42     }
43   }
44
     2 usages
45   static int isEven(int Defn) {
46     if (Usen == 0) {
47       return 1;
48     } else if (Usen == 1) {
49       return 0;
50     } else {
51       return isOdd(Use n: n - 1);
52     }
53   }
54
55   @Test
56   public void testEvenOdd() {
57     int Defe = isEven( n: 33);
58     assertEquals( expected: 0, Usee);
59     int Defo = isOdd( n: 29);
60     assertEquals( expected: 1, Useo);
61 }
```

```
tryme/EvenOdd  8 chains ✓
  isEven  3 chains ✓
    n  3 chains ✓
      n  Def: L45  Use: L46 ✓
      n  Def: L45  Use: L48 ✓
      n  Def: L45  Use: L51 ✓
  isOdd  3 chains ✓
    n  3 chains ✓
      n  Def: L35  Use: L36 ✓
      n  Def: L35  Use: L38 ✓
      n  Def: L35  Use: L41 ✓
  testEvenOdd  2 chains ✓
    e  1 chains ✓
      e  Def: L57  Use: L58 ✓
    o  1 chains ✓
      o  Def: L59  Use: L60 ✓
```

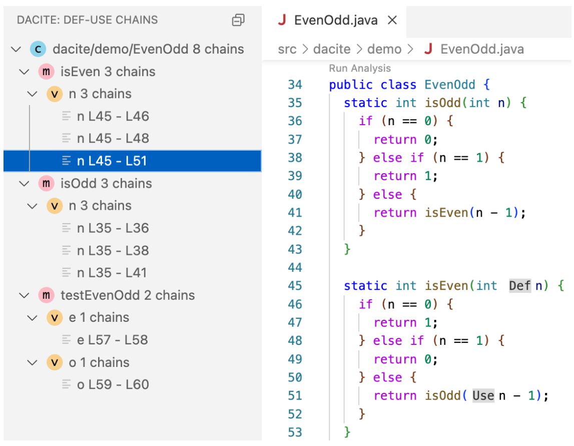
Figure 6: Exemplary screenshot of the Dacite visualization in IntelliJ.

dered and complementary information displayed in a lighter color (cf. Figure 6 on the right). Additionally, a checkbox is added for every level allowing the user to easily enable and disable the DUCs annotations. By clicking on a checkbox, all subordinate checkboxes are triggered as well to account for all DUCs within the selected level.

Third, the source code annotations have to be displayed to the user. When interacting with a checkbox, a command is sent to the language server updating the visibility status of the corresponding inlay hints (cf. Figure 4). Afterward, the inlay hints and their positions are retrieved from the language server. As all subordinate DUCs are highlighted, the corresponding positions can range in the complete document. Consequently, all inlay hints of the document are updated. Therefore, the existing inlay hints in the editor are removed and the newly retrieved ones iterated. For each iteration, the inlay hints decoration is retrieved from the server such that the inlay hint can be displayed with the color and font accordingly (cf. Figure 6 on the left).

5.3.2 Visual Studio Code

Contrary to IntelliJ, VS Code provides generic support for the LSP based on a dedicated library (Microsoft Corporation, 2022a). Hence, all standardized message types, such as inlay hints and code lenses, are already implemented for the client and automatically visualized. Although the tree view protocol is not yet a part of the standardized LSP, support for



```
DACITE: DEF-USE CHAINS
dacite/demo/EvenOdd 8 chains
  isEven 3 chains
    n 3 chains
      n L45 - L46
      n L45 - L48
      n L45 - L51
  isOdd 3 chains
    n 3 chains
      n L35 - L36
      n L35 - L38
      n L35 - L41
  testEvenOdd 2 chains
    e 1 chains
      e L57 - L58
    o 1 chains
      o L59 - L60
```

```
EvenOdd.java ×
src > dacite > demo > EvenOdd.java
   Run Analysis
34 public class EvenOdd {
35   static int isOdd(int n) {
36     if (n == 0) {
37       return 0;
38     } else if (n == 1) {
39       return 1;
40     } else {
41       return isEven(n - 1);
42     }
43   }
44
45   static int isEven(int Def n) {
46     if (n == 0) {
47       return 1;
48     } else if (n == 1) {
49       return 0;
50     } else {
51       return isOdd( Use n - 1);
52     }
53   }
```

Figure 7: Exemplary screenshot of the Dacite visualization in VS Code.

this message type has been implemented for VS Code (Metals, 2022). Therefore, VS Code supports all necessary protocols for the Dacite integration except the inlay hint decorations without custom implementation effort. However, this information is only designed to enhance usability and does not contain crucial information. The steps required to integrate Dacite into VS Code mainly involved configuring how the language server binary is started. The remaining communication with the server and visualization in the editor is performed by the standard language client implementation.

Figure 7 shows the visual integration of Dacite for VS Code using the provided client implementations. Small custom visual adaptions to increase usability and comprehensibility similar to IntelliJ still have to be made. However, all necessary information is already available. This minimal effort in integrating Dacite into another IDE underlines the added value of utilizing the LSP for the communication involved in analyzing and visualizing data flows.

6 EVALUATION

In order to evaluate and validate the results of the data-flow analysis and its visualization as a proof of concept, the prototype was executed for a set of different examples. The data-flow analysis was already evaluated for a set of smaller examples (Troost and Kuchen, 2022). Due to the lack of comparable tools, the validation was executed manually which is not feasible for larger examples with several hundreds of DUCs. By adding a comprehensible visualization to the data-flow output, this impediment is mitigated so that the validation of larger examples is facilitated. Three larger examples are retrieved from the

Table 1: Executed examples for the data-flow analysis and its visualization. LOC, number of program classes, number of identified DUCs, and run times in ms without and with Dacite execution and its visualization based on LSP.

Example	**LOC**	**Classes**	**DUCs**	**without Dacite**	**with Dacite**
svComp.alarm	2,171	16	236	10 ms	428 ms
svComp.printtokens	623	4	155	4 ms	339 ms
svComp.siena	2,113	11	212	6 ms	368 ms
binaryTree	210	4	288	42 ms	390 ms
AVL	321	4	321	38 ms	495 ms

SV-COMP set of software verification. SV-COMP is an annual competition for software verification that releases a publicly available repository as a benchmark suite for verification and validation software tools (Beyer, 2021). The `alarm` example implements a complex alarm system, while `printtokens` uses a stream reader to parse given input and process it further. `Siena` is an event notification middleware and uses encoding for its notification. Those three examples were selected for their complexity in the context of data flows including aliasing and the data flow spanning over multiple methods and classes. To also account for different types of data structures, two further examples were added (binaryTree, AVL) which provide different operations for their tree structures. All examples consist of at least four different classes and range from 210 to 2171 Lines of Code (LOC) (cf. Table 1).

For all the mentioned examples, JUnit test cases were added for the execution. As discussed in (Troost and Kuchen, 2022), analyzing the program with Dacite introduces a small overhead to the execution ranging in milliseconds which is still acceptable when performing program analysis. However, by adding a visualization including program parsing and communication between the language server and client, additional overhead is introduced. This is again analyzed by executing the JUnit test cases of the examples with and without Dacite and its visualization. As the Dacite visualization is dependent on several user interactions which impedes comparable run time measurements, the source code annotations for the identified DUCs are enabled per default for this analysis. This way, the execution time with Dacite is measured from the moment the user triggers the Dacite analysis until the list of DUCs and the source code annotations are shown. Note that the initialization and synchronization of the language server upon startup of the language client as well as the display of a code lens is neglected for this run time measurement as this is not an essential part of the analysis but the language client. The results of this run time analysis can be seen in Table 1. While the run time of the execution with Dacite is higher than without, it is still ranging in milliseconds and, thus, is acceptable for the analysis of Java programs.

Deriving all possible DUCs for each example per hand for validation is not feasible as these consist of several hundred chains (cf. Table 1). However, due to the advanced visualization and source code highlighting the data flow can be comprehended and missing chains identified by a missing annotation. This is especially relevant in the context of test case generation. By visualizing all tracked DUCs in the source code, the user can identify which parts of the program and its corresponding data flow were not covered by the given JUnit tests.

7 RELATED WORK

As stated in the introduction, there exists a lack of appropriate tools for precisely tracking the data-flow information of a program (Su et al., 2017; Troost and Kuchen, 2022). The large majority of tools are limited to the static analysis of the data flow which impedes the identification of aliases and distinction of traversable and non-traversable DUCs. Moreover, these tools are either not available or not working reliably (Troost and Kuchen, 2022). Only two tools provide a visualization of the data flow information. JaBUTi (Java Bytecode Understanding and Testing) displays the data-flow graph and highlights the associated lines in the source code. However, the tool is a standalone application and not integrated into any IDE and is not able to discern different usages or definitions in one line (Vincenzi et al., 2003; Vincenzi et al., 2006). The other tool, DFC (Data Flow Coverage) is an Eclipse plugin. Here, the visualization consists of the data flow graph and a list of found DUCs. Moreover, an interface is given as the data flow is not derived completely automatically but by interacting with the user (Bluemke and Rembiszewski, 2009).

Another similar tool is the JaCoCo library which provides code coverage analysis in JVM-based environments. It is open-source and can be integrated into different tools, e.g., Eclipse or IntelliJ. Similar to Dacite, it visualizes the identified coverage information in a tree-like table and enables source code annotations. However, JaCoCo does not support data flow analysis but focuses on other coverage metrics such as branch coverage or line coverage. Moreover, each IDE integration was developed separately and is not based on the LSP (EclEmma, 2017).

The Language Server Protocol (LSP) has been utilized for the integration of various programming languages. Additionally, extensions for functionalities that are not typically not needed for integrating programming languages have emerged, e.g., in the context of model checking or theorem proving (Rask et al., 2021). However, to the best of our knowledge, the LSP has not yet been applied to the area of code coverage.

8 CONCLUSION AND OUTLOOK

Considering that there is a lack of appropriate tools for the analysis of the data flow within a program, this paper introduced an approach to visualize DUCs within code editors based on the LSP. After presenting some background on how the data flow is analyzed, we outlined the system design. Then, we described how the LSP is employed in our use case and introduced protocol extensions for selected aspects enabling a more comprehensible visualization. Based on this, we presented a prototype including implementations of a language server and two language clients (IntelliJ IDEA and VS Code). We specifically outlined how the components interact based on the LSP. We evaluated and validated our results based on five benchmark examples and also pointed out related work.

Future work should integrate the language server with support for the custom extensions to additional popular IDEs such as Eclipse in order to make it greatly available for Java developers. Also, plugins for build tools such as Maven[10] and Gradle[11] should be implemented. This way, Dacite could be used as part of the build pipeline and the analysis output (i.e., the XML file) could be used by third-party tools for further applications. Moreover, by deriving the data flow information during the execution, only those data flows are considered that have been passed. Enabling a visualization for this data flow is a first step for identifying data flow which was not passed. In the future, we plan to integrate the dynamic analysis of Dacite with symbolic execution to be able to identify the data flow of every executable path of a given program (Winkelmann et al., 2022). This way, DUCs which were not covered by given JUnit test cases could be identified and forwarded to the user.

[10]https://maven.apache.org

[11]https://gradle.org

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