

Assisted Specification of Code Using Search

Steven P. Reiss
Brown University
Providence, RI, USA
spr@cs.brown.edu

Abstract

We describe an intelligent assistant based on mining existing software repositories to help the developer interactively create checkable specifications of code. To be most useful we apply this at the subsystem level, that is chunks of code of 1000-10000 lines that can be standalone or integrated into an existing application to provide additional functionality or capabilities. The resultant specifications include both a syntactic description of what should be written and a semantic specification of what it should do, initially in the form of test cases. The generated specification is designed to be used for automatic code generation using various technologies that have been proposed including machine learning, code search, and program synthesis. Our research goal is to enable these technologies to be used effectively for creating subsystems without requiring the developer to write detailed specifications from scratch.

1 Motivation

Our initial goal is to provide a tool to assist the developer in creating complex, informal, yet checkable specifications for software. Checkable specifications define a software component so that there is a means of determining if the software does what is expected. For many purposes, the expected behavior is good enough. If the software is existing or generated by a trusted tool and behaves properly on standard examples, it is a good starting point. For example, an agile development sprint can start with a set of interfaces to implement along with test cases to specify the basic functionality of those interfaces.

We are interested in assisting the developer in building checkable specifications for non-trivial software components of between about 1 and 10 KLOC of code we call *subsystems*. Smaller components are generally single methods which are fairly easy to specify. Larger components bring additional problems to be addressed later.

Such specifications, beyond common tasks such as agile development, will become increasingly important. Codex has demonstrated that machine learning techniques can be used to generate code [8]; advanced code search results

demonstrating code reuse from repositories can also be used [36]; program synthesis is becoming increasingly powerful [16]. The initial definition of what should be built is often informal and ambiguous, for example one might ask for an embedded HTML server or a contact manager. A variety of quite different results can be generated. A practical system using these approaches would need to better understand what the developer wanted to better direct the generation, to choose appropriately from multiple results, and to do validation on the results. Moreover, specifications that are close or related to existing code will typically yield better results with both machine learning and code search since the prior inputs are likely to cover something close.

With current technology a developer needs to create these specifications manually, for example defining the set of classes and interfaces along with their methods. Moreover, they need to provide semantics for these, defining what the methods do in a checkable manner, typically by providing test cases, but also possibly with contracts, UML state or event diagrams, or even formal mathematics. This can be difficult and creative work that is important to get right.

For many problems, other developers have had to create a similar specification as part of another system. Going through our own systems, we estimated conservatively that 25% of the code could be reused in or from other systems. Our approach involves mining software repositories to find similar specifications as a starting point, let the developer choose among and edit those specifications to match their particular needs, then use the edited specification as the basis for mining the software repositories to find or generate test cases that can become part of a checkable result. This approach is encompassed in the ASCUS (Assisted Specification of Code Using Search) framework for Java.

ASCUS makes use of several innovative techniques in developing specifications. It provides a means for searching for and isolating compilable subsystems from existing code in repositories. It offers heuristics that seem to be effective in providing simplified abstractions of subsystems. It demonstrates that the type of adaptation that developers do to make external code meet their requirements can be automated using transformations. It shows how test cases can be generated effectively using code search for a particular subsystem specification.

ASCUS, combined with automatic code generation technologies, has the potential to transform software development by easing much of the burden from the developer, by making code reuse easier, and by building new software using lessons learned from existing software. It can provide a practical framework for reusing non-trivial software components by automatically adapting them to the particular needs of a new application. It can form the basis for practical automatic programming. Our eventual goal is to use ASCUS as the basis for such code generation.

2 Related Work

Our overall efforts build on top of and are related to a variety of different efforts. The work that is closest to generating whole systems using a step-by-

step approach involves Model-Driven Development (MDD) [11, 33]. In MDD the user writes the system using a variety of design notations provided by UML (class diagrams, sequence diagrams, state charts), and the system generates code from those specifications. While this approach is interesting and has a growing community of practitioners and researchers, it does not accomplish our objectives. It does not address full applications or the addition of subsystems to an existing application. With MDD the programmer is still writing the code, albeit at a slightly higher level and the specification is procedural. Finally, the resultant systems do not make use of the large body of existing code and implementations and their embedded experience and knowledge.

This work is also closely related to reverse engineering and model-driven reverse engineering [35] where the purpose is to understand existing systems. This is often done for larger systems with graphic models [5, 26]. Work has also been done on simplifying specifications for program synthesis [23].

There has been extensive work on code search, generally using information retrieval and aiming for either code fragments or methods. While today's repository code search engines are keyword-based, many other approaches have been tried. Sourcerer [3] incorporates program structure and semantics in the search base, SNIFF incorporates knowledge about libraries and APIs [7], and newer efforts use semantics [20, 40], test cases [32], or machine learning [6, 31]. CodeGenie [24] lets the user define test cases as part of the development process in Eclipse and then uses the method names and signatures from the test case to build a search query for an internal search engine. Wang uses topic-enhanced dependence graphs [42]. Code recommendation based on source code has also studied at the fragment [19, 38, 45] and component level [10].

Our work on building abstractions of the retrieved code is loosely related to work on automated domain model extraction which attempts to extract a domain model from natural language requirements [2]. It is more closely related to work on displaying student code examples [17, 18], simple API usage [14], or variation in small programs [13], all abstracted over a large set of programs. Typical abstraction techniques, such as UML, provide another alternative, but are geared more toward the design of a single system rather than showing a set of abstractions. Using UML to describe software product lines [15], takes a step towards abstraction, but is limited in scope and flexibility. Finally, there has been recent work on partitioning code to find microservices [41].

Most existing work on matching programs concentrates on finding differences rather than similarities. Yang proposed identifying the syntactic differences between two programs by matching their syntax trees using dynamic programming [44]. Neamtii matches two successive programs by visiting their abstract syntax trees in parallel and create maps of their names and types [29]. The tools JDiff [1] and UMLDiff [43] focus on identifying changes and correspondences between object-oriented programs. LSDiff [21] identifies program differences from the changes of structural dependencies of code elements. Dex [34] creates abstract semantic graphs for two versions of programs and then uses the graph differencing algorithm to obtain their differences. Their differencing algorithm iteratively matches graph nodes and computes the corresponding costs.

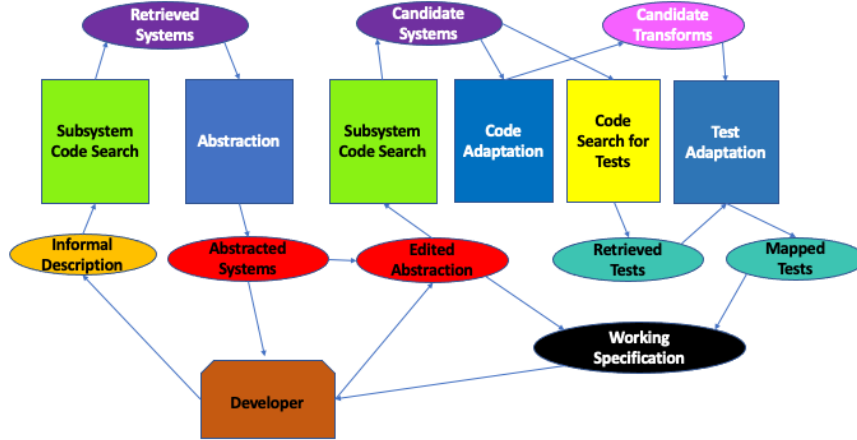


Figure 1: Overview of ASCUS.

iDiff [30] looks at the interaction to compare program entities of classes and methods. More recent work looks at finding similar software projects [4].

The adaptation phases of ASCUS are most closely related to the various refactorings that have been proposed and incorporated into various development environments starting with Elbereth [22]. Follow-up work looked into how these were used and the problems developers had with them [27,28]. This work is also related to the transformations done by the semantic code search tool S6 [36].

There has been significant work on automatically generating test cases. white-box techniques look to find method or program inputs that achieve a desired level of coverage. Many systems have been proposed and are used in practice, for example, EvoSuite [12]. These systems use a variety of techniques include symbol execution engines and genetic programming. Black-box techniques are less common since they typically require a model of the code and generate the test cases from the model. Models have been based on JML [9] and UML activity diagrams [39]. Black box test cases have also been generated for special cases, for example by monitoring program execution [25]. Code search has also been used to find method-level tests [37].

3 Overview

Ideally, any subsystem the developer wanted to incorporate would be available as a separate library that could easily be reused. In practice, however, these are typically tightly integrated into existing systems require substantial work to extract, understand, adapt, and reuse. ASCUS attempts to automate much of this process. An overview of the ASCUS approach can be seen in Figure 1.

The developer starts by providing an informal description of the subsystem they are interested in. This description is used as the basis for a code search from a code repository. Code search typically will yield only an individual file, but ASCUS does multiple searches to extract a whole subsystem, find the needed libraries, and attempt to make the result compilable.

The returned systems are too complex to be easily understood by a developer. ASCUS next simplifies them by abstracting out the essential portions to create a simple, clear interface describing the subsystem. It does this using a variety of heuristics based on search terms, visibility, and usage. These are then presented to the developer either as a Java interface or as a UML class diagram.

The developer can then edit these abstractions to better meet their needs, adding or removing classes and methods, using local types, changing names, etc. The edited abstractions are then used as the basis for a second code search for subsystems to yield a set of candidate systems. The returned subsystems are matched against the developer's edited abstraction and a set of transformations are developed to map the returned code to the abstract specifications.

Next the project containing each retrieved subsystem is searched for test cases. These are restricted to tests of the subsystem and then transformed using the mappings that were computed for the returned code. The result is a suite of tests for the developer's abstraction. These are then combined with the abstracted description to produce a checkable specification that meets the developer's needs.

4 Searching for Subsystems

ASCUS's first step is to extract potential subsystems from projects in the repository. This is done using the existing repository search facilities which are designed to retrieve projects, files, or methods, not subsystems.

Suppose the developer is interested in extending an existing IoT application by adding an embedded http server to support a front end that handles static pages for documentation and RESTful requests accessing data. They want the footprint of the server to be small.

ASCUS starts with an informal description from the developer consisting of several sets of keywords. The first set is optional and is used to identify projects in the repository likely to contain appropriate code. We found that searching for projects first and then searching within those projects works better when searching a large repository such as GitHub. For the web server example this could be the keywords *lightweight*, *http* and *server*. The second set of keywords is used to search for files. If no first set was given, then this search is over the whole repository; otherwise it is done once for each of the identified projects. For the http server example, this could be just the keyword *server* which would find server instances within the identified project.

The result of this search is a set of individual files that might be part of an appropriate subsystem. ASCUS next expands each of these files into a subsystem by finding other files that are required for compilation from the same

Figure 2: Sample Java-interface based abstraction.

```
@Ascus(source="GITREPO:https://github.com/Ruhrpottattacke/easyhttpserver/.../HttpServer.java")
@Ascus(library="com.sun.net.httpserver:http:20070405")
@Ascus(library="org.junit.platform:junit-platform-console-standalone:1.8.1")
@Ascus(search="PACKAGE,PACKAGE_USED,500,GITREPO")
@Ascus(keywords={"@lightweight","@http","server"})
@Ascus(keyterms={"server","request","ftp","@lightweight","uri","url","routing",...})
@Ascus(suggestedTerms={"exchange","logger","response","finest","server","handler"})
package edu.brown.cs.SAMPLE;
@AscusPackage
public interface HttpServer {
@AscusClass
interface HttpHandler {
void handle(HttpExchange exchange);
}
@AscusClass(uses={HttpHandler.class})
abstract class RawHandler implements HttpHandler {
public RawHandler(HttpHandler handler) { }
public abstract void handle(HttpExchange exchange);
}
@AscusClass
abstract class HttpServer {
public HttpServer(int port,int threads,int backlog) { }
public abstract void start();
public abstract void stop(int delay);
public abstract void stop();
public abstract void createContext(String path,HttpHandler handler);
public abstract void removeContext(String path);
public abstract boolean isRunning();
}
@AscusClass
abstract class HttpExchange {
private String response;
public HttpExchange(HttpExchange exchange) { }
public abstract void setResponse(String response);
}
}
```

or related projects. It starts by adding all files in the current package that are required to compile the original file or any file that is added. Then it identifies other related packages and adds any required file from those. It stops when either too many files have been added (the result is not a subsystem), or when nothing more can be found. It then transforms the result so that all the defined classes are in a single package.

Next, ASCUS filters the results to ensure their relevancy. It does this using the third set of keywords denoted as key terms. These are used to identify potentially relevant fields, methods, and classes. Occurrences of these are used to score the resultant subsystems based on relevancy. For the http server example, the key terms could be *url*, *uri*, *application*, *property*, *port*, *https*, *ftp*, *routing*, *callback*, *request* and *response*. ASCUS filtering removes results that are trivial; that are overly complex; that are primarily test cases; and that do not meet a minimal level of relevancy based on the key terms.

Finally ASCUS looks at the remaining results, finds references to external packages, and uses these to identify any required external libraries by searching in the Maven repository.

5 Creating Abstractions

The subsystems returned by search are still too complex to be quickly understood by developers. ASCUS simplifies them by creating abstractions that

can be shared with the developer and used as a basis for a second code search. The abstractions present the essentials of the subsystem without unnecessary details. An example of an abstraction can be seen in Figure 2.

Abstractions are created hierarchically. First data types are matched for compatibility. Next fields are considered in the same field abstraction if their data types are compatible. Methods are considered in the same method abstraction if their parameters and return types are compatible disregarding parameter order.

To abstract a class, ASCUS first identified the relevant fields and methods by considering their visibility and the occurrence of key terms in their names or bodies. Private fields with a public getter and setter are considered relevant. The resultant initial abstraction of a class is just the set of visible elements. Similar class abstractions are merged by finding the maximal matching of their fields and methods taking into account their abstractions and names.

Next subsystems are abstracted based on their class abstractions. The set of relevant classes for a subsystem starts with all non-trivial, non-private, non-test classes. Then any subclasses, including classes that implement an interface in the set are removed. Finally, any classes that are referenced by fields or methods in the abstract class are added back in. Subsystem abstractions are then merged using a maximal matching with a reasonable threshold.

Finally ASCUS adds additional information to the subsystem abstractions that might be helpful to the developer. This includes any libraries that are needed to get it to compile and possible additional keywords for future search based on a tf-idf analysis of the matched code. Then the resultant abstractions are then sorted by relevance and presented to the developer. ASCUS creates both a single Java interface containing the various elements that can be seen by the developer and a UML diagram that can be viewed using UMLet or Umbrello. For the http server example, ASCUS found 110 possible subsystems in GitHub and returned 18 abstractions to the developer after filtering including the one shown in Figure 2.

6 Matching Abstractions to Retrieved Subsystems

ASCUS generates abstractions for the developer to edit. The developer can adapt the abstraction to their naming conventions and to use their types. They can remove unneeded methods and classes and add other methods and classes they think are useful. The resultant edited abstraction then forms the syntactic basis of the specifications for their subsystem. Once this is done, ASCUS uses the information in the edited abstraction as the basis to search for subsystems in the repository a second time.

Once this is done, ASCUS attempts to match the retrieved subsystems with the abstraction and to find a sequence of code transformations that will map the retrieved code to the specifications of the abstraction. For each retrieved

subsystem it first builds an abstraction of that subsystem. Then it matches that abstraction to the developer's edited abstraction. This first does a matching of data types, then computes maximal matchings of fields and methods combined with matching words in methods names, comments, and content to find the best mapping from the retrieved code to the abstraction.

Then ASCUS computes a sequence of code transformations that will map the retrieved code to code matching the specification. These handle renaming, type changes, parameter order changes, moving classes into or out of other classes, adding missing elements, optionally removing unused elements, and ensuring the code obeys the developer's naming conventions.

For the http server example with relatively simple specifications, ASCUS found and transformed 11 candidate subsystems ranging in size from 800 to 7000 lines.

7 Generating Test Cases

ASCUS next uses the retrieved subsystems that matched the abstraction to find test cases. It finds tests for each retrieved subsystem and then combines the resultant tests into a single test suite for the abstraction that can be edited by the developer.

To find tests for a retrieved subsystem, ASCUS first does a code search of the repository to find all files containing JUnit test cases and either an import or package statement from the original retrieved code. It takes all the resultant files and converts them into a set of files in the package associated with the abstraction.

It then transforms this file into a set of useful tests. It starts by applying the transformations computed by the abstraction matching process to convert types, names, parameter order, etc. from the original code to the abstraction. Then it prunes the result by removing any unneeded methods, removing any test methods that invoke methods not in the abstraction, and ensuring the remaining tests compile against the abstraction. Finally, it transforms the result to match the developer's naming conventions.

The final step in ASCUS's test generation is to combine the results from the different retrieved subsystems, discard any duplicate tests, and then incorporate the resultant tests into the completed abstraction.

While this step often fails since only about 1/3 of the projects that are retrieved include formal test cases, it can find actual tests. For the http server example, about half the subsystems included tests and ASCUS was able to generate 80 test cases (50 from one subsystem).

8 Future Plans

ASCUS currently exists as a proof-of-concept prototype, with no user interface, simple heuristics, simple matching algorithms, and a small set of code transfor-

mations. Our experiences to date show that it is possible to interactively create non-trivial specifications from an informal description in under 5 minutes. However, much needs to be done before this becomes a usable system.

Our short term research plan includes extending the prototype with a suitable web-based user interface; creating evaluation criteria for the returned abstractions to avoid presenting too many irrelevant ones to the developers and improve the presentation order; improving code search to make it less sensitive to the selection of keywords; and extending the transformations, heuristics and algorithms used. We are also looking at better ways of creating checkable semantics since test cases are not as common or comprehensive as one would hope. We are looking at creating test cases from examples of how the subsystem is used in the retrieved package. We are also looking at other simple means for letting the developer describe the expected behavior including UML sequence diagrams and contracts. Finally, we are investigating different means of evaluating an interactive tool such as ASCUS.

Checkable specifications of non-trivial subsystems are only a first step. The ultimate goal of our research is to generate working versions or at least working skeletons of the described subsystems. ASCUS actually does a little of this in transforming the retrieved subsystems to meet the syntactic specifications of the edited abstraction. However this is insufficient.

Generating working code that meets a checkable specification will require not only adapting a retrieved subsystem to the abstraction, but also simplifying that code to remove unnecessary features; merging multiple retrieved subsystems to provide additional features; editing the retrieved code to pass the tests, possibly using automatic program repair techniques; generating code for missing methods using technologies such as program synthesis, code search, or machine learning; adapting code to use versions of libraries consistent with what the developer is using; and generally ensuring the code is something the developer actually would want to use.

References

- [1] Taweessup Apiwattanapong, Alessandro Orso, and Mary Jean Harrold. A differencing algorithm for object-oriented programs. *ASE 2004*, pages 2–13, September 2004.
- [2] Chetan Arora, Mehrdad Sabetzadeh, Shiva Nejati, and Lionel C. Briand. An active learning approach for improving the accuracy of automated domain model extraction. *ACM Trans. Softw. Eng. Methodol.*, 28:4:1–4:34, 2019.
- [3] Sushil Bajracharya, Trung Ngo, Erik Linstead, Yimeng Dou, Paul Rigor, Pierre Baldi, and Cristina Lopes. Sourcerer: a search engine for open source code supporting structure-based search. In *Proceedings ACM SIG-PLAN Conference on Object-Oriented Programming, Systems, Languages, and Applications 2006*, pages 682–682, October 2006.
- [4] Egor Bogomolov, Yaroslav Golubev, Artyom Lobanov, Vladimir Kovalenko, and Timofey Bryksin. Sosed: a tool for finding similar software projects, 2020.
- [5] Hugo BruneliC(re, Jordi Cabot, GrC)goire DupC), and FrC)dC)ric Madiot. Modisco: A model driven reverse engineering framework. *Information and Software Technology*, 56(8):1012–1032, 2014.
- [6] Jose Cambroner, Hongyu Li, Seohyun Kim, Koushik Sen, and Satish Chandra. When deep learning met code search. In *Proceedings of the 2019 27th ACM Joint Meeting on European Software Engineering Conference and Symposium on the Foundations of Software Engineering, ESEC/FSE 2019*, page 964–974, New York, NY, USA, 2019. Association for Computing Machinery.
- [7] Shaunak Chatterjee, Sudeep Juvekar, and Koushik Sen. SNIFF: A search engine for java using free-form queries. In *Proceedings of the 12th International Conference on Fundamental Approaches to Software Engineering: Held as Part of the Joint European Conferences on Theory and Practice of Software, ETAPS 2009*, pages 385–400, 2009.
- [8] Mark Chen, Jerry Tworek, Heewoo Jun, Qiming Yuan, Henrique Ponde de Oliveira Pinto, Jared Kaplan, and et al. Evaluating large language models trained on code. *CoRR*, abs/2107.03374, 2021.
- [9] Yoonsik Cheon and Carlos E. Rubio-Medrano. Random test data generation for java classes annotated with JML specifications. *SERP*, 11:385–392, June 2007.
- [10] Themistoklis Diamantopoulos, Klearchos Thomopoulos, and Andreas Symeonidis. Qualboa: Reusability-aware recommendations of source code

- components. In *Proceedings of the 13th International Conference on Mining Software Repositories*, MSR '16, page 488–491, New York, NY, USA, 2016. Association for Computing Machinery.
- [11] Robert France and Bernhard Rumpe. Model-driven development of complex software: a research roadmap. *FOSE 2007*, pages 37–54, 2007.
 - [12] Gordon Fraser and Andrea Arcuri. Evosuite: automatic test suite generation for object-oriented software. In *Proceedings of the 19th ACM SIGSOFT symposium and the 13th European conference on Foundations of software engineering*, pages 416–419, 2011.
 - [13] Elena L. Glassman, Jeremy Scott, Rishabh Singh, Philip J. Guo, and Robert C. Miller. Overcode: Visualizing variation in student solutions to programming problems at scale. *ACM Trans. Comput.-Hum. Interact.*, 22(2):1–35, 2015. 10.1145/2699751.
 - [14] Elena L. Glassman, Tianyi Zhang, Bjrn Hartmann, and Miryung Kim. Visualizing API usage examples at scale. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pages 1–12, Montreal QC, Canada, 2018. ACM.
 - [15] Hassan Gomaa. *Designing Software Product Lines with UML: From Use Cases to Pattern-Based Software Architectures*. Addison Wesley Longman Publishing Co., Inc., 2004.
 - [16] Sankha Narayan Guria, Jeffrey S. Foster, and David Van Horn. Rbsyn: Type- and effect-guided program synthesis. In *Proceedings of the 42nd ACM SIGPLAN International Conference on Programming Language Design and Implementation*, PLDI 2021, page 344–358, New York, NY, USA, 2021. Association for Computing Machinery.
 - [17] Andrew Head, Elena Glassman, Gustavo Soares, Ryo Suzuki, Lucas Figueredo, Loris D’Antoni, and Bjrn Hartmann. Writing reusable code feedback at scale with mixed-initiative program synthesis. In *Proceedings of the Fourth (2017) ACM Conference on Learning @ Scale*, pages 89–98, Cambridge, Massachusetts, USA, 2017. ACM. 10.1145/3051457.3051467.
 - [18] Andrew Head, Elena L. Glassman, Bjrn Hartmann, and Marti A. Hearst. Interactive extraction of examples from existing code. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pages 1–12, Montreal QC, Canada, 2018. ACM. 10.1145/3173574.3173659.
 - [19] Reid Holmes, Gail C. Murphy, Rylan Cottrell, Robert J. Walker, and Jorg Denzinger. Using structural context to recommend source code examples semi-automating small-scale source code reuse via structural correspondence. In *International Conference on Software Engineering 05 FSE 16*, pages 117–125 214–225, May 2005 November 2008.

- [20] Vineeth Kashyap, David Bingham Brown, Ben Liblitt, David Melski, and Thomas W. Reps. Source forager: a search engine for similar source code. *arXiv:1706.02769*, 2017.
- [21] Miryung Kim and David Notkin. Discovering and representing systematic code changes. In *Proceedings of the 31st International Conference on Software Engineering*, pages 309–319, 2009.
- [22] Walter Korman and William G. Griswold. Elbereth: tool support for refactoring java programs. UCSD Dept. of Computer Science and Engineering Technical Report CS98-590, June 1998.
- [23] Emmanouil Krasanakis and Andreas Symeonidis. Defining behaviorizeable relations to enable inference in semi-automatic program synthesis. *Journal of Logical and Algebraic Methods in Programming*, 123:100714, 2021.
- [24] Otavio Augusto Lazzarini Lemos, Sushil Bajracharya, Joel Ossher, Paulo Cesar Masiero, and Cristina Lopes. A test-driven approach to code search and its application to the reuse of auxiliary functionality. *Information and Software Technology*, 53(4):294–306, April 2011.
- [25] Leonardo Mariani, Mauro Pezz, Oliviero Riganelli, and Mauro Santoro. Autoblacktest: a tool for automatic black-box testing. In *Proceedings of the 33rd International Conference on Software Engineering*, pages 1013–1015, 2011.
- [26] H. A. Muller, S. R. Tilley, M. A. Orgun, B. D. Corrie, and N. H. Madhavji. A reverse engineering environment based on spatial and visual software interconnection models. *Software Engineering Notices*, 17(5):88–98, December 1992.
- [27] Emerson Murphy-Hill and Andrew P. Black. Refactoring tools: fitness for purpose. *IEEE Softw.*, 25(5):38–44, 2008.
- [28] Emerson Murphy-Hill, Chris Parnin, and Andrew P. Black. How we refactor, and how we know it. In *Proceedings of the 31st International Conference on Software Engineering*, pages 287–297, 2009.
- [29] Iulian Neamtiu, Jeffrey S. Foster, and Michael Hicks. Understanding source code evolution using abstract syntax tree matching. In *Proceedings of the 2005 international workshop on Mining software repositories*, pages 1–5, 2005.
- [30] Hoan Anh Nguyen, Tung Thanh Nguyen, Hung Viet Nguyen, and T.N Nguyen. idiff: Interaction-based program differencing tool. In *26th IEEE/ACM International Conference on Automated Software Engineering (ASE)*, pages 572–575, 2011.

- [31] Haoran Niu, Iman Keivanloo, and Ying Zou. Learning to rank code examples for code search engines. *Empirical Softw. Engg.*, 22(1):259–291, 2017. 10.1007/s10664-015-9421-5.
- [32] Mehrdad Nurolahzade, Robert J. Walker, and Frank Maurer. An assessment of test-driven reuse: promises and pitfalls. In *13th International Conference on Software Reuse*, pages 65–80, 2013.
- [33] Oscar Pastor, Sergio Espana, Jose Ignacio Panach, and Nathalie Aquino. Model-driven development: piecing together the MDA jigsaw puzzle. *Informatik-Spektrum*, 31(5):394–407, October 2008.
- [34] Shruti Raghavan, Rosanne Rohana, David Leon, Andy Podgurski, and Vinay Augustine. Dex: A semantic-graph differencing tool for studying changes in large code bases. In *2013 IEEE International Conference on Software Maintenance*, pages 188–197, 2004.
- [35] Claudia Raibulet, Francesca Arcelli Fontana, and Marco Zanoni. Model-driven reverse engineering approaches: A systematic literature review. *IEEE Access*, 5:14516–14542, 2017.
- [36] Steven P. Reiss. Semantics-based code search. In *International Conference on Software Engineering 2009*, pages 243–253, May 2009.
- [37] Steven P. Reiss. Towards creating test cases using code search. In *IEEE International Conference on Software Maintenance and Evolution*, pages 436–440, 2014.
- [38] Martin Robillard, Robert Walker, and Thomas Zimmermann. Recommendation systems for software engineering. *IEEE Software*, 27(4):80–86, 2010.
- [39] Philip Samuel and Rajib Mall. Slicing-based test case generation from UML activity diagrams. *SIGSOFT Softw. Eng. Notes*, 34(6):1–14, 2009.
- [40] Fang-Hsiang Su, Jonathan Bell, Kenneth Harvey, Simha Sethumadhavan, Gail Kaiser, and Tony Jebara. Code relatives: detecting similarly behaving software. In *Proceedings of the 2016 24th ACM SIGSOFT*, pages 702–714, Seattle, WA, USA, 2016. ACM.
- [41] Shmuel Tyszberowicz, Robert Heinrich, Bo Liu, and Zhiming Liu. Identifying microservices using functional decomposition. In Xinyu Feng, Markus Müller-Olm, and Zijiang Yang, editors, *Dependable Software Engineering. Theories, Tools, and Applications*, pages 50–65, Cham, 2018. Springer International Publishing.
- [42] Shaowei Wang, David Lo, and Lingxiao Jiang. Code search via topic-enriched dependence graph matching. *18th Working Conf. on Reverse Engineering*, pages 119–123, 2011.

- [43] Zhenchang Xing and Eleni Stroulia. Umldiff: an algorithm for object-oriented design differencing. In *Proceedings of the 20th IEEE/ACM international Conference on Automated software engineering*, pages 54–65, 2005.
- [44] Wu Yang. Identifying syntactic difference between two programs. *Software Practice and Experience*, 21(7):739–755, July 1991.
- [45] Hongyu Zhang, Anuj Jain, Gaurav Khandelwal, Chandrashekhar Kaushik, Scott Ge, and Wenxiang Hu. Bing developer assistant: Improving developer productivity by recommending sample code. In *Proceedings of the 2016 24th ACM SIGSOFT International Symposium on Foundations of Software Engineering*, page 956–961. Association for Computing Machinery, 2016.