Scalable Call Graph Constructor for Maven

1st Mehdi Keshani

Technical University of Delft, m.keshani@tudelft.nl

Abstract—As a rich source of data, Call Graphs are used for various applications including security vulnerability detection. Despite multiple studies showing that Call Graphs can drastically improve the accuracy of analysis, existing ecosystem-scale tools like Dependabot do not use Call Graphs and work at the package-level. Using Call Graphs in ecosystem use cases is not practical because of the scalability problems that Call Graph generators have. Call Graph generation is usually considered to be a “full program analysis” resulting in large Call Graphs and expensive computation. To make an analysis applicable to ecosystem scale, this pragmatic approach does not work, because the number of possible combinations of how a particular artifact can be combined in a full program explodes. Therefore, it is necessary to make the analysis incremental. There are existing studies on different types of incremental program analysis. However, none of them focuses on Call Graph generation for an entire ecosystem.

In this paper, we propose an incremental implementation of the CHA algorithm that can generate Call Graphs on-demand, by stitching together partial Call Graphs that have been extracted for libraries before. Our preliminary evaluation results show that the proposed approach scales well and outperforms the most scalable existing framework called OPAL.

Index Terms—Theory of computation, Logic and verification, Program analysis

I. INTRODUCTION

In modern Software Engineering, the choice of the programming language is as important as the surrounding ecosystem. Many tools and reusable components exist that make developers more productive. Software ecosystems ease the management of third-party libraries. They pull in the dependencies on demand when necessary. Maven is a popular ecosystem that hosts more than six million software artifacts. However, importing dependencies into a project also introduces risks like security vulnerabilities of the dependency. On the other hand, fine-grained analysis can have positive impacts on reliability of software reuse in ecosystems by improving the accuracy of analyses such as vulnerability detection [1], [2]. Such fine-grained analysis needs to be performed on Call Graphs (CGs). The common approach for constructing a CG is to provide a complete application, including all of its dependencies for the CG algorithm. However, this approach is not practical for an entire ecosystem. It is not scalable due to redundant computations. The main challenges that cause redundancy in ecosystem CG generation are as follows: (1) Existing Java CG generators generate a CG for a given ClassPath (CP). Suppose we want to generate CGs for an ecosystem, we have to provide the CP of all packages that exist in the ecosystem. These CPs also include the libraries that each package uses. On the other hand, “a majority of packages depends on a small minority of other packages” [3]. Moreover, different versions of a package, especially if they are minor releases apart, share a lot of similar dependencies. Therefore, an ecosystem like Maven, results in constructing the same CG again and again for each popular library. (2) Version range dependency specification on Maven can cause non-deterministic dependency sets. If there is a version range dependency specification in a package the result of the dependency resolution may be different based on the time of the resolution [4]. Moreover, various resolution rules of companies or different package managers also make resolution results diverse. Transitive dependencies can also make dependency sets non-deterministic. If direct dependencies of an application have one transitive dependency in common and they use different versions of it, there will be a version conflict. The resolver solves this based on the resolution policies. Maven chooses the closest version to the root package. In any case, if the resolved dependency set slightly changes the resulting CG will be different for the same package, hence a new CG generation needs to be triggered from scratch unless we pre-compute the common parts. (3) On-demand analysis on top of CGs such as fine-grained vulnerability analysis is time-consuming and expensive. Such analyses are useful for developers or library maintainers. An analysis provider needs to load binary files into memory and construct CGs for them which is overly expensive. Additionally, duplicate computations lower the performance of query responses. For example, if two clients query the server of an analysis provider at the same time and both of them are using log4j:log4j:jar:1.2.17 library, the server has to construct CG for this library twice at the same time.

In this paper, we propose an incremental CG construction approach that makes ecosystem-scale CG generation achievable. Although there are a few studies [5]–[7] on incremental program analysis, to the best of our knowledge, none of them constructs CGs in the scale of the entire Java ecosystem.

We exploit the Maven central ecosystem in this study. Our approach has three main steps. First, we construct and store partial CGs for packages without their dependencies. And then, we stitch them whenever it is needed. Although in this paper we focus on the Maven and CG generation for Java, the idea of pre-computation per package can be used for other ecosystems. We use the OPAL CG generator to generate the partial CGs. We also compare our results with this framework as a baseline. Our evaluation results show that the proposed approach can highly affect the scalability of CG generation and outperform the most scalable existing framework, OPAL [8]. The main contribution of this work is a novel CG generation technique that; (1) makes CG generation possible for Maven ecosystems, (2) improves the scalability of...
Therefore, we generate and store a partial CG for each package. We untangle the resolution process and CG construction by dependency resolution as the pre-step of CG construction. Considering that whenever a new release is out on Maven, after we create the CG pool, any custom dependency set can be used to generate a full CG. Whenever we have a set of packages as a result of a resolution, we fetch the computed CGs from the CG pool and stitch them together using the algorithm that we have implemented.

Once we have a resolution set, we combine the CGs that we have previously fetched from the CG pool and create a Universal Class Hierarchy (UCH). Then the Stitching algorithm walks through the edges of CGs, and based on the type of the invocation\(^2\) decides how to resolve new edges or correct the existing edges. That is, edges that we have in the CGs of the CG pool, are not complete due to lack of information in partial CG construction. Hence, stitching tries to complete these edges by adding new edges to libraries or replacing the existing edges that are incorrect.

### II. Related Work

There are several studies on the scalability of different analyses. Tip et al. [9] proposed various algorithms to improve the scalability of CG generation. However, in their study, they focus on large programs, not an entire ecosystem. Alexandru et al. [10] took advantage of the same concept that we do, which is avoiding multiple analysis of redundant parts. However, CG generation is not the focus of their study.

There also exist several studies on incremental static analysis. Souter et al. [5] made the CPA algorithm incremental. Their proposed approach updates a CG with the changed parts of new versions. However, the scale of their work is multiple releases, not an ecosystem. Arzt et al. [7] uses summary pre-computation to improve the scalability of data flow analysis on android applications. Although the pre-computation is very relevant to our approach, they do not use it for CG generation. To the best of our knowledge, no existing study uses pre-computation of packages to generate ecosystem-scale CGs.

### III. Methodology

As opposed to existing approaches, we propose to remove dependency resolution as the pre-step of CG construction. We untangle the resolution process and CG construction by using the dependency set as a parameter of CG construction. Therefore, we generate and store a partial CG for each package only once and use it many times in the future. Considering that CG construction is a heavy computation and resulting CGs are mostly heavy object\(^1\) by removing duplications from the process we save a lot of time and storage.

In the proposed approach, we first download binaries of packages from Maven Central. Then, we generate CGs for them using an existing CG generator. Next, we parse the output of the CG generator and extract concise yet sufficient information for further steps. This information includes class hierarchy and CG information of the package and will be stored in a storage called CG Pool. In the CG Pool, each CG is indexed by its package reference which in the case of Maven is a Maven Coordinate. A Maven Coordinate is composed of groupId:artifactId:version, that uniquely identifies a package within the whole ecosystem. This CG pool can be updated, whenever a new release is out on Maven. After we create the CG pool, any custom dependency set can be used to generate a full CG. Whenever we have a set of packages as a result of a resolution, we fetch the computed CGs from the CG pool and stitch them together using the algorithm that we have implemented.

| Maven Coordinate | #Deps | OPAL CG Pool(1) | Stitching(2) | UCH(3) | 1+2+3 |
|------------------|-------|----------------|-------------|--------|-------|
| 1 com.google.code.maven-play-plugin.org.playframework:play:1.3.2 | 61 | 2:39min | 0:54min | 0:55min | 330ms | 1:50min |
| ... | | | | | | |
| 9 org.apache.solr:solr-map-reduce:5.4.1 | 121 | 5:03min | 1:15min | 3:33min | 459ms | 4:49min |
| 10 org.digidoc4j:digidoc4j:1.0.8.beta.2 | 49 | 0:34min | 0:21min | 0:13min | 106ms | 0:35min |
| First round of generation excluding redundant deps | 605 | 18:46min | 4:33min | 8:32min | 0:02min | 13:05min |
| +Second round of generation | 605 | 18:46min | 0:00min | 8:32min | 0:02min | 8:34min |

\(^1\)Objects that occupy a lot of memory in the program.

\(^2\)There are five types of invocations in the JVM bytecode e.g. invokevirtual.
REFERENCES

[1] P. Boldi and G. Gousios, “Fine-grained network analysis for modern software ecosystems,” ACM Transactions on Internet Technology, vol. 21, no. 1, pp. 1–14, 2020.

[2] J. Hejderup, A. van Deursen, and G. Gousios, “Software ecosystem call graph for dependency management,” in 2018 IEEE/ACM 40th International Conference on Software Engineering: New Ideas and Emerging Technologies Results. IEEE, 2018, pp. 101–104.

[3] A. Decan, T. Mens, and P. Grosjean, “An empirical comparison of dependency network evolution in seven software packaging ecosystems,” Empirical Software Engineering, vol. 24, no. 1, pp. 381–416, 2019.

[4] J. Hejderup, M. Beller, and G. Gousios, “Prazi: From package-based to precise call-based dependency network analyses,” 2018.

[5] A. L. Souter and L. L. Pollock, “Incremental call graph reanalysis for object-oriented software maintenance,” in Proceedings IEEE International Conference on Software Maintenance. ICSM 2001. IEEE, 2001, pp. 682–691.

[6] J. Toman and D. Grossman, “Taming the static analysis beast,” in 2nd Summit on Advances in Programming Languages. Schloss Dagstuhl-Leibniz-Zentrum fuer Informatik, 2017.

[7] S. Arzt and E. Bodden, “Stubdroid: automatic inference of precise data-flow summaries for the android framework,” in 2016 IEEE/ACM 38th International Conference on Software Engineering. IEEE, 2016, pp. 725–735.

[8] M. Reif, F. Kübler, M. Eichberg, D. Helm, and M. Mezini, “Judge: identifying, understanding, and evaluating sources of unsoundness in call graphs,” in Proceedings of the 28th ACM SIGSOFT International Symposium on Software Testing and Analysis. ACM, 2019, pp. 251–261.

[9] F. Tip and J. Palsberg, “Scalable propagation-based call graph construction algorithms,” in Proceedings of the 15th ACM SIGPLAN conference on Object-oriented programming, systems, languages, and applications, 2000, pp. 281–293.

[10] C. V. Alexandru, S. Panichella, S. Proksch, and H. C. Gall, “Redundancy-free analysis of multi-revision software artifacts,” Empirical Software Engineering, vol. 24, no. 1, pp. 332–380, 2019.