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Software Ecosystem Call Graph for Dependency Management

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ABSTRACT

A popular form of software reuse is the use of open source software libraries hosted on centralized code repositories, such as Maven or npm. Developers only need to declare dependencies to external libraries, and automated tools make them available to the workspace of the project. Recent incidents, such as the Equifax data breach and the leftpad package removal, demonstrate the difficulty in assessing the severity, impact and spread of bugs in dependency networks. While dependency checkers are being adapted as a counter measure, they only provide indicative information. To remedy this situation, we propose a fine-grained dependency network that goes beyond the versioning between libraries and the edges are dependencies on the libraries. The structural properties of these graphs can significantly affect the functionality of thousands of end-user projects. Moreover, including arbitrary code from an online repository induces trust and security implications; how can developers ensure that the imported code contains no security holes? How can they know when a security issue discovered in a transitive dependency requires an update? Dependency networks also present challenges to library maintainers: how can they assess the direct or transitive impact of their changes?

In the recent years, we have witnessed dependency network failures with severe implications on client programs:

- A dispute over a library name in the npm ecosystem led to the removal of a library called leftpad. The package removal further lead to the collapse of thousands of libraries which directly depended on leftpad, and hence a major disruption for client programs. After the leftpad incident, a study estimated that there exist libraries whose removal can affect more than 30% of the core components of the network.
- A company named Equifax leaked over 100,000 credit card records due to a dependency that was not updated. The compromised systems included a vulnerable version of the Apache Struts library, whose update was postponed as the bug's severity was underestimated. The Equifax security team erroneously underestimated the impact of the bug on their codebase.
- Malicious developers uploaded to the Python package manager (PyPI) libraries whose name was deliberately misspelled, leading to highly interconnected ecosystems which were required to build the client program. The intention was to steal information from client applications of developers who had accidentally mistyped the library name in the dependency file.

Recent research has been focused on the evolution of code repositories and how libraries are growing together in a shared environment. To study ecosystems, developers typically build dependency graphs, in which nodes represent either libraries or library versions. To represent a dependency (i.e. creating an edge), researchers emulate the version resolution algorithm of the original package manager. While this model is useful for initial evaluations of dependency networks, it can only provide partial information due to the following limitations:

1. The dependency relationship in the network is on a version-basis (e.g. library A v1.2.3 depends on library B v2.3.4). Reasoning about how a library can influence other connected libraries on a dependency is not resolved in a well-defined manner. Increasingly, libraries are being used as building blocks for creating other libraries, leading to highly interconnected ecosystems. The interconnections form a graph, in which the nodes are versioned libraries and the edges are dependencies on the libraries. The structural properties of these graphs can significantly affect the functionality of thousands of end-user projects. Moreover, including arbitrary code from an online repository induces trust and security implications; how can developers ensure that the imported code contains no security holes? How can they know when a security issue discovered in a transitive dependency requires an update?

Dependency networks also present challenges to library maintainers: how can they assess the direct or transitive impact of their changes?
version-based such as bug propagation is limited. (2) A dependency on a library does not necessarily mean that the code in that library is actually used. Providing developers with actionable information such as security alerts on dependencies requires further analysis of dependency relationships. (3) Dependency networks do not enable developers (or researchers) to perform change impact analysis beyond a single library; this leads to lost opportunities of evaluating problems at the ecosystem level.

In our work, we propose to extend dependency networks with call graph information, within and across dependencies, thereby constructing ecosystem-wide dependency network call graphs. This takes into account how libraries are interconnected at the source code level.

Our vision is the following: (1) Construct a dependency network at the function-level granularity. (2) Evaluate the dynamics of changes made to libraries in a dependency network from a program analysis perspective. (3) Study and evaluate historical changes in a dependency network.

In the following sections, we outline concepts of our call graph based dependency network and highlight how it can enable a fine-grained impact analysis assessment.

2 CALL GRAPH BASED DEPENDENCY NETWORK

Most package managers for OSS libraries use a variation of semantic versioning to specify dependency versions. Semantic versioning allows developers to specify dependencies, not only as an exact version but also a version range. The resolution of version ranges has received a

method invocations recorded at runtime. Our only requirement is that the call graph construction will be able to (statically) construct call graphs that extend beyond a single project to the transitive set of dependencies the project specifies. This requirement is akin to the linking process in compiled languages, and is already supported by many tools.

Next, we need to map the call graph on the dependency network. There are two ways to do this: i) include the generated call graph as an attribute to a dependency network node, or ii) decorate the call graph nodes with metadata about the dependency (e.g., the dependency name and version). We choose the second option, as the graph nodes are functions and represents our end goal of being able to perform impact analysis at an ecosystem level.

By following the steps above, we arrive to the definition of our dependency network call graph as follows:

**Definition.** A dependency network call graph for an ecosystem is a directed and immutable graph \( G = (V, C) \) where:

1. \( V \) is a set of versioned functions. Each \( v \in V \) is a 3-tuple \( < id, v, c > \), where \( id \) is a fully qualified function name, \( v \) is the version of the library and \( c \) is the commit.
2. \( E \) is a set of edges that connects functions. Each \( (v_1, v_2) \in E \) represents a function call from \( v_1 \) to \( v_2 \).

Although the dependency network shares some similarities with the work of Hejderup and Kikas et al [5, 6], it differs in that the network is a large interconnected call graph and the versioning is annotated at the function call level. Figure 1 illustrates a simple call graph based dependency network where dependency 1 depends on dependency 2. Inside each dependency block, the nodes represent versioned functions with full function identifier, version and commit revision. The edges in the network can be classified into internal and external calls. An external call is made from the \( a() \) node in dependency 1 to the \( c() \) node in dependency 2. The process to decide and resolve an external function call into the correct versioned one is not trivial and is explained in the following subsection.

2.1 Network Construction

The process of constructing the network is shown in Algorithm 1. The initial step is to select commits that include changes to the dependency file of the repository (line 3). A change can be a new release of the library or a change to the list of specified dependencies.
The time stamp of the provided commit is extracted and the closest level. Depending on the type of the change in the processed commit, there are two sub-cases:

1. If the change is a new release of the library, a copy of the edges representing function calls to external libraries in the previous version is added to the graph.
2. If the change specifies a new dependency, the dependencies need to be re-evaluated and edges from each function in $CG_{ann}$ to functions in external libraries need to be created.

The process to resolve dependencies is presented in Algorithm 2. The dependency file is obtained and parsed from the commit (lines 1-2). After the edges are created, the process of identifying the affected nodes in a dependency network is summarized in Algorithm 3.

### 2.2 Impact Analysis

Impact analysis helps in the determination of the subset of the dependency network that is affected by a given set of changes or bugs. The identified subset allows developers and library maintainers to evaluate the impact within or across dependencies at the function call level. As an example, library maintainers can assess the potential impact of a set of changes in the network before releasing a new version. Further, developers can localize functions or methods in the program that are implicitly affected by a critical bug in a transitive dependency. Finally, the commit revision in the set of affected function nodes could be extended with using tools such as git-diff or git-log to track and identify function additions, removals or renames.

The process of identifying the affected nodes in a dependency network is summarized in Algorithm 3. Given the name and version of a library and the set of changed functions, the initial process is to find the corresponding versioned functions of $f$ in the dependency network (line 3). For each versioned function, a reachability analysis is performed that traverses the dependency network for identifying one or more calls to the set of changed functions (line 5). The result of $CG_{reach}$ contains a subset of the impacted (e.g. reachable) function calls to one versioned function. The partial impact set $CG_{reach}$ is added to the result in $G$ (line 7). Finally, after all versioned functions are processed, the impact set is returned (line 10).

### Algorithm 1: Network Construction

**Input**: git-based repository  
$G \leftarrow \emptyset$;  
`buildNetwork repo`

```plaintext
C \leftarrow filterDependencyCommits(repo);
if $C \neq \emptyset$ then
  foreach $c \in C$ do
    $rev \leftarrow$ checkout($c$);
    $CG \leftarrow$ constructCG($rev$);
    $CG_{ann} \leftarrow$ annotateFunctions($CG$);
    if $c$ specifies new library version then
      $G \leftarrow G \cup$ getPrevCommitEdges($c$, $CG_{ann}$);
    end
    if $c$ specifies a dependency update then
      $G \leftarrow G \cup$ resolveDependencies($c$, $G$, $CG_{ann}$);
    end
  end
end
```

### Algorithm 2: Resolving Dependencies

**Input**: commit, $G$, $CG_{ann}$  
**Output**: set of resolved dependency call edges  
`resolveDependencies commit, $G$, $CG_{ann}$`

```plaintext
$E \leftarrow \emptyset$;  
`depfile \leftarrow getDependencyFile(commit)`;  
$D \leftarrow$ parse(depfile);
if $D \neq \emptyset$ then
  foreach $d \in D$ do
    $Gname \leftarrow$ sliceByName($G$, $d$.name);
    $ver \leftarrow$ resolveVersion($d$.constraint, $c$);
    $Gver \leftarrow$ sliceByVersion($Gname$, $ver$);
    $CGd \leftarrow$ sliceByCommit($Gver$, commit);
    $E \leftarrow E \cup$ [getDependencyCalls($CGd$, $CG_{ann}$)];
  end
end
return $E$
```

### Algorithm 3: Impact Analysis

**Input**: A set of affected $f$ in name and version of library  
**Output**: Affected slice of the dependency network  
`impact (name, version, f)`

```plaintext
$G \leftarrow \emptyset$;
`impact (name, version, f)`

```plaintext
$F \leftarrow$ findVersionedFunctions(name, version, f);
foreach function $f_i \in F$ do
  $Greach \leftarrow$ reachability($f_i$);
  if $CG_{reach} \neq \emptyset$ then
    $G \leftarrow G \cap CG_{reach}$;
  end
end
return $G$
```

### 3 INITIAL EVALUATION

The concepts presented in the previous section are implemented in an early prototype in JavaScript and currently process npm-based projects. The dependency resolution mechanism in the prototype is based on npm’s semver\(^4\) library, and call graphs are extracted.

\(^4\)https://github.com/npm/node-semver
improper time configuration. We intent to mitigate this by using the build time of a commit from TravisCI-connected repositories [1].

To make the technique practical for developers and library maintainers, it is necessary to process ecosystems events such as changes made to a library and their dependencies in real-time. Building a real-time pipeline and adapting program analysis techniques to process on an event-basis calls for modifying current tools to work on an incremental basis.

5 RELATED WORK

In several studies [3–7], dependency networks have been used to study the dynamics of interconnected libraries in software ecosystems. However, there is a lack of research on dependency management, and yet, it is among some of the most common activities a developer needs to handle. To the best of our knowledge, there is one qualitative study by Bogart et al [2] that reasons about the cost of changes between library maintainers and their clients. However, none of these studies focus on techniques for a fine-grained and actionable dependency management for developers and library maintainers.

6 SUMMARY

In this paper, we present a technique to construct and analyze dependency relationships in a software ecosystem at the function-level granularity. The technique combines historical dependency data from version-controlled repositories with call graph construction to build a fine-grained representation of a dependency network. This representation can extend program analysis to diagnose problems at an ecosystem level, such as the spread of a security bug to affected clients or libraries by inspecting their interconnected function call relationship. We believe that our approach points towards actionable dependency management, where dependencies and their changes are evaluated at the source code level.

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