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### IDENTIFYING AN UPDATE OF A CODE DEPENDENCY TO USE BASED ON RISK AND BENEFIT TRADE-OFFS

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#### Abstract

In some examples, a package is selected and a set of dependencies associated with the package determined. A set of upgrade candidates for a dependency is determined. For an upgrade candidate, issues associated with upgrading the package to use the upgrade candidate are determined, a state of a dependency graph associated with upgrading are determined, diamond dependencies in the dependency graph are determined, a number of vulnerabilities and a severity of the vulnerabilities addressed by upgrading to the upgrade candidate are determined, and a risk-benefit score associated with each upgrade candidate is determined. The upgrade candidates are prioritized based on the associated risk-benefit score to create prioritized upgrade candidates that are provided to a software developer.

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## Background/Summary

[0001] The present patent application is a continuation of U.S. patent application Ser. No. 18/951,189, entitled “IDENTIFYING AN UPDATE OF A CODE DEPENDENCY TO USE BASED ON RISK AND BENEFIT TRADE-OFFS” filed on Nov. 18, 2024 which itself claims priority from (1) U.S. Provisional Application 63/552,793 filed on Feb. 13, 2024, (2) U.S. Provisional Application 63/680,135 filed on Aug. 7, 2024, (3) U.S. Non-Provisional application Ser. No. 18/740,976 filed on Jun. 12, 2024, all of which are incorporated herein by reference in their entirety and for all purposes as if completely and fully set forth herein.

### BACKGROUND

[0002] In recent years, software applications have increasingly relied on third-party components, many of which are released under open-source license. These components are typically declared as dependencies in the manifest files of the software applications, e.g., by specifying the name and version of the component to be used. Prebuilt open-source components or packages are made available on package registries. Package managers download these prebuilt packages from the registries according to the dependency declarations in the applications' manifest files, making the code included within these packages available in the applications' development or runtime environments.

[0003] However, these open-source components often suffer from security vulnerabilities, which can negatively impact the applications that use them, either directly or indirectly. To determine whether a particular application is affected by these vulnerabilities, code-level information about the vulnerability, such as the identifiers of vulnerable functions and the identifiers of components that include those functions, are identified. Obtaining such information enables developers to employ program analysis techniques, such as static analysis or dynamic analysis, to study the vulnerable component and its use in the context of a given application. For example, reachability analysis, determines whether a particular function that is part of an open-source component can be reached by an application that directly or indirectly uses the particular function.

[0004] When a developer of a software package that uses a component in a third library determines that the component has a vulnerability, the developer may consider upgrading the software package to use a newer version of the component. Often, multiple newer versions of the component are available. A newer version may fix the vulnerability but may introduce other issues, including breaking the functionality of the package (e.g., causing it to function in a manner different than the developer intended, sometimes referred to as a breaking change). It is challenging and time consuming for the developer to review the newer versions available for each third party component that the developer's code uses to determine which newer version of each component to use, particularly with open source libraries that are maintained by a third party.

### SUMMARY OF THE INVENTION

[0005] This Summary provides a simplified form of concepts that are further described below in

the Detailed Description. This Summary is not intended to identify key or essential features and should therefore not be used for determining or limiting the scope of the claimed subject matter. [0006] In some examples, a package in a software project is selected and a set of dependencies associated with the package determined. A set of upgrade candidates for a particular dependency is determined. For an upgrade candidate, issues associated with upgrading the package to use the upgrade candidate are determined, a state of a dependency graph associated with upgrading are determined, diamond dependencies in the dependency graph are determined, a number of vulnerabilities addressed by upgrading to the upgrade candidate are determined, and a risk-benefit score associated with the upgrade candidate is determined. The upgrade candidates are prioritized based on the associated risk-benefit score to create prioritized candidates. The prioritized candidates are provided to a developer associated with the package.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

[0007] A more complete understanding of the present disclosure may be obtained by reference to the following Detailed Description when taken in conjunction with the accompanying Drawings. In the figures, the left-most digit(s) of a reference number identifies the figure in which the reference number first appears. The same reference numbers in different figures indicate similar or identical items.

[0008] FIG. 1 is a system illustrating a system to create a prioritized subset of upgrade candidates, according to some embodiments.

[0009] FIG. 2 is a process to create a prioritized subset of upgrade candidates, according to some embodiments.

[0010] FIG. 3 is a process to create a recommended upgrade for multiple projects, according to some embodiments.

[0011] FIG. 4 is a block diagram of a computing device with memory, processors, storage, and network components for vulnerability management, highlighting the various modules configured to perform the steps of the vulnerability identification and addressing process.

### DETAILED DESCRIPTION

[0012] It should be understood, that the following descriptions, while indicating preferred aspects and numerous specific details thereof, are given by way of illustration only and should not be treated as limitations. Changes and modifications may be made within the scope herein without departing from the spirit and scope thereof, and the present invention herein includes all such modifications.

[0013] The systems and techniques enhance the security of software applications that use third-party components by determining when to upgrade to a new version of a third-party component and identifying a “best” version. The best version refers to a particular version of a component that is determined to introduce the least amount of issues after upgrading project code to use the particular component. For example, if multiple new versions of a component are available, the systems and techniques may analyze the dependency graphs associated with each version to determine which version is least likely to introduce issues, such as a breaking change (e.g., that causes the project code to function in a manner different than the developer intended). To illustrate, each of the newer versions may address a vulnerability in an older version of the component but a first version may introduce a new issue (e.g., vulnerability) while a second version may not introduce any new issues or may introduce a new issue for which a workaround is available. For these reasons, the systems and techniques may recommend the second version. If there are a large number of newer versions available, the systems and techniques may heuristically pare down the number of candidates to analyze, analyze the pared down candidates, determine a risk-benefit score (e.g., low, medium,

high, a score from 0 to 9, a score from 0 to 100, or the like), and provide a prioritized list ordered based on the risk-benefit score (also referred to as a recommendation score), including a newer version having the lowest risk-benefit score (or a highest recommendation score). Each upgrade candidate is scored (risk-benefit score) based on a tradeoff between (1) the upgrade risk and (2) the benefit of the upgrade (vulnerabilities addressed by the upgrade). The benefit of the upgrade takes into account the number of vulnerabilities and a severity of each of the vulnerabilities addressed by the upgrade. For example, given the same upgrade risk, an upgrade that resolves one or two major (severe) vulnerabilities receives a better risk-benefit score than an upgrade that resolves three or four relatively minor vulnerabilities.

[0014] Project code that uses (e.g., has a dependency) on a third-party component is typically upgraded when there is a newer version that is “better” than the current version that is currently being used by the project code. A newer version that is better means the newer version addresses issues (e.g., vulnerabilities) present in the current version and, based on an analysis of the dependency graph, does not appear to introduce new issues. Such a version may receive a highest recommendation score (lowest risk-benefit score). Determining when to upgrade and to which version to upgrade is very time consuming for a developer. The systems and techniques described herein dramatically reduce the amount of developer time used to maintain the dependencies of a project by performing an analysis of a set of possible updates and providing an ordered subset of one or more recommended updates.

[0015] A software development project (“project”) includes project code (also referred to as source code) comprised of one or more packages. Each package has dependencies that are introduced when the source code imports (references) components in third-party libraries, such as open-source software libraries. Individual components may have multiple versions, with each version having a set of (zero or more) known vulnerabilities. Each version may have an associated set of scores including, for example, quality scores, security scores, popularity scores, activity scores, and other factors, such as number of licenses.

[0016] The systems and techniques maintain a database that includes information about multiple projects in the software development system, the packages included in each project, dependencies (e.g., third party components used by) each of the packages, vulnerabilities associated with each of the dependencies, and one or more scores associated with each of the vulnerabilities. A scheduler periodically or in response to an occurrence of a particular event, determines when an analysis of the multiple projects takes place. The particular event may include, for example, (1) publication of a new version of a third-party component used by one of the packages, (2) discovery of a new vulnerability in a dependency, or (3) a change to the project code that introduces and/or removes one or more dependencies.

[0017] As a first example, a computer-implemented method includes selecting a package in a software project and determining a set of dependencies associated with the package. The dependencies are located in third-party libraries. The method includes determining a set of upgrade candidates for a particular dependency in the set of dependencies and, based on determining that the number of upgrade candidates in the set of upgrade candidates is greater than a predetermined threshold, heuristically selecting a subset of the upgrade candidates. If the number of upgrade candidates in the set of upgrade candidates is less than or equal to the predetermined threshold, then the set of upgrade candidates is selected as the subset of upgrade candidates. The method includes determining issues associated with upgrading the package to use the upgrade candidate, emulating a state of a dependency graph associated with upgrading the package to use the upgrade candidate, determining diamond dependencies in the dependency graph associated with upgrading the package to use the upgrade candidate, determining a number of vulnerabilities addressed by upgrading the package to use the upgrade candidate, and determining a severity of vulnerabilities addressed by upgrading the package to use the upgrade candidate. The method includes determining a risk-benefit score associated with each upgrade candidate in the subset based at least

in part on: (1) the issues associated with upgrading the package to use the upgrade candidate, (2) the diamond dependencies in the dependency graph associated with upgrading the package to use the upgrade candidate, (3) the number of vulnerabilities addressed by upgrading the package to use the upgrade candidate, and (4) a severity of the vulnerabilities addressed by upgrading the package to use the upgrade candidate. The method includes prioritizing each upgrade candidate in the subset based on the associated risk-benefit score to create a prioritized subset. The method may include providing the prioritized subset to a developer associated with the package. In some cases, the method may include automatically (without human interaction) upgrading the package to use the highest priority upgrade candidate. Determining the issues associated with upgrading the package to use the upgrade candidate may include determining a number of breaking changes associated with upgrading the package to use the upgrade candidate. Determining the issues associated with upgrading the package to use the upgrade candidate may include determining an activity score indicating an amount of development activity associated with a third-party package in which the upgrade candidate is included. Determining the issues associated with upgrading the package to use the upgrade candidate may include determining a security score indicating a number of security-related issues associated with a third-party package in which the upgrade candidate is included. Determining the issues associated with upgrading the package to use the upgrade candidate may include determining a popularity score indicating an amount of usage received by a particular third-party package based at least in part on: (1) tracking source code management system metrics and (2) how many other packages have a dependency on the particular package. Determining the issues associated with upgrading the package to use the upgrade candidate may include determining a code quality score indicating how well a particular third-party package complies with best practices for code development. Determining the issues associated with upgrading the package to use the upgrade candidate may include determining a number of licenses associated with the upgrade candidate.

[0018] As a second example, a server includes one or more processors and one or more non-transitory computer readable media storing instructions executable by the one or more processors to perform various operations. The operations include selecting a package in a software project and determining a set of dependencies associated with the package. The dependencies are located in one or more third-party libraries. The operations include determining a set of upgrade candidates for a particular dependency in the set of dependencies. Based on determining that the number of upgrade candidates in the set of upgrade candidates is greater than a predetermined threshold, the operations include heuristically selecting a subset of the upgrade candidates. Based on determining that the number of upgrade candidates in the set of upgrade candidates is less than or equal to the predetermined threshold, the operations include selecting the set of upgrade candidates as the subset. The operations include selecting an upgrade candidate in the subset, determining issues associated with upgrading the package to use the upgrade candidate, emulating a state of a dependency graph associated with upgrading the package to use the upgrade candidate, determining diamond dependencies in the dependency graph associated with upgrading the package to use the upgrade candidate, determining a number of vulnerabilities addressed by upgrading the package to use the upgrade candidate, and determining a severity of vulnerabilities addressed by upgrading the package to use the upgrade candidate. The operations include determining a risk-benefit score associated with each upgrade candidate in the subset based at least in part on: (1) the issues associated with upgrading the package to use the upgrade candidate, (2) the diamond dependencies in the dependency graph associated with upgrading the package to use the upgrade candidate, (3) the number of vulnerabilities addressed by upgrading the package to use the upgrade candidate, and (4) a severity of the vulnerabilities addressed by upgrading the package to use the upgrade candidate. The operations include prioritizing each upgrade candidate in the subset based on the associated risk-benefit score to create a prioritized subset. The operations may include providing the prioritized subset to a developer associated with the package. In some cases,

the operations may include automatically (without human interaction) upgrading the package to use the highest priority upgrade candidate. Heuristically selecting the subset of the upgrade candidates may include selecting a predetermined number of early versions of the upgrade candidates and selecting a predetermined number of later versions of the upgrade candidates. The third-party libraries may include at least one open-source library. Determining the issues associated with upgrading the package to use the upgrade candidate may include determining a number of breaking changes that would result from upgrading the package to use the upgrade candidate. Determining the set of dependencies associated with the package may include ignoring test dependencies and ignoring unused dependencies. The operations may include determining a recommended upgrade candidate for each dependency in the set of dependencies across multiple projects with each project of the multiple projects including one or more packages and determining a set of upgrade candidates for the multiple projects. Determining the issues associated with upgrading the package to use the upgrade candidate may include determining a number of licenses associated with the upgrade candidate.

[0019] As a third example, one or more non-transitory computer readable media capable of storing instructions are executable by one or more processors to perform various operations. The operations include selecting a package in a software project and determining a set of dependencies associated with the package. The dependencies are located in third-party libraries. The operations include determining a set of upgrade candidates for a particular dependency in the set of dependencies. Based on determining that the number of upgrade candidates in the set of upgrade candidates is greater than a predetermined threshold, the operations include heuristically selecting a subset of the upgrade candidates. Based on determining that the number of upgrade candidates in the set of upgrade candidates is less than or equal to the predetermined threshold, the operations include selecting the set of upgrade candidates as the subset. The operations include selecting an upgrade candidate in the subset. The operations include determining issues associated with upgrading the package to use the upgrade candidate, emulating a state of a dependency graph associated with upgrading the package to use the upgrade candidate, determining diamond dependencies in the dependency graph associated with upgrading the package to use the upgrade candidate, determining a number of vulnerabilities addressed by upgrading the package to use the upgrade candidate, and determining a severity of the vulnerabilities addressed by upgrading the package to use the upgrade candidate. The operations include determining a risk-benefit score associated with each upgrade candidate in the subset based at least in part on: the issues associated with upgrading the package to use the upgrade candidate, the diamond dependencies in the dependency graph associated with upgrading the package to use the upgrade candidate, the number of vulnerabilities addressed by upgrading the package to use the upgrade candidate, and a severity of the vulnerabilities addressed by upgrading the package to use the upgrade candidate. The operations include prioritizing each upgrade candidate in the subset based on the associated risk-benefit score to create a prioritized subset. The operations may include providing the prioritized subset to a developer associated with the package. In some cases, the operations may include automatically (without human interaction) upgrading the package to use the highest priority upgrade candidate. Determining the issues associated with upgrading the package to use the upgrade candidate may include determining a number of breaking changes associated with upgrading the package to use the upgrade candidate. Determining the issues associated with upgrading the package to use the upgrade candidate may include determining an activity score indicating an amount of development activity associated with a third-party package in which the upgrade candidate is included. Determining the issues associated with upgrading the package to use the upgrade candidate may include determining a security score indicating a number of security-related issues associated with a third-party package in which the upgrade candidate is included. Determining the issues associated with upgrading the package to use the upgrade candidate may include determining a popularity score indicating an amount of usage received by a particular third-

party package based at least in part on: (1) tracking source code management system metrics and (2) how many other packages have a dependency on the particular package. Determining the issues associated with upgrading the package to use the upgrade candidate may include determining a code quality score indicating how well a particular third-party package complies with best practices for code development.

[0020] FIG. 1 is a system **100** illustrating the components and relationships within a software development system, according to some embodiments. The system **100** includes a development system **102**, project code **104**, packages **106**, dependencies **107**, and types **108**. The development system **102** includes a compiler **110**, a project binary **112** (binary code created by compiling the project code **104**), a representative project function **114**, 3rd party libraries **116**, components **118(A)**, **118(B)**, sub-component **118(C)**, component functions **120(A1)**, **120(B1)**, **120(C1)**, **120(C2)**, and relationships (dependencies) **132(1)**, **132(2)**, **132(3)**, **132(4)**. The relationships may include any type of relationship between the project function **114** and component functions **120** in the third-party libraries **116**.

[0021] The development system **102** is a software environment that allows software developers to facilitate the creation, modification, and management of the project code **104**. The project code **104** includes the source code files of the software project that may be managed using a version control system (VCS), such as Git or Mercurial.

[0022] The types **108** and dependencies **107** include metadata associated with the project code **104**. The types **108** may include information about the data types used in the project code **104**, while the dependencies **107** may include information about the other software components that the project code (**104**) relies on for its functionality.

[0023] The compiler **110** is a software tool that transforms the project code **104** into the project binary **112**. The project binary **112** is the executable form of the software project that can be run on a computer system. The representative project function **114** is a specific part of the project code **104** that performs a particular task within the software project. Typically, a project binary has multiple project functions. For ease of understanding, the representative project function **114** is used to illustrate the function of the systems and techniques,

[0024] The 3rd party libraries **116** are software components that are not developed by the project maintainers but are used within the software project to provide certain functionalities. These libraries can include components **118(A)**, **118(B)**, and sub-component **118(C)** that provide specific functionalities used by the project code **104** (and the project binary **112**).

[0025] The system **100** includes the development system **102** used by one or more programmers to create code, such as representative project code **104**. The project code **104** is also referred to as source code and is written in a high-level language. The project code **104** may include types **108** that are explicitly defined and implicitly inherited. The project code **104** includes relationships **108** that are explicitly defined and implicitly inherited. FIG. 1 is merely an example to illustrate the systems and techniques. It should be understood that in practice, the development system **102** may include multiple project code being developed and each project code, such as the representative project code **104**, may include tens or even hundreds of calls to components in third-party libraries. The development system **102** may include other project code **140** and corresponding other project binaries **142**.

[0026] A compiler **110** may be used to compile the project code **104** to create a project binary **112**. The project binary **112** may be an intermediate code (e.g., byte code) that is interpreted by a virtual machine, machine level code, or any combination thereof. The project binary **112** may implement at least one project function **114** to provide a particular type of functionality. The development system **102** may include other project code **128** and other project binaries **130** that are compiled versions of the other project code **128**. The project code **104** may include dependencies **107** that identify portions of the other project code **128** that depends on (e.g., is called by or calls) the project code **128**. The project binary **112** includes the dependencies **107**, with portions of the other

project binaries **130** depending on (e.g., called by or calling) the project binary **112**. The compiler **110** may be used to compile the other project code **140** to create the other project binaries **142**. [0027] The project function **114** makes a call to one or more components in one or more third-party libraries **116**. The one or more third-party libraries **116** may include open-source libraries or other types of libraries. Each component function **120** shown in FIG. **1** is a compiled file that is in a binary or intermediate code (e.g., bytecode) format. For illustration purposes, components **118(A)**, **118(B)**, and **118(C)** are shown in the third-party libraries **116**. However, it should be understood that these are merely examples and that the project function **114** may use hundreds or even thousands of components accessible via third-party libraries **116**. For illustration purposes, the component **118(A)** includes at least component functions **120(A1)**, **120(A2)**, the component **118(B)** includes a component function **120(B1)**, and the component **118(C)** includes sub-component function versions **120(C1)** to **120(CN)** ( $N > 0$ ).

[0028] For illustration purposes, the project function **114** has a relationship **132(1)** (a dependency) to component function **120(A1)**, a relationship **132(2)** to component function **120(B1)**, and a relationship **132(3)** to component function **120(C1)**. For example, the relationships **132** may include importing a type, making a call (from a project function to a component function), or another type of dependency. The relationships **132(1)**, **132(2)**, and **132(3)** are direct dependencies. If component function **120(A1)** has a relationship with component function **120(C1)** (as illustrated by the dotted arrow), then the project function **114** has a direct dependency to component function **120(A1)** and an indirect (also referred to as a transitive) dependency to component function **120(C1)**. Such transitive dependencies can give rise to diamond dependencies. For example, in FIG. **1**, the component function **118(A)** has a function with two versions, component function **120(A1)** (version A1) and component function **120(A2)** (version A2). Assume component functions **120(A1)** and component function **120(A2)** both have a dependency on component function **120(C1)**, as illustrated by the dotted arrows in FIG. **1**. Assume that the developer discovers an issue with component function **120(A1)** and therefore upgrades to using component function **120(A2)**. For example, the developer modifies project function **114** to call component function **120(A2)** instead of component function **120(A1)**. If the issue attributed to component function **120(A1)** is actually caused by the transitively referenced function, component function **120(C1)**, then modifying the project function **114** to use component function **120(A2)** instead of component function **120(A1)** will not resolve the issue. For this reason, the system **100** determines dependency graphs to identify diamond dependencies and provide upgrade recommendations to the developer that take into account the diamond dependencies. If the diamond dependencies were not discovered, the developer might, for example, modify project function **114** to use component function **120(A2)** instead of component function **120(A1)**, and still have the issue (e.g., vulnerability) caused by the transitively referenced function, component function **120(C1)**.

[0029] A database **122** is communicatively coupled to the development system **102**. The database **122** includes multiple projects **123** in the development system **102**, packages **124** used by each of the projects **123**, dependencies **126** associated with each of the packages **124**, and known vulnerabilities **127** associated with the dependencies **127**.

[0030] A scheduler **129** causes a recommendation engine **128** to execute periodically (e.g., at a pre-determined time interval, such as every day, every week, or the like) or in response to an occurrence of a particular event, such as discovery of a new vulnerability associated with one or more of the dependencies **126**. For each particular project of the projects **123**, the recommendation engine **128** determines the associated packages **124**. For each of the packages **124**, the recommendation engine **128** determines the associated dependencies **126**. For each particular dependency (in the dependencies **126**) associated with a particular package of the packages **124**, the recommendation engine **128** determines if the dependency is to be analyzed.

Ignoring Particular Types of Dependencies

[0031] The recommendation engine **128** may ignore certain types of direct dependencies, based on



how the recommendation engine **128** is configured. For example, the recommendation engine **128** may ignore test dependencies. A test dependency provides a test-related functionality (e.g., dump of values of local parameters or other troubleshooting-related functionality, or the like) and is used when developing the code. After code development is complete and the code is deployed, the test dependency is not present. Thus, any vulnerabilities associated with the test dependency do not matter. The recommendation engine **128** may ignore unused dependencies. An unused dependency is a dependency that is declared but not actually used in the code. Thus, the recommendation engine **128** can ignore any vulnerabilities related to an unused dependency. The recommendation engine **128** may ignore dependencies that have no vulnerabilities. In this case, even though the dependency is used, the dependency does not have any vulnerabilities. The software developer may not want to go to the trouble of upgrading the dependency because the dependency does not introduce any vulnerabilities. The configuration of the recommendation engine **128** is something that is under the control of the software developer. For example, the software developer can select “ignore test dependencies” or “ignore unused dependencies” in the settings and these selections will configure the recommendation engine **128** accordingly.

[0032] For each particular dependency (in the dependencies **126**), the recommendation engine **128** determines a set of (one or more) upgrade candidates **139**. If a number of upgrade candidates **139** satisfies a particular threshold, then the recommendation engine **128** may heuristically trim the set of upgrade candidates **139** to create a subset **140** (of upgrade candidates) to reduce the execution time. For example, the subset **140** may include component functions **120(1)** to **120(P)**, where  $0 < P \leq N$ .

#### Detect Breaking Changes

[0033] For each upgrade candidate (component functions **120(1)** to **120(P)**) in the subset **140**, the recommendation engine **128** determines whether the upgrade would cause a breaking change. The process of detecting breaking changes is described in more detail in patent application Ser. No. 18/740,976, from which this application claims priority and which is incorporated herein in its entirety by reference. Determining whether an upgrade candidate would cause a breaking change takes as input a high-level description of a vulnerability associated with an open-source component and produces as output an enriched vulnerability description that includes code-level information about affected functions and affected component versions. Based on a security advisory, the recommendation engine **128** determines an existence of a vulnerability in a function in a third-party library. For example, an artificial intelligence (AI) **146** may determine information about one of the vulnerabilities **127** in one of the functions **120** from the security advisory. The security advisory may be published by the National Vulnerability Database (NVD) or another similar organization. The recommendation engine **128** determines vulnerability data, including function versions (e.g., **120(C1)**, **120(C2)**, to **120(CN)**) associated with a particular function of the functions **120**.

[0034] The recommendation engine **128** may determine a commit history associated with the particular function (that was identified in the security advisory). Each commit includes both (1) the actual code changes, e.g., lines of code that have been added, removed, and/or changed in particular source code files, as well as (2) metadata, such as author information, a textual summary of the changes, a timestamp, other change-related information, or any combination thereof. The recommendation engine **128** may determine fix commits associated with the particular function, based on the commit history. Fix commits are a set of the particular changes (commits) that change the project's source code by fixing or otherwise resolving the vulnerability. The identification of fix commits may be done using various techniques, including using an artificial intelligence AI **146**. In some cases, the commits, which are a textual description or summary of the changes, may include either a function identifier or a description of the vulnerability, similar to what is described in vulnerability information included in the advisory. In other cases, the code changes in the third-party libraries **116** may be analyzed to determine whether a particular commit is related to the vulnerability. The set of candidate commits may be reduced by comparing commit timestamps,

publication dates of vulnerability disclosure, and the like. In some cases, additional resources may be used to identify fix commits, such as other documents that discuss or describe the vulnerability, e.g., tickets in project management software (e.g., Jira), or resources describing how to exploit the vulnerability.

[0035] The fix commits may be used to identify functions **120** affected by the vulnerability and to determine the functions **120** that have been modified to address the vulnerability by one of the commits. For example, this may be done by comparing the files before and after a change is made, using either their textual representation or using various abstractions and representations of source code, such as abstract syntax trees. In some cases, functions that are not directly related to the vulnerability may be excluded to keep the data being analyzed to a manageable amount. For example, functions **120** may be included as part of fix commits, if the developers, in addition to providing a fix for the vulnerability, performed other changes at the same time and included them in the commit, e.g., the fix commit was not limited to the vulnerability. A resulting set of functions may include both (1) the signature of the respective function, as well as (2) different representations of the functions, such as, for example, abstract syntax trees, data or control flow graphs, bytecode, and the like.

[0036] The recommendation engine **128** may perform a search to identify components and component versions that include the affected functions (e.g., functions affected by the vulnerability). The recommendation engine **128** may search downloaded packages to determine if the function affected by the vulnerability is included and if so which version of the function is included. The recommendation engine **128** may determine identifiers of package versions that include fixed or vulnerable versions of the function. For example, a search may be performed by obtaining packages from package registries (e.g., the third-party libraries **116**, such as Maven Central, npm registry, or the like) and determining whether they include the function in the vulnerable form or in a fixed form. For example, some package registries may provide a search function to facilitate performing such a search, while other package registries may be downloaded and indexed to enable the entire package registries to be searched. In some cases, the code portion of downloaded packages may be searched and compared against affected functions to determine not only whether the function is included, but whether the function is included in the vulnerable form or the fixed form (vulnerability addressed). Such a comparison may involve the source code representation, abstractions thereof (e.g., abstract syntax trees or control flow graphs), their compiled form, or any combination thereof.

[0037] The result is an enhanced vulnerability description that includes information about functions affected by one or more vulnerabilities, including their signatures as well as representations of vulnerable and fixed function bodies, e.g., the source code as found in the version control system (VCS), or other representations, depending on the programming language, as well as abstract syntax trees, control and data flow graphs, bytecode, compiled code, or any combination thereof. In some cases, the results may include identifiers of package versions that include fixed or vulnerable versions of the affected functions. Vulnerable functions within the context of software development projects may be identified by searching the commit history of an open-source project (e.g., Github) repository for fixes. In addition, vulnerability databases, such as npm and the like, that document vulnerabilities for which a fix is available, may be searched. The project code **104** in the development system **102** may be modified in such a way that the project code **104** uses the fixed versions of the function and does not use vulnerable version of the function. Thus, vulnerability databases may be augmented using various types of analysis, including reachability analysis. The recommendation engine **128** may query vulnerability databases for component names of components that include a vulnerability. In many systems, such as the Java ecosystem, code that includes a vulnerability may be copied and used in multiple components with each of the multiple components having different names. Thus, the systems and techniques search third-party libraries for code segments that include known vulnerabilities, including code segments that have been

reused in multiple components.

[0038] The recommendation engine **128** may emulate a state of a dependency graph **125** after the candidate upgrade and determine potential issues, such as diamond dependencies. A diamond dependency occurs when a current version and a newer version of a component in a third party library both have a dependency on (e.g., use) a same sub-component. If the sub-component has an issue (e.g., vulnerability), then upgrading to the newer version will not address the vulnerability.

[0039] The recommendation engine **128** determines the previously mentioned information (e.g., vulnerabilities, breaking changes, diamond dependencies, and the like) and determines the number of issues (e.g., vulnerability and the like) that will be fixed if an upgrade is performed. The recommendation engine **128** determines additional information associated with each upgrade candidate version, such as, for example, a quality score, a security score, popularity, an activity score and other factors such as licenses **158** and the like. The recommendation engine **128** combines the above information into a risk-benefit score that describes the potential improvements and potential risks if the upgrade is performed.

#### Scores

[0040] The recommendation engine **128** collects and analyzes a large amount of information associated with (1) the packages **124** (that includes the packages **106** specific to the project code **104**) and (2) the components in the third-party libraries **116** to compute scores **130**. Every open-source package and private package is scored across different characteristics to capture both the security and the operational aspects of a risk. The scores **130** include, for example, activity score **150**, popularity score **152**, security score **154**, and quality score **156**. The scores **150**, **152**, **154**, **156** provide a high-level, easy-to-understand metric associated with a particular characteristic (e.g., security, activity, popularity, and code quality) of a package.

[0041] The security score **154** indicates the number of security-related issues associated with a particular third-party (e.g., open-source) package, including known vulnerabilities, how well the package developers follow security best practices when developing the code for the package, and the results of static code analysis. Packages with a lower security score **154** have more security-related issues when compared with packages with a higher security score **154**.

[0042] The activity score **150** indicates the level of development activity associated with a particular third-party (e.g., open-source) package based on information provided by the source code management system in which the package is developed. A particular package with a higher activity score **150** has more active and is presumably better maintained as compared to a package with a lower activity score **150**.

[0043] The popularity score **152** indicates how widely (popular) a particular package is used in its ecosystem based on (1) tracking both source code management system metrics (e.g., the number of stars in GitHub) and (2) how many other packages import (have a dependency on) the particular package. Thus, a particular package with a high popularity score **152** indicates that it is more widely used and therefore probably has fewer issues compared to a package with a lower popularity score. A package with a higher popularity score **152** is used by many people and so any issues associated with the package are likely to be identified and resolved fairly quickly compared to a less popular package.

[0044] The code quality score **156** indicates how well a particular third-party (e.g., open-source) package complies with best practices for code development and includes the results of a static code analysis of that package's source code. A package with a higher quality score **156** has fewer code issues compared to a package with a lower quality score **156**.

[0045] After determining a set of upgrade candidates **139** for each of the dependencies **126**, the recommendation engine **128** uses the scores **150**, **152**, **154**, **156** to compute a risk-benefit score **134** for each upgrade candidate in the set of upgrade candidates **139**. The risk-benefit score **134** may, for example, be (i) a score between 1 and 99 (with 1 indicating a low risk/high benefit and 99 indicating a high risk/low benefit), (ii) a score between 1 and 9 (with 1 indicating a low risk/high

benefit and 9 indicating a high risk/low benefit), (iii) one of “low”, “medium”, or “high”, or (iv) another type of scoring system.

[0046] The recommendation engine **128** may create a subset **140** identifying a portion of the upgrade candidates **139** having the lowest risk-benefit scores **134**. For example, the subset **140** may include component functions **120(1)** to **120(P)** (upgrade candidates) having the N lowest risk-benefit scores ( $N > 0$ ). The upgrade candidates in the subset **140** may be ordered based on the risk-benefit scores **134** to create a prioritized subset **144**.

[0047] In some cases, the recommendation engine **128** may heuristically trim the set of candidate upgrades **139** to reduce the number of candidates under consideration, without reducing the chances of finding a best upgrade (e.g., resolves one or more major issues, such as vulnerabilities, and has a relatively low risk-benefit score and is therefore unlikely to introduce any new issues). For example, the recommendation engine **128** may spill the upgrade candidates into version ranges (e.g. version 4.5.\*, version 4.6.\*, and so on) and include the first version and the last version in the range, since it is more likely for a major improvement to be introduced early in the range or vulnerabilities getting fixed towards the end of the range. To illustrate, if there are versions 4.5.1, 4.5.2, 4.5.3, 4.5.4, 4.5.5, 4.5.6, and 4.5.7, then the first version 4.5.1 and the last version 4.5.7 may be analyzed and a risk-benefit score determined for each one prior to selecting one of them as an upgrade candidate. In this way, two candidates instead of seven candidates may be analyzed, thereby reducing the time taken and use of computational resources to identify an upgrade candidate. Of course, the number of versions selected may vary based on the total number of versions that are available. For example, if there are versions 4.5.01 to 4.5.99, then a percentage (Q %) of early versions of a component in a third-party library and a percentage (Q %) of later versions of the component may be selected for analysis. To illustrate, versions 4.5.1, 4.5.2, and 4.5.3 (e.g.,  $Q=3\%$ ) of the early versions and versions 4.5.97, 4.5.98, and 4.5.99 of the later versions may be selected for analysis. The number of versions to select is controlled by a user selectable configuration threshold.

[0048] The recommendation engine **128** may create emulations of the dependency graphs **125** that emulate a dependency graph if the individual upgrades were to be performed. The dependencies **126** are organized in a graph, with the source project as the root, a node for each dependency, and a link between node A and node B if the dependency A imports/depends on dependency B. Each version of a dependency (e.g. A@v1, A@v2) has a corresponding (different) dependency graph. If the current project uses dependency A@v1, the project's dependency graph contains, as a subset, the dependency graph of A@v1. To emulate the dependency graph after an upgrade A@v1 to A@v2, the A@v1 dependency graph is replaced with that of A@v2 and the recommendation engine **128** looks for issues. In some cases, the issues may include diamond dependencies. The recommendation engine performs an analysis to select a version that fixes issues in the direct dependency and in the transitive dependencies and avoids selecting a version that introduces a new issue (e.g., vulnerability) in the direct dependency itself or in any of the transitive dependencies.

[0049] The recommendation engine **128** selects the set of upgrade candidates **139**, e.g., a portion of the available versions, such as Q % of the first versions and Q % of the last versions. The recommendation engine **128** emulates the dependency graphs for each upgrade candidate in the set of upgrade candidates **139**, determines an associated risk-benefit score **134**, and creates the subset **140** with the component functions **120(1)** to **120(P)** (upgrade candidates) with the lowest risk-benefit scores **134**. The recommendation engine **128** orders the component functions **120(1)** to **120(P)** (upgrade candidates) based on the risk-benefit scores **134** to create the prioritized subset **144** in which the upgrade candidates are prioritized based on the risk-benefit score **134**, presenting the lowest risk upgrade candidates first.

[0050] The recommendation engine **128** may operate across multiple projects. For each project, the recommendation engine **128** determines the recommended upgrades of direct dependencies. At the end, do a global computation to find the recommended upgrade candidates across the multiple

projects. The recommendation engine **128** aligns the upgrades across the multiple projects. For example, the recommendation engine **128** may recommend upgrading project A from dependency D@v1 to D@v4. If project A were not taken into account when determining upgrades for project B, the recommendation engine **128** may recommend upgrading project B from D@v2 to D@v3. To align recommendations across multiple projects, the recommendation engine **128** may recommend upgrading to a same version (e.g., D@v4). The result is a smaller number of different versions across all projects after the upgrade (e.g., D@v4, instead of both D@v4 and D@v3).

[0051] The recommendation engine **128** generates recommendations for upgrading a single dependency at a time (e.g. upgrade D@v1 to D@v4). In some cases, upgrading a single dependency may not be possible due to conflicts with other direct dependencies. In such cases, the recommendation engine **128** may recommend upgrading multiple direct dependencies at the same time. For example, with languages such as Java, the software developer can directly upgrade a transitive dependency to a new version. The recommendation engine **128** may be configured to determine the best upgrade for a transitive dependency.

[0052] Thus, a recommendation engine may determine when to upgrade a dependency of a package to a new version and recommend which is the best version to which to upgrade. At a high-level, a dependency may be upgraded when there is a newer version that is “better”, e.g., meaning less vulnerabilities or better scores (e.g., lower risk-benefit scores) or both. Without the recommendation engine, determining when to upgrade and to which version to upgrade a dependency is very time consuming for a software developer. The recommendation engine dramatically reduces the amount of time the developer uses to maintain the dependencies of a project.

[0053] In the flow diagrams of FIGS. **2** and **3**, each block represents one or more operations that can be implemented in hardware, software, or a combination thereof. In the context of software, the blocks represent computer-executable instructions that, when executed by one or more processors, cause the processors to perform the recited operations. Generally, computer-executable instructions include routines, programs, objects, modules, components, data structures, and the like that perform particular functions or implement particular abstract data types. The order in which the blocks are described is not intended to be construed as a limitation, and any number of the described operations can be combined in any order and/or in parallel to implement the processes. The processes **200** and **300** may be implemented using various models, frameworks, systems and environments.

[0054] FIG. **2** is a process **200** to create a prioritized subset of upgrade candidates, according to some embodiments. The process **200** may be performed by the recommendation engine **128** of FIG. **1**.

[0055] At **202**, the process may select a package in a project. At **204**, the process may determine a set of dependencies (in third-party code) associated with the package. For example, in FIG. **1**, the recommendation engine **128** may select a particular package of the packages **124** and determine the dependencies **126** associated with the particular package. For example, the dependencies **126** may identify one or more components in the third-party libraries **116** that are called by code in the particular package.

[0056] At **206**, for each dependency in the set of dependencies, the process may determine a set of upgrade candidates. At **208**, if the number of update candidates in the set of upgrade candidates is greater than a threshold number, then the process may heuristically select a subset of the upgrade candidates. For example, in FIG. **1**, for each dependency in the dependencies **126**, the recommendation engine **128** may determine the set of upgrade candidates **139**. For example, the upgrade candidates **139** may include all available versions of a particular component **118** and the third-party libraries **116**. To illustrate, if the project function **114** uses the component function **120(C1)**, the set of upgrade candidates **139** may include the component functions **120(C2)** to **120(CN)**. If the recommendation engine **128** determines that the number of upgrade candidates in

the set of upgrade candidates **139** is greater than a predetermined threshold, then the recommendation engine **128** may heuristically select the subset **140**. For example, if the predetermined threshold is six and there are five upgrade candidates, then the recommendation engine **128** uses all five of the upgrade candidates as the subset **140**. If the predetermined threshold is six and there are 10 upgrade candidates (V1.1.0 to V1.1.9), then the recommendation engine **128** may heuristically select the first three versions (e.g., V1.1.0, V1.1.1, V1.1.2) and the last three versions (e.g., V1.1.7, V1.1.8, V1.1.9) for inclusion in the subset **140**.

[0057] At **210**, the process may select an upgrade candidate in the subset of upgrade candidates and determine whether upgrading would cause an issue (e.g., a breaking change). At **212**, the process may emulate a state of a dependency graph for the package if the package were modified to use the upgrade candidate. At **214**, the process may determine if there are any diamond dependencies. At **216**, the process may determine a number of vulnerabilities addressed if the package were modified to use the upgrade candidate. At **218**, the process may determine other information associated with the upgrade candidate, such as, for example, a quality score, security score, a popularity score, an activity score, a number of licenses, and the like. At **220**, the process may determine a risk-benefit score for each upgrade candidate in the subset of upgrade candidates based on the information gathered, including the state of the dependency graph, diamond dependencies, number vulnerabilities addressed, and other information (quality score, security score, popularity score, activity score, number of licenses, and the like) associated with each upgrade candidate. At **222**, the process may prioritize each upgrade candidate in the set of upgrade candidates based on the risk-benefit score and provide a prioritized subset of upgrade candidates to a code developer associated with the package. For each upgrade candidate, e.g. the component functions **120(1)** to **120(P)**, in the subset **140**, the recommendation engine **128** may determine an associated risk-benefit score **134** based on multiple factors. The risk-benefit score **134** may be determined based on determining whether upgrading to the associated component function **120** would cause an issue such as a breaking change. The risk-benefit score **134** may be determined based on emulating a state of the dependency graph **125** for the package if the package were modified to use the component function **120**. The risk-benefit score **134** may be determined based on determining if there are any diamond dependencies for the associated component function **120**. The risk-benefit score **134** may be determined based on a number of vulnerabilities addressed if the package were modified to use the upgrade candidate (component function **120**). The risk-benefit score **134** may be determined based on other information, such as a quality score **156**, a security score **154**, a popularity score **152**, an activity score **150**, a number of licenses **158**, and the like. The component functions **120** in the subset **140** may be ordered based on the risk-benefit scores **134** to create the prioritized subset **144**, with the lowest risk upgrade candidates being listed first and the highest risk upgrade candidates being listed last. The recommendation engine **128** may present the prioritized subset **144** to one or more code developers associated with the package that was analyzed to enable the code developers to make an informed decision as to which upgrade candidates to use to address as many issues (e.g., vulnerabilities) as possible and to reduce the number of additional issues introduced by using the upgrade candidates.

[0058] Thus, a project may be analyzed to determine dependencies in each particular package included in the project. The dependencies are relationships between the package and third-party libraries, such as open-source software. For example, the code in the package may call functions or import types in the third-party library. For each dependency, a recommendation engine may determine a set of upgrade candidates. If the number of upgrade candidates in the set of upgrade candidates is greater than a threshold amount, then the recommendation engine may heuristically select a subset of the upgrade candidates. For each upgrade candidate in the subset of upgrade candidates, the recommendation engine may determine various information, such as whether upgrading would cause an issue (e.g., a breaking change), determine if there are any diamond dependencies, emulate a state of a dependency graph for the package if the package were upgraded

to use the upgrade candidate, determine a number of vulnerabilities addressed if the package were to use the upgrade candidate, and determine other information, such as a quality score, a security score, popularity score, an activity score, a number of licenses, and the like. Based on the various information, the recommendation engine may determine a risk-benefit score for each upgrade candidate in the subset of upgrade candidates and prioritize each upgrade candidate based on the risk-benefit score to provide a prioritized subset to a developer associated with the package.

[0059] FIG. 3 is a process 300 to create a recommended upgrade for multiple projects, according to some embodiments. The process 300 may be performed by the recommendation engine 128 of FIG. 1.

[0060] At 302, the process determines, for each project of multiple projects, determine a set of upgrade candidates based on dependencies in the project. At 304, the process performs a global computation to identify a recommended upgrade candidate for each dependency in each project across the multiple projects. At 306, the process determines a set of upgrade candidates with a lowest (cumulative) risk-benefit score. For example, in FIG. 1, the recommendation engine 128 determines, for each project of multiple projects 123, determine the set of upgrade candidates 139 based on dependencies 126 in each of the projects 123. The recommendation engine 128 performs a global computation to identify a recommended upgrade candidate (from the set of upgrade candidates 139) for each of the dependencies 126 in each of the projects 123 across the multiple projects 123. The recommendation engine 128 determines the prioritized subset of upgrade candidates with a lowest (cumulative) risk-benefit score.

[0061] The recommendation engine 128 may operate across multiple projects. For each project, the recommendation engine 128 determines the recommended upgrades of direct dependencies. At the end, the recommendation engine 128 does a global computation to find the recommended upgrade candidates across the multiple projects. The recommendation engine 128 aligns the upgrades across the multiple projects. For example, the recommendation engine 128 may recommend upgrading project A from dependency D@v1 to D@v4. If project A were not taken into account when determining upgrades for project B, the recommendation engine 128 may recommend upgrading project B from D@v2 to D@v3. To align recommendations across multiple projects, the recommendation engine 128 may recommend upgrading to a same version (e.g., D@v4). This results in a smaller number of different versions across all projects 123 after the upgrade (e.g., D@v4, instead of both D@v4 and D@v3), making the code easier to maintain.

[0062] FIG. 4 illustrates an example configuration of a computing device that can be used to implement the systems and techniques described herein, such as hosting the development system 102 of FIG. 1 or being used to train the AI 146. The computing device 400 may include one or more processors 402 (e.g., central processing unit (CPU), graphics processing unit (GPU), AI processing units (AIPU), or any combination thereof), a memory 404, communication interfaces 406, a display device 408, other input/output (I/O) devices 410 (e.g., keyboard, trackball, and the like), and one or more mass storage devices 412 (e.g., disk drive, solid state disk drive, or the like), configured to communicate with each other, such as via one or more system buses 414 or other suitable connections. While a single system bus 414 is illustrated for case of understanding, it should be understood that the system buses 414 may include multiple buses, such as a memory device bus, a storage device bus (e.g., serial ATA (SATA) and the like), data buses (e.g., universal serial bus (USB) and the like), video signal buses (e.g., ThunderBolt®, digital video interface (DVI), High-Definition Multimedia Interface (HDMI), and the like), power buses, etc.

[0063] The processors 402 are one or more hardware devices that may include a single processing unit or a number of processing units, all of which may include single or multiple computing units or multiple cores. The processors 402 may include a GPU and/or AIPU that is integrated into the CPU or the GPU and/or AIPU may be a separate processor device from the CPU. The processors 402 may be implemented as one or more microprocessors, microcomputers, microcontrollers, digital signal processors, central processing units, graphics processing units, state machines, logic

circuitries, and/or any devices that manipulate signals based on operational instructions. Among other capabilities, the processors **402** are configured to fetch and execute computer-readable instructions stored in the memory **404**, mass storage devices **412**, and other types of non-transitory computer-readable media.

[0064] Memory **404** and mass storage devices **412** are examples of non-transitory computer storage media (e.g., memory storage devices) for storing instructions that can be executed by the processors **402** to perform the various functions described herein. For example, memory **404** may include both volatile memory and non-volatile memory (e.g., RAM, ROM, or the like) devices. Further, mass storage devices **412** may include hard disk drives, solid-state drives, removable media, including external and removable drives, memory cards, flash memory, floppy disks, optical disks (e.g., compact disc (CD), digital versatile disc (DVD)), a storage array, a network attached storage, a storage area network, or the like. Both memory **404** and mass storage devices **412** may be collectively referred to as memory or computer storage media herein and include any type of non-transitory media capable of storing computer-readable, processor-executable program instructions as computer program code that can be executed by the processors **402** as a particular machine configured for carrying out the operations and functions described in the implementations herein.

[0065] The computing device **400** may include one or more communication interfaces **406** for exchanging data via the network(s) **106**. The communication interfaces **406** can facilitate communications within a wide variety of networks and protocol types, such as a representative network **416** that may include wired networks (e.g., Ethernet, DOCSIS, DSL, Fiber, USB etc.) and wireless networks (e.g., WLAN, GSM, CDMA, 802.11, Bluetooth, Wireless USB, ZigBee, cellular, satellite, etc.), the Internet and the like. Communication interfaces **406** can also provide communication with external storage, such as a storage array, network attached storage, storage area network, cloud storage, or the like.

[0066] The display device **408** may be used for displaying content (e.g., information and images) to users. Other I/O devices **410** may be devices that receive various inputs from a user and provide various outputs to the user, and may include a keyboard, a touchpad, a mouse, a printer, audio input/output devices, and so forth.

[0067] The computer storage media, such as memory **404** and mass storage devices **412**, may be used to store software and data as shown in FIG. 4. For example, the memory **404** may be used to store the development system **102**, the database **122**, the recommendation engine **128**, the set of upgrade candidates, and the prioritized subset **144**. The computing device **400** may be connected to one or more third-party libraries **116** via one or more networks **420**.

[0068] The systems and computing devices described herein are merely examples suitable for some implementations and are not intended to suggest any limitation as to the scope of use or functionality of the environments, architectures and frameworks that can implement the processes, components and features described herein. Thus, implementations herein are operational with numerous environments or architectures, and may be implemented in general purpose and special-purpose computing systems, or other devices having processing capability. Generally, any of the functions described with reference to the figures can be implemented using software, hardware (e.g., fixed logic circuitry) or a combination of these implementations. The term “module,” “mechanism” or “component” as used herein generally represents software, hardware, or a combination of software and hardware that can be configured to implement prescribed functions. For instance, in the case of a software implementation, the term “module,” “mechanism” or “component” can represent program code (and/or declarative-type instructions) that performs specified tasks or operations when executed on a processing device or devices (e.g., CPUs or processors). The program code can be stored in one or more computer-readable memory devices or other computer storage devices. Thus, the processes, components and modules described herein may be implemented by a computer program product.



[0069] Furthermore, this disclosure provides various example implementations, as described and as illustrated in the drawings. However, this disclosure is not limited to the implementations described and illustrated herein, but can extend to other implementations, as would be known or as would become known to those skilled in the art. Reference in the specification to “one implementation,” “this implementation,” “these implementations” or “some implementations” means that a particular feature, structure, or characteristic described is included in at least one implementation, and the appearances of these phrases in various places in the specification are not necessarily all referring to the same implementation.

[0070] Although the present invention has been described in connection with several embodiments, the invention is not intended to be limited to the specific forms set forth herein. On the contrary, it is intended to cover such alternatives, modifications, and equivalents as can be reasonably included within the scope of the invention as defined by the appended claims.

## Claims

1. A computer-implemented method executed by one or more processors, the method comprising: determining a set of dependencies associated with a package in a software project, wherein individual dependencies of the set of dependencies are located in network accessible third-party libraries; determining a set of upgrade candidates for a particular dependency in the set of dependencies; based on determining that a number of upgrade candidates in the set of upgrade candidates is greater than a predetermined threshold, selecting a subset of the upgrade candidates by selecting a predetermined number of versions of the upgrade candidates; selecting an upgrade candidate in the subset of the upgrade candidates; determining issues associated with upgrading the package to use the upgrade candidate; emulating a state of a dependency graph associated with upgrading the package to use the upgrade candidate; determining diamond dependencies in the dependency graph associated with upgrading the package to use the upgrade candidate; determining a number of vulnerabilities addressed by upgrading the package to use the upgrade candidate; determining a severity of vulnerabilities addressed by upgrading the package to use the upgrade candidate; determining a risk-benefit score associated with each upgrade candidate in the subset of the upgrade candidates based at least in part on: the issues associated with upgrading the package to use the upgrade candidate; the diamond dependencies in the dependency graph associated with upgrading the package to use the upgrade candidate; the number of vulnerabilities addressed by upgrading the package to use the upgrade candidate; and the severity of the vulnerabilities addressed by upgrading the package to use the upgrade candidate; prioritizing individual upgrade candidates in the subset of the upgrade candidates based on the associated risk-benefit score to create a prioritized subset of the upgrade candidates; and providing, on a display device, the prioritized subset of the upgrade candidates to a developer associated with the package.
2. The computer-implemented method of claim 1, wherein determining the issues associated with upgrading the package to use the upgrade candidate comprises: determining a number of breaking changes associated with upgrading the package to use the upgrade candidate.
3. The computer-implemented method of claim 1, wherein determining the issues associated with upgrading the package to use the upgrade candidate comprises: determining an activity score indicating an amount of development activity associated with a third-party package in which the upgrade candidate is included.
4. The computer-implemented method of claim 1, wherein determining the issues associated with upgrading the package to use the upgrade candidate comprises: determining a security score indicating a number of security-related issues associated with a third-party package in which the upgrade candidate is included.
5. The computer-implemented method of claim 1, wherein determining the issues associated with upgrading the package to use the upgrade candidate comprises: determining a popularity score

indicating an amount of usage received by a particular third-party package based at least in part on: tracking source code management system metrics; and how many other packages have a dependency on the particular package.

**6.** The computer-implemented method of claim 1, wherein determining the issues associated with upgrading the package to use the upgrade candidate comprises: determining a code quality score indicating how well a particular third-party package complies with best practices for code development.

**7.** The computer-implemented method of claim 1, wherein determining the issues associated with upgrading the package to use the upgrade candidate comprises: determining a number of licenses associated with the upgrade candidate.

**8.** A server comprising: one or more processors; and one or more non-transitory computer readable media storing instructions executable by the one or more processors to perform operations comprising: determining a set of dependencies associated with a package in a software project, wherein individual dependencies of the set of dependencies are located in network accessible third-party libraries; determining a set of upgrade candidates for a particular dependency in the set of dependencies; based on determining that a number of upgrade candidates in the set of upgrade candidates is greater than a predetermined threshold, selecting a subset of the upgrade candidates by selecting a predetermined number of versions of the upgrade candidates; selecting an upgrade candidate in the subset of the upgrade candidates; determining issues associated with upgrading the package to use the upgrade candidate; emulating a state of a dependency graph associated with upgrading the package to use the upgrade candidate; determining diamond dependencies in the dependency graph associated with upgrading the package to use the upgrade candidate; determining a number of vulnerabilities addressed by upgrading the package to use the upgrade candidate; determining a severity of vulnerabilities addressed by upgrading the package to use the upgrade candidate; determining a risk-benefit score associated with each upgrade candidate in the subset of the upgrade candidates based at least in part on: the issues associated with upgrading the package to use the upgrade candidate; the diamond dependencies in the dependency graph associated with upgrading the package to use the upgrade candidate; the number of vulnerabilities addressed by upgrading the package to use the upgrade candidate; and the severity of the vulnerabilities addressed by upgrading the package to use the upgrade candidate; prioritizing individual upgrade candidates in the subset of the upgrade candidates based on the associated risk-benefit score to create a prioritized subset of the upgrade candidates; and providing, on a display device, the prioritized subset of the upgrade candidates to a developer associated with the package.

**9.** The server of claim 8, the operations further comprising: determining a recommended global upgrade candidate for individual dependencies in a global set of dependencies across multiple projects, with individual projects of the multiple projects including one or more packages; and determining a set of global upgrade candidates for the multiple projects.

**10.** The server of claim 9, wherein determining the set of global upgrade candidates for the multiple projects comprises: performing a global computation to identify a recommended global upgrade candidate for individual dependencies in the multiple projects.

**11.** The server of claim 9, wherein determining the set of global upgrade candidates for the multiple projects comprises: determining a set of global upgrade candidates having a lowest cumulative risk-benefit score.

**12.** The server of claim 8, wherein determining the issues associated with upgrading the package to use the upgrade candidate comprises: determining a number of breaking changes associated with upgrading the package to use the upgrade candidate; determining an activity score indicating an amount of development activity associated with a third-party package in which the upgrade candidate is included; determining a security score indicating a number of security-related issues associated with a third-party package in which the upgrade candidate is included; determining a popularity score indicating an amount of usage received by a particular third-party package based

at least in part on: tracking source code management system metrics; and how many other packages have a dependency on the particular package; or any combination thereof.

**13.** The server of claim 8, wherein determining the set of dependencies associated with the package comprises: ignoring test dependencies.

**14.** The server of claim 8, wherein determining the set of dependencies associated with the package comprises: ignoring unused dependencies.

**15.** One or more non-transitory computer readable media capable of storing instructions executable by one or more processors to perform operations comprising: determining a set of dependencies associated with a package in a software project, wherein individual dependencies of the set of dependencies are located in network accessible third-party libraries; determining a set of upgrade candidates for a particular dependency in the set of dependencies; based on determining that a number of upgrade candidates in the set of upgrade candidates is greater than a predetermined threshold, selecting a subset of the upgrade candidates by selecting a predetermined number of versions of the upgrade candidates; selecting an upgrade candidate in the subset of the upgrade candidates; determining issues associated with upgrading the package to use the upgrade candidate; emulating a state of a dependency graph associated with upgrading the package to use the upgrade candidate; determining diamond dependencies in the dependency graph associated with upgrading the package to use the upgrade candidate; determining a number of vulnerabilities addressed by upgrading the package to use the upgrade candidate; determining a severity of vulnerabilities addressed by upgrading the package to use the upgrade candidate; determining a risk-benefit score associated with each upgrade candidate in the subset of the upgrade candidates based at least in part on: the issues associated with upgrading the package to use the upgrade candidate; the diamond dependencies in the dependency graph associated with upgrading the package to use the upgrade candidate; the number of vulnerabilities addressed by upgrading the package to use the upgrade candidate; and the severity of the vulnerabilities addressed by upgrading the package to use the upgrade candidate; prioritizing individual upgrade candidates in the subset of the upgrade candidates based on the associated risk-benefit score to create a prioritized subset of the upgrade candidates; and providing, on a display device, the prioritized subset of the upgrade candidates to a developer associated with the package.

**16.** The one or more non-transitory computer readable media of claim 15, the operations further comprising: determining a recommended upgrade candidate for individual dependencies in the set of project dependencies across multiple projects, wherein individual projects of the multiple projects include one or more packages.

**17.** The one or more non-transitory computer readable media of claim 16, the operations further comprising: determining a set of global upgrade candidates for the multiple projects in the set of project dependencies.

**18.** The one or more non-transitory computer readable media of claim 17, wherein determining the set of upgrade candidates for the multiple projects comprises: determining a set of global upgrade candidates with a lowest cumulative risk-benefit score.

**19.** The one or more non-transitory computer readable media of claim 16, the operations further comprising: performing a global computation to identify a recommended global upgrade candidate for individual dependencies in the multiple projects.

**20.** The one or more non-transitory computer readable media of claim 15, wherein determining the issues associated with upgrading the package to use the upgrade candidate comprises: determining a code quality score indicating how well a particular third-party package complies with best practices for code development.

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