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(54) **OPEN-SOURCE SOFTWARE VULNERABILITY ANALYSIS**

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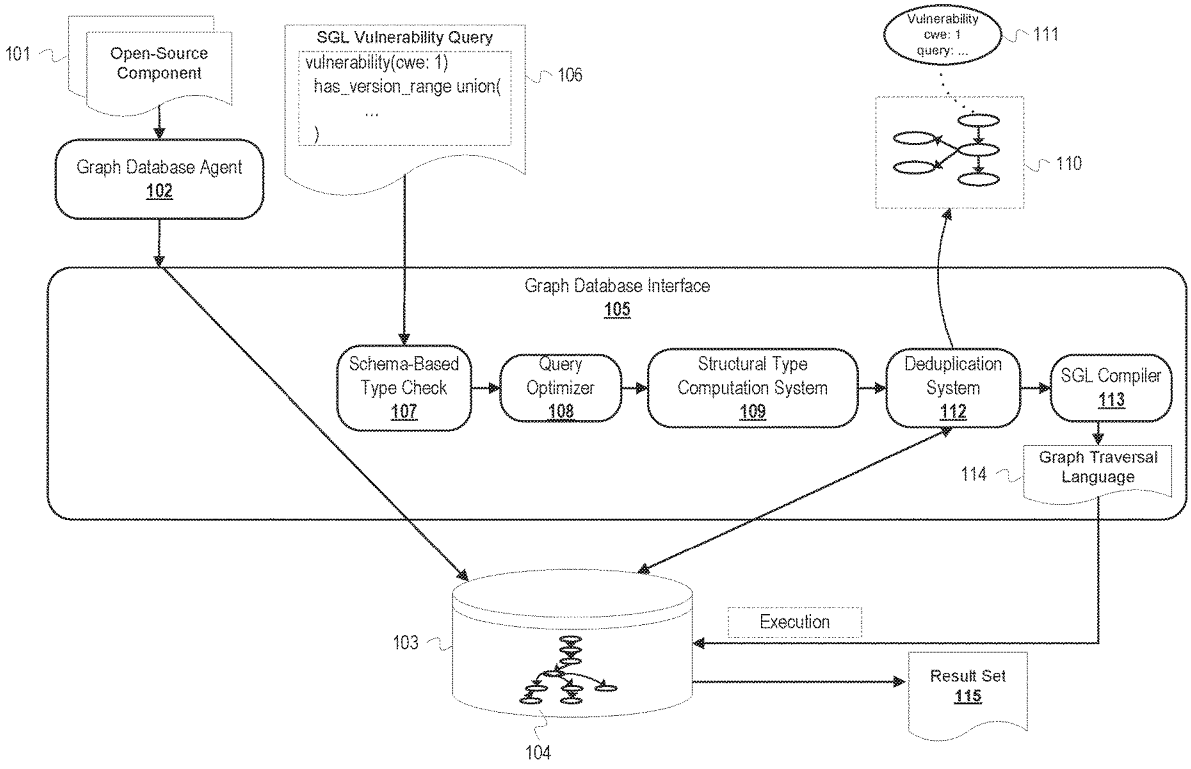
(57) **ABSTRACT**

To analyze open-source code at a large scale, a security domain graph language ("SGL") has been created that functions as a vulnerability description language and facilitates program analysis queries. The SGL facilitates building and maintaining a graph database to catalogue vulnerabilities found in open-source components. This vulnerability database generated with SGL is used for analysis of software projects which use open source components. An agent which interacts with the vulnerability database can perform a scan of a software project to identify open-source components used in the project and submit queries to the vulnerability database to identify vulnerabilities which may affect the open-source components in the project. Results of the scan are presented to a user in the form of a vulnerability report which indicates vulnerabilities that have been discovered and which open-source components the vulnerabilities affect.



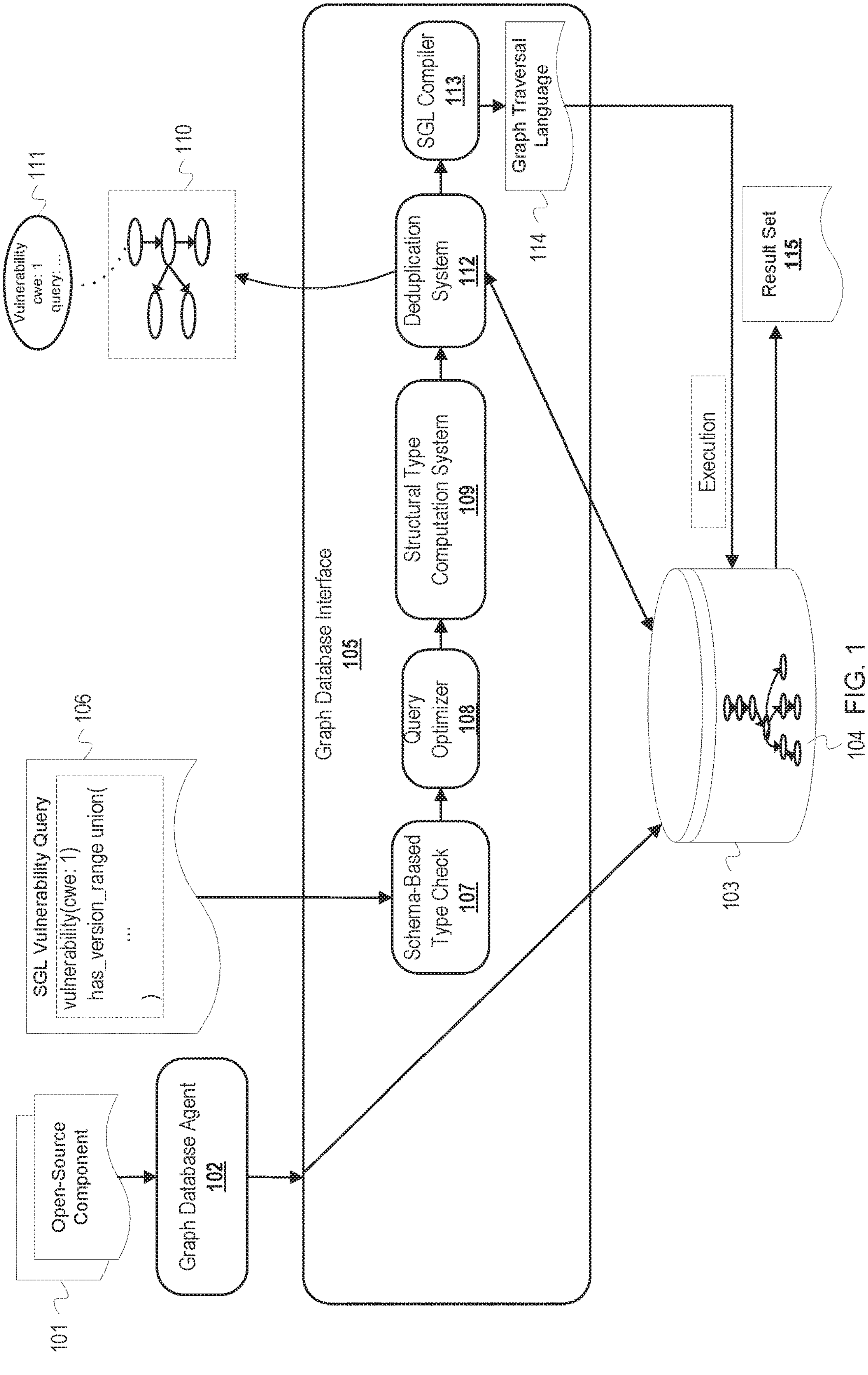

101
Open-Source Component
Graph Database Agent 102
106
SGL Vulnerability Query
vulnerability(cwe: 1)
has_version_range union(
...
)
Graph Database Interface 105
Schema-Based Type Check 107
Query Optimizer 108
Structural Type Computation System 109
Deduplication System 112
SGL Compiler 113
Graph Traversal Language
114
110
111
Vulnerability
cwe: 1
query: ...
Execution
Result Set 115
103
104

FIG. 1

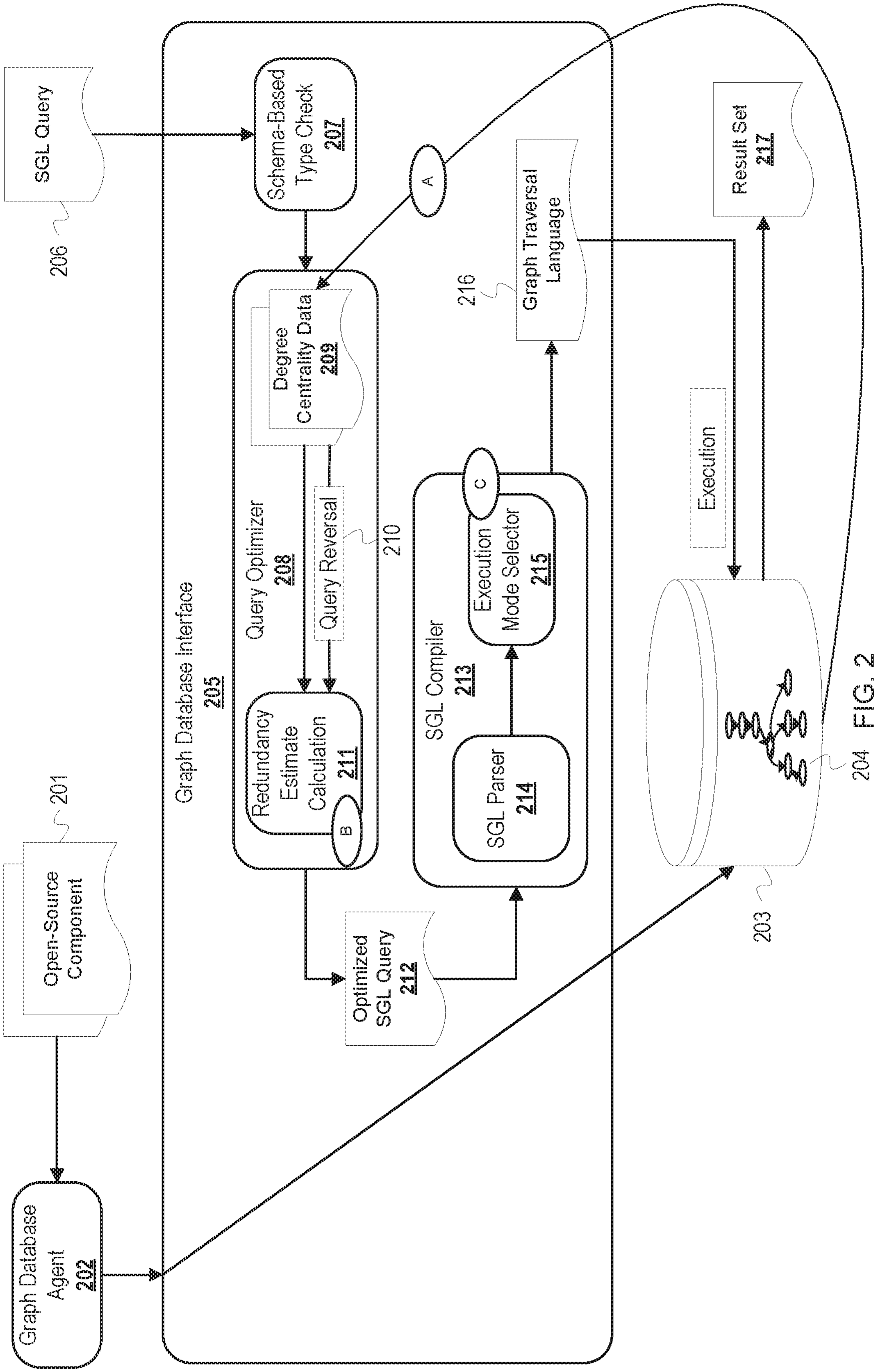

SGL Query
206
Schema-Based Type Check 207
Open-Source Component
201
Graph Database Interface 205
Query Optimizer 208
Degree Centrality Data 209
A
Query Reversal
210
Redundancy Estimate Calculation 211
B
Optimized SGL Query 212
SGL Compiler 213
SGL Parser 214
Execution Mode Selector 215
C
Graph Traversal Language
216
Execution
Result Set 217
Graph Database Agent 202
203
204

FIG. 2

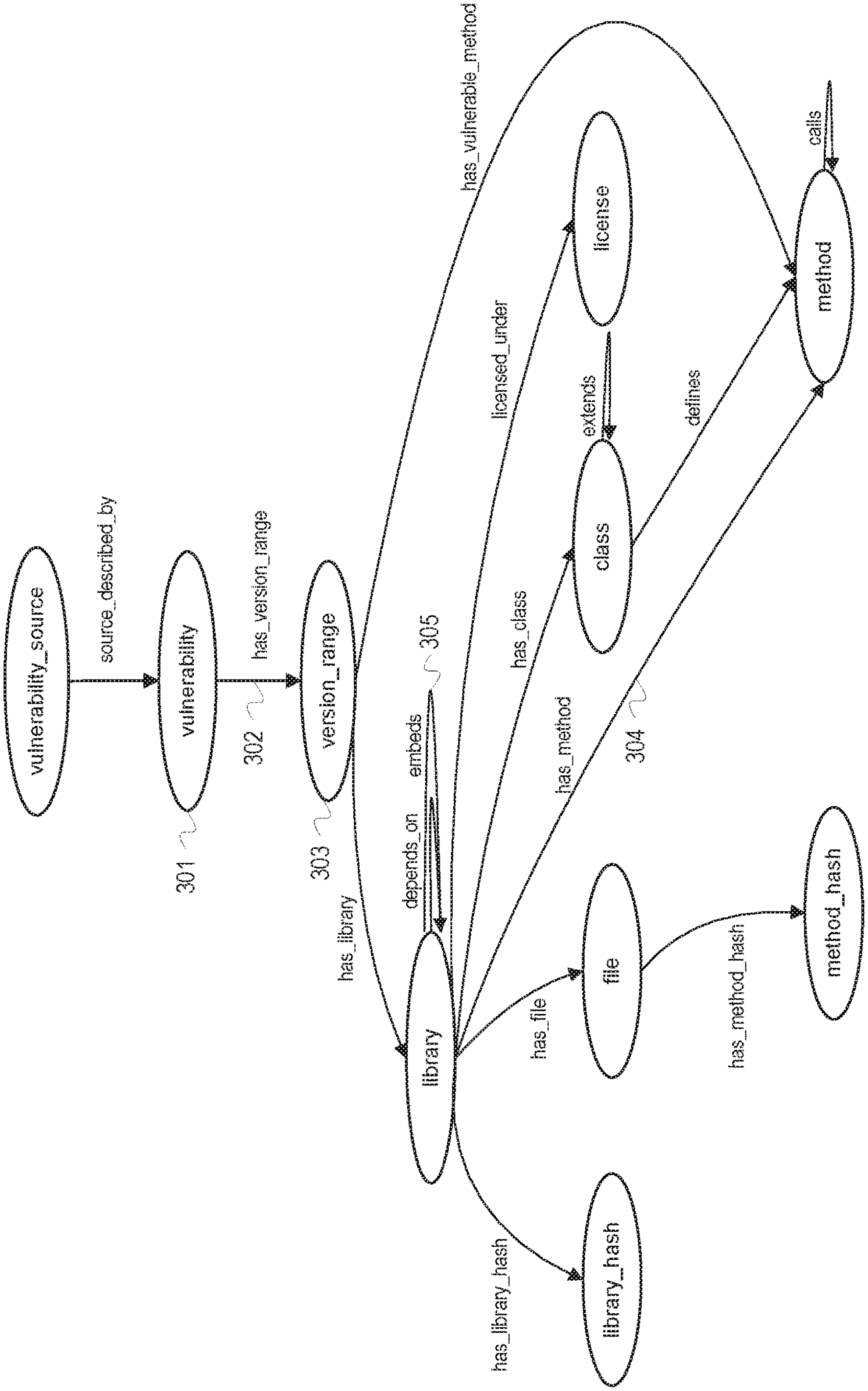

vulnerability_source
source_described_by
vulnerability
301
has_version_range
302
version_range
303
has_library
library
depends_on
embeds
305
has_vulnerable_method
licensed_under
license
has_class
class
extends
defines
has_method
304
method
calls
has_file
file
has_method_hash
method_hash
has_library_hash
library_hash

FIG. 3

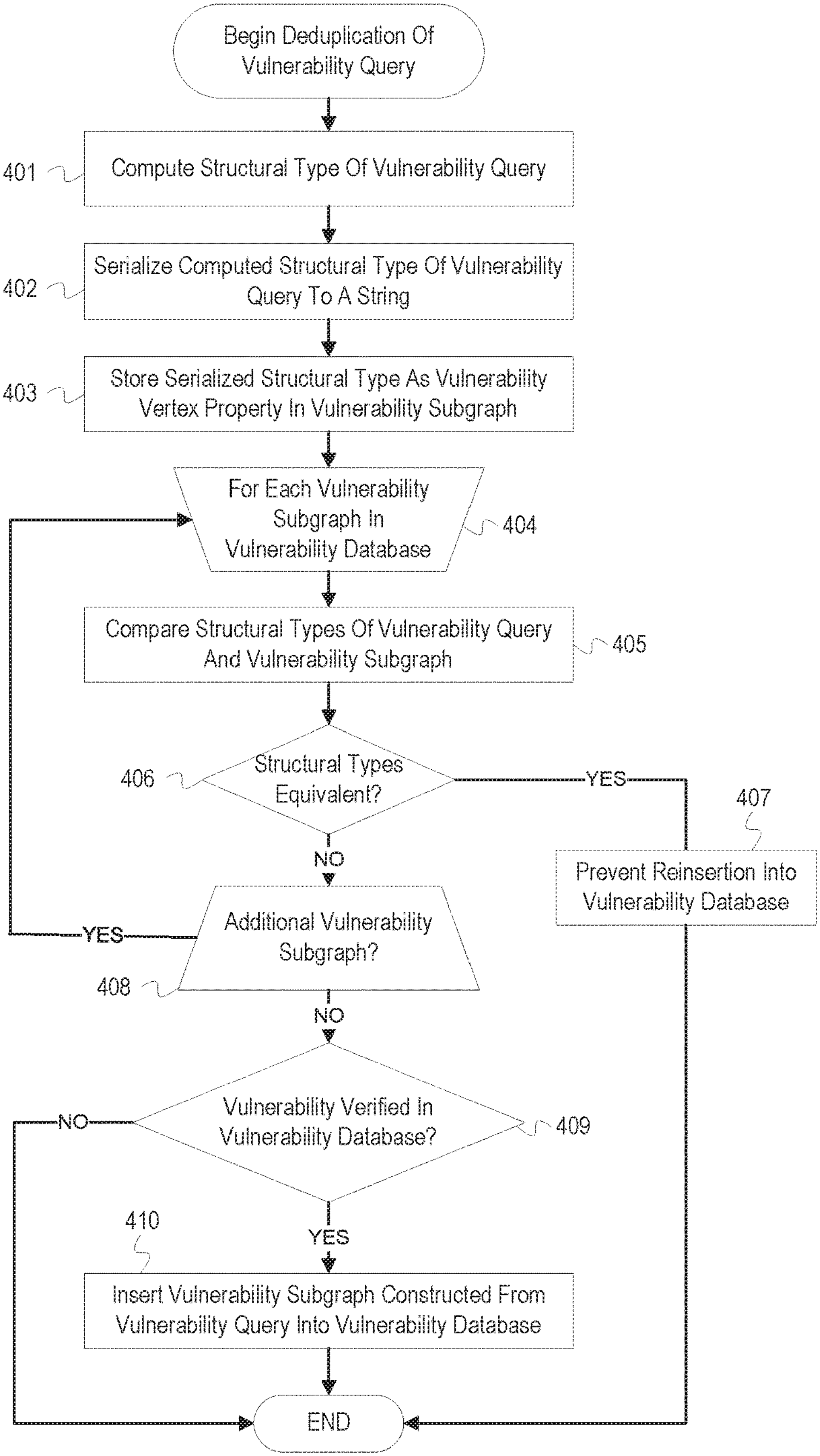

Begin Deduplication Of Vulnerability Query
401
Compute Structural Type Of Vulnerability Query
402
Serialize Computed Structural Type Of Vulnerability Query To A String
403
Store Serialized Structural Type As Vulnerability Vertex Property In Vulnerability Subgraph
For Each Vulnerability Subgraph In Vulnerability Database
404
Compare Structural Types Of Vulnerability Query And Vulnerability Subgraph
405
406
Structural Types Equivalent?
YES
407
Prevent Reinsertion Into Vulnerability Database
NO
YES
Additional Vulnerability Subgraph?
408
NO
NO
Vulnerability Verified In Vulnerability Database?
409
410
YES
Insert Vulnerability Subgraph Constructed From Vulnerability Query Into Vulnerability Database
END

FIG. 4

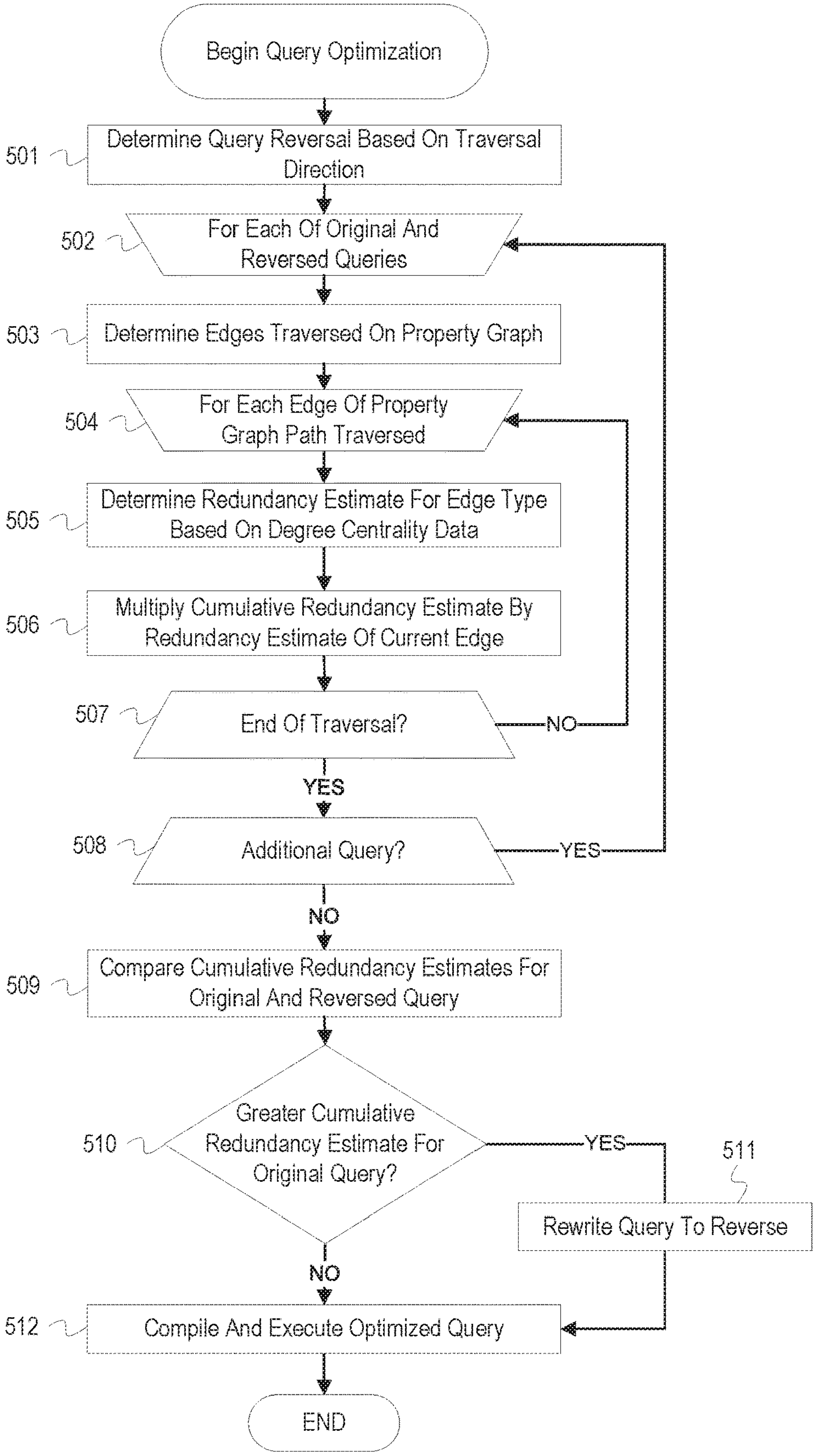

Begin Query Optimization
501
Determine Query Reversal Based On Traversal Direction
502
For Each Of Original And Reversed Queries
503
Determine Edges Traversed On Property Graph
504
For Each Edge Of Property Graph Path Traversed
505
Determine Redundancy Estimate For Edge Type Based On Degree Centrality Data
506
Multiply Cumulative Redundancy Estimate By Redundancy Estimate Of Current Edge
507
End Of Traversal?
NO
YES
508
Additional Query?
YES
NO
509
Compare Cumulative Redundancy Estimates For Original And Reversed Query
510
Greater Cumulative Redundancy Estimate For Original Query?
YES
511
Rewrite Query To Reverse
NO
512
Compile And Execute Optimized Query
END

FIG. 5

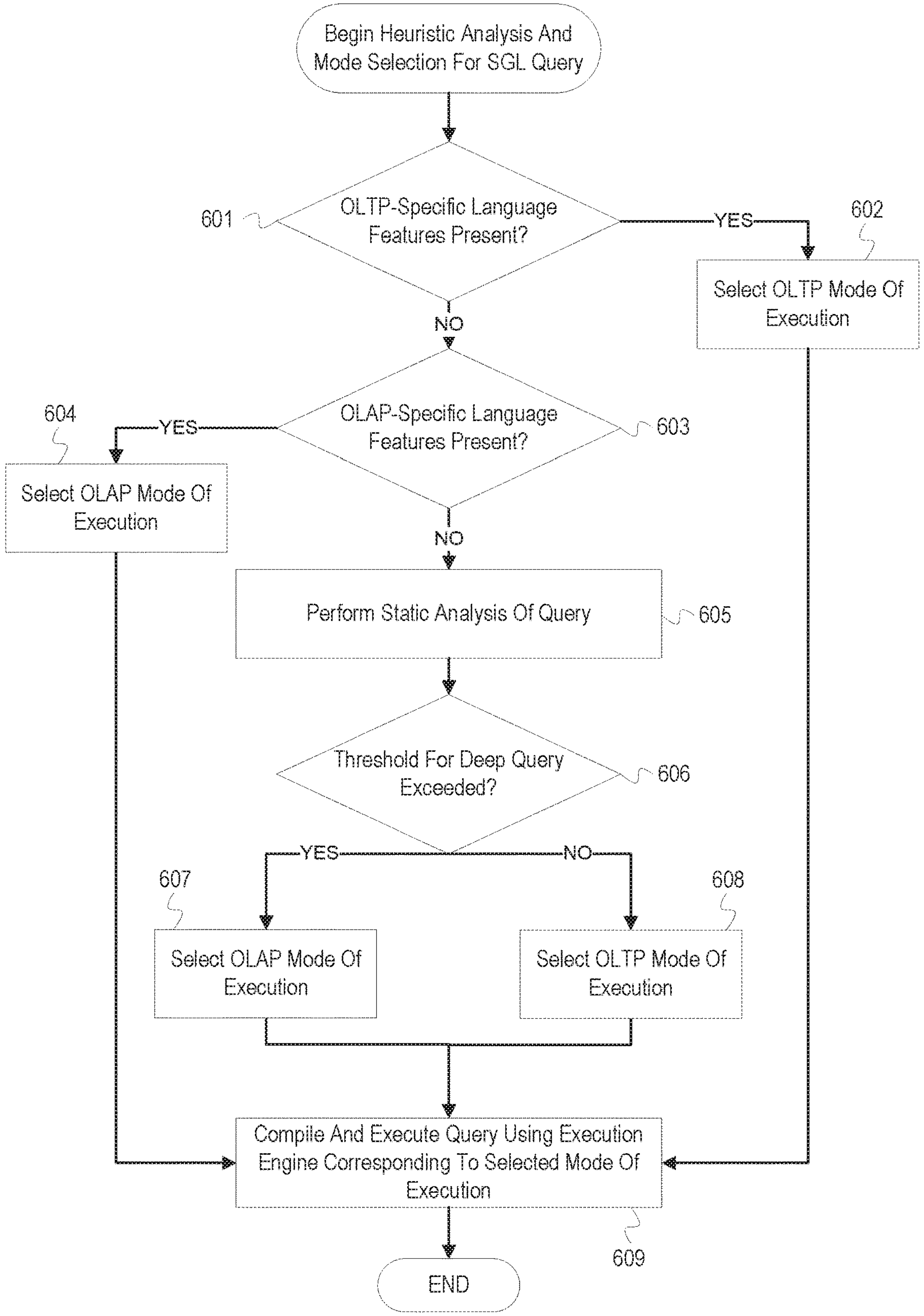

Begin Heuristic Analysis And Mode Selection For SGL Query
601
OLTP-Specific Language Features Present?
YES
602
Select OLTP Mode Of Execution
NO
604
YES
OLAP-Specific Language Features Present?
603
Select OLAP Mode Of Execution
NO
Perform Static Analysis Of Query
605
Threshold For Deep Query Exceeded?
606
YES
NO
607
608
Select OLAP Mode Of Execution
Select OLTP Mode Of Execution
Compile And Execute Query Using Execution Engine Corresponding To Selected Mode Of Execution
609
END

FIG. 6

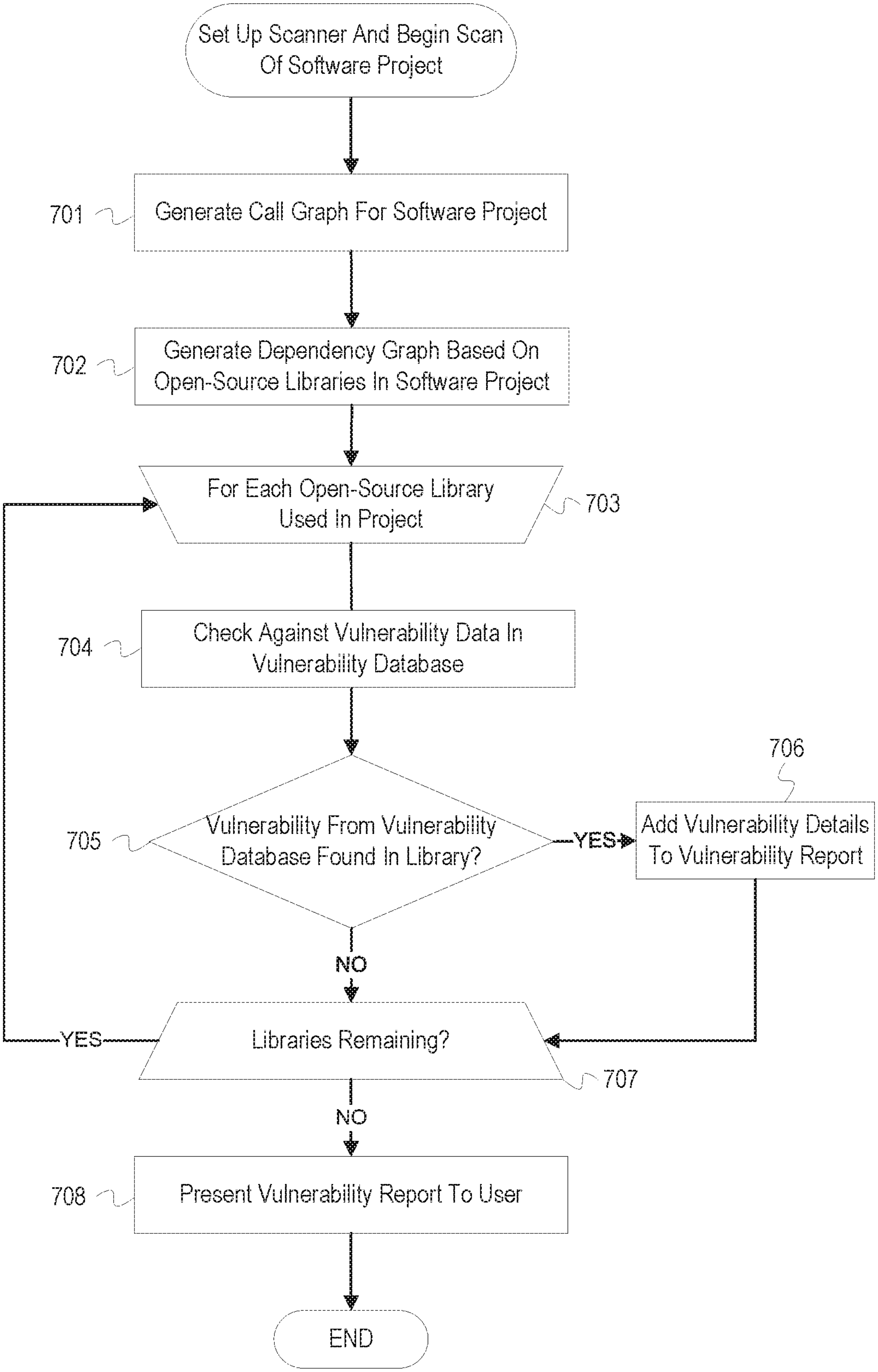

Set Up Scanner And Begin Scan Of Software Project
701
Generate Call Graph For Software Project
702
Generate Dependency Graph Based On Open-Source Libraries In Software Project
For Each Open-Source Library Used In Project
703
704
Check Against Vulnerability Data In Vulnerability Database
706
705
Vulnerability From Vulnerability Database Found In Library?
YES
Add Vulnerability Details To Vulnerability Report
NO
YES
Libraries Remaining?
707
NO
708
Present Vulnerability Report To User
END

FIG. 7

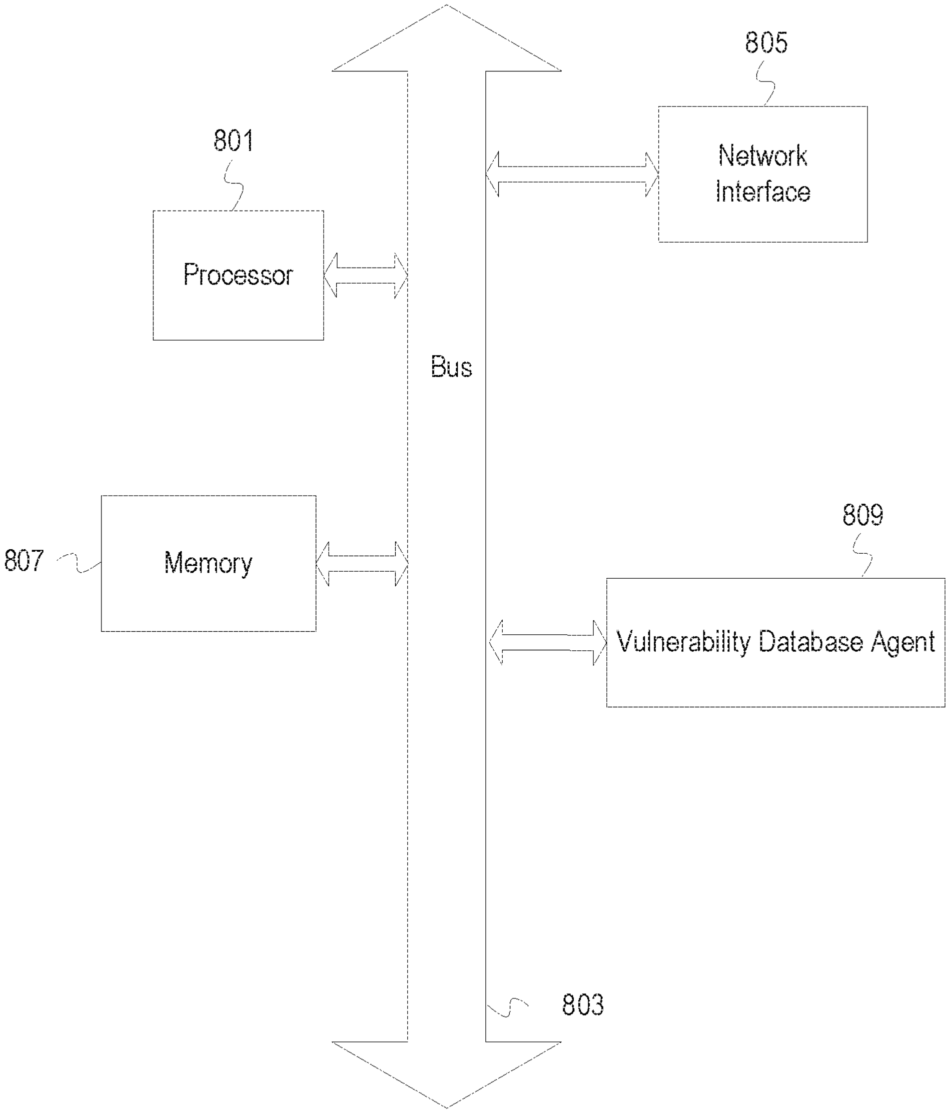

805
Network Interface
801
Processor
Bus
807
Memory
809
Vulnerability Database Agent
803

FIG. 8

OPEN-SOURCE SOFTWARE VULNERABILITY ANALYSIS

BACKGROUND

[0001] The disclosure generally relates to the field of information security, and more particularly to software development, installation, and management.

[0002] Increasingly widespread use of open-source components in software development has correspondingly propagated vulnerabilities affecting the open-source component to downstream applications. Vulnerability description languages have been developed to provide a system for discovering vulnerabilities. Vulnerability description languages can utilize vulnerability datasets that associate discovered vulnerabilities with an identifier and a description. Commonly used vulnerability datasets are centralized and may provide the identifier and description for a vulnerability in plain text.

[0003] Some domains compatible with graph computing frameworks are modeled graphically by generating a graph database representing the domain. These graph databases represent data as property graphs: with a series of vertices and edges associated with properties, where directed edges between vertices indicate relationships between entities. Some graph traversal languages enable executing queries on the graph database. Executing queries results in a traversal of the graph database generated from the original domain.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] Aspects of the disclosure may be better understood by referencing the accompanying drawings.

[0005] FIG. **1** is a conceptual diagram depicting structural type computation and automatic deduplication of an SGL vulnerability query.

[0006] FIG. **2** is a conceptual diagram depicting optimization and compilation of an SGL query for analysis of an open-source domain.

[0007] FIG. **3** depicts an example of a graph database schema for the domain of open-source libraries and vulnerabilities.

[0008] FIG. **4** is a flowchart of example operations for automatic deduplication of queries describing vulnerabilities.

[0009] FIG. **5** is a flowchart of example operations for optimizing an SGL query based on degree centrality data.

[0010] FIG. **6** is a flowchart of example operations for automatically selecting a mode of execution for an SGL query.

[0011] FIG. **7** depicts a flowchart of example operations for scanning a software project to identify open-source components and generating a vulnerability report based on results of the scan.

[0012] FIG. **8** depicts an example computer system with a vulnerability database agent which generates and submits queries to a vulnerability database to complete a vulnerability scan of a software project.

DESCRIPTION

[0013] The description that follows includes example systems, methods, techniques, and program flows that embody aspects of the disclosure. However, it is understood that this disclosure may be practiced without these specific details. In other instances, well-known instruction instances, protocols, structures and techniques have not been shown in detail in order not to obfuscate the description.

Terminology

[0014] This description uses the term "open-source component" to refer to a standalone open-source code unit (e.g., a single library file, standalone routine or subroutine, etc.) or a collection of open-source code units. A collection of open-source code units may refer to an open-source library having multiple files or a package of files (e.g., compressed collection of files).

[0015] Overview

[0016] Frequent use of open-source components in software development projects has placed an increasing number of downstream applications at risk of impact by vulnerabilities within the components. Some technologies enable graphical representation of these open-source components and analysis of the resulting graph database. However, duplicate instances of vulnerabilities may arise during documentation. Further, users of current technologies manually choose to execute queries in either a ("OLTP") mode depending on the scope of the graph database that will be accessed, which depends on the user knowing the distinctions between the different execution engines. This knowledge may not be acquired until after a test execution by the user of a query.

[0017] To analyze open-source code at a large scale, a security domain graph language ("SGL") has been created that functions as a vulnerability description language and facilitates program analysis queries. The SGL facilitates building and maintaining a graph database to catalogue vulnerabilities found in open-source components. This graphical database can be accessed via a database interface directly or accessed by an agent that interacts with the database interface. To build the graph database, a database interface processes an open-source component and creates graph structures which represent relationships present in the open-source component. The database interface transforms a vulnerability description into a canonical form based on a schema for the graph database and updates the database based on a determination of whether the vulnerability is a duplicate. This ensures quality and consistency of the vulnerability dataset maintained in the graph database.

[0018] Prior to query execution for database maintenance or project analysis, an SGL optimizer embodied in the database interface determines the optimal direction of traversal for queries with known starting and ending points based on redundancy calculations for both the query and its reverse. If the reversed traversal yields an improved performance estimate, the query is rewritten to its reverse and is subsequently executed, reducing runtime by as many as several orders of magnitude. An additional analysis before execution automatically determines if a query should be executed in OLTP or OLAP mode by implementing heuristics based on query syntax. This maintains a level of abstraction from the user by allowing the user to query the database without requiring knowledge of which language features correspond to a particular mode of execution.

[0019] The following description includes two sections which depict two distinct scenarios of SGL use cases. The first section describes creating and maintaining a graph database with SGL. The second section describes using the graph database and vulnerability database generated with SGL for analysis of software projects that use open source components.

Creation and Maintenance of a Graph Database with SGL

[0020] FIG. **1** is a conceptual diagram depicting structural type computation and automatic deduplication of an SGL vulnerability query. FIG. **1** depicts generating a graph database modeling the domain of an open-source component and maintaining the graph database by submitting verified vulnerabilities to the database. Updating the graph database with vulnerability subgraphs as vulnerabilities are identified through SGL queries provides current documentation of vulnerabilities affecting the component.

[0021] Prior to processing an SGL vulnerability query **106** from user input, a graph database agent **102** generates a graph database **103** representing the domain of an open-source component **101**. Over time, the graph database **103** scope expands with the addition of open-source repositories and/or the addition of individual open-source components. In some embodiments, a crawler searches commit databases of open-source repositories. This search of commit databases enables identification of open-source components that are not represented in the graph database **103**. The crawler ignores open-source components which are determined to be present in the graph database **103** from previous additions based on the commit database logs. The remaining open-source components can be added to the graph database **103** upon discovery by the crawler.

[0022] The open-source component **101** may have been obtained from a repository using one of a plurality of dependency management tools. The graph database **103** contains data corresponding to the open-source domain organized in an explicit schema. The explicit schema is further detailed in the description of FIG. **3**.

[0023] FIG. **3** depicts an example of a graph database schema for the domain of open-source libraries and vulnerabilities. SGL queries should conform to this explicit schema, and SGL-specific functionality follows from the use of the schema. For instance, schema knowledge allows for the computation of degree centrality data, which results in enabling some SGL queries to be rewritten to their reverse for optimization. A type check prior to query optimization and compilation ensures that SGL queries conform to the schema as to be compatible with this SGL-specific functionality.

[0024] The SGL schema organizes vertices and directed edges representing relationships between entities. For example, a vulnerability vertex **301** is connected to a version_range vertex **303** by a directed edge **302** corresponding to the relationship has version_range. In this example, the directed edge **302** indicates that the vulnerability identified by the vulnerability vertex **301** affects a certain range of versions. The versions are given in the version_range vertex **303**. Relationships further down the schema are read in a similar manner.

[0025] Edges in the schema are either many-to-one or many-to-many. Many-to-one edges are analogous to a parent-child relationship. For instance, a many-to-one edge **304** connects library and method vertices. The directed edge names a relationship where a library has a certain method, where the method is given by the method vertex. Many-to-many edges connect do not exhibit a parent-child relationship. For example, a many-to-many edge **305** connects library vertices. The directed edge names a relationship where a library embeds another library. One-to-one edges may not be present in the schema, as the vertices that the edge would connect can be combined into a single vertex.

[0026] The previously mentioned type checking of queries is done against a set of typing rules. Table 1 below depicts a subset of logical inference rules used for SGL query type checking to ensure a query comports with the explicit schema. The logical inference rules depicted in each row of Table 1 correspond to query steps start, vertex, traversal, aggregation, where, and union rules, respectively.

TABLE 1

Logical Inference Rules for Query Step Type Checking
$t_1, \ldots, t_n$: Type
start: $\{t_1, \ldots, t_n\}$
start: $\{t_1, \ldots, t_n\}$ v: $\{t, \ldots\} \rightarrow \{t\}$
start v: $\{t\}$
a: $\{t, \ldots\}$ edge: $\{t, \ldots\} \rightarrow \{u, \ldots\}$
a edge: $\{u, \ldots\}$
a: $\{\ldots\}$ count: $\{\ldots\} \rightarrow$ Int
a count: Int
a: $\{t, \ldots\}$ b: $\{t, \ldots\} \rightarrow \{u, \ldots\}$ where: $\{t, \ldots\} \rightarrow (\{t, \ldots\} \rightarrow \{u, \ldots\}) \rightarrow \{t, \ldots\}$
a where(b): $\{t, \ldots\}$
a: $\{t, \ldots\}$ x_1: $u_1, \ldots, x_n$: u_n union: $\{t, \ldots\} \rightarrow [\{t, \ldots\} \rightarrow \{u_1, \ldots\}, \ldots, \{t, \ldots\} \rightarrow \{u_n, \ldots\}] \rightarrow \{u_1, \ldots, u_n\}$
a union(b): $\{u_1, \ldots, u_n\}$

[0027] The typing rules assume the presence of an implicit start symbol at the beginning of an SGL query. The implicit start symbol corresponds to a symbol in the graph traversal language to which SGL is compiled which represents all graph vertices and has as its type the set of all vertex types of the schema.

[0028] In addition to the start rule, several examples of rules involved in SGL type checking are rules for vertex, traversal, aggregation, where, and union query steps. The vertex rule for vertex steps involves, for a vertex type t represented by the vertex step v, filtering out vertices which are not of type t. The vertex step v may be seen as a function from a set of types containing at least t to a singleton set containing only t. The traversal and aggregation rules express that both types of steps are functions from their source vertex type to a destination type, which may be either another vertex type or, in the case of a count step, an integer. The where rule expresses that the argument to the step should have the same domain type as the result of the preceding step and that the type of the preceding step is unchanged as a result of the where step. The union rule indicates that steps of multiple types may all be applied to a bag of vertices as long as the source types of the steps all appear. The result type is the union of the destination types. SGL queries which do not conform to these typing rules are not able to be executed.

[0029] Returning to FIG. **1**, the graph database **103** is organized as a property graph **104** which uses vertices and edges to indicate relationships between entities in the open-source component **101**. For instance, the property graph **104** may include a dependency graph generated from the open-source component **101**. Vertices and edges contained in the property graph are labeled with properties, or key-value pairs, where the keys are symbols from some alphabet p and the values are Java virtual machine primitives or objects. A label and property key set denotes the type of its associated vertex or edge. The graph database **103** may contain at least one vulnerability subgraph that indicates a vulnerability and details about its underlying cause, such as affected libraries, methods, and version ranges. The graph database **103** can be accessed through the graph database agent **102** or with a graph database interface **105**. The graph database interface **105** performs a schema-based type check **107** for the SGL vulnerability query **106** and also includes a query optimizer **108**, a structural type computation system **109**, a deduplication system **112**, and an SGL compiler **113**.

[0030] The SGL vulnerability query **106** describes a vulnerability that may be present in the open-source component **101** modeled by graph database **103**. The SGL vulnerability query **106** is submitted to determine whether the vulnerability should be added to the graph database **103**. Prior to executing the SGL vulnerability query **106** on the graph database **103**, the schema-based type check **107** determines if the SGL vulnerability query **106** conforms to an explicit schema corresponding to SGL typing rules. With SGL schema typing, vertex and edge types are given by a combination of their label and key from the property graph. The type of a query is given by the set of vertex and edge types which occur in its result set. If the SGL vulnerability query **106** does not conform to this explicit schema, the user should be unable to execute the query.

[0031] After checking that the SGL vulnerability query **106** conforms to the SGL schema, the query optimizer **108** optimizes the SGL vulnerability query **106**. The query optimizer **108** determines if reversing the direction of traversal on the property graph **104** will improve performance during execution. If the reversed direction of traversal is estimated to improve performance, the query optimizer **108** rewrites the SGL vulnerability query **106** to its reverse. The reverse of the SGL vulnerability query **106** is the representation of the query that yields the reversed direction of traversal identified during optimization. The optimized query which corresponds to either the SGL vulnerability query from user input or its reverse is used for the remainder of the vulnerability query deduplication, compilation, and execution process.

[0032] Vulnerability queries from user input are normalized to a canonical representation of an SGL vulnerability in order to maintain consistency in describing vulnerabilities stored in the vulnerability database. Existing centralized vulnerability databases associate instances of vulnerabilities with an assigned identifier for reference. However, the process of assigning identifiers is bottlenecked by limitations of numbering authorities, leaving some vulnerabilities without an identifier. Identifier units may also lack consistency in how they are defined. This may contribute to imprecision and false positives when determining which portions of an open-source component are vulnerable. Additionally, vulnerability representation formats are not consistently machine-readable due to a lack of standardized structure. As a result, deduplication and verification of vulnerabilities represented with these formats may be done manually to ensure accuracy.

[0033] SGL functionality described with respect to computing the structural type of vulnerability queries and cataloging vulnerabilities provides for automatic deduplication and verification. Automatic deduplication and verification are possible as a result of normalization of SGL vulnerabilities to a canonical representation for documentation in the vulnerability database. A single vertex property for a vulnerability subgraph contains a string representation of this canonical form for the vulnerability, which reduces the deduplication process to a test for string equality. Vulnerabilities are verified by checking for the presence of affected open-source attributes in the graph database, such as version ranges and libraries. The SGL vulnerability query **106** has a structural type τ that is computed with the structural type computation system **109**. The structural type computation system **109** performs a series of syntactic transformations on the SGL vulnerability query **106**. The syntactic transformation may begin by expanding bindings and expanding values in “within” predicates to their cross product. Because ordering should not matter during the structural type computation, arguments present in the transformed query may be given in lexicographical sorted order. This series of syntactic transformations generates a canonical representation of a vulnerability in SGL. This canonical representation of the SGL vulnerability query **106** is serialized to a string and stored in a query property in a vulnerability vertex **111** for a vulnerability subgraph **110** which represents the vulnerability query.

[0034] The deduplication system **112** automatically deduplicates vulnerability queries based on the structural type τ. The deduplication system **112** performs a string equality test on the serialized structural types for each vulnerability subgraph present in the graph database **103** against the serialized structural type computed for the SGL vulnerability query **106**. A positive test for equivalence indicates that the SGL vulnerability query **106** is a duplicate and prevents the duplicate vulnerability from becoming reinserted into the graph database **103**. Otherwise, the SGL vulnerability query **106** can be verified automatically to determine if its underlying cause is present in the graph database **103**.

[0035] To verify a vulnerability that is not a duplicate of a vulnerability already represented in the graph database **103**, the SGL compiler **113** compiles the SGL vulnerability query **106** to a translation or representation in the graph traversal language **114**. The graph traversal language translation **113** of the SGL vulnerability query **106** will be executed on the graph database **103** to produce the result set **115**. The result set **115** may contain a series of vertices and edges satisfying the SGL vulnerability query **106**. A non-empty result set **115** indicates that the vulnerability described by the SGL vulnerability query **106** could be verified.

[0036] If the vulnerability represented by the SGL vulnerability query **106** is verified, the user can submit the vulnerability represented by SGL vulnerability query **106** into the graph database **103**. Submitting the vulnerability inserts the vulnerability subgraph into the graph database **103**. The structural type associated with the vulnerability should be stored in the query property of the vulnerability subgraph that is inserted into the graph database **103**. Future vulnerability queries with the same structural type as the SGL vulnerability query **106** will detect the vulnerability in the graph database **103** and will thus prevent reinsertion of the vulnerability subgraph. The functionality of vulnerability verification and insertion into the graph database with SGL permits community-submitted vulnerability entries to be reflected in the graph database with a structure that is consistent throughout submissions. The graph database agent **102** can also submit vulnerability queries to the graph database interface **105** for identification and verification. Vulnerabilities discovered through agent-submitted vulnerability queries are verified and inserted into the graph database **103** as described above.

Graph Database Analysis

[0037] FIG. **2** is a conceptual diagram of optimization and compilation of an SGL query for analysis of a project that includes an open-source component. FIG. **2** depicts submitting a query for large-scale analysis to determine impact of an open-source component upon a utilizing project. For instance, SGL supports queries that enable the user to find inherited and embedded vulnerabilities stemming from an open-source component. Queries operate on a graph database which models the open-source component. The graph database may also contain documentation of vulnerabilities known to affect the open-source component. Updates to the graph database and its associated vulnerabilities occur using the process described with reference to FIG. **1**.

[0038] Prior to processing an SGL query **206**, an existing graph database agent **202** has generated a graph database **203** representing the domain of an open-source component **201**. As described with reference to FIG. **1**, the graph database may be created and/or expanded through various means, such as a crawler that searches commit databases of open-source repositories.

[0039] As also described with reference to FIG. **1**, the open-source component **201** may have been obtained from a centralized repository using one of a plurality of dependency management tools. The graph database **203** contains data corresponding to the open-source domain organized in an explicit schema. The graph database **203** is organized as a property graph **204** which represents relationships between entities in the open-source component **201** with a series of vertices and edges. For instance, the property graph **204** may in part indicate dependencies identified in the open-source component **201**. Vertices and edges contained in the property graph are labeled with properties, or key-value pairs, where the keys are symbols from some alphabet p and the values are Java virtual machine primitives or objects. A label and property key set denotes the type of its associated vertex or edge. The graph database **203** can be accessed through the graph database agent **202** or with a graph database interface **205**. The graph database interface **205** performs a schema-based type check **207** for the SGL query **206** and also includes a query optimizer **208** and an SGL compiler **213**.

[0040] The graph database agent **202** can generate a vulnerability report for a software project that uses open-source components. The graph database agent **202** performs a scan of the project to generate a call graph and dependency graph describing the software project. The graphs are used to identify the portions of the project that use open-source components. Once the open-source components in the project have been identified, the graph database agent **202** searches the graph database **203** for vulnerabilities that have been catalogued in the graph database **203** based upon the identified open-source components. The graph database agent **202** presents the user with a report listing the vulnerabilities and the affected open-source components used in the project that were found. This functionality enables users to identify vulnerable portions of the project.

[0041] To search the graph database for vulnerabilities, the graph database agent **202** generates and submits an SGL query for each of the identified open-source components used in the software project. FIG. **2** depicts the agent **202** generating and submitting the SGL query **206** for an identified open-source component. The SGL query **206** indicates an analysis of the open source component **201** to perform via traversal of the property graph **204**. For example, the SGL query **206** may indicate a search for inherited and embedded libraries based on dependencies of a vulnerable library. In some embodiments, the SGL query **206** may be obtained from user input. The SGL query **206** may have been previously written and cached ("filed") by the agent **202** to the interface **205** during an analysis scan of the graph database **203**. The graph database **203** may also contain documentation of user-submitted vulnerabilities that have been discovered in the open-source component **201** through previous vulnerability queries.

[0042] As similarly described with reference to FIG. **1**, a schema-based type check **207** determines if the SGL query **206** conforms to a particular SGL schema. With the SGL schema typing, vertex and edge types are given by a combination of their label and key from the property graph. The type of a query is given by the set of vertex or edge types which occur in its result set. Using this explicit schema with known types enables SGL to perform schema-specific operations, such as error checking and query optimization. If the SGL query does not conform to the schema, the query does not execute. Previously filed queries that have already passed type-checking would skip this evaluation. The explicit schema is further detailed in the description of FIG. **3**.

[0043] A query optimizer **208** computes and stores degree centrality data **209** from the graph database **203**. The degree centrality data **209** contains the average in-degree edge cardinality and average out-degree edge cardinality for each edge type. Prior to parsing and compiling the SGL query **206**, the query optimizer **208** determines if the query can be optimized. Queries can be optimized through reversal if the starting and ending points for the query traversal on property graph **204** are known. For instance, typical reachability queries have definite starting and ending points and therefore can be reversed. If the query can be reversed, the query optimizer **208** determines a query reversal **210**, or the traversal resulting from reversing the direction of the property graph path traversed by the SGL query **206** at execution.

[0044] The redundancy estimate calculation **211** computes an estimate of redundancy for both the SGL query **206** and the query reversal **210**. The redundancy of a query is defined as the number of vertices reachable from some starting set vs that do not eventually have a path to some ending set v_e without going back along an edge already traversed. Queries with lower redundancies exhibit faster execution times and lower memory usage. Redundancy estimates are calculated from the in-degree and out-degree averages stored in the degree centrality data **209** by calculating a cumulative product from each edge in the query's path of traversal. If the redundancy estimate calculation **211** estimates a lower redundancy for the query reversal **210**, the query optimizer **208** rewrites the SGL query **206** to its reverse.

[0045] The SGL compiler **213** includes an SGL parser **214** and an execution mode selector **215**. The SGL parser **214** parses the optimized SGL query **212**. During compile time, the execution mode selector **215** performs a syntactic analysis of the parsed query to select between the OLAP and OLTP modes of execution based on a plurality of heuristics. Heuristics are based on particular language features that are specific to either the OLAP or OLTP execution engine. For example, queries containing the construct "where" are executed in OLTP mode. Queries containing a transitive step such as "calls*" are executed in OLAP mode. If the optimized SGL query **212** does not contain any particular language features corresponding to a respective mode of execution, the execution mode selector **215** may perform a cost analysis of the query and select the mode with a lower estimated cost. For instance, though a query may be compatible with either mode of execution, a deep query yields improved performance when executed in OLAP mode. The cost analysis for queries that are potentially deep queries may include calculating the length of the succession of steps present in the query. If the length is above a certain threshold indicated by the heuristics, the query is determined to be a deep query, and the execution mode selector **215** chooses OLAP mode. After selecting a mode, the parsed query is compiled to a graph traversal language **216** and executed with the execution engine corresponding to the mode of execution selected by the execution mode selector **215**. Executing the optimized SGL query **212** that has been translated to a graph traversal language **216** produces a result set **217** as an output which contains the set of vertices and edges that satisfy the query.

[0046] FIG. **2** is annotated with a series of letters A-C. These letters represent stages of operations. Although these stages are ordered for this example, the stages illustrate one example to aid in understanding this disclosure and should not be used to limit the claims. Subject matter falling within the scope of the claims can vary with respect to the order and some of the operations.

[0047] During stage A, the query optimizer **208** uses the graph database **203** to compute the degree centrality data. The explicit schema that should be used with SGL enables computation of degree centrality data by enforcing the use of known edge types that consistently connect the same vertex types. For each type of edge in the property graph **204**, the optimizer calculates the average in-degree cardinality and the average out-degree cardinality and stores the averages corresponding to each edge type in a data structure.

[0048] Before calculating the redundancy estimate, edges are stratified into many-to-one and many-to-many categories to facilitate computation. Many-to-one edges are analogous to parent-child relationships, where traversing from the child to the parent exhibits no redundancy, as the directed edge connects to a single child vertex. Traversing many-to-one edges from the child vertex to the parent vertex is preferable to the reverse. Many-to-many edges do not exhibit this parent-child relationship. The two categories of edges in the SGL schema are depicted in FIG. **3**.

[0049] Once degree centrality data has been obtained, at stage B, the redundancy estimate calculation **211** calculates an estimated redundancy. The estimated redundancy is computed for the edges in the path traversed on the property graph **204** by the SGL query **206** in both the forward and reverse directions. The cardinalities of both the average in-degree and average out-degree are considered when calculating the redundancy. The redundancy estimate calculation **211** generates this result by multiplying average edge cardinalities on the path using the average edge cardinality corresponding to the appropriate direction of traversal.

[0050] Following the estimate calculation, the redundancy calculations for the SGL query **206** and the query reversal **210** are compared. If the query reversal **210** yields the lower estimate, the SGL query **206** is rewritten to its reverse. The reverse of the SGL query **206** is the query that, when executed, gives the property graph traversal represented by query reversal **210**. Otherwise, the SGL query **206** is unaltered. The query optimizer **208** outputs the optimized SGL query **212** to be compiled and executed, where the optimized SGL query **212** is the query corresponding to the direction of property graph traversal with a lower estimated redundancy.

[0051] Stage C occurs at compile time. At stage C, the execution mode selector **215** performs an analysis of the query syntax to determine if the optimized SGL query **212** should be executed in OLTP mode, which uses an OLTP execution engine, or OLAP mode, which uses an OLAP execution engine. The underlying graph database **203** upon which SGL is implemented supports functionality of both execution engines. This enables the execution mode selector **215** to maintain a level of abstraction from the user by automatically selecting between the two execution engines in the underlying implementation of the graph database following an analysis of the optimized SGL query **212**.

[0052] The execution mode selector **215** first performs a heuristic analysis of the syntax of the optimized SGL query **212**. The implemented heuristics indicate which of certain language features correspond to a respective mode of execution. The execution mode selector **215** should select OLTP mode if expressive constructs, such as "where," are required. The execution mode selector **215** should select OLAP mode if the optimized SGL query **212** is a scan query that does not begin at a known point or a deep query that contains a transitive step, a succession of steps with a length above a certain threshold, or an estimated accumulated cardinality that is above a certain threshold. For example, the query "library(_) count" starts at all libraries and returns the total number of libraries in the database and is thus a scan query that will be executed in OLAP mode.

[0053] If the heuristic analysis of the optimized SGL query **212** syntax does not indicate the presence of language features corresponding to a particular execution mode, the query can be executed in either mode. Deep queries that access larger subsets of the database are more appropriate for OLAP mode, and queries that utilize expressive language constructs and access a limited subset of the database are more appropriate for OLTP mode. The execution mode selector **215** performs a cost analysis to determine which mode is appropriate for the optimized SGL query **212** based on either querying being available after heuristic analysis. The cost analysis determines if the query is a deep query that should be executed in OLAP mode, as executing deep queries in OLTP mode exhibits a high cost of execution. To identify deep queries that do not contain OLAP-specific language features, the execution mode selector **215** determines a threshold for the length of a succession of steps involved in executing a query and a threshold for estimated accumulated cardinality for the query traversal. The execution mode selector **215** calculates the length of the succession of steps resulting from executing the query and/or the estimate of accumulated cardinality from the query traversal. Calculations are compared to the threshold, and if the calculated values are above the threshold, the query is considered to be a deep query that should be executed in OLAP mode. Otherwise, the query can be executed in OLTP mode without hindering performance. The execution mode selector **215** chooses the appropriate mode based on the results of the cost analysis.

[0054] In addition to building the vulnerabilities database and using it for project analysis, the vulnerabilities database can use itself to expand upon the vulnerabilities knowledge therein. In some embodiments, the graph database agent **202** performs an analysis of the graph database **203**. The analysis occurs after the graph database **203** has been generated and updated with any vulnerability subgraphs. The analysis functions as a scan of the graph database **203** without prompting the user for specific SGL queries. The graph database agent **202** files SGL queries to the graph database interface **205** which use the same SGL graph engine as queries from user input, such as SGL query **206**. The optimization and compilation processes occur as described previously.

[0055] Graph database analysis queries filed by the graph database agent **202** to the graph database interface **205** enable large-scale and comprehensive vulnerability analysis of the graph database **203**. For instance, the queries filed by the graph database agent **202** may enable a user to identify vulnerabilities similar to those that have been documented in the database based on patterns present in the catalogued vulnerabilities by generalizing vulnerability queries. For instance, keyword arguments can be added to or removed from queries for known vulnerabilities to result in identification of interactions between methods and classes that may also contain vulnerabilities. The queries filed by the graph database agent **202** may serve to find inherited and embedded vulnerabilities based on implicit dependencies. Queries can produce an estimate of the impact of known vulnerabilities in the open-source ecosystem. Queries may also yield suggestions for safe dependency upgrades if a vulnerability affecting a library is in a transitive dependency. The graph database agent **202** may additionally file queries that perform an analysis of application programming interfaces ("APIs") used in an open-source component, such as identifying uses of unsafe APIs.

Example Flowchart Illustrations

[0056] FIG. **4** depicts a flowchart of example operations for automatic deduplication of queries that describe vulnerabilities. For consistency with FIG. **1**, the description of FIG. **4** refers to a structural type computation system ("STCS") and a deduplication system performing the operations. Computation of the structural type and deduplication may occur using the optimized representation of the SGL vulnerability query.

[0057] Vulnerability queries utilize a subset of SGL in which the query may indicate vulnerability, version_range, method, and library vertices, has_version_range, has_library, and has_vulnerable_method edges, and "eq" and within" predicates. The vulnerability query begins at a vulnerability vertex. The STCS computes the structural type of the vulnerability query conforming to this subset of SGL through a series of syntactic transformations, which generates a canonical representation of a vulnerability with respect to its format for documentation in a vulnerability database (**401**). Generating the canonical representation of a vulnerability normalizes the query from user input to a standardized description of the vulnerability, which allows for automatic deduplication and verification when documenting vulnerabilities. To syntactically transform the vulnerability query, bindings are expanded. Values in "within" predicates are expanded into their cross product. For example, the SGL syntax library(within('a', 'b'), within(V, 'd')) is expanded to become four library clauses. Arguments are given in lexicographical sorted order, and order does not matter with respect to keyword arguments. The syntactically transformed query is organized as a vulnerability subgraph in accordance with the SGL schema depicted by FIG. **3** and contains vertices for the vulnerability and an affected version range, method, and set of affected libraries associated with the version range. Once the query from user input is transformed, the result is the canonical representation of the vulnerability, or the syntactic normal form of the vulnerability query. The canonical representation of the vulnerability is serialized to a string (**402**) and stored corresponding to the property "query" in the vulnerability vertex of a vulnerability subgraph containing values obtained from the vulnerability query (**403**). Computing and storing the structural type for the query facilitates automatic deduplication of vulnerabilities.

[0058] For each vulnerability subgraph in a vulnerability database containing known vulnerabilities that have been documented previously (**404**), the deduplication system compares the serialized structural type stored in the query property of the subgraph vulnerability vertex with the serialized structural type computed for the vulnerability query through a test for string equality (**405**). A string equality test is sufficient because the syntactically transformed query is the canonical representation of a vulnerability for SGL vulnerability queries conforming to the schema. If the structural types are equivalent (**406**), the deduplication system detects that the query and the subgraph represent the same vulnerability and are thus duplicates. The deduplication system prevents the vulnerability from becoming reinserted into the graph database (**407**). Otherwise, the remaining vulnerability subgraphs in the vulnerability database are tested for equivalence with respect to the vulnerability query (**408**).

[0059] If the vulnerability is not identified as representing a duplicate of a vulnerability already present in the vulnerability database, the vulnerability query can be verified to determine if the underlying cause of the vulnerability is present in the graph database (**409**). Checking for the underlying cause of the vulnerability may include searching for and identifying the affected libraries, version ranges, and methods in the graph database. If the vulnerability can be verified, the vulnerability is documented by inserting the vulnerability subgraph into the vulnerability database (**410**). Future attempts to insert the vulnerability into the vulnerability database will result in recognition that the vulnerability is already present in the vulnerability database.

[0060] FIG. **5** depicts a flowchart of example operations for optimizing an SGL query based on degree centrality data obtained from a graph database. For consistency with FIG. **2**, the description of FIG. **5** refers to a query optimizer performing the operations. Queries using a subset of SGL containing vertex steps, traversal steps, and where steps as well as predicates are eligible for optimization. Queries conforming to this subset of SGL should have a known starting and ending point so the query can be reversed based on knowledge of the organization of the SGL schema. The flowchart assumes that the query conforms to these guidelines and can therefore be optimized through reversal.

[0061] Prior to beginning the optimization process, the query optimizer determines the query reversal by identifying the reversed path of traversal on the property graph from the query's end vertex to the start vertex (**501**). The reversed path and the forward path contain the same set of vertices visited during traversal. The paths differ in that the direction of each edge is reversed in the path of the query reversal. For each of the two directions of path traversal, forward and reverse (**502**), the query optimizer determines the edge types on the path of traversal (**503**). The vertices and edges in the path of traversal are represented in the underlying property graph (i.e., schema based graph that expresses the structure independent of content). Edge types indicate relationships between the vertices they connect. For instance, the edge has_library may connect version range and library vertices. Each edge type has an associated average edge cardinality for its use as an in-degree edge and an out-degree edge. Edge cardinality averages are calculated and stored as degree centrality data prior to execution of SGL queries and after generating or updating the graph database.

[0062] For each edge and its associated type on the property graph path of traversal (**504**), the query optimizer determines the redundancy estimate for the edge based on average in-degree or out-degree edge cardinality for the particular edge type, where the redundancy estimate is the average cardinality for the given direction (**505**). The averages are obtained from the degree centrality data calculated from cardinalities found in the graph database. The degree centrality data can be calculated in advance and stored as metadata for the vulnerability database. The vulnerability database (i.e., program code that maintains the vulnerability database) can recompute the degree centrality data based on detection of changes to the property graph. The query optimizer will select between the in-degree and out-degree average for the edge according to the direction of traversal in consideration. If the current edge is the first edge in the path, the redundancy estimate for the current edge is set as the cumulative redundancy estimate product. Otherwise, the cumulative redundancy estimate is multiplied by the redundancy estimate of the current edge (**506**). The query optimizer repeats this calculation for each of the remaining edges to compute the total cumulative product for the traversal (**507**). The query optimizer computes the cumulative product estimating redundancy of property graph traversal for both the query provided by the user and its reverse traversal (**508**).

[0063] Once the cumulative redundancy estimates for the original and reverse queries have been obtained, the query optimizer compares the calculations (**509**). The lower redundancy estimate corresponds to the direction of traversal that may exhibit optimal runtime performance. If the cumulative redundancy estimate for the query provided by the user in the original direction of traversal is greater than the cumulative redundancy estimate associated with the reversed direction of traversal (**510**), the query is rewritten to its reverse (**511**). The reverse of the query is the query which will yield the reversed direction of traversal that was determined prior to redundancy estimation. Rewriting the query occurs based on knowledge of the SGL schema. The reversed query is then considered to be the optimized version of the query for the remainder of the process, and the original query is no longer considered. Otherwise, the original query remains unaltered and is chosen as the optimized representation of the query. The optimized query is compiled to an existing graph traversal language and executed on the underlying graph database (**512**).

[0064] FIG. **6** depicts a flowchart of example operations for automatically selecting a mode of execution for an SGL query based on a heuristic analysis of the query syntax. For consistency with FIG. **2**, the description of FIG. **6** refers to an execution mode selector performing the operations. If the SGL query has been optimized, references to the SGL query in the description that follows imply that the optimized query is used for the heuristic analysis.

[0065] A heuristic analysis is initially performed to determine if the SGL query syntax contains language features corresponding to either the OLAP or OLTP mode of execution. Heuristics are implemented such that the parsed query is analyzed during compilation to an existing graph traversal language. If language features corresponding to OLTP mode are detected (**601**), the execution mode selector chooses OLTP as the mode of execution (**602**). Language features corresponding to OLTP mode include expressive constructs or constructs used for simple queries that do not access large portions of the graph database, such as "union" or "where." Queries containing these OLTP-specific features are incompatible with the OLAP execution engine. Otherwise, the syntax will be examined to check if language features corresponding to OLAP are present (**603**), and if so, the execution mode selector selects OLAP as the mode of execution (**604**). Language features corresponding to OLAP mode include transitive steps or wildcard flags that indicate a scan of the database. For example, the query "library(_) count" contains a wildcard flag indicating that all libraries in the database are scanned, and the query should be executed in OLAP mode. If the query does not contain language features specific to either execution mode, the query is compatible with both execution engines and thus may be executed in either mode. Operations may be compatible with both execution engines, but the query may be more appropriate for one of the two execution modes depending on the extent of the graph database that operations indicated by the query will act upon.

[0066] To determine which mode of execution is preferable for executing the query, the execution mode selector may perform a static query analysis (**605**). The analysis estimates which of the two execution mode options will result in optimal execution. The analysis determines if the SGL query is a deep query that should be executed with the OLAP execution engine. Deep queries can be identified using a threshold for a length of a succession of steps involved with the query or for an estimate of accumulated edge cardinality. The analysis may include calculating the length of the succession of steps associated with the query or estimating the accumulated edge cardinality as a result of query traversal. The values calculated from performing the analysis are compared with a threshold predetermined by the execution mode selector. If the calculated value exceeds the threshold (**606**), the query is a deep query with a large or no depth bound, and the mode selector chooses the OLAP mode of execution (**607**). Otherwise, the query has a limited depth bound and is not a deep query, and OLTP mode is selected (**608**). Following selection of an execution mode, the SGL compiler compiles the SGL query to a graph traversal language and executes the graph traversal representation of the query with the execution engine that corresponds to the mode selected by the execution mode selector (**609**). The graph traversal language translation of the SGL query is compatible with both the graph database and the execution engine selected.

[0067] FIG. **7** depicts a flowchart of example operations for scanning a software project for open-source components and subsequently generating a vulnerability report. The vulnerability report enables a user to identify which portions of a software project contain vulnerable open-source libraries. The scan utilizes a vulnerability database containing descriptions of known vulnerabilities affecting open-source components.

[0068] After setting up a scanner and beginning a scan of a software project containing open-source components, the scanner generates a call graph from the software project (**701**). The scanner uses the call graph to identify open-source components in a project. The scanner traverses the call graph and determines whether a call is made by the project to an open source component. The scanner can analyze attribution information in the project to determine whether a call to a subroutine or routine is a call to an open source component. The scanner can also leverage the vulnerability database to concurrently determine whether the call graph indicates an open source component that has a vulnerability since the vulnerability database will return a result for an open source component with a vulnerability description. The scanner can also evaluate routine/subroutines against databases of open source components.

[0069] Based on the open-source components discovered during traversal of the call graph, the scanner determines library dependencies and generates a dependency graph depicting dependencies between open-source libraries used in the software project as well as versions of the libraries used (**702**). The dependency graph depicts both direct and indirect dependencies between libraries discovered during the scan. For example, the scanner can identify explicit dependencies by searching library declarations in a manifest file associated with the software project. The dependency graph also indicates implicit dependencies between libraries used in the project. The scanner may identify these indirect dependencies by checking for libraries which occur within other libraries. The scanner utilizes the vulnerability database to determine whether the project is impacted by vulnerabilities of the identified open source libraries. For each open-source library used in the project indicated by the dependency graph (**703**), the scanner searches the vulnerability database (**704**). To search the vulnerability database, the scanner writes a query or requests a database agent to write a query that identifies the open source library (e.g., library name and version). The vulnerability database contains information about which version ranges or methods within a library are affected by vulnerabilities. The scanner uses this information from the vulnerability database to check against the call graph and dependency graph to identify vulnerable methods and libraries used in the open-source component.

[0070] If a vulnerability documented in the vulnerability database is found to affect the library (**705**), the scanner adds an entry including a description of the vulnerability and the affected library to a vulnerability report that is generated for the project (**706**). A response to the query will include this description or elements for the description. The entry in the vulnerability report indicates an identifier of the vulnerability and the affected open-source library and version range that is used in the software project. The entry in the vulnerability report may also include results of an impact analysis of the vulnerability relative to the use of the affected open-source components in the software project. To perform an impact analysis, the scanner determines the frequency of use of the vulnerable open-source component in the software project. The scanner generates a count of the instances of use of the vulnerable open-source component within the software project. For example, a count indicating the number of times a method from a vulnerable library is used in a software project will be computed for the vulnerability affecting the library, and the count will be included in the entry for the vulnerability in the vulnerability report. If multiple code units within the software project utilize the vulnerable open-source component, the scanner will generate a count of the number of code units utilizing the vulnerable open-source component. This count is included in the entry for the vulnerability in the vulnerability report. For example, if several distinct code units utilize a method from a vulnerable library, the vulnerability report will identify the vulnerable library used and the number of code units which use it. The vulnerability report will also indicate the location of the code units within the software project. Further, the report will indicate if the vulnerability was discovered in a library exhibiting an explicit or implicit dependency as well as listing the associated dependencies. The scan continues for each of the remaining libraries. After all libraries and library versions indicated in the dependency graph have been scanned (**707**), the completed vulnerability report containing data indicating all vulnerabilities affecting the open-source components used in the software project as well as the analysis of their impact is provided for the user (**708**). The final report enables users to identify which portions of the software project are vulnerable to security threats.

[0071] FIG. **8** depicts an example computer system with a query optimizer, SGL compiler, structural type computation system, deduplication system, and vulnerability database agent. The computer system includes a processor unit **801** (possibly including multiple processors, multiple cores, multiple nodes, and/or implementing multi-threading, etc.). The computer system includes memory **807**. The memory **807** may be system memory (e.g., one or more of cache, SRAM, DRAM, zero capacitor RAM, Twin Transistor RAM, eDRAM, EDO RAM, DDR RAM, EEPROM, NRAM, RRAM, SONOS, PRAM, etc.) or any one or more of the above already described possible realizations of machine-readable media. The computer system also includes a bus **803** (e.g., PCI, ISA, PCI-Express, HyperTransport® bus, InfiniBand® bus, NuBus, etc.) and a network interface **805** (e.g., a Fiber Channel interface, an Ethernet interface, an internet small computer system interface, SONET interface, wireless interface, etc.). The system also includes a vulnerability database agent **809**. The vulnerability database agent **809** can perform a scan of a software project which uses open-source components by generating and submitting queries to a vulnerability database. The agent **809** generates a vulnerability report indicating the results of the scan. Any one of the previously described functionalities may be partially (or entirely) implemented in hardware and/or on the processor unit **801**. For example, the functionality may be implemented with an application specific integrated circuit, in logic implemented in the processor unit **801**, in a co-processor on a peripheral device or card, etc. Further, realizations may include fewer or additional components not illustrated in FIG. **8** (e.g., video cards, audio cards, additional network interfaces, peripheral devices, etc.). The processor unit **801** and the network interface **805** are coupled to the bus **803**. Although illustrated as being coupled to the bus **803**, the memory **807** may be coupled to the processor unit **801**.

[0072] The examples often refer to an "execution mode selector." The execution mode selector is a construct used to refer to implementation of functionality for selecting a graph computation engine for execution of a graph database query. This construct is utilized since numerous implementations are possible. An execution mode selector may be a particular component or components of a machine (e.g., a particular circuit card enclosed in a housing with other circuit cards/boards), machine-executable program or programs, firmware, a circuit card with circuitry configured and programmed with firmware for execution mode selection, etc. The term is used to efficiently explain content of the disclosure. The execution mode selector can also be referred to as a graph computation engine selector. Although the examples refer to operations being performed by an execution mode selector, different entities can perform different operations.

[0073] The flowcharts are provided to aid in understanding the illustrations and are not to be used to limit scope of the claims. The flowcharts depict example operations that can vary within the scope of the claims. Additional operations may be performed; fewer operations may be performed; the operations may be performed in parallel; and the operations may be performed in a different order. For example, with respect to FIG. **6**, the operations depicted in blocks **601** and **603** can be performed in parallel or concurrently. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, can be implemented by program code. The program code may be provided to a processor of a general purpose computer, special purpose computer, or other programmable machine or apparatus.

[0074] As will be appreciated, aspects of the disclosure may be embodied as a system, method or program code/instructions stored in one or more machine-readable media. Accordingly, aspects may take the form of hardware, software (including firmware, resident software, micro-code, etc.), or a combination of software and hardware aspects that may all generally be referred to herein as a "circuit," "module" or "system." The functionality presented as individual modules/units in the example illustrations can be organized differently in accordance with any one of platform (operating system and/or hardware), application ecosystem, interfaces, programmer preferences, programming language, administrator preferences, etc.

[0075] Any combination of one or more machine readable medium(s) may be utilized. The machine readable medium may be a machine readable signal medium or a machine readable storage medium. A machine readable storage medium may be, for example, but not limited to, a system, apparatus, or device, that employs any one of or combination of electronic, magnetic, optical, electromagnetic, infrared, or semiconductor technology to store program code. More specific examples (a non-exhaustive list) of the machine readable storage medium would include the following: a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), a portable compact disc read-only memory (CD-ROM), an optical storage device, a magnetic storage device, or any suitable combination of the foregoing. In the context of this document, a machine readable storage medium may be any tangible medium that can contain, or store a program for use by or in connection with an instruction execution system, apparatus, or device. A machine readable storage medium is not a machine readable signal medium.

[0076] A machine readable signal medium may include a propagated data signal with machine readable program code embodied therein, for example, in baseband or as part of a carrier wave. Such a propagated signal may take any of a variety of forms, including, but not limited to, electro-magnetic, optical, or any suitable combination thereof. A machine readable signal medium may be any machine readable medium that is not a machine readable storage medium and that can communicate, propagate, or transport a program for use by or in connection with an instruction execution system, apparatus, or device.

[0077] Program code embodied on a machine readable medium may be transmitted using any appropriate medium, including but not limited to wireless, wireline, optical fiber cable, RF, etc., or any suitable combination of the foregoing.

[0078] Computer program code for carrying out operations for aspects of the disclosure may be written in any combination of one or more programming languages, including an object oriented programming language such as the Java® programming language, C++ or the like; a dynamic programming language such as Python; a scripting language such as Perl programming language or PowerShell script language; and conventional procedural programming languages, such as the "C" programming language or similar programming languages. The program code may execute entirely on a stand-alone machine, may execute in a distributed manner across multiple machines, and may execute on one machine while providing results and or accepting input on another machine.

[0079] The program code/instructions may also be stored in a machine readable medium that can direct a machine to function in a particular manner, such that the instructions stored in the machine readable medium produce an article of manufacture including instructions which implement the function/act specified in the flowchart and/or block diagram block or blocks.

[0080] While the aspects of the disclosure are described with reference to various implementations and exploitations, it will be understood that these aspects are illustrative and that the scope of the claims is not limited to them. In general, techniques for scanning an open-source project to perform a vulnerability analysis using a database which documents vulnerabilities known to affect open-source projects as described herein may be implemented with facilities consistent with any hardware system or hardware systems. Many variations, modifications, additions, and improvements are possible.

[0081] Plural instances may be provided for components, operations or structures described herein as a single instance. Finally, boundaries between various components, operations and data stores are somewhat arbitrary, and particular operations are illustrated in the context of specific illustrative configurations. Other allocations of functionality are envisioned and may fall within the scope of the disclosure. In general, structures and functionality presented as separate components in the example configurations may be implemented as a combined structure or component. Similarly, structures and functionality presented as a single component may be implemented as separate components. These and other variations, modifications, additions, and improvements may fall within the scope of the disclosure.

[0082] Use of the phrase "at least one of" preceding a list with the conjunction "and" should not be treated as an exclusive list and should not be construed as a list of categories with one item from each category, unless specifically stated otherwise. A clause that recites "at least one of A, B, and C" can be infringed with only one of the listed items, multiple of the listed items, and one or more of the items in the list and another item not listed.

What is claimed is:

1. A method comprising:

identifying open source components used in a software project;

for each identified open source component,

generating a graph database query that indicates an identifier of the open source component and indicates a version of the open source component;

submitting the graph database query to a graph database of open source component vulnerabilities; and

generating a vulnerability report for the software project with results from the submitted graph database queries.

2. The method of claim **1** further comprising generating a call graph for the software project, wherein identifying the open source components comprises traversing the call graph.

3. The method of claim **2**, wherein identifying the open source components comprises determining for each vertex in the call graph whether open source attribution information exists in the software project.

4. The method of claim **1** further comprising generating a dependency graph indicating dependencies of code units in the software project upon each identified open source component.

5. The method of claim **4**, wherein generating the vulnerability report comprises correlating each vulnerability indicated in the results with code units of the software project based on the dependency graph.

6. The method of claim **5**, wherein generating the vulnerability report also comprises determining an impact of each identified vulnerability and indicating the impact in the vulnerability report, wherein determining the impact of each identified vulnerability comprises determining frequency of use of the open source component corresponding to the identified vulnerability and number of different code units of the software project that use the open source component corresponding to the identified vulnerability.

7. The method of claim **1** further comprising distinguishing between code units with direct dependencies upon an open source component corresponding to a vulnerability indicated in the results and code units with indirect dependencies upon an open source component corresponding to a vulnerability indicated in the results.

8. The method of claim **1**, wherein an open source component is an open source library.

9. The method of claim **1**, wherein generating the graph database query comprises generating the graph database query according to a schema of the graph database that indicates a graph structure comprising a first vertex to represent a vulnerability source, a second vertex to represent a vulnerability, a third vertex to indicate a software component version or version range, a plurality of vertices to represent different types of software components, and edges among the vertices to indicate types of relationships among the vertices.

10. A non-transitory, computer-readable medium having instructions stored thereon that are executable by a computing device to perform operations comprising:

identifying a set of one or more open source libraries used in a software project;

for each of the set of open source libraries,

generating a graph database query that indicates an identifier of the open source library and that indicates a version of the open source library;

submitting the graph database query to a graph database of open source vulnerabilities; and

generating a vulnerability report for the software project with results from the submitted graph database queries.

11. The non-transitory, computer-readable medium of claim **10**, wherein the operations further comprise generating a call graph for the software project, wherein identifying the set of one or more open source libraries comprises traversing the call graph.

12. The non-transitory, computer-readable medium of claim **11**, wherein identifying the set of one or more open source libraries comprises determining open source attribution information based on traversing the call graph.

13. The non-transitory, computer-readable medium of claim **10**, wherein the operations further comprise determining dependencies upon the set of one or more open source libraries.

14. The non-transitory, computer-readable medium of claim **13**, wherein generating the vulnerability report comprises correlating each vulnerability indicated in the results with code units of the software project based on the dependencies.

15. The non-transitory, computer-readable medium of claim **14**, wherein generating the vulnerability report also comprises determining an impact of each identified vulnerability and indicating the impact in the vulnerability report.

16. The non-transitory, computer-readable medium of claim **15**, wherein determining the impact of each identified vulnerability comprises determining at least one of frequency of use of the open source library corresponding to the identified vulnerability and number of different code units of the software project that use the open source library corresponding to the identified vulnerability.

17. An apparatus comprising:

a processor; and

a machine-readable medium having program code stored therein, the program code executable by the processor to cause the apparatus to,

scan a software project to identify each open source component used in the software project and dependencies upon each open source component;

for each open source component identified,

generate a graph database query that indicates an identifier of the open source component;

submit the graph database query to begin traversal of a subgraph of a graph database of open source vulnerabilities from a vertex that indicates the identifier of the open source component; and

generate vulnerability information with results from the submitted graph database queries.

18. The apparatus of claim **17**, wherein the program code to generate the graph database query comprises program code to generate the graph database query to also indicate a version of the open source component.

19. The apparatus of claim **17**, wherein the program code to generate the vulnerability information comprises program code to indicate correspondence between code units of the software project and vulnerability descriptions from the results based on the dependencies.

20. The apparatus of claim **17**, wherein the program code to generate the graph database query comprises program code to generate the graph database query in accordance with a graph database schema that includes vertices at least representing different types of software components, a vulnerability, and a vulnerability source and that includes edges representing different types of relationships among vertices.

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