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(54) **OPTIMIZING GRAPH QUERIES BY PERFORMING EARLY PRUNING**

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(57) **ABSTRACT**

Techniques are described herein for early pruning of potential graph query results. Specifically, based on determining that property values of a path through graph data cannot affect results of a query, the path is pruned from a set of potential query solutions prior to fully exploring the path. Early solution pruning is performed on prunable queries that project prunable functions including MIN, MAX, SUM, and DISTINCT, the results of which are not tied to a number of paths explored for query execution. A database system implements early solution pruning for a prunable query based on intermediate results maintained for the query during query execution. Specifically, when a system determines that property values of a given potential solution path cannot affect the query results reflected in intermediate results maintained for the query, the path is discarded from the set of possible query solutions without further exploration of the path.

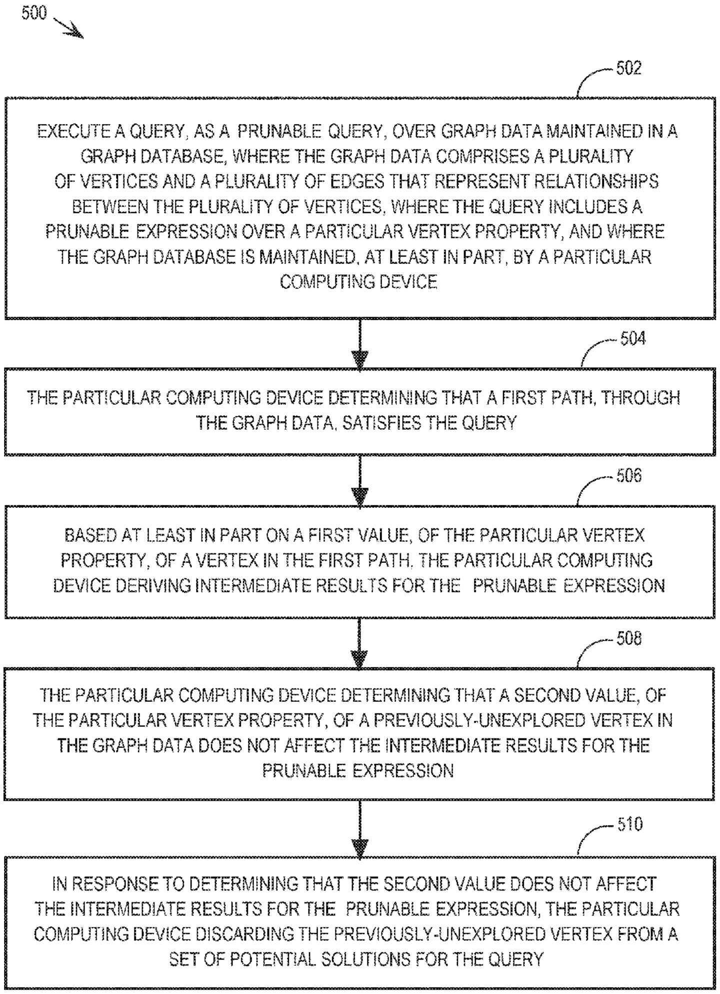

500
502
EXECUTE A QUERY, AS A PRUNABLE QUERY, OVER GRAPH DATA MAINTAINED IN A GRAPH DATABASE, WHERE THE GRAPH DATA COMPRISES A PLURALITY OF VERTICES AND A PLURALITY OF EDGES THAT REPRESENT RELATIONSHIPS BETWEEN THE PLURALITY OF VERTICES, WHERE THE QUERY INCLUDES A PRUNABLE EXPRESSION OVER A PARTICULAR VERTEX PROPERTY, AND WHERE THE GRAPH DATABASE IS MAINTAINED, AT LEAST IN PART, BY A PARTICULAR COMPUTING DEVICE
504
THE PARTICULAR COMPUTING DEVICE DETERMINING THAT A FIRST PATH, THROUGH THE GRAPH DATA, SATISFIES THE QUERY
506
BASED AT LEAST IN PART ON A FIRST VALUE, OF THE PARTICULAR VERTEX PROPERTY, OF A VERTEX IN THE FIRST PATH, THE PARTICULAR COMPUTING DEVICE DERIVING INTERMEDIATE RESULTS FOR THE PRUNABLE EXPRESSION
508
THE PARTICULAR COMPUTING DEVICE DETERMINING THAT A SECOND VALUE, OF THE PARTICULAR VERTEX PROPERTY, OF A PREVIOUSLY-UNEXPLORED VERTEX IN THE GRAPH DATA DOES NOT AFFECT THE INTERMEDIATE RESULTS FOR THE PRUNABLE EXPRESSION
510
IN RESPONSE TO DETERMINING THAT THE SECOND VALUE DOES NOT AFFECT THE INTERMEDIATE RESULTS FOR THE PRUNABLE EXPRESSION, THE PARTICULAR COMPUTING DEVICE DISCARDING THE PREVIOUSLY-UNEXPLORED VERTEX FROM A SET OF POTENTIAL SOLUTIONS FOR THE QUERY

FIG. 1

Query 100

```
SELECT MAX(a.age) MATCH (a)->(b) WHERE b.age > 40
```

Query 102

```
SELECT a.age, b.age, MIN(c.age), d.age MATCH
                (a)->(b)->(c)->(d) WHERE d.age > 40
```

Query 104

```
SELECT MAX(a.age), SUM(b.age), 42 MATCH (a)->(b)->(c)
               WHERE c.age > 40
```

FIG. 2

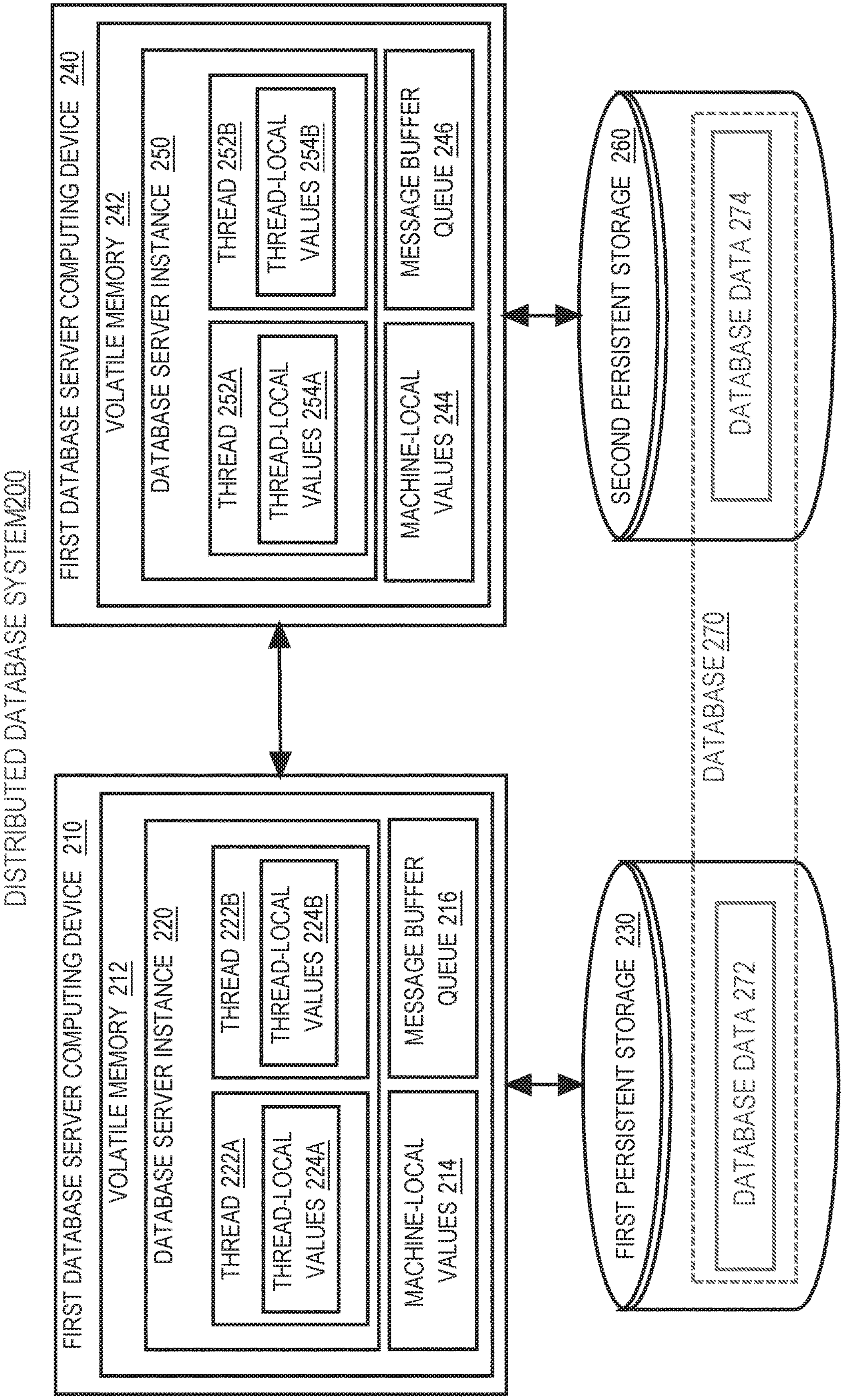

DISTRIBUTED DATABASE SYSTEM200
FIRST DATABASE SERVER COMPUTING DEVICE 240
VOLATILE MEMORY 242
DATABASE SERVER INSTANCE 250
THREAD 252A
THREAD-LOCAL VALUES 254A
THREAD 252B
THREAD-LOCAL VALUES 254B
MACHINE-LOCAL VALUES 244
MESSAGE BUFFER QUEUE 246
SECOND PERSISTENT STORAGE 260
DATABASE DATA 274
DATABASE 270
FIRST DATABASE SERVER COMPUTING DEVICE 210
VOLATILE MEMORY 212
DATABASE SERVER INSTANCE 220
THREAD 222A
THREAD-LOCAL VALUES 224A
THREAD 222B
THREAD-LOCAL VALUES 224B
MACHINE-LOCAL VALUES 214
MESSAGE BUFFER QUEUE 216
FIRST PERSISTENT STORAGE 230
DATABASE DATA 272

FIG. 3

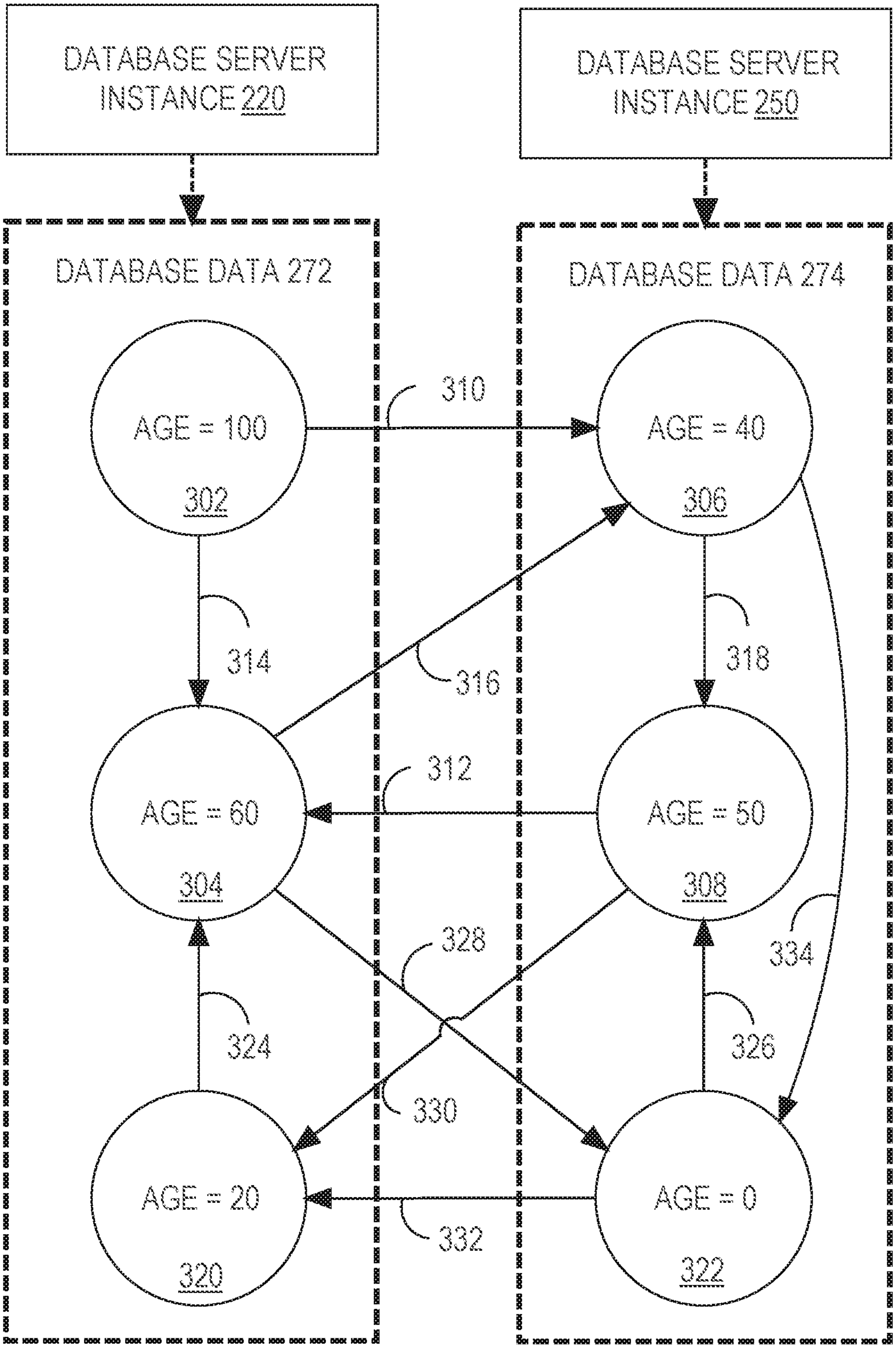

DATABASE SERVER INSTANCE 220
DATABASE SERVER INSTANCE 250
DATABASE DATA 272
DATABASE DATA 274
AGE = 100
302
AGE = 40
306
AGE = 60
304
AGE = 50
308
AGE = 20
320
AGE = 0
322
310
312
314
316
318
324
326
328
330
332
334

FIG. 4

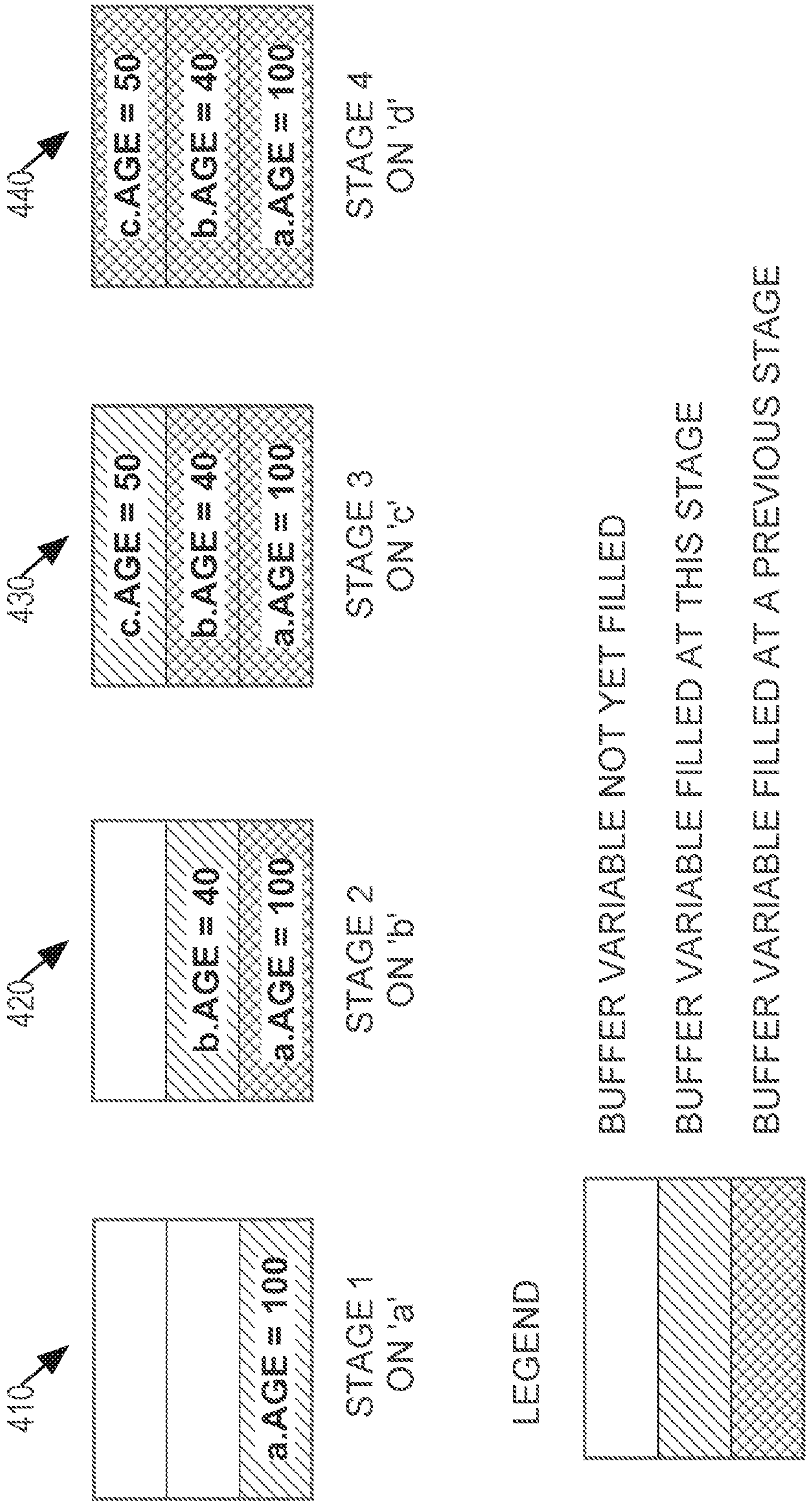
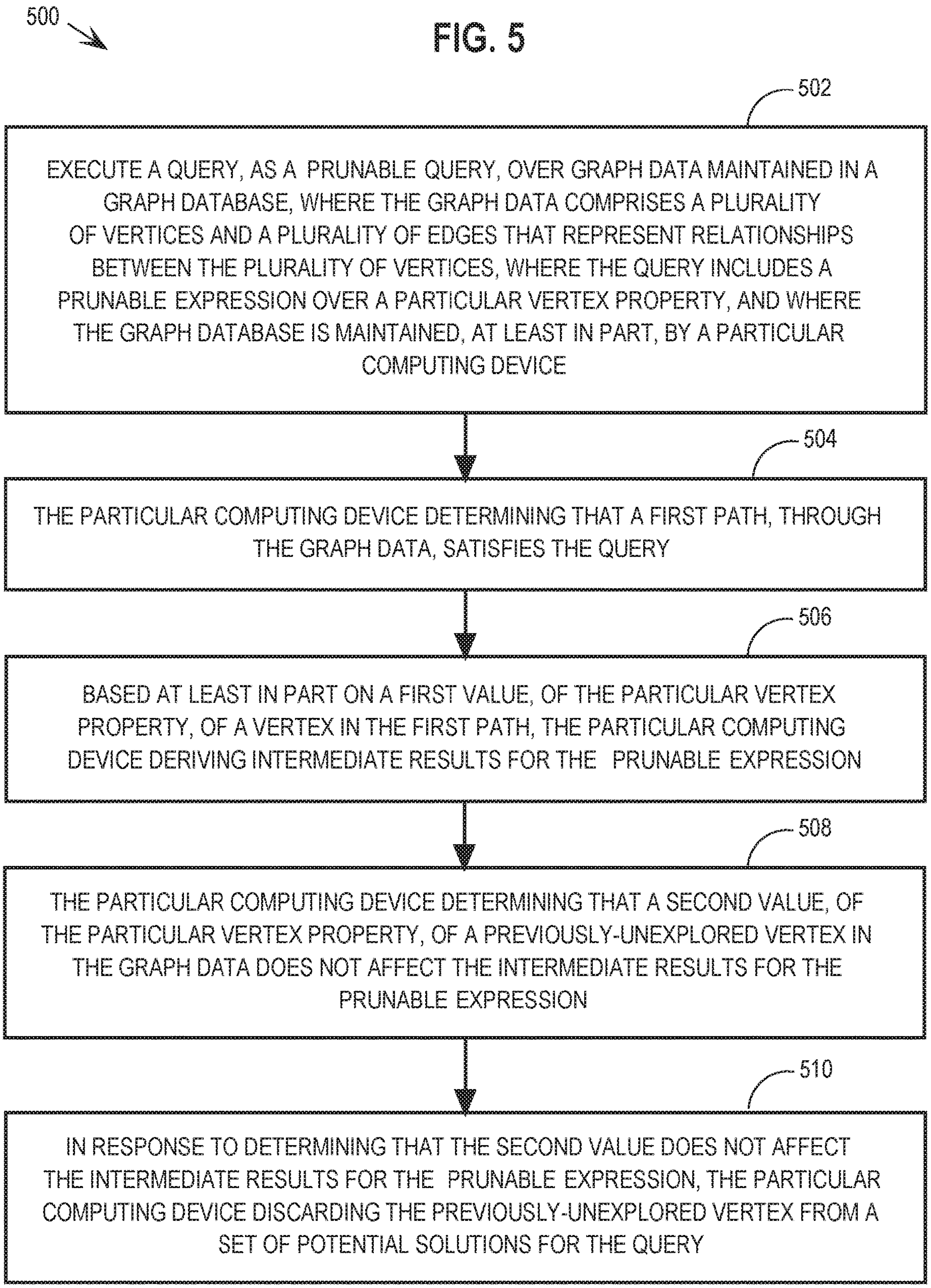

410
a.AGE = 100
STAGE 1
ON 'a'
420
b.AGE = 40
a.AGE = 100
STAGE 2
ON 'b'
430
c.AGE = 50
b.AGE = 40
a.AGE = 100
STAGE 3
ON 'c'
440
c.AGE = 50
b.AGE = 40
a.AGE = 100
STAGE 4
ON 'd'
LEGEND
BUFFER VARIABLE NOT YET FILLED
BUFFER VARIABLE FILLED AT THIS STAGE
BUFFER VARIABLE FILLED AT A PREVIOUS STAGE

FIG. 5


500
502
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510
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FIG. 6

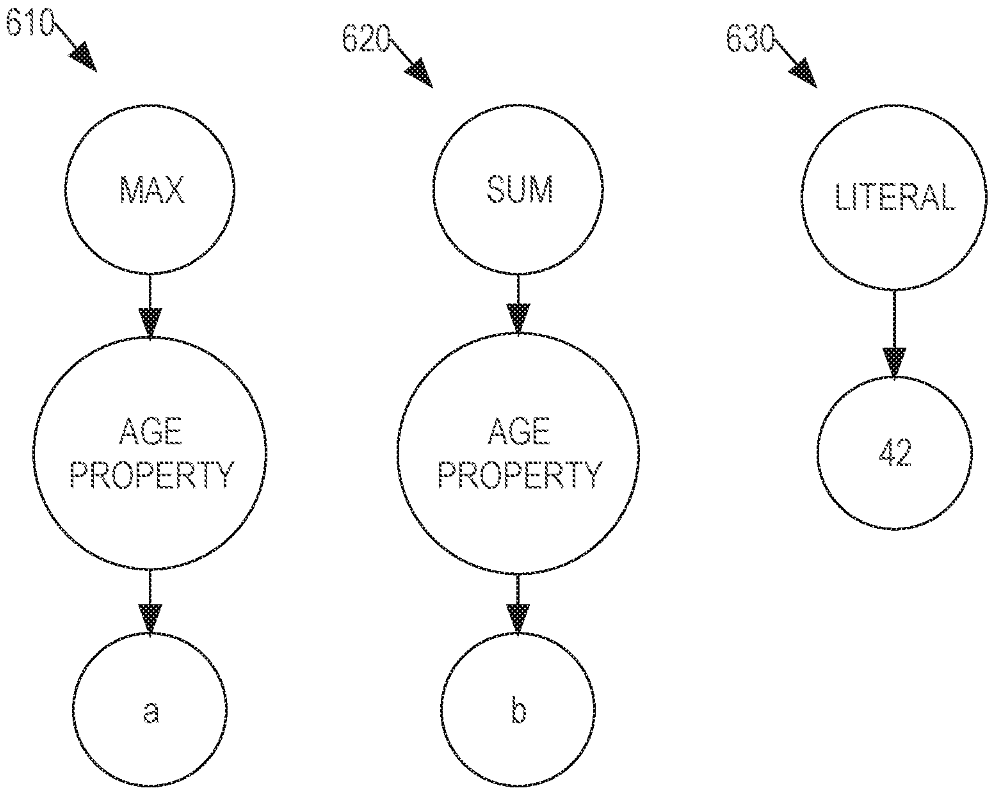
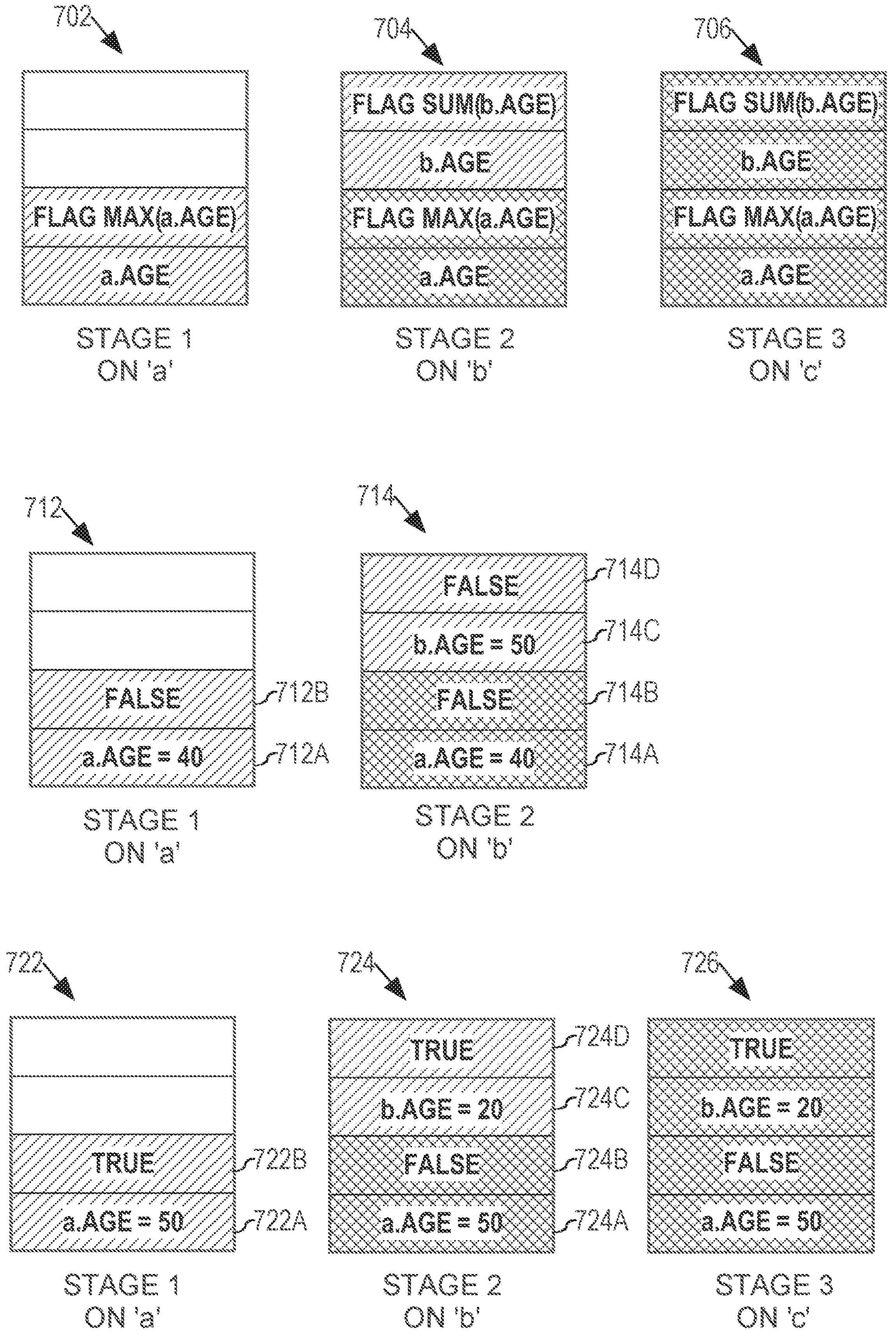


FIG. 7


702
FLAG MAX(a.AGE)
a.AGE
STAGE 1
ON 'a'
704
FLAG SUM(b.AGE)
b.AGE
FLAG MAX(a.AGE)
a.AGE
STAGE 2
ON 'b'
706
FLAG SUM(b.AGE)
b.AGE
FLAG MAX(a.AGE)
a.AGE
STAGE 3
ON 'c'
712
FALSE
712B
a.AGE = 40
712A
STAGE 1
ON 'a'
714
FALSE
714D
b.AGE = 50
714C
FALSE
714B
a.AGE = 40
714A
STAGE 2
ON 'b'
722
TRUE
722B
a.AGE = 50
722A
STAGE 1
ON 'a'
724
TRUE
724D
b.AGE = 20
724C
FALSE
724B
a.AGE = 50
724A
STAGE 2
ON 'b'
726
TRUE
b.AGE = 20
FALSE
a.AGE = 50
STAGE 3
ON 'c'

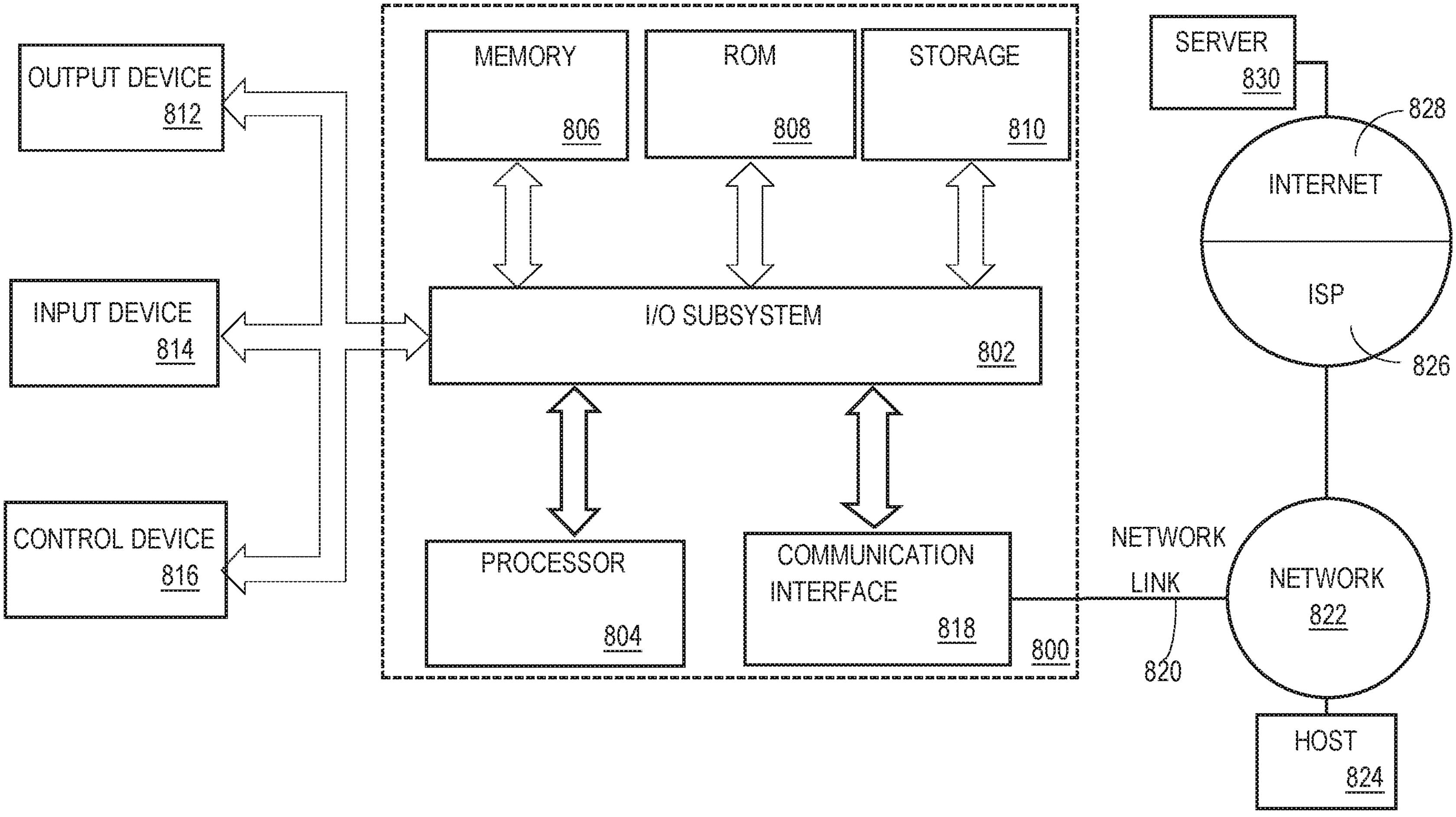

OUTPUT DEVICE
812
INPUT DEVICE
814
CONTROL DEVICE
816
MEMORY
806
ROM
808
STORAGE
810
I/O SUBSYSTEM
802
PROCESSOR
804
COMMUNICATION
INTERFACE
818
800
NETWORK
LINK
820
SERVER
830
828
INTERNET
ISP
826
NETWORK
822
HOST
824

FIG. 8

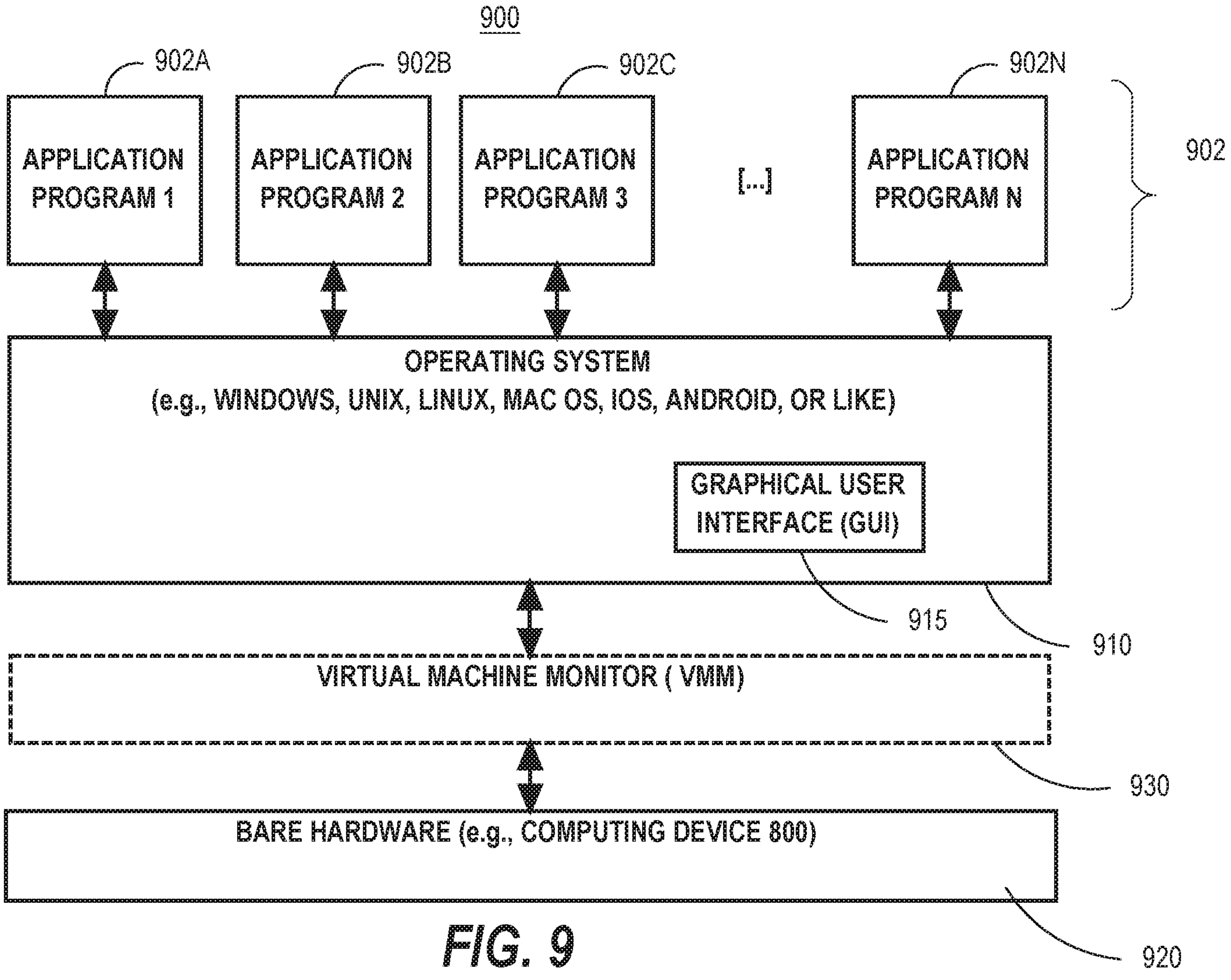

900
902A
902B
902C
902N
APPLICATION PROGRAM 1
APPLICATION PROGRAM 2
APPLICATION PROGRAM 3
[...]
APPLICATION PROGRAM N
902
OPERATING SYSTEM
(e.g., WINDOWS, UNIX, LINUX, MAC OS, IOS, ANDROID, OR LIKE)
GRAPHICAL USER INTERFACE (GUI)
915
910
VIRTUAL MACHINE MONITOR (VMM)
930
BARE HARDWARE (e.g., COMPUTING DEVICE 800)
920

FIG. 9

OPTIMIZING GRAPH QUERIES BY PERFORMING EARLY PRUNING

FIELD OF THE INVENTION

[0001] The present invention relates to querying graph database data and, more specifically, to optimizing implementation of graph data queries by using early pruning to discard potential solution paths that cannot affect query results.

BACKGROUND

[0002] Graph processing is a method in data processing where the fine-grained relationships between data entities are materialized, in a graph database, as graph edges (or simply "edges") between graph vertices (or simply "vertices"). Graph databases may be implemented by single-node database systems, multi-node shared-memory database systems, multi-node distributed-memory database systems, multi-tenant database systems, etc. Information about the entities, represented by vertices, and relationships between the entities, represented by edges, may be queried and analyzed to gain insights into the represented data.

[0003] The most prominent model of representing graph data is the "property-graph model". In the property-graph model, both vertices and edges that represent connections between the vertices can be associated with properties. For example, in particular property-graph modeled graph data, a vertex has a property, 'age', with an integer value, such as '20'. A graph query may be run over the particular graph data to analyze the represented information, e.g., a query that returns the maximum value of the 'age' property of vertices that have an outgoing neighbor with a value of the 'age' property that is greater than 40.

[0004] Herein, graph queries are represented using property graph query language (PGQL), which is a graph query language with a syntax close to structured query language (SQL). (Additional information about PGQL can be found in "PGQL: a Property Graph Query Language", by Oskar van Rest et al., GRADES 2016, Jun. 24, 2016, the entire contents of which is incorporated by reference as if fully set forth herein.) To illustrate, the query described above can be expressed in PGQL as query **100** of FIG. **1**. Note that the construct (a)->(b) in query **100** is referred to herein as the query path pattern.

[0005] Graph data tends to be very extensive. As such, efficient execution of graph queries is important to successful graph database implementations. Further, performance is a critical point of graph database and analysis infrastructures, where large delays in query response time can make the difference between commercial success and failure.

[0006] Graph query execution within a single-node database system or a multi-node shared-memory database system is generally much more efficient than query execution within a distributed database system because execution of graph queries on a distributed system generally requires communication among the different machines implementing the system. Such communication subjects query execution to network latencies, which generally represent a bottleneck for query execution. For example, if vertices of particular graph data are maintained by different machines, where a particular vertex is stored on machine A and its neighbor is stored on machine B, execution of query **100** (FIG. **1**) against this path requires machine A to send information regarding the particular vertex to machine B (in this case, the value of 'a.age').

[0007] Many techniques to speed up graph query execution are helpful for all implementations of graph databases. For example, indices can be used to speed up query execution. Also, intelligent query planning can reduce the number of paths that need to be explored for a given query. An example of intelligent query planning is starting exploration of potential solutions for query **100** from vertices corresponding to vertex 'b' in the query **100** path pattern, which eliminates the need to explore paths that do not satisfy the filter over vertex 'b'. This technique of intelligent query planning can reduce the number of inter-machine hops required to explore the graph data when the graph database is implemented in a distributed database system. Another technique for mitigating inter-machine communication-based latency, for a distributed system, is grouping inter-machine messages. Grouping of messages enables sending large chunks of information in large packet groups instead of sending many smaller information packets between the machines.

[0008] Furthermore, the evaluation of queries on any implementation of a graph database may be performed in an asynchronous manner, where machines and threads need not wait for completion of a given query execution stage across all potentially-matching vertices in the graph data before starting the execution of a subsequent query execution stage. Specifically, in asynchronous query execution, threads of the database system pick up work (e.g., testing filters, sending data to another machine for a distributed system, etc.) independently from other threads. The main benefit of asynchronous query execution is the reduced memory footprint of the query, given that the query execution engine need not store all intermediate results of earlier query execution stages for all explored vertices to facilitate performance of subsequent query execution stages. Thus, asynchronous query execution allows graph database systems to more efficiently execute queries that would otherwise use a tremendous amount of memory in maintaining intermediate query results.

[0009] Notwithstanding existing techniques to improve the execution time of queries in graph database systems, it would be beneficial for any implementation of a graph database management system to further optimize execution of graph data queries by reducing the size of the set of explored paths.

[0010] The approaches described in this section are approaches that could be pursued, but not necessarily approaches that have been previously conceived or pursued. Therefore, unless otherwise indicated, it should not be assumed that any of the approaches described in this section qualify as prior art merely by virtue of their inclusion in this section. Further, it should not be assumed that any of the approaches described in this section are well-understood, routine, or conventional merely by virtue of their inclusion in this section.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] In the drawings:

[0012] FIG. **1** depicts example graph data queries.

[0013] FIG. **2** is a block diagram that depicts an example arrangement for a database management system.

[0014] FIG. **3** depicts example graph data.

[0015] FIG. **4** depicts message buffers with path-specific intermediate results for various stages of query execution.

[0016] FIG. **5** depicts a flowchart for performing early solution pruning by utilizing expression-specific intermediate results to eliminate, from a set of potential query solutions, paths whose property values cannot influence the final result of the query.

[0017] FIG. **6** depicts an example expression tree.

[0018] FIG. **7** depicts message buffers with path-specific intermediate results for various stages of query execution and boolean flags associated with values stored in the buffers.

[0019] FIG. **8** is a block diagram of a computer system on which embodiments may be implemented.

[0020] FIG. **9** depicts a software system that may be used in an embodiment.

DETAILED DESCRIPTION

[0021] In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, that the present invention may be practiced without these specific details. In other instances, well-known structures and devices are shown in block diagram form in order to avoid unnecessarily obscuring the present invention.

General Overview

[0022] Techniques are described herein for early pruning of potential graph query results to increase the efficiency of graph query execution. Specifically, based on determining that one or more paths through graph data that represent potential solutions to a query cannot affect the results of the query, those paths are pruned from the set of potential query solutions prior to fully exploring the paths.

[0023] Early solution pruning is performed on prunable queries, the results of which are not tied to a number of paths explored for query execution. More specifically, the results of prunable queries are determined using prunable expressions, which employ one or more of a set of prunable functions that includes: MIN and MAX (with or without GROUP BY); SUM (with or without GROUP BY); and DISTINCT. Once a database system has determined that a given query is prunable based on the projected expressions of the query being prunable, the system uses intermediate results maintained for the query during query execution to implement early solution pruning. When the system determines that property values of a given potential solution path cannot affect the query results reflected in intermediate results maintained for the query, the path is discarded from the set of possible query solutions without further exploration of the path.

[0024] For example, a database server instance executes query **100** (FIG. **1**) against a graph database. At a given point in time, the database server instance maintains expression-specific intermediate results indicating that the current 'MAX(a.age)' encountered by the instance is '100'. Based on such intermediate results, the database server instance is able to determine that any potential solution path that has vertex 'a', according to the query **100** path pattern, with a value of the 'age' property that is less than '100' cannot affect the final query result. Such potential solution paths can be discarded from the set of possible solutions for query **100** without further analysis of the paths.

[0025] Early pruning of potential solutions for prunable queries improves query response times and reduces hardware and energy costs. In the context of a distributed system, early solution pruning also decreases the volume of inter-machine communication, which alleviates network congestion that is often a limiting factor in distributed systems. The performance gains resulting from application of techniques described herein are especially noticeable when exploration of pruned paths would require inter-machine communication and when paths are pruned before requiring exploration of a large number (e.g., several thousands) of hops.

Distributed Graph Data

[0026] Embodiments herein are described in the context of a distributed database system **200** comprising multiple database server instances that maintain database data on disks that are not shared among the multiple database server instances, as depicted in FIG. **2**. Nevertheless, techniques described herein for early solution pruning may be performed by any implementation of a database system, e.g., on a single-node database system that comprises a single database server instance, one a multi-node shared-memory database system that comprises multiple database server instances that access the same shared storage, on a multi-tenant database system comprising a single database server instance that serves multiple distinct databases, etc.

[0027] FIG. **2** depicts an example distributed database system **200** comprising a first database server instance **220** running on a first database server computing device **210**, and a second database server instance **250** running on a second database server computing device **240**. Instances **220** and **250** maintain portions of a graph database **270**, i.e., database data **272** maintained in persistent storage **230** by instance **220**, and database data **274** maintained in persistent storage **260** by instance **250**. Examples of graph database implementations include Spatial and Graph Analytics Oracle RDBMS, Big Data Appliance, Parallel Graph AnalytiX (PGX), and Oracle Graph Cloud Service. (More information regarding Spatial and Graph Analytics Oracle RDBMS may be found in "Spatial and Graph Analytics with Oracle Database 18c", an Oracle White Paper, February 2018, the entire contents of which are hereby incorporated as if fully set forth herein.)

[0028] FIG. **3** depicts example graph data from database **270**. Herein, a machine "owns" data that is maintained by a database server instance running on the machine. Thus, the vertices and edges defined in database data **272** are "owned" by computing device **210**, and the vertices and edges defined in database data **274** are "owned" by computing device **240**. According to a non-limiting embodiment, an edge is owned by the machine that owns the source vertex of the edge. Thus, the owner of an edge maintains an identifier of a destination vertex of the edge, and an identifier of the owner of the destination vertex, as well as any properties of the edge. To illustrate in the context of FIG. **3**, device **210** owns vertices **302**, **304**, and **320** and edges **310**, **314**, **316**, **324**, and **328**, and device **240** owns vertices **306**, **308**, and **322** and edges **312**, **318**, **326**, **330**, **332**, and **334**. Information for an edge (such as an identifier of the source vertex of the edge, and an identifier of the owner of the source vertex) may also be stored with the destination vertex of the edge as a "reverse" edge.

Querying Graph Data

[0029] Execution a query against database **270** is split into one or more execution stages, where each stage of query execution comprises one of (a) exploration of a hop (going from one vertex to another) in a path that is a potential solution for the query, or (b) processing of a final vertex in a path that is a potential solution for the query. These stages may be performed asynchronously and in parallel by multiple processing entities, e.g., multiple instances of a multi-node database system, multiple threads on a single-node database system, multiple threads running on multiple machines of a multi-node database system, etc. References to "processing entities" herein refer to computer system processes, threads running within a computer system process, and/or database server instances, depending upon implementation.

[0030] In the context of distributed system **200** depicted in FIG. **2**, both machines initiate path exploration for a given query on every vertex that the machine owns, excluding any vertices that are determined to be excluded by the query. At each stage of query execution, if property values of a given path do not match query requirements, the processing entity ceases exploration of the path and discards the path from the set of potential query solutions.

[0031] To illustrate, database system **200** receives a query **102** (FIG. **1**) over database **270**. The path pattern for query **102** is (a)->(b)->(c)->(d). Note that query **102** is not prunable, as described in further detail below. Database system **200** organizes execution of query **102** into four execution stages illustrated in FIG. **4**, where each stage corresponds to a corresponding vertex in the query **102** path pattern. In this case, because there are no limitations on vertex 'a' in the query **102** path pattern, database system **200** causes the first execution stage of query **102** to be initiated for all vertices in database **270**.

[0032] As a further illustration, during the first stage of query **102** execution (corresponding to vertex 'a' in the query path pattern), thread **222**A, of database server instance **220**, performs a look up of the value of the 'age' property of vertex **302** in database data **272** ('age'=='100'), and inserts the 'age' property value into a message buffer **410** that is allocated to store path-specific intermediate results for query **102**. Thread **222**A then looks up the neighbors of vertex **302** (i.e., destination vertices for edges that originate with vertex **302**), which are vertex **304** (connected by edge **314**) and vertex **306** (connected by edge **310**). Device **210** sends a copy of message buffer **410** to the owner machine of each neighbor of vertex **302** with information identifying the target neighbor vertex for the second phase of query **102** processing (corresponding to vertex 'b' in the query path pattern). Thus, thread **222**A sends a copy of message buffer **410** to device **240** with information identifying vertex **306**, and also causes message buffer **410** to be stored, with information identifying vertex **304**, in a buffer queue **216** in volatile memory **212**. Specifically, a thread causes a message buffer to be stored in a buffer queue in any way, e.g., by saving the message buffer to the buffer queue, by allowing a service that manages the queue to access a copy of the message buffer, etc.

[0033] Buffer queue **216** stores message buffers that hold path-specific intermediate results for paths that require further exploration in database data **272**. As they become available for additional work, threads **222**A and **222**B initiate the first stage of query **102** execution (corresponding to vertex 'a' in the query path pattern) over vertices in database data **272**, and initiate more advanced execution stages of query **102** (corresponding to vertices 'b', 'c', and 'd' in the query path pattern) based on message buffers in buffer queue **216**. Similarly, buffer queue **246** in volatile memory **242** stores message buffers that hold path-specific intermediate results for paths that require further exploration in database data **274**.

[0034] Continuing the example with respect to the potential solution path (vertex **302**)->(vertex **306**), device **240** receives the copy of the message buffer with the record of the completed first execution stage (corresponding to vertex 'a' in the query path pattern) and places the message buffer copy in buffer queue **246**. Thread **252**A becomes available and initiates second stage processing for query **102** (corresponding to vertex 'b' in the query path pattern) based on information for the message buffer. Specifically, according to the second execution stage of Query **102**, thread **252**A inserts the 'age' property value of vertex **306** ('age'=='40') into a message buffer **420**. Thread **252**A determines that the neighbor vertices of vertex **306** are vertex **308** (via edge **318**) and vertex **322** (via edge **344**). As such, thread **252**A causes a first copy of the message buffer to be stored in buffer queue **246** with an identifier of vertex **308** and a second copy of the message buffer to be stored in buffer queue **246** with an identifier of vertex **322**.

[0035] Subsequently, thread **252**B picks up the message buffer associated with the identifier of vertex **308** from buffer queue **246**. In connection with the third stage of processing for query **102** (corresponding to vertex 'c' in the query path pattern), thread **252**B looks up the value of the 'age' property of vertex **308** and inserts this value into message buffer **430**. In preparation for the final query execution stage for the path (corresponding to vertex 'd' in the query path pattern), thread **252**B sends a copy of message buffer **430** to the owner machines of each neighbor of vertex **308**. In this case, vertices **304** and **320** are neighbors to vertex **308** (connected by edges **312** and **330**, respectively). Thus, thread **252**B sends two copies of message buffer **430** to the owner machine of vertices **304** and **320** (i.e., device **210**), where a first copy of the message buffer is associated with an identifier of vertex **304** and a second copy of the message buffer is associated with an identifier of vertex **320**. Instance **220** stores the received message buffers in buffer queue **216**.

[0036] Thread **222**A retrieves, from buffer queue **216**, message buffer **440** that is associated with the identifier of vertex **304**. Thread **222**A initiates processing of the final execution stage of query **102** (corresponding to vertex 'd' in the query path pattern) for the indicated path. Specifically, in accordance with the filter WHERE d.age>40 in query **102**, thread **222**A determines whether the value of the 'age' property of vertex **304** is greater than '40' and only continues with the final stage of query **102** execution for vertex **304** if the 'age' property is larger than '40'. In this case, the 'age' property of vertex **304** is '60'. Thus, at the final stage of query execution, thread **222**A inserts the values of 'a.age', 'b.age', and 'd.age', which are the results of the property access-type projected expressions of query **102**, into a result table for query **102**. Furthermore, thread **222**A aggregates, based on the MIN aggregation function, the value of c.age' with other values of 'c.age' from any other paths that have been validated for query **102**. After all solutions for query

102 have been identified in database **270**, the final result for MIN(c.age) is inserted into the result table for query **102**.

Prunable Queries

[0037] According to one or more embodiments, database server instances use early solution pruning to expedite computation of prunable queries. A prunable query is a query whose results are calculated based on expressions that are prunable, the results of which are unrelated to a number of paths that are explored during query execution. An expression is a construct that expresses how to compute a value, and can be comprised of mathematical functions, literals, vertex and edge property accesses, etc.

[0038] Examples of functions for prunable expressions include MAX and MIN aggregation, DISTINCT, and SUM. According to an embodiment, a prunable expression is an expression of the form 'MAX(sub_expression)', 'MIN(sub_expression)', SUM(sub_expression)', or 'DISTINCT(sub_expression)', where 'sub_expression' is any other expression. An expression is prunable if all sub-expressions of the expression are prunable. For example, the following expression is prunable because it employs only prunable functions: 'MAX(sub_expression)'+'MIN(sub_expression)'. A non-prunable expression is an expression whose result is determined by exploring all paths in the applicable graph data set, such as property accesses, count-based aggregation functions such as 'COUNT(sub_expression)' and 'AVG(sub_expression)', etc.

[0039] The following queries are examples of prunable queries, where the result of the query is calculated using prunable expressions:

[0040] SELECT MAX(a.age) MATCH (a)->(b)->(c)->(d) WHERE d.age>40

[0041] Specifically, a database server instance is able to prune a given potential solution path, from a set of potential solutions for the query, if the instance has record of a validated solution path in which the value of 'a.age' was equal to or larger than the value of 'a.age' in the potential solution path.

[0042] SELECT SUM(a.age) MATCH (a)->(b)->(c)->(d) WHERE d.age>40

[0043] Specifically, a database server instance is able to prune a given potential solution path, from a set of potential solutions for the query, if the value of 'a.age' for the potential solution path is '0'.

[0044] SELECT DISTINCT(a.age) MATCH (a)->(b)->(c)->(d) WHERE d.age>40

[0045] Specifically, a database server instance is able to prune a given potential solution path, from a set of potential solutions for the query, if the value of 'a.age' for the potential solution path is already in a set of distinct 'a.age' values from solution paths that have been validated for the query.

[0046] SELECT MAX(a.age) MATCH (a)->(b)->(c)->(d) GROUP BY b.age WHERE d.age>40

[0047] Specifically, a database server instance is able to prune a given potential solution path, from a set of potential solutions for the query, if the instance has record of a validated solution path with the same value of 'b.age' as the potential solution path, in which the value of 'a.age' is equal to or larger than the value of 'a.age' in the potential solution path.

Detecting Prunable Queries

[0048] FIG. **5** depicts a flowchart **500** for performing early solution pruning by utilizing expression-specific intermediate results to eliminate, from a set of potential query solutions, paths whose property values cannot influence the final result of the query, according to one or more embodiments. At step **502**, a query is executed, as a prunable query, over graph data maintained in a graph database, where the graph data comprises a plurality of vertices and a plurality of edges that represent relationships between the plurality of vertices, where the query includes a prunable expression over a particular vertex property, and where the graph database is maintained, at least in part, by a particular computing device. For example, system **200** receives a query **104** (FIG. **1**) over database **270**. Query **104** includes the following projected expressions (i.e., the expressions in the SELECT clause of the query), which define the results requested by the user: 'MAX(a.age)', 'SUM(b.age)', and the literal '42'.

[0049] According to an embodiment, as part of processing a received query, system **200** determines whether the received query is a prunable query. Specifically, system **200** inspects the projected expressions for the received query, which can range in complexity from literals to complex user-defined functions.

[0050] Projected expressions for a query may be represented by system **200** as a set of expression trees. FIG. **6** depicts example expression trees **610**, **620**, and **630** that represent the projected expressions of query **104**. To analyze whether query **104** is prunable, a query optimizer for system **200** traverses the expression tree for each projected expression of query **104** to compute the set of prunable expressions for the query. In the case of query **104**, because all of the expressions in the SELECT clause of query **104** are prunable (MAX, SUM, and a literal, which is not affected by the contents of graph database **270**), system **200** determines that query **104** is prunable.

[0051] In response to determining that a received query is prunable, system **200** determines at which stage, during query execution, the query is eligible for early solution pruning. The determined stage at which the query is eligible for early solution pruning is referred to herein as the "early pruning-eligible" stage. Returning to the example of query **104**, system **200** determines that both vertex 'a' and vertex 'b' of the query **104** path pattern must be traversed in order to determine whether a given path may be pruned according to techniques described herein. Specifically, traversal of vertex 'a' is required to determine whether the 'age' property of vertex 'a' affects intermediate results for the MAX function, and traversal of vertex 'b' is required to determine whether the 'age' property of vertex 'b' affects the intermediate results for the SUM function. Thus, system **200** determines that the early pruning-eligible stage for query **104** is the second query execution stage on vertex 'b'.

[0052] According to an embodiment, if the early pruning-eligible stage for a query is within a threshold number (e.g., 0) of the last stage of query execution, early pruning is not implemented for the query despite the query being prunable. In the case of query **104**, the early pruning-eligible stage is the second of four stages. Based on a threshold number of 0, system **200** determines to utilize early solution pruning techniques for query **104**.

[0053] A further illustration is presented based on system **200** receiving query **102**. As part of processing the received query, system **200** reviews all projected expressions of query **102** to determine whether the query is prunable. A query is not prunable if any number of non-prunable expressions are projected by the query. In the case of query **102**, the projected expressions are property access-type expressions targeting 'a.age', 'b.age', 'd.age', and a MIN aggregation function. The property access expressions-type are not prunable, and inclusion of these non-prunable expressions in the projected expressions of query **102** renders the query non-prunable (despite the inclusion of a prunable expression based on the MIN function) given that solutions for query **102** would need to be positively identified and traversed in order to compute the non-prunable projected expressions.

[0054] The following example pseudocode (in C++ style) illustrates an operation for detection of prunable queries, by which the list of expressions that can be pruned is known during the compilation of a query:

```
set<expression> get__prunable__expressions(vector<expression>
                projected__expressions) {
    set<expression prunable__expressions;
    bool at__least__one__non__prunable = false;
    for (expression projected__expression : projected__expressions) {
        prunable__expressions.insert(
                get__prunable__expressions(projected__expression,
                            at__least__one__non__prunable)
        );
        /* Note that 'at__least__one__non__prunable' is passed by reference to
        the function*/
        if (at__least__one__non__prunable) {
            return set<expression>( );
        }
    }
    return prunable__expressions;
}
set<expression> get__prunable__expressions(expression
                projected__expression, bool &at__least__one__non__prunable) {
    if (projected__expression.type == MAX || projected__expression.type ==
                        MIN || projected__expression.type == SUM ||
                        projected__expression.type == DISTINCT) {
        return set<expression>({projected__expression});
    }
    else if (projected__expression.is__leaf( )) {
        at__least__one__non__prunable = true;
        return set<expression>( );
    }
    set<expression prunable__expressions;
    for (expression child__expression :
                    projected__expression.get__children( )) {
        prunable__expressions.insert__many(get__prunable__expressions(
                        child__expression));
    }
    return prunable__expressions;
}
```

Machine-Local and Thread-Local Intermediate Results

[0055] Returning to the discussion of flowchart **500** of FIG. **5**, executing a query, as a prunable query, over graph data comprises steps **504-510**. Specifically, at step **504**, the particular computing device determines that a first path, through the graph data, satisfies the query. For example, after system **200** receives query **104** and determines that it is a prunable query, database server instance **220** initiates the first stage of query **104** against vertices in database data **272** and database server instance **250** initiates the first stage of query **104** against vertices in database data **274**. In connection with executing the query, database server instance **250** validates the following path (vertex **302**)->(vertex **306**)->(vertex **308**) as a solution for query **104**.

[0056] At step **506**, based at least in part on a first value, of the particular vertex property, of a vertex in the first path, the particular computing device derives intermediate results for the prunable expression. For example, based on validating path (vertex **302**)->(vertex **306**)->(vertex **308**) as a solution for query **104**, instance **250** derives two expression-specific intermediate results indicating the current aggregate values known for the projected expressions in query **104**: 'MAX(a.age)'=='100'; and 'SUM(b.age)'=='40'. These expression-specific intermediate results are used to efficiently compute aggregate values projected by a query, and also to affect early solution pruning, as described in further detail below.

[0057] According to an embodiment, the expression-specific intermediate results are maintained in machine-local values, such as machine local values **214** in volatile memory **212** of device **210** and machine-local values **244** in volatile memory **242** of device **240**. According to an embodiment, in the case of a distributed graph database system, these machine-local values are periodically synchronized with the machine-local values from other machines in the system. For example, every machine in a distributed database system broadcasts its machine-local values periodically (such as after a predetermined number of updates). When a machine receives a broadcast from another machine indicating an expression-specific intermediate result, the corresponding machine-local value is updated, if needed. For example, for expression-specific intermediate results for a MAX function, the machine-local value that corresponds to the broadcast value is updated if the broadcast value is higher than the machine-local value. These updated expression-specific intermediate values increase the accuracy of the local intermediate values maintained by the various machines of the distributed system, thereby facilitating more effective early pruning of potential solution paths.

[0058] According to an embodiment, since query exploration is generally performed in parallel by a large number of threads, each thread running on a given machine avoids contention for machine-local value access by keeping expression-specific intermediate results in thread-local values (such as thread-local values **224**A for thread **222**A), when possible. Maintenance of thread-local values avoids the requirement to access the machine-local values for every update by every thread. According to an embodiment, to gain performance, thread-local values are periodically synchronized with the corresponding machine-local values. The periodic synchronization may be performed after a certain number of updates by a given thread. Such periodic synchronization allows for a balance between performance and up-to-date intermediate results that provide for discarding the most paths possible via early pruning.

[0059] According to an embodiment, intermediate results that are set-type values are stored as machine-local values and not as thread-local values because, in general, it would be too costly and ineffective to have a per-thread set of values. For example, in the case of a DISTINCT-type expression, the set of distinct values required for DISTINCT expression-specific intermediate results is maintained in machine-local values in a way to support concurrent accesses by multiple threads.

[0060] Returning to a discussion of step **506** of flowchart **500**, in the context of the distributed system **200** of FIG. **2** executing query **104**, each device **210** and **240** stores an expression-specific intermediate value for each of 'MAX(a.age)' and 'SUM(b.age)'. When a given instance validates a given path as a solution to query **104**, the instance updates the local expression-specific intermediate results maintained by the instance based on the property values of the validated solution. At the end of query execution by a distributed database system, all local values from the machines in the system are used to calculate the final value for each expression projected by the query.

Early Pruning of a Potential Solution Path

[0061] At step **508**, the particular computing device determines that a second value, of the particular vertex property, of a previously-unexplored vertex in the graph data does not affect the intermediate results for the prunable expression. For example, thread **222**A maintains, in thread-local values **224**A, the following expression-specific intermediate results for the projected expressions in query **104**: 'MAX(a.age)'=='100'; and 'SUM(b.age)'=='40'. While maintaining these expression-specific intermediate results, thread **222**A performs the first query execution stage for query **104** against vertex **304**. Thread **222**A determines that the 'age' property of vertex **304**, i.e., '60', is less than '100', and thus does not affect the intermediate results for 'MAX(a.age)' stored in machine-local values **224**A.

[0062] Since the early pruning-eligible stage for query **104** is the second execution stage, thread **222**A moves on evaluation of the neighbors of vertex **304** (i.e., vertex **322**) according to the second execution stage of query **104**. Thus, thread **222**A populates a message buffer, as described in further detail below, with the value of the 'age' property of vertex **304** and sends the message buffer with an identifier of vertex **322** to the owner of vertex **322** (device **240**). Upon receipt of the message buffer, device **240** places the message buffer in buffer queue **246**.

[0063] While thread **252**A maintains, in thread-local values **254**A, 'MAX(a.age)'=='100', and 'SUM(b.age)'=='40' as the expression-specific intermediate results for the projected expressions in query **104**, thread **252**A picks up the message buffer from buffer queue **246** and performs the second execution stage for query **104** against vertex **322**. At this stage, thread **252**A determines that the 'age' property of vertex **322**, i.e., '0', does not affect expression-specific intermediate results for 'SUM(b.age)' maintained by thread **252**A for query **104**. Specifically, a value of '0' for 'b.age' does not affect intermediate results stored for a SUM-type expression no matter the value of the intermediate results.

[0064] At step **510**, in response to determining that the second value does not affect the intermediate results for the prunable expression, the particular computing device discards the previously-unexplored vertex from a set of potential solutions for the query. For example, because query execution for the current path has reached the early pruning-eligible stage for query **104**, and it has been determined that none of the properties of (vertex **304**)->(vertex **322**) affect the expression-specific intermediate results maintained for the query, thread **252**A discards, from the set of potential solutions for query **104**, all paths that start with (vertex **304**)->(vertex **322**).

[0065] In this case, discarding this subset of paths from consideration for query **104** prevents instance **250** from having to determine whether vertex **308** is a match for vertex 'c' of the query **104** path pattern, thus saving processing power. Furthermore, instance **250** need not send information for the path exploration to instance **220** to cause instance **220** to explore vertex **320** as a potential match for vertex 'c' of the query **104** path pattern, thus saving processing power and network bandwidth that would be required for that further path exploration.

[0066] According to an embodiment, a database server instance prunes message buffers, from the buffer queue maintained by the instance, based on current and/or past pruning decisions. For example, when a thread has detected that a sub-path can be pruned, the thread reviews the pending message buffers and discards those message buffers whose paths start with the pruned sub-path. In this example, a message buffer that matches the pruned sub-path but is placed in the buffer queue after the thread reviews the queue based on the pruned sub-path, the message buffer is not discarded. This technique does not require maintenance of previously-pruned sub-paths, which conserves instance resources.

[0067] As a further example, a database server instance maintains (e.g., in a cache) a set of pruned sub-paths based on which message buffers in the message buffer queue may be discarded. The maintained pruned sub-paths are determined based on one of: a pruning decision made by the instance that maintains the set of pruned sub-paths, and/or periodic sharing, by database server instances of a distributed database system of which the instance is a part, of sub-paths that have been pruned, which allows instances to leverage pruning decisions made by other processing entities.

[0068] To illustrate proactive pruning of buffer messages based on a cache of saved sub-paths, instance **250** determines that (vertex **304**)->(vertex **322**) is a pruned sub-path from the set of potential solution paths for query **104** (either based on a pruning decision made by instance **250** or based on information shared by instance **220**), and stores the sub-path in a pruned sub-path cache. Instance **250** periodically reviews message buffer queue **246** to determine if any of the message buffers in the queue match a sub-path in the maintained set of pruned sub-paths. The instance discards any message buffer identified to incorporate the pruned sub-path without performing any further processing based on the message buffer.

Group-by

[0069] According to techniques described herein, having a GROUP BY clause in a query indicates that the aggregation function associated with the GROUP BY clause will be performed on every distinct group given by an argument of the GROUP BY clause. For instance, the query 'SELECT MAX (a.salary) MATCH (a) GROUP BY a.age' returns the highest salary for each age category. Not having such a GROUP BY clause means that the aggregation is to be performed once on all elements.

[0070] Early pruning of a query with a GROUP BY clause is similar to implementation of early pruning techniques for an equivalent query without the GROUP BY clause. For a GROUP BY-based expression, processing entities store sets of local results per 'group', instead of a single local result for the expression.

[0071] Further, the early pruning-eligible stage for a query having a GROUP BY clause is at or after a stage at which the required one or more grouping categories have been determined. To illustrate, the following query 'SELECT MAX (a.age) MATCH (a)->(b)->(c) GROUP BY b.age WHERE c.age>40' selects the maximum value of the 'age' property of vertex 'a' for each 'age' property value category of vertex 'b' in cases where the value of the 'age' property of vertex 'c' is over '40'.

[0072] For this query, in the absence of the GROUP BY expression and based only on the MAX expression, the early pruning-eligible stage would be the first stage of execution (i.e., the stage that represents exploration of the 'a' vertex in the query path pattern). However, because the GROUP BY expression requires determining groups based on a property of vertex 'b' of the query path pattern, the early pruning-eligible stage is the second stage of execution (i.e., the stage that represents exploration of the 'b' vertex in the query path pattern) to allow expression-specific intermediate results for the query to reflect 'MAX(a.age)' correlated with the age groups of the 'b' vertex.

[0073] Because expressions that are affected by a GROUP BY clause produce a set of results, maintenance, in thread-local values, of expression-specific intermediate results for such expressions may be too costly. Thus, according to an embodiment, intermediate results for expressions that are affected by a GROUP BY clause are maintained in machine-local values.

Early Pruning Based on Additional Boolean Flags

[0074] According to an embodiment, processing entities include, in message buffers that store path-specific intermediate results for query solution exploration, a boolean flag for each prunable expression in the query. The boolean flags in the message buffer for a particular path are used to communicate, among processing entities, whether property values associated with the boolean flags affected local expression-specific intermediate results. Because each processing entity maintains and updates a respective set of local expression-specific intermediate results for the query, each processing entity may maintain different expression-specific intermediate results between periodic synchronization events. Including such flags in message buffers allows for discarding the maximum number of solution paths that cannot affect query results.

[0075] A flag in a given message buffer is set to TRUE if the associated message buffer variable would affect the corresponding expression-specific intermediate result maintained by the current processing entity and all previous processing entities. Thus, the presence of a flag set to TRUE in a message buffer for a given path indicates that there is a chance that the property values of the path could change the final results of the query.

[0076] Conversely, a flag in a given message buffer has a value of FALSE if the value of the associated message buffer variable would not affect the corresponding expression-specific intermediate result maintained by a previous or current processing entity. It is noted that, if the value of a path property does not affect a local expression-specific intermediate result, the value necessarily does not affect the final result for the expression. If, upon completion of the early pruning-eligible stage of a query for a given path, all of the flags in the message buffer maintained for the path are FALSE, then the potential solution path may safely be discarded from the set of possible query solutions because the values of the path cannot affect the final query result.

[0077] At every processing stage, the processing entity for that stage attempts to set any TRUE flags in the message buffer to FALSE, i.e., the processing entity sets a TRUE flag to FALSE when the property value associated with the flag does not affect the corresponding expression-specific intermediate results maintained by the current processing entity. This additional optimization is not costly since the previously identified values required for prunable expressions from a given path are stored in the message buffer maintained for the path. Furthermore, the verification required for additional pruning is inexpensive in terms of computation since such verification involves one of: (a) a comparison between locally-stored expression-specific intermediate results and a value (for MAX and MIN); (b) a comparison between a value and 0 (for SUM); or (c) an 'exists' test to determine if a value is in a set of values for an expression-specific intermediate result (for DISTINCT).

[0078] Once a boolean flag is set to FALSE, subsequent processing entities leave the flag as FALSE, even if the associated message buffer variable would change the corresponding expression-specific intermediate results maintained by the current processing entity. According to an embodiment, when a property value in a received message buffer, which is associated with a flag that is set to FALSE, would change the corresponding expression-specific intermediate results maintained by a current processing entity, the entity updates the expression-specific intermediate results based on the property value (thereby increasing the processing entity's power to discard future potential solution paths). The local expression-specific intermediate results may be safely updated because the property value, on which the update is based, is necessarily a value that would not affect the final results for the corresponding prunable expression, as determined by one of the previous processing entities. Such an update can be safely performed even if the path is later discarded (either by early pruning or because of a query filter) because it is based on intermediate results from another processing entity.

[0079] To illustrate, when executing query **104**, compilation of the query by system **200** identifies three execution stages for query **104**, one for each vertex in the query **104** path pattern. FIG. **7** depicts message buffers **702**, **704**, and **706**, including boolean flags, at the three execution stages for evaluation of query **104**. The legend depicted in FIG. **4** is also applicable to FIG. **7**. A message buffer **702** is created upon initiation of the first execution stage of query **104** over a given vertex, with a message buffer variable storing the value of the 'age' property of the vertex and a corresponding boolean message buffer variable with the flag indicating whether the associate value affected the corresponding expression-specific intermediate value maintained by the processing entity. When a processing entity initiates the second execution stage of query **104**, the processing entity inserts, into message buffer **704**, a message buffer variable with the value of the 'age' property of the vertex being evaluated as the 'b' vertex in the query **104** path pattern, and also a corresponding boolean message buffer variable with the flag for the stored 'b.age'. (According to another embodiment, a boolean flag is not used for SUM-type expressions given that the value of 'b.age' is sufficient to determine whether the value affected the intermediate results maintained by a previous processing entity.) When a processing entity initiates the third execution stage of query **104** based on message buffer **706**, any values for vertex 'c' of the query **104** path pattern would not need to be sent to any other processing entity and, as such, are not included in the message buffer.

[0080] To illustrate utilization of flags for execution of query **104** in the context of database data **272** and **274** as depicted in FIG. **3**, thread **252**A maintains the following expression-specific intermediate results for query **104**: 'MAX(a.age)'=='100'; 'SUM(b.age)'=='40'. These intermediate results may be maintained in thread-local values **254**A, or may be maintained in machine-local values **244**.

[0081] While maintaining those expression-specific intermediate results, thread **252**A initiates the first execution stage for query **104** against vertex **306**. Thread **252**A determines that the 'age' property of vertex **306** does not change the local intermediate results for 'MAX(a.age)' since the expression-specific intermediate results show a 'MAX(a.age)' of '100' and the 'age' property of vertex **306** is '40'. As such, as shown in message buffer **712** at the first stage of query **104** execution, thread **252**A populates message buffer **712** with a variable **712**A that indicates an a.age' value of '40', and also sets an associated boolean message buffer variable **712**B to FALSE. The flag at variable **712**B shows that message buffer variable **712**A does not affect the local expression-specific intermediate results for 'MAX(a.age)' that is maintained by thread **252**A.

[0082] Thread **252**A identifies vertex **322** as a neighbor of vertex **306**, and a potential match for vertex 'b' of the query **104** path pattern. Thus, thread **252**A causes message buffer **712** to be stored in buffer queue **246** with an identifier of vertex **322**. Thread **252**B picks up the message buffer **714** from buffer queue **246** and performs the second stage of query execution against vertex **322**. At the time that thread **252**B performs the second stage of execution for query **104**, thread **252**B maintains the following expression-specific intermediate values for query **104** in thread-local values **254**B: 'MAX(a.age)'=='20'; 'SUM(b.age)'=='60'. In this example, thread-local values **254**B are different from thread-local values **254**A because one or both of the thread-local values have changed since they were initialized or since they were last synchronized to machine-local values **244**.

[0083] Thread **252**B determines that the buffer variable **714**A in message buffer **714** is higher than the expression-specific intermediate value for 'MAX(a.age)' in thread-local values **254**B. Thread **252**B does not change the flag in buffer variable **714**B (associated with buffer variable **714**A), since the flag indicates that the 'a.age' stored in buffer variable **714**A did not affect the expression-specific intermediate value for 'MAX(a.age)' of the previous processing entity. According to an embodiment, based on this determination, thread **252**B updates the expression-specific intermediate value for 'MAX(a.age)' in thread-local values **254**B based on the value for a.age' in buffer variable **714**A, i.e., 'MAX (a.age)'=='40'. The expression-specific intermediate results maintained by thread **252**B may be safely updated based on this information because the value of 'a.age' in the buffer variable **714**A is necessarily less than or equal to the intermediate results for 'MAX(a.age)' maintained by the previous processing entity.

[0084] Thread **252**B also determines that the value of the 'age' property of vertex **322**, i.e., '0, does not affect the intermediate results maintained in thread-local values **254**B, i.e., SUM(b.age)'=='60'. Since the current (second) stage of execution for query **104** is the early pruning-eligible stage for the query, and because neither of the age properties of the explored vertices affect the local expression-specific intermediate results for the query, thread **252**B discards all paths, from the potential path matches for query **104**, that start with (vertex **306**)->(vertex **322**). Thread **252**B need not update message buffer **714** with the results of the second execution stage given that the path is pruned from the set of potential solutions for query **104**, and the message buffer is not used to perform any further stages of query **104** execution.

[0085] As a further example, while thread **252**B maintains expression-specific intermediate results for query **104** of 'MAX(a.age)'=='40'; 'SUM(b.age)'=='60', thread **252**B initializes the first stage of query **104** evaluation against vertex **308**. Thread **252**B determines that the value of the 'age' property of vertex **308**, i.e., '50', would affect the expression-specific intermediate results in thread-local values **254**B for 'MAX(a.age)', i.e., 'MAX(a.age)'=='40'. Thread **252**B populates a message buffer **722** (FIG. **7**) with a message buffer variable **722**A indicating 'a.age'=='50'. Thread **252**B further inserts a message buffer variable **722**B with a boolean flag set to TRUE, which indicates that the value of 'a.age' in buffer variable **722**A affected the expression-specific intermediate results maintained by thread **252**B.

[0086] Thread **252**B identifies vertex **320**, maintained in database data **272**, as a neighbor of vertex **308** that is a possible candidate to match the 'b' vertex of the query **104** path pattern. Accordingly, thread **252**B sends a copy of message buffer **722**, with an identifier of vertex **320**, to database server instance **220**. Instance **220** places the copy of the message buffer in message buffer queue **216**.

[0087] Thread **222**A picks up the copy of the message buffer (depicted in FIG. **7** as message buffer **724**) based on which the thread will perform the second phase of query **104** execution against vertex **320**. When thread **222**A picks up the message buffer, thread-local values **224**A indicate the following expression-specific intermediate values for query **104**: ‘MAX(a.age)’==‘100’; ‘SUM(b.age)’==‘110’. Thread **222**A determines that the value of ‘a.age’ in message buffer variable **724**A, i.e., ‘50’, does not affect the expression-specific intermediate results for ‘MAX(a.age)’ maintained by thread **222**A. Based on this determination, thread **222**A changes the flag in buffer variable **724**B, associated with ‘a.age’, to FALSE.

[0088] Thread **222**A then performs the second execution phase of query **104** against vertex **320**. The value of the ‘age’ property of vertex **320** is ‘20’, which, as a non-zero number, would affect the expression-specific intermediate results for ‘SUM(b.age)’ maintained by thread **222**A, i.e., ‘110’. The second stage of execution of query **104** is the early pruning-eligible stage. However, because one of the values of the currently-explored path affects the intermediate results maintained by the processing entities for path, the current path is not pruned. Thus, thread **222**A populates message buffer **724** with the value of ‘b.age’ (**20**') in buffer variable **724**C, and a boolean flag set to TRUE in buffer variable **724**D to indicate that the value in buffer variable **724**C affected the expression-specific intermediate results for ‘SUM(b.age)’.

[0089] Thread **222**A identifies vertex **304** (maintained by instance **220**) as a neighbor of vertex **320** that is a potential match for vertex ‘c’ in the query **104** path pattern. As such, thread **222**A causes a copy of message buffer **724**, associated with an identifier of vertex **304**, to be stored in buffer queue **216**.

[0090] Thread **222**B picks up the copy of the message buffer (depicted in FIG. **7** as message buffer **726**) from message buffer queue **216** based on which thread **222**B performs the third execution stage of query **104** for the current path. Specifically, the value of the ‘age’ property of vertex **304** is ‘60’, and, as such, vertex **304** satisfies the condition on vertex ‘c’ in query **104**, i.e., c.age>40'. Based on this determination, thread **222**B validates the path (vertex **308**)->(vertex **320**)->(vertex **304**) as a solution to query **104**.

[0091] According to an embodiment, when a path is validated as a solution to the query, the expression-specific intermediate results maintained, by the processing entity of the final query execution stage, are updated to reflect any changes caused by the property values of the validated path. For example, based on validating the path (vertex **308**)->(vertex **320**)->(vertex **304**) as a solution to query **104**, thread **222**B updates the expression-specific intermediate results maintained by the thread based on the property values in the validated path. When all potential solution paths for query **104** have been explored by system **200**, the results maintained by the processing entities are shared, and the final values of ‘MAX(a.age)’ and ‘SUM(b.age)’ are computed and returned as a result of query **104**.

[0092] According to an embodiment, a processing entity that processes a query execution stage after the early pruning-eligible stage of a query determines whether the values in the path-specific intermediate results would affect the expression-specific intermediate results maintained by that processing entity. The processing entity updates the flags in the message buffer if some, but not all, values marked with a TRUE flag would not affect the expression-specific intermediate values maintained by the processing entity. Further, the processing entity prunes the path from the set of potential solutions for the query (at the later query execution stage) if all of the message buffer variables associated with TRUE flags would not affect the intermediate results maintained by the entity. This optimization saves processing power required to perform further query evaluation, and is especially useful if there are multiple processing stages required to be performed after the early pruning-eligible processing stage.

[0093] The following pseudocode illustrates the technique of pruning for previously-computed values:

```
// Returns true iff the path exploration needs to be continued
bool update__prunable__flags(set<expression> prunable__expressions,
                    buffer query__buffer) {
    if (prunable__expressions.empty( )) {
        return true;
}
    bool need__to__continue__path = false;
        for (expression prunable__expression : prunable__expressions) {
            if (query__buffer.get__flag(prunable__expression) == true) {
            // Value would change all previous local values
                if (prunable__expression.get__local__value( ).would__be__changed(
                        query__buffer.get__value (prunable__expression)))
                {
                    need__to__continue__path = true;
                } else {
                    query__buffer.set__flag(prunable__expression, false);
                }
            }
        }
    return need__to__continue__path;
}
```

[0094] The following is pseudocode describing the implementation of verifying whether a path is prunable after evaluation of prunable expressions, i.e., at the early pruning-eligible stage:

```
 // Returns true iff the path exploration needs to be continued
bool verify__prunable__after__evaluation(expression evaluated__expression,
                    value evaluated__value, set<expression>
                    prunable__expressions, buffer query__buffer) {
    if (!evaluated__expression.is__prunable( )) {
        return true;
    }
    query__buffer.set__value(evaluated__expression, evaluated__value);
```

-continued

```
    if (evaluated__expression.get__local__value( ).would__be__changed(
                                evaluated__value)) {
        query__buffer.set__flag(evaluated__expression, true);
        return true;
    } else {
        query__buffer.set__flag(evaluated__expression, false);
        for (expression prunable__expression : prunable__expressions) {
            if (query__buffer.get__flag(prunable__expression) == true) {
            // Value would change all previous local values
                return true;
            }
        }
    return false;
    }
}
```

Query Planning & Optimization

[0095] For simplicity of illustration herein, no additional query optimizations, such as reordering of explored vertices, are described. However, query optimization is orthogonal to techniques described herein, and may be implemented as desired in connection with techniques described herein. For example, when integrating early solution pruning techniques described herein into a database management system, the query optimizer of the system should be carefully modified to integrate early pruning techniques with existing optimizations, such as vertex match re-ordering and utilization of indices. In many instances, the benefits from techniques described herein are amplified when solution path explorations start at (or close to) a vertex on which a prunable result is computed.

[0096] To illustrate, when optimizing query **104** (FIG. **1**), a query optimizer might choose to start the path exploration from vertex 'c' of the query path pattern because this vertex is associated with a filter in the query. In this case, the query optimizer uses reverse edges to go to vertices 'b' and 'a' in the query pattern.

[0097] If such an optimization is applied, early pruning could not be used. However, for example, if the query optimizer has information that all vertices in the graph data have a value of the 'age' property that is larger than 40, and that there is a large range of different values for the 'age' property, the query optimizer may decide that it would be more beneficial to execute the query starting at vertex 'a' in the query pattern, and to use an early pruning optimization. In this example, reordering the query would not optimize query execution because the filter c.age>40 is true for all vertices in the graph data, and the existence of different values of the 'age' property means that there will likely be many opportunities to prune the query early.

Database System Configuration

[0098] A database client, not depicted in FIG. **2**, connects to database system **200**. The client may comprise a database application running on a client node. The client interacts with an instance of database system **200**, such as one of instances **220** and **250**, by submitting commands that cause the instance to perform operations on data stored in the database. For example, a command may be a request to access or modify data from the database, perform operations on the data, and/or return the data to the client.

[0099] Typically, distributed database system **200** is implemented by multiple machines (including device **210** and device **240**) that are remotely connected. Referring to FIG. **2**, database server instance **220**, running on device **210**, maintains first database data **272** in persistent storage **230**, and database server instance **250**, running on device **240**, maintains second database data **274** in persistent storage **260**. Both database data **272** and database data **274** include graph database data for database **270**.

[0100] According to an embodiment, devices **210** and **240** correspond to clustered machines known as nodes, each running a database server instance, as described above. A database server instance (or "instance") is a server that comprises a combination of the software and allocation of resources from a machine node. Specifically, a server, such as a database server, or any other process is a combination of integrated software components and an allocation of computational resources, such as memory, a node (i.e., a computing device and/or memory accessible to the computing device), and/or sub-processes on the node for executing the integrated software components on a processor, the combination of the software and computational resources being dedicated to performing a particular function on behalf of one or more clients. Instances **220** and **250** collectively implement server-side functions of distributed database system **200**.

[0101] Database data **272** and **274** may each reside in volatile and/or non-volatile storage, such as first volatile memory **212**, second volatile memory **242**, first persistent storage **230**, and second persistent storage **260**. Each node implementing distributed database system **200** may include a virtual disk and/or a set of physical disks. Additionally or alternatively, database data **272** and **274** may each be stored, at least in part, in main memory of a database server computing device.

[0102] Database data for database **270** may be stored in any type of computer-readable storage media, such as flash storage or non-volatile memory. In some embodiments, database **270** is a distributed database comprising a plurality of databases each stored in a respective one or more storage media. In other embodiments, machines implementing the database system have shared access to database **270** via shared access to storage storing database data for database **270**.

[0103] One or more of the functions attributed to any process described herein, may be performed any other logical entity that may or may not be depicted in FIG. **2**, according to one or more embodiments. In an embodiment, each of the techniques and/or functionality described herein is performed automatically and may be implemented using one or more computer programs, other software elements, and/or digital logic in any of a general-purpose computer or a special-purpose computer, while performing data retrieval, transformation, and storage operations that involve interacting with and transforming the physical state of memory of the computer.

Hardware Overview

[0104] According to one embodiment, the techniques described herein are implemented by one or more special-purpose computing devices. The special-purpose computing devices may be hard-wired to perform the techniques, or may include digital electronic devices such as one or more application-specific integrated circuits (ASICs) or field programmable gate arrays (FPGAs) that are persistently programmed to perform the techniques, or may include one or more general purpose hardware processors programmed to perform the techniques pursuant to program instructions in firmware, memory, other storage, or a combination. Such special-purpose computing devices may also combine custom hard-wired logic, ASICs, or FPGAs with custom programming to accomplish the techniques. The special-purpose computing devices may be desktop computer systems, portable computer systems, handheld devices, networking devices or any other device that incorporates hard-wired and/or program logic to implement the techniques.

[0105] For example, FIG. **8** is a block diagram that illustrates a computer system **800** upon which an embodiment of the invention may be implemented. Computer system **800** includes a bus **802** or other communication mechanism for communicating information, and a hardware processor **804** coupled with bus **802** for processing information. Hardware processor **804** may be, for example, a general purpose microprocessor.

[0106] Computer system **800** also includes a main memory **806**, such as a random access memory (RAM) or other dynamic storage device, coupled to bus **802** for storing information and instructions to be executed by processor **804**. Main memory **806** also may be used for storing temporary variables or other intermediate information during execution of instructions to be executed by processor **804**. Such instructions, when stored in non-transitory storage media accessible to processor **804**, render computer system **800** into a special-purpose machine that is customized to perform the operations specified in the instructions.

[0107] Computer system **800** further includes a read only memory (ROM) **808** or other static storage device coupled to bus **802** for storing static information and instructions for processor **804**. A storage device **810**, such as a magnetic disk, optical disk, or solid-state drive is provided and coupled to bus **802** for storing information and instructions.

[0108] Computer system **800** may be coupled via bus **802** to a display **812**, such as a cathode ray tube (CRT), for displaying information to a computer user. An input device **814**, including alphanumeric and other keys, is coupled to bus **802** for communicating information and command selections to processor **804**. Another type of user input device is cursor control **816**, such as a mouse, a trackball, or cursor direction keys for communicating direction information and command selections to processor **804** and for controlling cursor movement on display **812**. This input device typically has two degrees of freedom in two axes, a first axis (e.g., x) and a second axis (e.g., y), that allows the device to specify positions in a plane.

[0109] Computer system **800** may implement the techniques described herein using customized hard-wired logic, one or more ASICs or FPGAs, firmware and/or program logic which in combination with the computer system causes or programs computer system **800** to be a special-purpose machine. According to one embodiment, the techniques herein are performed by computer system **800** in response to processor **804** executing one or more sequences of one or more instructions contained in main memory **806**. Such instructions may be read into main memory **806** from another storage medium, such as storage device **810**. Execution of the sequences of instructions contained in main memory **806** causes processor **804** to perform the process steps described herein. In alternative embodiments, hard-wired circuitry may be used in place of or in combination with software instructions.

[0110] The term "storage media" as used herein refers to any non-transitory media that store data and/or instructions that cause a machine to operate in a specific fashion. Such storage media may comprise non-volatile media and/or volatile media. Non-volatile media includes, for example, optical disks, magnetic disks, or solid-state drives, such as storage device **810**. Volatile media includes dynamic memory, such as main memory **806**. Common forms of storage media include, for example, a floppy disk, a flexible disk, hard disk, solid-state drive, magnetic tape, or any other magnetic data storage medium, a CD-ROM, any other optical data storage medium, any physical medium with patterns of holes, a RAM, a PROM, and EPROM, a FLASH-EPROM, NVRAM, any other memory chip or cartridge.

[0111] Storage media is distinct from but may be used in conjunction with transmission media. Transmission media participates in transferring information between storage media. For example, transmission media includes coaxial cables, copper wire and fiber optics, including the wires that comprise bus **802**. Transmission media can also take the form of acoustic or light waves, such as those generated during radio-wave and infra-red data communications.

[0112] Various forms of media may be involved in carrying one or more sequences of one or more instructions to processor **804** for execution. For example, the instructions may initially be carried on a magnetic disk or solid-state drive of a remote computer. The remote computer can load the instructions into its dynamic memory and send the instructions over a telephone line using a modem. A modem local to computer system **800** can receive the data on the telephone line and use an infra-red transmitter to convert the data to an infra-red signal. An infra-red detector can receive the data carried in the infra-red signal and appropriate circuitry can place the data on bus **802**. Bus **802** carries the data to main memory **806**, from which processor **804** retrieves and executes the instructions. The instructions received by main memory **806** may optionally be stored on storage device **810** either before or after execution by processor **804**.

[0113] Computer system **800** also includes a communication interface **818** coupled to bus **802**. Communication interface **818** provides a two-way data communication coupling to a network link **820** that is connected to a local network **822**. For example, communication interface **818** may be an integrated services digital network (ISDN) card, cable modem, satellite modem, or a modem to provide a data communication connection to a corresponding type of telephone line. As another example, communication interface **818** may be a local area network (LAN) card to provide a data communication connection to a compatible LAN. Wireless links may also be implemented. In any such implementation, communication interface **818** sends and receives electrical, electromagnetic or optical signals that carry digital data streams representing various types of information.

[0114] Network link **820** typically provides data communication through one or more networks to other data devices. For example, network link **820** may provide a connection through local network **822** to a host computer **824** or to data equipment operated by an Internet Service Provider (ISP) **826**. ISP **826** in turn provides data communication services through the worldwide packet data communication network now commonly referred to as the "Internet" **828**. Local network **822** and Internet **828** both use electrical, electromagnetic or optical signals that carry digital data streams.

The signals through the various networks and the signals on network link **820** and through communication interface **818**, which carry the digital data to and from computer system **800**, are example forms of transmission media.

[0115] Computer system **800** can send messages and receive data, including program code, through the network(s), network link **820** and communication interface **818**. In the Internet example, a server **830** might transmit a requested code for an application program through Internet **828**, ISP **826**, local network **822** and communication interface **818**.

[0116] The received code may be executed by processor **804** as it is received, and/or stored in storage device **810**, or other non-volatile storage for later execution.

Software Overview

[0117] FIG. **9** is a block diagram of a basic software system **900** that may be employed for controlling the operation of computer system **800**. Software system **900** and its components, including their connections, relationships, and functions, is meant to be exemplary only, and not meant to limit implementations of the example embodiment(s). Other software systems suitable for implementing the example embodiment(s) may have different components, including components with different connections, relationships, and functions.

[0118] Software system **900** is provided for directing the operation of computer system **800**. Software system **900**, which may be stored in system memory (RAM) **806** and on fixed storage (e.g., hard disk or flash memory) **810**, includes a kernel or operating system (OS) **910**.

[0119] The OS **910** manages low-level aspects of computer operation, including managing execution of processes, memory allocation, file input and output (I/O), and device I/O. One or more application programs, represented as **902**A, **902**B, **902**C . . . **902**N, may be "loaded" (e.g., transferred from fixed storage **810** into memory **806**) for execution by the system **900**. The applications or other software intended for use on computer system **800** may also be stored as a set of downloadable computer-executable instructions, for example, for downloading and installation from an Internet location (e.g., a Web server, an app store, or other online service).

[0120] Software system **900** includes a graphical user interface (GUI) **915**, for receiving user commands and data in a graphical (e.g., "point-and-click" or "touch gesture") fashion. These inputs, in turn, may be acted upon by the system **900** in accordance with instructions from operating system **910** and/or application(s) **902**. The GUI **915** also serves to display the results of operation from the OS **910** and application(s) **902**, whereupon the user may supply additional inputs or terminate the session (e.g., log off).

[0121] OS **910** can execute directly on the bare hardware **920** (e.g., processor(s) **804**) of computer system **800**. Alternatively, a hypervisor or virtual machine monitor (VMM) **930** may be interposed between the bare hardware **920** and the OS **910**. In this configuration, VMM **930** acts as a software "cushion" or virtualization layer between the OS **910** and the bare hardware **920** of the computer system **800**.

[0122] VMM **930** instantiates and runs one or more virtual machine instances ("guest machines"). Each guest machine comprises a "guest" operating system, such as OS **910**, and one or more applications, such as application(s) **902**, designed to execute on the guest operating system. The VMM **930** presents the guest operating systems with a virtual operating platform and manages the execution of the guest operating systems.

[0123] In some instances, the VMM **930** may allow a guest operating system to run as if it is running on the bare hardware **920** of computer system **800** directly. In these instances, the same version of the guest operating system configured to execute on the bare hardware **920** directly may also execute on VMM **930** without modification or reconfiguration. In other words, VMM **930** may provide full hardware and CPU virtualization to a guest operating system in some instances.

[0124] In other instances, a guest operating system may be specially designed or configured to execute on VMM **930** for efficiency. In these instances, the guest operating system is "aware" that it executes on a virtual machine monitor. In other words, VMM **930** may provide para-virtualization to a guest operating system in some instances.

[0125] A computer system process comprises an allotment of hardware processor time, and an allotment of memory (physical and/or virtual), the allotment of memory being for storing instructions executed by the hardware processor, for storing data generated by the hardware processor executing the instructions, and/or for storing the hardware processor state (e.g. content of registers) between allotments of the hardware processor time when the computer system process is not running. Computer system processes run under the control of an operating system, and may run under the control of other programs being executed on the computer system.

Cloud Computing

[0126] The term "cloud computing" is generally used herein to describe a computing model which enables on-demand access to a shared pool of computing resources, such as computer networks, servers, software applications, and services, and which allows for rapid provisioning and release of resources with minimal management effort or service provider interaction.

[0127] A cloud computing environment (sometimes referred to as a cloud environment, or a cloud) can be implemented in a variety of different ways to best suit different requirements. For example, in a public cloud environment, the underlying computing infrastructure is owned by an organization that makes its cloud services available to other organizations or to the general public. In contrast, a private cloud environment is generally intended solely for use by, or within, a single organization. A community cloud is intended to be shared by several organizations within a community; while a hybrid cloud comprises two or more types of cloud (e.g., private, community, or public) that are bound together by data and application portability.

[0128] Generally, a cloud computing model enables some of those responsibilities which previously may have been provided by an organization's own information technology department, to instead be delivered as service layers within a cloud environment, for use by consumers (either within or external to the organization, according to the cloud's public/private nature). Depending on the particular implementation, the precise definition of components or features provided by or within each cloud service layer can vary, but common examples include: Software as a Service (SaaS), in which consumers use software applications that are running upon a cloud infrastructure, while a SaaS provider manages or controls the underlying cloud infrastructure and applications. Platform as a Service (PaaS), in which consumers can use software programming languages and development tools supported by a PaaS provider to develop, deploy, and otherwise control their own applications, while the PaaS provider manages or controls other aspects of the cloud environment (i.e., everything below the run-time execution environment). Infrastructure as a Service (IaaS), in which consumers can deploy and run arbitrary software applications, and/or provision processing, storage, networks, and other fundamental computing resources, while an IaaS provider manages or controls the underlying physical cloud infrastructure (i.e., everything below the operating system layer). Database as a Service (DBaaS) in which consumers use a database server or Database Management System that is running upon a cloud infrastructure, while a DbaaS provider manages or controls the underlying cloud infrastructure, applications, and servers, including one or more database servers.

[0129] In the foregoing specification, embodiments of the invention have been described with reference to numerous specific details that may vary from implementation to implementation. The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense. The sole and exclusive indicator of the scope of the invention, and what is intended by the applicants to be the scope of the invention, is the literal and equivalent scope of the set of claims that issue from this application, in the specific form in which such claims issue, including any subsequent correction.

What is claimed is:

1. A computer-executed method comprising:

executing a query, as a prunable query, over graph data maintained in a graph database;

wherein the graph data comprises a plurality of vertices and a plurality of edges that represent relationships between the plurality of vertices;

wherein the query includes a prunable expression over a particular vertex property;

wherein the graph database is maintained, at least in part, by a particular computing device;

wherein executing the query, as a prunable query, over the graph data comprises:

the particular computing device determining that a first path, through the graph data, satisfies the query;

based at least in part on a first value, of the particular vertex property, of a vertex in the first path, the particular computing device deriving intermediate results for the prunable expression;

the particular computing device determining that a second value, of the particular vertex property, of a previously-unexplored vertex in the graph data does not affect the intermediate results for the prunable expression;

in response to determining that the second value does not affect the intermediate results for the prunable expression, the particular computing device discarding the previously-unexplored vertex from a set of potential solutions for the query.

2. The computer-executed method of claim **1**, wherein data for the previously-unexplored vertex, including the second value, is stored in storage that is local to the particular computing device.

3. The computer-executed method of claim **1**, wherein:

the graph database is a distributed graph database that is maintained by a plurality of computing devices that includes the particular computing device and a second computing device;

the previously-unexplored vertex includes edge data that refers to a second vertex stored by the second computing device; and

exploring the previously-unexplored vertex, for the query, requires sending intermediate results to the second computing device.

4. The computer-executed method of claim **1**, wherein the prunable expression is of a type included in a group of prunable expression types comprising: max-type expressions, min-type expressions, sum-type expressions, and distinct-type expressions.

5. The computer-executed method of claim **4**, wherein:

the query includes one or more expressions; and

the method further comprises determining whether the query is prunable by:

determining that types of the one or more expressions are included in the group of prunable expression types, and

determining that there are no expressions, in the query, having a type that is not included in the group of prunable expression types;

executing the query as a prunable query is performed in response to determining that the query is prunable.

6. The computer-executed method of claim **5**, wherein the one or more expressions, in the query, are sub-expressions to an expression in the query.

7. The computer-executed method of claim **1**, wherein executing the query, as a prunable query, over the graph data further comprises:

the particular computing device determining that a third value, of the particular vertex property, of a second previously-unexplored vertex in the graph data affects the intermediate results for the prunable expression;

in response to determining that the third value affects the intermediate results for the prunable expression, the particular computing device causing one or more edges, from the second previously-unexplored vertex in the graph data, to be traversed for the query.

8. The computer-executed method of claim **7**, wherein causing the one or more edges, from the second previously-unexplored vertex in the graph data, to be traversed for the query comprises storing, in a message buffer, at least the third value and information indicating that the third value affected the intermediate results for the prunable expression.

9. The computer-executed method of claim **1**, wherein:

the prunable expression is a first prunable expression;

the query comprises a second prunable expression over a second vertex property;

the graph database is a distributed graph database that is maintained by a plurality of computing devices that includes the particular computing device; and

executing the query, as a prunable query, over the graph data further comprises:

a first thread, running on a computing device of the plurality of computing devices, populating a message buffer with, at least, a value of the second vertex property and a flag that indicates whether the value of the second vertex property affects intermediate results maintained by the first thread;

a second thread, running on the particular computing device:

receiving the message buffer;

performing said discarding the previously-unexplored vertex from the set of potential solutions for the query in response to both determining that the second value does not affect the intermediate results for the prunable expression and determining that the flag, of the message buffer, indicates that the value of the second vertex property does not affect intermediate results maintained by the first thread.

10. The computer-executed method of claim **1**, wherein:

the prunable expression is a first prunable expression;

the query comprises a second prunable expression over a second vertex property;

the graph database is a distributed graph database that is maintained by a plurality of computing devices that includes the particular computing device; and

executing the query, as a prunable query, over the graph data further comprises:

a first thread, running on a computing device of the plurality of computing devices, populating a message buffer with, at least, a value of the second vertex property and a flag that indicates that the value of the second vertex property affects intermediate results maintained by the first thread;

a second thread, running on the particular computing device:

maintaining second intermediate results for the second prunable expression,

receiving the message buffer,

determining that the flag, in the message buffer, indicates that the value of the second vertex property affects intermediate results maintained by the first thread,

in response to determining that the flag, in the message buffer, indicates that the value of the second vertex property affects intermediate results maintained by the first thread, determining whether the value of the second vertex property, in the message buffer, affects the second intermediate results for the second prunable expression, and

in response to determining that the value of the second vertex property, in the message buffer, does not affect the second intermediate results for the second prunable expression maintained by the second thread, the particular computing device changing the flag to indicate that the value of the second vertex property, in the message buffer, does not affect intermediate results.

11. The computer-executed method of claim **1**, wherein the query is a first query, the method further comprising:

receiving a second query over the graph data;

determining that the second query includes at least one expression that is non-prunable;

in response to determining that the second query includes at least one expression that is non-prunable, executing the second query, over the graph data, as a non-prunable query.

12. One or more non-transitory computer-readable media storing instructions that, when executed by one or more processors, cause:

executing a query, as a prunable query, over graph data maintained in a graph database;

wherein the graph data comprises a plurality of vertices and a plurality of edges that represent relationships between the plurality of vertices;

wherein the query includes a prunable expression over a particular vertex property;

wherein the graph database is maintained, at least in part, by a particular computing device;

wherein executing the query, as a prunable query, over the graph data comprises:

the particular computing device determining that a first path, through the graph data, satisfies the query;

based at least in part on a first value, of the particular vertex property, of a vertex in the first path, the particular computing device deriving intermediate results for the prunable expression;

the particular computing device determining that a second value, of the particular vertex property, of a previously-unexplored vertex in the graph data does not affect the intermediate results for the prunable expression;

in response to determining that the second value does not affect the intermediate results for the prunable expression, the particular computing device discarding the previously-unexplored vertex from a set of potential solutions for the query.

13. The one or more non-transitory computer-readable media of claim **12**, wherein data for the previously-unexplored vertex, including the second value, is stored in storage that is local to the particular computing device.

14. The one or more non-transitory computer-readable media of claim **12**, wherein:

the graph database is a distributed graph database that is maintained by a plurality of computing devices that includes the particular computing device and a second computing device;

the previously-unexplored vertex includes edge data that refers to a second vertex stored by the second computing device; and

exploring the previously-unexplored vertex, for the query, requires sending intermediate results to the second computing device.

15. The one or more non-transitory computer-readable media of claim **12**, wherein the prunable expression is of a type included in a group of prunable expression types comprising: max-type expressions, min-type expressions, sum-type expressions, and distinct-type expressions.

16. The one or more non-transitory computer-readable media of claim **15**, wherein:

the query includes one or more expressions; and

the instructions further comprise instructions that, when executed by one or more processors, cause determining whether the query is prunable by:

determining that types of the one or more expressions are included in the group of prunable expression types, and

determining that there are no expressions, in the query, having a type that is not included in the group of prunable expression types;

executing the query as a prunable query is performed in response to determining that the query is prunable.

17. The one or more non-transitory computer-readable media of claim **16**, wherein the one or more expressions, in the query, are sub-expressions to an expression in the query.

18. The one or more non-transitory computer-readable media of claim **12**, wherein executing the query, as a prunable query, over the graph data further comprises:

the particular computing device determining that a third value, of the particular vertex property, of a second previously-unexplored vertex in the graph data affects the intermediate results for the prunable expression;

in response to determining that the third value affects the intermediate results for the prunable expression, the particular computing device causing one or more edges, from the second previously-unexplored vertex in the graph data, to be traversed for the query.

19. The one or more non-transitory computer-readable media of claim **18**, wherein causing the one or more edges, from the second previously-unexplored vertex in the graph data, to be traversed for the query comprises storing, in a message buffer, at least the third value and information indicating that the third value affected the intermediate results for the prunable expression.

20. The one or more non-transitory computer-readable media of claim **12**, wherein:

the prunable expression is a first prunable expression;

the query comprises a second prunable expression over a second vertex property;

the graph database is a distributed graph database that is maintained by a plurality of computing devices that includes the particular computing device; and

executing the query, as a prunable query, over the graph data further comprises:

a first thread, running on a computing device of the plurality of computing devices, populating a message buffer with, at least, a value of the second vertex property and a flag that indicates whether the value of the second vertex property affects intermediate results maintained by the first thread;

a second thread, running on the particular computing device:

receiving the message buffer;

performing said discarding the previously-unexplored vertex from the set of potential solutions for the query in response to both determining that the second value does not affect the intermediate results for the prunable expression and determining that the flag, of the message buffer, indicates that the value of the second vertex property does not affect intermediate results maintained by the first thread.

21. The one or more non-transitory computer-readable media of claim **12**, wherein:

the prunable expression is a first prunable expression;

the query comprises a second prunable expression over a second vertex property;

the graph database is a distributed graph database that is maintained by a plurality of computing devices that includes the particular computing device; and

executing the query, as a prunable query, over the graph data further comprises:

a first thread, running on a computing device of the plurality of computing devices, populating a message buffer with, at least, a value of the second vertex property and a flag that indicates that the value of the second vertex property affects intermediate results maintained by the first thread;

a second thread, running on the particular computing device:

maintaining second intermediate results for the second prunable expression,

receiving the message buffer,

determining that the flag, in the message buffer, indicates that the value of the second vertex property affects intermediate results maintained by the first thread,

in response to determining that the flag, in the message buffer, indicates that the value of the second vertex property affects intermediate results maintained by the first thread, determining whether the value of the second vertex property, in the message buffer, affects the second intermediate results for the second prunable expression, and

in response to determining that the value of the second vertex property, in the message buffer, does not affect the second intermediate results for the second prunable expression maintained by the second thread, the particular computing device changing the flag to indicate that the value of the second vertex property, in the message buffer, does not affect intermediate results.

22. The one or more non-transitory computer-readable media of claim **12**, wherein the query is a first query, and the instructions further comprise instructions that, when executed by one or more processors, cause:

receiving a second query over the graph data;

determining that the second query includes at least one expression that is non-prunable;

in response to determining that the second query includes at least one expression that is non-prunable, executing the second query, over the graph data, as a non-prunable query.

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