US 20170090807A1

(19) United States
(12) Patent Application Publication
Gupta et al.
(10) Pub. No.: US 2017/0090807 A1
(43) Pub. Date: Mar. 30, 2017

(54) TECHNOLOGIES FOR MANAGING CONNECTED DATA ON PERSISTENT MEMORY-BASED SYSTEMS

(71) Applicants: **Vishakha Gupta**, Beaverton, OR (US); **Alain Kagi**, Portland, OR (US); **Philip Lantz**, Cornelius, OR (US); **Subramanya Dulloor**, Santa Clara, CA (US)

(72) Inventors: **Vishakha Gupta**, Beaverton, OR (US); **Alain Kagi**, Portland, OR (US); **Philip Lantz**, Cornelius, OR (US); **Subramanya Dulloor**, Santa Clara, CA (US)

(21) Appl. No.: **14/866,941**

(22) Filed: **Sep. 26, 2015**

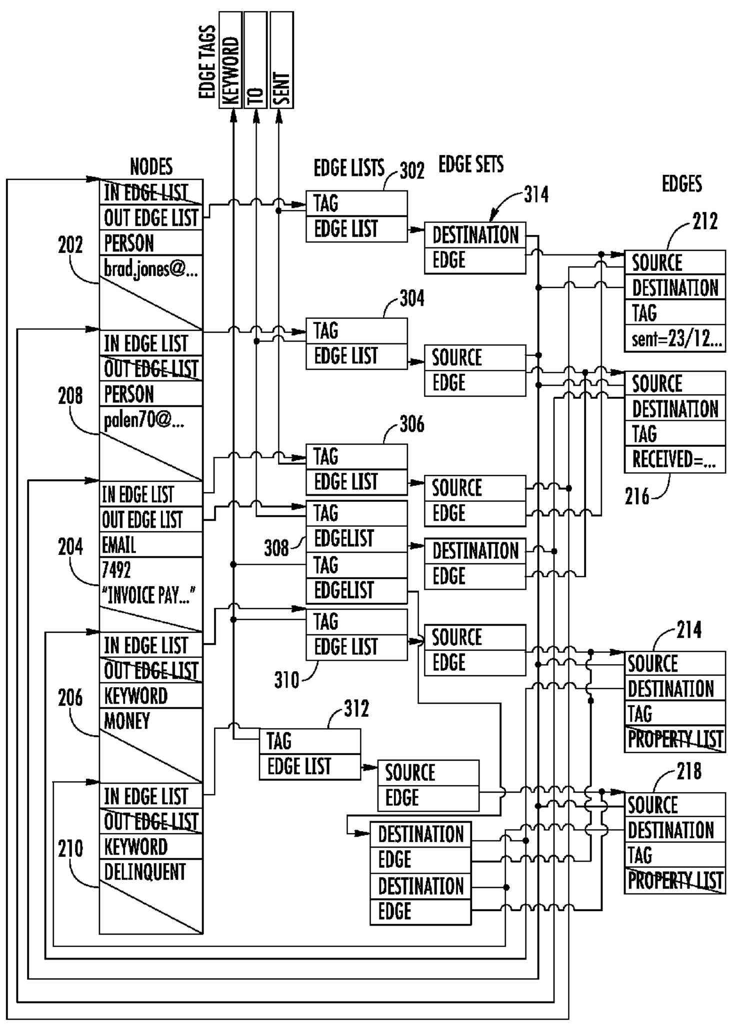
Publication Classification

(51) **Int. Cl.**
G06F 3/06 (2006.01)

(52) **U.S. Cl.**
CPC *G06F 3/0631* (2013.01); *G06F 3/0604* (2013.01); *G06F 3/0683* (2013.01)

(57) **ABSTRACT**

Managing connected data, such as a graph data store, includes a computing device with persistent memory and volatile memory. The computing device stores a graph data store with a plurality of nodes and edges in persistent memory. Each of the edges defines the relationship between at least two of the nodes. The nodes and edges may contain tags and properties containing additional information. In response to a search request query, the computing device generates an iterator object stored in volatile memory with a reference to one or more nodes and/or edges in the graph data store. The split between volatile and persistent memory allocation could be used for other objects, such as allocators and transactions. Other embodiments are described and claimed.



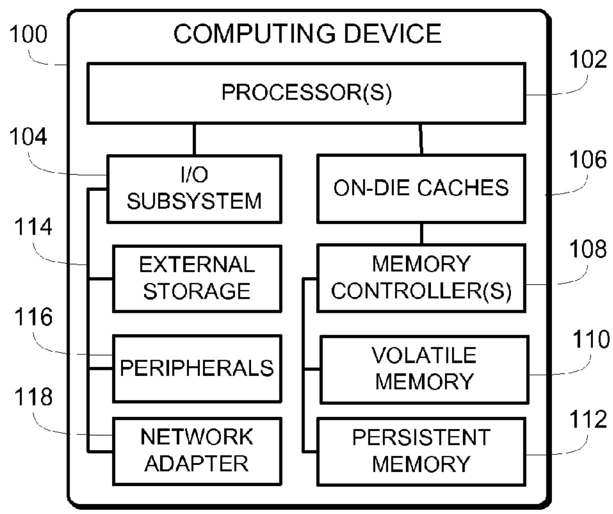

100
COMPUTING DEVICE
102
PROCESSOR(S)
104
I/O SUBSYSTEM
106
ON-DIE CACHES
114
EXTERNAL STORAGE
108
MEMORY CONTROLLER(S)
116
PERIPHERALS
110
VOLATILE MEMORY
118
NETWORK ADAPTER
112
PERSISTENT MEMORY

FIG. 1

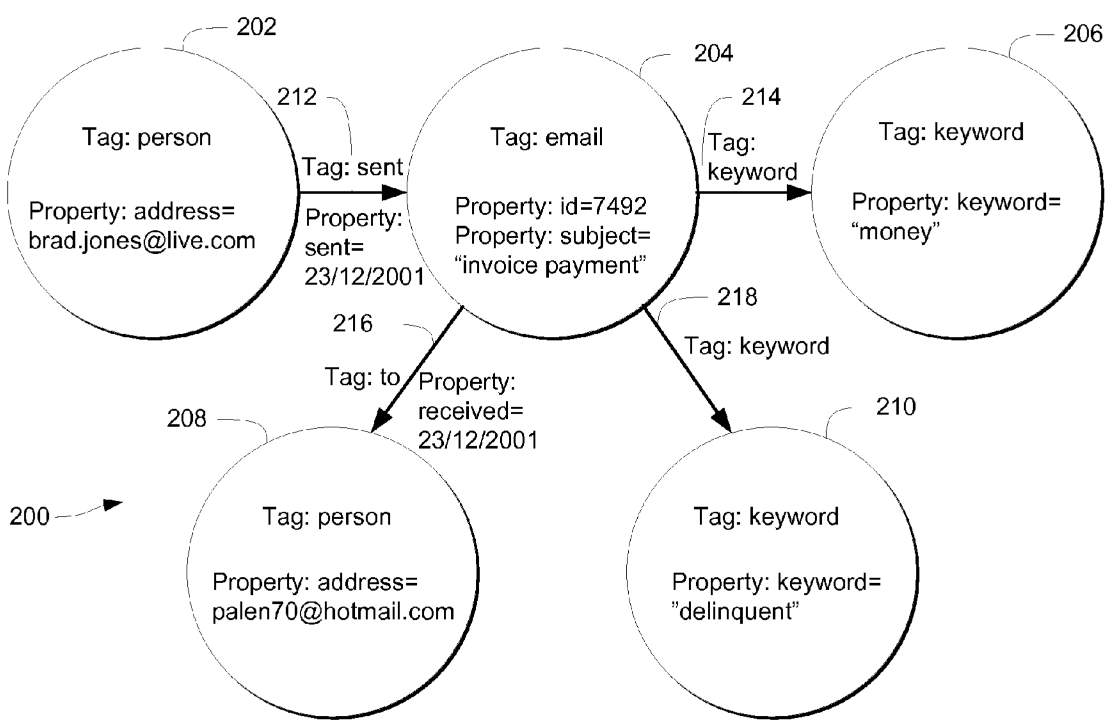

202
Tag: person
Property: address= brad.jones@live.com
212
Tag: sent
Property: sent= 23/12/2001
204
Tag: email
Property: id=7492
Property: subject= “invoice payment”
214
Tag: keyword
206
Tag: keyword
Property: keyword= “money”
216
Tag: to
Property: received= 23/12/2001
218
Tag: keyword
208
Tag: person
Property: address= palen70@hotmail.com
210
Tag: keyword
Property: keyword= ”delinquent”
200

FIG. 2

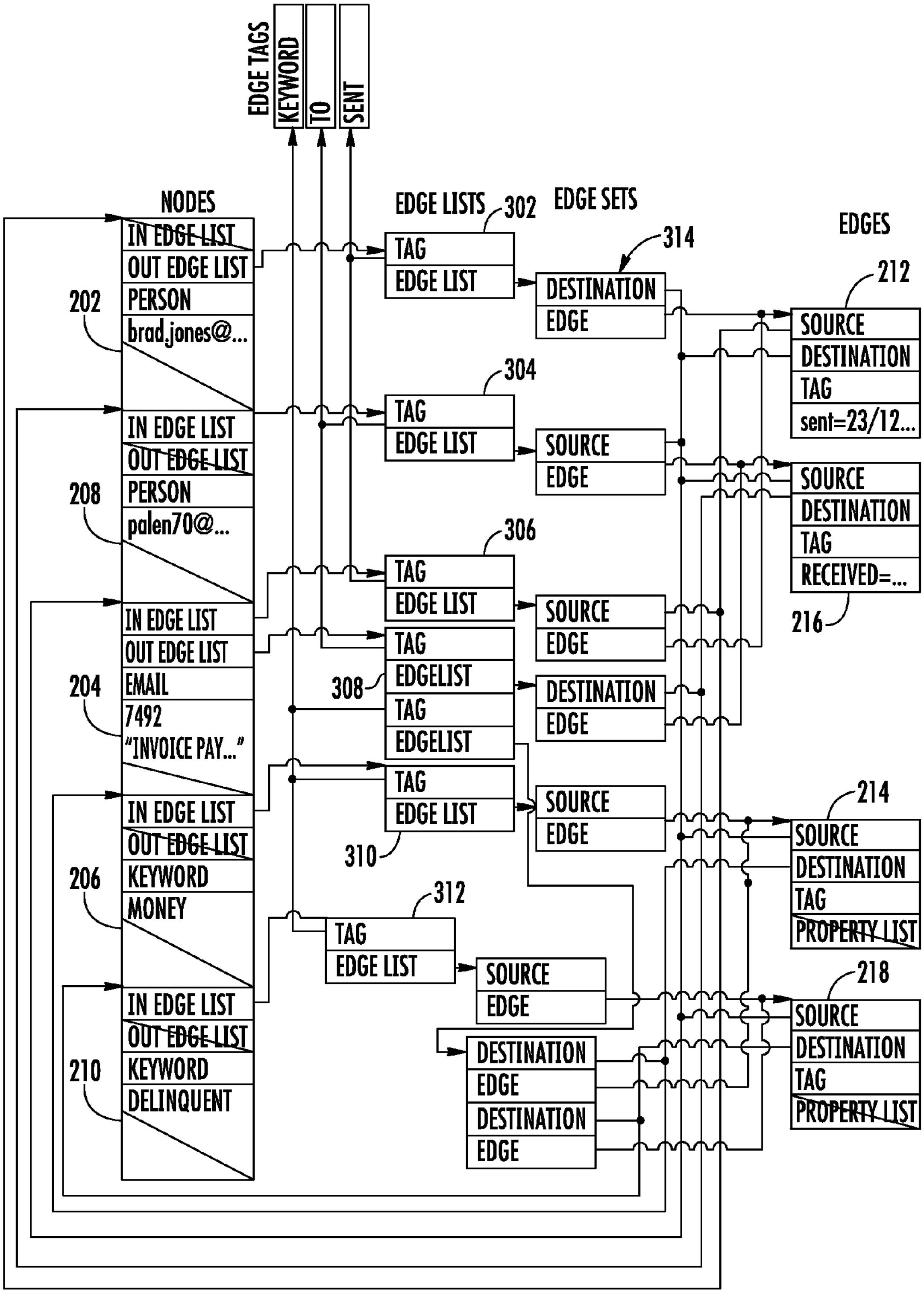

EDGE TAGS
KEYWORD
TO
SENT
NODES
IN EDGE LIST
OUT EDGE LIST
PERSON
brad.jones@...
202
IN EDGE LIST
OUT EDGE LIST
PERSON
palen70@...
208
IN EDGE LIST
OUT EDGE LIST
EMAIL
7492
"INVOICE PAY..."
204
IN EDGE LIST
OUT EDGE LIST
KEYWORD
MONEY
206
IN EDGE LIST
OUT EDGE LIST
KEYWORD
DELINQUENT
210
EDGE LISTS
302
304
306
308
310
312
TAG
EDGE LIST
EDGELIST
EDGE SETS
314
DESTINATION
SOURCE
EDGE
EDGES
212
SOURCE
DESTINATION
TAG
sent=23/12...
RECEIVED=...
216
214
218
PROPERTY LIST

FIG. 3

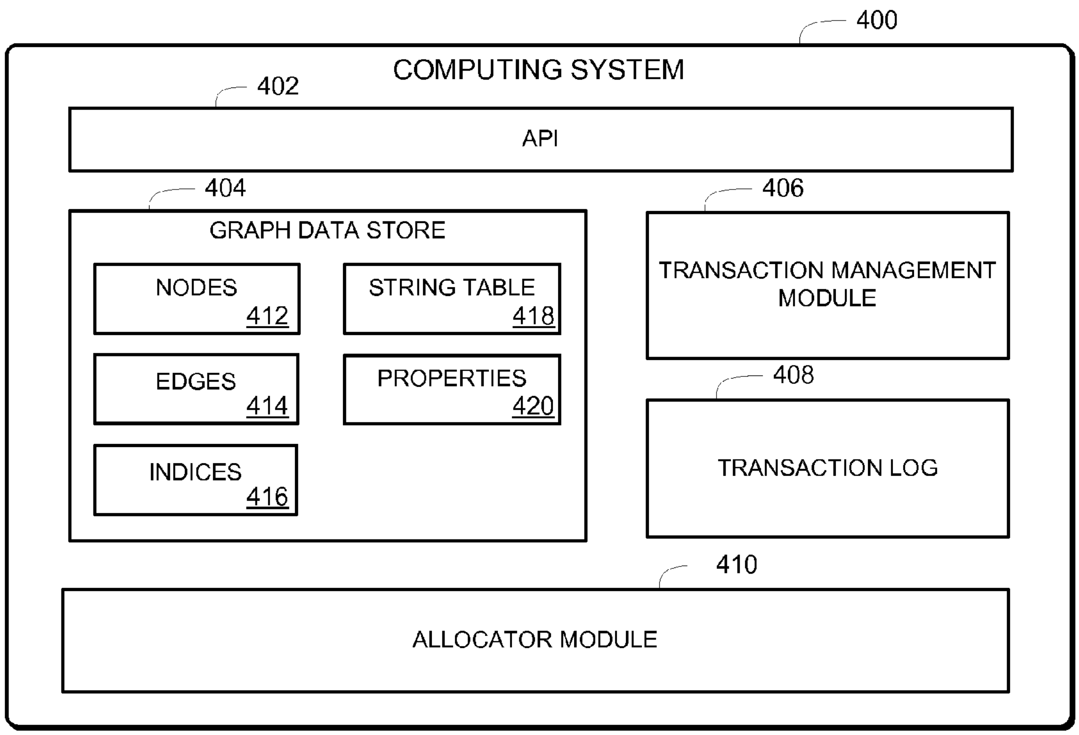

400
COMPUTING SYSTEM
402
API
404
GRAPH DATA STORE
NODES 412
STRING TABLE 418
EDGES 414
PROPERTIES 420
INDICES 416
406
TRANSACTION MANAGEMENT MODULE
408
TRANSACTION LOG
410
ALLOCATOR MODULE

FIG. 4

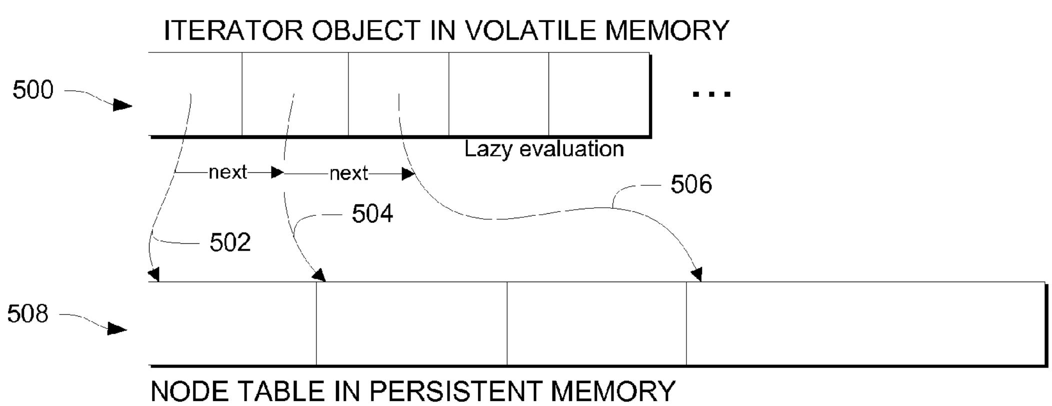

ITERATOR OBJECT IN VOLATILE MEMORY
500
...
Lazy evaluation
next
next
506
504
502
508
NODE TABLE IN PERSISTENT MEMORY

FIG. 5

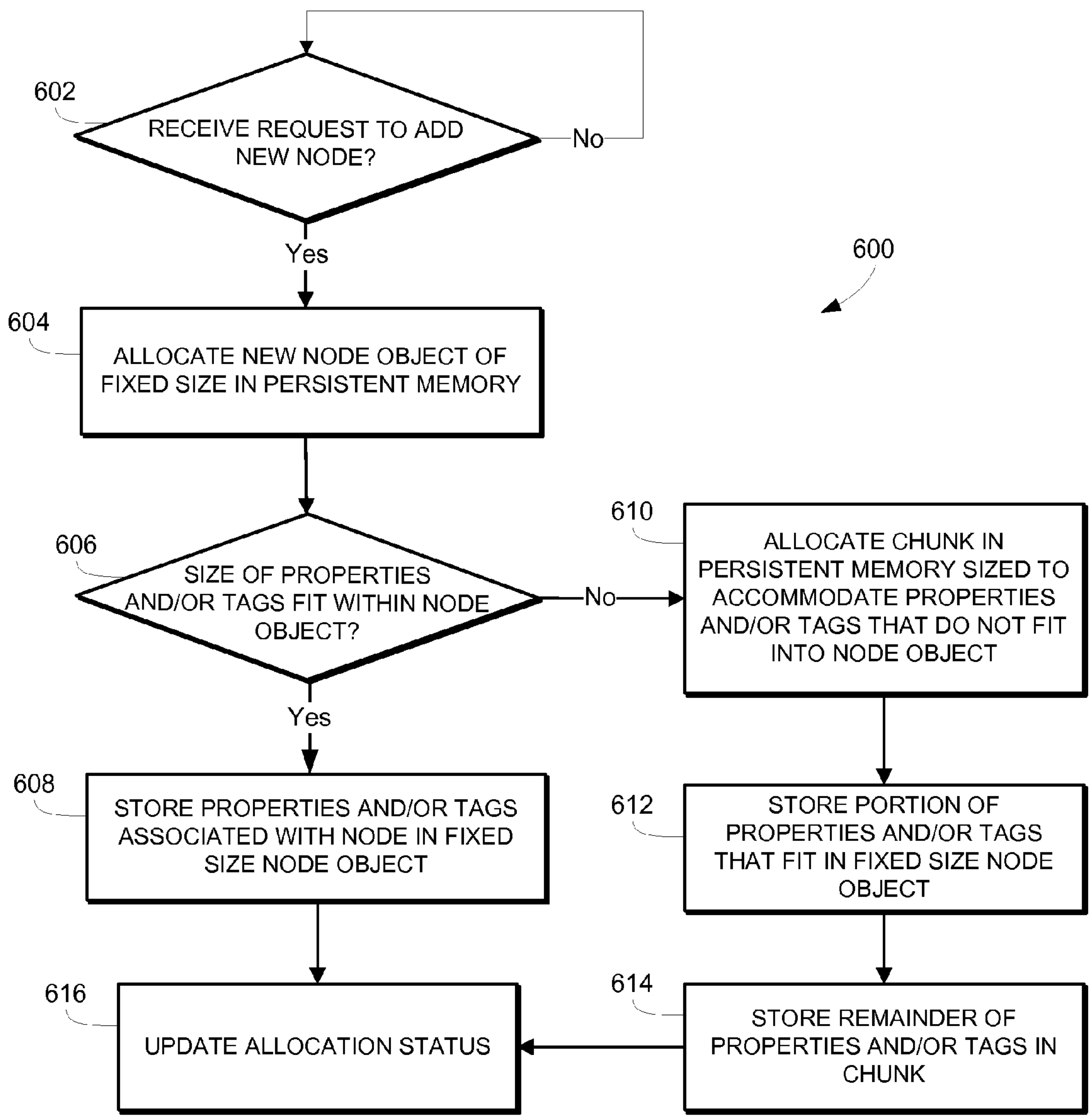

602
RECEIVE REQUEST TO ADD NEW NODE?
No
Yes
600
604
ALLOCATE NEW NODE OBJECT OF FIXED SIZE IN PERSISTENT MEMORY
606
SIZE OF PROPERTIES AND/OR TAGS FIT WITHIN NODE OBJECT?
No
610
ALLOCATE CHUNK IN PERSISTENT MEMORY SIZED TO ACCOMMODATE PROPERTIES AND/OR TAGS THAT DO NOT FIT INTO NODE OBJECT
Yes
608
STORE PROPERTIES AND/OR TAGS ASSOCIATED WITH NODE IN FIXED SIZE NODE OBJECT
612
STORE PORTION OF PROPERTIES AND/OR TAGS THAT FIT IN FIXED SIZE NODE OBJECT
616
UPDATE ALLOCATION STATUS
614
STORE REMAINDER OF PROPERTIES AND/OR TAGS IN CHUNK

FIG. 6

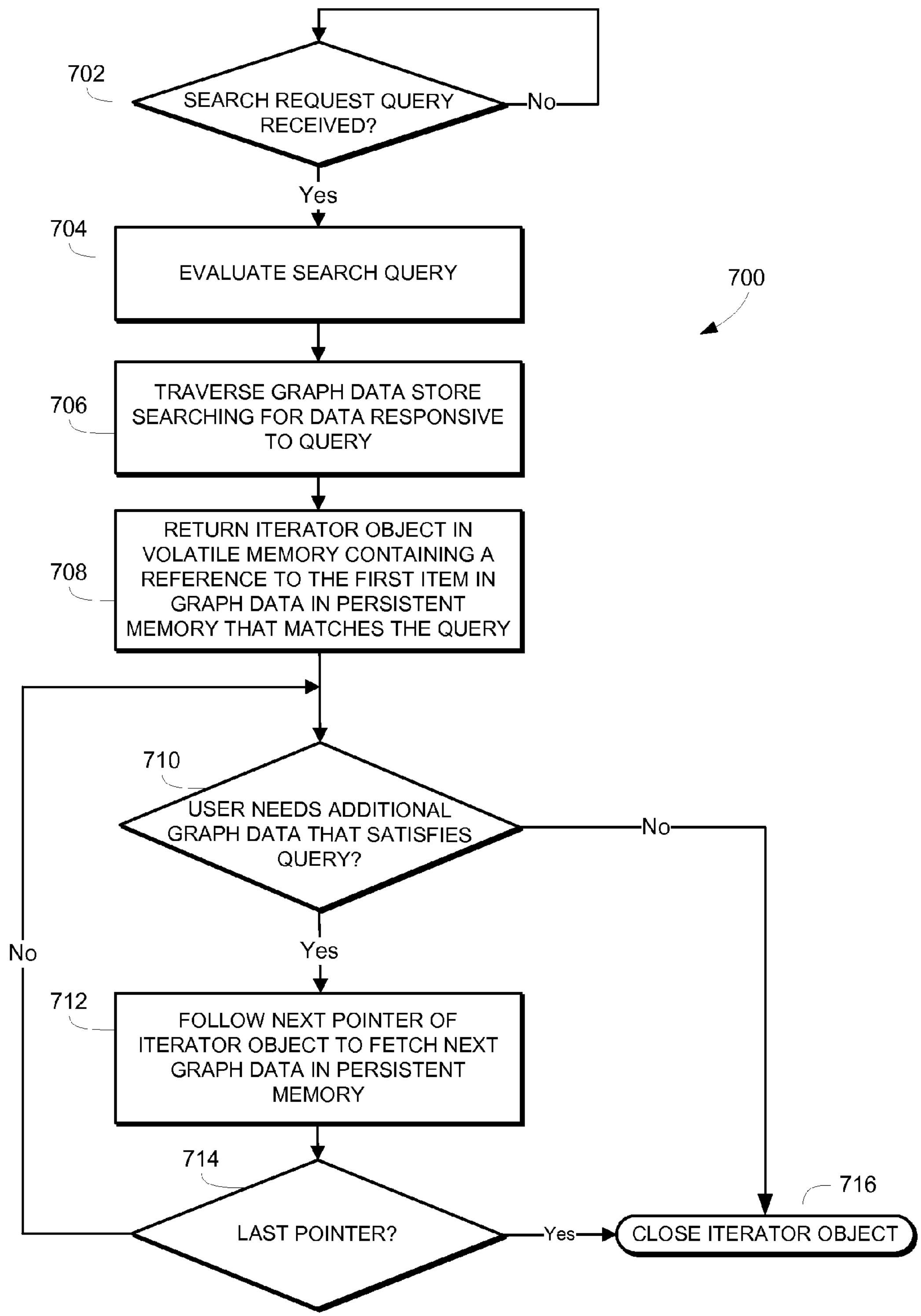

700
702
SEARCH REQUEST QUERY RECEIVED?
No
Yes
704
EVALUATE SEARCH QUERY
706
TRAVERSE GRAPH DATA STORE SEARCHING FOR DATA RESPONSIVE TO QUERY
708
RETURN ITERATOR OBJECT IN VOLATILE MEMORY CONTAINING A REFERENCE TO THE FIRST ITEM IN GRAPH DATA IN PERSISTENT MEMORY THAT MATCHES THE QUERY
710
USER NEEDS ADDITIONAL GRAPH DATA THAT SATISFIES QUERY?
No
Yes
712
FOLLOW NEXT POINTER OF ITERATOR OBJECT TO FETCH NEXT GRAPH DATA IN PERSISTENT MEMORY
714
LAST POINTER?
No
Yes
716
CLOSE ITERATOR OBJECT

FIG. 7

TECHNOLOGIES FOR MANAGING CONNECTED DATA ON PERSISTENT MEMORY-BASED SYSTEMS

BACKGROUND

[0001] Queries for neighbors, friends-of-friends connections, paths between nodes or other interesting patterns have grown tremendously important on today's ever evolving datasets. Graph-based databases (or data stores) have the potential to bring the important ACID (Atomicity, Consistency, Isolation, Durability) properties associated with transactions to a data organization that treats relationships as a first-class concept. For example, unknown or non-obvious relationships between nodes can be identified.

[0002] New persistent memory technologies, such as memristors and phase change memory, offer a byte-addressable interface and memory access latencies that are comparable to those of volatile memory, such as dynamic random-access memory (DRAM). These persistent memory technologies may have a profound influence on organized data storage due to the availability of faster persistent storage and larger main memories. However, none of the existing graph-based databases support a completely in-memory database model.

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] The concepts described herein are illustrated by way of example and not by way of limitation in the accompanying figures. For simplicity and clarity of illustration, elements illustrated in the figures are not necessarily drawn to scale. Where considered appropriate, reference labels have been repeated among the figures to indicate corresponding or analogous elements.

[0004] FIG. **1** is a simplified block diagram of at least one embodiment of a computing device for managing connected data;

[0005] FIGS. **2** and **3** are a simplified block diagrams of an illustrative graph data store that may be generated and/or managed by the computing device of FIG. **1**;

[0006] FIG. **4** is a simplified block diagram of at least one embodiment of an environment of the computing device of FIG. **1**;

[0007] FIG. **5** is a simplified flow diagram of at least one embodiment in which an interactor object includes pointers to a graph data store;

[0008] FIG. **6** is a simplified flow diagram of at least one embodiment of a method for generating and/or modifying a graph data store that may be executed by the computing device of FIGS. **1** and **4**; and

[0009] FIG. **7** is a simplified flow diagram of at least one embodiment of a method for responding to a search request that may be executed by the computer system of FIGS. **1** and **4**.

DETAILED DESCRIPTION OF THE DRAWINGS

[0010] While the concepts of the present disclosure are susceptible to various modifications and alternative forms, specific embodiments thereof have been shown by way of example in the drawings and will be described herein in detail. It should be understood, however, that there is no intent to limit the concepts of the present disclosure to the particular forms disclosed, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives consistent with the present disclosure and the appended claims.

[0011] References in the specification to "one embodiment," "an embodiment," "an illustrative embodiment," etc., indicate that the embodiment described may include a particular feature, structure, or characteristic, but every embodiment may or may not necessarily include that particular feature, structure, or characteristic. Moreover, such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure, or characteristic is described in connection with an embodiment, it is submitted that it is within the knowledge of one skilled in the art to effect such feature, structure, or characteristic in connection with other embodiments whether or not explicitly described. Additionally, it should be appreciated that items included in a list in the form of "at least one A, B, and C" can mean (A); (B); (C); (A and B); (A and C); (B and C); or (A, B, and C). Similarly, items listed in the form of "at least one of A, B, or C" can mean (A); (B); (C); (A and B); (A and C); (B and C); or (A, B, and C).

[0012] The disclosed embodiments may be implemented, in some cases, in hardware, firmware, software, or any combination thereof. The disclosed embodiments may also be implemented as instructions carried by or stored on a transitory or non-transitory machine-readable (e.g., computer-readable) storage medium, which may be read and executed by one or more processors. A machine-readable storage medium may be embodied as any storage device, mechanism, or other physical structure for storing or transmitting information in a form readable by a machine (e.g., a volatile or non-volatile memory, a media disc, or other media device).

[0013] In the drawings, some structural or method features may be shown in specific arrangements and/or orderings. However, it should be appreciated that such specific arrangements and/or orderings may not be required. Rather, in some embodiments, such features may be arranged in a different manner and/or order than shown in the illustrative figures. Additionally, the inclusion of a structural or method feature in a particular figure is not meant to imply that such feature is required in all embodiments and, in some embodiments, may not be included or may be combined with other features.

[0014] Referring now to FIG. **1**, an illustrative computing device **100** for managing connected data, such as a graph data store, includes at least one processor **102**, an I/O subsystem **104**, at least one on-die cache **106**, and a memory controller **108** to control a volatile memory **110** and a persistent memory **112**. In use, as described below, an entire graph data store is stored in the persistent memory **112**. The graph data store includes a plurality of nodes and edges that define relationships between the nodes. In some embodiments, the nodes and/or edges each includes a unique identifier. The computing device **100** is configured to add, delete, and/or read nodes and/or edges (and other data) in the graph data store. The computing device **100** is also configured to generate an iterator object in response to a search request query. The iterator object includes pointers (or references) to nodes and/or edges in the graph data store that are responsive to the search request. The iterator object is stored in the volatile memory **110** and accesses the graph data store in the persistent memory based on the pointers of the iterator object. The terms "pointers" and "references" are broadly intended to encompass any reference to a value in memory.

[0015] The computing device **100** may be embodied as any type of device capable of performing the functions described herein. For example, the computing device **100** may be embodied as, without limitation, a computer, a workstation, a server computer, a laptop computer, a notebook computer, a tablet computer, a smartphone, a mobile computing device, a desktop computer, a distributed computing system, a multiprocessor system, a consumer electronic device, a smart appliance, and/or any other computing device capable of executing software code segments. As shown in FIG. **1**, the illustrative computing device **100** includes the processor **102**, the I/O subsystem **104**, the on-die cache **106**, and the memory controller **108** to control volatile memory **110** and persistent memory **112**. Of course, the computing device **100** may include other or additional components, such as those commonly found in a workstation (e.g., various input/output devices), in other embodiments. For example, the computing device **100** may include an external storage **114**, peripherals **116**, and/or a network adapter **118**. Additionally, in some embodiments, one or more of the illustrative components may be incorporated in, or otherwise form a portion of, another component. For example, the memory **110**, **112** or portions thereof, may be incorporated in the processor **102** in some embodiments.

[0016] The processor **102** may be embodied as any type of processor capable of performing the functions described herein. For example, the processor may be embodied as a single or multi-core processor(s), digital signal processor, microcontroller, or other processor or processing/controlling circuit. The volatile memory **110** and persistent memory **112** may be embodied as any type of volatile memory and persistent memory, respectively, capable of performing the functions described herein. Volatile memory **110** contrasts with persistent memory **112** in that the persistent memory **112** does not lose content when power is lost. In operation, the volatile memory **110** and persistent member **112** may store various data and software used during operation of the computing device **100** such as operating systems, applications, programs, libraries, and drivers. The memory **110**, **112** is communicatively coupled to the processor **102** via the memory bus using memory control(s) **108**, which may be embodied as circuitry and/or components to facilitate input/output operations with the processor **102**, the memory **110**, **112**, and other components of the computing device **100**.

[0017] The I/O subsystem **104** may be embodied as, or otherwise include, memory controller hubs, input/output control hubs, firmware devices, communication links (i.e., point-to-point links, bus links, wires, cables, light guides, printed circuit board traces, etc.) and/or other components and subsystems to facilitate the input/output operations. In some embodiments, the I/O subsystem **104** may form a portion of a system-on-a-chip (SoC) and be incorporated, along with the processor **102**, the memory **110**, **112**, and other components of the computing device **100**, on a single integrated circuit chip.

[0018] An external storage device **114** may be coupled to the processor **102** with the I/O subsystem **104**. The external storage device **114** may be embodied as any type of device or devices configured for short-term or long-term storage of data such as, for example, memory devices and circuits, memory cards, hard disk drives, solid-state drives, or other data storage devices. Unlike existing systems, however, one or more embodiments contemplate that computing device **100** would not include any external storage **114** and that a graph database and all other data needed by computing device **100** would be stored on the persistent memory **112** on the memory bus instead of the external storage **114**.

[0019] The computing device **100** may also include peripherals **116**. The peripherals **116** may include any number of additional input/output devices, interface devices, and/or other peripheral devices. By way of example only, the peripheral **116** may include a display that could be embodied as any type of display capable of displaying digital information such as a liquid crystal display (LCD), a light emitting diode (LED), a plasma display, a cathode ray tube (CRT), or other type of display device.

[0020] The computing device **100** illustratively includes a network adapter **118**, which may be embodied as any communication circuit, device, or collection thereof, capable of enabling communications between the computing device **100** and other remote devices over a computer network (not shown). The network adapter **118** may be configured to use any one or more communication technology (e.g., wired or wireless communications) and associated protocols (e.g., Ethernet, Bluetooth®, Wi-Fi®, WiMAX, etc.) to effect such communication.

[0021] Referring to FIG. **2**, an illustrative embodiment is shown with an example graph data store **200**, which may be stored in persistent memory **112**. The graph data store **200** includes a plurality of nodes (also called vertices) that are connected with a plurality of edges that establish relationships between the nodes. The graph data store **200** is shown for purposes of example only. Although the graph data store **200** shown includes five nodes and four edges for purposes of example, one skilled in the art should understand that more or less nodes and/or edges could be used depending on the data set. In some circumstances, for example, millions of nodes and/or edges (or more) could be provided in a graph data store.

[0022] As shown, the example graph data store **200** includes a first node **202**, a second node **204**, a third node **206**, a fourth node **208**, and a fifth node **210** and a first edge **212**, a second edge **214**, a third edge **216**, and a fourth edge **218**. Each node and edge of the graph data store **200** has an associated tag that can be used for classification. For example, the classification could identify entity types, document types, or other attribute types of a node and/or edge. In the example shown, the first and fourth nodes **202**, **208** are associated with the tag "person," the second node **204** with the tag "email," and the third and fifth nodes **206**, **210** with the tag "keyword." Likewise, the first edge **212** is associated with the tag "sent," the second and fourth edges **214**, **218** with the tag "keyword," and the third edge **208** with the tag "person." In cases where usage does not require a tag, a default tag could be used. In some embodiments, the tag may be a short string.

[0023] In addition to and distinct from tags, one or more properties may be associated with the nodes and/or edges of the graph data store **200**. A property is illustratively embodied as a key-value pair, in which the key is a short string and the value is one of a plurality of pre-defined types. By way of example only, the predefined property types may include Booleans, integers, floats, strings, times, and/or blobs (i.e., arbitrary strings of bits). In some embodiments, all predefined types, with the exception of blobs, are orderable. In the example shown, the first node **202** is associated with the property key "address" and has a value of "brad.jones@live.com." As shown, the second node **204** is associated with two properties. The first property has a key of "id" and a value of "7482" and a second property key of "subject" and a value of "invoice payment." Likewise, the edges of the graph data store **200** may include one or more properties. For example, the first edge **212** includes a property key of "sent" and a value of "23/12/2001." By way of another example, the third edge **216** includes the property key "received" and a value of "23/12/2001."

[0024] FIG. **3** illustratively shows an example layout of the graph data store **200** in persistent memory **112**. In this example, the tags and properties associated with nodes **202**, **204**, **206**, **208** are stored in node objects within the node table. The nodes **202**, **204**, **206**, **208** include an in and/or out edge list that points to an edge list **300**; however, in some embodiments, the edges could be undirected. As shown, for example, node **202** includes an out edge list pointer to an edge list **302** associated with edge **212**. By way of another example, node **208** includes an in edge list pointer to an edge list **304** associated with **216**. As shown, node **204** includes both an in edge list pointer and an out edge list pointer. The in edge list pointer points to an edge list **306** associated with edge **212**. The out edge list point points to an edge list **308** associated with edge **216**. Node **206**, in the example shown, includes an in edge list pointer that points to an edge list **310** associated with edge **214**. Additionally, node **210** includes an in edge list pointer that points to an edge list **312** associated with edge **218**. The edge lists **302**, **304**, **306**, **308**, **310**, **312** include pointers to edge tags. In the example shown, edge lists **310**, **312** include a pointer to edge tag "keyword." Edge lists **304**, **308** include pointers to edge tag "to." Additionally, edge lists **302**, **306** include pointers to the edge tag "sent." In some embodiments, an intermediate data structure could be used called a tag-sorted edgeset **314** to speed up neighbor lookups in particular and graph traversal in general. Tag-sorted edgesets collate edge information with identical tags to allow efficient iteration over related edges. In addition, the edge-sets may contain source/destination node information to allow efficient accessing of neighbor nodes.

[0025] Referring now to FIG. **4**, in the illustrative embodiment, the computing device **100** establishes an environment **400** during operation. The illustrative environment **400** includes an API **402**, a graph data store **404**, a transaction management module **406**, a transaction log **408**, and an allocator module **410**. The graph data store **404** illustratively includes a plurality of nodes **412**, a plurality of edges **414**, tag-based and/or property-based indices **416**, a string table **418**, and a plurality of properties **420** associated with the nodes **412** and/or edges **414**. The various modules of the environment **400** may be embodied as hardware, firmware, software, or a combination thereof. As such, in some embodiments, one or more of the modules of the environment **400** may be embodied as circuitry or collection of electrical devices (e.g., transaction management circuitry **406** and/or allocator circuitry **410**). It should be appreciated that, in such embodiments, one or more of the transaction management circuitry **406** and/or the allocator circuitry **410** may form a portion of one or more of the processor **102**, the I/O subsystem **104**, the memory **110**, **112**, the external storage **114**, the network adapter **118**, and/or other components of the computing device **100**. Additionally, in some embodiments, one or more of the illustrative modules may form a portion of another module and/or one or more of the illustrative modules may be independent of one another.

[0026] As shown, the environment **400** includes an API **402** through which programs may interact with the graph data store **404**. For example, the API **402** may be used as an interface by a program to add (or create), read, remove (delete) and/or modify the nodes **412**, edges **414**, indices **416**, string table **418** and/or properties **420** of the graph data store **400**. The transaction management module **406** manages transactions with the graph data store **400** and updates the transaction log **408** so that the state of the data store is consistent at transaction boundaries and can be recovered if a failure occurs within a transaction.

[0027] The allocator module **410** is configured to manage allocations or partitions in the persistent memory **112** for the various entities (e.g., nodes, edges, properties). The allocator module **410** chooses the data structure sizes and layout to be cache-efficient, organizes data and logs to be streaming and prefetch friendly, and avoids unnecessary writes to persistent memory **112** because the write bandwidth is lower than that of volatile memory **110**. In some embodiments, the allocator module **410** stores nodes **408** and edges **410** in one or more tables with fixed-size objects. To maximize storage utilization inside each node or edge element, the properties of these entities are stored inline in a best-fit manner. For example, the properties of entities could be stored in-line to maximize storage. For properties that exceed the amount of space available within a node or edge object, the allocator module **410** allocates separate chunks that are also filled in a best-fit manner. Despite the space-efficient layout, these properties are accessible directly, without the need to "deserialize" them into an accessible format, as is the case with other compact data storage options or disk-based storage options.

[0028] Based on current projections, the persistent memory **112** will be slower than volatile memory **110** for read and write, and will have limited durability, meaning the probability of failure increases after some large number of writes. In one embodiment, the data structures, such as iterator objects, allocator objects, and transaction objects, can be split between volatile memory **110** and persistent memory **112** to optimize wear and access times. For example, the allocator module **410** could include statistics and the actual persistent memory areas that it manages. Since the statistics are updated quite frequently with each allocation/de-allocation and also since they are primarily used internally rather than part of the user data, this data can be stored in volatile memory **110** and perhaps a checkpoint to this data in the allocator header could be stored in persistent memory **112** if required.

[0029] In some embodiments, the API **402** provides an interface through which the graph data store **404** can be searched. In the illustrative embodiment, the API **402** is configured to return an iterator object in response to a search request on the graph data store **404**. An illustrative iterator object **500** is shown in FIG. **5**. The iterator object **500** includes a reference to data in the graph data store **404**. For example, the iterator object **500** could include a first pointer **502** that points to the first node in the graph data store **404** that matches the search query. If the user requests additional data that satisfies the query, the API **402** could be used to advance the iterator object **500** to the next node matching the query. As shown, a second pointer **504** illustrates the iterator object **500** having been advanced by the API **402** to the next pointer, which points to the next node matching the query. A third pointer **506** illustrates the iterator object **500** having been advanced, yet again, to the next node matching the query. This process would continue with the iterator object **500** advancing to the next pointer as the user requests additional matches in the graph data store **404** using the API **402**. The iterator object **500** is stored in volatile memory **110** and maintains its volatile state, such as the next pointer, for speed of access, but points to the actual graph data (such as nodes or properties) of the graph data store **404** in persistent memory **112**, which is accessed as the iterator object **500** progresses. Although FIG. **5** illustratively shows pointers **502** of the iterator object **500** pointing to data in a node table **508**, the pointers could point to any data in the graph data store **404** in other embodiments. As shown, a program searching the graph data store **404** through the API **402**, will be returned an iterator object **500** that can be examined by the program one element at a time (next pointer to next pointer). In that sense, the queries are evaluated lazily and follow the "next" pointers only when requested by the user causing a data fetch. Since the entire graph data store **404** is stored in directly-accessible persistent memory **112**, serializing and de-serializing data can be avoided, unlike existing graph stores, which use disks for making data persistent, and managed languages that do not provide a way to access data from buffer caches without creating temporary objects that reside in memory.

[0030] Referring now to FIG. **6**, in use, the computing device **100** may execute a method **600** to create a new entity, such as a node and/or edge in the graph data store **404**. Although the method **600** is directed to the creation of a new node, the method **600** may also be used to create, delete and/or update other entities in the graph data store **404**. In the example shown, the node being created is associated with properties; however, nodes and edges need not necessarily be associated with properties and/or tags. In the example embodiment shown, the method **600** begins with block **602** in which the computing device **100** determines whether a request has been received, such as through the API **402**, to create a new node. If a new request is received, the method **600** advances to block **604** in which the computing device **100** creates a new node object of a fixed size in persistent memory **112**. Subsequently, in block **606**, the computing device **100** evaluates the size of the properties and/or tags (and any other data) associated with the new node to determine whether this data will fit within the fixed size of the node object. If the size of the properties and/or tags associated with the new node will fit within the new node object, the method **600** advances to block **608** in which the properties and/or tags are stored within the new node object. Alternatively, if the size of the properties and/or tags associated with the new node exceeds the size of the node object, the method **600** advances to block **610** in which the computing device **100** allocates a chunk in persistent memory. Subsequently, in block **612**, the computing device **100** stores the portions of the properties and/or tags that will fit in the fixed sized node object. Additionally, in block **614**, the computing device **100** stores the remainder of properties and/or tags in the allocated chunk of persistent memory. The method **600** will next advance to block **616** in which the allocation status is updated since the operation was completed successfully. This is consistent with ACID principles since a failure would not result in inconsistent data, but would be reverted without an update to the allocation status.

[0031] Referring now to FIG. **7**, in use, the computing device **100** may also execute a method **700** for performing a search on the graph data store **404**. The method **700** begins with block **702** in which the computing device **100** determines whether a search query has been received. The search query may be received via the API **402** from a requesting computing device, service, program, and/or other source. If a search request query has been received, the method **700** advances to block **704** in which the computing device **100** evaluates the search query. For example, the computing device **100** may parse the search query to prepare for searching of the graph data store **404**. Subsequently, in block **706**, the computing device **100** traverses the graph data store **404** to find data responsive to the search query. In block **708**, in response to locating data responsive to the search query, the computing device **100** generates and returns an iterator object stored in volatile memory **110** that includes a reference to the first item in the graph data store **404** in persistent memory **112** that matches the query. As such, in block **710**, the computing device **100** may receive a user request for additional graph data that matches the query. If the user requests this additional graph data, the method **700** advances to block **712** in which the computing device **100** fetches the graph data associated with the next reference in the iterator object. Subsequently, in block **714**, the computing device **100** determines whether the last data responsive to the query has been reached. If not, the method loops back to block **710** in which the computing device **100** determines whether another user request for graph data associated with the next pointer in the iterator object has been received. If, however, the last data responsive to the query has been reached, the method **700** advances to block **716**.

[0032] It should be appreciated that, in some embodiments, any one or more of the methods described herein may be embodied as various instructions stored on a computer-readable media, which may be executed by the processor **102**, a peripheral device **116**, and/or other components of the computing device **100** to cause the computing device **100** to perform the corresponding method. The computer-readable media may be embodied as any type of media capable of being read by the computing device **100** including, but not limited to, the memory **110**, **112**, the external storage **114**, a local memory or cache **106** of the processor **102**, other memory or data storage devices of the computing device **100**, portable media readable by a peripheral device **116** of the computing device **100**, and/or other media.

EXAMPLES

[0033] Illustrative examples of the technologies disclosed herein are provided below. An embodiment of the technologies may include any one or more, and any combination of, the examples described below.

[0034] Example 1 includes computing device comprising at least one processor; at least one memory controller to access a volatile memory device and a persistent memory device on a memory bus, the persistent memory device having stored therein a graph data store including a plurality of nodes relationally arranged with a plurality of edges, each of the plurality of edges defining a relationship between at least two of the plurality of nodes, the volatile memory device having stored therein a plurality of instructions that, when executed by the processor, causes the processor to in response to an operation on the graph data store, partition data between the volatile memory device and the persistent memory device to minimize writes on the persistent memory device.

[0035] Example 2 includes the subject matter of Example 1, and wherein at least a portion of the nodes are associated with at least one tag representing a classification of the node.

[0036] Example 3 includes the subject matter of any of Example 1 or 2, and wherein at least a portion of the edges are associated with at least one tag representing a classification of the edge.

[0037] Example 4 includes the subject matter of any of Examples 1-3, and wherein the graph data store includes a tag sorted edge set to collate edges and associated nodes with identical tags.

[0038] Example 5 includes the subject matter of any of Examples 1-4, and wherein at least a portion of the nodes are associated with at least one property in the form of a key-value pair.

[0039] Example 6 includes the subject matter of any of Examples 1-5, and wherein at least a portion of the edges are associated with at least one property in the form of a key-value pair.

[0040] Example 7 includes the subject matter of any of Examples 1-6, and wherein the plurality of instructions further cause the processor to organize the nodes and/or edges of the graph data store in the persistent memory device as fixed size objects.

[0041] Example 8 includes the subject matter of any of Examples 1-7, and wherein the plurality of instructions further cause the processor to store at least one property and/or tag associated with a node and/or edge in-line in the fixed-size object representing the node and/or edge.

[0042] Example 9 includes the subject matter of any of Examples 1-8, and wherein the plurality of instructions further cause the processor to allocate, in response to the property and/or tag associated with the node and/or edge exceeding the size of the fixed-size object, a chunk of the persistent memory device separate from the fixed-size object.

[0043] Example 10 includes the subject matter of any of Examples 1-9, and wherein the plurality of instructions further cause the processor, in response to a search request query, to generate an iterator object stored on the volatile memory device that includes a reference to one or more nodes and/or edges in the graph data store on the persistent memory device.

[0044] Example 11 includes the subject matter of any of Examples 1-10, and wherein the plurality of instructions further cause the processor to advance the iterator object to directly access nodes and/or edges of the graph data store in response to a request for an additional match to the search query.

[0045] Example 12 includes the subject matter of any of Examples 1-11, and wherein the processor stores an allocator on the volatile memory device, the allocator comprising one or more memory addresses of the graph data store in the persistent memory device.

[0046] Example 13 includes the subject matter of any of Examples 1-12, and wherein the processor stores a portion of a transaction object on volatile memory and a portion of the transaction object on persistent memory such that writes to persistent memory are minimized while still maintaining the atomicity, consistency, isolation, durability ("ACID") properties of the graph data store.

[0047] Example 14 includes a method for managing a graph data store on a persistent memory device. The method includes storing, on a persistent memory device, a graph data store comprising a plurality of nodes and a plurality of edges, each of the plurality of edges defining a relationship between at least two of the plurality of nodes; managing a operation on the graph data store by storing a first portion of resulting data on a volatile memory device and a second portion of the resulting data on the persistent memory device to minimize writes on the persistent memory device.

[0048] Example 15 includes the subject matter of Example 14, further including allocating, by a computing device, a fixed size object on a persistent memory device to each of the plurality of nodes and edges.

[0049] Example 16 includes the subject matter of any of Example 14 or 15, and further including evaluating, by a computing device, a search request query on the graph data store; and generating, by a computing device, an iterator object including a reference to one or more nodes and/or edges in the graph data store in response to the search request query, wherein the iterator object is stored on a volatile memory device

[0050] Example 17 includes the subject matter of any of Examples 14-16, and wherein the computing device manages the operation by partitioning the first portion and the second portion of resulting data to minimize writes to the persistent memory device.

[0051] Example 18 includes the subject matter of any of Examples 14-17, and further including storing at least one property and/or tag associated with a node and/or edge in-line in a fixed-size object.

[0052] Example 19 includes the subject matter of any of Examples 14-18, and wherein responsive to the property and/or tag associated with the node and/or edge exceeding the size of the fixed-size object, allocating a chunk of the persistent memory device separate from the fixed-size object.

[0053] Example 20 includes the subject matter of any of Examples 14-19, and wherein responsive to a search request query on the graph data store, further comprising storing an iterator that is an output to the search request query in a volatile memory device, the iterator including a reference to one or more nodes and/or edges in the graph data store on the persistent memory device.

[0054] Example 21 includes the subject matter of any of Examples 14-20, and further including advancing the iterator to directly access nodes and/or edges of the graph data store in response to a request for an additional match to the search query.

[0055] Example 22 includes the subject matter of any of Examples 14-21, and wherein at least a portion of the nodes are associated with at least one tag representing a classification of the node.

[0056] Example 23 includes the subject matter of any of Examples 14-22, and wherein at least a portion of the edges are associated with at least one tag representing a classification of the edge.

[0057] Example 24 includes the subject matter of any of Examples 14-23, and wherein the graph data store includes a tag sorted edge set to collate edges with identical tags to allow efficient iteration over related edges.

[0058] Example 25 includes the subject matter of any of Examples 14-24, and, wherein at least a portion of the nodes are associated with at least one property in the form of a key-value pair.

[0059] Example 26 includes the subject matter of any of Examples 14-25, and wherein at least a portion of the edges are associated with at least one property in the form of a key-value pair.

[0060] Example 27 includes one or more machine readable storage media comprising a plurality of instructions stored thereon that in response to being executed result in a computing device performing the method of any of Examples 14-26.

[0061] Example 28 includes a computing device comprising means for storing, on a persistent memory device, a graph data store comprising a plurality of nodes and a plurality of edges, each of the plurality of edges defining a relationship between at least two of the plurality of nodes; and means for managing a operation on the graph data store by storing a first portion of resulting data on a volatile memory device and a second portion of the resulting data on the persistent memory device to minimize writes on the persistent memory device.

[0062] Example 29 includes the subject matter of Example 28, and further including means for allocating a fixed size object on a persistent memory device to each of the plurality of nodes and edges.

[0063] Example 30 includes the subject matter of Examples 28 or 29, and further including means for evaluating a search request query on the graph data store; and means for generating an iterator object including a reference to one or more nodes and/or edges in the graph data store in response to the search request query, wherein the iterator object is stored on a volatile memory device

[0064] Example 31 includes the subject matter of any of Examples 28-30, and further including means for managing the operation by partitioning the first portion and the second portion of resulting data to minimize writes to the persistent memory device.

[0065] Example 32 includes the subject matter of any of Examples 28-31, and further including means for storing at least one property and/or tag associated with a node and/or edge in-line in a fixed-size object.

[0066] Example 33 includes the subject matter of any of Examples 28-32, and further including means for allocating, responsive to the property and/or tag associated with the node and/or edge exceeding the size of the fixed-size object, a chunk of the persistent memory device separate from the fixed-size object.

[0067] Example 34 includes the subject matter of any of Examples 28-33, and further including means for storing, responsive to a search request query on the graph data store, an iterator that is an output to the search request query in a volatile memory device, the iterator including a reference to one or more nodes and/or edges in the graph data store on the persistent memory device.

[0068] Example 35 includes the subject matter of any of Examples 28-34, and further including means for advancing the iterator to directly access nodes and/or edges of the graph data store in response to a request for an additional match to the search query.

[0069] Example 36 includes the subject matter of any of Examples 28-35, and wherein at least a portion of the nodes are associated with at least one tag representing a classification of the node.

[0070] Example 37 includes the subject matter of any of Examples 28-36, and wherein at least a portion of the edges are associated with at least one tag representing a classification of the edge.

[0071] Example 38 includes the subject matter of any of Examples 28-37, and wherein the graph data store includes a tag sorted edge set to collate edges with identical tags to allow efficient iteration over related edges.

[0072] Example 39 includes the subject matter of any of Examples 28-38, and wherein at least a portion of the nodes are associated with at least one property in the form of a key-value pair.

[0073] Example 40 includes the subject matter of any of Examples 28-39, and wherein at least a portion of the edges are associated with at least one property in the form of a key-value pair.

1. A computing device comprising:

at least one processor;

at least one memory controller to access a volatile memory device and a persistent memory device on a memory bus, the persistent memory device having stored therein a graph data store including a plurality of nodes relationally arranged with a plurality of edges, each of the plurality of edges defining a relationship between at least two of the plurality of nodes, the volatile memory device having stored therein a plurality of instructions that, when executed by the processor, causes the processor to:

in response to an operation on the graph data store, partition data between the volatile memory device and the persistent memory device to minimize writes on the persistent memory device.

2. The computing device of claim **1**, wherein at least a portion of the nodes are associated with at least one tag representing a classification of the node.

3. The computing device of claim **1**, wherein at least a portion of the edges are associated with at least one tag representing a classification of the edge.

4. The computing device of claim **3**, wherein the graph data store includes a tag sorted edge set to collate edges and associated nodes with identical tags.

5. The computing device of claim **1**, wherein at least a portion of the nodes are associated with at least one property in the form of a key-value pair.

6. The computing device of claim **1**, wherein at least a portion of the edges are associated with at least one property in the form of a key-value pair.

7. The computing device of claim **1**, wherein the plurality of instructions further cause the processor to organize the nodes and/or edges of the graph data store in the persistent memory device as fixed size objects.

8. The computing device of claim **7**, wherein the plurality of instructions further cause the processor to store at least one property and/or tag associated with a node and/or edge in-line in the fixed-size object representing the node and/or edge.

9. The computing device of claim **8**, wherein the plurality of instructions further cause the processor to allocate, in response to the property and/or tag associated with the node and/or edge exceeding the size of the fixed-size object, a chunk of the persistent memory device separate from the fixed-size object.

10. One or more machine readable storage media comprising a plurality of instructions stored thereon that, when executed, cause a computing device to:
- store, on a persistent memory device, a graph data store comprising a plurality of nodes and a plurality of edges, each of the plurality of edges defining a relationship between at least two of the plurality of nodes;
- manage an operation on the graph data store by storing a first portion of resulting data on a volatile memory device and a second portion of the resulting data on the persistent memory device to minimize writes on the persistent memory device.

11. The one or more machine readable storage media of claim **10**, wherein the plurality of instructions further cause the computing device to manage the operation by partitioning the first portion and the second portion of resulting data to minimize writes to the persistent memory device.

12. The one or more machine readable storage media of claim **10**, wherein the plurality of instructions further cause the computing device to:
- storie at least one property and/or tag associated with a node and/or edge in-line in a fixed-size object; and
- allocate, responsive to the property and/or tag associated with the node and/or edge exceeding the size of the fixed-size object, a chunk of the persistent memory device separate from the fixed-size object.

13. The one or more machine readable storage media of claim **10**, wherein at least a portion of the nodes are associated with at least one tag representing a classification of the node.

14. The one or more machine readable storage media of claim **10**, wherein at least a portion of the edges are associated with at least one tag representing a classification of the edge.

15. The one or more machine readable storage media of claim **14**, wherein the graph data store includes a tag sorted edge set to collate edges with identical tags to allow efficient iteration over related edges.

16. The one or more machine readable storage media of claim **10**, wherein at least a portion of the nodes are associated with at least one property in the form of a key-value pair.

17. The one or more machine readable storage media of claim **10**, wherein at least a portion of the edges are associated with at least one property in the form of a key-value pair.

18. A method for managing a graph data store on a persistent memory device, the method comprising:
- storing, on a persistent memory device, a graph data store comprising a plurality of nodes and a plurality of edges, each of the plurality of edges defining a relationship between at least two of the plurality of nodes; and
- managing a operation on the graph data store by storing a first portion of resulting data on a volatile memory device and a second portion of the resulting data on the persistent memory device to minimize writes on the persistent memory device.

19. The method of claim **18**, wherein the computing device manages the operation by partitioning the first portion and the second portion of resulting data to minimize writes to the persistent memory device.

20. The method of claim **18**, further comprising:
- storing at least one property and/or tag associated with a node and/or edge in-line in a fixed-size object; and
- allocating, responsive to the property and/or tag associated with the node and/or edge exceeding the size of the fixed-size object, a chunk of the persistent memory device separate from the fixed-size object.

21. The method of claim **18**, wherein at least a portion of the nodes are associated with at least one tag representing a classification of the node.

22. The method of claim **18**, wherein at least a portion of the edges are associated with at least one tag representing a classification of the edge.

23. The method of claim **22**, wherein the graph data store includes a tag sorted edge set to collate edges with identical tags to allow efficient iteration over related edges.

24. The method of claim **18**, wherein at least a portion of the nodes are associated with at least one property in the form of a key-value pair.

25. The method of claim **18**, wherein at least a portion of the edges are associated with at least one property in the form of a key-value pair.

* * * * *