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(54) **WEB-SCALE DATA PROCESSING SYSTEM AND METHOD**

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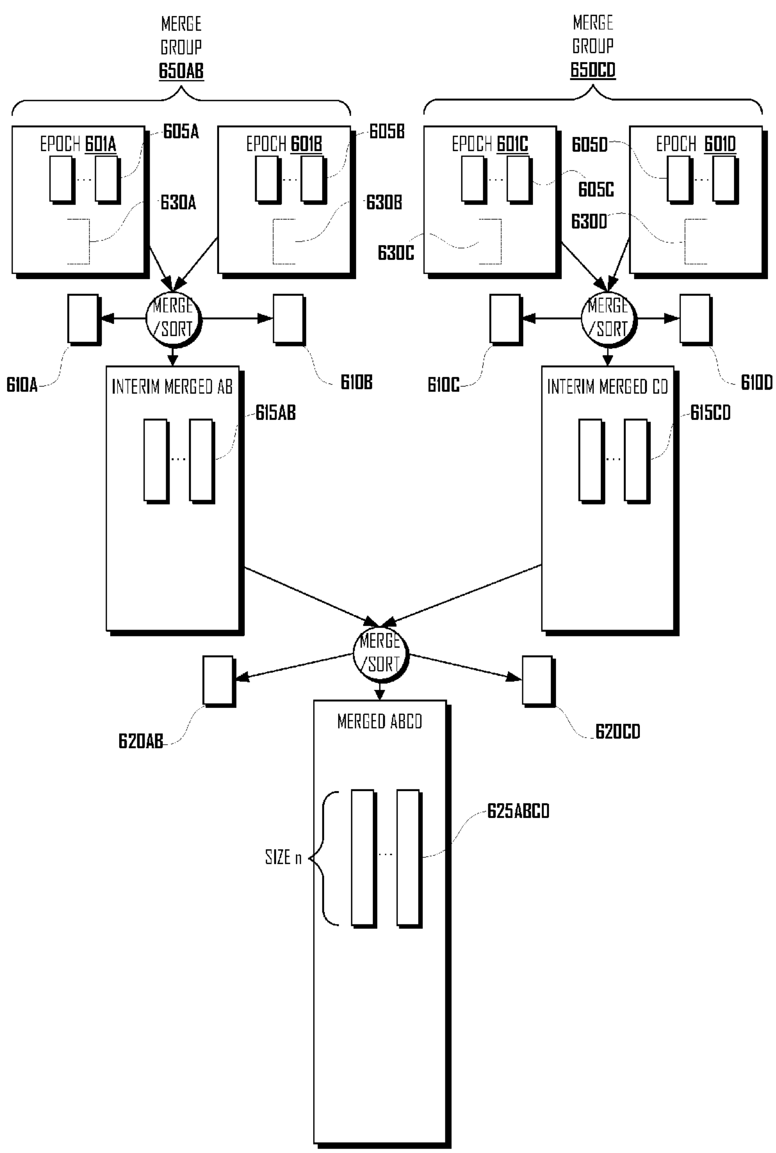
(57) **ABSTRACT**

A web-scale data processing system and method are provided herein. More particularly, a web-scale data processing system and method for crawling, storing, processing, encoding, and/or serving web-scale data are disclosed.



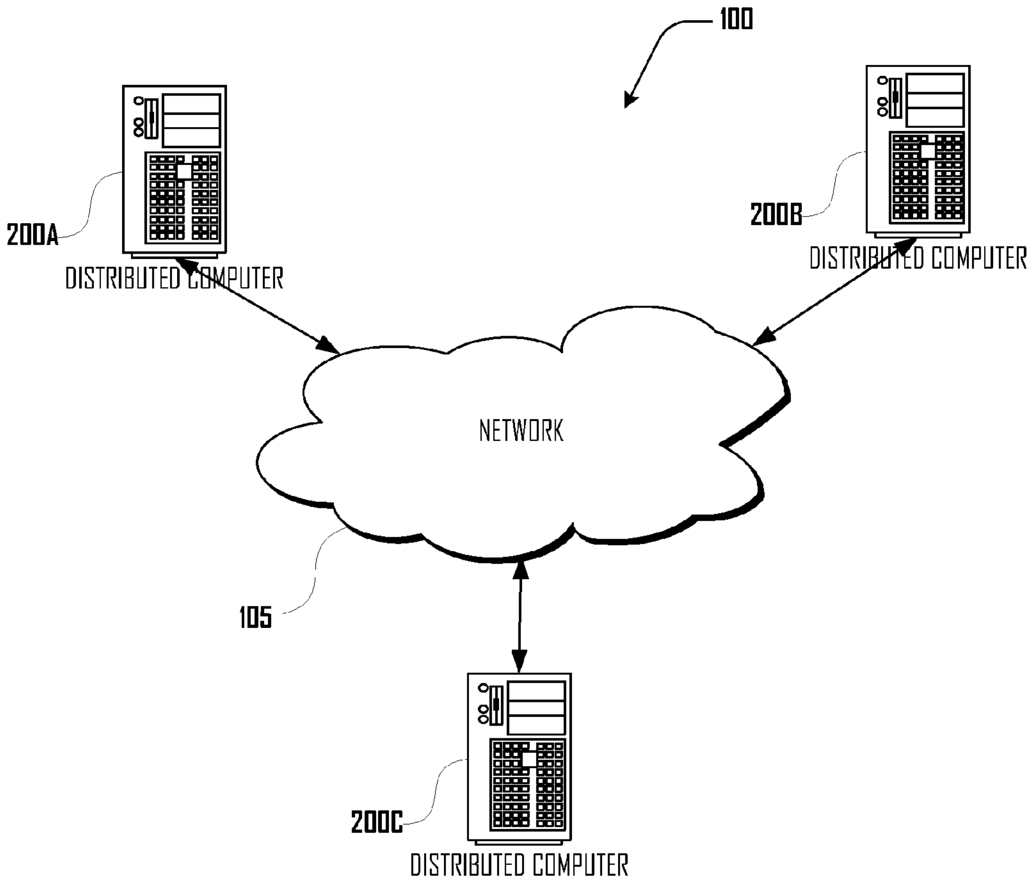

100
200A
DISTRIBUTED COMPUTER
200B
DISTRIBUTED COMPUTER
NETWORK
105
200C
DISTRIBUTED COMPUTER

Fig. 1

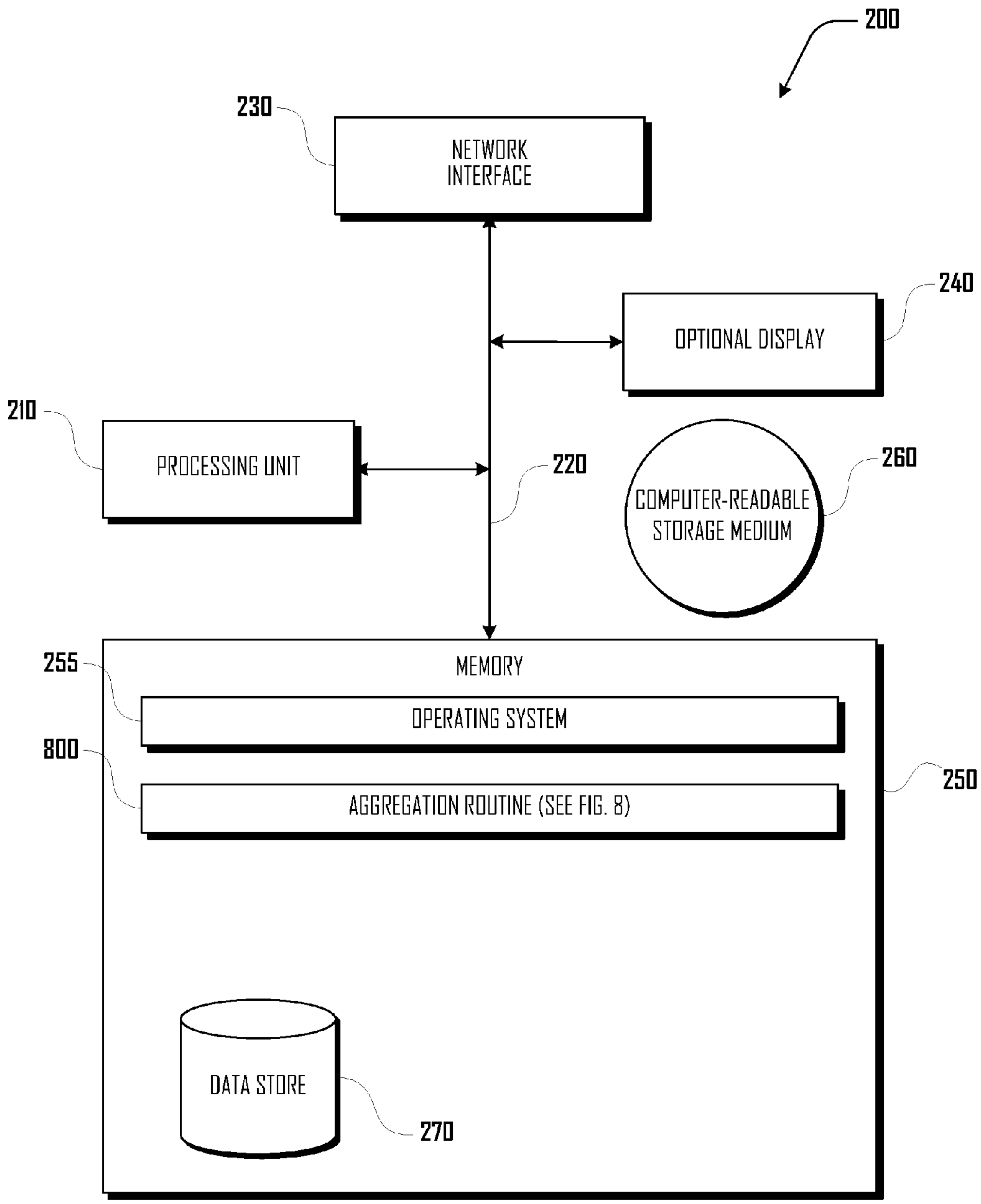

200
230
NETWORK INTERFACE
240
OPTIONAL DISPLAY
210
PROCESSING UNIT
220
260
COMPUTER-READABLE STORAGE MEDIUM
MEMORY
255
OPERATING SYSTEM
800
AGGREGATION ROUTINE (SEE FIG. 8)
250
DATA STORE
270

Fig. 2

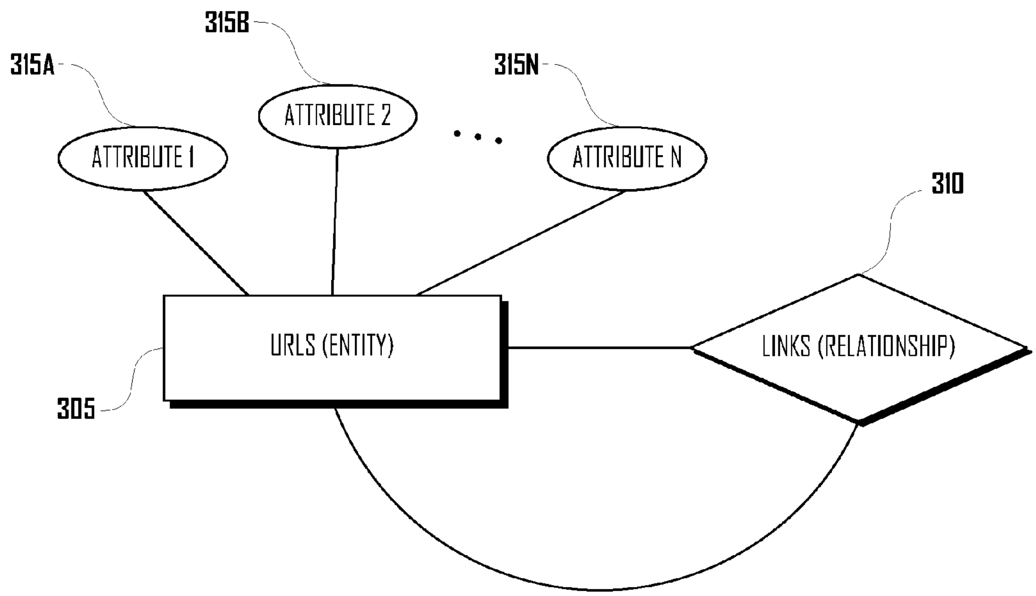

315B
315A
315N
ATTRIBUTE 1
ATTRIBUTE 2
ATTRIBUTE N
310
URLS (ENTITY)
LINKS (RELATIONSHIP)
305

Fig.3

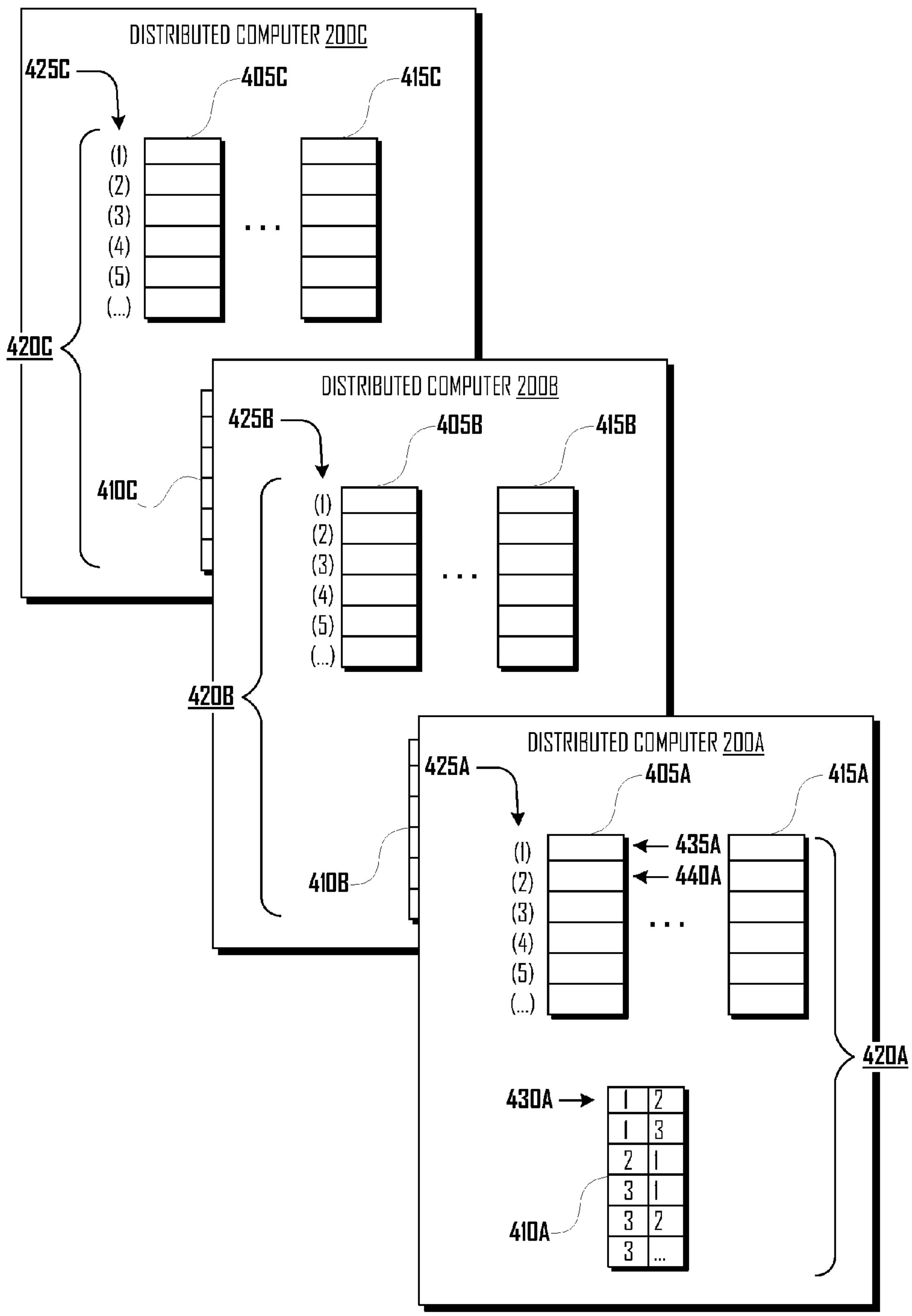

DISTRIBUTED COMPUTER 200C
425C
405C
415C
(1)
(2)
(3)
(4)
(5)
(...)
420C
410C
DISTRIBUTED COMPUTER 200B
425B
405B
415B
420B
410B
DISTRIBUTED COMPUTER 200A
425A
405A
415A
435A
440A
420A
430A
410A

Fig. 4

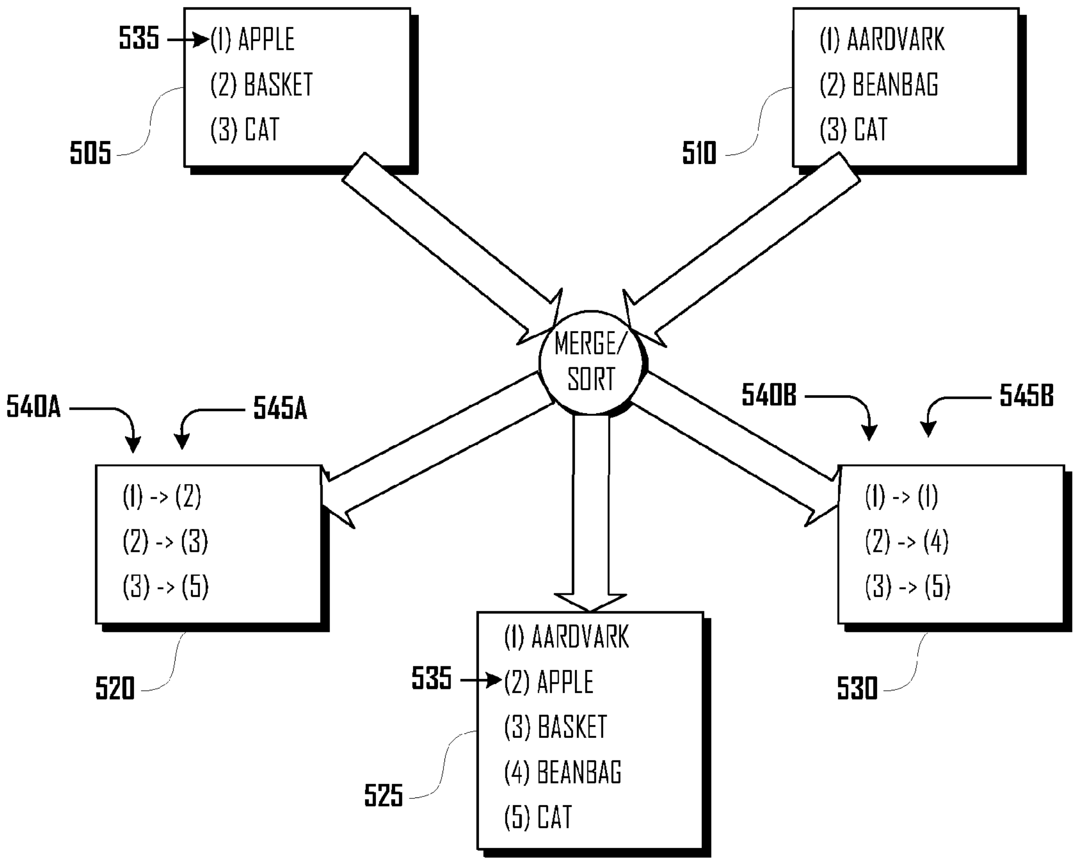

535
(1) APPLE
(2) BASKET
(3) CAT
505
(1) AARDVARK
(2) BEANBAG
(3) CAT
510
MERGE/
SORT
540A
545A
(1) -> (2)
(2) -> (3)
(3) -> (5)
520
540B
545B
(1) -> (1)
(2) -> (4)
(3) -> (5)
530
(1) AARDVARK
535
(2) APPLE
(3) BASKET
(4) BEANBAG
(5) CAT
525

Fig. 5

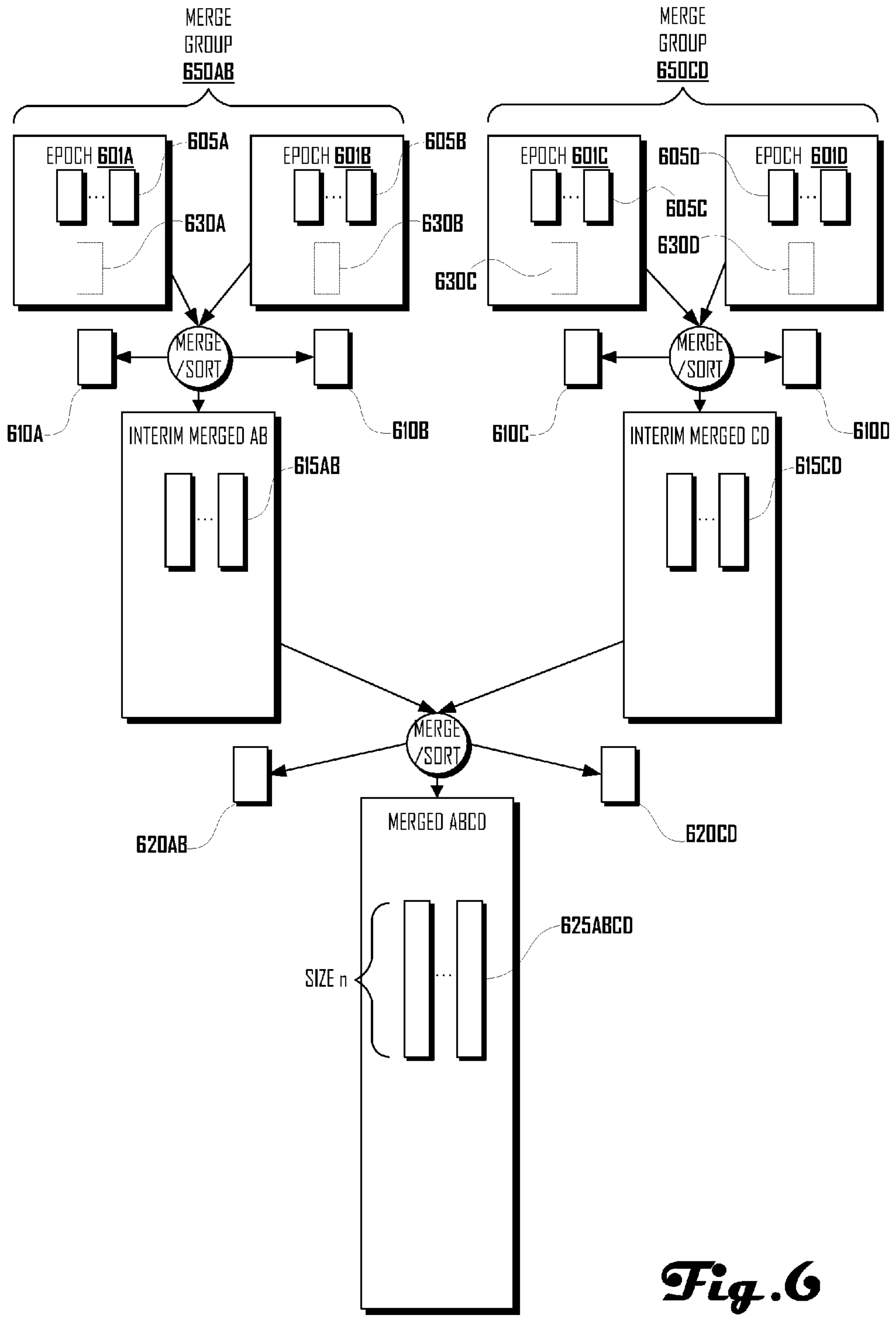

MERGE
GROUP
650AB
MERGE
GROUP
650CD
EPOCH 601A
605A
630A
EPOCH 601B
605B
630B
EPOCH 601C
605C
630C
EPOCH 601D
605D
630D
MERGE
/SORT
MERGE
/SORT
610A
610B
610C
610D
INTERIM MERGED AB
615AB
INTERIM MERGED CD
615CD
MERGE
/SORT
620AB
620CD
MERGED ABCD
625ABCD
SIZE n

Fig. 6

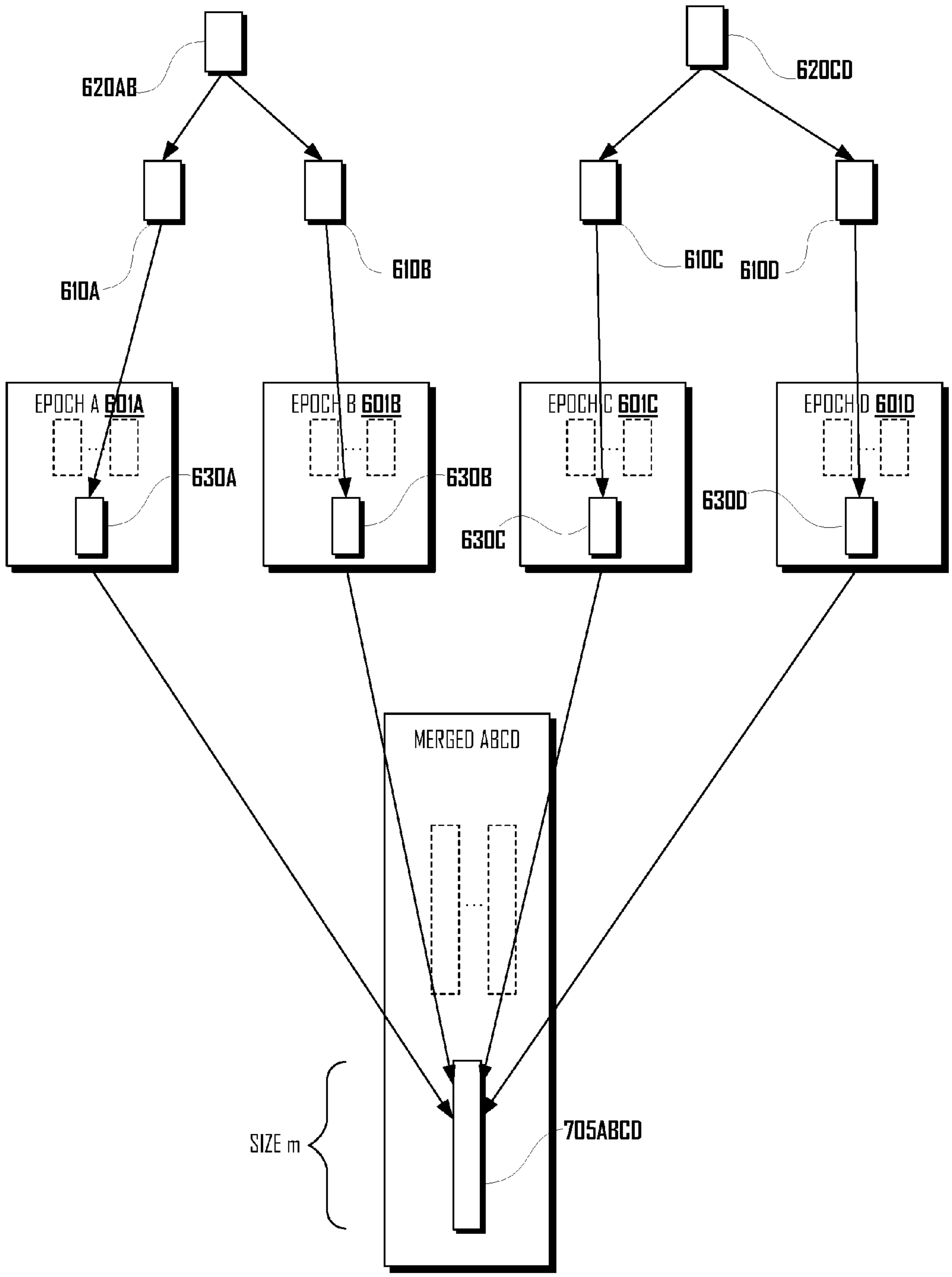

620AB
620CD
610A
610B
610C
610D
EPOCH A 601A
EPOCH B 601B
EPOCH C 601C
EPOCH D 601D
630A
630B
630C
630D
MERGED ABCD
SIZE m
705ABCD

Fig.7

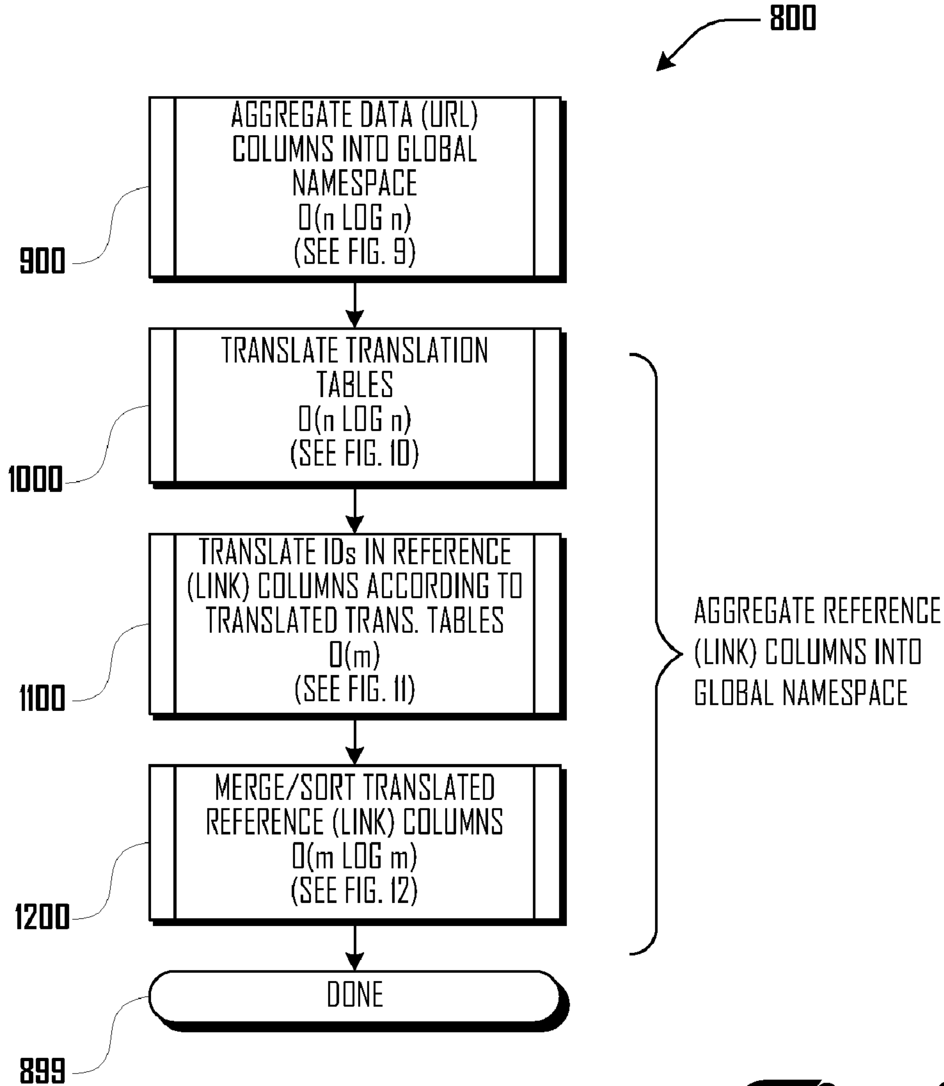

800
AGGREGATE DATA (URL) COLUMNS INTO GLOBAL NAMESPACE O(n LOG n) (SEE FIG. 9)
900
TRANSLATE TRANSLATION TABLES O(n LOG n) (SEE FIG. 10)
1000
TRANSLATE IDs IN REFERENCE (LINK) COLUMNS ACCORDING TO TRANSLATED TRANS. TABLES O(m) (SEE FIG. 11)
1100
MERGE/SORT TRANSLATED REFERENCE (LINK) COLUMNS O(m LOG m) (SEE FIG. 12)
1200
DONE
899
AGGREGATE REFERENCE (LINK) COLUMNS INTO GLOBAL NAMESPACE

Fig. 8

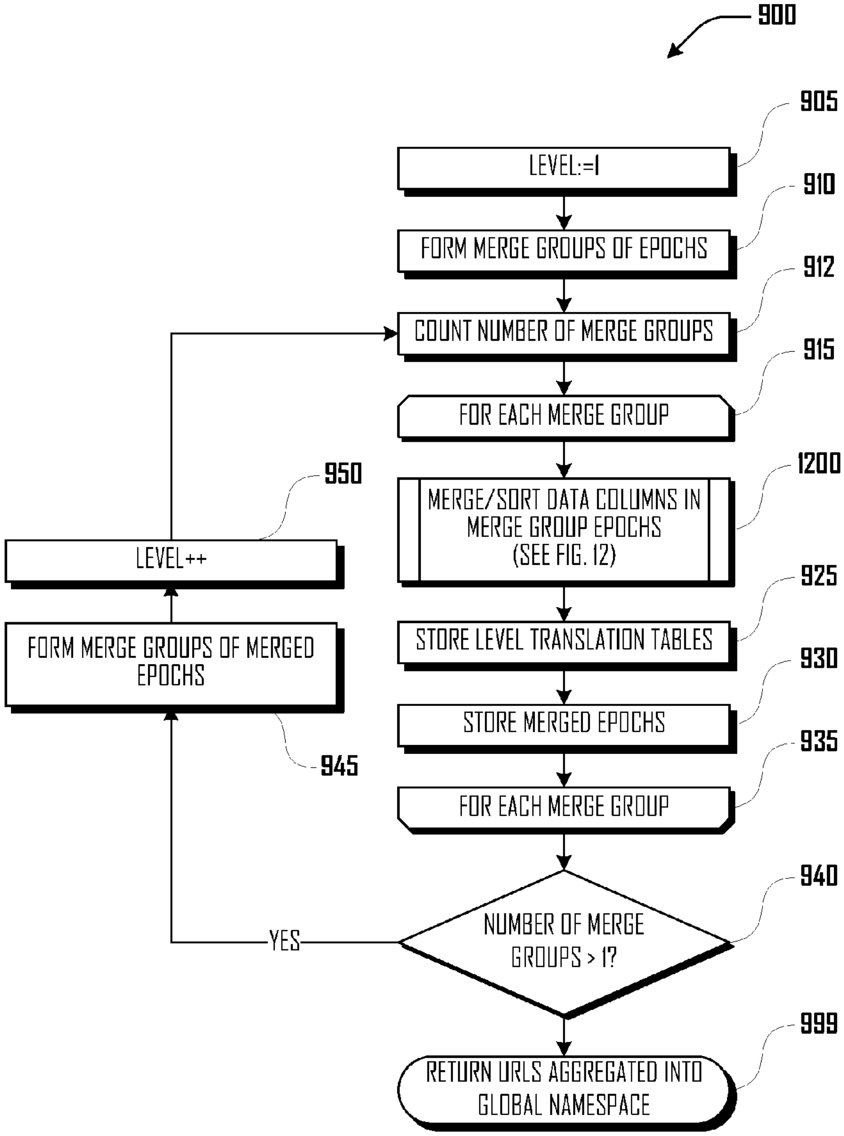

900
905
LEVEL:=1
910
FORM MERGE GROUPS OF EPOCHS
912
COUNT NUMBER OF MERGE GROUPS
915
FOR EACH MERGE GROUP
1200
MERGE/SORT DATA COLUMNS IN MERGE GROUP EPOCHS (SEE FIG. 12)
925
STORE LEVEL TRANSLATION TABLES
930
STORE MERGED EPOCHS
935
FOR EACH MERGE GROUP
940
NUMBER OF MERGE GROUPS > 1?
YES
945
FORM MERGE GROUPS OF MERGED EPOCHS
950
LEVEL++
999
RETURN URLS AGGREGATED INTO GLOBAL NAMESPACE

Fig. 9

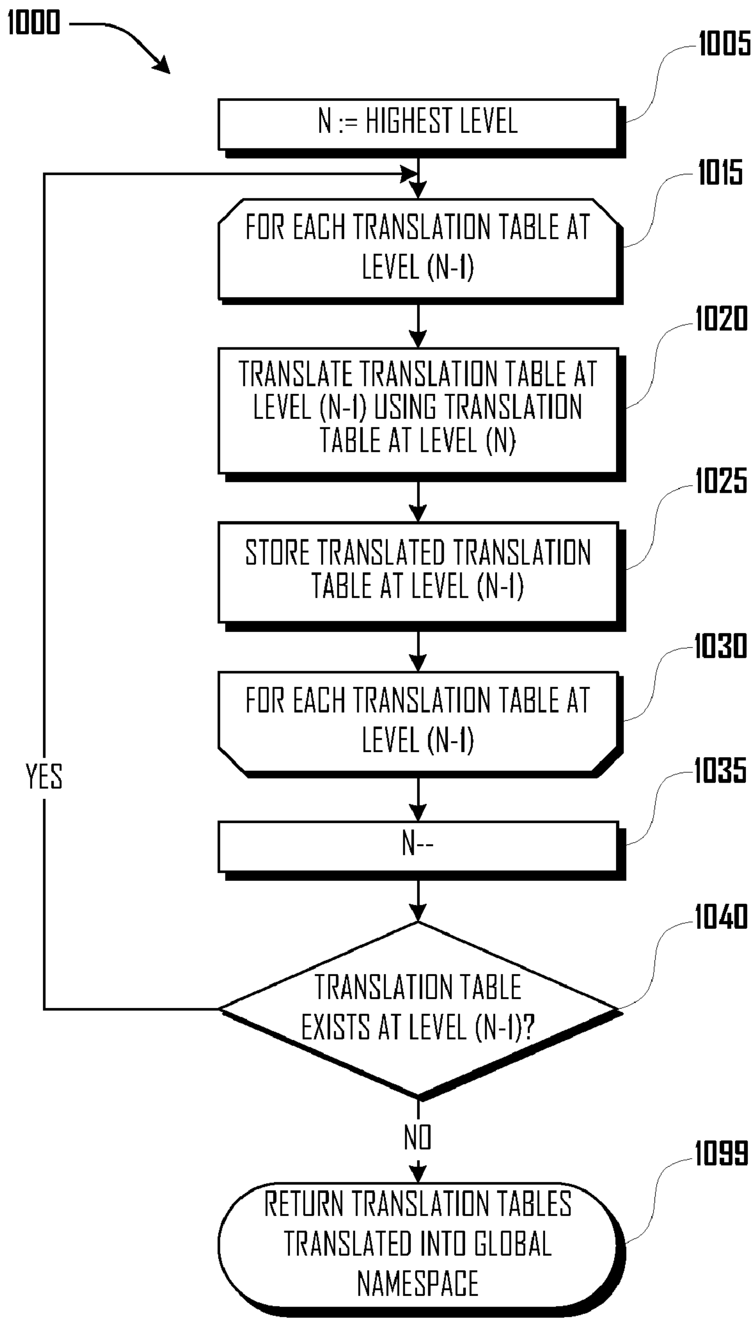

1000
1005
N := HIGHEST LEVEL
1015
FOR EACH TRANSLATION TABLE AT LEVEL (N-1)
1020
TRANSLATE TRANSLATION TABLE AT LEVEL (N-1) USING TRANSLATION TABLE AT LEVEL (N)
1025
STORE TRANSLATED TRANSLATION TABLE AT LEVEL (N-1)
1030
FOR EACH TRANSLATION TABLE AT LEVEL (N-1)
1035
N--
1040
TRANSLATION TABLE EXISTS AT LEVEL (N-1)?
YES
NO
1099
RETURN TRANSLATION TABLES TRANSLATED INTO GLOBAL NAMESPACE

Fig. 10

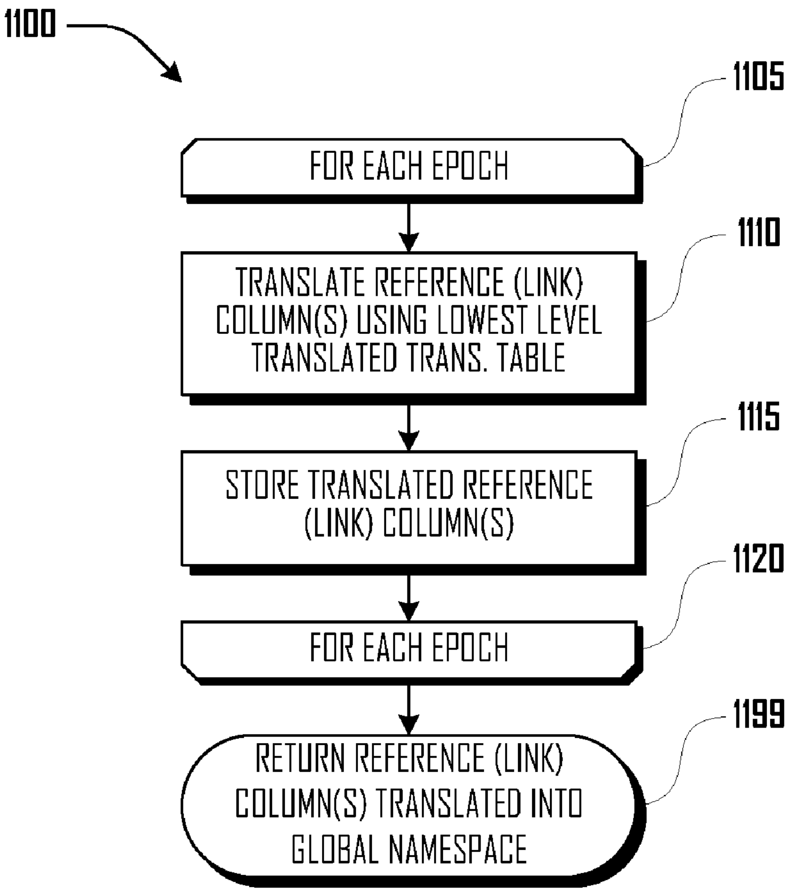

1100
1105
FOR EACH EPOCH
1110
TRANSLATE REFERENCE (LINK) COLUMN(S) USING LOWEST LEVEL TRANSLATED TRANS. TABLE
1115
STORE TRANSLATED REFERENCE (LINK) COLUMN(S)
1120
FOR EACH EPOCH
1199
RETURN REFERENCE (LINK) COLUMN(S) TRANSLATED INTO GLOBAL NAMESPACE

Fig.11

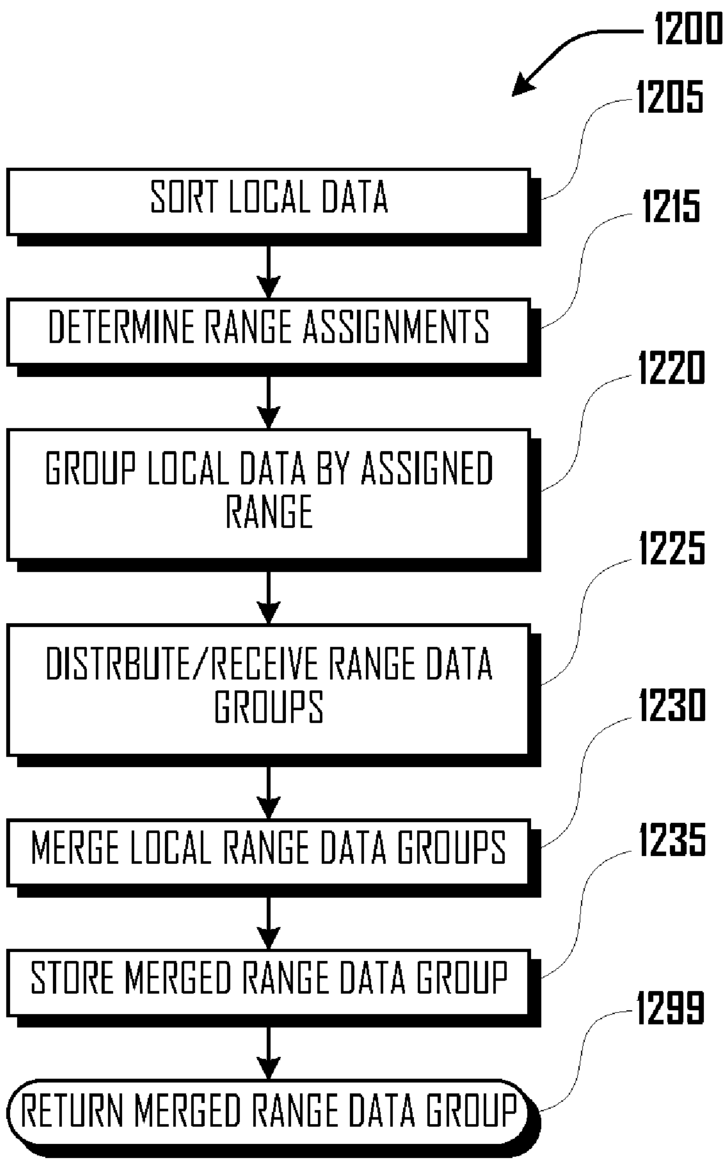

1200
1205
SORT LOCAL DATA
1215
DETERMINE RANGE ASSIGNMENTS
1220
GROUP LOCAL DATA BY ASSIGNED RANGE
1225
DISTRBUTE/RECEIVE RANGE DATA GROUPS
1230
MERGE LOCAL RANGE DATA GROUPS
1235
STORE MERGED RANGE DATA GROUP
1299
RETURN MERGED RANGE DATA GROUP

Fig.12

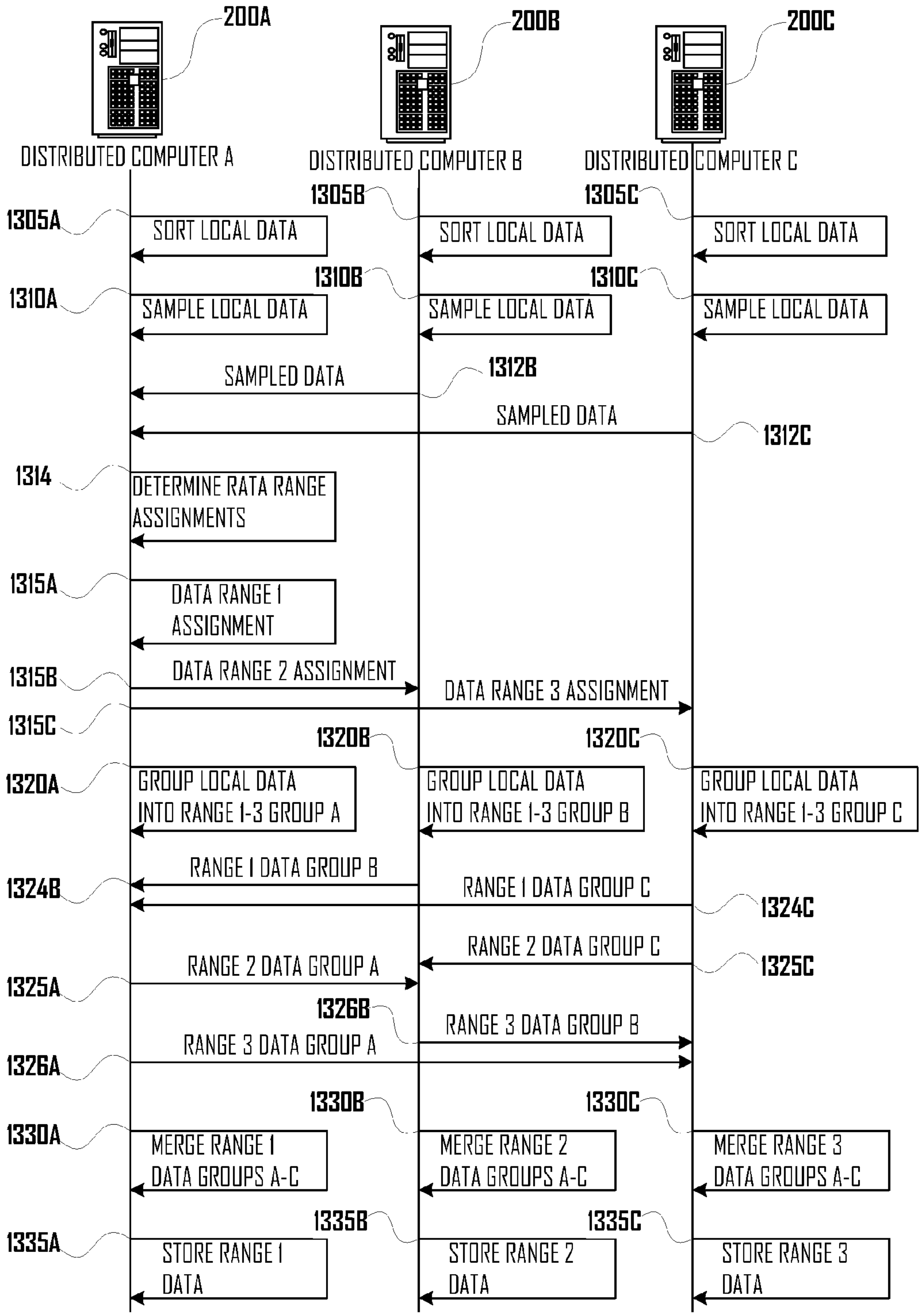

200A
200B
200C
DISTRIBUTED COMPUTER A
DISTRIBUTED COMPUTER B
DISTRIBUTED COMPUTER C
1305A
SORT LOCAL DATA
1305B
SORT LOCAL DATA
1305C
SORT LOCAL DATA
1310A
SAMPLE LOCAL DATA
1310B
SAMPLE LOCAL DATA
1310C
SAMPLE LOCAL DATA
SAMPLED DATA
1312B
SAMPLED DATA
1312C
1314
DETERMINE RATA RANGE ASSIGNMENTS
1315A
DATA RANGE 1 ASSIGNMENT
1315B
DATA RANGE 2 ASSIGNMENT
DATA RANGE 3 ASSIGNMENT
1315C
1320A
GROUP LOCAL DATA INTO RANGE 1-3 GROUP A
1320B
GROUP LOCAL DATA INTO RANGE 1-3 GROUP B
1320C
GROUP LOCAL DATA INTO RANGE 1-3 GROUP C
RANGE 1 DATA GROUP B
1324B
RANGE 1 DATA GROUP C
1324C
RANGE 2 DATA GROUP C
1325C
RANGE 2 DATA GROUP A
1325A
1326B
RANGE 3 DATA GROUP B
RANGE 3 DATA GROUP A
1326A
1330A
MERGE RANGE 1 DATA GROUPS A-C
1330B
MERGE RANGE 2 DATA GROUPS A-C
1330C
MERGE RANGE 3 DATA GROUPS A-C
1335A
STORE RANGE 1 DATA
1335B
STORE RANGE 2 DATA
1335C
STORE RANGE 3 DATA

Fig. 13

WEB-SCALE DATA PROCESSING SYSTEM AND METHOD

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of U.S. patent application Ser. No. 12/572,989, filed Oct. 2, 2009, titled "WEB-SCALE DATA PROCESSING SYSTEM AND METHOD," naming inventors Benjamin Cappel Hendrickson and Nicholas Stefan Gerner, and having Attorney Docket No. SEOM-2009003. application Ser. No. 12/572,989 claims the benefit of priority to U.S. Provisional Application No. 61/102,785, filed Oct. 3, 2008, titled "WEB-SCALE DATA PROCESSING SYSTEM AND METHOD," naming inventors Benjamin Cappel Hendrickson and Nicholas Stefan Gerner, and having Attorney Docket No. SEOM-2008003. application Ser. No. 12/572,989 also claims the benefit of priority to U.S. Provisional Application No. 61/102,775, filed Oct. 3, 2008, titled "INDEX RANK OPTIMIZATION SYSTEM AND METHOD," naming inventors Benjamin Cappel Hendrickson, Nicholas Stefan Gerner, and S. Rand Mitchell Fishkin, and having Attorney Docket No. SEOM-2008002. This application is related to U.S. patent application Ser. No. 12/572,990 (now U.S. Pat. No. 7,965,207), filed Oct. 2, 2009, titled "VARIABLE LENGTH INTEGER ENCODING SYSTEM AND METHOD", naming inventor Benjamin Cappel Hendrickson, and having attorney docket number SEOM-2009004. The above-cited applications are incorporated herein by reference in their entirety, for all purposes.

FIELD

[0002] The present disclosure relates to obtaining and processing web-scale data, and more particularly to systems and methods for crawling, storing, processing, encoding, and/or serving web-scale data.

BACKGROUND

[0003] The Internet is a worldwide, publicly accessible network of interconnected computer networks that transmit data by packet switching using the standard Internet Protocol (IP). The "network of networks" consists of millions of smaller domestic, academic, business, and government networks, which together enable various services, such as electronic mail, online chat, file transfer, and the interlinked web pages and other documents of the World Wide Web.

[0004] Web Links

[0005] The World Wide Web (commonly shortened to the Web) is a system of interlinked hypertext documents accessed via the Internet. With a Web browser, a user may view Web pages that may contain text, images, videos, and other multimedia. Most pertinently, a Web page may also contain hyperlinks or simply "links" that allow users to navigate from one page to another. A link is a reference or navigation element in a Web page or document that refers or "points" to a destination. The destination may be another location within the source page, or the destination may be a different page or a point within a different page.

[0006] Within a HyperText Markup Language (("HTML") document, links are typically specified using the <a> (anchor) elements. HTML code may specify some or all of the five main characteristics of a link:

[0007] link destination ("href" pointing to a Uniform Resource Locator ("URL"))

[0008] link label or "anchor text"

[0009] link title

[0010] link target

[0011] link class or link id

[0012] For example, an HTML link specification may use the HTML element "a" with the attribute "href" and optionally also the attributes "title", "target", and "class" or "id":

[0013] anchor text

[0014] Web Crawling [Para **10**] A vast amount of information is available via the Internet, taking the form of Web pages, images, and other types of files. At the present time, "search engines" offer one of the primary resources used by Internet users to locate information of interest. Due at least to the staggering number of pages on the Internet, search engines tend to operate largely algorithmically. Oversimplifying, search engines operate generally as follows. The search engine "crawls" the Web, storing data from pages it encounters on the search engine's own server or servers, where a second program, known as an indexer, extracts various information about the page, such as the words it contains and where these are located. The indexer may also extract information about links contained on the page.

[0015] In recent years, the Web has grown so large that creating such indexes involves so many resources that only very large, very well funded corporations have the resources to crawl and index the Web. Indeed, assuming that the average size of the HTML code of pages on the Web is roughly 25 kilobytes, then 3.9 billion pages (which is a small portion of what would be required to keep an up-to-date index of the Web) represent approximately 90 terabytes of data. Merely storing 90 terabytes of data, let alone processing it, would cost many thousands of dollars at today's bulk-storage rates. Processing such quantities of data is also typically difficult and expensive in part because the data sets tend to be too large to be stored and processed on a single modern-day computer in a timely fashion. Accordingly, crawling and indexing the Web has largely been the exclusive province of large, well-funded organizations.

[0016] Column-Oriented Database

[0017] Put simply, a column-oriented database management system (DBMS) stores its content by column rather than by row. DBMS systems are commonly used to store tabular data made up of rows and columns. The set of columns is often fixed by program design, while the number of rows is generally variable.

[0018] Many DBMS implementations are row-oriented in that they may store every attribute of a given row in sequence, with the last entry of one row followed by the first entry of the next. For example, row-oriented DBMS might store a set of data organized in the following manner:

[0019] [101, Smith, 40000], [102, Jones, 50000], [103, Johnson, 44000].

[0020] This set of data includes three rows and three columns. The first column is an incrementing ID (number) field; the second a name (text) field; the third, a salary (number) field. By contrast, a column-oriented implementation of a DBMS might organize the same set of data as follows:

[0021] [101, 102, 103]; [Smith, Jones, Johnson]; [40000, 50000, 44000].

[0022] Column data is of uniform type; therefore, there may be opportunities for storage optimizations in column oriented data that are not available in row oriented data. For example, many modern compression schemes, such as those derived from the LZ78 algorithm published by Lempel and Ziv in 1978, make use of the similarity of adjacent data to achieve compression. While the same techniques may be used on row-oriented data, a typical implementation will achieve less effective results.

[0023] Implicit Record IDs

[0024] A common practice, especially in row-oriented databases, is to assign an explicit unique record ID to each record. However, using explicit record IDs is not required—column-oriented or other databases may be used with implicit record IDs. In other words, the first entry in the column has an implicit ID of "1," the second entry has an implicit ID of "2," and so on. Problems may arise when data is segregated into two or more independent "epochs" whose internal record IDs collide with each other, and the data in the epochs must be unified into a consistent record ID space.

BRIEF DESCRIPTION OF THE DRAWINGS

[0025] FIG. **1** is a system diagram of a number of devices in a network in accordance with one embodiment.

[0026] FIG. **2** is a diagram of components of a distributed computer in accordance with one embodiment.

[0027] FIG. **3** is a diagram of an exemplary data structure in accordance with one embodiment.

[0028] FIG. **4** is a diagram of an exemplary set of data tables in accordance with one embodiment.

[0029] FIG. **5** is a diagram of an exemplary merge process and associated breadcrumbs in accordance with one embodiment.

[0030] FIG. **6** is a diagram of an exemplary hierarchical data aggregation in accordance with one embodiment.

[0031] FIG. **7** is a flow diagram of an exemplary hierarchical links aggregation in accordance with one embodiment.

[0032] FIG. **8** is a flow diagram of an exemplary high level aggregation routine in accordance with one embodiment.

[0033] FIG. **9** is a flow diagram of an exemplary data aggregation subroutine in accordance with one embodiment.

[0034] FIG. **10** is a flow diagram of an exemplary hierarchical breadcrumb translation subroutine in accordance with one embodiment.

[0035] FIG. **11** is a flow diagram of an exemplary link translation subroutine in accordance with one embodiment.

[0036] FIG. **12** is a flow diagram of an exemplary cluster sort subroutine in accordance with one embodiment.

[0037] FIG. **13** is a data flow diagram of an exemplary cluster sort subroutine in accordance with one embodiment.

DESCRIPTION

[0038] The detailed description that follows is represented largely in terms of processes and symbolic representations of operations by conventional computer components, including a processor, memory storage devices for the processor, connected display devices, and input devices. Furthermore, these processes and operations may utilize conventional computer components in a heterogeneous distributed computing environment, including remote file Servers, computer Servers and memory storage devices. Each of these conventional distributed computing components is accessible by the processor via a communication network.

[0039] Described herein are several processes and technologies to crawl, store, process, and serve web-scale data. Broadly speaking, an exemplary embodiment consists of a logical pipeline, beginning with a list of URLs to crawl. At the other end are final results ready for consumption by a user (or web front-end). The first step in the exemplary pipeline crawls URLs producing a large set of raw meta-data about those URLs, including many duplicates. These data may be stored on disk temporarily before being saved to stable storage (e.g. Amazon's S**3**). When crawling is complete, the whole dataset may be retrieved for various processing steps including duplication, elimination, and deeper link-analysis. Once processing is complete, the processed dataset is merged into any existing index data. The index may then be available for serving user queries where data is efficiently retrieved from disk and combined into answer sets.

[0040] In an exemplary embodiment, crawling methodology may decouple the output of fetching and parsing data from the input of the crawl. An exemplary crawler may begin with a large input set of URLs containing the complete set of URLs to crawl in the immediate future. These URLs may be assumed to contain no duplicates, and could be pre-filtered for Robots Exclusion Protocol (REP). In one embodiment, decoupling the input and output of the crawl by doing duplicate elimination and REP filtering before the crawl results in an O(n) cost for these requirements.

[0041] In an exemplary embodiment, a crawl may be distributed across several computing devices for scale. Each computing device may be responsible for retrieving a set of URLs. In some embodiments, URLs may be assigned to computing devices so that all URLs from a particular Pay Level Domain (PLD) (e.g. seomoz.org, or distilled.co.uk) are likely to be crawled by a single computing device (which helps to ensure politeness of crawling). PLDs may be mixed to promote a homogenous mix of URLs across computing devices. Each computing device may further mix URLs to increase domain diversity, which may improve throughput in the face of politeness considerations. In one embodiment, crawling is done in "epochs," with each epoch producing an internally, but not globally consistent namespace of URLs (so URL **32** from one epoch might be different than URL **32** from another). See, e.g., FIG. **4**.

[0042] In one embodiment, a crawl focuses on page links rather than page content, so page content can be discarded immediately, although some content can be selectively saved if desired. Discarding some or all content may reduce the storage cost by an order of magnitude or more, while retaining high quality data (i.e. links) for internet marketing or other purposes. For example, if the average page size on the web were roughly 25 kilobytes, then 3.9 billion pages (a small portion of what may be required to keep an up-to-date index of the web) are approximately 90 terabytes of data, not including any other useful metadata. Assuming a compression ratio of 10:1, storing this data would require approximately 9TB. Discarding most or all page content, while still keeping some amount of data about links (e.g., page titles and anchor texts) as well as other meta data, may reduce this requirement to approximately 2TB.

[0043] Reference is now made in detail to the description of the embodiments as illustrated in the drawings. While embodiments are described in connection with the drawings and related descriptions, there is no intent to limit the scope to the embodiments disclosed herein. On the contrary, the intent is to cover all alternatives, modifications and equivalents. In alternate embodiments, additional devices, or combinations of illustrated devices, may be added to, or combined, without limiting the scope to the embodiments disclosed herein.

[0044] FIG. **1** illustrates a typical distributed computing environment. In alternate embodiments, more distributed computing devices **200** may be present. In other embodiments, only a single distributed computing device **200** may be present. In many embodiments, network **105** may be the Internet. In other embodiments, network **105** may be a local or wide area network, a private network, a virtual local area network, or other means of physically or logically connecting computers. In some embodiments, distributed computing devices **200** may be virtual machines, and/or they may be provided as part of a cloud or grid computing service. For example, in one embodiment, some or all distributed computing devices **200** may be virtual machines in the Amazon Elastic Compute Cloud ("EC2"), operated by Amazon.com, Inc. of Seattle Wash.

[0045] FIG. **2** illustrates an exemplary distributed computing device **200**. In some embodiments, a distributed computing device **200** may include many more components than those shown in FIG. **2**. However, it is not necessary that all of these generally conventional components be shown in order to disclose an illustrative embodiment. As shown in FIG. **2**, a distributed computing device **200** includes a network interface **230** for connecting to network **105**. Network interface **230** includes the necessary circuitry for such a connection and is constructed for use with the appropriate protocol.

[0046] Distributed computing device **200** also includes a processing unit **210**, a memory **250** and may include an optional display **240**, all interconnected along with network interface **230** via a bus **220**. Memory **250** generally comprises a random access memory ("RAM"), a read only memory ("ROM"), and a permanent mass storage device, such as a disk drive. The memory **250** stores program code for aggregation routine **800**, as described herein. [Para **43**] In addition, memory **250** also stores an operating system **255**. In various embodiments, these software components may be loaded from a computer readable storage medium into memory **250** of the distributed computing device **200** using a drive mechanism (not shown) associated with a computer readable storage medium **260** (such as a floppy disc, tape, DVD/CD-ROM drive, memory card, and the like), via the network interface **230**, or via other like means. Some or all of the components described herein may be "virtual" components.

[0047] Memory **250** also includes a data store **270** to house some or all of the data structures as described below. In some embodiments, data store **270** may take the form of a conventional hard drive, an array of hard drives, or other accessible storage device or service. In some embodiments, data store **270** may comprise an online storage service, such as Amazon Simple Storage Service (S3), operated by Amazon.com, Inc. of Seattle Wash.

[0048] In an exemplary embodiment, one or more distributed computing devices **200** may be used to "crawl" or index links on the World Wide Web. FIG. **3** illustrates an exemplary data structure that may be operated on by the routines described herein. As used herein, the term "column" refers to a distinct set of data. Although an exemplary embodiment is implemented using a column-oriented database, the processes disclosed herein are applicable regardless of the particular architecture used to store the data. In one embodiment, a data structure may comprise a column of URLs **305** or other entities, a column of links **310** or other relationships between entities, and zero or more columns of attributes **315**. In one embodiment, attributes columns may include information about URLs, such as page sizes, page titles, other metadata, and the like. In some embodiments, links **310** may also have one or more attributes (e.g., anchor text, surrounding text, and the like).

[0049] At the present time, indexing the number of URLs (i.e., pages or link destination) on the web may exceed the storage and processing capacity of most or all readily-available individual computing devices. Accordingly, in an exemplary embodiment, an indexing task may be divided up into a number of manageable-sized chunks, with one distributed computing device **200** being responsible for each chunk. As a result, as illustrated in FIG. **4**, each distributed computing device may construct its own group of columns of data, referred to as an "epoch." In one embodiment, an epoch is sized to fit into the memory available on a single distributed computing device **200**. Generally speaking, each epoch will have an internally-consistent namespace, but different epochs are likely to have collisions within their respective namespaces. For example, epoch **420**A includes columns of data **405**A, **410**A, **415**A gathered by distributed computing device **200**A. Each record in each column in epoch **420**A has a record ID ("RID") **425**A. In one embodiment, RIDs **425** are implicit or capable of being inferred from a record's position within a column (e.g., the 32nd integer in an integer column has RID **32**). In other embodiments, RIDs **425** may be explicitly assigned. Either way, RIDs are consistent within each epoch.

[0050] In one embodiment, column **405**A may represent a set of entity or URL data **305**; column **410**A may represent link data **310**; and column **415**A may represent attribute data **315**. In other embodiments, there may be more, fewer, and/or different columns of data. Records in the link column **410** may comprise RIDs corresponding to entries in another column. For example, the first record **430**A in link column **410**A may indicate that a page corresponding to record "1" **435**A in URL column **405**A includes a link to the URL at record "2" **440**A in the URL column **405**A.

[0051] Epochs **420**B and **420**C each include the same types of columns as epoch **420**A. However, FIG. **4** illustrates that RIDs **425**B and **425**C collide or overlap with RIDs **425**A. In other words, although each epoch has an internally-consistent namespace, the different epochs have namespaces that collide with at least some other epochs. The colliding namespaces may be a problem when data from different epochs is merged or aggregated together.

[0052] FIG. **5** illustrates an exemplary merge of one column from two epochs with colliding namespaces. Column **505** (from epoch A) includes three records with RIDs of 1-3. Column **510** (from epoch B) also includes three records with RIDs of 1-3. When columns **505** and **510**, from two epochs, are merged into a merged column **525**, RIDs in the merged column **525** may differ from those in the original columns. For example, record "1" **535** in column **505** became record "2" **535** in the merged column **525**.

[0053] As part of the merge process, translation tables **520** and **530** are created. Translation tables associate RIDs **540**A-B from a source namespace with RIDs **545**A-B in a destination namespace. In the illustrated example, translation table **520** associates RIDs **540**A from column **505** with RIDs **545**A in merged column **525**. Specifically, translation table **520** indicates that record "1" **535** in column **505** corresponds to record "2" **535** in merged column **525**, record "2" in column **505** corresponds to record "3" in merged column **525**, and so on. Translation table **530** indicates similar correspondences between records in column **510** and merged column **525**.

[0054] FIG. **6** illustrates a conceptual overview of an exemplary hierarchical aggregation process, including two levels of translation tables. (See also FIG. **9** and associated text.) Epochs **601**A-D each include one or more columns comprising data **605**A-D and one or more columns **630**A-D comprising relationships between records in data columns **605**A-D. RIDs in columns **630**A-D, **605**A-D within each epoch **601**A-D are internally consistent, but collide with each other. In an exemplary embodiment, data columns **605**A-D in each epoch **601**A-D include an URL column and one or more attributes columns, and columns **630**A-D contains links. In the illustrated example, epochs **601**A-D are grouped into two merge groups, merge group **650**AB including epochs **601**A-B and merge group **650**CD including epochs **601**C-D. In other embodiments, there may be fewer or many more epochs, and merge groups may consist of more than two epochs.

[0055] In the illustrated example, merge group **650**AB (comprising data columns **605**A and **605**B) is merged/sorted into a first interim set of data columns **615**AB. Similarly, merge group **650**CD (comprising data columns **605**C and **605**D) is merged/sorted into a second interim set of data columns **615**CD. At this stage, link tables **630**A-D are left alone, but translation tables **610**A-D are created and stored during the merge/sort process. In the illustrated example, translation table **610**A maps RIDs from original data columns **605**A to RIDs in interim data columns **615**AB. Translation tables **610**B-D map RIDs from columns **605**B-D to their respective interim data columns **615**AB and **615**CD. RIDs are internally consistent within interim data columns AB and interim data columns CD, but RIDs in the interim data columns collide with each other.

[0056] In the illustrated example, interim columns **615**AB are further merged/sorted with columns **615**CD, in a similar manner, to form a unified set of data columns **625**ABCD, incorporating all data from epochs A-D into a global unified namespace. Translation tables **620**AB and **620**CD map RIDs from columns **615**AB and **615**CD, respectively, to RIDs in columns **625**ABCD. Columns **625**ABCD include N records, where N is less than or equal to the sum of the number of records in epochs A-D. In one embodiment, N is typically smaller than this sum because the individual epoch columns **605**A-D may contain duplicates.

[0057] In the illustrated example, two merge/sort levels are depicted, but in other embodiments, there may be more or fewer merge/sort levels. After the operations depicted in FIG. **6**, all data columns have been unified into a globally consistent namespace. However, link columns **630**A-D have not been aggregated, and RIDs referenced in link columns **630**A-D are not accurate with respect to the globally unified namespace.

[0058] FIG. **7** illustrates an exemplary link columns aggregation. Translation tables **620**AB and **620**CD (created at the second level) are used to respectively translate destination RID references in translation tables **610**A-D (created at the first level) into the global namespace. Unified translation tables **610**A-D are then used to translate link columns **630**A-D into the global unified namespace, after which a simple merge/sort operation creates a global unified link column **705**ABCD having M entries. In an exemplary embodiment, M is greater than N, often much greater.

[0059] FIG. **8** illustrates an aggregation routine **800** for performing the operations discussed above in reference to FIG. **6**-**7**. In subroutine **900**, illustrated in FIG. **9** and discussed below, data columns (e.g., link and attribute columns) from separate epochs are aggregated into a unified global namespace and translation tables are created at each level. In an exemplary embodiment, the resources required to compute subroutine **900** scale according to O(n log n) . In subroutine **1000**, illustrated in FIG. **10** and discussed below, the translation tables created in subroutine **900** are translated into the global namespace. In an exemplary embodiment, the resources required to compute subroutine **1000** scale according to O(n log n) . In subroutine **1100**, illustrated in FIG. **11** and discussed below, link columns in separate epochs are translated into the global namespace. In an exemplary embodiment, the resources required to compute subroutine **1100** scale according to O(m). In subroutine **1200**, the translated link columns from each epoch are cluster sorted and merged into a unified, consistent set of links. In an exemplary embodiment, the resources required to compute routine **805** scale according to O(m log m). Routine **800** ends at step **899**.

[0060] FIG. **9** illustrates an exemplary data column aggregation subroutine **900**. As previously discussed in reference to FIG. **6**, data column aggregation subroutine **900** operates hierarchically on a plurality of separate epochs of data. In block **905**, the current level of the hierarchy is initialized to a starting value. In an illustrative embodiment, the starting value is 1. As used herein, the term "level" in this context represents merely a convenient shorthand for conceptually distinguishing between various sets of merge groups and translation tables. In some embodiments, subroutine **900** may be implemented using a literal numeric counter. However, other embodiments may be implemented without explicitly initializing and/or incrementing a literal numeric counter (e.g., subroutine **900** may be implemented as a recursive, rather than iterative, process).

[0061] In step **910**, epochs are grouped into merge groups comprising two or more epochs. In one embodiment, the size of merge groups is determined in accordance with an amount of data that can be stored in memory and/or processed on a single distributed computing device **200**. In block **912**, the number of merge groups is counted. In an exemplary embodiment, there may be several merge groups on low levels of the hierarchy, but only one merge group on the highest level.

[0062] Beginning in starting loop block **915**, subroutine **900** processes each merge group. Although subroutine **900** depicts the exemplary process as iterative, in many embodiments, merge groups may be processed in parallel on multiple distributed computing devices **200**. In subroutine **1200**, one or more data columns in each epoch making up the merge group are merge/sorted (see FIG. **12** and associated text). In block **925**, translation tables for the current level are created, one for each group member. In block **930**, merged columns from the epochs in the current merge group are stored into an internally consistent namespace. (See items **615** in FIG. **6**.) If there were two or more merge groups at the current level, the two or more sets of merged data will have colliding namespaces. From ending loop block **935**, subroutine **900** loops back to block **915** to process the next merge group (if any).

[0063] After each merge group has been processed, in block **940**, subroutine **900** determines whether the most recent count of merge groups (block **912**) found more than one group. If there were two or more merge groups, then all columns of data have not yet been merged and sorted into a consistent namespace, as there are still at least two sets of merged columns with colliding namespaces. Therefore, subroutine **900** branches to block **945**, where the most recently stored merged epochs are divided into new merge groups. At block **950**, the level counter is incremented and processing returns to block **912**.

[0064] If in block **940**, subroutine **900** determines that the most recent count of merge groups (block **912**) found only one group, then the most recently stored set of merged data (block **930**) represents a unified set of data from all epochs, merged into a consistent namespace, and routine **900** returns the merged and sorted columns at block **999**.

[0065] FIG. **10** illustrates an exemplary translation table transformation (or translation) subroutine **1000**. At block **1005**, a level counter is initialized to the highest level reached in subroutine **900**. Similar to this disclosure's use of the term "level" in the context of subroutine **900** (discussed above), subroutine **1000**'s "level counter" is merely a convenient shorthand for conceptually distinguishing between various sets of merge groups and translation tables. Various embodiments may be implemented with or without initializing and/or decrementing a literal numeric level counter.

[0066] Beginning in starting loop block **1010**, translation tables from higher levels are applied to transform translation tables from the immediate lower level (if any). In some embodiments, higher and/or lower level translation tables may be distributed in ranges across more than one distributed computing device **200**. In such embodiments, there may be additional "housekeeping" required to obtain and/or concatenate ranges from multiple devices into a single table. From starting loop block **1015** to ending loop block **1030**, destination RIDs in each translation table at the next lower level are transformed or translated using the translation table at the current level. Although the exemplary process is depicted as iterative, in some embodiments, lower-level translation tables may be processed in parallel on one or more distributed computing devices. For example, a translation table at level one may indicate that source RID "1" becomes destination RID "2," and a translation table at level two may indicate that source RID "2" becomes destination RID "3." After the level 1 table is translated according to the level 2 table, the level 1 table would indicate that source RID "1" becomes destination RID "3." After each destination RID in the lower-level translation table is transformed (or translated) accordingly, the transformed lower-level translation table is stored. In some embodiments, the lower-level table may be overwritten. In other embodiments, a new lower-level translation table having transformed destination RIDs may be written.

[0067] After all lower-level translation tables are translated from blocks **1015**-**30**, in block **1035**, the level counter is decremented. If translation tables exist at the next lower level, then routine **1000** loops back to beginning loop block **1015** from ending loop block **1040**. If not, then destination RIDs in all translation tables have been translated into the global namespace, and routine **1000** ends at **1099**.

[0068] FIG. **11** illustrates a flow diagram of an exemplary link column translation subroutine **1100**. Beginning in starting loop block **1105**, subroutine **1100** processes link columns in each epoch. Although the exemplary process is depicted as iterative, in some embodiments, epoch-level link columns may be translated into global namespace in parallel on one or more distributed computing devices. At block **1110**, both the source RID and destination RID, of each record in all link columns, are translated according to the appropriate lowest-level global-namespace translation table. For example, an exemplary link column includes the following records: [1,2] [1,3] [2,3]. An exemplary translation table (after being transformed into the global namespace) includes the following records: [1,3], [2,4], [3,5]. Using the translation table to translate the exemplary link column into the global namespace would result in the following records: [3,4], [3,5], [4,5]. In block **1115**, the translated link columns, which refer to RIDs in the global namespace, are stored. From ending loop block **1120**, subroutine **1100** loops back to block **1105** to process the next epoch (if any). Once all link columns in all epochs have been processed, all link columns have been translated into the global namespace, and processing ends at block **1199**.

[0069] FIG. **12** illustrates a flow diagram of an exemplary cluster merge/sort subroutine **1200**. It is often true that serving web-scale data may be efficiently accomplished by dividing the entire dataset into sorted chunks, each of which is served by a different distributed computing device (or by multiple load balanced devices, or according to other load-distribution schemes).

[0070] By way of illustration, in an exemplary embodiment, columns of URLs may be sorted alphabetically, with an implicit or explicit RID attached to each entry. If such a data set were distributed across three computing devices, the first computing device might be responsible for serving entries beginning with A-I, the second might serve J-Q, and the third might serve R-Z. Thus, the exemplary cluster merge/sort subroutine **1200** not only sorts data, but also distributes data to the appropriate distributed computing device, while minimizing the amount of coordination required among the distributed computing devices.

[0071] Beginning in block **1205**, a distributed computing device sorts local data. For example, after block **1205**, a distributed computing device may have the following data set: [A, B, D, G, K, L, M, Q, Z]. In block **1215**, the distributed computing device determines which range of data it will be assigned to serve. In one embodiment, the distributed computing device may determine its assignment by sampling local data, sharing the sampled data with one or more other distributed computing devices that are also participating in the cluster merge/sort operation, and determining range assignments in accordance with the sampled data. In other embodiments, each device may be assigned a pre-determined range. In still other embodiments, the device may determine a range in accordance with another method. After block **1215**, for example, distributed computing device A may be assigned data range A-I; device B, J-P; and device C, Q-Z.

[0072] In block **1220**, the distributed computing device groups its local data according to the ranges assigned to it and to other participating distributed computing devices. For example, the distributed computing device may divide its local data into three groups as follows: Range **1**, [A, B, D, G]; Range **2**, [K, L, M]; Range **3**, [Q, Z]. In block **1225**, the distributed computing device distributes one or more data groups to the appropriate other participating distributed computing device. In the illustrative example, the distributed computing device would retain range 1 group A, but would send range 2 and 3 data groups to other participating distributed computing devices. In turn, the distributed computing device would receive range 1 data groups from the other participating distributed computing devices. After block **1225**, the distributed computing device has a local copy of all data in its assigned range (e.g., range 1). In block **1230**, the distributed computing device merges its local data groups into a single column, and in block **1235**, it stores the merged local data. The routine ends at block **1299**.

[0073] FIG. **13** illustrates a data flow diagram of one possible implementation of a distributed merge/sort subroutine **1200**. In the illustrated exemplary implementation, each participating distributed computing device **200**A-C begins with a local data set that is distributed across a spectrum (e.g., from A-Z), including data that should be assigned to one of the other participating distributed computing devices. Although three computing devices are illustrated, in some embodiments, more or fewer computing devices may be present. In other embodiments, there may be only a single computing device.

[0074] Each participating distributed computing device **200**A-C sorts **1305**A-C local data. For example, after local sorting, distributed computing device **200**A may have the following data set: [A, B, D, G, K, L, M, Q, Z]. Participating distributed computing devices **200**A-C then assign data ranges among themselves. In one embodiment, participating distributed computing device **200**A-C assign ranges by sampling **1310**A-C local data, sharing **1312**B-C the sampled data with a designated (or selected, determined, or the like) one of the participating distributed computing devices **200**A. The designated device **200**A determines **1314** data range assignments in accordance with the sampled data. The designated distributed computing device **200**A distributes **1315**A-C data range assignments to the other participating distributed computing devices **200**B-C. For example, distributed computing device A may be assigned A-I; device B, J-P; and device C, Q-Z.

[0075] Participating distributed computing devices **200**A-C each group **1320**A-C their respective local data according to their assigned ranges. For example, distributed computing device A may group its data into Range 1 [A, B, D, G], Range 2 [K, L, M], and Range 3 [Q, Z]. Distributed computing devices **200**A-C then distribute **1324-26** data groups to their respective assigned computing device. For example, distributed computing device **200**A would retain range 1 group A, but would send **1325**A range 2 group A to distributed computing device **200**B, and would send **1326**A range 3 data group A to distributed computing device **200**C. In turn, distributed computing device **200**A would receive **1324**B range 1 data group B from distributed computing devices **200**B, and would receive **1324**C range 1 data group C from distributed computing devices **200**C. Similarly, distributed computing device **200**A sends **1325**A range 2 data group A to distributed computing device **200**B, and distributed computing device **200**C sends **1325**C range 2 data group C to distributed computing device **200**B. At this point, each participating distributed computing device **200**A-C has a local copy of all data in its assigned range. Distributed computing devices **200**A-C merge **1330**A-C their local data groups into a single column, and store **1335**A-C their merged local data.

[0076] In some embodiments, distributed merge/sort subroutine **1200** may operate on translation table data. In such embodiments, merged local data columns may be re-distributed and concatenated together to serve as a top-level translation table, which may be used to propagate translations to other data sets.

[0077] In one embodiment, once data is sorted and distributed across participating distributed computing device **200**A-C, each column of data may be indexed by creating much smaller (e.g., 64 kilobyte) chunks that can still be compressed. A clustered index may be built on the first record in each of these chunks. Queries for specific records may first hit the chunk index. Once the relevant chunk is identified, it may be scanned for matching records. This technique may be well-suited to sorted index scans and sorted merge joins. In one embodiment, all request logic may be cast as sorted index scans and sorted merge joins.

[0078] In one embodiment, communication and data transfer between distributed computing devices may be implemented according to a remote execution protocol such as Secure Shell ("SSH") or JSON Shell (short for JavaScript Object Notation, a lightweight computer data interchange format).

[0079] In some embodiments, data may be compressed according to any of several well-known algorithms (e.g., Lempel-Zev implementations such as lzo, and gz, or other types of lossless encoding, such as Huffman, Arithmetic, Golomb, run-length encoding, and the like). In some embodiments, data may also be compressed according to gap encoding schemes tailored for links (i.e., runs of pairs of monotonic increasing integers according to a fixed pattern), run-length encoding schemes also tailored for links (i.e., runs of pairs of sequentially incrementing integers according to a fixed pattern), and/or variable length integer encoding schemes.

[0080] Although specific embodiments have been illustrated and described herein, it will be appreciated by those of ordinary skill in the art that a whole variety of alternate and/or equivalent implementations may be substituted for the specific embodiments shown and described without departing from the scope of the present disclosure. This application is intended to cover any adaptations or variations of the embodiments discussed herein.

1. A method executing on at least one computing system for merging records from a plurality of conflicting namespaces into a globally-unified namespace, the method comprising:

performing steps a-d for an initial iteration level; and

performing at least steps a-c for a next iteration level:

a. obtaining a first plurality of source columns associated with a current iteration level, each source column including a plurality of records with source-column-unique, but not first-plurality-unique, identifiers;

b. grouping said first plurality of source columns into a current merge-group set comprising at least two merge groups for said initial iteration level and at least one merge group for said next iteration level, each merge group including at least two source columns;

c. for each merge group in said current merge-group set:

i. sorting and merging records from said at least two source columns in the current merge group into a merged column having a plurality of records with merged-column-unique identifiers;

ii. storing the current merged column; and

iii. for each of said at least two source columns in the current merge group, creating a translation table associated with the current iteration-level identifier, said translation table comprising a source entry for each source-column-unique record identifier in the current source column and a destination entry for each corresponding merged-column-unique record identifier in the current merged column;

d. associating the at least two current merged columns with said next iteration level.

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