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(54) **STORAGE SYSTEM WITH DISTRIBUTED DELETION**

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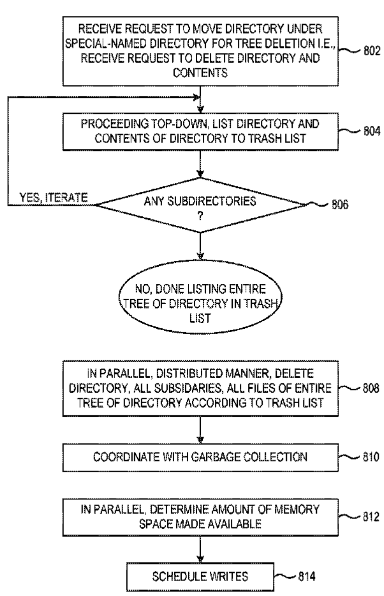
(57) **ABSTRACT**

A method of distributed file deletion, performed by a storage system, is provided. The method includes receiving, at the storage system, a request to delete a directory and contents of the directory and adding the directory to a first set, listed in a memory in the storage system. The method includes operating on the first set, by examining each directory in the first set to identify subdirectories, adding each identified subdirectory to the first set as a directory, and adding each examined directory to a second set listed in the memory. The method includes deleting in a distributed manner across the storage system without concern for order, contents of directories, and the directories listed in the second set.

17 Claims, 11 Drawing Sheets



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(58) **Field of Classification Search**

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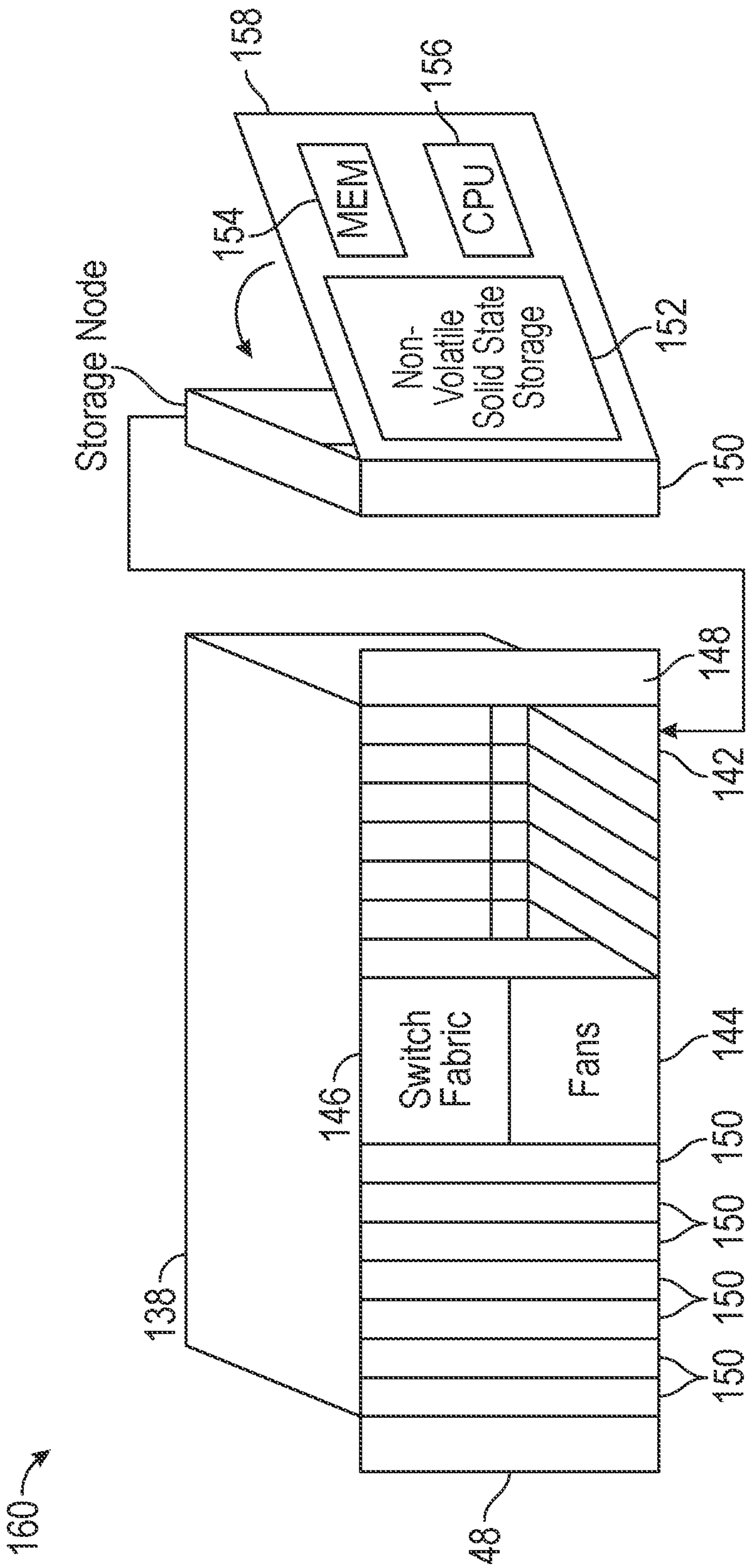

Storage Node
158
156
154
MEM
CPU
Non-Volatile Solid State Storage
152
150
148
142
146
Switch Fabric
Fans
144
150
150
150
150
138
160
148

FIG. 1

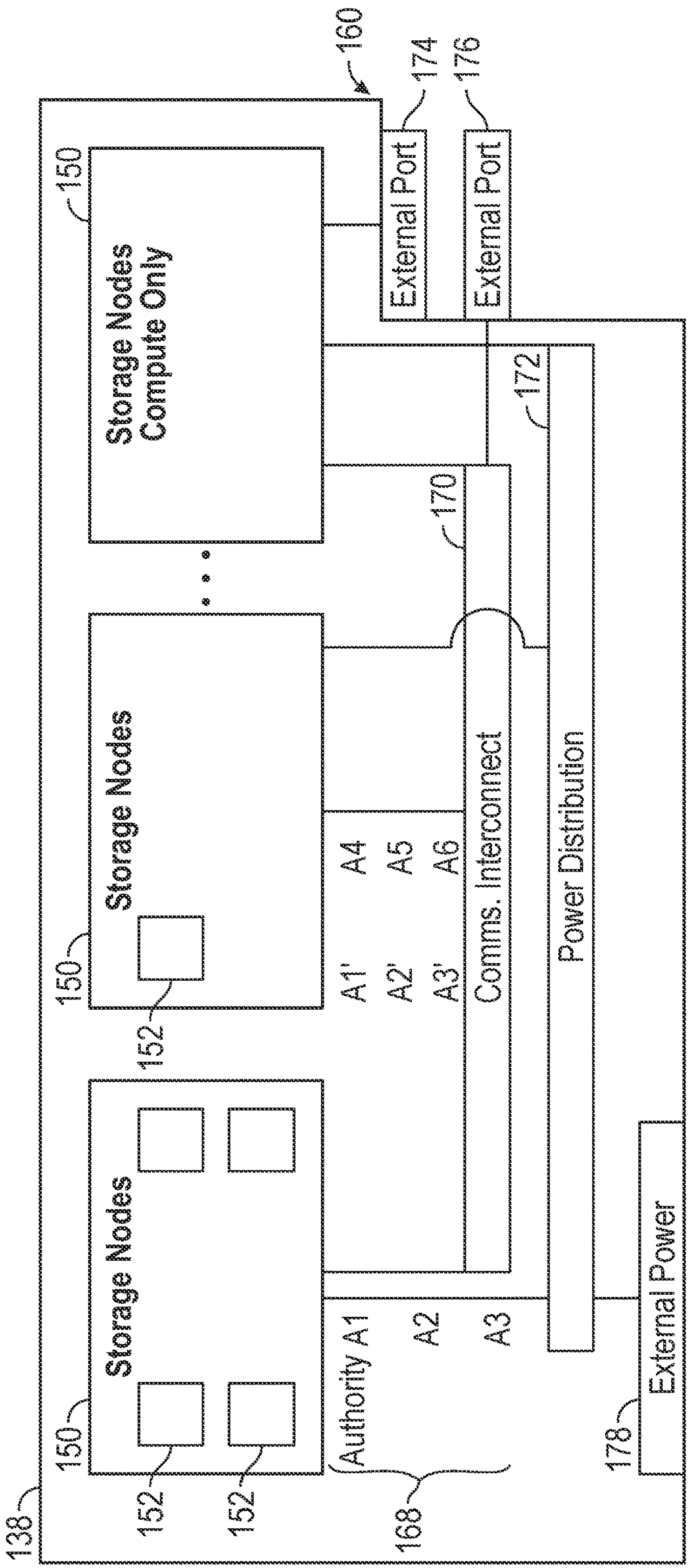

160
174
176
External Port
External Port
150
Storage Nodes
Compute Only
172
170
150
Storage Nodes
152
A1'
A2'
A3'
A4
A5
A6
Comms. Interconnect
Power Distribution
150
Storage Nodes
152
152
Authority A1
A2
A3
168
138
External Power
178

FIG. 2

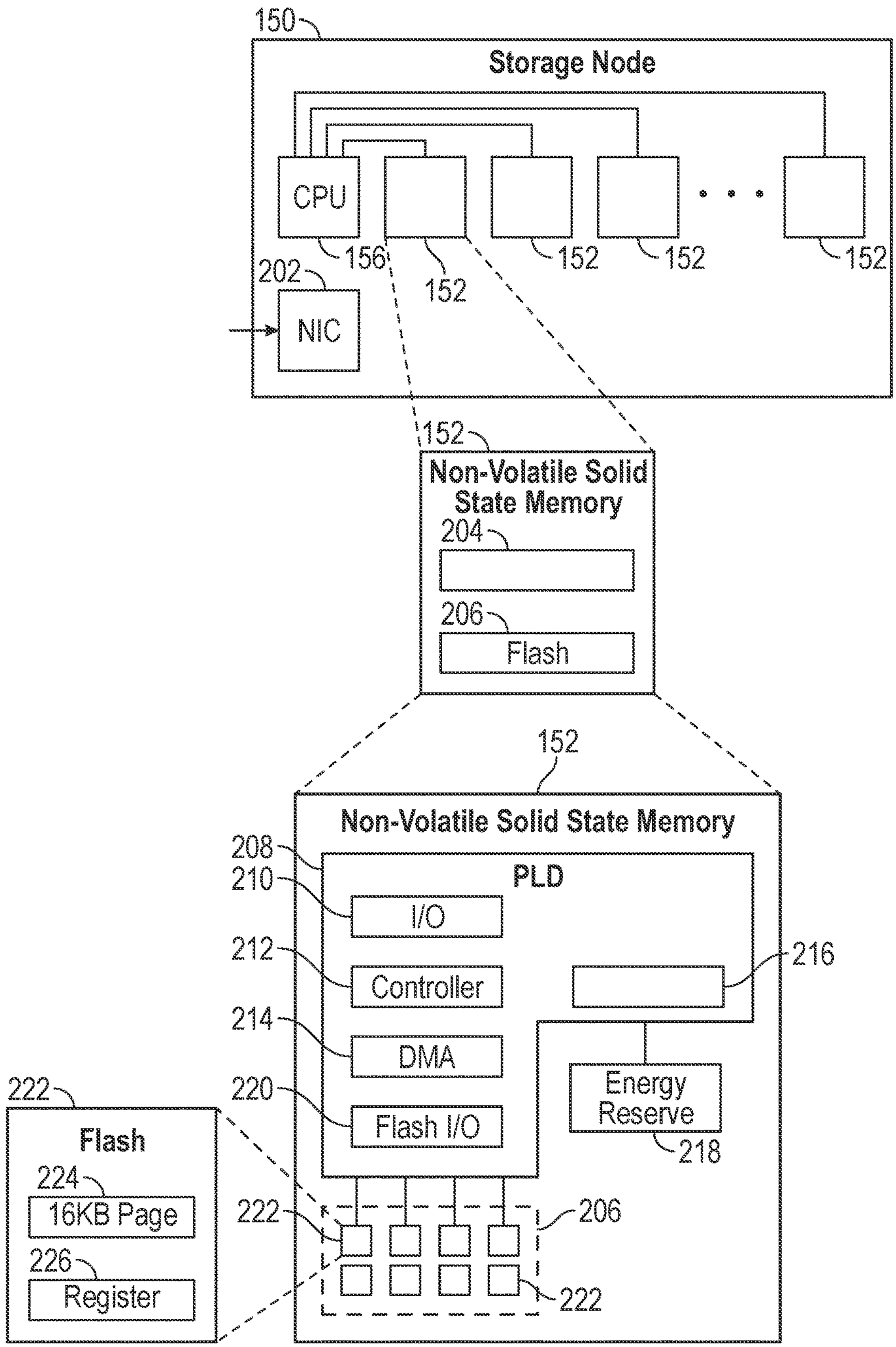
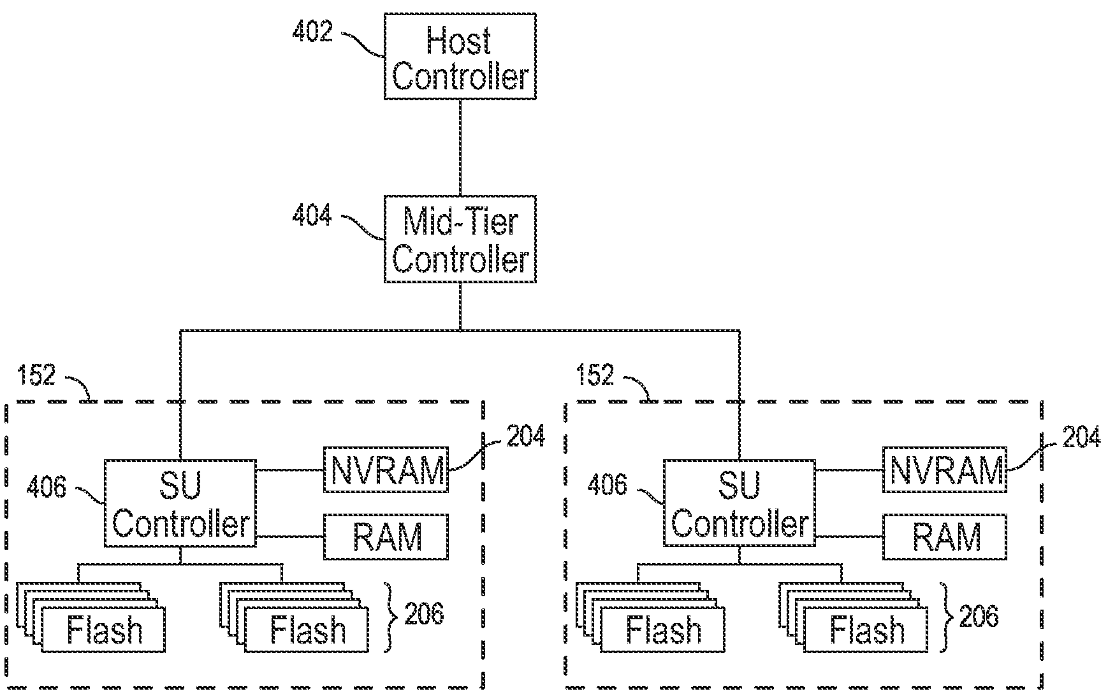

150
Storage Node
CPU
156
152
152
152
152
152
202
NIC
152
Non-Volatile Solid State Memory
204
206
Flash
152
Non-Volatile Solid State Memory
208
210
PLD
I/O
212
Controller
216
214
DMA
220
Flash I/O
Energy Reserve
218
222
Flash
224
16KB Page
226
Register
222
206
222

FIG. 3



402
Host Controller
404
Mid-Tier Controller
152
406
SU Controller
NVRAM
204
RAM
Flash
Flash
206
152
406
SU Controller
NVRAM
204
RAM
Flash
Flash
206

FIG. 4

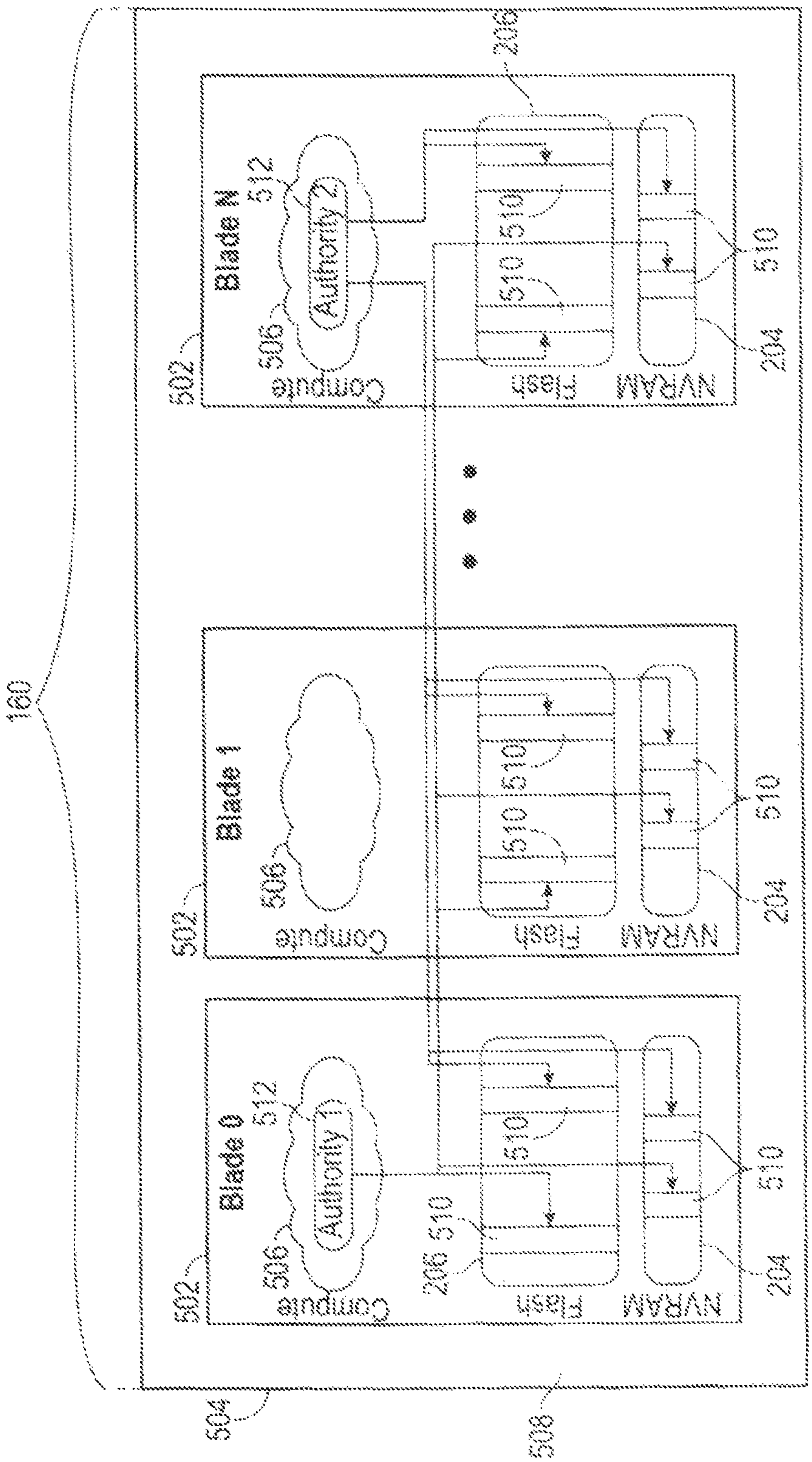
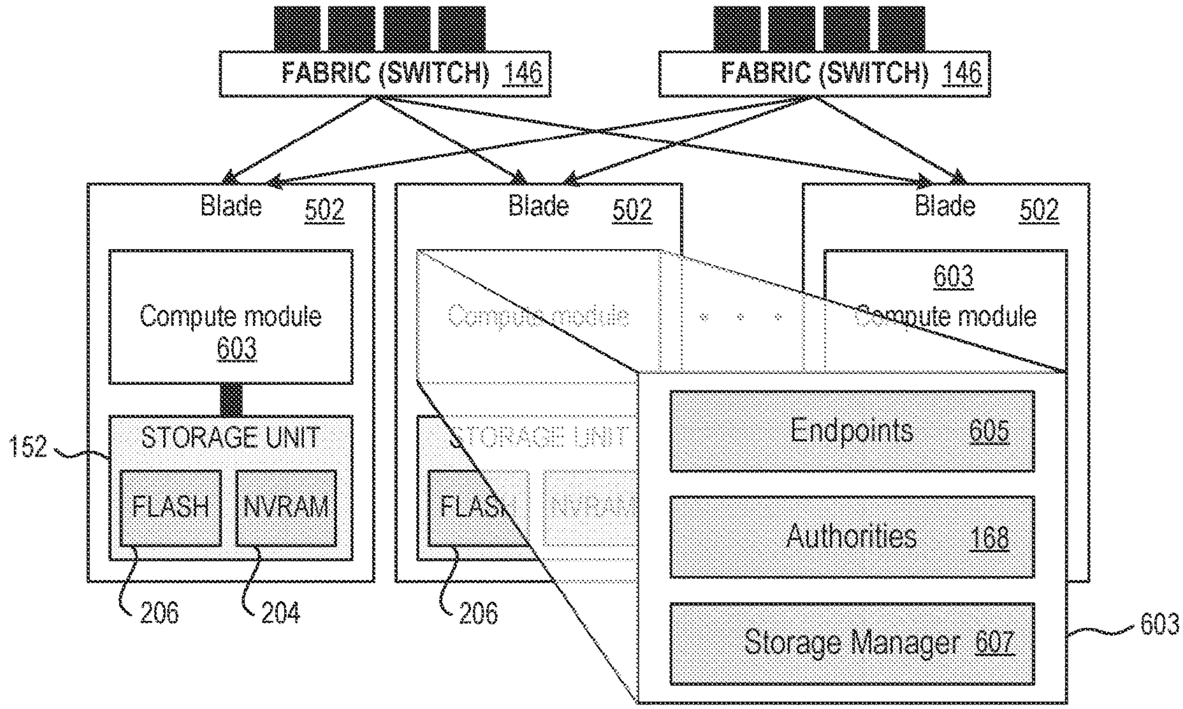
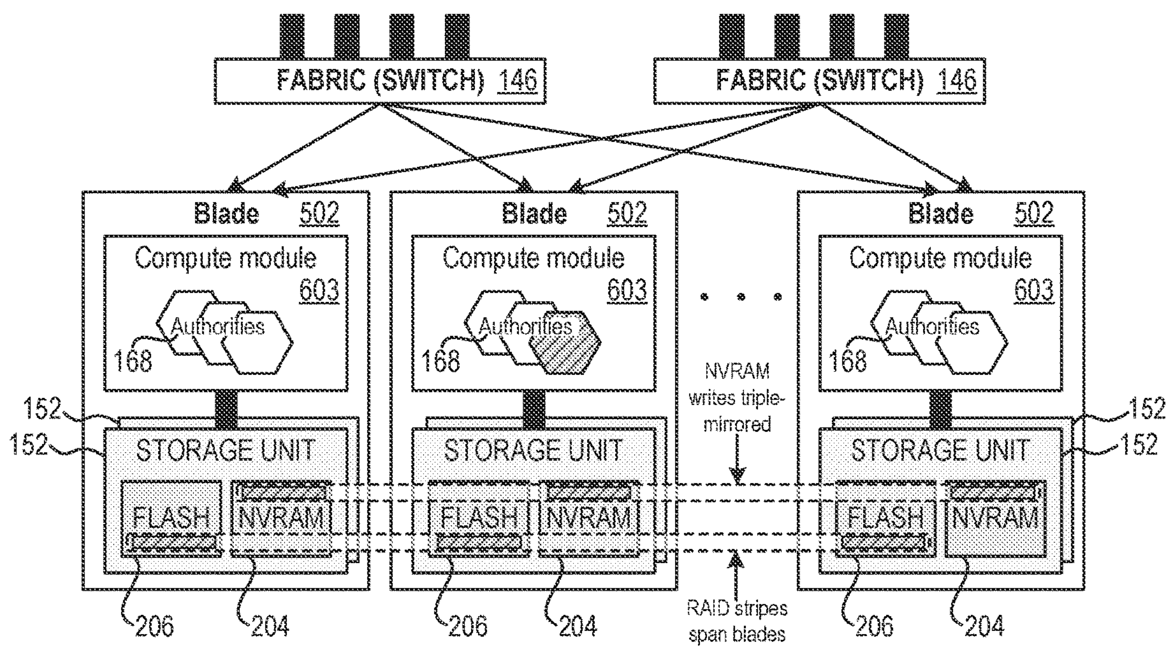

160
504
508
502
Blade 0
Blade 1
Blade N
Compute
Flash
NVRAM
506
512
Authority 1
Authority 2
510
204
206

FIG. 5



FABRIC (SWITCH) 146
FABRIC (SWITCH) 146
Blade 502
Blade 502
Blade 502
Compute module 603
Compute module
603
Compute module
152
STORAGE UNIT
FLASH
NVRAM
STORAGE UNIT
FLASH
NVRAM
Endpoints 605
Authorities 168
Storage Manager 607
206
204
206
603

FIG. 6



FABRIC (SWITCH) 146
FABRIC (SWITCH) 146
Blade 502
Blade 502
Blade 502
Compute module 603
Compute module 603
Compute module 603
Authorities
168
Authorities
168
Authorities
168
NVRAM writes triple-mirrored
152
152
152
152
STORAGE UNIT
STORAGE UNIT
STORAGE UNIT
FLASH
NVRAM
FLASH
NVRAM
FLASH
NVRAM
RAID stripes span blades
206
204
206
204
206
204

FIG. 7

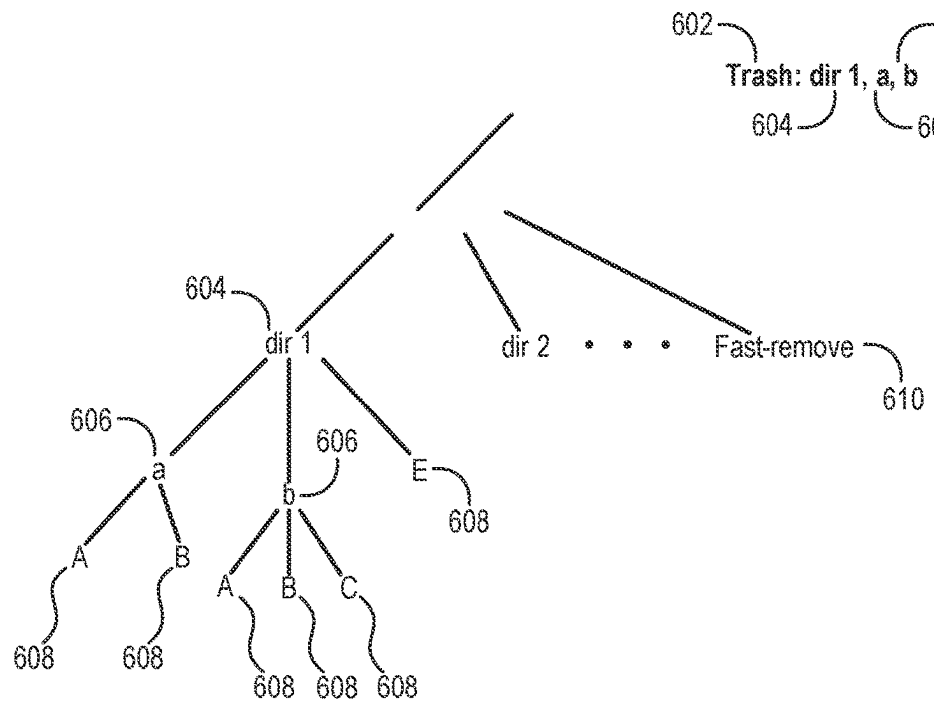

602
606
Trash: dir 1, a, b
604
606
604
dir 1
dir 2
Fast-remove
610
606
a
606
b
E
608
A
B
A
B
C
608
608
608
608
608

FIG.8A

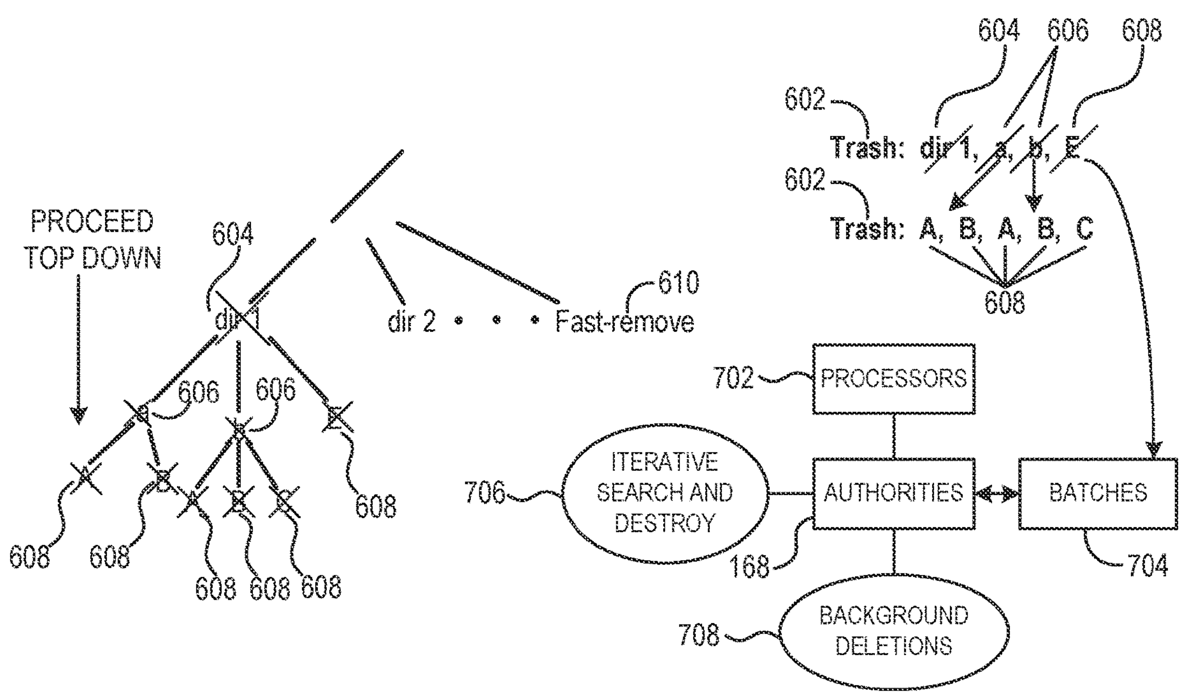

604
606
608
602
Trash: dir 1, a, b, E
602
Trash: A, B, A, B, C
608
PROCEED TOP DOWN
604
610
dir 1
dir 2
Fast-remove
606
606
702
PROCESSORS
706
ITERATIVE SEARCH AND DESTROY
AUTHORITIES
BATCHES
168
704
608
608
608
608
608
608
708
BACKGROUND DELETIONS

FIG.8B

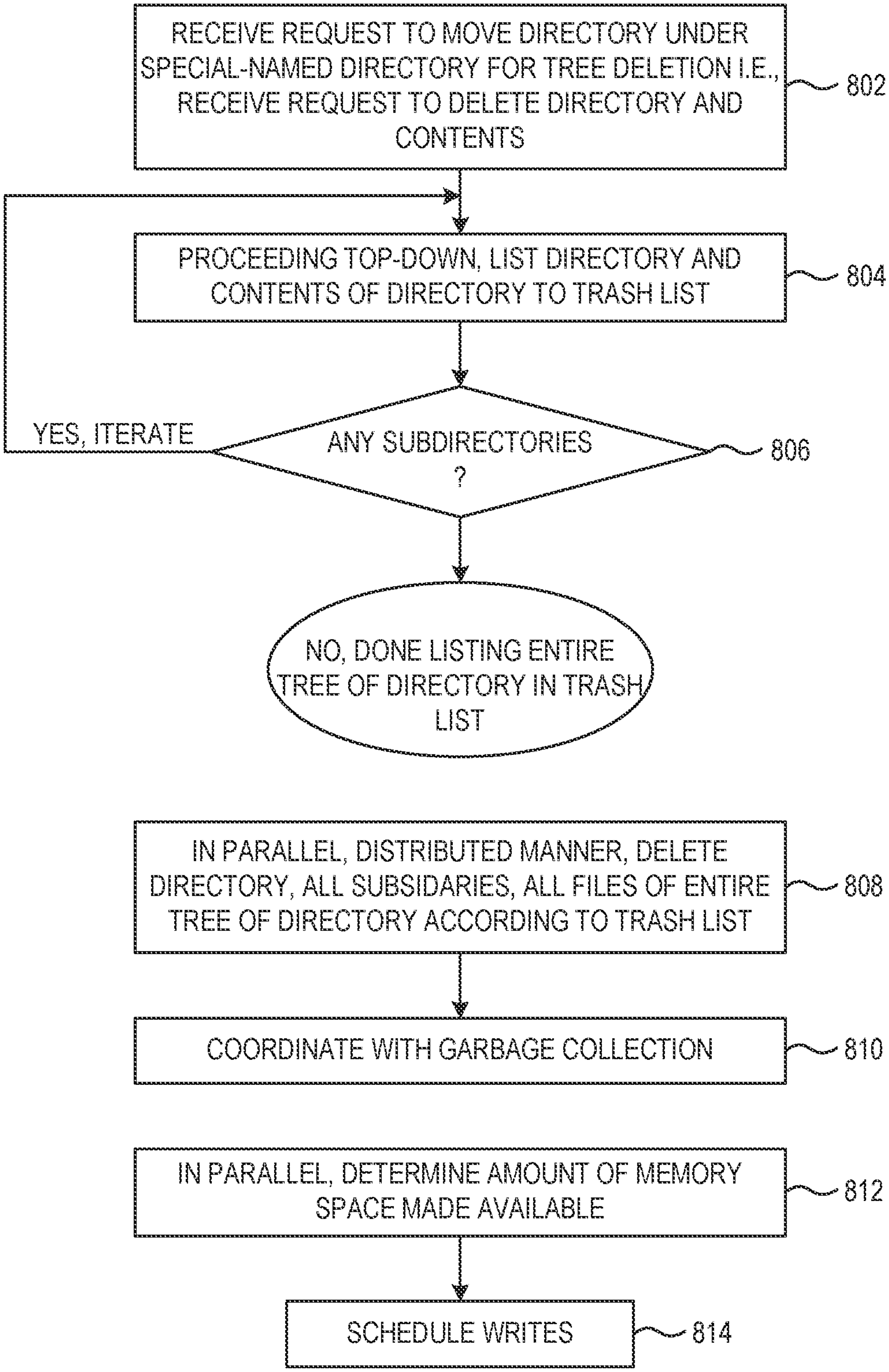

RECEIVE REQUEST TO MOVE DIRECTORY UNDER SPECIAL-NAMED DIRECTORY FOR TREE DELETION I.E., RECEIVE REQUEST TO DELETE DIRECTORY AND CONTENTS
802
PROCEEDING TOP-DOWN, LIST DIRECTORY AND CONTENTS OF DIRECTORY TO TRASH LIST
804
YES, ITERATE
ANY SUBDIRECTORIES ?
806
NO, DONE LISTING ENTIRE TREE OF DIRECTORY IN TRASH LIST
IN PARALLEL, DISTRIBUTED MANNER, DELETE DIRECTORY, ALL SUBSIDARIES, ALL FILES OF ENTIRE TREE OF DIRECTORY ACCORDING TO TRASH LIST
808
COORDINATE WITH GARBAGE COLLECTION
810
IN PARALLEL, DETERMINE AMOUNT OF MEMORY SPACE MADE AVAILABLE
812
SCHEDULE WRITES
814

FIG.9A

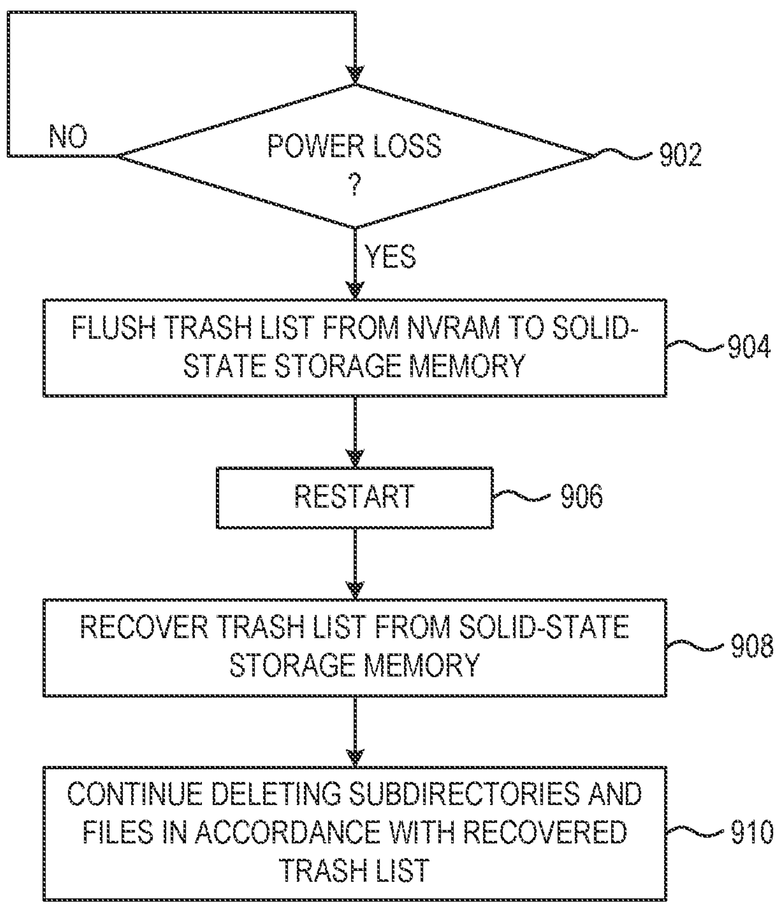

POWER LOSS
?
NO
YES
902
FLUSH TRASH LIST FROM NVRAM TO SOLID-STATE STORAGE MEMORY
904
RESTART
906
RECOVER TRASH LIST FROM SOLID-STATE STORAGE MEMORY
908
CONTINUE DELETING SUBDIRECTORIES AND FILES IN ACCORDANCE WITH RECOVERED TRASH LIST
910

FIG.9B

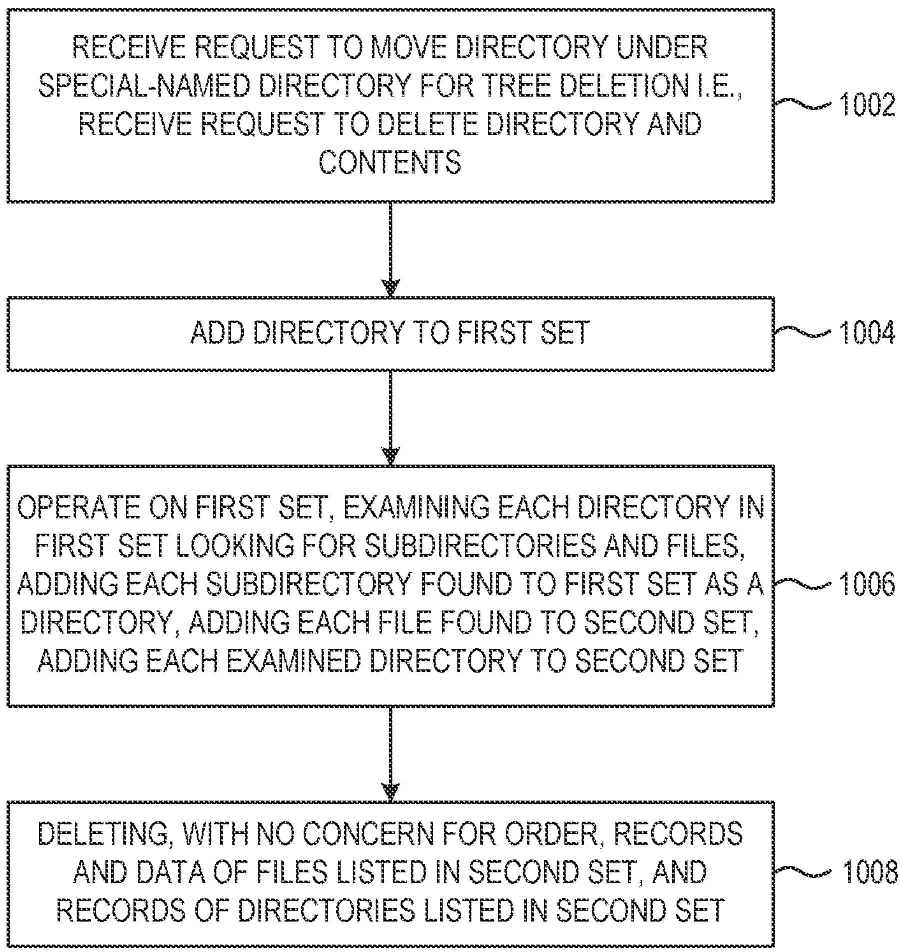
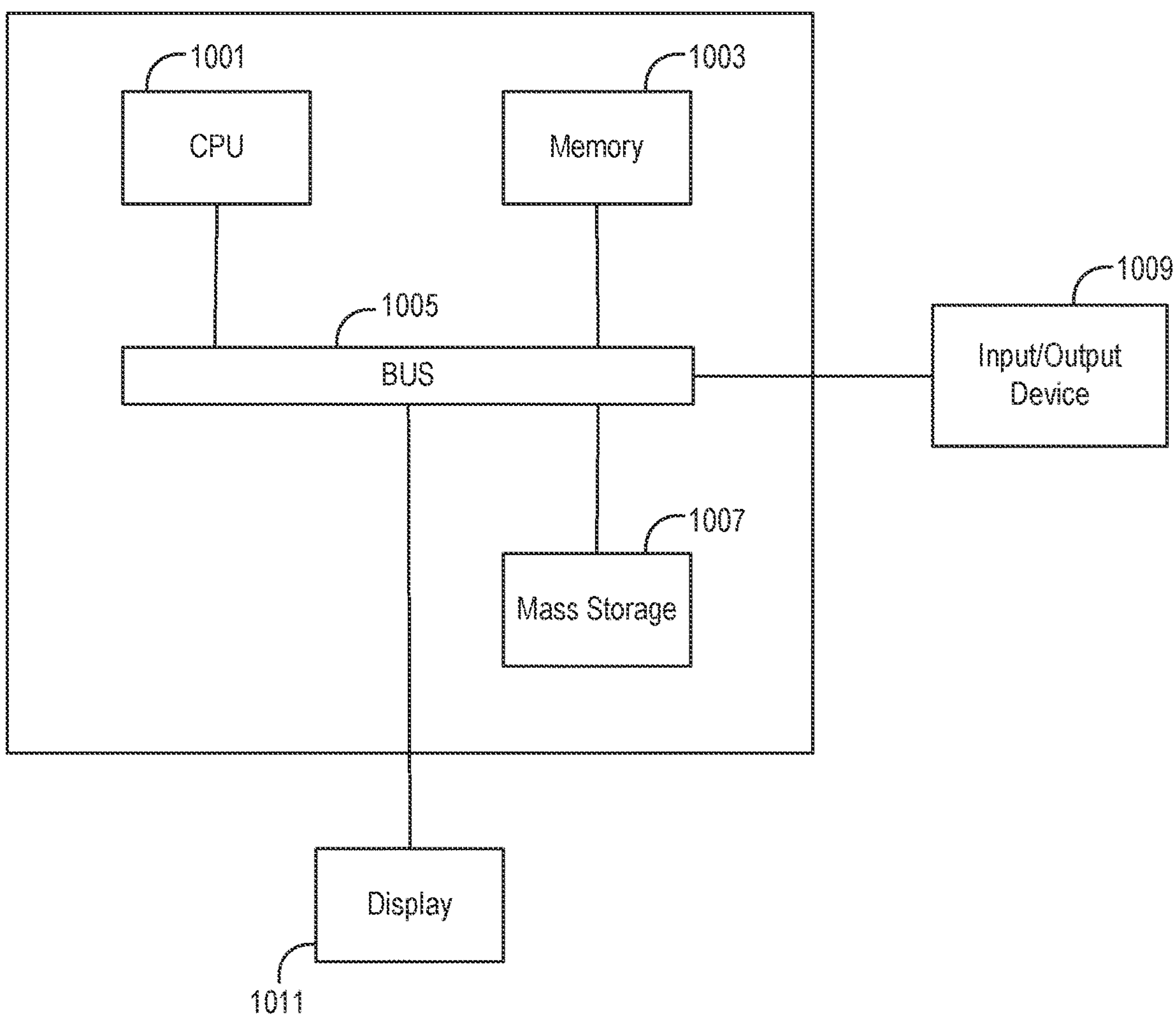

RECEIVE REQUEST TO MOVE DIRECTORY UNDER SPECIAL-NAMED DIRECTORY FOR TREE DELETION I.E., RECEIVE REQUEST TO DELETE DIRECTORY AND CONTENTS
1002
ADD DIRECTORY TO FIRST SET
1004
OPERATE ON FIRST SET, EXAMINING EACH DIRECTORY IN FIRST SET LOOKING FOR SUBDIRECTORIES AND FILES, ADDING EACH SUBDIRECTORY FOUND TO FIRST SET AS A DIRECTORY, ADDING EACH FILE FOUND TO SECOND SET, ADDING EACH EXAMINED DIRECTORY TO SECOND SET
1006
DELETING, WITH NO CONCERN FOR ORDER, RECORDS AND DATA OF FILES LISTED IN SECOND SET, AND RECORDS OF DIRECTORIES LISTED IN SECOND SET
1008

FIG. 10



1001
CPU
1003
Memory
1005
BUS
1009
Input/Output Device
1007
Mass Storage
Display
1011

FIG. 11

STORAGE SYSTEM WITH DISTRIBUTED DELETION

CROSS REFERENCE TO RELATED APPLICATIONS

This is a continuation application for patent entitled to a filing date and claiming the benefit of earlier-filed U.S. patent application Ser. No. 16/863,464, filed Apr. 30, 2020, herein incorporated by reference in its entirety, which is a continuation of U.S. Pat. No. 10,678,452, issued Jun. 9, 2020, which claims priority from a U.S. Provisional Application No. 62/395,338, filed Sep. 15, 2016, each of which is hereby incorporated by reference in their entirety.

BACKGROUND

With traditional file system kernels, to delete a directory a user must first traverse the entire directory and delete files and subdirectories from the bottom up, starting with the leafs (or leaves). Only when all of the contents of the parent directory have been manually deleted can the parent directory be deleted, for example using the UNIX command rmdir. The remove directory command, rmdir directory_name, will only remove an empty directory. There is a UNIX command that will remove a directory and all of the contents of the directory, however, these commands require the user specify the entire directory tree. In addition, the operating system that is interpreting the command must still communicate with the file system to do the directory tree tracing from the top down, and removal of the leafs from bottom-up, which incurs a lot of communication overhead. Other equivalent commands for deleting an entire tree for other operating systems exist, but in all of these alternatives deletion occurs from bottom-up through the tree after the directory tree is first traced from top-down. Each subdirectory is only deleted after it is emptied. Deletion of the top directory must wait until all subdirectories below it have been emptied. The above mechanisms while arguably suitable for hard disk drives, are not optimized for solid-state media.

Solid-state memory, such as flash, is currently in use in solid-state drives (SSD) to augment or replace conventional hard disk drives (HDD), writable CD (compact disk) or writable DVD (digital versatile disk) drives, collectively known as spinning media, and tape drives, for storage of large amounts of data. Flash and other solid-state memories have characteristics that differ from spinning media. Yet, many solid-state drives are designed to conform to hard disk drive standards for compatibility reasons, which makes it difficult to provide enhanced features or take advantage of unique aspects of flash and other solid-state memory. It is within this context that the embodiments arise.

SUMMARY

In some embodiments, a method of distributed file deletion, performed by a storage system, is provided. The method includes receiving, at the storage system, a request to delete a directory and contents of the directory and adding the directory to a first set, listed in a memory in the storage system. The method includes operating on the first set, by examining each directory in the first set to identify subdirectories, adding each identified subdirectory to the first set as a directory, and adding each examined directory to a second set listed in the memory. The method includes deleting in a distributed manner across the storage system without concern for order, contents of directories, and the directories, listed in the second set. The method may be embodied on a computer readable medium or executed by a storage system in some embodiments.

Other aspects and advantages of the embodiments will become apparent from the following detailed description taken in conjunction with the accompanying drawings which illustrate, by way of example, the principles of the described embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

The described embodiments and the advantages thereof may best be understood by reference to the following description taken in conjunction with the accompanying drawings. These drawings in no way limit any changes in form and detail that may be made to the described embodiments by one skilled in the art without departing from the spirit and scope of the described embodiments.

FIG. **1** is a perspective view of a storage cluster with multiple storage nodes and internal storage coupled to each storage node to provide network attached storage, in accordance with some embodiments.

FIG. **2** is a block diagram showing an interconnect switch coupling multiple storage nodes in accordance with some embodiments.

FIG. **3** is a multiple level block diagram, showing contents of a storage node and contents of one of the non-volatile solid state storage units in accordance with some embodiments.

FIG. **4** shows a storage server environment, which uses embodiments of the storage nodes and storage units of FIGS. **1**-**3** in accordance with some embodiments.

FIG. **5** is a blade hardware block diagram, showing a control plane, compute and storage planes, and authorities interacting with underlying physical resources, in accordance with some embodiments.

FIG. **6** depicts elasticity software layers in blades of a storage cluster, in accordance with some embodiments.

FIG. **7** depicts authorities and storage resources in blades of a storage cluster, in accordance with some embodiments.

FIG. **8**A is an action diagram showing a directory tree and a special-named directory for deleting a specified directory and the entire tree below that directory.

FIG. **8**B continues the action diagram of FIG. **8**A, and shows top-down iterative or recursive listing of a directory, subdirectories and files in a trash list, in some embodiments performed by processors on behalf of authorities, in iterative search and destroy processes with batch communication and background deletions.

FIG. **9**A is a flow diagram of a method for distributed directory and file deletion of a directory tree, which can be practiced in the storage cluster of FIGS. **1**-**5**, and in further storage systems, in accordance with some embodiments as described with reference to FIGS. **6** and **7**.

FIG. **9**B is a further flow diagram of a method for recovery from power loss, which can be practiced to augment the method of FIG. **9**A.

FIG. **10** is a further flow diagram of a method for distributed directory and file deletion of a directory tree, as a variation of the method shown in FIG. **8**.

FIG. **11** is an illustration showing an exemplary computing device which may implement the embodiments described herein.

DETAILED DESCRIPTION

Various mechanisms described herein efficiently delete a directory and an entire directory tree extending from the specified directory, without requiring the user to manually specify an entire directory tree or have an operating system or file system communicate requests for deletion of each file and each subdirectory to a storage system. Instead of tracing a directory tree from top-down, then deleting leafs from bottom-up and only deleting subdirectories when empty, as is usually the case in file systems, various embodiments of a storage system perform iterative search and destroy processes and background deletions in parallel for greater efficiency and decreased latency in response to a request to delete a directory tree. In some embodiments, a special-named directory is established for deletion of an entire directory tree. FIGS. **1-7** show various embodiments of a storage cluster, with storage nodes and solid-state storage units suitable for embodiments that practice distributed directory and file deletion. FIGS. **8**A-**10** show aspects of distributed file deletion, and distributed directory deletion.

The embodiments below describe a storage cluster that stores user data, such as user data originating from one or more user or client systems or other sources external to the storage cluster. The storage cluster distributes user data across storage nodes housed within a chassis, using erasure coding and redundant copies of metadata. Erasure coding refers to a method of data protection or reconstruction in which data is stored across a set of different locations, such as disks, storage nodes or geographic locations. Flash memory is one type of solid-state memory that may be integrated with the embodiments, although the embodiments may be extended to other types of solid-state memory or other storage medium, including non-solid state memory. Control of storage locations and workloads are distributed across the storage locations in a clustered peer-to-peer system. Tasks such as mediating communications between the various storage nodes, detecting when a storage node has become unavailable, and balancing I/Os (inputs and outputs) across the various storage nodes, are all handled on a distributed basis. Data is laid out or distributed across multiple storage nodes in data fragments or stripes that support data recovery in some embodiments. Ownership of data can be reassigned within a cluster, independent of input and output patterns. This architecture described in more detail below allows a storage node in the cluster to fail, with the system remaining operational, since the data can be reconstructed from other storage nodes and thus remain available for input and output operations. In various embodiments, a storage node may be referred to as a cluster node, a blade, or a server.

The storage cluster is contained within a chassis, i.e., an enclosure housing one or more storage nodes. A mechanism to provide power to each storage node, such as a power distribution bus, and a communication mechanism, such as a communication bus that enables communication between the storage nodes are included within the chassis. The storage cluster can run as an independent system in one location according to some embodiments. In one embodiment, a chassis contains at least two instances of both the power distribution and the communication bus which may be enabled or disabled independently. The internal communication bus may be an Ethernet bus, however, other technologies such as Peripheral Component Interconnect (PCI) Express, InfiniBand, and others, are equally suitable. The chassis provides a port for an external communication bus for enabling communication between multiple chassis, directly or through a switch, and with client systems. The external communication may use a technology such as Ethernet, InfiniBand, Fibre Channel, etc. In some embodiments, the external communication bus uses different communication bus technologies for inter-chassis and client communication. If a switch is deployed within or between chassis, the switch may act as a translation between multiple protocols or technologies. When multiple chassis are connected to define a storage cluster, the storage cluster may be accessed by a client using either proprietary interfaces or standard interfaces such as network file system (NFS), common internet file system (CIFS), small computer system interface (SCSI) or hypertext transfer protocol (HTTP). Translation from the client protocol may occur at the switch, chassis external communication bus or within each storage node.

Each storage node may be one or more storage servers and each storage server is connected to one or more non-volatile solid state memory units, which may be referred to as storage units or storage devices. One embodiment includes a single storage server in each storage node and between one to eight non-volatile solid state memory units, however this one example is not meant to be limiting. The storage server may include a processor, dynamic random access memory (DRAM) and interfaces for the internal communication bus and power distribution for each of the power buses. Inside the storage node, the interfaces and storage unit share a communication bus, e.g., PCI Express, in some embodiments. The non-volatile solid state memory units may directly access the internal communication bus interface through a storage node communication bus, or request the storage node to access the bus interface. The non-volatile solid state memory unit contains an embedded central processing unit (CPU), solid state storage controller, and a quantity of solid state mass storage, e.g., between 2-32 terabytes (TB) in some embodiments. An embedded volatile storage medium, such as DRAM, and an energy reserve apparatus are included in the non-volatile solid state memory unit. In some embodiments, the energy reserve apparatus is a capacitor, super-capacitor, or battery that enables transferring a subset of DRAM contents to a stable storage medium in the case of power loss. In some embodiments, the non-volatile solid state memory unit is constructed with a storage class memory, such as phase change or magnetoresistive random access memory (MRAM) that substitutes for DRAM and enables a reduced power hold-up apparatus.

One of many features of the storage nodes and non-volatile solid state storage is the ability to proactively rebuild data in a storage cluster. The storage nodes and non-volatile solid state storage can determine when a storage node or non-volatile solid state storage in the storage cluster is unreachable, independent of whether there is an attempt to read data involving that storage node or non-volatile solid state storage. The storage nodes and non-volatile solid state storage then cooperate to recover and rebuild the data in at least partially new locations. This constitutes a proactive rebuild, in that the system rebuilds data without waiting until the data is needed for a read access initiated from a client system employing the storage cluster. These and further details of the storage memory and operation thereof are discussed below.

FIG. **1** is a perspective view of a storage cluster **160**, with multiple storage nodes **150** and internal solid-state memory coupled to each storage node to provide network attached storage or storage area network, in accordance with some embodiments. A network attached storage, storage area network, or a storage cluster, or other storage memory, could include one or more storage clusters **160**, each having one or more storage nodes **150**, in a flexible and reconfigurable arrangement of both the physical components and the amount of storage memory provided thereby. The storage cluster **160** is designed to fit in a rack, and one or more racks can be set up and populated as desired for the storage memory. The storage cluster **160** has a chassis **138** having multiple slots **142**. It should be appreciated that chassis **138** may be referred to as a housing, enclosure, or rack unit. In one embodiment, the chassis **138** has fourteen slots **142**, although other numbers of slots are readily devised. For example, some embodiments have four slots, eight slots, sixteen slots, thirty-two slots, or other suitable number of slots. Each slot **142** can accommodate one storage node **150** in some embodiments. Chassis **138** includes flaps **148** that can be utilized to mount the chassis **138** on a rack. Fans **144** provide air circulation for cooling of the storage nodes **150** and components thereof, although other cooling components could be used, or an embodiment could be devised without cooling components. A switch fabric **146** couples storage nodes **150** within chassis **138** together and to a network for communication to the memory. In an embodiment depicted in FIG. **1**, the slots **142** to the left of the switch fabric **146** and fans **144** are shown occupied by storage nodes **150**, while the slots **142** to the right of the switch fabric **146** and fans **144** are empty and available for insertion of storage node **150** for illustrative purposes. This configuration is one example, and one or more storage nodes **150** could occupy the slots **142** in various further arrangements. The storage node arrangements need not be sequential or adjacent in some embodiments. Storage nodes **150** are hot pluggable, meaning that a storage node **150** can be inserted into a slot **142** in the chassis **138**, or removed from a slot **142**, without stopping or powering down the system. Upon insertion or removal of storage node **150** from slot **142**, the system automatically reconfigures in order to recognize and adapt to the change. Reconfiguration, in some embodiments, includes restoring redundancy and/or rebalancing data or load.

Each storage node **150** can have multiple components. In the embodiment shown here, the storage node **150** includes a printed circuit board **158** populated by a CPU **156**, i.e., processor, a memory **154** coupled to the CPU **156**, and a non-volatile solid state storage **152** coupled to the CPU **156**, although other mountings and/or components could be used in further embodiments. The memory **154** has instructions which are executed by the CPU **156** and/or data operated on by the CPU **156**. As further explained below, the non-volatile solid state storage **152** includes flash or, in further embodiments, other types of solid-state memory.

Referring to FIG. **1**, storage cluster **160** is scalable, meaning that storage capacity with non-uniform storage sizes is readily added, as described above. One or more storage nodes **150** can be plugged into or removed from each chassis and the storage cluster self-configures in some embodiments. Plug-in storage nodes **150**, whether installed in a chassis as delivered or later added, can have different sizes. For example, in one embodiment a storage node **150** can have any multiple of 4 TB, e.g., 8 TB, 12 TB, 16 TB, 32 TB, etc. In further embodiments, a storage node **150** could have any multiple of other storage amounts or capacities. Storage capacity of each storage node **150** is broadcast, and influences decisions of how to stripe the data. For maximum storage efficiency, an embodiment can self-configure as wide as possible in the stripe, subject to a predetermined requirement of continued operation with loss of up to one, or up to two, non-volatile solid state storage units **152** or storage nodes **150** within the chassis.

FIG. **2** is a block diagram showing a communications interconnect **170** and power distribution bus **172** coupling multiple storage nodes **150**. Referring back to FIG. **1**, the communications interconnect **170** can be included in or implemented with the switch fabric **146** in some embodiments. Where multiple storage clusters **160** occupy a rack, the communications interconnect **170** can be included in or implemented with a top of rack switch, in some embodiments. As illustrated in FIG. **2**, storage cluster **160** is enclosed within a single chassis **138**. External port **176** is coupled to storage nodes **150** through communications interconnect **170**, while external port **174** is coupled directly to a storage node. External power port **178** is coupled to power distribution bus **172**. Storage nodes **150** may include varying amounts and differing capacities of non-volatile solid state storage **152** as described with reference to FIG. **1**. In addition, one or more storage nodes **150** may be a compute only storage node as illustrated in FIG. **2**. Authorities **168** are implemented on the non-volatile solid state storages **152**, for example as lists or other data structures stored in memory. In some embodiments the authorities are stored within the non-volatile solid state storage **152** and supported by software executing on a controller or other processor of the non-volatile solid state storage **152**. In a further embodiment, authorities **168** are implemented on the storage nodes **150**, for example as lists or other data structures stored in the memory **154** and supported by software executing on the CPU **156** of the storage node **150**. Authorities **168** control how and where data is stored in the non-volatile solid state storages **152** in some embodiments. This control assists in determining which type of erasure coding scheme is applied to the data, and which storage nodes **150** have which portions of the data. Each authority **168** may be assigned to a non-volatile solid state storage **152**. Each authority may control a range of inode numbers, segment numbers, or other data identifiers which are assigned to data by a file system, by the storage nodes **150**, or by the non-volatile solid state storage **152**, in various embodiments.

Every piece of data, and every piece of metadata, has redundancy in the system in some embodiments. In addition, every piece of data and every piece of metadata has an owner, which may be referred to as an authority. If that authority is unreachable, for example through failure of a storage node, there is a plan of succession for how to find that data or that metadata. In various embodiments, there are redundant copies of authorities **168**. Authorities **168** have a relationship to storage nodes **150** and non-volatile solid state storage **152** in some embodiments. Each authority **168**, covering a range of data segment numbers or other identifiers of the data, may be assigned to a specific non-volatile solid state storage **152**. In some embodiments the authorities **168** for all of such ranges are distributed over the non-volatile solid state storages **152** of a storage cluster. Each storage node **150** has a network port that provides access to the non-volatile solid state storage(s) **152** of that storage node **150**. Data can be stored in a segment, which is associated with a segment number and that segment number is an indirection for a configuration of a RAID (redundant array of independent disks) stripe in some embodiments. The assignment and use of the authorities **168** thus establishes an indirection to data. Indirection may be referred to as the ability to reference data indirectly, in this case via an authority **168**, in accordance with some embodiments. A segment identifies a set of non-volatile solid state storage **152** and a local identifier into the set of non-volatile solid state storage **152** that may contain data. In some embodiments, the local identifier is an offset into the device and may be reused sequentially by multiple segments. In other embodiments the local identifier is unique for a specific segment and never reused. The offsets in the non-volatile solid state storage **152** are applied to locating data for writing to or reading from the non-volatile solid state storage **152** (in the form of a RAID stripe). Data is striped across multiple units of non-volatile solid state storage **152**, which may include or be different from the non-volatile solid state storage **152** having the authority **168** for a particular data segment.

If there is a change in where a particular segment of data is located, e.g., during a data move or a data reconstruction, the authority **168** for that data segment should be consulted, at that non-volatile solid state storage **152** or storage node **150** having that authority **168**. In order to locate a particular piece of data, embodiments calculate a hash value for a data segment or apply an inode number or a data segment number. The output of this operation points to a non-volatile solid state storage **152** having the authority **168** for that particular piece of data. In some embodiments there are two stages to this operation. The first stage maps an entity identifier (ID), e.g., a segment number, inode number, or directory number to an authority identifier. This mapping may include a calculation such as a hash or a bit mask. The second stage is mapping the authority identifier to a particular non-volatile solid state storage **152**, which may be done through an explicit mapping. The operation is repeatable, so that when the calculation is performed, the result of the calculation repeatably and reliably points to a particular non-volatile solid state storage **152** having that authority **168**. The operation may include the set of reachable storage nodes as input. If the set of reachable non-volatile solid state storage units changes the optimal set changes. In some embodiments, the persisted value is the current assignment (which is always true) and the calculated value is the target assignment the cluster will attempt to reconfigure towards. This calculation may be used to determine the optimal non-volatile solid state storage **152** for an authority in the presence of a set of non-volatile solid state storage **152** that are reachable and constitute the same cluster. The calculation also determines an ordered set of peer non-volatile solid state storage **152** that will also record the authority to non-volatile solid state storage mapping so that the authority may be determined even if the assigned non-volatile solid state storage is unreachable. A duplicate or substitute authority **168** may be consulted if a specific authority **168** is unavailable in some embodiments.

With reference to FIGS. **1** and **2**, two of the many tasks of the CPU **156** on a storage node **150** are to break up write data, and reassemble read data. When the system has determined that data is to be written, the authority **168** for that data is located as above. When the segment ID for data is already determined the request to write is forwarded to the non-volatile solid state storage **152** currently determined to be the host of the authority **168** determined from the segment. The host CPU **156** of the storage node **150**, on which the non-volatile solid state storage **152** and corresponding authority **168** reside, then breaks up or shards the data and transmits the data out to various non-volatile solid state storage **152**. The transmitted data is written as a data stripe in accordance with an erasure coding scheme. In some embodiments, data is requested to be pulled, and in other embodiments, data is pushed. In reverse, when data is read, the authority **168** for the segment ID containing the data is located as described above. The host CPU **156** of the storage node **150** on which the non-volatile solid state storage **152** and corresponding authority **168** reside requests the data from the non-volatile solid state storage and corresponding storage nodes pointed to by the authority. In some embodiments the data is read from flash storage as a data stripe. The host CPU **156** of storage node **150** then reassembles the read data, correcting any errors (if present) according to the appropriate erasure coding scheme, and forwards the reassembled data to the network. In further embodiments, some or all of these tasks can be handled in the non-volatile solid state storage **152**. In some embodiments, the segment host requests the data be sent to storage node **150** by requesting pages from storage and then sending the data to the storage node making the original request.

In some systems, for example in UNIX-style file systems, data is handled with an index node or inode, which specifies a data structure that represents an object in a file system. The object could be a file or a directory, for example. Metadata may accompany the object, as attributes such as permission data and a creation timestamp, among other attributes. A segment number could be assigned to all or a portion of such an object in a file system. In other systems, data segments are handled with a segment number assigned elsewhere. For purposes of discussion, the unit of distribution is an entity, and an entity can be a file, a directory or a segment. That is, entities are units of data or metadata stored by a storage system. Entities are grouped into sets called authorities. Each authority has an authority owner, which is a storage node that has the exclusive right to update the entities in the authority. In other words, a storage node contains the authority, and that the authority, in turn, contains entities.

A segment is a logical container of data in accordance with some embodiments. A segment is an address space between medium address space and physical flash locations, i.e., the data segment number, are in this address space. Segments may also contain meta-data, which enable data redundancy to be restored (rewritten to different flash locations or devices) without the involvement of higher level software. In one embodiment, an internal format of a segment contains client data and medium mappings to determine the position of that data. Each data segment is protected, e.g., from memory and other failures, by breaking the segment into a number of data and parity shards, where applicable. The data and parity shards are distributed, i.e., striped, across non-volatile solid state storage **152** coupled to the host CPUs **156** (See FIGS. **5** and **7**) in accordance with an erasure coding scheme. Usage of the term segments refers to the container and its place in the address space of segments in some embodiments. Usage of the term stripe refers to the same set of shards as a segment and includes how the shards are distributed along with redundancy or parity information in accordance with some embodiments.

A series of address-space transformations takes place across an entire storage system. At the top are the directory entries (file names) which link to an inode. Inodes point into medium address space, where data is logically stored. Medium addresses may be mapped through a series of indirect mediums to spread the load of large files, or implement data services like deduplication or snapshots. Medium addresses may be mapped through a series of indirect mediums to spread the load of large files, or implement data services like deduplication or snapshots. Segment addresses are then translated into physical flash locations. Physical flash locations have an address range bounded by the amount of flash in the system in accordance with some embodiments. Medium addresses and segment addresses are logical containers, and in some embodiments use a 128 bit or larger identifier so as to be practically infinite, with a likelihood of reuse calculated as longer than the expected life of the system. Addresses from logical containers are allocated in a hierarchical fashion in some embodiments. Initially, each non-volatile solid state storage unit **152** may be assigned a range of address space. Within this assigned range, the non-volatile solid state storage **152** is able to allocate addresses without synchronization with other non-volatile solid state storage **152**.

Data and metadata is stored by a set of underlying storage layouts that are optimized for varying workload patterns and storage devices. These layouts incorporate multiple redundancy schemes, compression formats and index algorithms. Some of these layouts store information about authorities and authority masters, while others store file metadata and file data. The redundancy schemes include error correction codes that tolerate corrupted bits within a single storage device (such as a NAND flash chip), erasure codes that tolerate the failure of multiple storage nodes, and replication schemes that tolerate data center or regional failures. In some embodiments, low density parity check (LDPC) code is used within a single storage unit. Reed-Solomon encoding is used within a storage cluster, and mirroring is used within a storage grid in some embodiments. Metadata may be stored using an ordered log structured index (such as a Log Structured Merge Tree), and large data may not be stored in a log structured layout.

In order to maintain consistency across multiple copies of an entity, the storage nodes agree implicitly on two things through calculations: (1) the authority that contains the entity, and (2) the storage node that contains the authority. The assignment of entities to authorities can be done by pseudo randomly assigning entities to authorities, by splitting entities into ranges based upon an externally produced key, or by placing a single entity into each authority. Examples of pseudorandom schemes are linear hashing and the Replication Under Scalable Hashing (RUSH) family of hashes, including Controlled Replication Under Scalable Hashing (CRUSH). In some embodiments, pseudo-random assignment is utilized only for assigning authorities to nodes because the set of nodes can change. The set of authorities cannot change so any subjective function may be applied in these embodiments. Some placement schemes automatically place authorities on storage nodes, while other placement schemes rely on an explicit mapping of authorities to storage nodes. In some embodiments, a pseudorandom scheme is utilized to map from each authority to a set of candidate authority owners. A pseudorandom data distribution function related to CRUSH may assign authorities to storage nodes and create a list of where the authorities are assigned. Each storage node has a copy of the pseudorandom data distribution function, and can arrive at the same calculation for distributing, and later finding or locating an authority. Each of the pseudorandom schemes requires the reachable set of storage nodes as input in some embodiments in order to conclude the same target nodes. Once an entity has been placed in an authority, the entity may be stored on physical devices so that no expected failure will lead to unexpected data loss. In some embodiments, rebalancing algorithms attempt to store the copies of all entities within an authority in the same layout and on the same set of machines.

Examples of expected failures include device failures, stolen machines, datacenter fires, and regional disasters, such as nuclear or geological events. Different failures lead to different levels of acceptable data loss. In some embodiments, a stolen storage node impacts neither the security nor the reliability of the system, while depending on system configuration, a regional event could lead to no loss of data, a few seconds or minutes of lost updates, or even complete data loss.

In the embodiments, the placement of data for storage redundancy is independent of the placement of authorities for data consistency. In some embodiments, storage nodes that contain authorities do not contain any persistent storage. Instead, the storage nodes are connected to non-volatile solid state storage units that do not contain authorities. The communications interconnect between storage nodes and non-volatile solid state storage units consists of multiple communication technologies and has non-uniform performance and fault tolerance characteristics. In some embodiments, as mentioned above, non-volatile solid state storage units are connected to storage nodes via PCI express, storage nodes are connected together within a single chassis using Ethernet backplane, and chassis are connected together to form a storage cluster. Storage clusters are connected to clients using Ethernet or fiber channel in some embodiments. If multiple storage clusters are configured into a storage grid, the multiple storage clusters are connected using the Internet or other long-distance networking links, such as a "metro scale" link or private link that does not traverse the internet.

Authority owners have the exclusive right to modify entities, to migrate entities from one non-volatile solid state storage unit to another non-volatile solid state storage unit, and to add and remove copies of entities. This allows for maintaining the redundancy of the underlying data. When an authority owner fails, is going to be decommissioned, or is overloaded, the authority is transferred to a new storage node. Transient failures make it non-trivial to ensure that all non-faulty machines agree upon the new authority location. The ambiguity that arises due to transient failures can be achieved automatically by a consensus protocol such as Paxos, hot-warm failover schemes, via manual intervention by a remote system administrator, or by a local hardware administrator (such as by physically removing the failed machine from the cluster, or pressing a button on the failed machine). In some embodiments, a consensus protocol is used, and failover is automatic. If too many failures or replication events occur in too short a time period, the system goes into a self-preservation mode and halts replication and data movement activities until an administrator intervenes in accordance with some embodiments.

As authorities are transferred between storage nodes and authority owners update entities in their authorities, the system transfers messages between the storage nodes and non-volatile solid state storage units. With regard to persistent messages, messages that have different purposes are of different types. Depending on the type of the message, the system maintains different ordering and durability guarantees. As the persistent messages are being processed, the messages are temporarily stored in multiple durable and non-durable storage hardware technologies. In some embodiments, messages are stored in RAM, NVRAM and on NAND flash devices, and a variety of protocols are used in order to make efficient use of each storage medium. Latency-sensitive client requests may be persisted in replicated NVRAM, and then later NAND, while background rebalancing operations are persisted directly to NAND.

Persistent messages are persistently stored prior to being transmitted. This allows the system to continue to serve client requests despite failures and component replacement. Although many hardware components contain unique identifiers that are visible to system administrators, manufacturer, hardware supply chain and ongoing monitoring quality control infrastructure, applications running on top of the infrastructure address virtualize addresses. These virtualized addresses do not change over the lifetime of the storage system, regardless of component failures and replacements. This allows each component of the storage system to be replaced over time without reconfiguration or disruptions of client request processing.

In some embodiments, the virtualized addresses are stored with sufficient redundancy. A continuous monitoring system correlates hardware and software status and the hardware identifiers. This allows detection and prediction of failures due to faulty components and manufacturing details. The monitoring system also enables the proactive transfer of authorities and entities away from impacted devices before failure occurs by removing the component from the critical path in some embodiments.

FIG. **3** is a multiple level block diagram, showing contents of a storage node **150** and contents of a non-volatile solid state storage **152** of the storage node **150**. Data is communicated to and from the storage node **150** by a network interface controller (NIC) **202** in some embodiments. Each storage node **150** has a CPU **156**, and one or more non-volatile solid state storage **152**, as discussed above. Moving down one level in FIG. **3**, each non-volatile solid state storage **152** has a relatively fast non-volatile solid state memory, such as nonvolatile random access memory (NVRAM) **204**, and flash memory **206**. In some embodiments, NVRAM **204** may be a component that does not require program/erase cycles (DRAM, MRAM, PCM), and can be a memory that can support being written vastly more often than the memory is read from. Moving down another level in FIG. **3**, the NVRAM **204** is implemented in one embodiment as high speed volatile memory, such as dynamic random access memory (DRAM) **216**, backed up by energy reserve **218**. Energy reserve **218** provides sufficient electrical power to keep the DRAM **216** powered long enough for contents to be transferred to the flash memory **206** in the event of power failure. In some embodiments, energy reserve **218** is a capacitor, super-capacitor, battery, or other device, that supplies a suitable supply of energy sufficient to enable the transfer of the contents of DRAM **216** to a stable storage medium in the case of power loss. The flash memory **206** is implemented as multiple flash dies **222**, which may be referred to as packages of flash dies **222** or an array of flash dies **222**. It should be appreciated that the flash dies **222** could be packaged in any number of ways, with a single die per package, multiple dies per package (i.e. multichip packages), in hybrid packages, as bare dies on a printed circuit board or other substrate, as encapsulated dies, etc. In the embodiment shown, the non-volatile solid state storage **152** has a controller **212** or other processor, and an input output (I/O) port **210** coupled to the controller **212**. I/O port **210** is coupled to the CPU **156** and/or the network interface controller **202** of the flash storage node **150**. Flash input output (I/O) port **220** is coupled to the flash dies **222**, and a direct memory access unit (DMA) **214** is coupled to the controller **212**, the DRAM **216** and the flash dies **222**. In the embodiment shown, the I/O port **210**, controller **212**, DMA unit **214** and flash I/O port **220** are implemented on a programmable logic device (PLD) **208**, e.g., a field programmable gate array (FPGA). In this embodiment, each flash die **222** has pages, organized as sixteen kB (kilobyte) pages **224**, and a register **226** through which data can be written to or read from the flash die **222**. In further embodiments, other types of solid-state memory are used in place of, or in addition to flash memory illustrated within flash die **222**.

Storage clusters **160**, in various embodiments as disclosed herein, can be contrasted with storage arrays in general. The storage nodes **150** are part of a collection that creates the storage cluster **160**. Each storage node **150** owns a slice of data and computing required to provide the data. Multiple storage nodes **150** cooperate to store and retrieve the data. Storage memory or storage devices, as used in storage arrays in general, are less involved with processing and manipulating the data. Storage memory or storage devices in a storage array receive commands to read, write, or erase data. The storage memory or storage devices in a storage array are not aware of a larger system in which they are embedded, or what the data means. Storage memory or storage devices in storage arrays can include various types of storage memory, such as RAM, solid state drives, hard disk drives, etc. The storage units **152** described herein have multiple interfaces active simultaneously and serving multiple purposes. In some embodiments, some of the functionality of a storage node **150** is shifted into a storage unit **152**, transforming the storage unit **152** into a combination of storage unit **152** and storage node **150**. Placing computing (relative to storage data) into the storage unit **152** places this computing closer to the data itself. The various system embodiments have a hierarchy of storage node layers with different capabilities. By contrast, in a storage array, a controller owns and knows everything about all of the data that the controller manages in a shelf or storage devices. In a storage cluster **160**, as described herein, multiple controllers in multiple storage units **152** and/or storage nodes **150** cooperate in various ways (e.g., for erasure coding, data sharding, metadata communication and redundancy, storage capacity expansion or contraction, data recovery, and so on).

FIG. **4** shows a storage server environment, which uses embodiments of the storage nodes **150** and storage units **152** of FIGS. **1-3**. In this version, each storage unit **152** has a processor such as controller **212** (see FIG. **3**), an FPGA (field programmable gate array), flash memory **206**, and NVRAM **204** (which is super-capacitor backed DRAM **216**, see FIGS. **2** and **3**) on a PCIe (peripheral component interconnect express) board in a chassis **138** (see FIG. **1**). The storage unit **152** may be implemented as a single board containing storage, and may be the largest tolerable failure domain inside the chassis. In some embodiments, up to two storage units **152** may fail and the device will continue with no data loss.

The physical storage is divided into named regions based on application usage in some embodiments. The NVRAM **204** is a contiguous block of reserved memory in the storage unit **152** DRAM **216**, and is backed by NAND flash. NVRAM **204** is logically divided into multiple memory regions written for two as spool (e.g., spool_region). Space within the NVRAM **204** spools is managed by each authority **512** independently. Each device provides an amount of storage space to each authority **512**. That authority **512** further manages lifetimes and allocations within that space. Examples of a spool include distributed transactions or notions. When the primary power to a storage unit **152** fails, onboard super-capacitors provide a short duration of power hold up. During this holdup interval, the contents of the NVRAM **204** are flushed to flash memory **206**. On the next power-on, the contents of the NVRAM **204** are recovered from the flash memory **206**.

As for the storage unit controller, the responsibility of the logical "controller" is distributed across each of the blades containing authorities **512**. This distribution of logical control is shown in FIG. **4** as a host controller **402**, mid-tier controller **404** and storage unit controller(s) **406**. Management of the control plane and the storage plane are treated independently, although parts may be physically co-located on the same blade. Each authority **512** effectively serves as an independent controller. Each authority **512** provides its own data and metadata structures, its own background workers, and maintains its own lifecycle.

FIG. **5** is a blade **502** hardware block diagram, showing a control plane **504**, compute and storage planes **506**, **508**, and authorities **512** interacting with underlying physical resources, using embodiments of the storage nodes **150** and storage units **152** of FIGS. **1-3** in the storage server environment of FIG. **4**. The control plane **504** is partitioned into a number of authorities **512** which can use the compute resources in the compute plane **506** to run on any of the blades **502**. The storage plane **508** is partitioned into a set of devices, each of which provides access to flash **206** and NVRAM **204** resources.

In the compute and storage planes **506**, **508** of FIG. **5**, the authorities **512** interact with the underlying physical resources (i.e., devices). From the point of view of an authority **512**, its resources are striped over all of the physical devices. From the point of view of a device, it provides resources to all authorities **512**, irrespective of where the authorities happen to run. Each authority **512** has allocated or has been allocated one or more partitions **510** of storage memory in the storage units **152**, e.g. partitions **510** in flash memory **206** and NVRAM **204**. Each authority **512** uses those allocated partitions **510** that belong to it, for writing or reading user data. Authorities can be associated with differing amounts of physical storage of the system. For example, one authority **512** could have a larger number of partitions **510** or larger sized partitions **510** in one or more storage units **152** than one or more other authorities **512**. Authorities **168** of FIG. **2** and authorities **512** of FIG. **5** refer to the same construct.

FIG. **6** depicts elasticity software layers in blades **502** of a storage cluster **160**, in accordance with some embodiments. In the elasticity structure, elasticity software is symmetric, i.e., each blade's **502** compute module **603** runs the three identical layers of processes depicted in FIG. **6**. Storage managers **607** execute read and write requests from other blades **502** for data and metadata stored in local storage unit **152** NVRAM **204** and flash **206**. Authorities **168** fulfill client requests by issuing the necessary reads and writes to the blades **502** on whose storage units **152** the corresponding data or metadata resides. Endpoints **605** parse client connection requests received from switch fabric **146** supervisory software, relay the client connection requests to the authorities **168** responsible for fulfillment, and relay the authorities' **168** responses to clients. The symmetric three-layer structure enables the storage system's high degree of concurrency. Elasticity scales out efficiently and reliably in these embodiments. In addition, elasticity implements a unique scale-out technique that balances work evenly across all resources regardless of client access pattern, and maximizes concurrency by eliminating much of the need for inter-blade coordination that typically occurs with conventional distributed locking.

Still referring to FIG. **6**, authorities **168** running in the compute modules **603** of a blade **502** perform the internal operations required to fulfill client requests. One feature of elasticity is that authorities **168** are stateless, i.e., they cache active data and metadata in their own blades' **168** DRAMs for fast access, but the authorities store every update in their NVRAM **204** partitions on three separate blades **502** until the update has been written to flash **206**. All the storage system writes to NVRAM **204** are in triplicate to partitions on three separate blades **502** in some embodiments. With triple-mirrored NVRAM **204** and persistent storage protected by parity and Reed-Solomon RAID checksums, the storage system can survive concurrent failure of two blades **502** with no loss of data, metadata, or access to either.

Because authorities **168** are stateless, they can migrate between blades **502**. Each authority **168** has a unique identifier. NVRAM **204** and flash **206** partitions are associated with authorities' **168** identifiers, not with the blades **502** on which they are running in some embodiments. Thus, when an authority **168** migrates, the authority **168** continues to manage the same storage partitions from its new location. When a new blade **502** is installed in an embodiment of the storage cluster **160**, the system automatically rebalances load by:

- Partitioning the new blade's **502** storage for use by the system's authorities **168**,
- Migrating selected authorities **168** to the new blade **502**,
- Starting endpoints **605** on the new blade **502** and including them in the switch fabric's **146** client connection distribution algorithm.

From their new locations, migrated authorities **168** persist the contents of their NVRAM **204** partitions on flash **206**, process read and write requests from other authorities **168**, and fulfill the client requests that endpoints **605** direct to them. Similarly, if a blade **502** fails or is removed, the system redistributes its authorities **168** among the system's remaining blades **502**. The redistributed authorities **168** continue to perform their original functions from their new locations.

FIG. **7** depicts authorities **168** and storage resources in blades **502** of a storage cluster, in accordance with some embodiments. Each authority **168** is exclusively responsible for a partition of the flash **206** and NVRAM **204** on each blade **502**. The authority **168** manages the content and integrity of its partitions independently of other authorities **168**. Authorities **168** compress incoming data and preserve it temporarily in their NVRAM **204** partitions, and then consolidate, RAID-protect, and persist the data in segments of the storage in their flash **206** partitions. As the authorities **168** write data to flash **206**, storage managers **607** perform the necessary flash translation to optimize write performance and maximize media longevity. In the background, authorities **168** "garbage collect," or reclaim space occupied by data that clients have made obsolete by overwriting the data. It should be appreciated that since authorities' **168** partitions are disjoint, there is no need for distributed locking to execute client and writes or to perform background functions.

FIG. **8A** is an action diagram showing a directory tree and a special-named directory **610** for deleting a specified directory **604** and the entire tree below that directory **604**. In this example, the special-named directory **610** is "fast_remove", but the directory could also be named "tree_destroy", "directory_tree_delete" or any other reserved name to invoke the directory tree deleting properties of the special-named directory **610**. Unlike ordinary directories **604**, the special-named directory **610** conceals contents from the user, and does not show subdirectories, files, a tree or a partial tree, etc. Moving a directory **604** to (i.e., under) the special-named directory **610**, for example using a UNIX command mv directory_name special-named_directory, directs or requests the storage system to delete the specified directory **604** and the entire tree below that directory **604**, i.e., the parent directory **604** and all subdirectories **606** and all files **608** below that directory **604**. Although this is one specific mechanism for requesting a tree deletion, other commands for deleting a tree, with or without specifying a special-named directory **610**, such as "delete_tree directory_name" could be devised as an extension to an operating system or file system.

When the storage system is directed to delete an entire tree, the storage system establishes a trash list **602**, which is then populated with names (or other identifying or addressing information) of directories **604**, subdirectories **606** and files to be deleted. In FIG. **8**A, this process has started, and the specified directory **604**, "dir 1", and subdirectories **606** "a", "b" under the specified directory **604** have been added to the trash list **602**.

FIG. **8**B continues the action diagram of FIG. **8**A, and shows top-down iterative or recursive listing of a directory **604**, subdirectories **606** and files **608** in a trash list **602**, in some embodiments performed by processors **702** on behalf of authorities **168**, in iterative search and destroy **706** processes with batch **704** communication and background deletions **708**. A multitasking computational system can parcel out threads and processes to perform the iterative search and destroy **706** and the background deletions **708** in parallel. In various embodiments as described with reference to FIGS. **1-7**, authorities **168** perform the iterative search and destroy **706** and background deletions **708**. The authorities **168** communicate among themselves, among storage nodes **150** and/or solid state storage units **152** in the storage cluster **160**.

In a specific scenario for one embodiment, as shown in FIGS. **8**A and **8**B, an authority **168** for the special-named directory **610** determines which authority **168** is the owner of the Mode for the specified directory **604** that has been moved to the special-named directory **610** for tree deletion, and listed in the trash list **602**. The special-named directory owning **610** authority **168** communicates with the specified directory **604** owning authority **168**, e.g., by sending a message, to initiate the top-down iterative search and destroy **706** processes. Alternatively, authorities **168** poll or consult the trash list **602** to determine if a task is available. The specified directory **604** owning authority **168** determines the contents and respective authorities **168** for the contents of the specified directory **604**, "dir 1", places those contents (e.g., names or other identifying information or addresses of subdirectories **606** or files **608**) on to the trash list **602** and deletes the specified directory **604** from memory and deletes the name of the specified directory **604**, or other identification or addressing information, from the trash list **602**. The link from the specified directory **604** to whichever directory is above, in this case the root directory "/", is severed, so that the specified directory **604** is no longer visible to the file system or to a user. Also, the special-named directory **610** conceals visibility of the specified directory **604** or any contents thereof.

Proceeding top-down, the specified directory **604** owning authority **168** communicates to the authorities **168** identified as owning contents of the specified directory **604**, e.g., by sending messages. Alternatively, authorities **168** discover what is on the trash list **602**. Those authorities **168** proceed in the same iterative top-down manner, identifying contents of their own directories (now subdirectories **606**) and respective authorities **168** for those contents (e.g., files **608** and/or further subdirectories **606**), placing names, identifying information or addressing of those contents onto the trash list **602** and deleting the directories (e.g., subdirectories) owned by those authorities **168** and deleting the directories from the trash list **602**. So, for example, after being contacted by the authority **168** for the specified directory **604** "dir 1", the authority **168** for the subdirectory **606** "a" identifies files **608** "A", "B" and authorities **168** for those files **608**, and communicates to those authorities **168**, while deleting the directory "a" and deleting the name "a" or other identifying or address information for the subdirectory **606** owned by the authority **168** from the trash list **602**. Similarly, the authority **168** for the subdirectory **606** "b" identifies files **608** "A", "B", "C" and authorities **168** for those files **608**, and communicates to those authorities **168**, while deleting the directory "b" from memory and deleting the name "b" or other identifying or address information for the subdirectory **606** owned by that authority **168** from the trash list **602**. Those authorities **168** for the inodes of the files **608** place identifying information or addresses for portions of the files **608**, e.g., segment ID numbers or ranges of segment ID numbers, onto the trash list **602**. Respective owners, i.e., authorities **168** in some embodiments, of entries on the trash list **602** perform background deletions **708** of the directory **604**, subdirectories **606** and files **608** or portions of files **608**, deleting these entries from the trash list as the background deletions **708** are performed. In some embodiments, the requests for performing the iterative search and destroy **706** processes, and the background deletions, are communicated among authorities **168** in batches **704**.

In FIG. **8**B, the trash list **602** is shown in various stages, with partial information present and deletions from the trash list **602** occurring as other entries are added. For example, in one iteration (at top right of FIG. **8**B), the trash list **602** shows entries for the specified directory **604** "dir 1" and subdirectories **606** "a", "b" and the file **608** "E" being deleted through batches **704**. Another iteration (at the middle right of FIG. **8**B) has the trash list **602** showing the files **608** "A", "B" from the subdirectory **606** "a" and the files **608** "A", "B", "C" from the subdirectory **606** "b", which will soon be deleted in batches **704**.

With ongoing reference to FIGS. **8**A and **8**B, one mechanism for employing the trash list **602** is as a communication center for the iterative search and destroy processes **706** and background deletions **708**. When an entry, such as a directory **604**, subdirectory **606**, or file **608**, is placed on the trash list **602**, a background process (e.g., an authority **168** in some embodiments) can pick up that entry and enumerate the entry, that is, list what are the contents of the entry. In the case of a directory **604** or subdirectory **606**, the background process lists the contents of the directory **604** or subdirectory **606** (e.g., more subdirectories **606** and/or files **608**), and places corresponding entries onto the trash list **602**. In the case of a file **608**, the background process lists portions of the file, such as are owned by further authorities **168** in various embodiments. Once the enumeration has been done for the immediate contents of the directory **604** or subdirectory **606** (i.e., not the entire depth of the tree), the background process can delete the entry on the trash list and actually delete or commit to deleting the corresponding item, such as a directory **604**, subdirectory **606**, or file **608**. Again in the case of a file **608**, that background process could then either delete the file or contact further authorities **168** each of which could delete portions of the file owned by those authorities **168**, or list the portions of the file on the trash list **602** for deletion by authorities **168** that own those portions of the file, in various embodiments. In some embodiments, the background deletions **708** are coordinated with garbage collection and recovery of physical memory, for example solid state storage memory. In some embodiments, authorities **168** other than owners of inodes could take on some of the iterative search and destroy **706** or background deletions **708**, for example authorities **168** that are not busy performing reads or writes of user data.

A further benefit of the parallelism in the above mechanisms is that authorities **168** exchange batches **704**, obtaining tasks according to the trash list **602**, finding entries in directories **604** or subdirectory **606** that other authorities should free, and returning memory space for storage of metadata and user data. In some embodiments, since the freeing up of storage space is happening in parallel, commitment to data writes can also be made in parallel. The authorities **168** collectively can determine the amount of memory space made available, and schedule writes in accordance with the memory space available.

It should be appreciated that the deletion of the parent or specified directory **604** "dir 1" referenced in the tree deletion request does not wait for deletion of the leafs at the bottom of the tree (e.g., the files **608** at the bottom of FIG. **8**B), and can proceed as soon as the specified directory **604** is placed on the trash list **602**. Similarly, deletion of subdirectories **606** can proceed as soon as these subdirectories **606** are placed on the trash list **602**. Or, deletion can occur later. Because the deletion of a directory **604** or subdirectory **606** does not depend on emptying that directory **604** or subdirectory **606**, the background deletions **708** can proceed in parallel and in any order. Processing of any subtree can be performed without concern of consistency with other processing of other subtrees. Further examples with taller or wider directory trees, and other names or conventions for directories or files are readily devised in keeping with the teachings herein. The above-described examples and mechanisms can be extended to trees with hundreds, thousands or millions, etc., of subdirectories and files.

With reference back to FIGS. **3**-**7**, some embodiments of the storage cluster **160** have power loss recovery for the distributed file and directory deletion mechanisms described above. In the case of power loss, the trash list **602** is flushed from NVRAM **204** to flash memory **206** (e.g., along with other data and metadata in the system). Upon restart, the trash list is recovered from the flash memory **206**, back to NVRAM **204**. Then, the iterative search and destroy **706** and background deletions **708** can continue.

FIG. **9**A is a flow diagram of a method for distributed directory and file deletion of a directory tree, which can be practiced in the storage cluster of FIGS. **1**-**7**, and in further storage systems, in accordance with some embodiments as described with reference to FIGS. **8**A and **8**B. Some or all of the actions in the method can be performed by various processors, such as processors in storage nodes or processors in storage units. In an action **802**, a request is received to move a directory under a special-named directory for tree deletion. That is, a request is received to delete a directory and contents. In some embodiments, the request is specific to the special-named directory and a specified directory for tree deletion, and in other embodiments, the request does not mention a special-named directory. In an action **804**, proceeding top-down, directory and contents of the directory are listed to a trash list. In the decision action **806**, it is determined whether there are any subdirectories below the listed directory. If yes, there is at least one subdirectory in the directory, flow proceeds to iterate, and returns to the action **804** to proceed from each subdirectory in a top-down manner to list the directory and contents of the directory to the trash list. Multiple processes can be spawned in parallel, in some embodiments. If no, there is no subdirectory in the directory, then the process is done listing the entire tree of the directory in the trash list. The actions **802**, **804**, **806** thus show an iterative, recursive, top-down process of listing directories and contents for an entire directory tree to the trash list, for deletion.

In the action **808**, in a parallel, distributed manner, the directory, all subdirectories and all files of the entire tree of the directory are deleted according to the trash list. In the action **810**, the parallel distributed deletions of the action **808** are coordinated with garbage collection. In the action **812**, in parallel with the actions **808**, **810**, the amount of memory space made available is determined. Authorities in the storage cluster, freeing up memory space by performing the deletions, make the determination collectively, in some embodiments. In the action **814**, writes are scheduled, in accordance with the amount of memory space made available. Authorities in the storage cluster schedule the writes, in some embodiments.

FIG. **9**B is a further flow diagram of a method for recovery from power loss, which can be practiced to augment the method of FIG. **9**A. In a decision action **902**, it is determined whether there is a power loss. If no power loss, flow loops back to the action **902**. If yes, there is a power loss, in the action **904** the trash list is flushed from NVRAM to solid state storage memory. The flushing is supported by an energy reserve in a storage unit, in some embodiments. In an action **906**, the storage system is restarted (e.g., upon restoration of power). In an action **908**, the trash list is recovered from solid-state storage memory. For example, the trash list is read from the flash memory and written to the NVRAM. In an action **910**, the storage system continues deleting subdirectories and files in accordance with the recovered trash list. It should be appreciated that while the embodiments describe a power loss as triggering the actions, this is not meant to be limiting. The actions may be triggered by any other faults that interrupt processing in a manner that requires recovery or a restart of the system. That is, the embodiments may be extended to include any type of faults, e.g., hardware faults, operating system faults, software faults, or network faults, that interrupt the process in a way that requires recovery.

FIG. **10** is a further flow diagram of a method for distributed directory and file deletion of a directory tree, as a variation of the method shown in FIGS. **9**A and **9**B. The method of FIG. **10** can be practiced in the storage cluster of FIGS. **1**-**7**, and in further storage systems, in accordance with some embodiments as described with reference to FIGS. **8**A and **8**B. Some or all of the actions in the method can be performed by various processors, such as processors in storage nodes or processors in storage units. In an action **1002**, a request is received to move a directory under a special-named directory for tree deletion. That is, a request is received to delete a directory and contents. In some embodiments, the request is specific to the special-named directory and a specified directory for tree deletion, and in other embodiments, the request does not mention a special-named directory. In an action **1004**, the directory is added to a first set. The first set is in a memory in the storage cluster or other storage system, in some embodiments. In an action **1006**, the first set is operated on, by examining each directory in the first set looking for subdirectories and files, adding each directory so found to a first set as a directory, adding each file so found to a second set stored in memory in the storage cluster or other storage system, and adding each examined directory to the second set. In some embodiments, the actions for operating on the first set are performed by various authorities in a storage cluster.

Still referring to FIG. **10**, in an action **1008**, records and data of files listed in the second set, and records of directories listed in the second set are deleted, with no concern for order. As soon as all sub-directories within a parent directory have been identified for deletion, all other contents in the parent directory can be deleted as can the parent directory itself. This mechanism can proceed at any rate, and all directories identified as having been processed for sub-directories can be deleted at any rate and in any order, and with any reasonable level of parallelism or distribution across the environment. It should be appreciated that this is due to the fact that there is no concern with either dangling references, e.g., a reference to a parent that no longer exists, or with transactional consistency of the tree, e.g., whether whatever does or does not remain of the directory hierarchy can be reconstructed back into a rooted tree.

This procedure identifies both files and directories for deletion based on the first set, and deletes both files and directories that have been added to the second set which is now of files and directories. A variation of this procedure identifies directories for deletion based on the first set, adding subdirectories of each directory examined in the first set back to the first set as directories and listing examined directories in the second set. The procedure also deletes files found in directories as well as the directories themselves when the directories are found in the second set, i.e., based on the listing of directories in the second set. The embodiments also allow deletions from the second set to proceed in parallel with generation of the second set from the first set. In some versions, the second set is used as a source for a trash list described in FIGS. **9**A and **9**B, and in other versions, the second set is the trash list.

The embodiments described above may be integrated with the ability to introduce a traditional trash delay that allows listing and retrieval for some period of time (e.g., 24 hours or some other suitable time period). For example, the trash directory can operate by continuing to contain whatever content is moved into the trash directory. When the time limit has expired the file or directory is unlinked from the trash directory and the procedure described above is then followed to ensure efficient parallel deletion. Thus, in some embodiments, there may be a delay for a time span, responsive to receiving the request in operation **1002**, wherein the adding, the operating, and the deleting (operations **1004**, **1006**, and **1008**) occur upon expiration of the time span, and wherein the contents of the directory are retrievable during the time span. In some embodiments, rather than a time limit expiring to trigger the embodiments described above, alternatives such as an additional step taken to mark a file or directory for immediate removal, perhaps by moving the file or directory to some other special directory, perhaps by allowing a delete or 'rmdir' operation even for a non-empty directory in the trash directory, or perhaps by running some another special command, may be utilized. A file or directory could be retrieved from the trash directory by moving the file or directory out prior to beginning its parallel removal. Some extended attribute could also be used to record the original location, and a utility could be written to restore the file or directory to its original location in some embodiments.

It should be appreciated that the methods described herein may be performed with a digital processing system, such as a conventional, general-purpose computer system. Special purpose computers, which are designed or programmed to perform only one function may be used in the alternative. FIG. **11** is an illustration showing an exemplary computing device which may implement the embodiments described herein. The computing device of FIG. **11** may be used to perform embodiments of the functionality for the distributed directory tree (i.e., hierarchy) and file deletion in accordance with some embodiments. The computing device includes a central processing unit (CPU) **1101**, which is coupled through a bus **1105** to a memory **1103**, and mass storage device **1107**. Mass storage device **1107** represents a persistent data storage device such as a floppy disc drive or a fixed disc drive, which may be local or remote in some embodiments. Memory **1103** may include read only memory, random access memory, etc. Applications resident on the computing device may be stored on or accessed via a computer readable medium such as memory **1103** or mass storage device **1107** in some embodiments. Applications may also be in the form of modulated electronic signals modulated accessed via a network modem or other network interface of the computing device. It should be appreciated that CPU **1101** may be embodied in a general-purpose processor, a special purpose processor, or a specially programmed logic device in some embodiments.

Display **1111** is in communication with CPU **1101**, memory **1103**, and mass storage device **1107**, through bus **1105**. Display **1111** is configured to display any visualization tools or reports associated with the system described herein. Input/output device **1109** is coupled to bus **1105** in order to communicate information in command selections to CPU **1101**. It should be appreciated that data to and from external devices may be communicated through the input/output device **1109**. CPU **1101** can be defined to execute the functionality described herein to enable the functionality described with reference to FIGS. **1**-**10**. The code embodying this functionality may be stored within memory **1103** or mass storage device **1107** for execution by a processor such as CPU **1101** in some embodiments. The operating system on the computing device may be iOS™, MS-WINDOWS™, OS/2™, UNIX™, LINUX™, or other known operating systems. It should be appreciated that the embodiments described herein may also be integrated with a virtualized computing system that is implemented with physical computing resources.

It should be understood that although the terms first, second, etc. may be used herein to describe various steps or calculations, these steps or calculations should not be limited by these terms. These terms are only used to distinguish one step or calculation from another. For example, a first calculation could be termed a second calculation, and, similarly, a second step could be termed a first step, without departing from the scope of this disclosure. As used herein, the term "and/or" and the "/" symbol includes any and all combinations of one or more of the associated listed items.

As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises", "comprising", "includes", and/or "including", when used herein, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof. Therefore, the terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting.

It should also be noted that in some alternative implementations, the functions/acts noted may occur out of the order noted in the figures. For example, two figures shown in succession may in fact be executed substantially concurrently or may sometimes be executed in the reverse order, depending upon the functionality/acts involved.

With the above embodiments in mind, it should be understood that the embodiments might employ various computer-implemented operations involving data stored in computer systems. These operations are those requiring physical manipulation of physical quantities. Usually, though not necessarily, these quantities take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated. Further, the manipulations performed are often referred to in terms, such as producing, identifying, determining, or comparing. Any of the operations described herein that form part of the embodiments are useful machine operations. The embodiments also relate to a device or an apparatus for performing these operations. The apparatus can be specially constructed for the required purpose, or the apparatus can be a general-purpose computer selectively activated or configured by a computer program stored in the computer. In particular, various general-purpose machines can be used with computer programs written in accordance with the teachings herein, or it may be more convenient to construct a more specialized apparatus to perform the required operations.

A module, an application, a layer, an agent or other method-operable entity could be implemented as hardware, firmware, or a processor executing software, or combinations thereof. It should be appreciated that, where a software-based embodiment is disclosed herein, the software can be embodied in a physical machine such as a controller. For example, a controller could include a first module and a second module. A controller could be configured to perform various actions, e.g., of a method, an application, a layer or an agent.

The embodiments can also be embodied as computer readable code on a non-transitory computer readable medium. The computer readable medium is any data storage device that can store data, which can be thereafter read by a computer system. Examples of the computer readable medium include hard drives, network attached storage (NAS), read-only memory, random-access memory, CD-ROMs, CD-Rs, CD-RWs, magnetic tapes, and other optical and non-optical data storage devices. The computer readable medium can also be distributed over a network coupled computer system so that the computer readable code is stored and executed in a distributed fashion. Embodiments described herein may be practiced with various computer system configurations including hand-held devices, tablets, microprocessor systems, microprocessor-based or programmable consumer electronics, minicomputers, mainframe computers and the like. The embodiments can also be practiced in distributed computing environments where tasks are performed by remote processing devices that are linked through a wire-based or wireless network.

Although the method operations were described in a specific order, it should be understood that other operations may be performed in between described operations, described operations may be adjusted so that they occur at slightly different times or the described operations may be distributed in a system which allows the occurrence of the processing operations at various intervals associated with the processing.

In various embodiments, one or more portions of the methods and mechanisms described herein may form part of a cloud-computing environment. In such embodiments, resources may be provided over the Internet as services according to one or more various models. Such models may include Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS). In IaaS, computer infrastructure is delivered as a service. In such a case, the computing equipment is generally owned and operated by the service provider. In the PaaS model, software tools and underlying equipment used by developers to develop software solutions may be provided as a service and hosted by the service provider. SaaS typically includes a service provider licensing software as a service on demand. The service provider may host the software, or may deploy the software to a customer for a given period of time. Numerous combinations of the above models are possible and are contemplated.

Various units, circuits, or other components may be described or claimed as "configured to" or "configurable to" perform a task or tasks. In such contexts, the phrase "configured to" or "configurable to" is used to connote structure by indicating that the units/circuits/components include structure (e.g., circuitry) that performs the task or tasks during operation. As such, the unit/circuit/component can be said to be configured to perform the task, or configurable to perform the task, even when the specified unit/circuit/component is not currently operational (e.g., is not on). The units/circuits/components used with the "configured to" or "configurable to" language include hardware—for example, circuits, memory storing program instructions executable to implement the operation, etc. Reciting that a unit/circuit/component is "configured to" perform one or more tasks, or is "configurable to" perform one or more tasks, is expressly intended not to invoke 35 U.S.C. 112, sixth paragraph, for that unit/circuit/component. Additionally, "configured to" or "configurable to" can include generic structure (e.g., generic circuitry) that is manipulated by software and/or firmware (e.g., an FPGA or a general-purpose processor executing software) to operate in manner that is capable of performing the task(s) at issue. "Configured to" may also include adapting a manufacturing process (e.g., a semiconductor fabrication facility) to fabricate devices (e.g., integrated circuits) that are adapted to implement or perform one or more tasks. "Configurable to" is expressly intended not to apply to blank media, an unprogrammed processor or unprogrammed generic computer, or an unprogrammed programmable logic device, programmable gate array, or other unprogrammed device, unless accompanied by programmed media that confers the ability to the unprogrammed device to be configured to perform the disclosed function(s).

The foregoing description, for the purpose of explanation, has been described with reference to specific embodiments. However, the illustrative discussions above are not intended to be exhaustive or to limit the invention to the precise forms disclosed. Many modifications and variations are possible in view of the above teachings. The embodiments were chosen and described in order to best explain the principles of the embodiments and its practical applications, to thereby enable others skilled in the art to best utilize the embodiments and various modifications as may be suited to the particular use contemplated. Accordingly, the present embodiments are to be considered as illustrative and not restrictive, and the invention is not to be limited to the details given herein, but may be modified within the scope and equivalents of the appended claims.

What is claimed is:

1. A method, comprising:

receiving a request to delete a directory and contents of the directory stored at one or more storage devices of a storage system;

adding the directory to a first set, listed in a memory in the storage system;

adding subdirectories associated with the directory to the first set;

adding the directory and the subdirectories of the first set to a second set in the memory;

identifying a plurality of authorities that own portions of contents of the directory and the subdirectories listed in the second set that are to be deleted;

delaying for a time span the deleting, and wherein the contents of the directory and the subdirectories are retrievable during the time span; and

deleting, by the plurality of authorities in a distributed manner across the storage system, the contents of the directory and the subdirectories.

2. The method of claim **1**, wherein the receiving the request comprises:

generating a request to move the directory under a named directory that conceals the directory and contents.

3. The method of claim **1**, wherein the one or more storage devices are flash memory storage devices.

4. The method of claim **1**, further comprising:

scheduling a plurality of writes to the storage system, in accordance with determining an amount of memory space made available by the request to delete the directory and in parallel with the deleting.

5. The method of claim **1**, wherein the deleting in a distributed manner across the storage system, the contents of the directory further comprises deleting data and records of files listed in the second set and wherein the deleting is performed without concern for order.

6. The method of claim **1**, wherein the deleting comprises:

coordinating the deleting of the directory with garbage collection in a plurality of solid-state storage units of the storage system.

7. The method of claim **1**, further comprising:

writing directory names of the directories listed in the second set and all files of the directories listed in the second set to a trash list in NVRAM (nonvolatile random-access memory) of the storage system; and

flushing the trash list from the NVRAM to solid-state storage memory in the storage system, responsive to detecting a power loss in the storage system.

8. A non-transitory computer readable storage medium storing instructions which, when executed, cause a processor to:

receive a request to delete a directory and contents of the directory;

add the directory to a first set, listed in a memory in a storage system;

add subdirectories associated with the directory to the first set;

add the directory and the subdirectories of the first set to a second set in the memory;

identify a plurality of authorities that own portions of contents of the directory and the subdirectories listed in the second set that are to be deleted;

delay for a time span the deleting, and wherein the contents of the directory and the subdirectories are retrievable during the time span; and

delete, by the plurality of authorities in a distributed manner across the storage system, contents of the directory and the subdirectories listed in the second set.

9. The non-transitory computer readable storage medium of claim **8**, wherein to receive the request, the processor is further to:

generate a request to move the directory under a named directory that conceals the directory and contents to a client.

10. The non-transitory computer readable storage medium of claim **8**, wherein the processor is further to:

communicate a plurality of batch lists to a plurality of processors in the storage system, the plurality of batch lists listing a subset of the directory, wherein the deleting the directory is in accordance with the plurality of batch lists.

11. The non-transitory computer readable storage medium of claim **8**, wherein the processor is further to:

determine an amount of memory space made available by the request to delete the directory; and

schedule a plurality of writes to the storage system, in accordance with the determining and in parallel with the deleting.

12. The non-transitory computer readable storage medium of claim **8**, wherein the deleting is performed by a plurality of authorities executed by one or more processors of the storage system, with each inode, range of data, and sub-directory owned by an authority.

13. The non-transitory computer readable storage medium of claim **8**, wherein the deleting comprises:

coordinating the deleting of the directory with garbage collection in each of a plurality of solid-state storage units of the storage system and wherein the deleting is performed without concern for order.

14. A storage system, comprising:

storage memory; and

a plurality of storage nodes comprising one or more storage devices and one or more processors, configured to:

receive a request to delete a directory and contents of the directory stored in the one or more storage devices;

add the directory to a first set, listed in a memory in a storage system;

add subdirectories associated with the directory to the first set;

adding the directory and the subdirectories of the first set to a second set in the memory;

identify a plurality of authorities that own portions of contents of the directory and the subdirectories listed in the second set that are to be deleted;

delay for a time span the deleting, and wherein the contents of the directory and the subdirectories are retrievable during the time span; and

delete in a distributed manner across the storage system, contents of the directory and the subdirectories listed in the second set.

15. The storage system of claim **14**, wherein to receive the request, the one or more processors are further configured to:

generate a request to move the directory under a named directory that conceals the directory and contents, and wherein the deleting is performed without concern for order.

16. The storage system of claim **14**, wherein the one or more processors are further configured to:

communicate a plurality of batch lists to a plurality of processors in the storage system, the plurality of batch lists listing a subset of the directory, wherein the deleting the directory is in accordance with the plurality of batch lists.

17. The storage system of claim **14**, wherein the deleting comprises:

coordinating the deleting of the directory with garbage collection in each of a plurality of solid-state storage units of the storage system.

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