United States Patent Application Publication	20250258695
Kind Code	A1
Publication Date	August 14, 2025
Inventor(s)	Iyer; Kshithij et al.

Using a Container-Aware Storage System to Deploy Virtual Machines on a Container Orchestration Platform

Abstract

An illustrative storage management system is configured to provide persistent data storage to workloads managed by a container orchestration platform deployed in a cluster of nodes. The storage management system is configured to receive a request comprising identifiers indicative of a plurality of layers associated with a virtual machine to be run in the cluster, generate, based on the request, a virtual machine disk image comprising the plurality of layers, the virtual machine disk image configured to be used to run the virtual machine in the cluster, and provide the virtual machine disk image in response to the request. In some implementations, the virtual machine disk image is used by a virtual machine handler associated with the container orchestration platform to run the virtual machine in a virtual machine type pod that is managed by the container orchestration platform.

Inventors: **Iyer; Kshithij (Gujarat, IN), Pabón; Luis Pablo (Sturbridge, MA)**

Applicant: **Pure Storage, Inc.** (Santa Clara, CA)

Family ID: **96661037**

Appl. No.: **19/191471**

Filed: **April 28, 2025**

Related U.S. Application Data

parent US continuation-in-part 18751818 20240624 PENDING child US 19191471
parent US continuation-in-part 17873988 20220726 parent-grant-document US 12019522 child US 18751818
parent US continuation-in-part 17733716 20220429 parent-grant-document US 12147313 child US 17873988
parent US continuation-in-part 17580098 20220120 parent-grant-document US 12175135 child US 17733716

Publication Classification

Int. Cl.: **G06F9/455** (20180101)

U.S. Cl.:

CPC **G06F9/45558** (20130101); G06F2009/4557 (20130101)

Background/Summary

RELATED APPLICATIONS [0001] The present application is a continuation-in-part of U.S. patent application Ser. No. 18/751,818, filed Jun. 24, 2024, which is a continuation-in-part of U.S. patent application Ser. No. 17/873,988, filed Jul. 26, 2022, now U.S. patent Ser. No. 12/019,522, which is a continuation-in-part application of U.S. patent application Ser. No. 17/733,716, filed Apr. 29, 2022, now U.S. patent Ser. No. 12/127,313, which is a continuation-in-part application of U.S. patent application Ser. No. 17/580,098, filed Jan. 20, 2022, now U.S. patent Ser. No. 12/175,135, each of which is expressly incorporated by reference herein.

BRIEF DESCRIPTION OF THE DRAWINGS
[0002] The accompanying drawings illustrate various embodiments and are a part of the specification. The illustrated embodiments are merely examples and do not limit the scope of the disclosure. Throughout the drawings, identical or similar reference numbers designate identical or similar elements.
[0003] FIG. **1**A illustrates a first example system for data storage in accordance with some implementations.
[0004] FIG. **1**B illustrates a second example system for data storage in accordance with some implementations.
[0005] FIG. **1**C illustrates a third example system for data storage in accordance with some implementations.
[0006] FIG. **1**D illustrates a fourth example system for data storage in accordance with some implementations.
[0007] FIG. **2**A 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.
[0008] FIG. **2**B is a block diagram showing an interconnect switch coupling multiple storage nodes in accordance with some embodiments.
[0009] FIG. **2**C 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.
[0010] FIG. **2**D shows a storage server environment, which uses embodiments of the storage nodes and storage units of some previous figures in accordance with some embodiments.
[0011] FIG. **2**E 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.
[0012] FIG. **2**F depicts elasticity software layers in blades of a storage cluster, in accordance with some embodiments.
[0013] FIG. **2**G depicts authorities and storage resources in blades of a storage cluster, in accordance with some embodiments.
[0014] FIG. **3**A sets forth a diagram of a storage system that is coupled for data communications with a cloud services provider in accordance with some embodiments of the present disclosure.

[0015] FIG. **3**B sets forth a diagram of a storage system in accordance with some embodiments of the present disclosure.
[0016] FIG. **3**C sets forth an example of a cloud-based storage system in accordance with some embodiments of the present disclosure.
[0017] FIG. **3**D illustrates an exemplary computing device that may be specifically configured to perform one or more of the processes described herein.
[0018] FIG. **3**E illustrates an example of a fleet of storage systems for providing storage services in accordance with some embodiments of the present disclosure.
[0019] FIG. **4** illustrates an example container system in accordance with some embodiments of the present disclosure.
[0020] FIG. **5** illustrates an example configuration of a container system and a container-aware storage system in accordance with some embodiments of the present disclosure.
[0021] FIG. **6** illustrates an example of a container-aware storage system receiving a container image and storing the container image as a volume in accordance with some embodiments of the present disclosure.
[0022] FIGS. **7**A-**7**B illustrate examples of a container-aware storage system providing volumes to a container system in accordance with some embodiments of the present disclosure.
[0023] FIGS. **8-11** illustrate flowcharts depicting example methods in accordance with some embodiments of the present disclosure.
[0024] FIGS. **12**A-**15** illustrate examples of using data volumes to store container images in accordance with some embodiments of the present disclosure.
[0025] FIGS. **15-18** illustrate flowcharts depicting example methods in accordance with some embodiments of the present disclosure.
[0026] FIGS. **19**A-**19**B illustrate computing environments depicting container recovery using volumes comprising container images in accordance with some embodiments of the present disclosure.
[0027] FIGS. **20-21** illustrate flowcharts depicting example methods in accordance with some embodiments of the present disclosure.
[0028] FIGS. **22**A-**22**E illustrate an example configuration in which a recovery process is applied in accordance with some embodiments of the present disclosure.
[0029] FIGS. **23-25** illustrate example container recovery methods in accordance with some embodiments of the present disclosure.
[0030] FIG. **26** illustrates an example configuration in which a container storage management framework coordinates with a storage system to leverage one or more capabilities of the storage system in accordance with some embodiments of the present disclosure.
[0031] FIG. **27** illustrates an example method of container layer storage management in accordance with some embodiments of the present disclosure.
[0032] FIG. **28** illustrates an example method of container layer storage management in accordance with some embodiments of the present disclosure.
[0033] FIG. **29** illustrates an example container system in accordance with some embodiments of the present disclosure.
[0034] FIG. **30** illustrates example volume request specifications in accordance with some embodiments of the present disclosure.
[0035] FIG. **31** illustrates example virtual machine disk images in accordance with some embodiments of the present disclosure.
[0036] FIG. **32** illustrates an example method for virtual machine deployment in accordance with some embodiments of the present disclosure.

Description

DESCRIPTION OF EMBODIMENTS

[0037] Example methods, systems, apparatus, and products for deploying virtual machines on a container orchestration platform in accordance with embodiments of the present disclosure are described with reference to the accompanying drawings, beginning with FIG. **1**A. FIG. **1**A illustrates an example system for data storage, in accordance with some implementations. System **100** (also referred to as "storage system" herein) includes numerous elements for purposes of illustration rather than limitation. It may be noted that system **100** may include the same, more, or fewer elements configured in the same or different manner in other implementations.

[0038] System **100** includes a number of computing devices **164**A-B. Computing devices (also referred to as "client devices" herein) may be embodied, for example, a server in a data center, a workstation, a personal computer, a notebook, or the like. Computing devices **164**A-B may be coupled for data communications to one or more storage arrays **102**A-B through a storage area network ('SAN') **158** or a local area network ('LAN') **160**.

[0039] The SAN **158** may be implemented with a variety of data communications fabrics, devices, and protocols. For example, the fabrics for SAN **158** may include Fibre Channel, Ethernet, Infiniband, Serial Attached Small Computer System Interface ('SAS'), or the like. Data communications protocols for use with SAN **158** may include Advanced Technology Attachment ('ATA'), Fibre Channel Protocol, Small Computer System Interface ('SCSI'), Internet Small Computer System Interface ('iSCSI'), HyperSCSI, Non-Volatile Memory Express ('NVMe') over Fabrics, or the like. It may be noted that SAN **158** is provided for illustration, rather than limitation. Other data communication couplings may be implemented between computing devices **164**A-B and storage arrays **102**A-B.

[0040] The LAN **160** may also be implemented with a variety of fabrics, devices, and protocols. For example, the fabrics for LAN **160** may include Ethernet (**802**.**3**), wireless (**802**.**11**), or the like. Data communication protocols for use in LAN **160** may include Transmission Control Protocol ('TCP'), User Datagram Protocol ('UDP'), Internet Protocol ('IP'), HyperText Transfer Protocol ('HTTP'), Wireless Access Protocol ('WAP'), Handheld Device Transport Protocol ('HDTP'), Session Initiation Protocol ('SIP'), Real Time Protocol ('RTP'), or the like.

[0041] Storage arrays **102**A-B may provide persistent data storage for the computing devices **164**A-B. Storage array **102**A may be contained in a chassis (not shown), and storage array **102**B may be contained in another chassis (not shown), in implementations. Storage array **102**A and **102**B may include one or more storage array controllers **110**A-D (also referred to as "controller" herein). A storage array controller **110**A-D may be embodied as a module of automated computing machinery comprising computer hardware, computer software, or a combination of computer hardware and software. In some implementations, the storage array controllers **110**A-D may be configured to carry out various storage tasks. Storage tasks may include writing data received from the computing devices **164**A-B to storage array **102**A-B, erasing data from storage array **102**A-B, retrieving data from storage array **102**A-B and providing data to computing devices **164**A-B, monitoring and reporting of disk utilization and performance, performing redundancy operations, such as Redundant Array of Independent Drives ('RAID') or RAID-like data redundancy operations, compressing data, encrypting data, and so forth.

[0042] Storage array controller **110**A-D may be implemented in a variety of ways, including as a Field Programmable Gate Array ('FPGA'), a Programmable Logic Chip ('PLC'), an Application Specific Integrated Circuit ('ASIC'), System-on-Chip ('SOC'), or any computing device that includes discrete components such as a processing device, central processing unit, computer memory, or various adapters. Storage array controller **110**A-D may include, for example, a data communications adapter configured to support communications via the SAN **158** or LAN **160**. In some implementations, storage array controller **110**A-D may be independently coupled to the LAN **160**. In implementations, storage array controller **110**A-D may include an I/O controller or the like that couples the storage array controller **110**A-D for data communications, through a midplane (not shown), to a persistent storage resource **170**A-B (also referred to as a "storage resource" herein). The persistent storage resource **170**A-B main include any number of storage drives **171**A-F (also referred to as "storage devices" herein) and any number of non-volatile Random Access Memory ('NVRAM') devices (not shown).

[0043] In some implementations, the NVRAM devices of a persistent storage resource **170**A-B may be configured to receive, from the storage array controller **110**A-D, data to be stored in the storage drives **171**A-F. In some examples, the data may originate from computing devices **164**A-B. In some examples, writing data to the NVRAM device may be carried out more quickly than directly writing data to the storage drive **171**A-F. In implementations, the storage array controller **110**A-D may be configured to utilize the NVRAM devices as a quickly accessible buffer for data destined to be written to the storage drives **171**A-F. Latency for write requests using NVRAM devices as a buffer may be improved relative to a system in which a storage array controller **110**A-D writes data directly to the storage drives **171**A-F. In some implementations, the NVRAM devices may be implemented with computer memory in the form of high bandwidth, low latency RAM. The NVRAM device is referred to as "non-volatile" because the NVRAM device may receive or include a unique power source that maintains the state of the RAM after main power loss to the NVRAM device. Such a power source may be a battery, one or more capacitors, or the like. In response to a power loss, the NVRAM device may be configured to write the contents of the RAM to a persistent storage, such as the storage drives **171**A-F.

[0044] In implementations, storage drive **171**A-F may refer to any device configured to record data persistently, where "persistently" or "persistent" refers as to a device's ability to maintain recorded data after loss of power. In some implementations, storage drive **171**A-F may correspond to non-disk storage media. For example, the storage drive **171**A-F may be one or more solid-state drives ('SSDs'), flash memory based storage, any type of solid-state non-volatile memory, or any other type of non-mechanical storage device. In other implementations, storage drive **171**A-F may include mechanical or spinning hard disk, such as hard-disk drives ('HDD').

[0045] In some implementations, the storage array controllers **110**A-D may be configured for offloading device management responsibilities from storage drive **171**A-F in storage array **102**A-B. For example, storage array controllers **110**A-D may manage control information that may describe the state of one or more memory blocks in the storage drives **171**A-F. The control information may indicate, for example, that a particular memory block has failed and should no longer be written to, that a particular memory block contains boot code for a storage array controller **110**A-D, the number of program-erase ('P/E') cycles that have been performed on a particular memory block, the age of data stored in a particular memory block, the type of data that is stored in a particular memory block, and so forth. In some implementations, the control information may be stored with an associated memory block as metadata. In other implementations, the control information for the storage drives **171**A-F may be stored in one or more particular memory blocks of the storage drives **171**A-F that are selected by the storage array controller **110**A-D. The selected memory blocks may be tagged with an identifier indicating that the selected memory block contains control information. The identifier may be utilized by the storage array controllers **110**A-D in conjunction with storage drives **171**A-F to quickly identify the memory blocks that contain control information. For example, the storage controllers **110**A-D may issue a command to locate memory blocks that contain control information. It may be noted that control information may be so large that parts of the control information may be stored in multiple locations, that the control information may be stored in multiple locations for purposes of redundancy, for example, or that the control information may otherwise be distributed across multiple memory blocks in the storage drive **171**A-F.

[0046] In implementations, storage array controllers **110**A-D may offload device management responsibilities from storage drives **171**A-F of storage array **102**A-B by retrieving, from the storage drives **171**A-F, control information describing the state of one or more memory blocks in the storage drives **171**A-F. Retrieving the control information from the storage drives **171**A-F may be carried out, for example, by the storage array controller **110**A-D querying the storage drives **171**A-F for the location of control information for a particular storage drive **171**A-F. The storage drives **171**A-F may be configured to execute instructions that enable the storage drive **171**A-F to identify the location of the control information. The instructions may be executed by a controller (not shown) associated with or otherwise located on the storage drive **171**A-F and may cause the storage drive **171**A-F to scan a portion of each memory block to identify the memory blocks that store control information for the storage drives **171**A-F. The storage drives **171**A-F may respond by sending a response message to the storage array controller **110**A-D that includes the location of control information for the storage drive **171**A-F. Responsive to receiving the response message, storage array controllers **110**A-D may issue a request to read data stored at the address associated with the location of control information for the storage drives **171**A-F.

[0047] In other implementations, the storage array controllers **110**A-D may further offload device management responsibilities from storage drives **171**A-F by performing, in response to receiving the control information, a storage drive management operation. A storage drive management operation may include, for example, an operation that is typically performed by the storage drive **171**A-F (e.g., the controller (not shown) associated with a particular storage drive **171**A-F). A storage drive management operation may include, for example, ensuring that data is not written to failed memory blocks within the storage drive **171**A-F, ensuring that data is written to memory blocks within the storage drive **171**A-F in such a way that adequate wear leveling is achieved, and so forth.

[0048] In implementations, storage array **102**A-B may implement two or more storage array controllers **110**A-D. For example, storage array **102**A may include storage array controllers **110**A and storage array controllers **110**B. At a given instance, a single storage array controller **110**A-D (e.g., storage array controller **110**A) of a storage system **100** may be designated with primary status (also referred to as “primary controller” herein), and other storage array controllers **110**A-D (e.g., storage array controller **110**A) may be designated with secondary status (also referred to as “secondary controller” herein). The primary controller may have particular rights, such as permission to alter data in persistent storage resource **170**A-B (e.g., writing data to persistent storage resource **170**A-B). At least some of the rights of the primary controller may supersede the rights of the secondary controller. For instance, the secondary controller may not have permission to alter data in persistent storage resource **170**A-B when the primary controller has the right. The status of storage array controllers **110**A-D may change. For example, storage array controller **110**A may be designated with secondary status, and storage array controller **110**B may be designated with primary status.

[0049] In some implementations, a primary controller, such as storage array controller **110**A, may serve as the primary controller for one or more storage arrays **102**A-B, and a second controller, such as storage array controller **110**B, may serve as the secondary controller for the one or more storage arrays **102**A-B. For example, storage array controller **110**A may be the primary controller for storage array **102**A and storage array **102**B, and storage array controller **110**B may be the secondary controller for storage array **102**A and **102**B. In some implementations, storage array controllers **110**C and **110**D (also referred to as “storage processing modules”) may neither have primary or secondary status. Storage array controllers **110**C and **110**D, implemented as storage processing modules, may act as a communication interface between the primary and secondary controllers (e.g., storage array controllers **110**A and **110**B, respectively) and storage array **102**B. For example, storage array controller **110**A of storage array **102**A may send a write request, via SAN **158**, to storage array **102**B. The write request may be received by both storage array controllers **110**C and **110**D of storage array **102**B. Storage array controllers **110**C and **110**D facilitate the communication, e.g., send the write request to the appropriate storage drive **171**A-F. It may be noted that in some implementations storage processing modules may be used to increase the number of storage drives controlled by the primary and secondary controllers.

[0050] In implementations, storage array controllers **110**A-D are communicatively coupled, via a midplane (not shown), to one or more storage drives **171**A-F and to one or more NVRAM devices (not shown) that are included as part of a storage array **102**A-B. The storage array controllers **110**A-D may be coupled to the midplane via one or more data communication links and the midplane may be coupled to the storage drives **171**A-F and the NVRAM devices via one or more data communications links. The data communications links described herein are collectively illustrated by data communications links **108**A-D and may include a Peripheral Component Interconnect Express (‘PCIe’) bus, for example.

[0051] FIG. **1**B illustrates an example system for data storage, in accordance with some implementations. Storage array controller **101** illustrated in FIG. **1**B may be similar to the storage array controllers **110**A-D described with respect to FIG. **1**A. In one example, storage array controller **101** may be similar to storage array controller **110**A or storage array controller **110**B. Storage array controller **101** includes numerous elements for purposes of illustration rather than limitation. It may be noted that storage array controller **101** may include the same, more, or fewer elements configured in the same or different manner in other implementations. It may be noted that elements of FIG. **1**A may be included below to help illustrate features of storage array controller **101**.

[0052] Storage array controller **101** may include one or more processing devices **104** and random access memory (‘RAM’) **111**. Processing device **104** (or controller **101**) represents one or more general-purpose processing devices such as a microprocessor, central processing unit, or the like. More particularly, the processing device **104** (or controller **101**) may be a complex instruction set computing (‘CISC’) microprocessor, reduced instruction set computing (‘RISC’) microprocessor, very long instruction word (‘VLIW’) microprocessor, or a processor implementing other instruction sets or processors implementing a combination of instruction sets. The processing device **104** (or controller **101**) may also be one or more special-purpose processing devices such as an ASIC, an FPGA, a digital signal processor (‘DSP’), network processor, or the like.

[0053] The processing device **104** may be connected to the RAM **111** via a data communications link **106**, which may be embodied as a high speed memory bus such as a Double-Data Rate **4** (‘DDR4’) bus. Stored in RAM **111** is an operating system **112**. In some implementations, instructions **113** are stored in RAM **111**. Instructions **113** may include computer program instructions for performing operations in in a direct-mapped flash storage system. In one embodiment, a direct-mapped flash storage system is one that that addresses data blocks within flash drives directly and without an address translation performed by the storage controllers of the flash drives.

[0054] In implementations, storage array controller **101** includes one or more host bus adapters **103**A-C that are coupled to the processing device **104** via a data communications link **105**A-C. In implementations, host bus adapters **103**A-C may be computer hardware that connects a host system (e.g., the storage array controller) to other network and storage arrays. In some examples, host bus adapters **103**A-C may be a Fibre Channel adapter that enables the storage array controller **101** to connect to a SAN, an Ethernet adapter that enables the storage array controller **101** to connect to a LAN, or the like. Host bus adapters **103**A-C may be coupled to the processing device **104** via a data communications link **105**A-C such as, for example, a PCIe bus.

[0055] In implementations, storage array controller **101** may include a host bus adapter **114** that is coupled to an expander **115**. The expander **115** may be used to attach a host system to a larger number of storage drives. The expander **115** may, for example, be a SAS expander utilized to enable the host bus adapter **114** to attach to storage drives in an implementation where the host bus adapter **114** is embodied as a SAS controller.

[0056] In implementations, storage array controller **101** may include a switch **116** coupled to the processing device **104** via a data communications link **109**. The switch **116** may be a computer hardware device that can create multiple endpoints out of a single endpoint, thereby enabling multiple devices to share a single endpoint. The switch **116** may, for example, be a PCIe switch that is coupled to a PCIe bus (e.g., data communications link **109**) and presents multiple PCIe connection points to the midplane.

[0057] In implementations, storage array controller **101** includes a data communications link **107** for coupling the storage array controller **101** to other storage array controllers. In some examples, data communications link **107** may be a QuickPath Interconnect (QPI) interconnect.

[0058] A traditional storage system that uses traditional flash drives may implement a process across the flash drives that are part of the traditional storage system. For example, a higher level process of the storage system may initiate and control a process across the flash drives. However, a flash drive of the traditional storage system may include its own storage controller that also performs the process. Thus, for the traditional storage system, a higher level process (e.g., initiated by the storage system) and a lower level process (e.g., initiated by a storage controller of the storage system) may both be performed.

[0059] To resolve various deficiencies of a traditional storage system, operations may be performed by higher level processes and not by the lower level processes. For example, the flash storage system may include flash drives that do not include storage controllers that provide the process. Thus, the operating system of the flash storage system itself may initiate and control the process. This may be accomplished by a direct-mapped flash storage system that addresses data blocks within the flash drives directly and without an address translation performed by the storage controllers of the flash drives.

[0060] In implementations, storage drive **171**A-F may be one or more zoned storage devices. In some implementations, the one or more zoned storage devices may be a shingled HDD. In implementations, the one or more storage devices may be a flash-based SSD. In a zoned storage device, a zoned namespace on the zoned storage device can be addressed by groups of blocks that are grouped and aligned by a natural size, forming a number of addressable zones. In implementations utilizing an SSD, the natural size may be based on the erase block size of the SSD. In some implementations, the zones of the zoned storage device may be defined during initialization of the zoned storage device. In implementations, the zones may be defined dynamically as data is written to the zoned storage device.

[0061] In some implementations, zones may be heterogeneous, with some zones each being a page group and other zones being multiple page groups. In implementations, some zones may correspond to an erase block and other zones may correspond to multiple erase blocks. In an implementation, zones may be any combination of differing numbers of pages in page groups and/or erase blocks, for heterogeneous mixes of programming modes, manufacturers, product types and/or product generations of storage devices, as applied to heterogeneous assemblies, upgrades, distributed storages, etc. In some implementations, zones may be defined as having usage characteristics, such as a property of supporting data with particular kinds of longevity (very short lived or very long lived, for example). These properties could be used by a zoned storage device to determine how the zone will be managed over the zone's expected lifetime.

[0062] It should be appreciated that a zone is a virtual construct. Any particular zone may not have a fixed location at a storage device. Until allocated, a zone may not have any location at a storage device. A zone may correspond to a number representing a chunk of virtually allocatable space that is the size of an erase block or other block size in various implementations. When the system allocates or opens a zone, zones get allocated to flash or other solid-state storage memory and, as the system writes to the zone, pages are written to that mapped flash or other solid-state storage memory of the zoned storage device. When the system closes the zone, the associated erase block(s) or other sized block(s) are completed. At some point in the future, the system may delete a zone which will free up the zone's allocated space. During its lifetime, a zone may be moved around to different locations of the zoned storage device, e.g., as the zoned storage device does internal maintenance.

[0063] In implementations, the zones of the zoned storage device may be in different states. A zone may be in an empty state in which data has not been stored at the zone. An empty zone may be opened explicitly, or implicitly by writing data to the zone. This is the initial state for zones on a fresh zoned storage device, but may also be the result of a zone reset. In some implementations, an empty zone may have a designated location within the flash memory of the zoned storage device. In an implementation, the location of the empty zone may be chosen when the zone is first opened or first written to (or later if writes are buffered into memory). A zone may be in an open state either implicitly or explicitly, where a zone that is in an open state may be written to store data with write or append commands. In an implementation, a zone that is in an open state may also be written to using a copy command that copies data from a different zone. In some implementations, a zoned storage device may have a limit on the number of open zones at a particular time.

[0064] A zone in a closed state is a zone that has been partially written to, but has entered a closed state after issuing an explicit close operation. A zone in a closed state may be left available for future writes, but may reduce some of the run-time overhead consumed by keeping the zone in an open state. In implementations, a zoned storage device may have a limit on the number of closed zones at a particular time. A zone in a full state is a zone that is storing data and can no longer be written to. A zone may be in a full state either after writes have written data to the entirety of the zone or as a result of a zone finish operation. Prior to a finish operation, a zone may or may not have been completely written. After a finish operation, however, the zone may not be opened a written to further without first performing a zone reset operation.

[0065] The mapping from a zone to an erase block (or to a shingled track in an HDD) may be arbitrary, dynamic, and hidden from view. The process of opening a zone may be an operation that allows a new zone to be dynamically mapped to underlying storage of the zoned storage device, and then allows data to be written through appending writes into the zone until the zone reaches capacity. The zone can be finished at any point, after which further data may not be written into the zone. When the data stored at the zone is no longer needed, the zone can be reset which effectively deletes the zone's content from the zoned storage device, making the physical storage held by that zone available for the subsequent storage of data. Once a zone has been written and finished, the zoned storage device ensures that the data stored at the zone is not lost until the zone is reset. In the time between writing the data to the zone and the resetting of the zone, the zone may be moved around between shingle tracks or erase blocks as part of maintenance operations within the zoned storage device, such as by copying data to keep the data refreshed or to handle memory cell aging in an SSD.

[0066] In implementations utilizing an HDD, the resetting of the zone may allow the shingle tracks to be allocated to a new, opened zone that may be opened at some point in the future. In implementations utilizing an SSD, the resetting of the zone may cause the associated physical erase block(s) of the zone to be erased and subsequently reused for the storage of data. In some implementations, the zoned storage device may have a limit on the number of open zones at a point in time to reduce the amount of overhead dedicated to keeping zones open.

[0067] The operating system of the flash storage system may identify and maintain a list of allocation units across multiple flash drives of the flash storage system. The allocation units may be entire erase blocks or multiple erase blocks. The operating system may maintain a map or address range that directly maps addresses to erase blocks of the flash drives of the flash storage system.

[0068] Direct mapping to the erase blocks of the flash drives may be used to rewrite data and erase data. For example, the operations may be performed on one or more allocation units that include a first data and a second data where the first data is to be retained and the second data is no longer being used by the flash storage system. The operating system may initiate the process to write the first data to new locations within other allocation units and erasing the second data and marking the allocation units as being available for use for subsequent data. Thus, the process may only be performed by the higher level operating system of the flash storage system without an additional lower level process being performed by controllers of the flash drives.

[0069] Advantages of the process being performed only by the operating system of the flash storage system include increased reliability of the flash drives of the flash storage system as unnecessary or redundant write operations are not being performed during the process. One possible point of novelty here is the concept of initiating and controlling the process at the operating system of the flash storage system. In addition, the process can be controlled by the operating system across multiple flash drives. This is contrast to the process being performed by a storage controller of a flash drive.

[0070] A storage system can consist of two storage array controllers that share a set of drives for failover purposes, or it could consist of a single storage array controller that provides a storage service that utilizes multiple drives, or it could consist of a distributed network of storage array controllers each with some number of drives or some amount of Flash storage where the storage array controllers in the network collaborate to provide a complete storage service and collaborate on various aspects of a storage service including storage allocation and garbage collection.

[0071] FIG. **1**C illustrates a third example system **117** for data storage in accordance with some implementations. System **117** (also referred to as “storage system” herein) includes numerous elements for purposes of illustration rather than limitation. It may be noted that system **117** may include the same, more, or fewer elements configured in the same or different manner in other implementations.

[0072] In one embodiment, system **117** includes a dual Peripheral Component Interconnect (‘PCI’) flash storage device **118** with separately addressable fast write storage. System **117** may include a storage device controller **119**. In one embodiment, storage device controller **119**A-D may be a CPU, ASIC, FPGA, or any other circuitry that may implement control structures necessary according to the present disclosure. In one embodiment, system **117** includes flash memory devices (e.g., including flash memory devices **120***a-n*), operatively coupled to various channels of the storage device controller **119**. Flash memory devices **120***a-n*, may be presented to the controller **119**A-D as an addressable collection of Flash pages, erase blocks, and/or control elements sufficient to allow the storage device controller **119**A-D to program and retrieve various aspects of the Flash. In one embodiment, storage device controller **119**A-D may perform operations on flash memory devices **120***a-n* including storing and retrieving data content of pages, arranging and erasing any blocks, tracking statistics related to the use and reuse of Flash memory pages, erase blocks, and cells, tracking and predicting error codes and faults within the Flash memory, controlling voltage levels associated with programming and retrieving contents of Flash cells, etc.

[0073] In one embodiment, system **117** may include RAM **121** to store separately addressable fast-write data. In one embodiment, RAM **121** may be one or more separate discrete devices. In another embodiment, RAM **121** may be integrated into storage device controller **119**A-D or multiple storage device controllers. The RAM **121** may be utilized for other purposes as well, such as temporary program memory for a processing device (e.g., a CPU) in the storage device controller **119**.

[0074] In one embodiment, system **117** may include a stored energy device **122**, such as a rechargeable battery or a capacitor. Stored energy device **122** may store energy sufficient to power the storage device controller **119**, some amount of the RAM (e.g., RAM **121**), and some amount of Flash memory (e.g., Flash memory **120***a*-**120***n*) for sufficient time to write the contents of RAM to Flash memory. In one embodiment, storage device controller **119**A-D may write the contents of RAM to Flash Memory if the storage device controller detects loss of external power.

[0075] In one embodiment, system **117** includes two data communications links **123***a*, **123***b*. In one embodiment, data communications links **123***a*, **123***b* may be PCI interfaces. In another embodiment, data communications links **123***a*, **123***b* may be based on other communications standards (e.g., HyperTransport, InfiniBand, etc.). Data communications links **123***a*, **123***b* may be based on non-volatile memory express ('NVMe') or NVMe over fabrics ('NVMf') specifications that allow external connection to the storage device controller **119**A-D from other components in the storage system **117**. It should be noted that data communications links may be interchangeably referred to herein as PCI buses for convenience.

[0076] System **117** may also include an external power source (not shown), which may be provided over one or both data communications links **123***a*, **123***b*, or which may be provided separately. An alternative embodiment includes a separate Flash memory (not shown) dedicated for use in storing the content of RAM **121**. The storage device controller **119**A-D may present a logical device over a PCI bus which may include an addressable fast-write logical device, or a distinct part of the logical address space of the storage device **118**, which may be presented as PCI memory or as persistent storage. In one embodiment, operations to store into the device are directed into the RAM **121**. On power failure, the storage device controller **119**A-D may write stored content associated with the addressable fast-write logical storage to Flash memory (e.g., Flash memory **120***a-n*) for long-term persistent storage.

[0077] In one embodiment, the logical device may include some presentation of some or all of the content of the Flash memory devices **120***a-n*, where that presentation allows a storage system including a storage device **118** (e.g., storage system **117**) to directly address Flash memory pages and directly reprogram erase blocks from storage system components that are external to the storage device through the PCI bus. The presentation may also allow one or more of the external components to control and retrieve other aspects of the Flash memory including some or all of: tracking statistics related to use and reuse of Flash memory pages, erase blocks, and cells across all the Flash memory devices; tracking and predicting error codes and faults within and across the Flash memory devices; controlling voltage levels associated with programming and retrieving contents of Flash cells; etc.

[0078] In one embodiment, the stored energy device **122** may be sufficient to ensure completion of in-progress operations to the Flash memory devices **120***a*-**120***n* stored energy device **122** may power storage device controller **119**A-D and associated Flash memory devices (e.g., **120***a-n*) for those operations, as well as for the storing of fast-write RAM to Flash memory. Stored energy device **122** may be used to store accumulated statistics and other parameters kept and tracked by the Flash memory devices **120***a-n* and/or the storage device controller **119**. Separate capacitors or stored energy devices (such as smaller capacitors near or embedded within the Flash memory devices themselves) may be used for some or all of the operations described herein.

[0079] Various schemes may be used to track and optimize the life span of the stored energy component, such as adjusting voltage levels over time, partially discharging the stored energy device **122** to measure corresponding discharge characteristics, etc. If the available energy decreases over time, the effective available capacity of the addressable fast-write storage may be decreased to ensure that it can be written safely based on the currently available stored energy.

[0080] FIG. **1**D illustrates a third example storage system **124** for data storage in accordance with some implementations. In one embodiment, storage system **124** includes storage controllers **125***a*, **125***b*. In one embodiment, storage controllers **125***a*, **125***b* are operatively coupled to Dual PCI storage devices. Storage controllers **125***a*, **125***b* may be operatively coupled (e.g., via a storage network **130**) to some number of host computers **127***a-n*.

[0081] In one embodiment, two storage controllers (e.g., **125***a* and **125***b*) provide storage services, such as a SCS) block storage array, a file server, an object server, a database or data analytics service, etc. The storage controllers **125***a*, **125***b* may provide services through some number of network interfaces (e.g., **126***a-d*) to host computers **127***a-n* outside of the storage system **124**. Storage controllers **125***a*, **125***b* may provide integrated services or an application entirely within the storage system **124**, forming a converged storage and compute system. The storage controllers **125***a*, **125***b* may utilize the fast write memory within or across storage devices **119***a-d* to journal in progress operations to ensure the operations are not lost on a power failure, storage controller removal, storage controller or storage system shutdown, or some fault of one or more software or hardware components within the storage system **124**.

[0082] In one embodiment, storage controllers **125***a*, **125***b* operate as PCI masters to one or the other PCI buses **128***a*, **128***b*. In another embodiment, **128***a* and **128***b* may be based on other communications standards (e.g., HyperTransport, InfiniBand, etc.). Other storage system embodiments may operate storage controllers **125***a*, **125***b* as multi-masters for both PCI buses **128***a*, **128***b*. Alternately, a PCI/NVMe/NVMf switching infrastructure or fabric may connect multiple storage controllers. Some storage system embodiments may allow storage devices to communicate with each other directly rather than communicating only with storage controllers. In one embodiment, a storage device controller **119***a* may be operable under direction from a storage controller **125***a* to synthesize and transfer data to be stored into Flash memory devices from data that has been stored in RAM (e.g., RAM **121** of FIG. **1**C). For example, a recalculated version of RAM content may be transferred after a storage controller has determined that an operation has fully committed across the storage system, or when fast-write memory on the device has reached a certain used capacity, or after a certain amount of time, to ensure improve safety of the data or to release addressable fast-write capacity for reuse. This mechanism may be used, for example, to avoid a second transfer over a bus (e.g., **128***a*, **128***b*) from the storage controllers **125***a*, **125***b*. In one embodiment, a recalculation may include compressing data, attaching indexing or other metadata, combining multiple data segments together, performing erasure code calculations, etc.

[0083] In one embodiment, under direction from a storage controller **125***a*, **125***b*, a storage device controller **119***a*, **119***b* may be operable to calculate and transfer data to other storage devices from data stored in RAM (e.g., RAM **121** of FIG. **1**C) without involvement of the storage controllers **125***a*, **125***b*. This operation may be used to mirror data stored in one storage controller **125***a* to another storage controller **125***b*, or it could be used to offload compression, data aggregation, and/or erasure coding calculations and transfers to storage devices to reduce load on storage controllers or the storage controller interface **129***a*, **129***b* to the PCI bus **128***a*, **128***b*.

[0084] A storage device controller **119**A-D may include mechanisms for implementing high availability primitives for use by other parts of a storage system external to the Dual PCI storage device **118**. For example, reservation or exclusion primitives may be provided so that, in a storage system with two storage controllers providing a highly available storage service, one storage controller may prevent the other storage controller from accessing or continuing to access the storage device. This could be used, for example, in cases where one controller detects that the other controller is not functioning properly or where the interconnect between the two storage controllers may itself not be functioning properly.

[0085] In one embodiment, a storage system for use with Dual PCI direct mapped storage devices with separately addressable fast write storage includes systems that manage erase blocks or groups of erase blocks as allocation units for storing data on behalf of the storage service, or for storing metadata (e.g., indexes, logs, etc.) associated with the storage service, or for proper management of the storage system itself. Flash pages, which may be a few kilobytes in size, may be written as data arrives or as the storage system is to persist data for long intervals of time (e.g., above a defined threshold of time). To commit data more quickly, or to reduce the number of writes to the Flash memory devices, the storage controllers may first write data into the separately addressable fast write storage on one more storage devices.

[0086] In one embodiment, the storage controllers **125***a*, **125***b* may initiate the use of erase blocks within and across storage devices (e.g., **118**) in accordance with an age and expected remaining lifespan of the storage devices, or based on other statistics. The storage controllers **125***a*, **125***b* may initiate garbage collection and data migration data between storage devices in accordance with pages that are no longer needed as well as to manage Flash page and erase block lifespans and to manage overall system performance.

[0087] In one embodiment, the storage system **124** may utilize mirroring and/or erasure coding schemes as part of storing data into addressable fast write storage and/or as part of writing data into allocation units associated with erase blocks. Erasure codes may be used across storage devices, as well as within erase blocks or allocation units, or within and across Flash memory devices on a single storage device, to provide redundancy against single or multiple storage device failures or to protect against internal corruptions of Flash memory pages resulting from Flash memory operations or from degradation of Flash memory cells. Mirroring and erasure coding at various levels may be used to recover from multiple types of failures that occur separately or in combination.

[0088] The embodiments depicted with reference to FIGS. **2**A-G illustrate 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, or across multiple 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.

[0089] The storage cluster may be 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 PCIe, 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. In some embodiments, multiple chassis may be coupled or connected to each other through an aggregator switch. A portion and/or all of the coupled or connected chassis may be designated as a storage cluster. As discussed above, each chassis can have multiple blades, each blade has a media access control (‘MAC’) address, but the storage cluster is presented to an external network as having a single cluster IP address and a single MAC address in some embodiments.

[0090] 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, 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 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.

[0091] 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.

[0092] FIG. **2**A is a perspective view of a storage cluster **161**, 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 **161**, 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 **161** 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 **161** 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 herein, 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.

[0093] Each storage node **150** can have multiple components. In the embodiment shown here, the storage node **150** includes a printed circuit board **159** 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.

[0094] Referring to FIG. **2**A, storage cluster **161** 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 **152** units or storage nodes **150** within the chassis.

[0095] FIG. **2**B is a block diagram showing a communications interconnect **173** and power distribution bus **172** coupling multiple storage nodes **150**. Referring back to FIG. **2**A, the communications interconnect **173** can be included in or implemented with the switch fabric **146** in some embodiments. Where multiple storage clusters **161** occupy a rack, the communications interconnect **173** can be included in or implemented with a top of rack switch, in some embodiments. As illustrated in FIG. **2**B, storage cluster **161** is enclosed within a single chassis **138**. External port **176** is coupled to storage nodes **150** through communications interconnect **173**, 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. **2**A. In addition, one or more storage nodes **150** may be a compute only storage node as illustrated in FIG. **2**B. Authorities **168** are implemented on the non-volatile solid state storage **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 storage **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.

[0096] 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 storage **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.

[0097] 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.

[0098] With reference to FIGS. **2**A and **2**B, 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.

[0099] In embodiments, authorities **168** operate to determine how operations will proceed against particular logical elements. Each of the logical elements may be operated on through a particular authority across a plurality of storage controllers of a storage system. The authorities **168** may communicate with the plurality of storage controllers so that the plurality of storage controllers collectively perform operations against those particular logical elements.

[0100] In embodiments, logical elements could be, for example, files, directories, object buckets, individual objects, delineated parts of files or objects, other forms of key-value pair databases, or tables. In embodiments, performing an operation can involve, for example, ensuring consistency, structural integrity, and/or recoverability with other operations against the same logical element, reading metadata and data associated with that logical element, determining what data should be written durably into the storage system to persist any changes for the operation, or where metadata and data can be determined to be stored across modular storage devices attached to a plurality of the storage controllers in the storage system.

[0101] In some embodiments the operations are token based transactions to efficiently communicate within a distributed system. Each transaction may be accompanied by or associated with a token, which gives permission to execute the transaction. The authorities **168** are able to maintain a pre-transaction state of the system until completion of the operation in some embodiments. The token based communication may be accomplished without a global lock across the system, and also enables restart of an operation in case of a disruption or other failure.

[0102] 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.

[0103] 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. **2**E and **2**G) 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.

[0104] 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 **152** unit 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**.

[0105] 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.

[0106] 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.

[0107] 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.

[0108] 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.

[0109] 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.

[0110] 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.

[0111] 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, i.e., the system supports non-disruptive upgrades.

[0112] 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.

[0113] FIG. **2**C 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. **2**C, 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. **2**C, 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., an 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**.

[0114] Storage clusters **161**, 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 **161**. 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 non-volatile solid state storage **152** units 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 **161**, as described herein, multiple controllers in multiple non-volatile sold state storage **152** units 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).

[0115] FIG. **2**D shows a storage server environment, which uses embodiments of the storage nodes **150** and storage **152** units of FIGS. **2**A-C. In this version, each non-volatile solid state storage **152** unit has a processor such as controller **212** (see FIG. **2**C), an FPGA, flash memory **206**, and NVRAM **204** (which is super-capacitor backed DRAM **216**, see FIGS. **2**B and **2**C) on a PCIe (peripheral component interconnect express) board in a chassis **138** (see FIG. **2**A). The non-volatile solid state storage **152** unit 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 non-volatile solid state storage **152** units may fail and the device will continue with no data loss.

[0116] 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 non-volatile solid state storage **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 **168** independently. Each device provides an amount of storage space to each authority **168**. That authority **168** further manages lifetimes and allocations within that space. Examples of a spool include distributed transactions or notions. When the primary power to a non-volatile solid state storage **152** unit 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**.

[0117] As for the storage unit controller, the responsibility of the logical "controller" is distributed across each of the blades containing authorities **168**. This distribution of logical control is shown in FIG. **2**D as a host controller **242**, mid-tier controller **244** and storage unit controller(s) **246**. 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 **168** effectively serves as an independent controller. Each authority **168** provides its own data and metadata structures, its own background workers, and maintains its own lifecycle.

[0118] FIG. **2**E is a blade **252** hardware block diagram, showing a control plane **254**, compute and storage planes **256**, **258**, and authorities **168** interacting with underlying physical resources, using embodiments of the storage nodes **150** and storage units **152** of FIGS. **2**A-C in the storage server environment of FIG. **2**D. The control plane **254** is partitioned into a number of authorities **168** which can use the compute resources in the compute plane **256** to run on any of the blades **252**. The storage plane **258** is partitioned into a set of devices, each of which provides access to flash **206** and NVRAM **204** resources. In one embodiment, the compute plane **256** may perform the operations of a storage array controller, as described herein, on one or more devices of the storage plane **258** (e.g., a storage array).

[0119] In the compute and storage planes **256**, **258** of FIG. **2**E, the authorities **168** interact with the underlying physical resources (i.e., devices). From the point of view of an authority **168**, its resources are striped over all of the physical devices. From the point of view of a device, it provides resources to all authorities **168**, irrespective of where the authorities happen to run. Each authority **168** has allocated or has been allocated one or more partitions **260** of storage memory in the storage units **152**, e.g., partitions **260** in flash memory **206** and NVRAM **204**. Each authority **168** uses those allocated partitions **260** 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 **168** could have a larger number of partitions **260** or larger sized partitions **260** in one or more storage units **152** than one or more other authorities **168**.

[0120] FIG. **2**F depicts elasticity software layers in blades **252** of a storage cluster, in accordance with some embodiments. In the elasticity structure, elasticity software is symmetric, i.e., each blade's compute module **270** runs the three identical layers of processes depicted in FIG. **2**F. Storage managers **274** execute read and write requests from other blades **252** 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 **252** on whose storage units **152** the corresponding data or metadata resides. Endpoints **272** 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.

[0121] Still referring to FIG. **2**F, authorities **168** running in the compute modules **270** of a blade **252** 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' **252** DRAMs for fast access, but the authorities store every update in their NVRAM **204** partitions on three separate blades **252** 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 **252** 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 **252** with no loss of data, metadata, or access to either.

[0122] Because authorities **168** are stateless, they can migrate between blades **252**. Each authority **168** has a unique identifier. NVRAM **204** and flash **206** partitions are associated with authorities' **168** identifiers, not with the blades **252** on which they are running in some. Thus, when an authority **168** migrates, the authority **168** continues to manage the same storage partitions from its new location. When a new blade **252** is installed in an embodiment of the storage cluster, the system automatically rebalances load by: partitioning the new blade's **252** storage for use by the system's authorities **168**, migrating selected authorities **168** to the new blade **252**, starting endpoints **272** on the new blade **252** and including them in the switch fabric's **146** client connection distribution algorithm.

[0123] 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 **272** direct to them. Similarly, if a blade **252** fails or is removed, the system redistributes its authorities **168** among the system's remaining blades **252**. The redistributed authorities **168** continue to perform their original functions from their new locations.

[0124] FIG. **2**G depicts authorities **168** and storage resources in blades **252** 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 **252**. 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 **274** 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.

[0125] The embodiments described herein may utilize various software, communication and/or networking protocols. In addition, the configuration of the hardware and/or software may be adjusted to accommodate various protocols. For example, the embodiments may utilize Active Directory, which is a database based system that provides authentication, directory, policy, and other services in a WINDOWS™ environment. In these embodiments, LDAP (Lightweight Directory Access Protocol) is one example application protocol for querying and modifying items in directory service providers such as Active Directory. In some embodiments, a network lock manager (‘NLM’) is utilized as a facility that works in cooperation with the Network File System (‘NFS’) to provide a System V style of advisory file and record locking over a network. The Server Message Block (‘SMB’) protocol, one version of which is also known as Common Internet File System (‘CIFS’), may be integrated with the storage systems discussed herein. SMP operates as an application-layer network protocol typically used for providing shared access to files, printers, and serial ports and miscellaneous communications between nodes on a network. SMB also provides an authenticated inter-process communication mechanism. AMAZON™ S3 (Simple Storage Service) is a web service offered by Amazon Web Services, and the systems described herein may interface with Amazon S3 through web services interfaces (REST (representational state transfer), SOAP (simple object access protocol), and BitTorrent). A RESTful API (application programming interface) breaks down a transaction to create a series of small modules. Each module addresses a particular underlying part of the transaction. The control or permissions provided with these embodiments, especially for object data, may include utilization of an access control list (‘ACL’). The ACL is a list of permissions attached to an object and the ACL specifies which users or system processes are granted access to objects, as well as what operations are allowed on given objects. The systems may utilize Internet Protocol version 6 (‘IPv6’), as well as IPv4, for the communications protocol that provides an identification and location system for computers on networks and routes traffic across the Internet. The routing of packets between networked systems may include Equal-cost multi-path routing (‘ECMP’), which is a routing strategy where next-hop packet forwarding to a single destination can occur over multiple “best paths” which tie for top place in routing metric calculations. Multi-path routing can be used in conjunction with most routing protocols, because it is a per-hop decision limited to a single router. The software may support Multi-tenancy, which is an architecture in which a single instance of a software application serves multiple customers. Each customer may be referred to as a tenant. Tenants may be given the ability to customize some parts of the application, but may not customize the application's code, in some embodiments. The embodiments may maintain audit logs. An audit log is a document that records an event in a computing system. In addition to documenting what resources were accessed, audit log entries typically include destination and source addresses, a timestamp, and user login information for compliance with various regulations. The embodiments may support various key management policies, such as encryption key rotation. In addition, the system may support dynamic root passwords or some variation dynamically changing passwords.

[0126] FIG. **3**A sets forth a diagram of a storage system **306** that is coupled for data communications with a cloud services provider **302** in accordance with some embodiments of the present disclosure. Although depicted in less detail, the storage system **306** depicted in FIG. **3**A may be similar to the storage systems described above with reference to FIGS. **1**A-**1**D and FIGS. **2**A-**2**G. In some embodiments, the storage system **306** depicted in FIG. **3**A may be embodied as a storage system that includes imbalanced active/active controllers, as a storage system that includes balanced active/active controllers, as a storage system that includes active/active controllers where less than all of each controller's resources are utilized such that each controller has reserve resources that may be used to support failover, as a storage system that includes fully active/active controllers, as a storage system that includes dataset-segregated controllers, as a storage system that includes dual-layer architectures with front-end controllers and back-end integrated storage controllers, as a storage system that includes scale-out clusters of dual-controller arrays, as well as combinations of such embodiments.

[0127] In the example depicted in FIG. **3**A, the storage system **306** is coupled to the cloud services provider **302** via a data communications link **304**. The data communications link **304** may be embodied as a dedicated data communications link, as a data communications pathway that is provided through the use of one or data communications networks such as a wide area network ('WAN') or LAN, or as some other mechanism capable of transporting digital information between the storage system **306** and the cloud services provider **302**. Such a data communications link **304** may be fully wired, fully wireless, or some aggregation of wired and wireless data communications pathways. In such an example, digital information may be exchanged between the storage system **306** and the cloud services provider **302** via the data communications link **304** using one or more data communications protocols. For example, digital information may be exchanged between the storage system **306** and the cloud services provider **302** via the data communications link **304** using the handheld device transfer protocol ('HDTP'), hypertext transfer protocol ('HTTP'), internet protocol ('IP'), real-time transfer protocol ('RTP'), transmission control protocol ('TCP'), user datagram protocol ('UDP'), wireless application protocol ('WAP'), or other protocol.

[0128] The cloud services provider **302** depicted in FIG. **3**A may be embodied, for example, as a system and computing environment that provides a vast array of services to users of the cloud services provider **302** through the sharing of computing resources via the data communications link **304**. The cloud services provider **302** may provide on-demand access to a shared pool of configurable computing resources such as computer networks, servers, storage, applications and services, and so on. The shared pool of configurable resources may be rapidly provisioned and released to a user of the cloud services provider **302** with minimal management effort. Generally, the user of the cloud services provider **302** is unaware of the exact computing resources utilized by the cloud services provider **302** to provide the services. Although in many cases such a cloud services provider **302** may be accessible via the Internet, readers of skill in the art will recognize that any system that abstracts the use of shared resources to provide services to a user through any data communications link may be considered a cloud services provider **302**.

[0129] In the example depicted in FIG. **3**A, the cloud services provider **302** may be configured to provide a variety of services to the storage system **306** and users of the storage system **306** through the implementation of various service models. For example, the cloud services provider **302** may be configured to provide services through the implementation of an infrastructure as a service ('IaaS') service model, through the implementation of a platform as a service ('PaaS') service model, through the implementation of a software as a service ('SaaS') service model, through the implementation of an authentication as a service ('AaaS') service model, through the implementation of a storage as a service model where the cloud services provider **302** offers access to its storage infrastructure for use by the storage system **306** and users of the storage system **306**, and so on. Readers will appreciate that the cloud services provider **302** may be configured to provide additional services to the storage system **306** and users of the storage system **306** through the implementation of additional service models, as the service models described above are included only for explanatory purposes and in no way represent a limitation of the services that may be offered by the cloud services provider **302** or a limitation as to the service models that may be implemented by the cloud services provider **302**.

[0130] In the example depicted in FIG. **3**A, the cloud services provider **302** may be embodied, for example, as a private cloud, as a public cloud, or as a combination of a private cloud and public cloud. In an embodiment in which the cloud services provider **302** is embodied as a private cloud, the cloud services provider **302** may be dedicated to providing services to a single organization rather than providing services to multiple organizations. In an embodiment where the cloud services provider **302** is embodied as a public cloud, the cloud services provider **302** may provide services to multiple organizations. In still alternative embodiments, the cloud services provider **302** may be embodied as a mix of a private and public cloud services with a hybrid cloud deployment.

[0131] Although not explicitly depicted in FIG. **3**A, readers will appreciate that a vast amount of additional hardware components and additional software components may be necessary to facilitate the delivery of cloud services to the storage system **306** and users of the storage system **306**. For example, the storage system **306** may be coupled to (or even include) a cloud storage gateway. Such a cloud storage gateway may be embodied, for example, as hardware-based or software-based appliance that is located on premise with the storage system **306**. Such a cloud storage gateway may operate as a bridge between local applications that are executing on the storage system **306** and remote, cloud-based storage that is utilized by the storage system **306**. Through the use of a cloud storage gateway, organizations may move primary iSCSI or NAS to the cloud services provider **302**, thereby enabling the organization to save space on their on-premises storage systems. Such a cloud storage gateway may be configured to emulate a disk array, a block-based device, a file server, or other storage system that can translate the SCSI commands, file server commands, or other appropriate command into REST-space protocols that facilitate communications with the cloud services provider **302**.

[0132] In order to enable the storage system **306** and users of the storage system **306** to make use of the services provided by the cloud services provider **302**, a cloud migration process may take place during which data, applications, or other elements from an organization's local systems (or even from another cloud environment) are moved to the cloud services provider **302**. In order to successfully migrate data, applications, or other elements to the cloud services provider's **302** environment, middleware such as a cloud migration tool may be utilized to bridge gaps between the cloud services provider's **302** environment and an organization's environment. Such cloud migration tools may also be configured to address potentially high network costs and long transfer times associated with migrating large volumes of data to the cloud services provider **302**, as well as addressing security concerns associated with sensitive data to the cloud services provider **302** over data communications networks. In order to further enable the storage system **306** and users of the storage system **306** to make use of the services provided by the cloud services provider **302**, a cloud orchestrator may also be used to arrange and coordinate automated tasks in pursuit of creating a consolidated process or workflow. Such a cloud orchestrator may perform tasks such as configuring various components, whether those components are cloud components or on-premises components, as well as managing the interconnections between such components. The cloud orchestrator can simplify the inter-component communication and connections to ensure that links are correctly configured and maintained.

[0133] In the example depicted in FIG. **3**A, and as described briefly above, the cloud services provider **302** may be configured to provide services to the storage system **306** and users of the storage system **306** through the usage of a SaaS service model, eliminating the need to install and run the application on local computers, which may simplify maintenance and support of the application. Such applications may take many forms in accordance with various embodiments of the present disclosure. For example, the cloud services provider **302** may be configured to provide access to data analytics applications to the storage system **306** and users of the storage system **306**. Such data analytics applications may be configured, for example, to receive vast amounts of telemetry data phoned home by the storage system **306**. Such telemetry data may describe various operating characteristics of the storage system **306** and may be analyzed for a vast array of purposes including, for example, to determine the health of the storage system **306**, to identify workloads that are executing on the storage system **306**, to predict when the storage system **306** will run out of various resources, to recommend configuration changes, hardware or software upgrades, workflow migrations, or other actions that may improve the operation of the storage system **306**.

[0134] The cloud services provider **302** may also be configured to provide access to virtualized computing environments to the storage system **306** and users of the storage system **306**. Such virtualized computing environments may be embodied, for example, as a virtual machine or other virtualized computer hardware platforms, virtual storage devices, virtualized computer network resources, and so on. Examples of such virtualized environments can include virtual machines that are created to emulate an actual computer, virtualized desktop environments that separate a logical desktop from a physical machine, virtualized file systems that allow uniform access to different types of concrete file systems, and many others.

[0135] Although the example depicted in FIG. **3**A illustrates the storage system **306** being coupled for data communications with the cloud services provider **302**, in other embodiments the storage system **306** may be part of a hybrid cloud deployment in which private cloud elements (e.g., private cloud services, on-premises infrastructure, and so on) and public cloud elements (e.g., public cloud services, infrastructure, and so on that may be provided by one or more cloud services providers) are combined to form a single solution, with orchestration among the various platforms. Such a hybrid cloud deployment may leverage hybrid cloud management software such as, for example, Azure™ Arc from Microsoft™, that centralize the management of the hybrid cloud deployment to any infrastructure and enable the deployment of services anywhere. In such an example, the hybrid cloud management software may be configured to create, update, and delete resources (both physical and virtual) that form the hybrid cloud deployment, to allocate compute and storage to specific workloads, to monitor workloads and resources for performance, policy compliance, updates and patches, security status, or to perform a variety of other tasks.

[0136] Readers will appreciate that by pairing the storage systems described herein with one or more cloud services providers, various offerings may be enabled. For example, disaster recovery as a service ('DRaaS') may be provided where cloud resources are utilized to protect applications and data from disruption caused by disaster, including in embodiments where the storage systems may serve as the primary data store. In such embodiments, a total system backup may be taken that allows for business continuity in the event of system failure. In such embodiments, cloud data backup techniques (by themselves or as part of a larger DRaaS solution) may also be integrated into an overall solution that includes the storage systems and cloud services providers described herein.

[0137] The storage systems described herein, as well as the cloud services providers, may be utilized to provide a wide array of security features. For example, the storage systems may encrypt data at rest (and data may be sent to and from the storage systems encrypted) and may make use of Key Management-as-a-Service ('KMaaS') to manage encryption keys, keys for locking and unlocking storage devices, and so on. Likewise, cloud data security gateways or similar mechanisms may be utilized to ensure that data stored within the storage systems does not improperly end up being stored in the cloud as part of a cloud data backup operation. Furthermore, microsegmentation or identity-based-segmentation may be utilized in a data center that includes the storage systems or within the cloud services provider, to create secure zones in data centers and cloud deployments that enables the isolation of workloads from one another.

[0138] For further explanation, FIG. **3**B sets forth a diagram of a storage system **306** in accordance with some embodiments of the present disclosure. Although depicted in less detail, the storage system **306** depicted in FIG. **3**B may be similar to the storage systems described above with reference to FIGS. **1**A-**1**D and FIGS. **2**A-**2**G as the storage system may include many of the components described above.

[0139] The storage system **306** depicted in FIG. **3**B may include a vast amount of storage resources **308**, which may be embodied in many forms. For example, the storage resources **308** can include nano-RAM or another form of nonvolatile random access memory that utilizes carbon nanotubes deposited on a substrate, 3D crosspoint non-volatile memory, flash memory including single-level cell ('SLC') NAND flash, multi-level cell ('MLC') NAND flash, triple-level cell ('TLC') NAND flash, quad-level cell ('QLC') NAND flash, or others. Likewise, the storage resources **308** may include non-volatile magnetoresistive random-access memory ('MRAM'), including spin transfer torque ('STT') MRAM. The example storage resources **308** may alternatively include non-volatile phase-change memory ('PCM'), quantum memory that allows for the storage and retrieval of photonic quantum information, resistive random-access memory ('ReRAM'), storage class memory ('SCM'), or other form of storage resources, including any combination of resources described herein. Readers will appreciate that other forms of computer memories and storage devices may be utilized by the storage systems described above, including DRAM, SRAM, EEPROM, universal memory, and many others. The storage resources **308** depicted in FIG. **3**A may be embodied in a variety of form factors, including but not limited to, dual in-line memory modules ('DIMMs'), non-volatile dual in-line memory modules ('NVDIMMs'), M.2, U.2, and others.

[0140] The storage resources **308** depicted in FIG. **3**B may include various forms of SCM. SCM may effectively treat fast, non-volatile memory (e.g., NAND flash) as an extension of DRAM such that an entire dataset may be treated as an in-memory dataset that resides entirely in DRAM. SCM may include non-volatile media such as, for example, NAND flash. Such NAND flash may be accessed utilizing NVMe that can use the PCIe bus as its transport, providing for relatively low access latencies compared to older protocols. In fact, the network protocols used for SSDs in all-flash arrays can include NVMe using Ethernet (ROCE, NVME TCP), Fibre Channel (NVMe FC), InfiniBand (iWARP), and others that make it possible to treat fast, non-volatile memory as an extension of DRAM. In view of the fact that DRAM is often byte-addressable and fast, non-volatile memory such as NAND flash is block-addressable, a controller software/hardware stack may be needed to convert the block data to the bytes that are stored in the media. Examples of media and software that may be used as SCM can include, for example, 3D XPoint, Intel Memory Drive Technology, Samsung's Z-SSD, and others.

[0141] The storage resources **308** depicted in FIG. **3**B may also include racetrack memory (also referred to as domain-wall memory). Such racetrack memory may be embodied as a form of non-volatile, solid-state memory that relies on the intrinsic strength and orientation of the magnetic field created by an electron as it spins in addition to its electronic charge, in solid-state devices. Through the use of spin-coherent electric current to move magnetic domains along a nanoscopic permalloy wire, the domains may pass by magnetic read/write heads positioned near the wire as current is passed through the wire, which alter the domains to record patterns of bits. In order to create a racetrack memory device, many such wires and read/write elements may be packaged together.

[0142] The example storage system **306** depicted in FIG. **3**B may implement a variety of storage architectures. For example, storage systems in accordance with some embodiments of the present disclosure may utilize block storage where data is stored in blocks, and each block essentially acts as an individual hard drive. Storage systems in accordance with some embodiments of the present disclosure may utilize object storage, where data is managed as objects. Each object may include the data itself, a variable amount of metadata, and a globally unique identifier, where object storage can be implemented at multiple levels (e.g., device level, system level, interface level). Storage systems in accordance with some embodiments of the present disclosure utilize file storage in which data is stored in a hierarchical structure. Such data may be saved in files and folders, and presented to both the system storing it and the system retrieving it in the same format.

[0143] The example storage system **306** depicted in FIG. **3**B may be embodied as a storage system in which additional storage resources can be added through the use of a scale-up model, additional storage resources can be added through the use of a scale-out model, or through some combination thereof. In a scale-up model, additional storage may be added by adding additional storage devices. In a scale-out model, however, additional storage nodes may be added to a cluster of storage nodes, where such storage nodes can include additional processing resources, additional networking resources, and so on.

[0144] The example storage system **306** depicted in FIG. **3**B may leverage the storage resources described above in a variety of different ways. For example, some portion of the storage resources may be utilized to serve as a write cache, storage resources within the storage system may be utilized as a read cache, or tiering may be achieved within the storage systems by placing data within the storage system in accordance with one or more tiering policies.

[0145] The storage system **306** depicted in FIG. **3**B also includes communications resources **310** that may be useful in facilitating data communications between components within the storage system **306**, as well as data communications between the storage system **306** and computing devices that are outside of the storage system **306**, including embodiments where those resources are separated by a relatively vast expanse. The communications resources **310** may be configured to utilize a variety of different protocols and data communication fabrics to facilitate data communications between components within the storage systems as well as computing devices that are outside of the storage system. For example, the communications resources **310** can include fibre channel ('FC') technologies such as FC fabrics and FC protocols that can transport SCSI commands over FC network, FC over ethernet ('FCoE') technologies through which FC frames are encapsulated and transmitted over Ethernet networks, InfiniBand ('IB') technologies in which a switched fabric topology is utilized to facilitate transmissions between channel adapters, NVM Express ('NVMe') technologies and NVMe over fabrics ('NVMeoF') technologies through which non-volatile storage media attached via a PCI express ('PCIe') bus may be accessed, and others. In fact, the storage systems described above may, directly or indirectly, make use of neutrino communication technologies and devices through which information (including binary information) is transmitted using a beam of neutrinos.

[0146] The communications resources **310** can also include mechanisms for accessing storage resources **308** within the storage system **306** utilizing serial attached SCSI ('SAS'), serial ATA ('SATA') bus interfaces for connecting storage resources **308** within the storage system **306** to host bus adapters within the storage system **306**, internet small computer systems interface ('iSCSI') technologies to provide block-level access to storage resources **308** within the storage system **306**, and other communications resources that that may be useful in facilitating data communications between components within the storage system **306**, as well as data communications between the storage system **306** and computing devices that are outside of the storage system **306**.

[0147] The storage system **306** depicted in FIG. **3**B also includes processing resources **312** that may be useful in useful in executing computer program instructions and performing other computational tasks within the storage system **306**. The processing resources **312** may include one or more ASICs that are customized for some particular purpose as well as one or more CPUs. The processing resources **312** may also include one or more DSPs, one or more FPGAs, one or more systems on a chip ('SoCs'), or other form of processing resources **312**. The storage system **306** may utilize the storage resources **312** to perform a variety of tasks including, but not limited to, supporting the execution of software resources **314** that will be described in greater detail below.

[0148] The storage system **306** depicted in FIG. **3**B also includes software resources **314** that, when executed by processing resources **312** within the storage system **306**, may perform a vast array of tasks. The software resources **314** may include, for example, one or more modules of computer program instructions that when executed by processing resources **312** within the storage system **306** are useful in carrying out various data protection techniques. Such data protection techniques may be carried out, for example, by system software executing on computer hardware within the storage system, by a cloud services provider, or in other ways. Such data protection techniques can include data archiving, data backup, data replication, data snapshotting, data and database cloning, and other data protection techniques.

[0149] The software resources **314** may also include software that is useful in implementing software-defined storage ('SDS'). In such an example, the software resources **314** may include one or more modules of computer program instructions that, when executed, are useful in policy-based provisioning and management of data storage that is independent of the underlying hardware. Such software resources **314** may be useful in implementing storage virtualization to separate the storage hardware from the software that manages the storage hardware.

[0150] The software resources **314** may also include software that is useful in facilitating and optimizing I/O operations that are directed to the storage system **306**. For example, the software resources **314** may include software modules that perform various data reduction techniques such as, for example, data compression, data deduplication, and others. The software resources **314** may include software modules that intelligently group together I/O operations to facilitate better usage of the underlying storage resource **308**, software modules that perform data migration operations to migrate from within a storage system, as well as software modules that perform other functions. Such software resources **314** may be embodied as one or more software containers or in many other ways.

[0151] For further explanation, FIG. **3**C sets forth an example of a cloud-based storage system **318** in accordance with some embodiments of the present disclosure. In the example depicted in FIG. **3**C, the cloud-based storage system **318** is created entirely in a cloud computing environment **316** such as, for example, Amazon Web Services ('AWS')™, Microsoft Azure™ Google Cloud Platform™, IBM Cloud™, Oracle Cloud™, and others. The cloud-based storage system **318** may be used to provide services similar to the services that may be provided by the storage systems described above.

[0152] The cloud-based storage system **318** depicted in FIG. **3**C includes two cloud computing instances **320**, **322** that each are used to support the execution of a storage controller application **324**, **326**. The cloud computing instances **320**, **322** may be embodied, for example, as instances of cloud computing resources (e.g., virtual machines) that may be provided by the cloud computing environment **316** to support the execution of software applications such as the storage controller application **324**, **326**. For example, each of the cloud computing instances **320**, **322** may execute on an Azure VM, where each Azure VM may include high speed temporary storage that may be leveraged as a cache (e.g., as a read cache). In one embodiment, the cloud computing instances **320**, **322** may be embodied as Amazon Elastic Compute Cloud ('EC2') instances. In such an example, an Amazon Machine Image ('AMI') that includes the storage controller application **324**, **326** may be booted to create and configure a virtual machine that may execute the storage controller application **324**, **326**.

[0153] In the example method depicted in FIG. **3**C, the storage controller application **324**, **326** may be embodied as a module of computer program instructions that, when executed, carries out various storage tasks. For example, the storage controller application **324**, **326** may be embodied as a module of computer program instructions that, when executed, carries out the same tasks as the controllers **110**A, **110**B in FIG. **1**A described above such as writing data to the cloud-based storage system **318**, erasing data from the cloud-based storage system **318**, retrieving data from the cloud-based storage system **318**, monitoring and reporting of disk utilization and performance, performing redundancy operations, such as RAID or RAID-like data redundancy operations, compressing data, encrypting data, deduplicating data, and so forth. Readers will appreciate that because there are two cloud computing instances **320**, **322** that each include the storage controller application **324**, **326**, in some embodiments one cloud computing instance **320** may operate as the primary controller as described above while the other cloud computing instance **322** may operate as the secondary controller as described above. Readers will appreciate that the storage controller application **324**, **326** depicted in FIG. **3**C may include identical source code that is executed within different cloud computing instances **320**, **322** such as distinct EC2 instances.

[0154] Readers will appreciate that other embodiments that do not include a primary and secondary controller are within the scope of the present disclosure. For example, each cloud computing instance **320**, **322** may operate as a primary controller for some portion of the address space supported by the cloud-based storage system **318**, each cloud computing instance **320**, **322** may operate as a primary controller where the servicing of I/O operations directed to the cloud-based storage system **318** are divided in some other way, and so on. In fact, in other embodiments where costs savings may be prioritized over performance demands, only a single cloud computing instance may exist that contains the storage controller application.

[0155] The cloud-based storage system **318** depicted in FIG. **3**C includes cloud computing instances **340***a*, **340***b*, **340***n* with local storage **330**, **334**, **338**. The cloud computing instances **340***a*, **340***b*, **340***n* may be embodied, for example, as instances of cloud computing resources that may be provided by the cloud computing environment **316** to support the execution of software applications. The cloud computing instances **340***a*, **340***b*, **340***n* of FIG. **3**C may differ from the cloud computing instances **320**, **322** described above as the cloud computing instances **340***a*, **340***b*, **340***n* of FIG. **3**C have local storage **330**, **334**, **338** resources whereas the cloud computing instances **320**, **322** that support the execution of the storage controller application **324**, **326** need not have local storage resources. The cloud computing instances **340***a*, **340***b*, **340***n* with local storage **330**, **334**, **338** may be embodied, for example, as EC2 M5 instances that include one or more SSDs, as EC2 R5 instances that include one or more SSDs, as EC2 I3 instances that include one or more SSDs, and so on. In some embodiments, the local storage **330**, **334**, **338** must be embodied as solid-state storage (e.g., SSDs) rather than storage that makes use of hard disk drives.

[0156] In the example depicted in FIG. **3**C, each of the cloud computing instances **340***a*, **340***b*, **340***n* with local storage **330**, **334**, **338** can include a software daemon **328**, **332**, **336** that, when executed by a cloud computing instance **340***a*, **340***b*, **340***n* can present itself to the storage controller applications **324**, **326** as if the cloud computing instance **340***a*, **340***b*, **340***n* were a physical storage device (e.g., one or more SSDs). In such an example, the software daemon **328**, **332**, **336** may include computer program instructions similar to those that would normally be contained on a storage device such that the storage controller applications **324**, **326** can send and receive the same commands that a storage controller would send to storage devices. In such a way, the storage controller applications **324**, **326** may include code that is identical to (or substantially identical to) the code that would be executed by the controllers in the storage systems described above. In these and similar embodiments, communications between the storage controller applications **324**, **326** and the cloud computing instances **340***a*, **340***b*, **340***n* with local storage **330**, **334**, **338** may utilize iSCSI, NVMe over TCP, messaging, a custom protocol, or in some other mechanism.

[0157] In the example depicted in FIG. **3**C, each of the cloud computing instances **340***a*, **340***b*, **340***n* with local storage **330**, **334**, **338** may also be coupled to block storage **342**, **344**, **346** that is offered by the cloud computing environment **316** such as, for example, as Amazon Elastic Block Store ('EBS') volumes. In such an example, the block storage **342**, **344**, **346** that is offered by the cloud computing environment **316** may be utilized in a manner that is similar to how the NVRAM devices described above are utilized, as the software daemon **328**, **332**, **336** (or some other module) that is executing within a particular cloud comping instance **340***a*, **340***b*, **340***n* may, upon receiving a request to write data, initiate a write of the data to its attached EBS volume as well as a write of the data to its local storage **330**, **334**, **338** resources. In some alternative embodiments, data may only be written to the local storage **330**, **334**, **338** resources within a particular cloud comping instance **340***a*, **340***b*, **340***n*. In an alternative embodiment, rather than using the block storage **342**, **344**, **346** that is offered by the cloud computing environment **316** as NVRAM, actual RAM on each of the cloud computing instances **340***a*, **340***b*, **340***n* with local storage **330**, **334**, **338** may be used as NVRAM, thereby decreasing network utilization costs that would be associated with using an EBS volume as the NVRAM. In yet another embodiment, high performance block storage resources such as one or more Azure Ultra Disks may be utilized as the NVRAM.

[0158] The storage controller applications **324**, **326** may be used to perform various tasks such as deduplicating the data contained in the request, compressing the data contained in the request, determining where to the write the data contained in the request, and so on, before ultimately sending a request to write a deduplicated, encrypted, or otherwise possibly updated version of the data to one or more of the cloud computing instances **340***a*, **340***b*, **340***n* with local storage **330**, **334**, **338**. Either cloud computing instance **320**, **322**, in some embodiments, may receive a request to read data from the cloud-based storage system **318** and may ultimately send a request to read data to one or more of the cloud computing instances **340***a*, **340***b*, **340***n* with local storage **330**, **334**, **338**.

[0159] When a request to write data is received by a particular cloud computing instance **340***a*, **340***b*, **340***n* with local storage **330**, **334**, **338**, the software daemon **328**, **332**, **336** may be configured to not only write the data to its own local storage **330**, **334**, **338** resources and any appropriate block storage **342**, **344**, **346** resources, but the software daemon **328**, **332**, **336** may also be configured to write the data to cloud-based object storage **348** that is attached to the particular cloud computing instance **340***a*, **340***b*, **340***n*. The cloud-based object storage **348** that is attached to the particular cloud computing instance **340***a*, **340***b*, **340***n* may be embodied, for example, as Amazon Simple Storage Service ('S3'). In other embodiments, the cloud computing instances **320**, **322** that each include the storage controller application **324**, **326** may initiate the storage of the data in the local storage **330**, **334**, **338** of the cloud computing instances **340***a*, **340***b*, **340***n* and the cloud-based object storage **348**. In other embodiments, rather than using both the cloud computing instances **340***a*, **340***b*, **340***n* with local storage **330**, **334**, **338** (also referred to herein as 'virtual drives') and the cloud-based object storage **348** to store data, a persistent storage layer may be implemented in other ways. For example, one or more Azure Ultra disks may be used to persistently store data (e.g., after the data has been written to the NVRAM layer).

[0160] While the local storage **330**, **334**, **338** resources and the block storage **342**, **344**, **346** resources that are utilized by the cloud computing instances **340***a*, **340***b*, **340***n* may support block-level access, the cloud-based object storage **348** that is attached to the particular cloud computing instance **340***a*, **340***b*, **340***n* supports only object-based access. The software daemon **328**, **332**, **336** may therefore be configured to take blocks of data, package those blocks into objects, and write the objects to the cloud-based object storage **348** that is attached to the particular cloud computing instance **340***a*, **340***b*, **340***n*.

[0161] Consider an example in which data is written to the local storage **330**, **334**, **338** resources and the block storage **342**, **344**, **346** resources that are utilized by the cloud computing instances **340***a*, **340***b*, **340***n* in 1 MB blocks. In such an example, assume that a user of the cloud-based storage system **318** issues a request to write data that, after being compressed and deduplicated by the storage controller application **324**, **326** results in the need to write 5 MB of data. In such an example, writing the data to the local storage **330**, **334**, **338** resources and the block storage **342**, **344**, **346** resources that are utilized by the cloud computing instances **340***a*, **340***b*, **340***n* is relatively straightforward as 5 blocks that are 1 MB in size are written to the local storage **330**, **334**, **338** resources and the block storage **342**, **344**, **346** resources that are utilized by the cloud computing instances **340***a*, **340***b*, **340***n*. In such an example, the software daemon **328**, **332**, **336** may also be configured to create five objects containing distinct 1 MB chunks of the data. As such, in some embodiments, each object that is written to the cloud-based object storage **348** may be identical (or nearly identical) in size. Readers will appreciate that in such an example, metadata that is associated with the data itself may be included in each object (e.g., the first 1 MB of the object is data and the remaining portion is metadata associated with the data). Readers will appreciate that the cloud-based object storage **348** may be incorporated into the cloud-based storage system **318** to increase the durability of the cloud-based storage system **318**.

[0162] In some embodiments, all data that is stored by the cloud-based storage system **318** may be stored in both: 1) the cloud-based object storage **348**, and 2) at least one of the local storage **330**, **334**, **338** resources or block storage **342**, **344**, **346** resources that are utilized by the cloud computing instances **340***a*, **340***b*, **340***n*. In such embodiments, the local storage **330**, **334**, **338** resources and block storage **342**, **344**, **346** resources that are utilized by the cloud computing instances **340***a*, **340***b*, **340***n* may effectively operate as cache that generally includes all data that is also stored in S3, such that all reads of data may be serviced by the cloud computing instances **340***a*, **340***b*, **340***n* without requiring the cloud computing instances **340***a*, **340***b*, **340***n* to access the cloud-based object storage **348**. Readers will appreciate that in other embodiments, however, all data that is stored by the cloud-based storage system **318** may be stored in the cloud-based object storage **348**, but less than all data that is stored by the cloud-based storage system **318** may be stored in at least one of the local storage **330**, **334**, **338** resources or block storage **342**, **344**, **346** resources that are utilized by the cloud computing instances **340***a*, **340***b*, **340***n*. In such an example, various policies may be utilized to determine which subset of the data that is stored by the cloud-based storage system **318** should reside in both: 1) the cloud-based object storage **348**, and 2) at least one of the local storage **330**, **334**, **338** resources or block storage **342**, **344**, **346** resources that are utilized by the cloud computing instances **340***a*, **340***b*, **340***n*.

[0163] One or more modules of computer program instructions that are executing within the cloud-based storage system **318** (e.g., a monitoring module that is executing on its own EC2 instance) may be designed to handle the failure of one or more of the cloud computing instances **340***a*, **340***b*, **340***n* with local storage **330**, **334**, **338**. In such an example, the monitoring module may handle the failure of one or more of the cloud computing instances **340***a*, **340***b*, **340***n* with local storage **330**, **334**, **338** by creating one or more new cloud computing instances with local storage, retrieving data that was stored on the failed cloud computing instances **340***a*, **340***b*, **340***n* from the cloud-based object storage **348**, and storing the data retrieved from the cloud-based object storage **348** in local storage on the newly created cloud computing instances. Readers will appreciate that many variants of this process may be implemented.

[0164] Readers will appreciate that various performance aspects of the cloud-based storage system **318** may be monitored (e.g., by a monitoring module that is executing in an EC2 instance) such that the cloud-based storage system **318** can be scaled-up or scaled-out as needed. For example, if the cloud computing instances **320**, **322** that are used to support the execution of a storage controller application **324**, **326** are undersized and not sufficiently servicing the I/O requests that are issued by users of the cloud-based storage system **318**, a monitoring module may create a new, more powerful cloud computing instance (e.g., a cloud computing instance of a type that includes more processing power, more memory, etc. . . .) that includes the storage controller application such that the new, more powerful cloud computing instance can begin operating as the primary controller. Likewise, if the monitoring module determines that the cloud computing instances **320**, **322** that are used to support the execution of a storage controller application **324**, **326** are oversized and that cost savings could be gained by switching to a smaller, less powerful cloud computing instance, the monitoring module may create a new, less powerful (and less expensive) cloud computing instance that includes the storage controller application such that the new, less powerful cloud computing instance can begin operating as the primary controller.

[0165] The storage systems described above may carry out intelligent data backup techniques through which data stored in the storage system may be copied and stored in a distinct location to avoid data loss in the event of equipment failure or some other form of catastrophe. For example, the storage systems described above may be configured to examine each backup to avoid restoring the storage system to an undesirable state. Consider an example in which malware infects the storage system. In such an example, the storage system may include software resources **314** that can scan each backup to identify backups that were captured before the malware infected the storage system and those backups that were captured after the malware infected the storage system. In such an example, the storage system may restore itself from a backup that does not include the malware—or at least not restore the portions of a backup that contained the malware. In such an example, the storage system may include software resources **314** that can scan each backup to identify the presences of malware (or a virus, or some other undesirable), for example, by identifying write operations that were serviced by the storage system and originated from a network subnet that is suspected to have delivered the malware, by identifying write operations that were serviced by the storage system and originated from a user that is suspected to have delivered the malware, by identifying write operations that were serviced by the storage system and examining the content of the write operation against fingerprints of the malware, and in many other ways.

[0166] Readers will further appreciate that the backups (often in the form of one or more snapshots) may also be utilized to perform rapid recovery of the storage system. Consider an example in which the storage system is infected with ransomware that locks users out of the storage system. In such an example, software resources **314** within the storage system may be configured to detect the presence of ransomware and may be further configured to restore the storage system to a point-in-time, using the retained backups, prior to the point-in-time at which the ransomware infected the storage system. In such an example, the presence of ransomware may be explicitly detected through the use of software tools utilized by the system, through the use of a key (e.g., a USB drive) that is inserted into the storage system, or in a similar way. Likewise, the presence of ransomware may be inferred in response to system activity meeting a predetermined fingerprint such as, for example, no reads or writes coming into the system for a predetermined period of time.

[0167] Readers will appreciate that the various components described above may be grouped into one or more optimized computing packages as converged infrastructures. Such converged infrastructures may include pools of computers, storage and networking resources that can be shared by multiple applications and managed in a collective manner using policy-driven processes. Such converged infrastructures may be implemented with a converged infrastructure reference architecture, with standalone appliances, with a software driven hyper-converged approach (e.g., hyper-converged infrastructures), or in other ways.

[0168] Readers will appreciate that the storage systems described in this disclosure may be useful for supporting various types of software applications. In fact, the storage systems may be ‘application aware’ in the sense that the storage systems may obtain, maintain, or otherwise have access to information describing connected applications (e.g., applications that utilize the storage systems) to optimize the operation of the storage system based on intelligence about the applications and their utilization patterns. For example, the storage system may optimize data layouts, optimize caching behaviors, optimize ‘QoS’ levels, or perform some other optimization that is designed to improve the storage performance that is experienced by the application.

[0169] As an example of one type of application that may be supported by the storage systems describe herein, the storage system **306** may be useful in supporting artificial intelligence (‘AI’) applications, database applications, XOps projects (e.g., DevOps projects, DataOps projects, MLOps projects, ModelOps projects, PlatformOps projects), electronic design automation tools, event-driven software applications, high performance computing applications, simulation applications, high-speed data capture and analysis applications, machine learning applications, media production applications, media serving applications, picture archiving and communication systems (‘PACS’) applications, software development applications, virtual reality applications, augmented reality applications, and many other types of applications by providing storage resources to such applications.

[0170] In view of the fact that the storage systems include compute resources, storage resources, and a wide variety of other resources, the storage systems may be well suited to support applications that are resource intensive such as, for example, AI applications. AI applications may be deployed in a variety of fields, including: predictive maintenance in manufacturing and related fields, healthcare applications such as patient data & risk analytics, retail and marketing deployments (e.g., search advertising, social media advertising), supply chains solutions, fintech solutions such as business analytics & reporting tools, operational deployments such as real-time analytics tools, application performance management tools, IT infrastructure management tools, and many others.

[0171] Such AI applications may enable devices to perceive their environment and take actions that maximize their chance of success at some goal. Examples of such AI applications can include IBM Watson™, Microsoft Oxford™, Google DeepMind™, Baidu Minwa™, and others.
[0172] The storage systems described above may also be well suited to support other types of applications that are resource intensive such as, for example, machine learning applications. Machine learning applications may perform various types of data analysis to automate analytical model building. Using algorithms that iteratively learn from data, machine learning applications can enable computers to learn without being explicitly programmed. One particular area of machine learning is referred to as reinforcement learning, which involves taking suitable actions to maximize reward in a particular situation.
[0173] In addition to the resources already described, the storage systems described above may also include graphics processing units (‘GPUs’), occasionally referred to as visual processing unit (‘VPUs’). Such GPUs may be embodied as specialized electronic circuits that rapidly manipulate and alter memory to accelerate the creation of images in a frame buffer intended for output to a display device. Such GPUs may be included within any of the computing devices that are part of the storage systems described above, including as one of many individually scalable components of a storage system, where other examples of individually scalable components of such storage system can include storage components, memory components, compute components (e.g., CPUs, FPGAs, ASICs), networking components, software components, and others. In addition to GPUs, the storage systems described above may also include neural network processors (‘NNPs’) for use in various aspects of neural network processing. Such NNPs may be used in place of (or in addition to) GPUs and may also be independently scalable.
[0174] As described above, the storage systems described herein may be configured to support artificial intelligence applications, machine learning applications, big data analytics applications, and many other types of applications. The rapid growth in these sort of applications is being driven by three technologies: deep learning (DL), GPU processors, and Big Data. Deep learning is a computing model that makes use of massively parallel neural networks inspired by the human brain. Instead of experts handcrafting software, a deep learning model writes its own software by learning from lots of examples. Such GPUs may include thousands of cores that are well-suited to run algorithms that loosely represent the parallel nature of the human brain.
[0175] Advances in deep neural networks, including the development of multi-layer neural networks, have ignited a new wave of algorithms and tools for data scientists to tap into their data with artificial intelligence (AI). With improved algorithms, larger data sets, and various frameworks (including open-source software libraries for machine learning across a range of tasks), data scientists are tackling new use cases like autonomous driving vehicles, natural language processing and understanding, computer vision, machine reasoning, strong AI, and many others. Applications of such techniques may include: machine and vehicular object detection, identification and avoidance; visual recognition, classification and tagging; algorithmic financial trading strategy performance management; simultaneous localization and mapping; predictive maintenance of high-value machinery; prevention against cyber security threats, expertise automation; image recognition and classification; question answering; robotics; text analytics (extraction, classification) and text generation and translation; and many others. Applications of AI techniques has materialized in a wide array of products include, for example, Amazon Echo's speech recognition technology that allows users to talk to their machines, Google Translate™ which allows for machine-based language translation, Spotify's Discover Weekly that provides recommendations on new songs and artists that a user may like based on the user's usage and traffic analysis, Quill's text generation offering that takes structured data and turns it into narrative stories, Chatbots that provide real-time, contextually specific answers to questions in a dialog format, and many others.
[0176] Data is the heart of modem AI and deep learning algorithms. Before training can begin, one

problem that must be addressed revolves around collecting the labeled data that is crucial for training an accurate AI model. A full scale AI deployment may be required to continuously collect, clean, transform, label, and store large amounts of data. Adding additional high quality data points directly translates to more accurate models and better insights. Data samples may undergo a series of processing steps including, but not limited to: 1) ingesting the data from an external source into the training system and storing the data in raw form, 2) cleaning and transforming the data in a format convenient for training, including linking data samples to the appropriate label, 3) exploring parameters and models, quickly testing with a smaller dataset, and iterating to converge on the most promising models to push into the production cluster, 4) executing training phases to select random batches of input data, including both new and older samples, and feeding those into production GPU servers for computation to update model parameters, and 5) evaluating including using a holdback portion of the data not used in training in order to evaluate model accuracy on the holdout data. This lifecycle may apply for any type of parallelized machine learning, not just neural networks or deep learning. For example, standard machine learning frameworks may rely on CPUs instead of GPUs but the data ingest and training workflows may be the same. Readers will appreciate that a single shared storage data hub creates a coordination point throughout the lifecycle without the need for extra data copies among the ingest, preprocessing, and training stages. Rarely is the ingested data used for only one purpose, and shared storage gives the flexibility to train multiple different models or apply traditional analytics to the data.

[0177] Readers will appreciate that each stage in the AI data pipeline may have varying requirements from the data hub (e.g., the storage system or collection of storage systems). Scale-out storage systems must deliver uncompromising performance for all manner of access types and patterns—from small, metadata-heavy to large files, from random to sequential access patterns, and from low to high concurrency. The storage systems described above may serve as an ideal AI data hub as the systems may service unstructured workloads. In the first stage, data is ideally ingested and stored on to the same data hub that following stages will use, in order to avoid excess data copying. The next two steps can be done on a standard compute server that optionally includes a GPU, and then in the fourth and last stage, full training production jobs are run on powerful GPU-accelerated servers. Often, there is a production pipeline alongside an experimental pipeline operating on the same dataset. Further, the GPU-accelerated servers can be used independently for different models or joined together to train on one larger model, even spanning multiple systems for distributed training. If the shared storage tier is slow, then data must be copied to local storage for each phase, resulting in wasted time staging data onto different servers. The ideal data hub for the AI training pipeline delivers performance similar to data stored locally on the server node while also having the simplicity and performance to enable all pipeline stages to operate concurrently.

[0178] In order for the storage systems described above to serve as a data hub or as part of an AI deployment, in some embodiments the storage systems may be configured to provide DMA between storage devices that are included in the storage systems and one or more GPUs that are used in an AI or big data analytics pipeline. The one or more GPUs may be coupled to the storage system, for example, via NVMe-over-Fabrics (‘NVMe-oF’) such that bottlenecks such as the host CPU can be bypassed and the storage system (or one of the components contained therein) can directly access GPU memory. In such an example, the storage systems may leverage API hooks to the GPUs to transfer data directly to the GPUs. For example, the GPUs may be embodied as Nvidia™ GPUs and the storage systems may support GPUDirect Storage (‘GDS’) software, or have similar proprietary software, that enables the storage system to transfer data to the GPUs via RDMA or similar mechanism.

[0179] Although the preceding paragraphs discuss deep learning applications, readers will appreciate that the storage systems described herein may also be part of a distributed deep learning (‘DDL’) platform to support the execution of DDL algorithms. The storage systems described above may also be paired with other technologies such as TensorFlow, an open-source software

library for dataflow programming across a range of tasks that may be used for machine learning applications such as neural networks, to facilitate the development of such machine learning models, applications, and so on.
[0180] The storage systems described above may also be used in a neuromorphic computing environment. Neuromorphic computing is a form of computing that mimics brain cells. To support neuromorphic computing, an architecture of interconnected “neurons” replace traditional computing models with low-powered signals that go directly between neurons for more efficient computation. Neuromorphic computing may make use of very-large-scale integration (VLSI) systems containing electronic analog circuits to mimic neuro-biological architectures present in the nervous system, as well as analog, digital, mixed-mode analog/digital VLSI, and software systems that implement models of neural systems for perception, motor control, or multisensory integration.
[0181] Readers will appreciate that the storage systems described above may be configured to support the storage or use of (among other types of data) blockchains and derivative items such as, for example, open source blockchains and related tools that are part of the IBM™ Hyperledger project, permissioned blockchains in which a certain number of trusted parties are allowed to access the block chain, blockchain products that enable developers to build their own distributed ledger projects, and others. Blockchains and the storage systems described herein may be leveraged to support on-chain storage of data as well as off-chain storage of data.
[0182] Off-chain storage of data can be implemented in a variety of ways and can occur when the data itself is not stored within the blockchain. For example, in one embodiment, a hash function may be utilized and the data itself may be fed into the hash function to generate a hash value. In such an example, the hashes of large pieces of data may be embedded within transactions, instead of the data itself. Readers will appreciate that, in other embodiments, alternatives to blockchains may be used to facilitate the decentralized storage of information. For example, one alternative to a blockchain that may be used is a blockweave. While conventional blockchains store every transaction to achieve validation, a blockweave permits secure decentralization without the usage of the entire chain, thereby enabling low cost on-chain storage of data. Such blockweaves may utilize a consensus mechanism that is based on proof of access (PoA) and proof of work (PoW).
[0183] The storage systems described above may, either alone or in combination with other computing devices, be used to support in-memory computing applications. In-memory computing involves the storage of information in RAM that is distributed across a cluster of computers. Readers will appreciate that the storage systems described above, especially those that are configurable with customizable amounts of processing resources, storage resources, and memory resources (e.g., those systems in which blades that contain configurable amounts of each type of resource), may be configured in a way so as to provide an infrastructure that can support in-memory computing. Likewise, the storage systems described above may include component parts (e.g., NVDIMMs, 3D crosspoint storage that provide fast random access memory that is persistent) that can actually provide for an improved in-memory computing environment as compared to in-memory computing environments that rely on RAM distributed across dedicated servers.
[0184] In some embodiments, the storage systems described above may be configured to operate as a hybrid in-memory computing environment that includes a universal interface to all storage media (e.g., RAM, flash storage, 3D crosspoint storage). In such embodiments, users may have no knowledge regarding the details of where their data is stored but they can still use the same full, unified API to address data. In such embodiments, the storage system may (in the background) move data to the fastest layer available—including intelligently placing the data in dependence upon various characteristics of the data or in dependence upon some other heuristic. In such an example, the storage systems may even make use of existing products such as Apache Ignite and GridGain to move data between the various storage layers, or the storage systems may make use of custom software to move data between the various storage layers. The storage systems described herein may implement various optimizations to improve the performance of in-memory computing

such as, for example, having computations occur as close to the data as possible.

[0185] Readers will further appreciate that in some embodiments, the storage systems described above may be paired with other resources to support the applications described above. For example, one infrastructure could include primary compute in the form of servers and workstations which specialize in using General-purpose computing on graphics processing units ('GPGPU') to accelerate deep learning applications that are interconnected into a computation engine to train parameters for deep neural networks. Each system may have Ethernet external connectivity, InfiniBand external connectivity, some other form of external connectivity, or some combination thereof. In such an example, the GPUs can be grouped for a single large training or used independently to train multiple models. The infrastructure could also include a storage system such as those described above to provide, for example, a scale-out all-flash file or object store through which data can be accessed via high-performance protocols such as NFS, S3, and so on. The infrastructure can also include, for example, redundant top-of-rack Ethernet switches connected to storage and compute via ports in MLAG port channels for redundancy. The infrastructure could also include additional compute in the form of whitebox servers, optionally with GPUs, for data ingestion, pre-processing, and model debugging. Readers will appreciate that additional infrastructures are also be possible.

[0186] Readers will appreciate that the storage systems described above, either alone or in coordination with other computing machinery may be configured to support other AI related tools. For example, the storage systems may make use of tools like ONXX or other open neural network exchange formats that make it easier to transfer models written in different AI frameworks. Likewise, the storage systems may be configured to support tools like Amazon's Gluon that allow developers to prototype, build, and train deep learning models. In fact, the storage systems described above may be part of a larger platform, such as IBM™ Cloud Private for Data, that includes integrated data science, data engineering and application building services.

[0187] Readers will further appreciate that the storage systems described above may also be deployed as an edge solution. Such an edge solution may be in place to optimize cloud computing systems by performing data processing at the edge of the network, near the source of the data. Edge computing can push applications, data and computing power (i.e., services) away from centralized points to the logical extremes of a network. Through the use of edge solutions such as the storage systems described above, computational tasks may be performed using the compute resources provided by such storage systems, data may be storage using the storage resources of the storage system, and cloud-based services may be accessed through the use of various resources of the storage system (including networking resources). By performing computational tasks on the edge solution, storing data on the edge solution, and generally making use of the edge solution, the consumption of expensive cloud-based resources may be avoided and, in fact, performance improvements may be experienced relative to a heavier reliance on cloud-based resources.

[0188] While many tasks may benefit from the utilization of an edge solution, some particular uses may be especially suited for deployment in such an environment. For example, devices like drones, autonomous cars, robots, and others may require extremely rapid processing—so fast, in fact, that sending data up to a cloud environment and back to receive data processing support may simply be too slow. As an additional example, some IoT devices such as connected video cameras may not be well-suited for the utilization of cloud-based resources as it may be impractical (not only from a privacy perspective, security perspective, or a financial perspective) to send the data to the cloud simply because of the pure volume of data that is involved. As such, many tasks that really on data processing, storage, or communications may be better suited by platforms that include edge solutions such as the storage systems described above.

[0189] The storage systems described above may alone, or in combination with other computing resources, serves as a network edge platform that combines compute resources, storage resources, networking resources, cloud technologies and network virtualization technologies, and so on. As part of the network, the edge may take on characteristics similar to other network facilities, from the customer premise and backhaul aggregation facilities to Points of Presence (PoPs) and regional data centers. Readers will appreciate that network workloads, such as Virtual Network Functions (VNFs) and others, will reside on the network edge platform. Enabled by a combination of containers and virtual machines, the network edge platform may rely on controllers and schedulers that are no longer geographically co-located with the data processing resources. The functions, as microservices, may split into control planes, user and data planes, or even state machines, allowing for independent optimization and scaling techniques to be applied. Such user and data planes may be enabled through increased accelerators, both those residing in server platforms, such as FPGAs and Smart NICs, and through SDN-enabled merchant silicon and programmable ASICs.

[0190] The storage systems described above may also be optimized for use in big data analytics, including being leveraged as part of a composable data analytics pipeline where containerized analytics architectures, for example, make analytics capabilities more composable. Big data analytics may be generally described as the process of examining large and varied data sets to uncover hidden patterns, unknown correlations, market trends, customer preferences and other useful information that can help organizations make more-informed business decisions. As part of that process, semi-structured and unstructured data such as, for example, internet clickstream data, web server logs, social media content, text from customer emails and survey responses, mobile-phone call-detail records, IoT sensor data, and other data may be converted to a structured form.

[0191] The storage systems described above may also support (including implementing as a system interface) applications that perform tasks in response to human speech. For example, the storage systems may support the execution intelligent personal assistant applications such as, for example, Amazon's Alexa™, Apple Siri™, Google Voice™, Samsung Bixby™, Microsoft Cortana™, and others. While the examples described in the previous sentence make use of voice as input, the storage systems described above may also support chatbots, talkbots, chatterbots, or artificial conversational entities or other applications that are configured to conduct a conversation via auditory or textual methods. Likewise, the storage system may actually execute such an application to enable a user such as a system administrator to interact with the storage system via speech. Such applications are generally capable of voice interaction, music playback, making to-do lists, setting alarms, streaming podcasts, playing audiobooks, and providing weather, traffic, and other real time information, such as news, although in embodiments in accordance with the present disclosure, such applications may be utilized as interfaces to various system management operations.

[0192] The storage systems described above may also implement AI platforms for delivering on the vision of self-driving storage. Such AI platforms may be configured to deliver global predictive intelligence by collecting and analyzing large amounts of storage system telemetry data points to enable effortless management, analytics and support. In fact, such storage systems may be capable of predicting both capacity and performance, as well as generating intelligent advice on workload deployment, interaction and optimization. Such AI platforms may be configured to scan all incoming storage system telemetry data against a library of issue fingerprints to predict and resolve incidents in real-time, before they impact customer environments, and captures hundreds of variables related to performance that are used to forecast performance load.

[0193] The storage systems described above may support the serialized or simultaneous execution of artificial intelligence applications, machine learning applications, data analytics applications, data transformations, and other tasks that collectively may form an AI ladder. Such an AI ladder may effectively be formed by combining such elements to form a complete data science pipeline, where exist dependencies between elements of the AI ladder. For example, AI may require that some form of machine learning has taken place, machine learning may require that some form of analytics has taken place, analytics may require that some form of data and information architecting has taken place, and so on. As such, each element may be viewed as a rung in an AI ladder that collectively can form a complete and sophisticated AI solution.

[0194] The storage systems described above may also, either alone or in combination with other computing environments, be used to deliver an AI everywhere experience where AI permeates wide and expansive aspects of business and life. For example, AI may play an important role in the delivery of deep learning solutions, deep reinforcement learning solutions, artificial general intelligence solutions, autonomous vehicles, cognitive computing solutions, commercial UAVs or drones, conversational user interfaces, enterprise taxonomies, ontology management solutions, machine learning solutions, smart dust, smart robots, smart workplaces, and many others.
[0195] The storage systems described above may also, either alone or in combination with other computing environments, be used to deliver a wide range of transparently immersive experiences (including those that use digital twins of various “things” such as people, places, processes, systems, and so on) where technology can introduce transparency between people, businesses, and things. Such transparently immersive experiences may be delivered as augmented reality technologies, connected homes, virtual reality technologies, brain-computer interfaces, human augmentation technologies, nanotube electronics, volumetric displays, 4D printing technologies, or others.
[0196] The storage systems described above may also, either alone or in combination with other computing environments, be used to support a wide variety of digital platforms. Such digital platforms can include, for example, 5G wireless systems and platforms, digital twin platforms, edge computing platforms, IoT platforms, quantum computing platforms, serverless PaaS, software-defined security, neuromorphic computing platforms, and so on.
[0197] The storage systems described above may also be part of a multi-cloud environment in which multiple cloud computing and storage services are deployed in a single heterogeneous architecture. In order to facilitate the operation of such a multi-cloud environment, DevOps tools may be deployed to enable orchestration across clouds. Likewise, continuous development and continuous integration tools may be deployed to standardize processes around continuous integration and delivery, new feature rollout and provisioning cloud workloads. By standardizing these processes, a multi-cloud strategy may be implemented that enables the utilization of the best provider for each workload.
[0198] The storage systems described above may be used as a part of a platform to enable the use of crypto-anchors that may be used to authenticate a product's origins and contents to ensure that it matches a blockchain record associated with the product. Similarly, as part of a suite of tools to secure data stored on the storage system, the storage systems described above may implement various encryption technologies and schemes, including lattice cryptography. Lattice cryptography can involve constructions of cryptographic primitives that involve lattices, either in the construction itself or in the security proof. Unlike public-key schemes such as the RSA, Diffie-Hellman or Elliptic-Curve cryptosystems, which are easily attacked by a quantum computer, some lattice-based constructions appear to be resistant to attack by both classical and quantum computers.
[0199] A quantum computer is a device that performs quantum computing. Quantum computing is computing using quantum-mechanical phenomena, such as superposition and entanglement. Quantum computers differ from traditional computers that are based on transistors, as such traditional computers require that data be encoded into binary digits (bits), each of which is always in one of two definite states (0 or 1). In contrast to traditional computers, quantum computers use quantum bits, which can be in superpositions of states. A quantum computer maintains a sequence of qubits, where a single qubit can represent a one, a zero, or any quantum superposition of those two qubit states. A pair of qubits can be in any quantum superposition of 4 states, and three qubits in any superposition of 8 states. A quantum computer with n qubits can generally be in an arbitrary superposition of up to 2{circumflex over ( )}n different states simultaneously, whereas a traditional computer can only be in one of these states at any one time. A quantum Turing machine is a theoretical model of such a computer.

[0200] The storage systems described above may also be paired with FPGA-accelerated servers as part of a larger AI or ML infrastructure. Such FPGA-accelerated servers may reside near (e.g., in the same data center) the storage systems described above or even incorporated into an appliance that includes one or more storage systems, one or more FPGA-accelerated servers, networking infrastructure that supports communications between the one or more storage systems and the one or more FPGA-accelerated servers, as well as other hardware and software components. Alternatively, FPGA-accelerated servers may reside within a cloud computing environment that may be used to perform compute-related tasks for AI and ML jobs. Any of the embodiments described above may be used to collectively serve as a FPGA-based AI or ML platform. Readers will appreciate that, in some embodiments of the FPGA-based AI or ML platform, the FPGAs that are contained within the FPGA-accelerated servers may be reconfigured for different types of ML models (e.g., LSTMs, CNNs, GRUs). The ability to reconfigure the FPGAs that are contained within the FPGA-accelerated servers may enable the acceleration of a ML or AI application based on the most optimal numerical precision and memory model being used. Readers will appreciate that by treating the collection of FPGA-accelerated servers as a pool of FPGAs, any CPU in the data center may utilize the pool of FPGAs as a shared hardware microservice, rather than limiting a server to dedicated accelerators plugged into it.
[0201] The FPGA-accelerated servers and the GPU-accelerated servers described above may implement a model of computing where, rather than keeping a small amount of data in a CPU and running a long stream of instructions over it as occurred in more traditional computing models, the machine learning model and parameters are pinned into the high-bandwidth on-chip memory with lots of data streaming though the high-bandwidth on-chip memory. FPGAs may even be more efficient than GPUs for this computing model, as the FPGAs can be programmed with only the instructions needed to run this kind of computing model.
[0202] The storage systems described above may be configured to provide parallel storage, for example, through the use of a parallel file system such as BeeGFS. Such parallel files systems may include a distributed metadata architecture. For example, the parallel file system may include a plurality of metadata servers across which metadata is distributed, as well as components that include services for clients and storage servers.
[0203] The systems described above can support the execution of a wide array of software applications. Such software applications can be deployed in a variety of ways, including container-based deployment models. Containerized applications may be managed using a variety of tools. For example, containerized applications may be managed using Docker Swarm, Kubernetes, and others. Containerized applications may be used to facilitate a serverless, cloud native computing deployment and management model for software applications. In support of a serverless, cloud native computing deployment and management model for software applications, containers may be used as part of an event handling mechanisms (e.g., AWS Lambdas) such that various events cause a containerized application to be spun up to operate as an event handler.
[0204] The systems described above may be deployed in a variety of ways, including being deployed in ways that support fifth generation ('5G') networks. 5G networks may support substantially faster data communications than previous generations of mobile communications networks and, as a consequence may lead to the disaggregation of data and computing resources as modem massive data centers may become less prominent and may be replaced, for example, by more-local, micro data centers that are close to the mobile-network towers. The systems described above may be included in such local, micro data centers and may be part of or paired to multi-access edge computing ('MEC') systems. Such MEC systems may enable cloud computing capabilities and an IT service environment at the edge of the cellular network. By running applications and performing related processing tasks closer to the cellular customer, network congestion may be reduced and applications may perform better.
[0205] The storage systems described above may also be configured to implement NVMe Zoned

Namespaces. Through the use of NVMe Zoned Namespaces, the logical address space of a namespace is divided into zones. Each zone provides a logical block address range that must be written sequentially and explicitly reset before rewriting, thereby enabling the creation of namespaces that expose the natural boundaries of the device and offload management of internal mapping tables to the host. In order to implement NVMe Zoned Name Spaces (‘ZNS’), ZNS SSDs or some other form of zoned block devices may be utilized that expose a namespace logical address space using zones. With the zones aligned to the internal physical properties of the device, several inefficiencies in the placement of data can be eliminated. In such embodiments, each zone may be mapped, for example, to a separate application such that functions like wear levelling and garbage collection could be performed on a per-zone or per-application basis rather than across the entire device. In order to support ZNS, the storage controllers described herein may be configured with to interact with zoned block devices through the usage of, for example, the Linux™ kernel zoned block device interface or other tools.

[0206] The storage systems described above may also be configured to implement zoned storage in other ways such as, for example, through the usage of shingled magnetic recording (SMR) storage devices. In examples where zoned storage is used, device-managed embodiments may be deployed where the storage devices hide this complexity by managing it in the firmware, presenting an interface like any other storage device. Alternatively, zoned storage may be implemented via a host-managed embodiment that depends on the operating system to know how to handle the drive, and only write sequentially to certain regions of the drive. Zoned storage may similarly be implemented using a host-aware embodiment in which a combination of a drive managed and host managed implementation is deployed.

[0207] The storage systems described herein may be used to form a data lake. A data lake may operate as the first place that an organization's data flows to, where such data may be in a raw format. Metadata tagging may be implemented to facilitate searches of data elements in the data lake, especially in embodiments where the data lake contains multiple stores of data, in formats not easily accessible or readable (e.g., unstructured data, semi-structured data, structured data). From the data lake, data may go downstream to a data warehouse where data may be stored in a more processed, packaged, and consumable format. The storage systems described above may also be used to implement such a data warehouse. In addition, a data mart or data hub may allow for data that is even more easily consumed, where the storage systems described above may also be used to provide the underlying storage resources necessary for a data mart or data hub. In embodiments, queries the data lake may require a schema-on-read approach, where data is applied to a plan or schema as it is pulled out of a stored location, rather than as it goes into the stored location.

[0208] The storage systems described herein may also be configured implement a recovery point objective (‘RPO’), which may be establish by a user, established by an administrator, established as a system default, established as part of a storage class or service that the storage system is participating in the delivery of, or in some other way. A “recovery point objective” is a goal for the maximum time difference between the last update to a source dataset and the last recoverable replicated dataset update that would be correctly recoverable, given a reason to do so, from a continuously or frequently updated copy of the source dataset. An update is correctly recoverable if it properly takes into account all updates that were processed on the source dataset prior to the last recoverable replicated dataset update.

[0209] In synchronous replication, the RPO would be zero, meaning that under normal operation, all completed updates on the source dataset should be present and correctly recoverable on the copy dataset. In best effort nearly synchronous replication, the RPO can be as low as a few seconds. In snapshot-based replication, the RPO can be roughly calculated as the interval between snapshots plus the time to transfer the modifications between a previous already transferred snapshot and the most recent to-be-replicated snapshot.

[0210] If updates accumulate faster than they are replicated, then an RPO can be missed. If more data to be replicated accumulates between two snapshots, for snapshot-based replication, than can be replicated between taking the snapshot and replicating that snapshot's cumulative updates to the copy, then the RPO can be missed. If, again in snapshot-based replication, data to be replicated accumulates at a faster rate than could be transferred in the time between subsequent snapshots, then replication can start to fall further behind which can extend the miss between the expected recovery point objective and the actual recovery point that is represented by the last correctly replicated update.

[0211] The storage systems described above may also be part of a shared nothing storage cluster. In a shared nothing storage cluster, each node of the cluster has local storage and communicates with other nodes in the cluster through networks, where the storage used by the cluster is (in general) provided only by the storage connected to each individual node. A collection of nodes that are synchronously replicating a dataset may be one example of a shared nothing storage cluster, as each storage system has local storage and communicates to other storage systems through a network, where those storage systems do not (in general) use storage from somewhere else that they share access to through some kind of interconnect. In contrast, some of the storage systems described above are themselves built as a shared-storage cluster, since there are drive shelves that are shared by the paired controllers. Other storage systems described above, however, are built as a shared nothing storage cluster, as all storage is local to a particular node (e.g., a blade) and all communication is through networks that link the compute nodes together.

[0212] In other embodiments, other forms of a shared nothing storage cluster can include embodiments where any node in the cluster has a local copy of all storage they need, and where data is mirrored through a synchronous style of replication to other nodes in the cluster either to ensure that the data isn't lost or because other nodes are also using that storage. In such an embodiment, if a new cluster node needs some data, that data can be copied to the new node from other nodes that have copies of the data.

[0213] In some embodiments, mirror-copy-based shared storage clusters may store multiple copies of all the cluster's stored data, with each subset of data replicated to a particular set of nodes, and different subsets of data replicated to different sets of nodes. In some variations, embodiments may store all of the cluster's stored data in all nodes, whereas in other variations nodes may be divided up such that a first set of nodes will all store the same set of data and a second, different set of nodes will all store a different set of data.

[0214] Readers will appreciate that RAFT-based databases (e.g., etcd) may operate like shared-nothing storage clusters where all RAFT nodes store all data. The amount of data stored in a RAFT cluster, however, may be limited so that extra copies don't consume too much storage. A container server cluster might also be able to replicate all data to all cluster nodes, presuming the containers don't tend to be too large and their bulk data (the data manipulated by the applications that run in the containers) is stored elsewhere such as in an S3 cluster or an external file server. In such an example, the container storage may be provided by the cluster directly through its shared-nothing storage model, with those containers providing the images that form the execution environment for parts of an application or service.

[0215] For further explanation, FIG. **3**D illustrates an exemplary computing device **350** that may be specifically configured to perform one or more of the processes described herein. As shown in FIG. **3**D, computing device **350** may include a communication interface **352**, a processor **354**, a storage device **356**, and an input/output ("I/O") module **358** communicatively connected one to another via a communication infrastructure **360**. While an exemplary computing device **350** is shown in FIG. **3**D, the components illustrated in FIG. **3**D are not intended to be limiting. Additional or alternative components may be used in other embodiments. Components of computing device **350** shown in FIG. **3**D will now be described in additional detail.

[0216] Communication interface **352** may be configured to communicate with one or more computing devices. Examples of communication interface **352** include, without limitation, a wired network interface (such as a network interface card), a wireless network interface (such as a wireless network interface card), a modem, an audio/video connection, and any other suitable interface.

[0217] Processor **354** generally represents any type or form of processing unit capable of processing data and/or interpreting, executing, and/or directing execution of one or more of the instructions, processes, and/or operations described herein. Processor **354** may perform operations by executing computer-executable instructions **362** (e.g., an application, software, code, and/or other executable data instance) stored in storage device **356**.

[0218] Storage device **356** may include one or more data storage media, devices, or configurations and may employ any type, form, and combination of data storage media and/or device. For example, storage device **356** may include, but is not limited to, any combination of the non-volatile media and/or volatile media described herein. Electronic data, including data described herein, may be temporarily and/or permanently stored in storage device **356**. For example, data representative of computer-executable instructions **362** configured to direct processor **354** to perform any of the operations described herein may be stored within storage device **356**. In some examples, data may be arranged in one or more databases residing within storage device **356**.

[0219] I/O module **358** may include one or more I/O modules configured to receive user input and provide user output. I/O module **358** may include any hardware, firmware, software, or combination thereof supportive of input and output capabilities. For example, I/O module **358** may include hardware and/or software for capturing user input, including, but not limited to, a keyboard or keypad, a touchscreen component (e.g., touchscreen display), a receiver (e.g., an RF or infrared receiver), motion sensors, and/or one or more input buttons.

[0220] I/O module **358** may include one or more devices for presenting output to a user, including, but not limited to, a graphics engine, a display (e.g., a display screen), one or more output drivers (e.g., display drivers), one or more audio speakers, and one or more audio drivers. In certain embodiments, I/O module **358** is configured to provide graphical data to a display for presentation to a user. The graphical data may be representative of one or more graphical user interfaces and/or any other graphical content as may serve a particular implementation. In some examples, any of the systems, computing devices, and/or other components described herein may be implemented by computing device **350**.

[0221] For further explanation, FIG. **3**E illustrates an example of a fleet of storage systems **376** for providing storage services (also referred to herein as 'data services'). The fleet of storage systems **376** depicted in FIG. **3** includes a plurality of storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n* that may each be similar to the storage systems described herein. The storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n* in the fleet of storage systems **376** may be embodied as identical storage systems or as different types of storage systems. For example, two of the storage systems **374***a*, **374***n* depicted in FIG. **3**E are depicted as being cloud-based storage systems, as the resources that collectively form each of the storage systems **374***a*, **374***n* are provided by distinct cloud services providers **370**, **372**. For example, the first cloud services provider **370** may be Amazon AWS™ whereas the second cloud services provider **372** is Microsoft Azure™, although in other embodiments one or more public clouds, private clouds, or combinations thereof may be used to provide the underlying resources that are used to form a particular storage system in the fleet of storage systems **376**.

[0222] The example depicted in FIG. **3**E includes an edge management service **382** for delivering storage services in accordance with some embodiments of the present disclosure. The storage services (also referred to herein as 'data services') that are delivered may include, for example, services to provide a certain amount of storage to a consumer, services to provide storage to a consumer in accordance with a predetermined service level agreement, services to provide storage to a consumer in accordance with predetermined regulatory requirements, and many others.

[0223] The edge management service **382** depicted in FIG. **3**E may be embodied, for example, as one or more modules of computer program instructions executing on computer hardware such as one or more computer processors. Alternatively, the edge management service **382** may be embodied as one or more modules of computer program instructions executing on a virtualized execution environment such as one or more virtual machines, in one or more containers, or in some other way. In other embodiments, the edge management service **382** may be embodied as a combination of the embodiments described above, including embodiments where the one or more modules of computer program instructions that are included in the edge management service **382** are distributed across multiple physical or virtual execution environments.

[0224] The edge management service **382** may operate as a gateway for providing storage services to storage consumers, where the storage services leverage storage offered by one or more storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n*. For example, the edge management service **382** may be configured to provide storage services to host devices **378***a*, **378***b*, **378***c*, **378***d*, **378***n* that are executing one or more applications that consume the storage services. In such an example, the edge management service **382** may operate as a gateway between the host devices **378***a*, **378***b*, **378***c*, **378***d*, **378***n* and the storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n*, rather than requiring that the host devices **378***a*, **378***b*, **378***c*, **378***d*, **378***n* directly access the storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n*.

[0225] The edge management service **382** of FIG. **3**E exposes a storage services module **380** to the host devices **378***a*, **378***b*, **378***c*, **378***d*, **378***n* of FIG. **3**E, although in other embodiments the edge management service **382** may expose the storage services module **380** to other consumers of the various storage services. The various storage services may be presented to consumers via one or more user interfaces, via one or more APIs, or through some other mechanism provided by the storage services module **380**. As such, the storage services module **380** depicted in FIG. **3**E may be embodied as one or more modules of computer program instructions executing on physical hardware, on a virtualized execution environment, or combinations thereof, where executing such modules causes enables a consumer of storage services to be offered, select, and access the various storage services.

[0226] The edge management service **382** of FIG. **3**E also includes a system management services module **384**. The system management services module **384** of FIG. **3**E includes one or more modules of computer program instructions that, when executed, perform various operations in coordination with the storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n* to provide storage services to the host devices **378***a*, **378***b*, **378***c*, **378***d*, **378***n*. The system management services module **384** may be configured, for example, to perform tasks such as provisioning storage resources from the storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n* via one or more APIs exposed by the storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n*, migrating datasets or workloads amongst the storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n* via one or more APIs exposed by the storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n*, setting one or more tunable parameters (i.e., one or more configurable settings) on the storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n* via one or more APIs exposed by the storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n*, and so on. For example, many of the services described below relate to embodiments where the storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n* are configured to operate in some way. In such examples, the system management services module **384** may be responsible for using APIs (or some other mechanism) provided by the storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n* to configure the storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n* to operate in the ways described below.

[0227] In addition to configuring the storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n*, the edge management service **382** itself may be configured to perform various tasks required to provide the various storage services. Consider an example in which the storage service includes a service that, when selected and applied, causes personally identifiable information ('PII') contained in a dataset to be obfuscated when the dataset is accessed. In such an example, the storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n* may be configured to obfuscate PII when servicing read requests directed to the dataset. Alternatively, the storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n* may service reads by returning data that includes the PII, but the edge management service **382** itself may obfuscate the PII as the data is passed through the edge management service **382** on its way from the storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n* to the host devices **378***a*, **378***b*, **378***c*, **378***d*, **378***n*.

[0228] The storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n* depicted in FIG. **3**E may be embodied as one or more of the storage systems described above with reference to FIGS. **1**A-**3**D, including variations thereof. In fact, the storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n* may serve as a pool of storage resources where the individual components in that pool have different performance characteristics, different storage characteristics, and so on. For example, one of the storage systems **374***a* may be a cloud-based storage system, another storage system **374***b* may be a storage system that provides block storage, another storage system **374***c* may be a storage system that provides file storage, another storage system **374***d* may be a relatively high-performance storage system while another storage system **374***n* may be a relatively low-performance storage system, and so on. In alternative embodiments, only a single storage system may be present.

[0229] The storage systems **374***a*, **374***b*, **374***c*, **374***d*, **374***n* depicted in FIG. **3**E may also be organized into different failure domains so that the failure of one storage system **374***a* should be totally unrelated to the failure of another storage system **374***b*. For example, each of the storage systems may receive power from independent power systems, each of the storage systems may be coupled for data communications over independent data communications networks, and so on. Furthermore, the storage systems in a first failure domain may be accessed via a first gateway whereas storage systems in a second failure domain may be accessed via a second gateway. For example, the first gateway may be a first instance of the edge management service **382** and the second gateway may be a second instance of the edge management service **382**, including embodiments where each instance is distinct, or each instance is part of a distributed edge management service **382**.

[0230] As an illustrative example of available storage services, storage services may be presented to a user that are associated with different levels of data protection. For example, storage services may be presented to the user that, when selected and enforced, guarantee the user that data associated with that user will be protected such that various recovery point objectives ('RPO') can be guaranteed. A first available storage service may ensure, for example, that some dataset associated with the user will be protected such that any data that is more than 5 seconds old can be recovered in the event of a failure of the primary data store whereas a second available storage service may ensure that the dataset that is associated with the user will be protected such that any data that is more than 5 minutes old can be recovered in the event of a failure of the primary data store.

[0231] An additional example of storage services that may be presented to a user, selected by a user, and ultimately applied to a dataset associated with the user can include one or more data compliance services. Such data compliance services may be embodied, for example, as services that may be provided to consumers (i.e., a user) the data compliance services to ensure that the user's datasets are managed in a way to adhere to various regulatory requirements. For example, one or more data compliance services may be offered to a user to ensure that the user's datasets are managed in a way so as to adhere to the General Data Protection Regulation ('GDPR'), one or data compliance services may be offered to a user to ensure that the user's datasets are managed in a way so as to adhere to the Sarbanes-Oxley Act of 2002 ('SOX'), or one or more data compliance services may be offered to a user to ensure that the user's datasets are managed in a way so as to adhere to some other regulatory act. In addition, the one or more data compliance services may be offered to a user to ensure that the user's datasets are managed in a way so as to adhere to some non-governmental guidance (e.g., to adhere to best practices for auditing purposes), the one or more data compliance services may be offered to a user to ensure that the user's datasets are managed in a way so as to adhere to a particular clients or organizations requirements, and so on.

[0232] Consider an example in which a particular data compliance service is designed to ensure that a user's datasets are managed in a way so as to adhere to the requirements set forth in the GDPR. While a listing of all requirements of the GDPR can be found in the regulation itself, for the purposes of illustration, an example requirement set forth in the GDPR requires that pseudonymization processes must be applied to stored data in order to transform personal data in such a way that the resulting data cannot be attributed to a specific data subject without the use of additional information. For example, data encryption techniques can be applied to render the original data unintelligible, and such data encryption techniques cannot be reversed without access to the correct decryption key. As such, the GDPR may require that the decryption key be kept separately from the pseudonymised data. One particular data compliance service may be offered to ensure adherence to the requirements set forth in this paragraph.

[0233] In order to provide this particular data compliance service, the data compliance service may be presented to a user (e.g., via a GUI) and selected by the user. In response to receiving the selection of the particular data compliance service, one or more storage services policies may be applied to a dataset associated with the user to carry out the particular data compliance service. For example, a storage services policy may be applied requiring that the dataset be encrypted prior to be stored in a storage system, prior to being stored in a cloud environment, or prior to being stored elsewhere. In order to enforce this policy, a requirement may be enforced not only requiring that the dataset be encrypted when stored, but a requirement may be put in place requiring that the dataset be encrypted prior to transmitting the dataset (e.g., sending the dataset to another party). In such an example, a storage services policy may also be put in place requiring that any encryption keys used to encrypt the dataset are not stored on the same system that stores the dataset itself. Readers will appreciate that many other forms of data compliance services may be offered and implemented in accordance with embodiments of the present disclosure.

[0234] The storage systems **374**_a_, **374**_b_, **374**_c_, **374**_d_, **374**_n_ in the fleet of storage systems **376** may be managed collectively, for example, by one or more fleet management modules. The fleet management modules may be part of or separate from the system management services module **384** depicted in FIG. **3**E. The fleet management modules may perform tasks such as monitoring the health of each storage system in the fleet, initiating updates or upgrades on one or more storage systems in the fleet, migrating workloads for loading balancing or other performance purposes, and many other tasks. As such, and for many other reasons, the storage systems **374**_a_, **374**_b_, **374**_c_, **374**_d_, **374**_n_ may be coupled to each other via one or more data communications links in order to exchange data between the storage systems **374**_a_, **374**_b_, **374**_c_, **374**_d_, **374**_n_.

[0235] The storage systems described herein may support various forms of data replication. For example, two or more of the storage systems may synchronously replicate a dataset between each other. In synchronous replication, distinct copies of a particular dataset may be maintained by multiple storage systems, but all accesses (e.g., a read) of the dataset should yield consistent results regardless of which storage system the access was directed to. For example, a read directed to any of the storage systems that are synchronously replicating the dataset should return identical results. As such, while updates to the version of the dataset need not occur at exactly the same time, precautions must be taken to ensure consistent accesses to the dataset. For example, if an update (e.g., a write) that is directed to the dataset is received by a first storage system, the update may only be acknowledged as being completed if all storage systems that are synchronously replicating the dataset have applied the update to their copies of the dataset. In such an example, synchronous replication may be carried out through the use of I/O forwarding (e.g., a write received at a first storage system is forwarded to a second storage system), communications between the storage systems (e.g., each storage system indicating that it has completed the update), or in other ways.

[0236] In other embodiments, a dataset may be replicated through the use of checkpoints. In checkpoint-based replication (also referred to as ‘nearly synchronous replication’), a set of updates to a dataset (e.g., one or more write operations directed to the dataset) may occur between different checkpoints, such that a dataset has been updated to a specific checkpoint only if all updates to the dataset prior to the specific checkpoint have been completed. Consider an example in which a first storage system stores a live copy of a dataset that is being accessed by users of the dataset. In this example, assume that the dataset is being replicated from the first storage system to a second storage system using checkpoint-based replication. For example, the first storage system may send a first checkpoint (at time t=0) to the second storage system, followed by a first set of updates to the dataset, followed by a second checkpoint (at time t=1), followed by a second set of updates to the dataset, followed by a third checkpoint (at time t=2). In such an example, if the second storage system has performed all updates in the first set of updates but has not yet performed all updates in the second set of updates, the copy of the dataset that is stored on the second storage system may be up-to-date until the second checkpoint. Alternatively, if the second storage system has performed all updates in both the first set of updates and the second set of updates, the copy of the dataset that is stored on the second storage system may be up-to-date until the third checkpoint. Readers will appreciate that various types of checkpoints may be used (e.g., metadata only checkpoints), checkpoints may be spread out based on a variety of factors (e.g., time, number of operations, an RPO setting), and so on.

[0237] In other embodiments, a dataset may be replicated through snapshot-based replication (also referred to as ‘asynchronous replication’). In snapshot-based replication, snapshots of a dataset may be sent from a replication source such as a first storage system to a replication target such as a second storage system. In such an embodiment, each snapshot may include the entire dataset or a subset of the dataset such as, for example, only the portions of the dataset that have changed since the last snapshot was sent from the replication source to the replication target. Readers will appreciate that snapshots may be sent on-demand, based on a policy that takes a variety of factors into consideration (e.g., time, number of operations, an RPO setting), or in some other way.

[0238] The storage systems described above may, either alone or in combination, by configured to serve as a continuous data protection store. A continuous data protection store is a feature of a storage system that records updates to a dataset in such a way that consistent images of prior contents of the dataset can be accessed with a low time granularity (often on the order of seconds, or even less), and stretching back for a reasonable period of time (often hours or days). These allow access to very recent consistent points in time for the dataset, and also allow access to access to points in time for a dataset that might have just preceded some event that, for example, caused parts of the dataset to be corrupted or otherwise lost, while retaining close to the maximum number of updates that preceded that event. Conceptually, they are like a sequence of snapshots of a dataset taken very frequently and kept for a long period of time, though continuous data protection stores are often implemented quite differently from snapshots. A storage system implementing a data continuous data protection store may further provide a means of accessing these points in time, accessing one or more of these points in time as snapshots or as cloned copies, or reverting the dataset back to one of those recorded points in time.

[0239] Over time, to reduce overhead, some points in the time held in a continuous data protection store can be merged with other nearby points in time, essentially deleting some of these points in time from the store. This can reduce the capacity needed to store updates. It may also be possible to convert a limited number of these points in time into longer duration snapshots. For example, such a store might keep a low granularity sequence of points in time stretching back a few hours from the present, with some points in time merged or deleted to reduce overhead for up to an additional day. Stretching back in the past further than that, some of these points in time could be converted to snapshots representing consistent point-in-time images from only every few hours.

[0240] Although some embodiments are described largely in the context of a storage system, readers of skill in the art will recognize that embodiments of the present disclosure may also take the form of a computer program product that includes instructions that, when executed, cause a computing device (e.g., one or more of the computing devices described herein) to perform a process that includes any of the operations or steps described herein. In some examples, the computer program product is embodied in or disposed upon a non-transitory computer readable medium for use with any suitable processing system. The non-transitory computer readable media may be any storage medium for machine-readable information, including magnetic media, optical media, solid-state media, or other suitable media. Examples of such media include magnetic disks in hard drives or diskettes, compact disks for optical drives, magnetic tape, and others as will occur to those of skill in the art. Persons skilled in the art will immediately recognize that any computer system having suitable programming means will be capable of executing the steps described herein as embodied in a computer program product. Persons skilled in the art will recognize also that, although some of the embodiments described in this specification are oriented to software installed and executing on computer hardware, nevertheless, alternative embodiments implemented as firmware or as hardware are well within the scope of the present disclosure.

[0241] In some examples, a non-transitory computer-readable medium storing computer-readable instructions may be provided in accordance with the principles described herein. The instructions, when executed by a processor of a computing device, may direct the processor and/or computing device to perform one or more operations, including one or more of the operations described herein. Such instructions may be stored and/or transmitted using any of a variety of known computer-readable media.

[0242] A non-transitory computer-readable medium as referred to herein may include any non-transitory storage medium that participates in providing data (e.g., instructions) that may be read and/or executed by a computing device (e.g., by a processor of a computing device). For example, a non-transitory computer-readable medium may include, but is not limited to, any combination of non-volatile storage media and/or volatile storage media. Exemplary non-volatile storage media include, but are not limited to, read-only memory, flash memory, a solid-state drive, a magnetic storage device (e.g., a hard disk, a floppy disk, magnetic tape, etc.), ferroelectric random-access memory ("RAM"), and an optical disc (e.g., a compact disc, a digital video disc, a Blu-ray disc, etc.). Exemplary volatile storage media include, but are not limited to, RAM (e.g., dynamic RAM).

[0243] One or more embodiments may be described herein with the aid of method steps illustrating the performance of specified functions and relationships thereof. The boundaries and sequence of these functional building blocks and method steps have been arbitrarily defined herein for convenience of description. Alternate boundaries and sequences can be defined so long as the specified functions and relationships are appropriately performed. Any such alternate boundaries or sequences are thus within the scope and spirit of the claims. Further, the boundaries of these functional building blocks have been arbitrarily defined for convenience of description. Alternate boundaries could be defined as long as the certain significant functions are appropriately performed. Similarly, flow diagram blocks may also have been arbitrarily defined herein to illustrate certain significant functionality.

[0244] To the extent used, the flow diagram block boundaries and sequence could have been defined otherwise and still perform the certain significant functionality. Such alternate definitions of both functional building blocks and flow diagram blocks and sequences are thus within the scope and spirit of the claims. One of average skill in the art will also recognize that the functional building blocks, and other illustrative blocks, modules and components herein, can be implemented as illustrated or by discrete components, application specific integrated circuits, processors executing appropriate software and the like or any combination thereof.

[0245] While particular combinations of various functions and features of the one or more embodiments are expressly described herein, other combinations of these features and functions are likewise possible. The present disclosure is not limited by the particular examples disclosed herein and expressly incorporates these other combinations.

[0246] In some embodiments, one or more storage systems or one or more elements of storage systems (e.g., features, services, operations, components, etc. of storage systems), such as any of the illustrative storage systems or storage system elements described herein, may be implemented in and/or provide storage services to one or more container systems. A container system may include any system that supports execution of one or more containerized applications or services. Such a service may be software deployed as infrastructure for building applications, for operating a run-time environment, and/or as infrastructure for other services. In the discussion that follows, descriptions of containerized applications generally apply to containerized services as well.

[0247] A container may combine one or more elements of a containerized software application together with a runtime environment for operating those elements of the software application bundled into a single image. For example, each such container of a containerized application may include executable code of the software application and various dependencies, libraries, and/or other components, together with network configurations and configured access to additional resources, used by the elements of the software application within the particular container in order to enable operation of those elements. A containerized application can be represented as a collection of such containers that together represent all the elements of the application combined with the various run-time environments needed for all those elements to run. As a result, the containerized application may be abstracted away from host operating systems as a combined collection of lightweight and portable packages and configurations, where the containerized application may be uniformly deployed and consistently executed in different computing environments that use different container-compatible operating systems or different infrastructures. In some embodiments, a containerized application shares a kernel with a host computer system and executes as an isolated environment (an isolated collection of files and directories, processes, system and network resources, and configured access to additional resources and capabilities) that is isolated by an operating system of a host system in conjunction with a container management framework. When executed, a containerized application may provide one or more containerized workloads and/or services.

[0248] The container system may include and/or utilize a cluster of nodes. For example, the container system may be configured to manage deployment and execution of containerized applications on one or more nodes in a cluster. The containerized applications may utilize resources of the nodes, such as memory, processing and/or storage resources provided and/or accessed by the nodes. The storage resources may include any of the illustrative storage resources described herein and may include on-node resources such as a local tree of files and directories, off-node resources such as external networked file systems, databases or object stores, or both on-node and off-node resources. Access to additional resources and capabilities that could be configured for containers of a containerized application could include specialized computation capabilities such as GPUs and AI/ML engines, or specialized hardware such as sensors and cameras.

[0249] In some embodiments, the container system may include a container orchestration system (which may also be referred to as a container orchestrator, a container orchestration platform, etc.) designed to make it reasonably simple and for many use cases automated to deploy, scale, and manage containerized applications. In some embodiments, the container system may include and/or communicate with a storage management system configured to provision and manage storage resources (e.g., virtual volumes) for private or shared use by cluster nodes and/or containers of containerized applications.

[0250] FIG. **4** illustrates an example container system **400**. In this example, the container system **400** includes a container storage system **402** that may be configured to perform one or more storage management operations to organize, provision, and manage storage resources for use by one or more containerized applications **404-1** through **404-**L of container system **400**. In particular, the container storage system **402** may organize storage resources into one or more storage pools **406** of storage resources for use by containerized applications **404-1** through **404-**L. The container storage system may itself be implemented as a containerized service.

[0251] The container system **400** may include or be implemented by one or more container orchestration systems, including Kubernetes™, Mesos™, Docker Swarm™, among others. The container orchestration system may manage the container system **400** running on a cluster **408** through services implemented by a control node, depicted as **410**, and may further manage the container storage system or the relationship between individual containers and their storage, memory and CPU limits, networking, and their access to additional resources or services.

[0252] A control plane of the container system **400** may implement services that include: deploying applications via a controller **412**, monitoring applications via the controller **412**, providing an interface via an API server **414**, and scheduling deployments via scheduler **416**. In this example, controller **412**, scheduler **416**, API server **414**, and container storage system **402** are implemented on a single node, node **410**. In other examples, for resiliency, the control plane may be implemented by multiple, redundant nodes, where if a node that is providing management services for the container system **400** fails, then another, redundant node may provide management services for the cluster **408**.

[0253] A data plane of the container system **400** may include a set of nodes that provides container runtimes for executing containerized applications. An individual node within the cluster **408** may execute a container runtime, such as Docker™, and execute a container manager, or node agent, such as a kubelet in Kubernetes (not depicted) that communicates with the control plane via a local network-connected agent (sometimes called a proxy), such as an agent **418**. The agent **418** may route network traffic to and from containers using, for example, Internet Protocol (IP) port numbers. For example, a containerized application may request a storage class from the control plane, where the request is handled by the container manager, and the container manager communicates the request to the control plane using the agent **418**.

[0254] Cluster **408** may include a set of nodes that run containers for managed containerized applications. A node may be a virtual or physical machine. A node may be a host system.

[0255] The container storage system **402** may orchestrate storage resources to provide storage to the container system **400**. For example, the container storage system **402** may provide persistent storage to containerized applications **404-1**-**404-**L using the storage pool **406**. The container storage system **402** may itself be deployed as a containerized application by a container orchestration system.

[0256] For example, the container storage system **402** application may be deployed within cluster **408** and perform management functions for providing storage to the containerized applications **404**. Management functions may include determining one or more storage pools from available storage resources, provisioning virtual volumes on one or more nodes, replicating data, responding to and recovering from host and network faults, or handling storage operations. The storage pool **406** may include storage resources from one or more local or remote sources, where the storage resources may be different types of storage, including, as examples, block storage, file storage, and object storage.

[0257] The container storage system **402** may also be deployed on a set of nodes for which persistent storage may be provided by the container orchestration system. In some examples, the container storage system **402** may be deployed on all nodes in a cluster **408** using, for example, a Kubernetes DaemonSet. In this example, nodes **420-1** through **420-**N provide a container runtime where container storage system **402** executes. In other examples, some, but not all nodes in a cluster may execute the container storage system **402**.

[0258] The container storage system **402** may handle storage on a node and communicate with the control plane of container system **400**, to provide dynamic volumes, including persistent volumes. A persistent volume may be mounted on a node as a virtual volume, such as virtual volumes **422-1** and **422-**P. After a virtual volume **422** is mounted, containerized applications may request and use, or be otherwise configured to use, storage provided by the virtual volume **422**. In this example, the container storage system **402** may install a driver on a kernel of a node, where the driver handles storage operations directed to the virtual volume. In this example, the driver may receive a storage operation directed to a virtual volume, and in response, the driver may perform the storage operation on one or more storage resources within the storage pool **406**, possibly under direction from or using additional logic within containers that implement the container storage system **402** as a containerized service.

[0259] The container storage system **402** may, in response to being deployed as a containerized service, determine available storage resources. For example, storage resources **424-1** through **424**-M may include local storage, remote storage (storage on a separate node in a cluster), or both local and remote storage. Storage resources may also include storage from external sources such as various combinations of block storage systems, file storage systems, and object storage systems. The storage resources **424-1** through **424**-M may include any type(s) and/or configuration(s) of storage resources (e.g., any of the illustrative storage resources described above), and the container storage system **402** may be configured to determine the available storage resources in any suitable way, including based on a configuration file. For example, a configuration file may specify account and authentication information for cloud-based object storage **348** or for a cloud-based storage system **318**. The container storage system **402** may also determine availability of one or more storage devices **356** or one or more storage systems. An aggregate amount of storage from one or more of storage device(s) **356**, storage system(s), cloud-based storage system(s) **318**, edge management services **382**, cloud-based object storage **348**, or any other storage resources, or any combination or sub-combination of such storage resources may be used to provide the storage pool **406**. The storage pool **406** is used to provision storage for the one or more virtual volumes mounted on one or more of the nodes **420** within cluster **408**.

[0260] In some implementations, the container storage system **402** may create multiple storage pools. For example, the container storage system **402** may aggregate storage resources of a same type into an individual storage pool. In this example, a storage type may be one of: a storage device **356**, a storage array **102**, a cloud-based storage system **318**, storage via an edge management service **382**, or a cloud-based object storage **348**. Or it could be storage configured with a certain level or type of redundancy or distribution, such as a particular combination of striping, mirroring, or erasure coding.

[0261] The container storage system **402** may execute within the cluster **408** as a containerized container storage system service, where instances of containers that implement elements of the containerized container storage system service may operate on different nodes within the cluster **408**. In this example, the containerized container storage system service may operate in conjunction with the container orchestration system of the container system **400** to handle storage operations, mount virtual volumes to provide storage to a node, aggregate available storage into a storage pool **406**, provision storage for a virtual volume from a storage pool **406**, generate backup data, replicate data between nodes, clusters, environments, among other storage system operations. In some examples, the containerized container storage system service may provide storage services across multiple clusters operating in distinct computing environments. For example, other storage system operations may include storage system operations described above with respect to FIGS. **1-3**. Persistent storage provided by the containerized container storage system service may be used to implement stateful and/or resilient containerized applications.

[0262] The container storage system **402** may be configured to perform any suitable storage operations of a storage system. For example, the container storage system **402** may be configured to perform one or more of the illustrative storage management operations described herein to manage storage resources used by the container system.

[0263] In some embodiments, one or more storage operations, including one or more of the illustrative storage management operations described herein, may be containerized. For example, one or more storage operations may be implemented as one or more containerized applications configured to be executed to perform the storage operation(s). Such containerized storage operations may be executed in any suitable runtime environment to manage any storage system(s), including any of the illustrative storage systems described herein.

[0264] In some embodiments, a storage system, such as the container storage system **402** described above, may be configured to store, manage, and provide immutable s (e.g., an image of a containerized application) to a container system for use by the container system to run container instances of the container images (e.g., a container instance of the containerized application). The storage system may be further configured to provide storage services, such as persistent data storage, to the container system (e.g., to container instances running in the container system) and may leverage elements of the storage services to store, manage, and provide container images to the container system. Such a storage system may be referred to as a container-aware storage system.

[0265] In some embodiments, the container-aware storage system may use volumes to store, manage, and provide immutable container images to the container system for use by the container system to run container instances of the container images. For example, the storage system may receive an immutable container image and store the immutable container image as a volume. This may include the storage system translating the immutable container image into the volume, examples of which are described herein, and storing the volume to one or more storage resources. The storage system may subsequently detect a request from a container system, such as a request to run a container instance of the immutable container image in the container system and, in response to the request, provide the volume to the container system. The providing of the volume may include mapping the volume to the container instance, such as by attaching and mounting a virtual volume, which is mapped to the volume, to a host node for use by the container instance. The container system may then use the immutable container image from the volume to run the container instance of the immutable container image in the container system.

[0266] In some embodiments, in addition to providing the immutable container image to the container system, the storage system may provide persistent data storage for use by the container system in running the container instance of the immutable container image in the container system, such as when the container instance is a stateful container instance or is otherwise configured to write data to persistent storage. The storage system may provide persistent data storage in any suitable way. As an example, the storage system may provide, to the container system, an additional volume configured to provide persistent storage for the container instance of the immutable container image in the container system. As another example, the volume that includes the immutable container image and that is provided by the storage system to the container system may comprise both an immutable layer including the immutable container image (e.g., an immutable snapshot of the container image) and a writeable layer configured to provide persistent storage for the container instance of the immutable container image in the container system.

[0267] Various illustrative implementations of a container-aware storage system and ways that the container-aware storage system may store, manage, and provide immutable container images and optionally persistent data storage to a container system, as well as ways that the container system may use the immutable container images and the persistent data storage to run container instances of the container images will now be described in more detail with reference to several figures.

[0268] FIG. **5** illustrates an example configuration **500** of a container system **502** and a container-aware storage system **504** (also referred to as the storage system **504**) configured to store, manage, and provide immutable container images and optionally persistent data storage to the container system **502**. The container system **502** and the storage system **504** may be communicatively coupled and configured to communicate one with another in any suitable way. For example, the container system **502** and the storage system **504** may communicate by way of an interface **506**, which may be any suitable interface (e.g., one or more APIs). The storage system **504** may provide an interface that allows the storage system **504** to function as a container image storage layer as well as a persistent storage layer. For example, the storage system may provide an interface configured to receive and interpret requests from the container system **502**, such as requests for container images, persistent storage, and/or volumes.

[0269] The container system **502** may include an orchestration system **508** and a container runtime system **510**. The orchestration system **508** may deploy, scale, and manage containerized applications within the container system **502**, such as by managing deployment of containerized applications to select nodes of a cluster. The container runtime system **510** may provide a container runtime environment on nodes of the cluster. When a containerized application is deployed to a node for execution on the node, the container runtime system **510** may perform operations to execute the containerized application within the container runtime environment on the node.

[0270] Execution of a containerized application may include the container runtime system **510** running, in the container runtime environment on the node, a container instance **512** of a container image that represents the containerized application. To this end, the container runtime system **510** may receive a request to run a container instance **512** of a container image and, in response to the request, access and use the container image associated with the request to run the container instance **512**. Instead of accessing the container image from the local storage of the node or accessing the container image over a network connection from a container image repository and loading the container image into the local storage of the node as is done in traditional container systems, the container system **510** may access the container image from the storage system **504**.

[0271] In response to one or more requests from the container system **502**, the storage system **504** may provide a container image **514** and optionally persistent storage **516** to the container system **502**. The container runtime system **510** may use the container image **514** to run the container instance **512** of the container image **514** in the container runtime environment of the node. In addition, when the persistent storage **516** is provided, the container runtime system **510** may use the persistent storage **516** to persistently store data associated with running the container instance **512** of the container image **514** in the container runtime environment of the node.

[0272] The storage system **504** may be configured to function as a repository of container images that may receive, store, manage, and provide container images. For example, the storage system **504** may be configured to receive and respond to push and pull requests to receive and provide container images. In certain embodiments, the storage system **504** is configured to receive container images, store the container images as volumes, manage the volumes, and provide the volumes to the container system **502** for use in running container instances of the container images.

[0273] FIG. **6** illustrates an example of the storage system **504** receiving a container image **602** and storing the container image **602** as a volume **604**. The container image **602** may be immutable and may include one or more image layers. In the illustrated example, the container image **602** includes three image layers—image layer **1**, image layer **2**, and image layer **3**. The image layers may have a hierarchical relationship. For example, image layer **3** may be the top-level image layer and may depend on and reference the next image layer, image layer **2**, which may depend on and reference the next image layer, image layer **1**. In some embodiments, each image layer may be considered an individual immutable container image.

[0274] The storage system **504** may receive the container image **602** from any suitable source and in any suitable way. In some embodiments, for example, the container image **602** may be pushed from a container runtime system to the storage system **504** with a push operation.

[0275] The storage system **504** may receive and store the container image **602** as the volume **604**. This may include translating the container image **602** into the volume **604**. The translation may include opening each image layer in the container image **602** and writing data from the image layer into an immutable volume snapshot. Specifically, in the illustrated example, image layer **3** may be translated into snapshot **3** of the volume **604**, image layer **2** may be translated into snapshot **2** of the volume **604**, and image layer **1** may be translated into snapshot **1** of the volume **604**. The snapshots may be defined to have relationships that correspond to the relationships between the image layers of the container image **602**. For example, snapshot **3** may depend on and reference snapshot **2**, and snapshot **2** may depend on and reference snapshot **1**. The relationships between the snapshots may be defined in any suitable way, including by snapshots referencing other snapshots, metadata indicating relationships between snapshots, and/or the use of indexing or naming conventions that indicate the relationships. In the illustrated example, all the snapshots are associated with the volume **604** (e.g., are treated as snapshots of the volume **604**). In some examples, volume **604** may be considered to be volume snapshot **3**, which references volume snapshot **2**, which references volume snapshot **1**. The storage system **504** may store any metadata that may be used to identify the volume **604** as being related to the container image **602** (e.g., to identify that the volume **604** should be provided in response to a request for the container image **602**).

[0276] As used herein, a volume, such as the volume **604**, may be an atomic unit of storage such as a logical drive or disk, which may be mapped to physical storage. The volume is an identifiable unit of data storage configured to be managed by the storage system **504** (e.g., by applying storage operations to the volume) and accessed by a client.

[0277] With the container image **602** stored as the volume **604**, the storage system **604** may apply one or more storage services of the storage system **604** to the volume **604**, including one or more of the storage services described herein. For example, the volume **604** may be the subject of storage service operations associated with logical mapping (e.g., attachment, mounting, etc.), deduplication, compression, replication, snapshotting, cloning, garbage collection, migration, disaster recovery, etc.

[0278] With the container image **602** stored as the volume **604**, the storage system **604** may be ready to provide the volume **604** to the container system **502** for use by the container system **502** to run a container instance of the container image **602**. In certain examples, the storage system **504** may provide the volume **604** to the container system **502** in response to a request for the container image **602**. The request may be from the container system **502**, such as from the orchestration system **508** or the container runtime system **510**. The storage system **504** may detect the request for the container image **602** in any suitable way, such as by detecting a pull request or a run request associated with the container image **602** (e.g., a request to run a container instance of the container image **602**).

[0279] The storage system **604** may provide the volume **604** to the container system **502** in any way that allows the container system **502** to run a container instance of the container image **602**. In some examples, the way that the storage system **604** provides the volume **604** to the container system **502** may depend on a configuration of the container system **502**, such as on a configuration of the orchestration system **508** or the container runtime system **510**. In other examples, the storage system **604** may provide the volume **604** to the container system **502** in any suitable way and how the container system **502** uses the volume **604** may depend on a configuration of the container system **502**, such as on a configuration of the orchestration system **508** or the container runtime system **510**.

[0280] In some embodiments, the storage system **504** may provide the volume **604** to the container system **502** by attaching and mounting the volume **604** on a node on which the container instance will run. For example, the storage system **504** may detect a request for the container image **602** on a node, identify the volume **604** as associated with the container image **602**, and provide the volume **604** by attaching and mounting the volume **604** on the node, such as by attaching and mounting a virtual volume that is mapped to the volume **604**.

[0281] In some examples in which the container image **602** includes multiple image layers represented as snapshots of the volume **604** in the storage system **504**, the mounting of the volume **604** may include the storage system **504** mounting the snapshots as individual volumes in an order that represents the layered relationships of the image layers to one another in the container image **602**. In other examples in which the container image **602** includes multiple image layers represented as snapshots of the volume **604** in the storage system **504**, the mounting of the volume **604** may include the storage system **504** mounting a virtual volume that is mapped to the volume **604** in any suitable way, such as by being mapped to the highest-level snapshot (snapshot **3**) of the volume **604**.

[0282] With the volume **604** mounted on the node, the container system **502** may access the volume **604** and read container image data from the volume **604**. For example, the container runtime system **510** may read container image data from the volume **604** and use the container image data to run the container instance of the container image **602**. In some embodiments, the container runtime system **510** may do this by reading the container image **602** from the volume **604** and loading the container image **602** into local storage of the node (e.g., using a container pull operation). The container runtime system **510** may then use the container image **602** in local storage of the node to run the container instance of the container image **602** on the node. In other embodiments, the container runtime system **510** may not load the container image **602** into the local storage of the node and may instead access and use the container image **602** in the mounted volume **604** to run the container instance of the container image **602** on the node. In such other embodiments, resources of the node may be conserved, such as by not having to use local storage of the node to store the container image **602**. This may allow the node to be equipped with less local storage resources than would be required to support conventional container runtime environments and/or to use local storage resources for other purposes. By not loading container image data into local storage of the node, container startup times may be reduced compared to conventional container runtime environments. In addition, the amount of data pulled onto the node may be reduced, which may conserve network resources and further reduce container startup times. Such savings in resource usage and startup times may be significant when a reboot is performed (e.g., when a node reboots) and/or when container instances are moved from a source node to one or more other nodes (e.g., due to an interruption on source node).

[0283] As mentioned above, in certain embodiments, the storage system **504** may be configured to provide persistent data storage for container instances running or that will run in the container system **502**. In some examples, whether the storage system **504** provides persistent data storage for a container instance may depend on the needs of the container instance. If the container instance will not use persistent storage, the container system **502** may not provide a request for persistent storage for the container instance to the storage system **504**, and the storage system **504** may not provide persistent storage for the container instance. On the other hand, if the container instance is to use persistent storage, the container system **502** may provide a request for persistent storage for the container instance to the storage system **504**, and the storage system **504** may provide persistent storage for the container instance.

[0284] The storage system **504** may be configured to provide persistent storage for the container instance in any suitable way. In some embodiments, the storage system **504** provides a volume to which the container instance may write persistent data. The storage system **504** may attach and mount the volume on a node for access by the container instance running on the node.

[0285] In some embodiments, the volume provided for persistent storage may be provided in addition to the volume **604** that contains data representing the container image **602**. Thus, the volume **604** may provide the container image **602** (in volume snapshot form) for use by the container system **502** to run the container instance, and the additional volume may provide persistent storage to which the running container instance may write persistent data and from which the running container instance may read persistent data. FIG. **7**A illustrates an example of the storage system **504** providing, to the container system **502**, **1**) the volume **604** that includes data representing the immutable container image **602** and **2**) an additional, separate volume **702** configured to provide persistent storage.

[0286] In some other embodiments, the volume provided for persistent storage may be included in and/or provided together with the volume that includes the immutable container image. In such embodiments, for example, the storage system **504** may provide, to the container system **502**, a single volume that comprises an immutable layer including data representing the container image (this immutable layer may include multiple sub-layers representing multiple snapshots) and a writeable layer configured to provide persistent storage for use by the container instance. FIG. 7B illustrates an example of the storage system **504** providing, to the container system **502**, a volume **704** that includes an immutable layer **706** and a writeable layer **708**. The immutable layer **706** includes data representing the immutable container image **602** (e.g., volume **604** that may include multiple sub-layers representing multiple volume snapshots). The writeable layer **708** may include one or more writeable volumes (e.g., writeable volume **710**) configured to be used to store persistent data for the container instance.

[0287] The storage system **504** may be configured to create the volume **704** that includes the writable layer **708** and the immutable layer **706** at any suitable time. For example, the storage system **504** may create the volume **704** in response to receiving one or more requests from the container system **502** for the container image **602** and persistent data storage. In other examples, the storage system **504** may create the volume **704** in advance of receiving one or more requests from the container system **502** for the container image **602** and persistent data storage.

[0288] The storage system **504** may be configured to create the volume **704** that includes the writable layer **708** and the immutable layer **706** in any suitable way. For example, the volume **704** may be created to represent a hierarchical chain of volumes that depend on one another in a way that corresponds to dependencies that will be used by the container system **502** to run a container instance of the container image **602**. In some embodiments, for example, the storage system **504** may provide the writeable volume **710** defined to depend on the volume **604** (e.g., the writeable volume **710** is a writeable layer on top of the volume **604**). Volume **704** may be the writeable volume **710** or an additional volume defined to depend on the writeable volume **710**. The writeable volume **710** may include one or more individual writeable volumes on top of the volume **604**. Accordingly, the volume **704** may define a stack of dependent volumes that may be used by the container system **502** to run a container instance of the container image **602** and to read and write persistent data while running the container instance. The stack path of the volume **704** may mirror the stack path of the container instance. The volume **704** may be attached and mounted as a single point from which an entire container instance may start and run.

[0289] The container system **502** (e.g., the container runtime system **510**) may map any area in the container instance to a volume in the storage system **504**. For example, the container system **502** may attach a namespace of the volume into a location in the container instance. Accordingly, the container system **502** may access and use mounted volumes, such as volume **704** or volumes **604** and **702**, to run the container instance from the container image **602** and to read and write persistent data. The container system **502** may provide an ephemeral layer, which may be a layer to which ephemeral data may be read and written while the container instance if running. The ephemeral layer may be a layer on top of a volume provided by the storage system **504**.

[0290] In embodiments in which a single volume, such as the volume **704**, includes writeable and immutable container data in one place, the container system **502** (e.g., the container runtime system **510**) may not have to individually request immutable container data and persistent storage from different sources. For example, the container system **502** may request to run a container instance of a container image, such as by requesting a volume associated with the container image. In response, the storage system **504** may provide a single volume that includes writeable and immutable container data in one place.

[0291] FIGS. **8-11** illustrate flowcharts depicting example methods. While the flowcharts depict illustrative operations according to some embodiments, other embodiments may omit, add to, reorder, combine, and/or modify any of the operations shown in the flowcharts. In some implementations, one or more of the operations shown in the flowcharts may be performed by a storage system such as the storage system **504**, a container system such as the container system **400** or **502**, any components of the storage system and/or the container system, and/or any implementation of the storage system and/or the container system.

[0292] As shown in FIG. **8**, an example method **800** includes: receiving, at **802**, an immutable container image; storing, at **804**, the container image as a volume; detecting, at **806**, a request from a container system for the container image; providing, at **808**, the volume to the container system; and using, at **810**, the volume to run a container instance in the container system. Operations of the method **800** may be performed in any of the ways described herein.

[0293] In certain embodiments, storing, at **804** of the method **800**, may be performed as illustrated in FIG. **9**. As shown in FIG. **9**, an example method **900** includes: opening, at **902**, an image layer in an immutable container image (e.g., the immutable container image received at **802** in the method **800**); translating, at **904**, the image layer to a volume snapshot; storing, at **906**, the volume snapshot; and storing, at **908**, metadata for the volume snapshot. Operations of the method **900** may be performed in any of the ways described herein. The metadata stored at **908** may include any data associated with the volume snapshot, including metadata associating the volume snapshot to the container image (e.g., metadata indicating an identifier of a container image and/or container image layer associated with the volume snapshot), any tags associated with the container image and/or container image layer associated with the volume snapshot; an image hash for the container image and/or container image layer associated with the volume snapshot, a time associated with receiving the container image and/or container image layer associated with the volume snapshot, an identifier for the volume snapshot, one or more relationships with one or more other volume snapshots (e.g., a reference from one snapshot to another snapshot), etc.

[0294] After **908**, the method **900** further includes determining, at **910**, whether there is another image layer in the container image. If there is another layer, the method **900** is repeated starting again at **902**. If there is not another layer, the method **900** ends.

[0295] As shown in FIG. **10**, an example method **1000** includes: receiving, at **1002**, a request from a container system for a container image; identifying, at **1004**, a volume corresponding to the container image; providing, at **1006**, the volume to the container system; receiving, at **1008**, a request from the container system for persistent storage; and providing, at **1010**, a persistent storage volume to the container system **1010**. Operations of the method **1000** may be performed in any of the ways described herein, including as described in reference to FIG. **7**A. The requests received at **1002** and **1008** may be received in parallel or sequentially in any suitable order.

[0296] As shown in FIG. **11**, an example method **1100** includes: receiving, at **1102**, a request from a container system for a volume that includes a container image and provides persistent storage; providing, at **1104**, the volume to the container system; and using, at **1106**, the volume to run a container instance in the container system and to write persistent data for the container instance. Operations of the method **1100** may be performed in any of the ways described herein, including as described in reference to FIG. **7**B.

[0297] As described herein, a volume may be specified to comprise one or more container images. Such a volume may be used by a container system, a container runtime, a container orchestrator, and/or a storage system to efficiently deploy or redeploy containers among nodes of a cluster. Deployment of a container using a volume may benefit from advantages of using a volume, such as access to data through a volume mount point and accessing container images associated with the volume over a storage area network.

[0298] In some embodiments, the disclosed volumes, in addition to comprising one or more container images, may comprise data storage. The data storage may be data generated during operation of one or more containers associated with the one or more container images within the data volumes. In this way, a same volume may comprise both a container image and persistent and/or ephemeral storage for data generated during operation of a container instance based on the container image. The data storage may comprise, in addition to or instead of data generated during operating of the one or more containers, configuration data useable by the one or more containers associated with the container images within the volume.

[0299] As described in greater detail below, an advantage of using a volume comprising a container image includes a container runtime mounting the volume on a node and accessing the container image. The container runtime, based on access to the container image via the mounted volume, may create an instance of a container associated with the container image without copying the entire container image to the node. Other advantages may include faster spin up time when creating a container instance on a given node of a cluster and, in some embodiments, capability for using a same volume that comprises a container image as storage usable by a container. One of more such features may allow containers to be efficiently deployed and/or redeployed (e.g., spun up/down) among nodes of a cluster of a container system.

[0300] In a container system, a container orchestrator may deploy one or more containers among one or more nodes of a cluster. In certain implementations, a container orchestrator may operate to deploy and/or redeploy containers within a cluster without any knowledge of a volume being associated with container images. In other implementations, a container orchestrator may operate to deploy and/or redeploy containers within a cluster based on knowledge of one or more volumes that store container images.

[0301] In some examples, subsequent to an initial deployment, a container may fail and/or be redeployed for a variety of reasons. As one example for a container orchestrator determining redeployment of a container, based on metrics regarding load balances among the nodes of a cluster, the container orchestrator may determine to move a container operating on a first node to a second node. In other examples, performance of a containerized application, security threats, system upgrades, increases or decreases in compute resources, failure of a node, among other reasons may be used by a container orchestrator to redeploy a container, such as by spinning down the container on one node and spinning up the container on one or more other nodes.

[0302] Failure or redeployment of containers may occur frequently enough that faster movement of a container among nodes of a container system may result in appreciable improvements in container system performance or resource utilization. The disclosed volumes that comprise container images may be a basis for quicker deployment of containers. Deployments or redeployments may be quicker based on having local access to a storage system that stores volumes associated with container images. In contrast, traditional systems may access a repository over the Internet to access container images.

[0303] Further, because the disclosed volumes may use logical structures and application programming interfaces that are compatible with existing components of a container system that use storage systems, an amount of modification of the components of a container system to use the disclosed volumes may be reduced. For example, a container runtime may have APIs to communicate with storage systems to identify, mount, read, write, or otherwise modify characteristics of data associated with a volume.

[0304] As another example, based on a container runtime accessing a container image associated with a volume similarly to accessing storage content within a volume, bursts of network traffic within a container system may be avoided. For example, network traffic may be managed based on a container runtime accessing portions of a container image over a scheduled period of time instead of copying over a full container image from a remote network location to local memory of a node where a container instance is created.

[0305] FIG. **12**A illustrates an example storage system **1202** that stores a volume **1204** comprising a container image according to some implementations. The storage system **1202** may be implemented similarly to one or more of the storage systems described with respect to FIGS. **1**A-**11**.

[0306] The volume **1204** may comprise volume metadata **1206** and a container image **1210**. In this example, the volume metadata **1206** includes container metadata **1208** that describes one or more layers **1212** of the container image **1210**. Metadata **1206** may describe a structured collection of data objects that represent logical relationships between layers of the container image **1210**. In certain implementations, different types of logical relationships may be implemented. In this example, the logical relationships between image layers **1212** may be structured as a directed

acyclic graph.
[0307] In certain implementations, a dependency between image layers **1212** may be represented by a directed link between the data objects associated with image layers **1212**. For example, image layer **1212-1** may be a base layer that is not dependent on another image layer, image layer **1212-2** may be dependent on image layer **1212-1**, and image layer **1212-3** may be dependent on image layer **1212-2**. A dependency between image layers may include one or more references from a first, dependent, image layer to a second image layer.
[0308] The one or more layers **1212** may be image layers as described with respect to FIG. **6**. In this example, the container image **1210** includes image layers **1212-1-1212-3**. In other examples, as described with respect to FIG. **12**B, the volume metadata **1206** may include both container metadata **1208** and storage metadata.
[0309] FIG. **12**B illustrates an example storage system **1202** that stores a volume **1204** comprising a container image according to some implementations.
[0310] As described with respect to FIG. **12**A, a volume **1204** may comprise volume metadata **1206** and a container image **1210**. In this example, the volume **1204** additionally comprises storage metadata **1220** and container storage **1222-1-1222**-M. In certain embodiments, a container runtime may mount a first volume that provides access to the container image **1210**, mount a second volume such as volume **1224** that provides access to the container storage **1221-1**, and mount an M volume such as volume **1228** that provides access to the container storage **1222**-M. In this example, the mounted volumes associated with container storage **1221** may be used during operating of the container to store data. Data stored within a volume associated with container storage **1221** may be persisted in the event that the container is redeployed, fails, or otherwise becomes unavailable.
[0311] Storage metadata **1220** may describe a dataset associated with the volume **1224**, and in examples, one or more snapshots **1226** of the dataset. The storage metadata **1220** may represent volume **1224** based on directed acyclic graph or in any other suitable way.
[0312] In certain implementations, the volume **1224** may be specified by the storage metadata **1220** as a directed acyclic graph, such as a B-tree, where leaves of the storage metadata **1220** representation may include pointers to stored data objects. A volume address, or volume reference and offset, may be used to navigate the storage metadata **1220** representation of the volume **1224**. For example, the storage metadata **1220** representation of the volume **1224** may include data objects as leaf nodes, and intermediate nodes may be references to leaf nodes. The volume **1224** may comprise an aggregate of the data objects at the leaf nodes of the storage metadata **1220**, where the organization of the data objects is specified by the intermediate nodes. A data object may be a logical extent, where a logical extent may be any specified size, such as 1 MB, 4 MB, or some other size.
[0313] A snapshot **1226** may be specified by a metadata representation similar to the metadata representation of a volume. For example, the snapshot **1226** may be a directed acyclic graph, where the snapshot **1226** includes references and data objects that are associated with one or more changes to the dataset of the volume **1224**. A given snapshot may comprise data objects that are associated with the one or more changes to the volume **1224** dataset in addition to one or more references to the metadata representation of the volume **1224** associated with data objects that have not been changed by the one or more changes associated with the given snapshot. Based on the references from the given snapshot to the volume **1224** dataset, the given snapshot may be considered dependent on the volume **1224**.
[0314] As depicted in this example, storage metadata **1220** describes container storage **1222-1-1222**-M. Container storage **1222-1** represents the volume **1224** and snapshots **1226-1** and **1226-2** of the volume **1224**. Snapshot **1226-1** is dependent on the volume **1224**, and snapshot **1226-2** is dependent on snapshot **1226-1**. Container storage **1222**-M represents volume **1228** and snapshot **1230-1** of the volume **1228**. Snapshot **1230-1** is dependent on the volume **1228**.
[0315] As described with respect to FIGS. **12**A-**12**B, various features of a volume that comprises

one or more container images, and in some examples, one or more storage volumes are described. As described with respect to FIGS. **13-15**, such a volume comprising one or more container images may be implemented within various computing environment architectures. Within various architectures, a container orchestrator, a container runtime, and/or a storage system may have different roles and features with respect to deployment or redeployment of a container among nodes of a container system. A first example, described with respect to FIG. **13**, describes a storage system implemented independently of a container system. In this example, the storage system may provide volumes comprising container images to either a container runtime or container orchestrator operating within the container system. A second example, described with respect to FIG. **14**, describes a cluster that comprises a storage system, such as any of the storage systems described with respect to FIGS. **5-11**. In this example, the cluster and the storage system operate within a cloud environment provided by a same cloud services provider, and utilize storage resources that are outside of the cluster and provided by the cloud services provider. The storage resources could be implemented in the cluster in other implementations. A third example, described with respect to FIG. **15**, describes a container system where a container runtime uses a volume to access container images, and where the volume is obtained from a cloud-based object storage operating as a repository for volumes comprising container images. In the following figures, components with reference numbers described with respect to previous figures are implemented similarly.

[0316] FIG. **13** illustrates an example computing environment **1300** that uses a volume **1204** comprising a container image **1210** according to some implementations.

[0317] In computing environment **1300**, a container orchestrator, such as orchestration system **508** described with respect to FIG. **5**, may deploy or redeploy a container among nodes **420** of a cluster **408**. The container orchestrator may communicate information about a deployment of the container to a container runtime **1302** running on a node **420**, where the container runtime may include a data volume module **1304** that is configured to interface with (e.g., interpret) volumes comprising container images. Based on the received information, the container runtime **1302** may communicate with a storage system **1306** to request a container image **1210** associated with the container. The request may be made in any suitable way, such as by sending, to the storage system **1306**, a request for the container image **1210** and/or the volume **1204**, where the volume **1204** may be used to access the container image **1210**. The storage system **1306** may generate, store, and/or provide volumes comprising one or more container images. In this example, as described above, the storage system **1306** is implemented outside of the cluster **408** and outside of and/or independent from a container system in which the cluster **408** operates.

[0318] In this example, the container runtime **1302** accesses a volume **1204** within the storage system **1306**. The container runtime **1302** may access the container image **1210** associated with the volume **1204** to create an instance of the container image **1210** on a node **420-1** within the cluster **408**. To create the instance of the container image **1210**, the container runtime **1302** may request the volume **1204** from a storage system **1306**. The container runtime **1302** may be implemented similarly to the container runtime **402**, where the container runtime **1302** may comprise fewer, additional, or all features described above with respect to the container runtime **402**. In this example, the container runtime **1302** comprises the data volume module **1304** configured to interpret and/or otherwise interface with volumes comprising container images.

[0319] The data volume module **1304** may be configured to access one or more image layers of a container image from a volume **1204** that comprises one or more container images **1210**. The data volume module **1304** may implement any of the operations described above with respect to FIGS. **5-11**, including generating container images within a volume, accessing a container image within a volume, modifying a container image within a volume, moving a volume from one node to another node within a container system, among others.

[0320] The storage system **1306**, similar to storage system **504** described with respect to FIGS. **5-**

11, may use an identifier of the container image **1210** to select the volume **1204** associated with the identifier. The storage system **1306** may be implemented similarly to storage systems **402** and **504**, where the storage system **1306** may comprise fewer, additional, or all features described above with respect to storage systems **402** and **504**.

[0321] Continuing with this example, to access the volume **1204**, the container runtime **1302** may send a request **1308-1** to the storage system **1306** for the volume **1204**. The request **1308-1** may indicate an identifier of the container image **1210**. In response to the request **1308-1**, the storage system **1306** may provide volume data **1310-1**, where the volume data **1310-1** is associated with the volume **1204**. The container runtime **1302** may use the volume data **1310-1** to mount the volume **1204** to access the container image **1210**. In some examples, volume data may be a network path or a network location and credentials, such as a username and/or password to an account associated with one or more storage resources. Based on mounting and accessing the volume **1204**, the container runtime **1302** may create the instance of the container image **1210** in response to a deployment of an application associated with the container image **1210**.

[0322] In contrast, in traditional systems, a container image repository is used to access a container image, where the container image is not included as part of a volume. A container image repository may be one such as a Docker™ image repository, among others. In certain implementations, a node **420** on which the container image **1210** is to be instantiated may have a connection to the storage system **1306** over a storage area network. A storage area network may be a Fibre Channel, iSCSI, NVMe, or some other storage area network implementation, such as storage area network **158** described with respect to FIGS. **1**A-**1**D. Access to the container image over a storage area network may avoid impacting network activity of other container system processes that may be using other types of network connections. Further, access to a container image via a storage area network using the volume data **1310-1** is in contrast to traditional container runtimes that may access container images over a wide area network, such as the internet, to reach a repository.

[0323] In certain implementations, the container orchestrator may deploy a same application on multiple nodes **420** of the cluster **408**. For example, a deployment configuration file may specify a replication factor of Z. Based on the replication factor of Z, the container orchestrator may deploy Z instances of the container image **1210** associated with the application among Z nodes **420**. Similar to the description of container runtime **402** with respect to FIGS. **5-11**, based on a container runtime **1302** mounting a volume to access a container image, a network load from transmission of Z copies of the container image **1210** is avoided.

[0324] In this example, to deploy a first instance of the container image **1210**, container runtime **1302** on node **420-1** issues the request **1308-1** and receives volume data **1310-1**. Similar to the description of container runtime **402** with respect to FIGS. **5-11**, the container runtime **1302** on node **420-1** may use the volume data **1310-1** to mount the volume **1204** to access and use the container image **1210** to run a container instance on the node **420-1**, thereby spinning up a container associated with the container image **1210** on the node **420-1**. Similarly, to deploy instance Z of the container image **1210**, container runtime **1302** on node **420**-N issues request **1308**-Z and receives volume data **1310**-Z. The container runtime **1302** on node **420**-N may use the volume data **1310**-Z to mount the same volume **1204** to access and use the container image **1210** to run a container instance on the node **420**-N, thereby spinning up another container associated with the container image **1210** on the node **420**-N.

[0325] FIG. **14** illustrates an example computing environment **1400** that uses a volume **1204** comprising a container image **1210** according to some implementations.

[0326] In computing environment **1400**, similar to computing environment **1300**, a container orchestrator may deploy or redeploy a container among nodes **420** of a cluster **408**. The container orchestrator may communicate information about a deployment of the container to a container runtime **1302** running on a node **420**. Based on the received information, the container runtime **1302** may communicate with a storage system **1402** to request a container image **1210** associated with the container. The request may be made in any suitable way, such as by sending, to the storage system **1306**, a request for the container image **1210** and/or the volume **1204**, where the volume **1204** may be used to access the container image **1210**. The storage system **1402** may generate, store, and/or provide volumes comprising one or more container images. However, in contrast to the computing environment **1300**, in computing environment **1400**, the storage system **1402** may be implemented among one or more nodes **410** and **420** of the cluster **408**.

[0327] The storage system **1402** may be implemented similarly to storage system **402** and **504**, where the storage system **1402** may comprise fewer, additional, or all features described above with respect to storage system **402** and **504**.

[0328] Deployment and redeployment of containers may be performed by a container orchestrator, container runtime **1302**, and/or storage system **1402** in computing environment **1400** similarly to the container orchestrator, container runtime **1302**, and/or storage system **1306** described with respect to FIG. **13**.

[0329] FIG. **15** illustrates an example computing environment **1500** that uses a volume **1204** comprising a container image **1210** according to some implementations.

[0330] In computing environment **1500**, similar to computing environment **1300**, a container orchestrator may deploy or redeploy a container among nodes **420** of a cluster **408**. The container orchestrator may communicate information about a deployment of the container to a container runtime **1302** running on a node **420**. As described with respect to computing environment **1300**, based on the received information, the container runtime **1302** may communicate with a storage system **1306** to request a container image **1210**. By contrast to the above example, in this example, the container runtime **1502** may use volume data to directly or indirectly access a cloud-based object store **348** that stores the volume **1204**. In some examples, the cloud-based object store **348** may be provided by a third-party cloud services provider, where the cloud-based object store **348** may serve as a repository for volumes comprising container images without comprising features described with respect to the container-aware storage system **504**. In this example, volume data may be used to mount a volume, or may comprise volume metadata, including container metadata and/or storage metadata. Based on access to the volume **1204**, the container runtime **1502** may access a container image **1210** to create a container instance, as described with respect to FIG. **13**.

[0331] Continuing this example, the container orchestrator may interpret a configuration file to determine that a container image is associated with a volume stored within a data store, such as the cloud-based object storage **348**. For example, the configuration file may comprise an identifier that is associated with one or more container images within the volume **1204**. The configuration file may comprise information indicative of deployment of the container within the container system, including numbers of replicas, storage parameters, among other configuration information.

[0332] As described with respect to FIG. **12**A, a container orchestrator may redeploy a container by spinning down a container on one node (e.g., a first node) and spinning up the container on another node (e.g., a second node). The container orchestrator may spin down a container on the first node in any suitable way, including using traditional mechanisms. In some examples, the spinning down may include unmounting a volume used by the container, such as by unmounting a volume comprising one or more container images used to run the container on the first node. The container orchestrator may spin up the container on the second node as described herein with respect to using a volume comprising one or more container images. For example, the container orchestrator may determine to redeploy the container from the first node to the second node of the container system. Based on determining to redeploy the container, the container orchestrator may provide volume data indicative of the volume to a container runtime on the second node.

[0333] In certain implementations, the configuration file may comprise a mount point on the node **420** where the container runtime **1502** may access the data store via the mounted volume **1204**. The container runtime **1502**, based on access to the volume **1204** via the mount point, may use the data volume module **1304** to access one or more container images **1210** associated with the volume

1204.

[0334] In other examples, the container orchestrator may provide the container runtime **1502** with an identifier for the container image **1210**. Based on the identifier, the container runtime **1502** may request volume data from a storage system storing a volume associated with the identifier, as described with respect to FIGS. **13-14**. For example, the container runtime **1302** may send a request **1308-1** to the storage system **1306** and receive the volume data **1310-1** that may be used to access the volume **1204**. In some examples, volume data may comprise an identifier for the container image **1210** and may be used by the container runtime **1502** to access the volume **1204**.

[0335] FIGS. **16-18** illustrate flowcharts depicting example methods that use a volume **1204** comprising a container image **1210** according to some implementations. While the flowcharts **1600**, **1700**, and **1800** depict illustrative operations according to some embodiments, other embodiments may omit, add to, reorder, combine, and/or modify any of the operations shown in the flowcharts. In some implementations, one or more of the operations shown in the flowcharts may be performed by a storage system such as the storage system **504**, a container system such as the container system **400** or **502**, any components of the storage system and/or the container system, and/or any implementation of the storage system and/or the container system. For example, the method shown in FIG. **16** may be performed by a storage system **1602**, which may include any of the illustrate storage systems described herein; the method shown in FIG. **17** may be performed by a container orchestrator **1702**, which may include any of the illustrative container orchestrators described herein; and the method shown in FIG. **18** may be performed by a container runtime **1801**, which may include any of the illustrative container runtimes described herein.

[0336] As shown in FIG. **16**, an example method includes: receiving, at **1604**, a request comprising an identifier indicative of a container image, where the request is associated with a node of a cluster of a container system, and where the storage system is associated with the container system; identifying, at **1606**, based on the identifier, a volume comprising one or more layers of a container; and providing, at **1608**, in response to the request, volume data indicative of the volume.

[0337] Receiving, at **1604**, the request comprising the identifier indicative of a container image may be implemented as described with respect to FIGS. **12**A-**15**. For example, as described with respect to FIG. **13**, the storage system **1306** receives a request **1308-1** from a container runtime **1302**.

[0338] Identifying, at **1606**, based on the identifier, the volume may be implemented as described with respect to FIGS. **12**A-**15**. For example, as described with respect to FIG. **13**, the storage system **1306** may use volume metadata **1206** and/or container metadata **1208** to identify a container image **1210** and/or corresponding volume based on an identifier.

[0339] Providing, at **1608**, in response to the request, volume data indicative of the volume may be implemented as described with respect to FIGS. **12**A-**15**. For example, as described with respect to FIG. **13**, the storage system **1306** provides volume data **1310-1** to the container runtime **1302**.

[0340] As shown in FIG. **17**, an example method includes: determining, at **1704**, an identifier indicative of a container image, where the container image is associated with a node of a cluster of a container system; identifying, at **1706**, based on the identifier, a volume comprising one or more layers of a container; and providing, at **1708**, to a container runtime within the container system, volume data indicative of the volume.

[0341] Determining, at **1704**, the identifier indicative of the container image may be implemented as described with respect to FIGS. **12**A-**15**. For example, as described with respect to FIG. **15**, a container orchestrator **1702** may interpret a configuration file to determine an identifier of the container image **1210**.

[0342] Identifying, at **1706**, based on the identifier, the volume comprising one or more layers of a container may be implemented as described in with respect to FIGS. **12**A-**15**. For example, with respect to FIG. **15**, a container orchestrator may identify the volume **1204** by requesting volume data and providing the identifier to the cloud-based object store **348**.

[0343] Providing, at **1708**, to a container runtime within the container system, volume data indicative of the volume may be implemented as described with respect to FIGS. **12**A-**15**. For example, based on the volume data, the container orchestrator may provide the container runtime **1502** with a mount point associated with the volume **1204** or with the volume data.
[0344] As shown in FIG. **18**, an example method includes: receiving, at **1802**, by a container runtime within a container system, an identifier indicative of a container image; identifying, at **1804**, by the container runtime and based on the identifier, a volume comprising one or more layers of a container; and, at **1806**, accessing, based on mounting the volume on a node of the container system, the container image.
[0345] Receiving, at **1802**, the identifier indicative of the container image may be implemented as described with respect to FIGS. **12**A-**15**. For example, as described with respect to FIG. **15**, the container runtime **1502** may receive an identifier indicative of a container image from a container orchestrator.
[0346] Identifying, at **1804**, based on the identifier, the volume comprising one or more layers of a container may be implemented as described with respect to FIGS. **12**A-**15**. For example, as described with respect to FIG. **13**, the container runtime **1302** may send a request **1308-1** to the storage system **1306** and receive the volume data **1310-1**.
[0347] Accessing, at **1806**, based on mounting the volume on a node of the container system, the container image may be implemented as described with respect to FIGS. **12**A-**15**. For example, as described with respect to FIG. **13**, the container runtime **1302** may use the volume data **1310-1** to mount the volume **1204** on node **420-1**, where the mounted volume **1204** may be accessed using one or more storage system operations.
[0348] In certain implementations, a recovery process determines to recover a container operating on a node of a container system and recovers the container onto a recovery node by using a volume comprising a container image for the container. The volume may be stored in a storage system and may be instantiated on the recovery node by a container runtime that mounts the volume and accesses the container image over a storage area network. The recovery process may be implemented as part of a storage system, a container orchestrator, or as part of both a storage system and container orchestrator.
[0349] The recovery process may determine to recover the container based on the detection of one or more events that have been defined as events that will or may lead to recovery of a container. For example, the recovery process may detect one or more of: a container failure, a performance degradation associated with a container or containerized application, or a security threat associated with a container. In response to detecting one or more of these events, the recovery process may determine to recover a container affected by the event(s).
[0350] In response to determining to recover a container, the recovery process may initiate recovery of the container using various techniques. As a first example, the recovery process may provide a container runtime on a recovery node with volume data, where the container runtime on the recovery node may use the volume data to access a container image usable to instantiate the container on the recovery node. As a second example, the recovery process may provide an identifier associated with a container image to the container runtime on the recovery node, where the container runtime may use the identifier to obtain volume data for the container image. The container runtime may use the volume data to mount a volume including the container image and, through the mounted volume, access and use the container image to instantiate the container on the recovery node.
[0351] Based on using a volume to recover a container, the recovery of the container may be performed faster than if the recovery of the container were performed using traditional techniques such as downloading the container image to local storage on the recovery node. In addition, based on using a volume to recover a container, the recovery process may use a storage area network, which may avoid the transfer of container image data onto the recovery node from affecting other

container system network traffic using other communication networks. In contrast, in traditional container systems, recovery of a container may use communication networks used by other network processes and applications. Use of communication networks used by other container system applications may degrade performance of the applications as a container runtime accesses a container image on a remote repository. The use of volumes to recover containers may help prevent or reduce the high demands that are conventionally placed on resources (e.g., network resources) when a large number of containers are recovered from one node (e.g., due to a node failure or lack of performance on the node) to one or more recovery nodes.

[0352] FIG. **19**A illustrates an example computing environment **1900** in which container recovery using volumes comprising container images is implemented according to some implementations. The storage system **1306** may be implemented similarly to one or more of the storage systems described with respect to FIGS. **1**A-**18**. The container system may be implemented similarly to one or more of the container systems described with respect to FIGS. **1**A-**18**.

[0353] As depicted in FIG. **19**A, within a cluster **408** of a container system, nodes **420-1-420-**L may comprise respective container instances **512-1-512-**L. In this example, the container instance **512-1** may comprise a containerized application **404-1** and the container instance **512-**L may comprise a containerized application **404-**L.

[0354] A recovery process module **1902** may implement the recovery process. The recovery process module **1902** may be implemented as part of either a container orchestrator, a storage system such as the storage system **1306**, or a combination of a container orchestrator and a storage system. The container orchestrator, such as the container orchestrator implemented by orchestration system **508**, may be implemented as described above with respect to FIG. **5** or in any other suitable way.

[0355] In certain implementations, the recovery process may determine, based on data such as node data and/or container data, to recover a container operating on a first node onto a second node. In some examples, such data may comprise telemetry data **1904**, which may include any information about a node and/or containers running on the node and may be provided from nodes **420** to recovery process module **1902**. For example, node data may comprise a status of a given node, such as an indication of failure, an indication of an error state, or some other indication associated with a status of the given node.

[0356] Telemetry data **1904** may indicate storage resource metrics for a node, such as IOPS, latencies, storage capacity, load data, among other metrics associated with operation of a given node. Based at least on the telemetry data **1904**, the recovery process may determine that a particular node has failed, does not satisfy a performance threshold, does not satisfy a service level agreement, or is otherwise identified for recovery of one or more containers operating on the node. Continuing this example, based on determining to recover a container, the recovery process may initiate recovery of one or more containers on the node onto one or more recovery nodes. A performance threshold may be indicative of a particular number of IOPS, a latency value, storage capacity data, load data, or any other metric indicated by the telemetry data **1904**.

[0357] Monitor **1906** may be used to determine telemetry data. The monitor **1906** may be implemented as part of either a container orchestrator or a storage system **1306**. The monitor **1906** may provide the telemetry data **1904** to the recovery process. The monitor **1906** may determine telemetry data **1904** by receiving the telemetry data **1904** from one or more monitor agents **1908** running on the nodes **420**.

[0358] Monitor agent **1908** may determine the telemetry data **1904** in any suitable way, including using one or more traditional techniques. For example, the monitor agent **1908** may use services such as DZone™ NR1™ Grafana™, Kubernetes™ tools, among other solutions. The monitor agent **1908** may provide the telemetry data **1904** to the container orchestrator and/or the storage system **1306** via a node **420** network interface **1910**.

[0359] Continuing this example, based on determining to recover the container operating on the first node onto the second node, the recovery process may initiate the recovery using various techniques.

[0360] As a first technique, the recovery process may determine, based on a container image associated with the container, volume data indicative of a volume comprising the container image. For example, the recovery process may be part of a container orchestrator and may request volume data from the storage system **1306**, where the request may indicate the requested container image. A response to the request may be received from the storage system **1306** and may indicate volume data for a volume comprising the container image. Examples of use of the container image to determine an associated volume is described with respect to FIGS. **5-11**. In certain examples, the container orchestrator may determine the volume data based on a deployment file that specifies the container image. The container orchestrator may request the volume data from the storage system **1306**, where the request may indicate the container image and a response received from the storage system **1306** may indicate volume data for the volume comprising the container image.

[0361] Based on the volume data, the recovery process may initiate the recovery of the container from the first node to the second node such as by providing the volume data to a container runtime on the second node. In this example, the container runtime on the second node may use the volume data to mount the volume comprising the container image, where the volume is stored by the storage system **1306**.

[0362] As described with respect to FIGS. **5-18**, based on the storage system **1306** storing the volume, the volume may be accessed over a storage area network. In some examples, the volume may, in addition to comprising the container image, comprise storage associated with an application operating within the container. The storage may comprise state information of the application, files, data objects, or other data used by the application that may be used to spin up the container and the application on the second node in a state that replicates the container and application as it existed on the first node. Use of a volume to include both container images and storage is described in greater detail with respect to FIGS. **5-18**.

[0363] As a second technique, the recovery process may determine a container image associated with the container, where a volume comprises the container image. For example, the recovery process may access a deployment file associated with the container, where the deployment file may include an indication of the container image. In this example, the recovery process may initiate, based on the container image, recovery of the container from the first node to the second node by providing information such as an identifier for the container image to a container runtime operating on the second node. As described with respect to FIGS. **5-18**, the container runtime may use the information such as the identifier to request the container image or volume data associated with the volume comprising the container image from the storage system **1306**, where the request may indicate the container image (e.g., by including an identifier and/or other information indicating the container image).

[0364] FIG. **19**B illustrates another example computing environment **1900** in which container recovery using volumes comprising container images is implemented according to some implementations.

[0365] As depicted in FIG. **19**B, the recovery process may determine to recover a container **512-1** operating on a first node **420-1** onto a second node, where the second node is depicted as recovery node **1912**.

[0366] In this example, a containerized application **404-1** may be operating within a container instance **512-1**, and a volume **1204** may comprise a container image **1210** associated with the container instance **512-1**. The volume **1204** may also comprise container storage **1222** associated with operation of the containerized application **404-1**. As the containerized application **404-1** operates, it may generate resource data **1914** comprising one or more of: state data, files, data objects, or other types of data generated and written to container storage **1222** by the containerized application **404-1**.

[0367] As described with respect to FIG. **19**A, initiating recovery by the recovery process may comprise the container runtime **1302** on the recovery node **1912** using volume data **1916** to mount volume **1204** onto the recovery node **1912**. Based on the mounted volume **1204** on the recovery node, the container runtime **1302** may create the container instance **512-1** and initiate the containerized application **404-1** based on accessing the container image **1210** and accessing the resource data **1914** stored within the container storage **1222**.
[0368] FIG. **20** illustrates a flowchart **2000** depicting a method for container recovery using volumes comprising container images according to some implementations. While the flowchart **2000** depicts illustrative operations according to some embodiments, other embodiments may omit, add to, reorder, combine, and/or modify any of the operations shown in the flowchart.
[0369] In some implementations, one or more of the operations shown in the flowchart may be performed by a storage system such as the storage system, a container system such as the container system **400** or **502**, any components of the storage system **1306** and/or the container system (e.g., a container orchestrator and/or a container runtime), and/or any implementation of the storage system and/or the container system.
[0370] As shown in FIG. **20**, an example method includes: determining, at **2002**, by a recovery process and based on node data, to recover a container operating on a first node onto a second node, where a container image is associated with the container; determining, at **2004**, by the recovery process and based on the container image, volume data indicative of a volume comprising the container image; and initiating, at **2006**, by the recovery process and based on the volume data, recovery of the container from the first node onto the second node.
[0371] In this example, operations of the flowchart **2000** may be performed in any of the ways described herein, including as described in reference to FIGS. **19**A and **19**B.
[0372] FIG. **21** illustrates a flowchart **2100** depicting a method for container recovery using volumes comprising container images according to some implementations. While the flowchart **2100** depicts illustrative operations according to some embodiments, other embodiments may omit, add to, reorder, combine, and/or modify any of the operations shown in the flowchart.
[0373] In some implementations, one or more of the operations shown in the flowchart may be performed by a storage system such as the storage system, a container system such as the container system **400** or **502**, any components of the storage system **1306** and/or the container system (e.g., a container orchestrator and/or a container runtime), and/or any implementation of the storage system and/or the container system.
[0374] As shown in FIG. **21**, an example method includes: determining, at **2102**, by a recovery process and based on node data, to recover a container operating on a first node onto a second node, where a container image is associated with the container; determining, at **2104**, by the recovery process, a container image associated with the container, where a volume comprises the container image; and initiating, at **2106**, by the recovery process and based on the container image, recovery of the container from the first node onto the second node.
[0375] In this example, operations of the flowchart **2100** may be performed in any of the ways described herein, including as described in reference to FIGS. **19**A and **19**B.
[0376] In some embodiments, a recovery process is provided that prioritizes container layers in a manner that, compared to other container recovery processes, may reduce downtime and/or may more quickly or efficiently recover containers from one compute location to another compute location, such as from one cluster of compute nodes to another cluster of compute nodes. For example, a recovery process may determine to recover containerized applications running on first cluster to a second cluster, meaning that the containerized applications will be deployed and run on the second cluster starting at a state of the containerized applications as they existed on the first cluster at a point in time. The determination may be made in any suitable way, such as by receiving a recovery request from an element of a container system (e.g., an orchestrator) or from an element of a container storage system that provides persistent storage to the container system. The recovery

may be requested for any suitable reason(s), such as because of performance or predicted performance of the first cluster, utilization load of the first cluster, failure of one or more components of the first cluster, etc.

[0377] FIGS. **22**A-**22**E illustrate an example configuration **2200** in which a recovery process is applied in accordance with some embodiments of the present disclosure. The recovery process depicted in these figures is illustrative. Other examples of the recovery process are contemplated and may include additional and/or alternative operations.

[0378] As shown in FIGS. **22**A-**22**E, the configuration **2200** includes a first cluster **2202-1** of compute nodes **2204-1** through **2204-**K ("first compute nodes **2204**") and a second cluster **2202-2** of compute nodes **2204-**M through **2204-**X ("second compute nodes **2204**"). Containerized applications **2206-1** through **2206-**L ("containerized applications **2206**") are running on the first set of compute nodes **2204** in the first cluster **2202**.

[0379] A first storage system **2208-1** is a container-aware storage system that provides storage services to the containerized applications **2206** running on the first cluster **2202-1**. To this end, the first storage system **2208-1** maintains a first dataset **2210-1** that includes immutable layers **2212** and mutable layers **2214**. In some implementations, the immutable layers **2212** and mutable layers **2214** are stored and managed as volumes such as described herein. In some implementations, the first storage system **2208-1** may include or be implemented as any of the illustrative container storage systems described herein.

[0380] The immutable layers **2212** include container layers, such as layers of container images (e.g., an operating system layer, and application layer, etc.), that do not change or only seldomly change. For example, the container images may be unchangeable by normal data writes and can only be changed by code updates, such as an update to an operating system layer or application layer. The first storage system **2208-1** may provide the immutable layers **2212** of container images to the first compute nodes **2204** for use by the first compute nodes **2204** to run instances of the container images, such as in any of the ways described herein.

[0381] The mutable layers **2214** include container layers that may change during normal operations, such as when IO requests write data to the mutable layers **2214**. The first storage system **2208-1** may provide the mutable layers **2214** to the first compute nodes **2204** as persistent storage for use by the first compute nodes **2204** to read and write data. The first compute nodes **2204** may access, from the first storage system **2208-1**, and use the immutable layers **2212** and the mutable layers **2214** to run the containerized applications **2206** on the first cluster **2202-1**.

[0382] In certain embodiments, one or more of the immutable layers **2212** may include or be implemented as immutable layer **706** shown in FIG. **7**B, and one or more of the mutable layers **2214** may include or be implemented as writable layer **708** shown in FIG. **7**B. Immutable layers **2212** and mutable layers **2214** may be implemented in any other suitable way in other embodiments.

[0383] Configuration **2200** may further include a recovery process module **2220** configured to provide a recovery process, which may be any recovery process described herein. The recovery process module **2220** may be implemented in the storage system **2208** as shown, in any other suitable storage system (container-aware storage system **504**), and/or by any element(s) of the first cluster **2202-1** and/or a container system such as container system **400**.

[0384] In some examples, the recovery process may perform operations to recover the container applications **2206** from the first cluster **2202-1** to the second cluster **2202-2**. The recovery process may be performed in a manner that prioritizes layers in the first dataset **2210-1** relative to one another in a manner that provides one or more benefits, which may include faster recovery time, less downtime, more efficient processing, etc.

[0385] The recovery process may perform operations to intelligently prepare in advance for a future recovery event. For example, the recovery process may identify a set of the immutable layers **2212** included in the first dataset **2210-1** and copy the identified set of immutable layers **2212** to the second cluster **2202-2**. The copying of the identified set of immutable layers **2212** to the second cluster **2202-2** is represented by dashed line **2222** in FIG. **22**A.

[0386] The identified set of immutable layers **2212** may include container images or layers of container images included in the dataset **2210-1** maintained by the first storage system **2208-1**, which layers may be represented as layers of volumes, such as snapshots of volumes as described above. In some examples, the recovery process may identify and include all such immutable layers **2212** of the dataset **2210-1** in the identified set of immutable layers **2212**. In other examples, the recovery process may identify and include only unique immutable layers **2212** of the dataset **2210-1** in the identified set of immutable layers **2212**. Thus, the identified set of immutable layers **2212** may include only unique, non-duplicative instances of immutable layers **2212**. The recovery process may identify the set of immutable layers **2212** in any suitable way. For example, the immutable layers **2212** may be labeled (e.g., as container images), and the recovery process may use the labels to identify layers as immutable layers. As another example, the recovery process may be configured to use modification metadata associated with layers in the dataset to determine when layers were last modified, and any layers that have not been modified within a time threshold may be identified as immutable layers.

[0387] After the set of immutable layers **2212** has been identified, the recovery process may copy the identified set of immutable layers **2212** to the second cluster **2202-2**. The copying may be performed in any suitable way that makes a copy of the set of immutable layers **2212** usable by the second cluster **2202-2** to deploy instances of the container applications **2206** on nodes **2204-**M through **2204-**X of the second cluster **2202-2**. As an example, the recovery process may copy the immutable layers **2212** from the first storage system **2208-1**, which provides storage services to the first cluster **2202-1**, to a second storage system **2208-2** that is configured to provide storage services to the second cluster **2202-2**. The second storage system **2208-2** may be implemented similar to the first storage system **2208-1** and may maintain and use a second dataset **2210-2** to provide storage services to the second cluster **2202-2**. The set of immutable layers **2212** may be copied from the first dataset **2210-1** of the first storage system **2208-1** to the second dataset **2210-2** as shown in FIG. **22**A, after which the copied immutable layers **2212** may be used by the second storage system **2208-2** to deploy instances of the container applications **2206** on nodes **2204-**M through **2204-**X of the second cluster **2202-2**.

[0388] In some implementations, the recovery process may avoid copying duplicative immutable layers to the second cluster **2202-2**. For example, as part of copying the set of immutable layers **2212** from the first cluster **2202-1** to the second cluster **2202-1**, the recovery process may check whether the second cluster **2202-2** already has a copy of an immutable layer before copying the immutable layer to the second cluster **2202-2**. If the second cluster **2202-2** already has a copy of an immutable layer, that copy may be referenced and used by the recovery process without having to copy the immutable layer from the first cluster **2202-1** to the second cluster **2202-1** as part of copying the set of immutable layers **2212** from the first cluster **2202-1** to the second cluster **2202-1**.

[0389] The recovery process may identify and copy the set of immutable layers **2212** from the first cluster **2202-1** to the second cluster **2202-2** in advance of a recovery event in preparation for such a recovery event. Accordingly, when a recovery event occurs after the set of immutable layers **2212** has been identified and copied from the first cluster **2202-1** to the second cluster **2202-2**, the set of immutable layers **2212** is already available for use by the second cluster **2202-2** to recover the containerized applications **2206** from the first cluster **2202-1** to the second cluster **2202-2**. Because the set of immutable layers **2212** has already been copied in advance in preparation for the recovery event, the set of immutable layers **2212** need not be copied from the first cluster **2202-1** to the second cluster **2202-1** as part of or in response to the recovery event. Compared to traditional recovery techniques, this may reduce downtime of the containerized applications **2206** being recovered and/or may make the recovery process more efficient.

[0390] The set of immutable layers **2212** may be identified and prioritized for advance copying in this manner at least because the immutable layers **2212** seldomly change and/or are not allowed to be changed by IO requests associated with normal operations of the containerized applications **2206**. Thus, the set of immutable layers **2212** may be unlikely to change between the time they are copied to the second cluster **2202-2** and a time when a recovery event occurs. In addition, if the set of immutable layers **2212** in the first dataset **2210-1** of the first cluster **2202-1** changes after being copied to the second cluster **2202-2**, such as when an immutable layer of a container image is updated or added to the first dataset **2210-1**, the recovery process may detect the updated or new immutable layer in the set of immutable layers **2212** in the first dataset **2210-1** and copy the updated or new immutable layer to the second cluster **2202-2** in advance of a recovery event.

[0391] After the set of immutable layers **2212** are copied to the second cluster, the recovery process may receive a recovery request to recover the containerized applications. The recovery request is represented as recovery request **2224** in FIG. **22**B. The recovery request may be associated with a recovery event and may be received by the recovery process from any suitable source. For example, an orchestrator of a container system or a storage system that provides storage services to the container system may detect a recovery event, which event may include a set of one or more conditions that make recovery of container applications from one cluster to another cluster desirable. Examples of such conditions may include, without limitation, performance of a cluster falling below or predicted to fall below a performance threshold, utilization of a cluster reaching or predicted to reach a utilization threshold, failure or predicted failure of one or more compute nodes or storage resources of a cluster, load balancing or rebalancing, or any other condition(s). Upon detecting the recovery event, the orchestrator or storage system of the container system may provide a recovery request that may be received (e.g., detected) by the recovery process in any suitable way.

[0392] The request may include any information associated with the recovery event and/or recovery of containerized applications. For example, the recovery request may indicate a target compute location, such as a second cluster, to which containerized applications will be recovered.

[0393] In response to the recovery request, the recovery process copies the set of mutable layers **1214** of the first dataset **1210-1** to the second cluster **2202-2**. The copying may be performed in any suitable way that makes a copy of the set of mutable layers **2214** usable by the second cluster **2202-2** to deploy instances of the container applications **2206** on nodes **2204-**M through **2204-**X of the second cluster **2202-2**. As an example, the recovery process may identify and copy the mutable layers **2214** from the first dataset **2210-1** of the first storage system **2208-1** to the second dataset **2210-2** of the second storage system **2208-2**. The set of immutable layers **2212** may be copied from the first dataset **2210-1** of the first storage system **2208-1** to the second dataset **2210-2** is represented by dashed line **2226** shown in FIG. **22**B.

[0394] After the mutable layers **2214** are copied to the second cluster **2202-2**, the second cluster **2202-2** may use the copied set of immutable layers **2212** and the copied set of mutable layers **2214** to recover the containerized applications **2206** on the second cluster **2202-2**. This may include the second cluster **2202-2** using the immutable layers **2212** to deploy the containerized applications **2206** on nodes **2204-**M through **2204-**X of the second cluster **2202-2** and the containerized applications **2206** accessing and using the mutable layers **2214** to start operations of the containerized applications **2206** at a recovery point in time at which the containerized applications **2206** existed on the first cluster **2202-1**. To this end, the second storage system **2208-2** may make the copied set of immutable layers **2212** and the copied set of mutable layers **2214** accessible to nodes **2204-**M through **2204-**X of the second cluster **2202-2**, such as in any of the ways described herein. FIG. **22**C illustrates the containerized applications **2206** recovered on nodes **2204-**M through **2204-**X of the second cluster **2202-2**.

[0395] As the containerized applications **2206** run on the second cluster **2202-2**, the copy of the set of mutable layers **2214** in the second dataset **2210-2** associated with the second cluster **2202-2** may be updated (e.g., written to) by the containerized applications **2206**. The updated set of mutable layers **2214** is represented as updated mutable layers **2228** in FIG. **22**D.

[0396] After the containerized applications **2206** have been recovered on the second cluster **2202-2** and have created the updated set of mutable layers **2228** in the second dataset **2210-2**, the recovery process may receive a request to recover the containerized applications **2206** back from the second cluster **2202-2** to the first cluster **2202-1**.

[0397] The recovery request may be associated with a recovery event and may be received by the recovery process from any suitable source. For example, an orchestrator of a container system or a storage system that provides storage services to the container system may detect a recovery event, which event may include a set of one or more conditions that make recovery of container applications back to the first cluster **2202-1** desirable. Examples of such conditions may include, without limitation, performance of the first cluster **2202-1** being restored to a performance threshold, utilization of the first cluster **2202-1** reaching or predicted to reach a utilization threshold, recovery of one or more compute nodes or storage resources of the first cluster **2202-1**, increased capacity of the first cluster **2202-1**, load balancing or rebalancing, or any other condition(s). Upon detecting the recovery event, the orchestrator or storage system of the container system may provide a recovery request that may be received (e.g., detected) by the recovery process in any suitable way.

[0398] The recovery request is represented as recovery request **2230** in FIG. **22**D. The request may include any information associated with the recovery event and/or recovery of containerized applications.

[0399] In response to the recovery request, the recovery process identifies and copies, from the second cluster **2202-2** to the first cluster **2202-1**, any mutable layers that have changed on the second cluster **2202-2**. In some implementations, this includes identifying and copying only the mutable layers that have been modified since the mutable layers **1214** were copied from the first cluster **2202-1** to the second cluster **2202-2**. The copying of the updated mutable layers from the second dataset **2210-2** of the second storage system **2208-2** to the first dataset **2210-1** is represented by dashed line **2232** shown in FIG. **22**D.

[0400] After the updated mutable layers **2228** are copied to the first cluster **2202-1**, the first cluster **2202-1** may use the set of immutable layers **2212** and the copied set of updated mutable layers **2228** to recover the containerized applications **2206** back on the first cluster **2202-1**. This may include the first cluster **2202-1** using the immutable layers **2212** to deploy the containerized applications **2206** on nodes **2204-1** through **2204**-K of the first cluster **2202-1** and the containerized applications **2206** accessing and using the updated mutable layers **2228** to start operations of the containerized applications **2206** at a recovery point in time at which the containerized applications **2206** existed on the second cluster **2202-2**. To this end, the first storage system **2208-1** may make the set of immutable layers **2212** and the copied set of updated mutable layers **2228** accessible to nodes **2204-1** through **2204**-K of the first cluster **2202-1**, such as in any of the ways described herein. FIG. **22**E illustrates the containerized applications **2206** recovered on nodes **2204-1** through **2204**-K of the first cluster **2202-1**.

[0401] FIGS. **23-25** illustrate example container recovery methods in accordance with some embodiments of the present disclosure.

[0402] As shown in FIG. **23**, an example method **2300** includes: identifying, at **2302**, a set of immutable layers included in a dataset used to run containerized applications on a first cluster; copying, at **2304**, the set of immutable layers to a second cluster in preparation for a recovery event; receiving, at **2306**, a recovery request to recover the containerized applications; copying, at **2308** and in response to the recovery request, a set of mutable layers included in the dataset to the second cluster; and using, at **2310**, the copied sets of immutable and mutable layers to recover the containerized applications on the second cluster. In this example, operations of the method **2300** may be performed in any of the ways described herein, including as described in reference to FIGS. **22**A-**22**C.

[0403] As shown in FIG. **24**, an example method **2400** includes: detecting, at **2402**, an updated or new immutable layer in a dataset; and copying, at **2404**, the updated or new immutable layer to a second cluster in preparation for a recovery event. In this example, operations of the method **2400** may be performed in any of the ways described herein, including as described in reference to FIGS. **22**A-**22**C.

[0404] As shown in FIG. **25**, an example method **2500** includes: receiving, at **2502**, a recovery request to recover containerized applications back from a second cluster to a first cluster; identifying and copying, at **2504** and from the second cluster to the first cluster, any mutable layers that have changed on the second cluster (e.g., any mutable layers that have changed after a set of mutable layers was copied to the second cluster); and using, at **2506**, any copied mutable layers that changed on the second cluster to recovery the containerized applications on the first cluster. In this example, operations of the method **2500** may be performed in any of the ways described herein, including as described in reference to FIGS. **22**D-**22**E.

[0405] In certain embodiments, a recovery process such as any of those described herein may be configured to prioritize more frequently used layers over less frequently used layers for one or more of the recovery operations described herein. As an example, a copying of immutable layers may include the recovery process prioritizing more frequently used immutable layers over less frequently used immutable layers, such as by copying more frequently used immutable layers first. As another example, a copying of mutable layers may include the recovery process prioritizing more frequently used mutable layers over less frequently used mutable layers, such as by copying more frequently used mutable layers first.

[0406] While certain illustrative examples have been described for recovering containerized applications from one cluster to another cluster, one or more of the operations described herein may be applied to recover containerized applications from any first compute location and resources to any second compute location and resources. For example, containerized applications may be recovered, in any of the ways described herein, from one node to another node in a same cluster.

[0407] As mentioned, one or more of the recovery operations described herein may be performed by a container-aware storage system, which may use its awareness of containers to optimize one or more aspects of disaster recovery of the storage system. To illustrate an example, the container-aware storage system may determine usage of specific layers of data and/or types of layers of data, such as immutable layers, container image layers, mutable layers, volume layers, etc., and utilize the usage and/or types of layers to prioritize one or more disaster recovery operations. In some implementations, this may include identifying mutable layers (layers that store mutable data such as persistent data being written by containerized applications) and immutable layers (layers that store immutable container image layers) and processing the different types of layers differently and/or in a prioritized manner for disaster recovery purposes, including in any of the ways described herein.

[0408] In some examples, the storage system may be configured to prepare a backup copy of data that may be used to recover from a disaster, such as by using the backup copy of the data to recover containerized applications from one compute location to another compute location. The storage system may preload the backup with immutable layers that are unlikely to change or that change less often that mutable data. For example, container image layers may be treated as immutable layers that are only modified when a containerized application is updated. The storage system may preload the backup with such immutable layers in advance in preparation for a recovery event.

[0409] In some implementations, a primary cluster of nodes running containerized applications prepares a secondary cluster for recovery. The preparation includes the storage system identifying immutable layers of container images and copying them over to the secondary cluster in advance. Then when a recovery event occurs and containerized applications are to be recovered from the primary cluster to the secondary cluster, a recovery process may copy over mutable layers to the second cluster to get things running on the secondary cluster. When the primary cluster comes back up, it already has the immutable layers and old mutable layers and can focus on looking for mutable layers that have changed and copying those over from the secondary cluster. This may allow the movement of running containerized applications from the primary cluster to the secondary cluster and from the secondary cluster back to the primary cluster to be performed in an optimized manner.

[0410] In some embodiments, a server or host application running on one or more server clusters, such as a container storage management system running on one or more server clusters, and a storage system that provides storage resources for use by the server clusters may be configured to work together to provide one or more technical benefits. To illustrate, a containerized application run-time environment (e.g., Docker software or the like) may operate on a server cluster (e.g., on server systems in a cluster). Containerized applications may be started and run in the containerized application run-time environment operating on servers of the server cluster as directed by a container management platform (e.g., a container orchestrator such as Kubernetes). A container storage management system may operate on the server cluster and may support the running of containerized applications on the server cluster. For example, the container storage management system may interact with a storage system to generate, store, and/or provide container images for containerized applications (e.g., in any of the ways described above), which container images are used to run the containerized applications on the server cluster. Additionally, the container storage management system may provide persistent storage used by running containerized applications to read and write data of the containerized applications (e.g., in any of the ways described above). The providing of persistent storage may include creating and providing virtual storage entities (e.g., virtual volumes), which are used by the container management platform to provide storage entities to the containerized applications. The container storage management system maps the virtual storage entities to storage resources (e.g., pools of storage devices) of a storage system that stores and manages data of the containerized applications, which data may include the container images used to run the containerized applications and/or data written to persistent storage by the containerized applications.

[0411] The container storage management system and the storage system may be configured to work together to provide one or more technical benefits. For example, the container storage management system may selectively leverage one or more capabilities of the storage system to perform certain functions, instead of using capabilities of the container storage management system and/or server cluster. Examples of capabilities of a storage system being leveraged by a container storage management system are described herein. In some embodiments, the container storage management system and the storage system may be configured to work together to provide container layer storage management that supports deployment and operation of containerized applications on server clusters, which management may leverage one or more storage system capabilities to support efficient recovery of containerized applications across server clusters.

[0412] Containerized applications, which may be referred to as containers, are typically formed using two mechanisms: copying container images that contain a tree of files (often these are from git repositories, but they can be from other sources) and layering file trees on top of each other with logical insertions, deletions, and replacements, such that a final set of files for a container are composed by some number of stages of adding, replacing, and removing files that come from the images. These base images are often presumed to be immutable, in that the set of files corresponding to the image for a particular identifier is always the same and in that they can be copied but not modified. This is true of git repositories where a version of a repository is identified by a unique identifier which corresponds only to that version. Base images can also be referred to by more generic identifiers (such as a particular distribution of Linux or a named application) for which there may be multiple immutable versions and for which one version is the most current, or where there might be a most current patch level for a particular named or numbered version (e.g., like naming updates to Windows 11 or updates to SQL Server 15 (commonly called SQL Server

2019)). In that case, the rules for constructing a container might not name a specific version, but when constructing the container, the container image management system will still copy a specific immutable version.
[0413] An illustrative rule for constructing an image for a virtual machine can often be abstracted as something like: [0414] copy image X [0415] overlay image Y and remove files X**1**, X**2**, . . . [0416] overlay image Z and remove files Y**1**, Y**2**, . . . [0417] . . .
[0418] This will copy images X, Y, and Z and construct an image by starting with the tree of files in X, removing zero or more files X**1**, X**2**, and so on, and overlaying the tree of files in Y (with files in both X and Y being replaced by the files in image Y), and then repeating that by removing the zero or more files Y**1**, Y**2**, and so on and overlaying the tree of files in Z, and repeating for as many edits as are represented. Images X, Y, and Z in these examples may refer to specific immutable images or to some more generic name for a set of immutable versions for a named versioned dataset.
[0419] Rules for creating a container image could also contain file edits, which are commonly used for adding or replacing entries in configuration files.
[0420] More generally, the rules for creating a container image describe a set of commands that can do the above by copying images, running commands to modify a constructed image, and copying the content of images over the container image being constructed. Rules can also configure virtual and other networking interfaces and addresses, add users, mount directories for use by the container, and so on.
[0421] Running a container, then, involves executing the root processes for the container in an execution environment that associates the constructed image, and any additionally mounted directories, with that execution environment in a sandboxed environment where the operating system executing the processes of the container limits what those processes can see and interact with to only those directory trees and virtual or other network addresses configured for use by the container's processes.
[0422] A container storage management system may be configured to operate to copy images and apply rules to construct container images from copied images. The container storage management system can further support one or more clusters of server systems that can run containers. A single cluster shares some namespace of constructed images and provides a distributed environment for concurrent sharing of constructed images through a network.
[0423] In an implementation in which the container storage management system operates in a distributed fashion and shares storage devices that are each local to a respective server system in a server cluster, particular data may be resident on storage devices in a subset of the server systems in the cluster, and so reading and writing a particular data item may involve transferring that data over a network to a server system that locally stores that data item.
[0424] The container storage management system can improve reliability in the face of server failures and improve read performance by mirroring or otherwise redundantly storing the data items across the server systems. An additional technique beyond mirroring is to use erasure coding (e.g., RAID-5 or RAID-6) to store shards of data and some number (denoted R) of parity shards across systems (in this case server systems) such that at least some data items may be local to particular systems and so that any data item can be reconstructed from remaining systems as long as no more than R systems are unavailable.
[0425] In this implementation, copying images (such as immutable images) between clusters generally involves copying the content of images between clusters. If optimized replication techniques are used, then it is possible to reduce the data copied by using compression and/or deduplication fingerprints to identify already copied data segments, or by calculating a difference between an image, or set of images, known to be at the target of the copy and some new image that is not yet copied to that target.
[0426] If instead of using storage devices that are each local to a respective server system, storage

is provided by an external storage system, such as a block volume server, a file server, or an object server, then that storage can be leveraged by all the server systems that share the storage system, and any data item that is accessible to one of the server systems can be accessed by any second server system as long as access to that data item by the second system is configured and authorized. With a block volume server, in particular, low latency, low overhead, and high bandwidth interfaces such as NVMe over fabric can be used to get performance that can come relatively close to rivaling local storage and that can exceed the performance from transferring data between server systems through their own networks. And for any storage type, the external storage systems may have more sophisticated mechanisms of ensuring data availability, reliability, durability, and manageability, and that can provide storage at higher densities than are typical with storage devices integrated directly into server system enclosures.

[0427] With external storage servers, all server systems in a cluster can share all images used by a cluster without transferring data items in images over the server-to-server network, and can also share images between clusters without copying the data between clusters, as long as the server systems in a second cluster are configured with network access and the necessary authorizations to access that data.

[0428] Data management functions in storage systems can further be leveraged to optimize how datasets for images can be provided and managed. Snapshots can provide immutable datasets. Clones of snapshots or of other clones can be used to provide modifiable copies from base immutable datasets that themselves remain unchanged. Clones in particular may be used to make mutable copies of base datasets that can be shared to server systems or clusters with separate access permissions, which may be used to provide identical base data to multiple clusters, for example, without those clusters sharing access (as each cluster is provided with its own separately modifiable image).

[0429] Data optimization functions including compression and deduplication can further reduce the physical capacity needed to store a set of images. In particular, operating system images can compress relatively effectively, and minor and even major variants of operating systems and applications can have a fair amount of data in common that can result in effective cross-image deduplication. Further, the fact that these images that deduplicate against each other can be shared effectively to a relatively large number of server systems can reduce the physical storage capacity across server systems and storage systems needed for sets of clusters of server systems running containers to operate against their containers.

[0430] Storage systems may be used that support sophisticated forms of replication including synchronous and nearly synchronous replication to store the same images at multiple locations. Snapshot-based and difference-based replication provided by storage systems may be configured to make use of knowledge of blocks or fingerprints of blocks already transferred to reduce the amount of data that needs to be transferred between locations in order to transfer additional images between those locations. This may be leveraged by the container storage management system to replicate images to other locations that might be needed to recover and restart a set of containers, or an application constructed of containers, at one of those locations, potentially enabling more efficient disaster recovery capabilities.

[0431] In some implementations, storage systems may be used that have virtual copy capabilities. These virtual copy capabilities may be used as an alternative way to merge multiple datasets together, such as by virtually copying files, or to transform images stored as file systems stored in a block volume into files stored in a file server, or as objects stored in an object server, or from a file server to a file system in a block volume, or into objects of an object server, etc. File system format conversions are also contemplated, such as converting from a file system embedded in a virtual machine image stored as a VMDK file in an NFS file server, or as a file in a VMFS file system, for an application that had been hosted in a set of virtual machines on VMware, into a volume formatted as an EXT4 file system storing the files of the embedded file system that could then be

mounted by a Linux server and used as an image for a container. The same types of transformations could also be done in reverse, where an image for a container, or a merged image generated from a set of layered images to form a container, could be merged with an operating system image to form a virtual machine image stored as a VMDK file on NFS or within a VMFS file system. VMware is used here as an example. This could also be done as a transformation into and out of QEMU, KVM, or any other hypervisor-based virtual machine platform with executables and directory structures that are compatible with a container platform.
[0432] In some implementations, data stored as objects may be copied (e.g., virtually copied in some examples) into files of a file server or file system, or into blocks of a block volume. In some examples, this may be used to bypass network copying and additional space consumption associated with copying immutable images from an object store to form the contents of a run-time file system. If the data stored in objects is in a compressed format (e.g., in a compressed archive format), the file system may recognize the compressed format and directly support reading files in the compressed format such that the virtual copying may be usefully applied to the compressed object data.
[0433] In some implementations, storage systems may be used that support managed directories. Storage systems supporting managed directories can further define datasets as collections of files supporting management operations that can be applied to managed directories (e.g., to all contents of a managed directory as a group), including snapshots, cloning, and replication policies.
[0434] For example, base images stored as immutable managed directory snapshots may be cloned to form a base image as a directory, and that directory may be edited by deleting files, modifying files, and overlaying files from another immutable directory using virtual file copy operations. The result may be a new managed directory that represents a new image. This may then be frozen (by disallowing updates or by making a snapshot to represent the frozen image) to represent another base image, and the process may repeat until a complete base container image is formed. From there, a clone of the container image can be used to create a mutable image which can be provided as a managed directory by the storage system to a container management service to run directly from that managed directory. Any modifications to that clone may be preserved or discarded just as would be the case with any modifiable clone.
[0435] FIG. **26** illustrates an example configuration **2600** in which a container storage management framework may coordinate with a storage system to leverage one or more capabilities of the storage system in accordance with embodiments of the present disclosure. For example, a recovery process may be performed to recover a container from a first server cluster **2602-1** to a second server cluster **2602-2** in a way that leverages data management and/or capabilities of the storage system. As another example, the container storage management framework may leverage capabilities of the storage system to form datasets for containers in an efficient manner.
[0436] As shown in FIG. **26**, configuration **2600** includes a first server cluster **2602-1** of servers **2604-1** through **2604**-K ("first servers **2604**") and a second cluster **2602-2** of servers **2604**-M through **2604**-X ("second servers **2604**"). Servers **2604** may include any computing entities (e.g., nodes such as nodes **2204**, hosts, virtual machines, physical computing devices, etc.) on which containerized applications may be run. FIG. **26** shows an instance of a containerized application **2606-1** running on server **2604-1** of server cluster **2602-1** and a containerized application **2606-2** running on server **2604**-M of server cluster **2602-2**. As will be described, containerized application **2606-2** running on server **2604**-M of server cluster **2602-2** may be a recovered instance of containerized application **2606-1** running on server **2604-1** of server cluster **2602-1**.
[0437] A containerized application run-time environment **2608-1** operates on first server cluster **2602-1** (e.g., on first servers **2604**), and a containerized application run-time environment **2608-2** operates on second server cluster **2602-2** (on second servers **2604**). Containerized application **2606-1** runs in containerized application run-time environment **2608-1** as directed by a container management platform **2610-1** coresident with containerized application run-time environment

2608-1 on first server cluster **2602-1**, and containerized application **2606-2** runs in containerized application run-time environment **2608-2** as directed by a container management platform **2610-2** coresident with containerized application run-time environment **2608-2** on second server cluster **2602-2**.

[0438] A container storage management framework **2612-1** operates on the first server cluster **2602-1** in any suitable way. Container storage management framework **2612-1** may be considered to be associated with containerized application run-time environment **2608-1** for one or more reasons, which may include container storage management framework **2612-1** providing container images used by containerized application run-time environment **2608-1** to run containerized applications in the containerized application run-time environment **2608-1**, container storage management framework **2612-1** providing persistent storage for use by containerized applications running or to be run in the containerized application run-time environment **2608-1**, container storage management framework **2612-1** being in communication with containerized application run-time environment **2608-1** and/or containerized applications running in containerized application run-time environment **2608-1**, and/or container storage management framework **2612-1** implemented as one or more containerized applications (that operate as container storage management systems) running in containerized application run-time environment **2608-1**. Similarly, configuration **2600** further includes a container storage management framework **2612-2** of containerized application run-time environment **2608-2** operating on second server cluster **2602-2**.

[0439] As shown in FIG. **26**, configuration **2600** further includes a first storage system **2614-1** and a second storage system **2614-2**. Storage systems **2614** may include, provide, or be in communication with one or more storage resources on which data may be stored. Storage systems **2614** and their respective storage resources may include and/or be implemented as any of the storage systems (e.g., any of storage systems **100**, **117**, **124**, **306**, **318**, **348**, **374**, **504**, **1202**, **1306**, **1602**, **2208**) and storage resources (e.g., any of storage resources **170**A-B, **308**, **424**) described herein or may be implemented in any other suitable way. First storage system **2614-1** may include a controller **2615-1** configured to control operations of first storage system **2614-1**, and second storage system **2614-2** may include a controller **2615-2** configured to control operations of first storage system **2614-2**. Controllers **2615** may be configured to control and/or perform operations of storage systems **2614**, including any of the illustrative operations of storage systems described herein. Controllers **2615** may be implemented as any of the storage system controllers (e.g., any of controllers **110**A-D, **101**, **119**, **212**, **242**, **244**, **246**) described herein or in any other suitable way. In some implementations, a controller includes non-transitory computer-readable instructions that when executed direct one or more computer processors to perform one or more of the operations of storage systems described herein.

[0440] First storage system **2614-1** (e.g., controller **2615-1** of first storage system **2614-1**) and container storage management framework **2612-1** of first server cluster **2602-1** may be in communication with one another. Accordingly, container storage management framework **2612-1** may utilize storage resources and/or capabilities of first storage system **2614-1** to provide data and/or storage features to first server cluster **2602-1** (e.g., to any components of first server cluster **2602-1**, such as the components of first server cluster **2602-1** shown in FIG. **26**). Second storage system **2614-2** and container storage management framework **2612-2** of second server cluster **2602-2** may be configured similarly.

[0441] Container storage management framework **2612-1** may coordinate a storing of container images in first storage system **2614-1**. This may be performed in any suitable way. For example, container storage management framework **2612-1** may form a dataset **2616-1** for a containerized application, such as containerized application **2606-1**, by instructing first storage system **2614-1** to merge collections of files from a set of source datasets **2618** (e.g., source datasets **2618-1** through **2618**-N). In some implementations, the set of source datasets **2618** includes at least one immutable source dataset. Container storage management framework **2612-1** may instruct first storage system **2614-1** to merge collections of files in any suitable way, including any of the ways described above to form dataset **2616-1** by copying images (e.g., image files) from the source datasets **2618** and overlaying and optionally modifying the images based on defined rules, to construct a container image for a containerized application. The container image is configured to be used by a containerized application run-time environment to run a containerized application. The container image may be used and reused by the containerized application run-time environment to start and run instances of the containerized application on first servers **2604** of first server cluster **2602-1**.

[0442] Container storage management framework **2612-1** may coordinate storing of container images in first storage system **2614-1** in any suitable way, such as by instructing first storage system **2614-1** to store container images. In addition, container storage management framework **2612-1** may form datasets for containerized applications in first storage system **2614-1** by instructing first storage system **2614-1** to merge collections of container images (e.g., files storing contents of container images) based on defined rules to form the datasets. First storage system **2614-1** may receive instructions from container storage management framework **2612-1** and perform operations (e.g., copying, storing, merging, modifying, deleting, etc.) based on the instructions. In doing so, first storage system **2614-1** may use its capabilities to perform the operations more efficiently than if the operations were performed by container storage management framework **2612-1**. For example, first storage system **2614-1** may merge files to form a dataset for a containerized application in any of the ways described above, such as by using virtual copy capabilities of first storage system **2614-1**, by reusing data items across various datasets, compressing image data, deduplicating image data, cloning data, etc.

[0443] In some embodiments, container storage management framework **2612-1** may coordinate storing of container images in first storage system **2614-1** by instructing first storage system **2614-1** to retrieve and store images from one or more external sources (e.g., one or more internet-accessible locations). For example, the storage system may be instructed to retrieve a specified dataset from an external source repository such as an internet-accessible GIT repository.

[0444] In some implementations, the container storage management framework and/or the storage system may manage retrieved and stored datasets in a cache of the storage system, or as directories or managed directories storing the retrieved datasets. The storage system may maintain a list of already retrieved datasets from such internet-accessible repositories to avoid retrieving them again. For example, if an image retrieved from an internet-accessible repository is stored as an immutable dataset in the storage system, then future references to the same image can reuse the immutable dataset stored by the storage system. This may reduce load on server-side infrastructure and allow the storage system to serve as a shared cached of internet-accessible container images from multiple sources.

[0445] In forming a dataset for a containerized application, container storage management framework **2612-1** may direct storage system **2614-1** to perform operations to access and perform operations on source datasets **2618**. The source datasets may include mutable datasets, immutable datasets, or a combination of mutable and immutable datasets. The source datasets may include immutable layers **2620-1** and/or mutable layers **2622-1**. Container storage management framework **2612-1** may direct storage system **2614-1** to perform operations to access and perform operations on such mutable and immutable layers, to form the dataset for the containerized application, such as in any of the ways described herein. The dataset may include a structured combination of immutable and/or mutable layers, portions of immutable and/or mutable layers, or modified versions of immutable and/or mutable layers.

[0446] The formed dataset for the containerized application may be implemented in any suitable way and using any suitable data structure format that may be presented to an entity such as any component of a server cluster. In some embodiments, for example, the dataset for the containerized application may be implemented as a volume (e.g., mutable volume) or a set of volumes (e.g., a set of mutable volumes, a set of immutable volumes, or a set of mutable and immutable volumes). For instance, the dataset for the containerized application may be implemented as any volume or set of volumes as described above.

[0447] In some embodiments, the dataset for the containerized application may be implemented as contents of one or more managed directories of a file system that may be presented to an entity such as a component of a server cluster. A managed directory defines a dataset as a collection of files and directories in a way that supports uniform application of storage management functions to all contents of the managed directory as a group. Thus, a managed directory may be a storage management feature that groups together a tree of files and directories to support operations and policies that apply uniformly to the files and directories within the managed directory. The content of the managed directory may be a tree of files and/or directories within the directory tree of the managed directory that, through association with a managed entity, all share an association with management metadata such that one or more storage management functions may be applied to the tree of files and/or directories as a group. For example, the tree of files and/or directories within the directory tree of the management directory may be replicated, cloned, versioned, and/or snapshotted as a group, or restored from a prior snapshot or overwritten as a whole, from another managed directory or from a clone of a managed directory. Management metadata may specify quotas and other limits on capacity consumption, quality of service grouping, capacity and performance reporting, user access controls, and/or selective visibility to content (or even visibility of the existence of content) of the managed directory and its encompassed tree of files and/or directories (such as based on user accessibility or some other characteristic of the file or directory of the access or accessor). Thus, the managed directory provides a storage management structure shared by all files and directories within the managed directory.

[0448] A managed entity may facilitate application of storage management functionality to the content of its associated directory in any suitable way. For example, the managed entity may include, maintain, and/or use management metadata for the content of the directory to apply storage management functionality to the content of the directory as a group. In some embodiments, one or more policies may be associated with (e.g., may be attached to, included in, or otherwise made a property of) the managed entity (e.g. a managed directory) such that those policies are applied by storage management functionality to the content of the directory as a group, at the directory level. For example, one or more policies may be part of or referenced by metadata for the managed directory. The one or more policies may include any suitable type of policy, including for example policies for snapshots, replication, backup, cloning, versioning, garbage collection, compression, encryption, retention, quota management, consumption management, user access controls, user-based visibility filtering, exporting, etc.

[0449] In some embodiments, any directory of a file system may be created as a managed directory. Thus, the root directory may be created as a managed directory and/or any directory or subdirectory within the root directory or the directory tree of the root directory may independently be created as or converted into a managed directory.

[0450] In some embodiments, container storage management framework **2612-1** may combine a dataset (e.g., dataset **2616-1**) stored in an external storage system with a local dataset stored locally at one or more of the first servers **2604** of first server cluster **2602-1**, such as by providing a local read-write dataset to store changes layered on a constructed dataset in the external storage system. This can allow, for example, the local storing of transient data needed for part of a running containerized application where those changes can be discarded when the application shuts down or otherwise stops running on a server.

[0451] Container storage management framework **2612-2** of containerized application run-time environment **2608-2** operating on second server cluster **2602-2** may receive a request for the dataset **2616-1** for the containerized application **2606-1** for recovery of the containerized application **2606-1** on second server cluster **2602-2** (e.g., as containerized application **2602-2** shown in FIG. **26**). Container storage management framework **2612-2** may receive the request from any suitable source, including from container management platform **2610-2**, container storage management framework **2612-2**, and/or a recovery process (e.g., recovery process module **2220** described above) of container storage management framework **2612-1** or **2612-2** or storage system **2614-1** or **2614-2**.

[0452] Based on and/or in response to the request, container storage management framework **2612-2** may coordinate a providing of access to a copy of dataset **2616-1** of the containerized application, by second storage system **2614-2**, to second servers **2604** in second server cluster **2602-2** to enable access by containerized application **2606-2** on second server cluster **2602-2**. Accordingly, the copy of the dataset, which copy is represented as dataset **2616-2** including immutable layers **2620-2** and mutable layers **2622-2** as shown in FIG. **26**, may be accessed and used to start and run containerized application **2602-2** in containerized application run-time environment **2608-2** operating on second server cluster **2602-2**, to recover containerized application from first server cluster **2602-1** to second server cluster **2602-2**.

[0453] Container storage management framework **2612-2** may coordinate the second storage system **2614-2** providing access to a copy of a dataset of a containerized application in various ways. In some examples, this may include container storage management framework **2612-2** instructing second storage system **2614-2** to create a copy of the dataset (e.g., a clone or replica o the dataset) and provide second servers **2604** of second server cluster **2602-2** with access to the copy of the dataset. Second storage system **2612-2** may then use its capabilities to create and provide access to the copy of the dataset. For example, second server system **2612-2** may use replication processes (e.g., snapshot-based replication, difference-based replication, synchronous replication, asynchronous replication, etc.) to efficiently create a replica copy of the dataset, or to identify an existing replica copy of the dataset. In some examples, the second storage system **2612-2** may make the copy of the dataset a clone of the dataset that can be independently modified. In one or more of these operations, second server system **2612-2** may utilize virtual copy capabilities and/or fingerprint-based identification of data to efficiently create a copy of the dataset. In FIG. **26**, dashed arrow **2624** represents creation of a copy of dataset **2616-2** from dataset **2616-1**.

[0454] In some embodiments, a container storage management framework such as container storage management framework **2612-1** or **2612-2** may selectively leverage capabilities of storage systems such as first or second storage system **2614** based on awareness of the storage systems and/or data stored in the storage systems. For example, a container storage management framework may maintain or have access to data indicating where data items of a server cluster **2602** are stored, such as data indicating specific storage resources (e.g., storage devices) and/or locations at which the data items are stored. Additionally or alternatively, a container storage management framework may maintain or have access to data indicating capabilities (e.g., virtual copy, replication, deduplication, compression capabilities) and/or operational states (e.g., loads, utilization rates, etc. such as may be determined based on telemetry data) of storage systems. In some embodiments, a container storage management framework may maintain or access data indicating mappings of storage systems to server clusters, thereby being aware of which storage system or storage system location serves which server cluster.

[0455] In some embodiments, container storage management framework **2612-2** may identify a capability of second storage system **2614-2** and instruct second storage system **2614-2** based on the identified capability. For example, container storage management framework **2612-2** may identify a cloning capability of second storage system **2614-2** and, based on this identification, instruct at least one of the first storage system **2614-1** or the second storage system **2614-2** to create a clone of the dataset.

[0456] While FIG. **26** illustrates first and second storage systems **2614** as separate storage systems, in other embodiments, a single storage system may serve multiple server clusters and perform operations of both the first and second storage systems **2614**. Thus, in some embodiments, the

second storage system is the first storage system.
[0457] FIG. **27** illustrates an exemplary method **2700** of container layer storage management. While FIG. **27** illustrates exemplary operations according to one embodiment, other embodiments may omit, add to, reorder, and/or modify any of the operations shown in FIG. **27**. One or more of the operations shown in FIG. **27** may be performed by a container storage management framework (e.g., one or more instances of a container storage management framework or container storage management system), any components included therein, and/or any implementation thereof.
[0458] In operation **2702**, a container storage management framework, such as a container storage management framework of a containerized application run-time environment operating on a first server cluster, coordinates a storing of container images in a first storage system, including forming a dataset for a containerized application to run on the first server cluster. The dataset may be formed in any suitable way, including by instructing the first storage system to merge collections of files (which may include the container images) from a set of source datasets (which may include at least one immutable source dataset). Operation **2702** may be performed in any of the ways described herein.
[0459] In operation **2704**, a container storage management framework, such as a container storage management framework of a containerized application run-time environment operating on a second server cluster, receives a request for the dataset for recovery of the containerized application on the second server cluster. Operation **2704** may be performed in any of the ways described herein.
[0460] In operation **2706**, a container storage management framework, such as the container storage management framework of the containerized application run-time environment operating on the second server cluster, coordinates, in response to the request, a providing of access to a copy of the dataset of the containerized application, by a second storage system, to servers in the second server cluster to enable access by the containerized application on the second server cluster. Operation **2706** may be performed in any of the ways described herein.
[0461] FIG. **28** illustrates another exemplary method **2800** of container layer storage management. While FIG. **28** illustrates exemplary operations according to one embodiment, other embodiments may omit, add to, reorder, and/or modify any of the operations shown in FIG. **28**. One or more of the operations shown in FIG. **28** may be performed by a storage system, such as any storage system described herein, or any components (e.g., a storage controller) included therein, and/or any implementation thereof.
[0462] In operation **2802**, a storage system stores container images. For example, the storage system may access the container images from one or more sources and store the container images in storage resources of the storage system. Operation **2802** may be performed in any suitable way.
[0463] In operation **2804**, the storage system forms a dataset for a containerized application based on the container images. For example, the storage system may merge collections of files from a set of source datasets (which may include at least one immutable source dataset) based on instructions received from a container storage management framework such as a container storage management framework of a containerized application run-time environment operating on a first server cluster. Operation **2804** may be performed in any of the ways described herein.
[0464] In operation **2806**, the storage system provides the dataset to one or more servers in the first server cluster to run the containerized application on the first server cluster. Operation **2802** may be performed in any suitable way, including in any of the ways described herein.
[0465] In operation **2808**, the storage system creates a copy of the dataset. In some embodiments, the storage system creates the copy of the dataset based on instructions received from a container storage management framework such as a container storage management framework of a containerized application run-time environment operating on the first server cluster or on a second server cluster. In other embodiments, the storage system may create the copy for another reason, such as based on a replication or disaster recovery policy. Operation **2808** may be performed in any of the ways described herein to create any suitable copy of the dataset (e.g., a clone or replica copy

of the dataset).

[0466] In operation **2810**, the storage system provides the copy of the dataset to one or more servers in the second server cluster to recover the containerized application on the second server cluster. Operation **2810** may be performed in any of the ways described herein.

[0467] Advantages and features of the present disclosure can be further described by the following statements: [0468] 1. A method comprising: receiving, by a storage management system configured to provide persistent data storage to workloads managed by a container orchestration platform deployed in a cluster of nodes, a request comprising identifiers indicative of a plurality of layers associated with a virtual machine to be run in the cluster; generating, by the storage management system and based on the request, a virtual machine disk image comprising the plurality of layers, the virtual machine disk image configured to be used to run the virtual machine in the cluster; and providing, by the storage management system and in response to the request, the virtual machine disk image. [0469] 2. The method of any of the preceding statements, wherein providing the virtual machine disk image comprises providing a volume comprising the virtual machine disk image. [0470] 3. The method of any of the preceding statements, wherein providing the volume comprises associating the volume with a persistent volume any of the preceding statements, wherein the volume comprises a Kubevirt data volume. [0471] 4. The method of any of the preceding statements, wherein the volume comprises a Kubevirt data volume. [0472] 5. The method of any of the preceding statements, wherein the request comprises a specification for the Kubevirt data volume. [0473] 6. The method of any of the preceding statements, wherein the request specifies an order in which to combine the plurality of layers to form the virtual machine disk image. [0474] 7. The method of any of the preceding statements, wherein the plurality of layers is: [0475] managed by the storage management system; and [0476] stored at one or more nodes in the cluster of nodes. [0477] 8. The method of any of the preceding statements, wherein the plurality of layers is: [0478] managed by the storage management system; and [0479] stored in a cluster of storage nodes comprising storage resources used by the storage management system to provide the persistent data storage to the workloads managed by the container orchestration platform. [0480] 9. The method of any of the preceding statements, wherein the plurality of layers comprises at least one immutable layer and at least one mutable layer. [0481] 10. The method of any of the preceding statements, wherein the storage management system is implemented as a containerized application managed by the container orchestration platform deployed in the cluster of nodes. [0482] 11. The method of any of the preceding statements, wherein the virtual machine disk image is used by a virtual machine handler associated with the container orchestration platform to run the virtual machine in a virtual machine type pod that is managed by the container orchestration platform. [0483] 12. The method of any of the preceding statements, further comprising: receiving, by the storage management system, a second request comprising identifiers indicative of a second plurality of layers associated with a containerized application to be run in the cluster; generating, by the storage management system and based on the second request, a container image comprising the plurality of layers, the container image configured to be used to run the containerized application in the cluster; and providing, by the storage management system and in response to the second request, the container image. [0484] 13. A computer program product embodied on a non-transitory computer-readable medium and comprising instructions that, when executed, cause a computing device to perform a process comprising: receiving, by a storage management system configured to provide persistent data storage to workloads managed by a container orchestration platform deployed in a cluster of nodes, a request comprising identifiers indicative of a plurality of layers associated with a virtual machine to be run in the cluster; generating, by the storage management system and based on the request, a virtual machine disk image comprising the plurality of layers, the virtual machine disk image configured to be used to run the virtual machine in the cluster; and providing, by the storage management system and in response to the request, the virtual machine disk image. [0485] 14. The computer program product of any of the preceding statements, wherein providing the virtual machine disk image comprises providing a volume comprising the virtual machine disk image. [0486] 15. The computer program product of any of the preceding statements, wherein providing the volume comprises associating the volume with a persistent volume any of the preceding statements, wherein the volume comprises a Kubevirt data volume. [0487] 16. The computer program product of any of the preceding statements, wherein the volume comprises a Kubevirt data volume. [0488] 17. The computer program product of any of the preceding statements, wherein the request comprises a specification for the Kubevirt data volume. [0489] 18. The computer program product of any of the preceding statements, wherein the request specifies an order in which to combine the plurality of layers to form the virtual machine disk image. [0490] 19. The computer program product of any of the preceding statements, wherein the virtual machine disk image is used by a virtual machine handler associated with the container orchestration platform to run the virtual machine in a virtual machine type pod. [0491] 20. A system comprising: at least one processor; and at least one memory storing instructions executable by the at least one processor to: receive, by a storage management system configured to provide persistent data storage to workloads managed by a container orchestration platform deployed in a cluster of nodes, a request comprising identifiers indicative of a plurality of layers associated with a virtual machine to be run in the cluster; generate, by the storage management system and based on the request, a virtual machine disk image comprising the plurality of layers, the virtual machine disk image configured to be used to run the virtual machine in the cluster; and provide, by the storage management system and in response to the request, the virtual machine disk image.

[0492] In some embodiments, a storage management system may be configured to perform operations associated with deployment of virtual machines by a container orchestration platform deployed in a cluster of nodes. In some implementations, the storage management system may include any of the illustrative container storage systems described herein that is further configured to perform operations associated with deployment of virtual machines by a container orchestration platform. Examples of such illustrative operations of the storage management system are described herein. The container orchestration platform may include any of the illustrative container orchestration systems or platforms described herein that is further configured to perform operations associated with virtualization and/or deployment of virtual machines in a cluster of nodes. In some embodiments, the software management system and the container orchestration platform may support deployment of both containerized application workloads and virtual machine workloads in a cluster of nodes. This may allow certain of the same features, operations, primitives, and interfaces of the container orchestration platform to be used to deploy container-based workloads and virtual machine-based workloads in a cluster of nodes (e.g., a server cluster of servers).

[0493] FIG. **29** illustrates a distributed workload management and execution system **2900**. In this example, storage pool **406**, cluster **408**, node **410**, controller **412**, API server **414**, scheduler **416**, agent **418**, nodes **420**, virtual volumes **422**, storage resources **424**, and container runtime **1302** may be implemented in any of the ways described above. Controller **412**, scheduler **416**, API server **414** and agent **418** may be components of a container orchestration system or platform (e.g., Kubernetes or another container orchestration platform) deployed in a cluster of nodes and configured to simplify and/or automate deployment, scaling, and management of containerized applications in the cluster of nodes. Accordingly, system **2900** may be configured to deploy, scale, and manage containerized applications (e.g., container instances) in cluster **408**, in any of the ways described herein.

[0494] System **2900** is further configured to deploy, manage, and execute virtual machine workloads in cluster **408**. For example, system **2900** includes a virtualization controller **2902** and a virtualization API **2904** implemented on node **410**, and a virtualization agent **2906** implemented on each of nodes **420**. Virtualization controller **2902**, API **2904**, and agent **2906** may be configured as extensions to the container orchestration platform of system **2900** that support virtualization operations and deployment and execution of virtual machines by the container orchestration platform. For example, the extended container orchestration platform may be configured to deploy and manage virtual machine-based workload in cluster **408**. Accordingly, system **2900** may be configured to support deployment, scaling, and management of both container workloads and virtual machine workloads by the container orchestration platform deployed in cluster **408**. In FIG. **29**, such workloads are represented as workloads **2908** (e.g., workloads **2908-1** through **2908-**L) that are deployed to and running on nodes **420** (e.g., nodes **420-1** through **420**-N).

[0495] Workloads **2908** may include one or more containerized applications that are deployed by the container orchestration platform (e.g., controller **412** and/or scheduler **416**) to one or more nodes **420** and that run on container runtime **1302** (e.g., a container runtime environment) deployed on the nodes **420**. Workloads **2908** may additionally or alternatively include one or more virtual machines that are deployed by the extended container orchestration platform (e.g., controller **2902**) to one or more nodes **420** and that run in a virtualized environment provided by virtualization agent **2906** and/or a type of virtualization data structure (e.g., a virtual machine type of pod defined for the container orchestration platform), which data structure may include one or more components for running a virtual machine.

[0496] In some embodiments, the container orchestration platform may be an implementation of Kubernetes deployed in cluster **408** and extended with an implementation of Kubevirt deployed in cluster **408**. For example, virtualization controller **2902** may include an implementation of a Kubevirt virt-controller, virtualization API **2904** may include an implementation of a Kubevirt virt-API, and virtualization agent **2906** may include an implementation of a Kubevirt virt-handler. In such embodiments, Kubernetes may be configured to handle container pods as it normally does, where a container pod is created by Kubernetes when a pod specification is posted to the Kubernetes API server and the specification is transformed into an object of a specific type (referred to as a specific “kind” in the specification). A container pod type object is detected and handled by the Kubernetes controller(s) to deploy the pod and any containers in the pod.

[0497] Kubevirt may use the same mechanism by defining one or more additional object types that are added to the Kubernetes API, additional controllers for cluster-wide operations for the new object types (e.g., Kubevirt virt-controller), and additional daemons for node specific operations for the new object types (e.g., Kubevirt virt-handler). Accordingly, virtual machine pods (e.g., virtual machine instance type pods, which may be referred to as VMI type pods) may be created when a certain pod specification is posted to the Kubernetes API server and the specification is transformed into an object of the virtual machine pod type. This object is detected and handled by the Kubevirt controller(s) to deploy the virtual machine type pod to a node of cluster **408** on which the virtual machine type pod is used by the Kubevirt handler on the node to run a virtual machine on the node.

[0498] The virtual machine type pod may include components configured to support running, on the node to which the virtual machine type pod is deployed, a virtual machine represented by the pod. For example, the virtual machine type pod may include or implement a Kubevirt virt-launcher that contains a process that runs the virtual machine using QEMU. The virtual machine type pod may include any libraries or other assets for use to run the virtual machine, such as a hypervisor, for example. The Kubevirt virt-launcher ensures pod isolation and that each virtual machine gets the required resources. The Kubevirt virt-launcher may also provide virtual machine status updates to the Kubevirt virt-handler running on the node. The Kubevirt virt-handler running on the node (e.g., as a DaemonSet) to which the virtual machine type pod is deployed may be configured to perform operations to get the virtual machine running and to a desired state on the node (e.g., including providing instructions to the Kubevirt virt-launcher on launching the virtual machine and required dependences), handle communications between the node and the virtual machine, and send telemetry data from the virtual machine to the Kubevirt virt-controller.

[0499] For illustrative purposes, certain example embodiments described herein are described in the context of a Kubevirt/Kubernetes implementation. It will be appreciated that in other embodiments, the container orchestration platform deployed in cluster **408** may be an implementation of Mesos, Docker Swarm, a proprietary container orchestration/management system, or another container orchestration system that is deployed in cluster **408** and extended to support virtualization and deployment of virtual machines on the container orchestration system deployed in cluster **408**.

[0500] System **2900** further includes a storage management system **2912** configured to perform one or more storage management operations to organize, provision, and/or manage storage resources for use by one or more workloads **2908** deployed or to be deployed in cluster **408**. In particular, storage management system **2912** may organize storage resources into one or more storage pools of storage resources, such as storage pool **406**. Storage management system **2912** may use the organized storage resources and/or storage pools to provide persistent storage to workloads **2908**, for use by workloads **2908** to write data to and/or read data from the persistent storage. In some implementations, the providing of persistent storage may include providing virtual volumes **422** that are mounted to nodes **420** and configured to receive storage operations from workloads **2908** and map those storage operations to backing logical volumes, such as described herein. Storage management system **2912** may be configured to perform any of the management functions for providing persistent storage to workloads **2908** that are described herein, including any of the functions of container storage system **402** and/or container storage management framework **2612** described above.

[0501] Storage management system **2912** may be configured to interface with one or more components of system **2900**, including one or more of controller **412**, scheduler **416**, API server **414**, agent **418**, container runtime **1302**, virtualization controller **2902**, virtualization API **2904**, and virtualization agent **2906**. In some implementations, storage management system **2912** may be configured to use a container storage interface (CSI) model to communicate and/or integrate with an extended container orchestration platform such Kubernetes extended with Kubevirt.

[0502] In some embodiments, storage management system **2912** may be software defined and may itself be deployed as a containerized application by a container orchestration system. For example, storage management system **2912** may be deployed as a privileged container pod managed by the container orchestration system and/or running in container runtime **1302** in cluster **408**.

[0503] In conventional implementations of Kubevirt, virtual machines may be run, deployed, and managed with Kubernetes as the underlying orchestration platform. Accordingly, virtual machine workloads may be deployed using Kubernetes primitives. In a typical Kubevirt implementation, Kubernetes receives a virtual machine deployment request specifying a virtual machine disk image and resource requirements of a virtual machine. Kubevirt schedules a virtual machine type pod to run the virtual machine. The virtual machine type pod contains a Kubevirt Qemu/KVM hypervisor instead of a regular container runtime (e.g., Docker) container. Instead of using a container runtime, Kubevirt launches a KVM-based virtual machine inside the virtual machine type pod.

[0504] The virtual machine deployment request may include a data volume specification that indicates a data volume is to be provided for the virtual machine type pod. Kubernetes/Kubevirt may create a persistent volume claim (PVC) and provide the data volume specification to storage management system as a request for a data volume to be associated with the PVC and the virtual machine type pod.

[0505] FIG. **30** illustrates two examples of volume request specifications that may be received by Kubernetes (e.g., by controller **412**) and/or provided by Kubernetes to storage management system **2912** as a request for a data volume. A first volume request specification **3002** is configured to cause creation of a configuration file that defines a data volume in Kubevirt and for which five gigabytes of storage are allocated for the volume. The source section of the specification **3002** specifies that the volume is to be populated with data from an external HTTP URL, which data represents a virtual machine raw disk image.

[0506] Based on this specification, Kubevirt uses the URL to access and import the virtual machine disk image from a source external of the Kubevirt/Kubernetes cluster, typically from a web server over an Internet connection. A containerized data importer (CDI) of Kubevirt receives a virtual machine disk image, puts the disk image in a data volume that is attached to a virtual machine type pod (e.g., by associating the data volume to the PVC of Kubernetes/Kubevirt). However, the process of importing a virtual machine disk image in this manner requires virtual machine disk images, such as Qcow2 and/or raw disk images to be maintained in a web server and pulled as needed. This slows down the process of providing a data volume and using the data volume to deploy a virtual machine in the cluster. The process also requires that the Kubevirt CDI be deployed in the Kubernetes cluster and used to import virtual machine disk images into a virtual machine disk image.

[0507] Rather than using the traditional process to import and use virtual machine disk images to provide Kubevirt data volumes, storage management system **2912** may be configured to store and manage layers, and to use the layers to generate and provide virtual machine disk images as data volumes to Kubevirt to use to deploy and run virtual machines in the cluster (e.g., on the container orchestration platform deployed in the cluster). With storage management system **2912** configured to provide virtual machine disk images in this manner, the need to maintain a web server that stores virtual machine disk images is eliminated, and the Kubevirt CDI is not needed or used to import the virtual machine disk images into Kubvirt data volumes. Because virtual machine disk images can be obtained from storage management system **2912** instead of from a web server that is external of the cluster, the process of deploying virtual machines in the cluster can be performed faster, allowing virtual machines to be more efficiently deployed in the cluster. In addition, there is no need to install the Kubevirt CDI in the Kubernetes cluster. One or more of these improvements is a technical improvement in the technical field of a container orchestration/management system deploying virtual machines in a cluster of nodes.

[0508] Storage management system **2912** may be configured to receive, store, and manage layers. The layers may include code, such as software code, in any format suitable to be executed and/or used by a computing device such as a computer processor. The layers may be considered layers because they may be combinable to form a layered data structure such as a container image containing one or more hierarchically arranged container image layers or a virtual machine disk image containing one or more hierarchically arranged virtual machine image layers. The layers may be modular such that they may be combinable in various ways to form various container images and/or virtual machine disk images.

[0509] Storage management system **2912** may be configured to store the layers as data structures having any suitable data format and/or specifications, including for example as objects in object storage, volumes in block storage, files in file storage, or in any other suitable data storage protocol or format.

[0510] Storage management system **2912** may be configured to store and maintain metadata for the layers. For example, such metadata may include identifiers for the layers and any information about attributes of the layers, including any hierarchical relationships and/or dependencies between the layers. In some examples, the metadata may indicate whether layers are mutable or immutable image layers.

[0511] Immutable layers are image layers that do not change or only seldomly change. For example, immutable layers may be unchangeable by normal data writes and can only be changed by code updates, such as an update to an operating system layer or application layer. Immutable layers may include container image layers, virtual machine image layers, and/or any other image layers that include code that is executable by a computing device and unchangeable by normal data writes from workloads running in the cluster.

[0512] Mutable layers are layers that may change during normal operations, such as when input/output (IO) requests write data to the mutable layers. Mutable layers may include code that is executable by a computing device and/or persistent data storage that may be written to and/or read from by workloads **2908**.

[0513] Storage management system **2912** may store and manage data representative of the layers at any suitable logical or physical location. In some implementations, storage management system **2912** stores data representative of layers within a compute cluster, such as at one or more compute nodes in a cluster in which a container orchestration platform is deployed (e.g., at one or more nodes of cluster **408**). In some implementations, storage management system **2912** stores data representative of layers within a location that is accessible by the storage management system **2912** by way of a storage area network connection. The storage area network connection may be any suitable storage area network protocol-based connection that supports one or more storage communication protocols and does not include or use the Internet or Internet protocols. In some implementations, storage management system **2912** stores data representative of layers within a cluster of storage nodes comprising storage resources used by the storage management system to provide persistent data storage to the workloads managed by the container orchestration platform and running in cluster **408**. Such a cluster of storage nodes may be referred to as storage cluster and may include nodes on which storage management system **2912** is deployed and/or nodes that are accessible by storage management system **2912** using a communications network of storage management system **2912**.
[0514] The layers may be implemented in any of the ways described herein, including in relation to container image layers, immutable layers (e.g., immutable layers **2620**), and mutable layers (e.g., mutable layers **2622**). In some embodiments, layers storage and managed by storage management system **2912** may include layers usable to form container images, layers usable to form virtual machine images, and layers usable to form both container images and virtual machine images.
[0515] Storage management system **2912** may receive a request for a virtual machine disk image. The request may be received from a component of an extended container orchestration platform, such as virtualization controller **2902**, virtualization API **2904**, controller **412**, and/or API server **414**. In some examples, the request may include a request for a volume to be associated with a persistent volume claim of the container orchestration platform.
[0516] In some embodiments, the request may include a data volume specification indicating a requested data volume, resource requirements, and information to use to populate the data volume. However, instead of the request including an identifier for a single virtual machine disk image to be obtained using an HTTP URL, the request may include identifiers indicative of layers that are stored and managed by storage management system **2912**, such as a plurality of layers that are associated with a virtual machine to be run in a cluster.
[0517] In FIG. **30**, a second volume request specification **3004** is shown. The second volume request specification **3004** is configured to cause creation of a configuration file that defines a data volume in Kubevirt and for which five gigabytes of storage are allocated for the volume. The source section of the specification **3004** specifies that the volume is to be populated with data representative of multiple layers. Specifically, as shown in the example specification **3004**, the specification **3004** includes identifiers **3006** indicative of a plurality of layers, namely a first layer identified as “Immutable Layer” and a second layer identified as “Mutable Layer.” The identifiers may include or may be indicated in the context of a path indicating where data representative of the layers can be accessed. While the example shows the request to include identifiers **3006** indicating two layers—one immutable layer and one mutable layer, a request may indicate any suitable number and/or combination of layers, including a combination of immutable layers, a combination of mutable layers, or a combination of immutable layers and mutable layers (e.g., at least one immutable layer and at least one mutable layer).
[0518] The request may specify an order in which to combine layers to form a virtual machine disk image. For example, in the example specification, the layers are ordered with layer[0] first and layer[1] second, indicating that layer[0] is the first layer, and layer[1] is the second layer that is to be layered on top of the first layer. Thus, “Mutable layer” will be arranged on top of “Immutable Layer” when the requested data volume is generated by storage management system **2912**.

[0519] Storage management system **2912** may generate, based on the request (e.g., volume request specification **3004**), a virtual machine disk image that includes the layers identified in the request. In particular, storage management system **2912** may be configured to use the identifiers indicative of the layers to access data representative of the layers from indicated data storage locations and process the data to combine the layers, such as in a hierarchical layered order that is indicated in the request. Storage management system **2912** may perform one or more operations on the data to put the combined layers into a virtual machine disk image format, such as a Qcow2 disk image, a raw disk image, or any other virtual machine disk image format or data that is similar to and can be used in the same way as a virtual machine disk image to deploy and run a virtual machine. The virtual machine disk image generated by storage management system **2912** may include one or more virtual machine disk images, such as one or more Qcow2 and/or raw disk images.
[0520] In some implementations, storage management system **2912** may put the generated virtual machine disk image in a data format, which data format may be hard-code-defined in storage management system **2912** or may be selected by storage management system **2912** based on the request specifying the data format. As an example, the request may include a Kubevirt data volume specification that requests a Kubevirt data volume be provided that includes the layers indicated in the request.
[0521] Storage management system **2912** may provide the virtual machine disk image in response to the request. For example, storage management system **2912** may provide data representative of the virtual machine disk image to one or more components of a container orchestration platform extended to support deployment of virtual machines on the container orchestration platform (e.g., to one or more components of Kubevirt to use to deploy and run a virtual machine on Kubernetes). For example, storage management system **2912** may provide the virtual machine disk image to virtualization controller **2902** (e.g., a Kubevirt controller) and/or virtualization agent **418** (e.g., a Kubevirt handler).
[0522] In some implementations, storage management system **2912** may provide the virtual machine disk image by generating and providing a volume that includes the virtual machine disk image. In some examples, this may include associating the volume with a persistent volume claim (PVC) of the container orchestration platform (e.g., a PVC associated with a virtual machine type pod of the container orchestration platform) such that the volume is configured to be used by one or more components of a container orchestration platform extended to support deployment of virtual machines on the container orchestration platform. For example, virtualization agent **2906**, which may be a Kubevirt virt-handler, may be configured to launch and run a virtual machine on a node using the virtual machine disk image included in a volume provided by storage management system **2912** and associated with a Kubernetes PVC and virtual machine type pod. In other words, a virtual machine handler associated with the container orchestration platform, such as a Kubevirt virt-handler, may use the virtual machine disk image included in a volume that is associated with a virtual machine type pod, which is deployed by the container orchestration platform to a node, to run the virtual machine in a virtual machine type pod on the node.
[0523] As described above, because storage management system **2912** generates and provides the volume using layered images as described herein, the virtual machine is deployed faster (e.g., with less latency) than if the volume were generated and provided using only conventional techniques that require a disk image of the virtual machine to be obtained from an external web server.
[0524] FIG. **31** two examples of a disk image that may be provided to one or more components of Kubevirt or Kubernetes in response to a request for a volume to be used to run a virtual machine in a cluster. A first example disk image **3102** includes a single monolithic virtual machine disk image containing code needed to launch and run an Apache Server virtual machine. In particular, disk image **3102** includes operating system code (e.g., CentOS code) and Apache server code. Disk image **3102** may be generated and provided in response to receiving volume request specification **3002** shown in FIG. **30**.

[0525] Conversely, a second example disk image **3104** includes a plurality of layered arranged hierarchically to form disk image **3104**. In particular, disk image **3104** includes an operating system immutable base image (e.g., CentOS minimal base image) as a first layer, an operating system additional packages mutable layer (e.g., CentOS additional packages installed layer) as a second layer arranged on the first layer, a web server mutable installation layer (e.g., Apache web server installation layer) as a third layer arranged on the second layer, and a web server mutable configuration layer (e.g., Apache web server configuration) as a fourth layer arranged on the third layer. Disk image **3104** may be generated and provided in response to receiving volume request specification **3004** shown in FIG. **30**.

[0526] By storing, management, and using modular layers to generate virtual machine disk images and container images as described herein, resources such as data storage resources and network bandwidth resources may be conserved. For example, there is no need to maintain two separate data storage sources, one for storing container images in a container registry and a second for storing virtual machine disk images, and support two separate communication interfaces. Rather, storage management system **2912** may store layers usable for generating container images and virtual machine disk images and provide a single interface to be used to access and use the layers for form such images.

[0527] FIG. **32** illustrates an exemplary method **3200** for deploying a virtual machine on a container orchestration platform. While FIG. **32** illustrates exemplary operations according to one embodiment, other embodiments may omit, add to, reorder, and/or modify any of the operations shown in FIG. **32**. The operations shown in FIG. **32** may be performed by a storage management system **3201**, which may be storage management system **2912** or any other storage management system or framework configured to provide persistent storage to workloads running in a cluster of nodes (e.g., workloads managed by a container orchestration platform deployed in the cluster) and to perform method **3200**.

[0528] In operation **3202**, the storage management system receives a request comprising identifiers indicative of a plurality of layers associated with a virtual machine to be run in a cluster. The request may be received in any suitable form and may include a data volume specification received from one or more components of a container orchestration platform extended to support deployment of virtual machines on the container orchestration platform. Operation **3202** may be performed in any of the ways described herein.

[0529] In operation **3204**, the storage management system generates, based on the request, a virtual machine disk image comprising the plurality of layers. Operation **3204** may be performed in any of the ways described herein and may include using the identifiers in the request to identify and access data representative of the plurality of layers, and to process the data to combine the layers in a specified order or hierarchy to form the virtual machine disk image. In some embodiments, the virtual machine disk image may be generated as a volume or included in a volume, such as a Kubevirt data volume, based on one or more parameters specified in the request.

[0530] In operation **3206**, the storage management system provides, in response to the request, the virtual machine disk image. Operation **3204** may be performed in any of the ways described herein. For example, the storage management system may provide a volume containing the disk image to one or more components (e.g., a Kubevirt handler) of the extended container orchestration platform to use to deploy and run a virtual machine on the container orchestration platform. As described above, in some examples, the providing of the volume comprises associating the volume with a persistent volume claim (PVC) of the container orchestration platform.

[0531] In the preceding description, various illustrative embodiments have been described with reference to the accompanying drawings. It will, however, be evident that various modifications and changes may be made thereto, and additional embodiments may be implemented, without departing from the scope of the invention as set forth in the claims that follow. For example, certain features of one embodiment described herein may be combined with or substituted for features of another embodiment described herein. The description and drawings are accordingly to be regarded in an illustrative rather than a restrictive sense.

Claims

1. A method comprising: receiving, by a storage management system configured to provide persistent data storage to workloads managed by a container orchestration platform deployed in a cluster of nodes, a request comprising identifiers indicative of a plurality of layers associated with a virtual machine to be run in the cluster; generating, by the storage management system and based on the request, a virtual machine disk image comprising the plurality of layers, the virtual machine disk image configured to be used to run the virtual machine in the cluster; and providing, by the storage management system and in response to the request, the virtual machine disk image.
2. The method of claim 1, wherein providing the virtual machine disk image comprises providing a volume comprising the virtual machine disk image.
3. The method of claim 2, wherein providing the volume comprises associating the volume with a persistent volume claim of the container orchestration platform.
4. The method of claim 2, wherein the volume comprises a Kubevirt data volume.
5. The method of claim 4, wherein the request comprises a specification for the Kubevirt data volume.
6. The method of claim 1, wherein the request specifies an order in which to combine the plurality of layers to form the virtual machine disk image.
7. The method of claim 1, wherein the plurality of layers is: managed by the storage management system; and stored at one or more nodes in the cluster of nodes.
8. The method of claim 1, wherein the plurality of layers is: managed by the storage management system; and stored in a cluster of storage nodes comprising storage resources used by the storage management system to provide the persistent data storage to the workloads managed by the container orchestration platform.
9. The method of claim 1, wherein the plurality of layers comprises at least one immutable layer and at least one mutable layer.
10. The method of claim 1, wherein the storage management system is implemented as a containerized application managed by the container orchestration platform deployed in the cluster of nodes.
11. The method of claim 1, wherein the virtual machine disk image is used by a virtual machine handler associated with the container orchestration platform to run the virtual machine in a virtual machine type pod.
12. The method of claim 1, further comprising: receiving, by the storage management system, a second request comprising identifiers indicative of a second plurality of layers associated with a containerized application to be run in the cluster; generating, by the storage management system and based on the second request, a container image comprising the plurality of layers, the container image configured to be used to run the containerized application in the cluster; and providing, by the storage management system and in response to the second request, the container image.
13. A computer program product embodied on a non-transitory computer-readable medium and comprising instructions that, when executed, cause a computing device to perform a process comprising: receiving, by a storage management system configured to provide persistent data storage to workloads managed by a container orchestration platform deployed in a cluster of nodes, a request comprising identifiers indicative of a plurality of layers associated with a virtual machine to be run in the cluster; generating, by the storage management system and based on the request, a virtual machine disk image comprising the plurality of layers, the virtual machine disk image configured to be used to run the virtual machine in the cluster; and providing, by the storage management system and in response to the request, the virtual machine disk image.

14. The computer program product of claim 13, wherein providing the virtual machine disk image comprises providing a volume comprising the virtual machine disk image.

15. The computer program product of claim 14, wherein providing the volume comprises associating the volume with a persistent volume claim of the container orchestration platform.

16. The computer program product of claim 14, wherein the volume comprises a Kubevirt data volume.

17. The computer program product of claim 16, wherein the request comprises a specification for the Kubevirt data volume.

18. The computer program product of claim 13, wherein the request specifies an order in which to combine the plurality of layers to form the virtual machine disk image.

19. The computer program product of claim 13, wherein the virtual machine disk image is used by a virtual machine handler associated with the container orchestration platform to run the virtual machine in a virtual machine type pod.

20. A system comprising: at least one processor; and at least one memory storing instructions executable by the at least one processor to: receive, by a storage management system configured to provide persistent data storage to workloads managed by a container orchestration platform deployed in a cluster of nodes, a request comprising identifiers indicative of a plurality of layers associated with a virtual machine to be run in the cluster; generate, by the storage management system and based on the request, a virtual machine disk image comprising the plurality of layers, the virtual machine disk image configured to be used to run the virtual machine in the cluster; and provide, by the storage management system and in response to the request, the virtual machine disk image.