

Stratis Software Design*

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About this Document

This document can be found in the stratis-docs repo, and is written using LyX.

Summary

Stratis is an easily configured, tightly integrated solution for storage that works within the existing Linux storage management stack. To achieve this, Stratis prioritizes a straightforward command-line experience, a rich API, and a fully automated, externally-opaque approach to storage management. It builds upon elements of the existing storage stack as much as possible.

Part I

Background

1 Problem Statement

Linux has gained many storage-related features over the years, but each of these features has required the user to manage the configuration of these features in a layered, additive manner. Genuinely new and useful features such as thin provisioning, RAID, and multipath are dependent on the user correctly configuring many different layers via different tools to achieve a complete result. Furthermore, since each layer's configuration tool only has a command-line interface (CLI), higher-level management tools must each construct input and parse the

human-oriented output for each of these layers' CLIs. This causes a waste of effort and opportunity for bugs, as each higher-level tool builds its own internal API for the feature on top of the lower level tool's CLI.

1.1 Goal: Bring advanced features to users in a simpler form

Linux storage features are modular and stackable. This promotes flexibility and allows independent development efforts, but leads to a huge number of possible configurations. This requires the user to manage the stack because there's not enough commonality to enable effective automation.

But really, there *is* a single configuration that can work for most use cases. By assuming a fixed layering of storage features (some perhaps optional), we enable software to effectively manage these on behalf of the user.

Automated management then leads to less administrative burden placed on the user. The user still specifies resources, desired features, and results – what hardware resources to use, what features to enable, how storage should be logically presented – using a smaller number of concepts with well-defined relations. Software manages the rest, and handles most runtime issues without user involvement.

1.2 Proposal: Implement a hybrid Volume Managing Filesystem

In the past ten years, *volume-managing filesystems* (VMFs) such as ZFS and Btrfs have come into vogue and gained users, after being previously available only on other UNIX-based operating systems. These incorporate what would be handled by multiple tools under traditional Linux into a single tool. Redundancy, thin provisioning, volume management, and filesystems become features within a single comprehensive, consistent configuration system. Where a traditional Linux storage stack exposes the layers of block devices to the user to manage, VMFs hide everything in a *pool*. The user puts raw storage in the pool, the VMF manages the storage in the pool, providing the features the user wants, and allows the user to create filesystems from the pool without being concerned with the details.

Unfortunately, existing VMFs aren't easily used on enterprise Linux distributions like RHEL. ZFS isn't an option RHEL can embrace due to licensing, Ubuntu notwithstanding. Btrfs has no licensing issues, but maintaining up-to-date support for it in enterprise kernels proved difficult.

We can see from the many developer-years of effort that have gone into these two projects that writing a VMF is a tremendous, time-consuming undertaking. We also can hear our users demanding their features and ease of use.

Rather than writing a new VMF from scratch, Stratis proposes to satisfy VMF-like requirements by managing existing technologies on behalf of the user, so that users can manage their storage using high-level concepts like “pool” and

“filesystem”, and remain unconcerned with the more complex details under the covers.

This is also a chance to learn from the benefits and shortcomings of existing solutions. We should not just copy ZFS. ZFS is now fifteen years old and the storage landscape has changed since its design. We seek to satisfy the same needs that ZFS does, but also integrate more tightly into today’s increasingly automated storage management solutions that span the data center as well as the local machine. This is made possible by a hybrid, userspace-based approach.

1.3 Requirements

1. *Make features easier to use in combination with each other*: thin provisioning, snapshots, multipath, encryption, hardware reconfiguration, monitoring, and a caching tier
2. Simple and comprehensive command-line interface
 - (a) Simple
 - i. Single way to do things
 - ii. Do not expose internal implementation details. Gives Stratis more implementation freedom, and of little value since internals are too complex to make manual user repairs practical
 - iii. User typically will not use on a daily basis
 - A. Consistent commands that a user can guess at, and probably be right
 - B. Require explicitness from the user for potentially data-losing operations, such as giving a “–force” option.
 - (b) Comprehensive
 - i. User must master only one tool
 - ii. Helps user learn: if task not possible through tool, it must not be worth doing (or a good idea)
3. Programmatic language-neutral API for higher-level management tool integration
 - (a) A clear next step for users after hitting the limitations of scripting the CLI
 - (b) Encourages tight integration and use of all features by higher-level tools
4. Event-driven monitoring and alerts
 - (a) Monitoring and alert messages expressed in terms of Stratis user-visible simple concepts, not implementation details
 - (b) Low CPU/memory overhead to monitoring

- (c) Only alert when action really is needed
 - (d) Fail gracefully if alerts are unheeded
5. Eliminate manual resizing of filesystems
 - (a) Numerous problem reports throughout the years indicate that resizing filesystems is an area where users feel unease, due to potential data loss if a mistake is made. No real reason to require the user do this any more.
 - (b) Simpler for DevOps
 - (c) Makes storage “demand-allocated”, similar to virtual memory. Current technology allows us to manage a filesystem’s actual usage up (growfs) or down (thin provisioning).
 6. Initrd-capable
 - (a) Allows root fs, all other filesystems except /boot to use Stratis. Needed for ease of use
 - (b) Limited environment – alternate IPC mechanism that works in the initrd is available
 7. Adaptable to emerging storage technologies
 - (a) Persistent memory
 - i. Block-appearing pmem can be used by Stratis
 8. Implementable in 1-2 years
 - (a) We’re already behind, waiting another 10 years isn’t an option

Part II

Solution Overview

2 Introduction

Stratis is a local storage solution that lets multiple logical filesystems share a pool of storage that is allocated from one or more block devices. Instead of an entirely in-kernel approach like ZFS or Btrfs, Stratis uses a hybrid user/kernel approach that builds upon existing block capabilities like device-mapper, existing filesystem capabilities like XFS, and a user space daemon for monitoring and control.

The goal of Stratis is to provide the conceptual simplicity of volume-managing filesystems, and surpass them in areas such as monitoring and notification, automatic reconfiguration, and integration with higher-level storage management frameworks.

3 Stratis and the Linux storage stack

Stratis simplifies many aspects of local storage provisioning and configuration. This, along with its API, would let projects dependent on configuring local storage do so much more easily.

For example, installing the OS to a Stratis pool using Anaconda. After selecting the disks to use for the pool, the first benefit would be the complex flow around sizing of filesystems could be omitted. Second, since Stratis has an API, Anaconda could use it, instead of needing work in Blivet to build an API on top of command line tools.

Other management tools like Cockpit, virtualization products like RHEV, or container products like Atomic would find it much simpler and less error-prone to use storage and snapshots with Stratis, for the same two reasons: don't need to worry about per-filesystem sizing (only that the pool has enough "backing store"); and the API, which allows better tool-to-tool integration than using CLI programmatically.

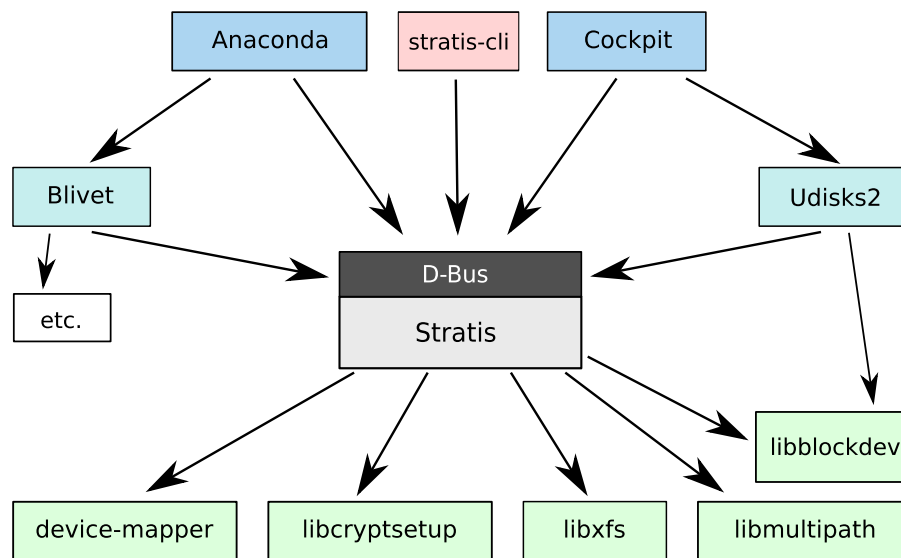


Figure 1: Future Stratis Position in the Linux Storage Management Stack

4 Conceptual Model

4.1 Blockdevs, pools, and filesystems

Stratis's conceptual model consists of *blockdevs*, *pools*, and *filesystems*. A pool is created from one or more blockdevs (block devices), and then filesystems are created from the pool. Filesystems are mountable hierarchical collections of files that allocate backing storage from the pool as it is needed. The key difference

between a Stratis filesystem and a conventional Unix filesystem is that Stratis filesystem sizing and maintenance are not managed by the user, but by Stratis.

4.2 Attributes and features of a pool

A pool is created with an initial set of one or more blockdevs. Blockdevs may also be added after the pool is created. The pool's primary collection of blockdevs is called the *data tier*.

A pool also optionally has a *cache tier* that uses a separate collection of faster blockdevs to improve performance instead of increasing the pool's capacity.

Since a single system may have multiple pools, each pool has a name, as does each filesystem within a pool. These are both settable by the user. Blockdevs, pools, and filesystems also have UUIDs, which are not settable by the user.

Stratis supports large numbers of blockdevs and up to 2^{24} filesystems per pool. However, practical limits on these values may compel users to restrict themselves to smaller numbers of blockdevs and filesystems.

A new filesystem is either a new empty filesystem or a snapshot of an existing filesystem within the pool. Stratis currently does not distinguish between snapshots and filesystems.

5 Scalability and Performance Considerations

Stratis doesn't optimize performance within its data tier, instead focusing there on flexibility and integrity. Improved performance is the job of caching tier, or perhaps building the pool using blockdevs with higher IOPs, such as SSDs.

Part III

Implementation

6 Software Components

Stratis consists of a command-line tool, *stratis*, and a service, *stratisd*.

stratis implements the command-line interface, and converts commands into D-Bus API calls to *stratisd*.

stratisd implements the D-Bus interface, and manages and monitors Stratis internal pool blockdevs, as described below. It is started by the system and continues to run as long as Stratis pools or blockdevs are present in the system.

stratisd includes a simulator engine. The simulator engine is purely computational and does not affect the environment, although it does communicate over the D-Bus.

Figure 2 shows the basic Stratis architecture.

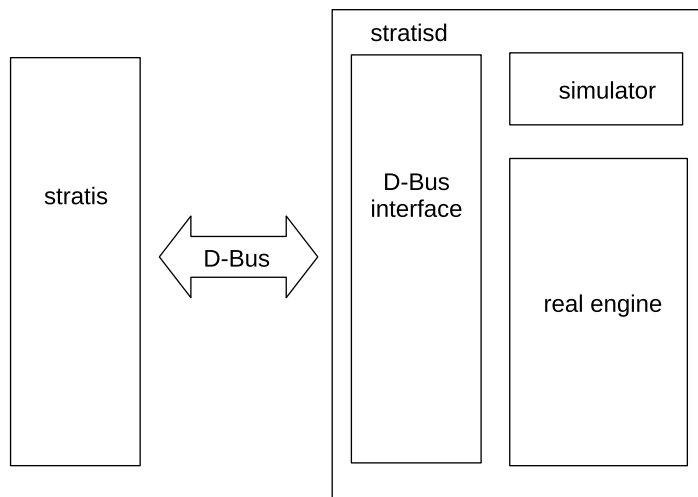


Figure 2: Stratis Architecture

7 User Experience

Stratis has a command-line tool that enables the administrator to create a Stratis pool from one or more blockdevs, and then allocate filesystems from the pool.

See reference implementation at <https://github.com/stratis-storage/stratis-cli> for the most up-to-date status of the CLI design.

This component is not required to be installed, in cases such as an appliance where a higher-level application such as Cockpit or Ansible uses the D-Bus API directly.

7.1 Known shortcomings

Stratis’ goal is to hide the complexity of its implementation from the user, but by using a reuse/layering approach to its implementation, there will be places where Stratis’ implementation details will peek through. This could cause user confusion, and also could threaten Stratis integrity if the user makes changes.

- For Stratis filesystems, ‘df’ will report the current used and free sizes as seen and reported by XFS. This is not useful information, because the filesystem’s actual storage usage will be less due to thin provisioning, and also because Stratis will automatically grow the filesystem if it nears XFS’s currently sized capacity.
- Users should not try to reformat or reconfigure XFS filesystems that are managed by Stratis. Stratis has no way to enforce this or warn the user to avoid this, other than in the documentation.

- Stratis will use many device-mapper devices, which will show up in ‘dm-setup’ listings and /proc/partitions. Similarly, ‘lsblk’ output on a Stratis system will reflect Stratis’ internal workings and layers.
- Stratis requires a userspace daemon, which must remain running at all times for proper monitoring and pool maintenance.

8 D-Bus Programmatic API

The Stratis service process exposes a D-Bus interface, for other programs to integrate support for Stratis. This is considered the primary Stratis interface. The command-line tool uses the D-Bus API.

8.1 Overview

The D-Bus API is part of `stratisd`. It is a thin layer that receives messages on the D-Bus, processes them, transmits them to the Stratis engine, receives the results from the engine, and returns the result to the invoker of the API. When processing method calls, its responsibilities are confined to:

- Receiving arguments and verifying that they conform to the signature of the invoked method.
- Transforming method arguments received on the D-Bus to arguments of the appropriate type to be passed to engine methods.
- Converting tuple arguments used to represent non-mandatory arguments to values which inhabit the Rust Option type.
- Invoking the appropriate engine methods and capturing their return values.
- Marshalling the appropriate return values to place on the D-Bus along with the return code and message.
- Adding or removing objects from the D-Bus tree.

The D-Bus API is implemented using the `dbus-rs` library¹.

The Stratisd D-Bus API Reference Manual contains a description of the API.

8.2 D-Bus Access Control

8.2.1 Security Policy

Most `stratisd` D-Bus methods require root permissions. However, listing operations do not; these can be done by an unprivileged user. The default permissions are specified in the policy file, `stratisd.conf`, included in the `stratisd` distribution.

¹<https://github.com/diwic/dbus-rs>

These defaults permit all actions by root users but restrict unprivileged users to read-only actions. Systems administrators can adjust permissions by editing the `stratisd` D-Bus policy files.

8.3 Querying `stratisd` state via D-Bus

`stratisd` exposes a reporting interface that allows users to query the state of `stratisd`'s internal data structures for debugging and error reporting. The D-Bus query returns a JSON string that can be parsed to detect state programmatically; however, the report interface is unstable, and consequently the names and schemas of provided reports do not follow the semantic versioning rules to which the rest of `stratisd`'s API conforms.

9 JSON RPC IPC mechanism

9.1 Overview

Due to restrictions in the `initramfs` where D-Bus is not currently present, there is an alternate mechanism for IPC in the `initramfs`. This IPC mechanism implements a JSON RPC framework passed over Unix sockets. The motivation for using Unix sockets is that:

1. They are available in the `initramfs` as a form of IPC
2. They allow passing file descriptors from process to process in the same network packet as the JSON

The JSON RPC IPC mechanism uses the exact same code for the `stratisd` storage engine and is simply a thin layer that handles all of the network operations and input parsing to provide arguments to the engine. The `initramfs` IPC API is more limited than that of the D-Bus API and is not versioned for backwards compatibility given that it is expected that the corresponding CLI will be used to communicate with the minimal daemon.

10 Internals

Stratis internals aim to be opaque to the user. This allows its implementation maximum flexibility to do whatever it needs in Stratis version 1, as well as to be extended in later versions without violating any user-visible expectations.

10.1 Data Tier Requirements

The data tier of Stratis must manage blockdevs on behalf of the user to provide the following:

1. Managed filesystems that consume only as much space as the files they contain

2. Fast snapshots of existing filesystems
3. The ability to add individual blockdevs to grow the physical space available to filesystems
4. Encryption

10.2 Data Tier

The data tier achieves these requirements by layering device-mapper (DM) devices on top of the pool's blockdevs. The topmost layer consists of thin devices allocated from a thinpool. Stratis initializes these thin devices with a filesystem, and manages the DM devices and filesystems to meet the above requirements.

10.2.1 Blockdevs

This layer is responsible for discovering existing blockdevs in a pool, initializing and labeling new blockdevs unambiguously as part of the pool, setting up any disk-specific parameters, and storing pool metadata on each blockdev. The minimum blockdev size Stratis will accept is 1 GiB. Blockdevs may be encrypted or unencrypted. See 10.5 for details on the implementation of encryption.

10.2.2 Flex

Pools need to cope with the addition of block devices.

Stratis allows adding a blockdev to an existing pool, and using it to grow the pool's allocated space.

The flexibility layer contains four linear DM devices made up of segments from lower-level devices. The first two devices will be used by Layer 4 (Thin Provisioning) as metadata and data devices. The flex layer will track what lower-level devices these are allocated from, and allow the two devices to grow as needed.

The third linear DM device is a spare metadata device to be used in the case that the metadata device requires offline repair. It will not usually be instantiated on the system, but guarantees there is room if needed. This device's size tracks the size of the metadata device, both as initially allocated, and as the metadata device is extended.

The fourth and final linear DM device is used for the Metadata Volume (MDV, see 10.3.6). The MDV is used to store metadata about upper layers, layer five and above.

The initial sizes of all flex layer devices should be chosen to allow an entire pool to fit within a single blockdev of the minimum size (1 GiB).

10.2.3 Thin Provisioning

The two linear targets from L3 are used as a metadata device and data device for a DM thinpool device. The thinpool device implements a copy-on-write

(CoW) algorithm, so that blocks in the data device are only allocated as needed to back the thin volumes created from the thinpool.

Stratis manages the thinpool device by extending the two subdevices in the thinpool when either runs low on available blocks. If the pool approaches a point where it no longer has empty lower-level space to extend onto, Stratis alerts the user and takes action to avoid data corruption.

10.2.4 Thin Volumes

Stratis creates thin volumes from the thin pool. It will automatically give a new volume a default size, format it with a filesystem, and make it available to the user.

Stratis also enables creating a new volume as a read/write snapshot of an existing volume. Although the underlying implementation does not require maintaining the relation between a snapshot and its origin, Stratis records this relation in its metadata. This relation may be of use to users who may, for example, use snapshots for backups and may make use of the origin information to identify a particular backup snapshot to restore from.

10.2.5 Filesystem

Stratis monitors each filesystem's usage against its capacity and automatically extends them online without user intervention. Extending involves changing the thin dev's logical size, and then using a tool such as `xfs_growfs` to grow the filesystem.

10.3 Data Tier Metadata

Stratis must track the blockdevs that make up the data tier of the pool, the three linear targets that span the block devices, the thinpool device and the attributes of the thin devices and filesystems created from the thinpool.

10.3.1 Requirements

1. Uniquely identify a blockdev as used by Stratis, which pool it is a member of, and parameters needed to recreate all layers
2. Detect incomplete or corrupted metadata and recover via second copy
3. Allow for blockdevs being expanded underneath Stratis
4. Redundant on each blockdev to tolerate unreadable sectors²
5. Redundant across blockdevs to handle missing or damaged members. Can provide metadata of missing blockdevs

²Recovery from accidental start-of-blockdev overwrite by placing a second copy at the end of the disk was also considered, but raised other issues that outweighed its benefit.

6. Handle thousand+ blockdevs in a pool
7. Handle million+ filesystems in a pool and updates without writing to each blockdev
8. Extensible/upgradable metadata format

10.3.2 Conventions

Sectors are 512 bytes in length³.

UUIDs are written as un-hyphenated ASCII encodings of their lower-case hexadecimal representation⁴ except in JSON-formatted metadata where they are unhyphenated.

All checksums are calculated using an implementation of the CRC-32C (Castagnoli) algorithm.

10.3.3 Design Overview

Stratis metadata is in three places:

1. Blockdev Data Area (BDA)
 - (a) Signature Block within Static Header
 - (b) Metadata Area (MDA)
2. Metadata Volume (MDV)

(Specific DM targets such as the thinpool also place their own metadata on disk.)

Information is duplicated across all blockdevs within an on-disk metadata format called the Blockdev Data Area (BDA). The BDA consists of a binary Signature Block, and the Metadata Area (MDA), which stores information in a text-based JSON format. Both the binary and text-based portions of the BDA define redundancy and integrity-checking measures.

The Metadata Volume (MDV) stores metadata on Layers 5 and up in a conventional block device and filesystem that is part of the Flex layer. Choosing to split overall metadata storage into two schemes allows upper layers' metadata to be free of limitations that would apply if a single scheme was used. For example, on-disk metadata formats find it hard to support runtime size extension, may keep redundant copies to ensure reliability, and aggressively check for corruption. This can work well with small amounts of data that is infrequently changed, but has trouble as data grows, or we wish to do updates in-place.

³Historically this is the minimum storage unit of a hard drive. Many Linux kernel APIs assume this value is constant (as does this document), and use another term such as 'block size' for dealing with cases where the minimum storage unit is different.

⁴UUIDs are 128-bit values and therefore require only 16 bytes to represent their numeric value. However, since each ASCII value requires a byte, and the hexadecimal representation of an 128-bit value requires 32 hexadecimal digits, the chosen encoding requires 32 bytes.

Upper-level metadata can achieve redundancy and integrity by building on the pre-existing lower layers, and work under looser restrictions around updating in place, and the total size to which it may grow. It can reuse an existing, well-tested solution for solving data organization and storage issues – a general-purpose filesystem.

10.3.4 BlockDev Data Area (BDA)

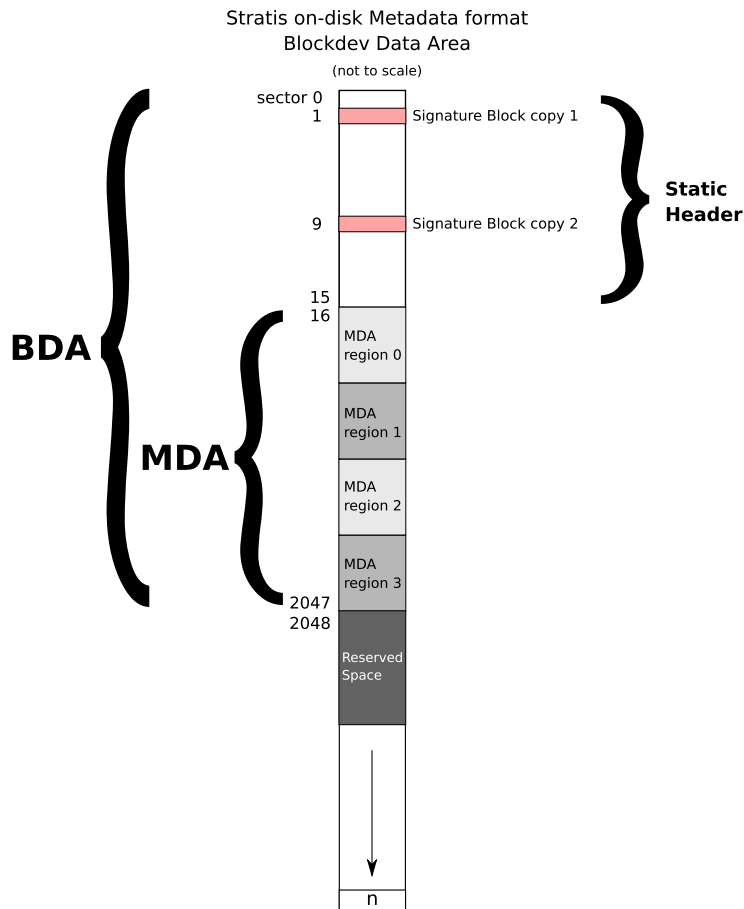


Figure 3: BDA format

The BDA consists of a fixed-length Static Header of sixteen sectors, which contains two copies of the Signature Block; and the metadata area (MDA), whose length is specified in the Signature Block. These are written to the beginning of the blockdev as described below.

Stratis reserves the first 16 sectors of each blockdev for the Static Header.

When initializing or modifying the Signature Block, identical data is written to locations 1 and 2.

Static Header

| sector offset | length (sectors) | contents |
|---------------|------------------|----------------------------|
| 0 | 1 | unused |
| 1 | 1 | Signature Block location 1 |
| 2 | 7 | unused |
| 9 | 1 | Signature Block location 2 |
| 10 | 6 | unused |

Signature Block

| byte offset | length (bytes) | description |
|-------------|----------------|--|
| 0 | 4 | checksum of signature block (bytes at offset 4 length 508) |
| 4 | 16 | Stratis signature: '!Stra0tis\x86\xff\x02^\x41rh' |
| 20 | 8 | Device size in 512-byte sectors (u64) |
| 28 | 1 | Signature Block version (u8) (value = 1) |
| 29 | 3 | unused |
| 32 | 32 | UUID of the Stratis pool |
| 64 | 32 | UUID of the blockdev |
| 96 | 8 | sector length of blockdev metadata area (MDA) (u64) |
| 104 | 8 | sector length of reserved space (u64) |
| 112 | 8 | flags (u64) |
| 120 | 8 | initialization time: UNIX timestamp (seconds since Jan 1 1970) using UTC (u64) |
| 128 | 384 | unused |

- No flags are yet defined, so 'flags' field is zeroed.
- All 'unused' fields are zeroed, and are reserved for future use.
- If not zero, blockdev metadata area length (offset 96) must be a number divisible by four of at least 2032.
- The BDA is followed immediately by *reserved space*, whose size is specified in the signature block (offset 104).
- Minimum length of BDA (static header and MDA) plus Reserved Space is 2048 sectors (1 MiB).
- When a blockdev is removed from a pool, or is part of a pool that is destroyed, Stratis wipes the Static Header.
- The purpose of the unused sectors is twofold. First, placing the Signature Block copy locations in two separate 4K blocks helps to prevent a single

bad write operation on 4K-block disks from corrupting both copies. Second, using a single sector for the Signature Block helps to minimize the likelihood of corruption on disks with 512 byte blocks.

- Each time that Stratis writes one or both Signature Block locations, it also zeroes the unused sectors that share the same 4K block.

The MDA is divided into four equal-size regions, numbered 0-3. When updating metadata, identical data is written to either the odd (1 and 3) or even (0 and 2) regions, chosen by examining the timestamps and overwriting the older of two pairs.

Each MDA region's update consists of a fixed-length MDA Region Header, followed by variable-length JSON data.

MDA Region Header

| byte offset | length (bytes) | description |
|-------------|----------------|---|
| 0 | 4 | checksum covering remainder of MDA header |
| 4 | 4 | checksum covering JSON data |
| 8 | 8 | length of JSON data in bytes (u64) |
| 16 | 8 | UNIX timestamp (seconds since Jan 1 1970) using UTC (u64) |
| 24 | 4 | nanoseconds (u32) |
| 28 | 1 | Region Header version (u8) (value = 1) |
| 29 | 1 | Variable-length metadata version (u8) (value = 1) |
| 30 | 2 | unused |
| 32 | variable | JSON data |

- Metadata updates write to the older of the odd or even MDA regions. This is determined by lowest timestamp, and then lowest nanoseconds if timestamps are equal.
- MDA updates include the MDA Header, which includes the current time. However, if using the current time would not result in the update having the latest time across all MDA regions on all blockdevs in the pool, instead use a time of one nanosecond later than the latest MDA region time across all blockdevs.
- The procedure for updating metadata is:
 1. Determine which regions in the MDA to use (odd or even) as described above.
 2. Write MDA header and JSON data to the first MDA region (0 or 1)
 3. Perform a Flush/FUA
 4. Write MDA header and JSON data to the second MDA region (2 or 3)
 5. Perform a Flush/FUA

6. Repeat for additional blockdevs. Also see 10.3.7

- Multiple blockdevs being updated with the same metadata must write identical data to each MDA region, but which regions (odd or even) is used may vary, if the blockdevs have received differing numbers of metadata updates over time.

10.3.5 Metadata Area (MDA)

The MDA contains a JSON object that represents the pool's overall configuration from L0 to L4.

Top level objects:

| key | JSON type | required | description |
|--------------|-----------|----------------------|--|
| name | string | y | the name of the pool |
| backstore | object | y | the block devices in the pool |
| flex_devs | object | y | layout of the data and metadata linear devices |
| thinpool_dev | object | y | parameters of the thinpool device |
| started | boolean | as of stratids 3.2.0 | indicates whether a pool is started or stopped |

backstore: An object describing the data tier and the cache tier.

| key | JSON type | required | description |
|------------|-----------|----------|---|
| data_tier | object | y | the block devices in the data tier |
| cap | object | y | the cap device, from which segments are allocated to the flex layer |
| cache_tier | object | n | the block devices in the cache tier |

data_tier: An object describing the data tier.

| key | JSON type | required | description |
|----------|-----------|----------|--|
| blockdev | object | y | Settings and mappings describing block devices that make up the tier |

blockdev: An object describing physical block devices that make up the tier.

| key | JSON type | required | description |
|--------|-----------|----------|---|
| devs | array | y | an array of base_block_dev objects |
| allocs | array | y | an array of arrays of base_dev objects |

base_dev: An object describing an allocation from a block device.

| key | JSON type | required | description |
|--------|-----------|----------|---|
| parent | string | y | UUID of the device the segment is created from |
| start | integer | y | the starting sector offset within the parent device |
| length | integer | y | the length in sectors of the segment |

base_block_dev: An object describing a block device in the lowest layer.

| key | JSON type | required | description |
|---------------|-----------|----------|--|
| uuid | string | y | The UUID of the block device, as recorded in its Signature Block |
| user_info | string | n | user-provided information for tracking the device |
| hardware_info | string | n | uniquely identifying information for the blockdev, such as SCSI VPD83 or serial number |

cap: An object describing a view of the top-level linear device provided by the backstore to the flex layer.

| key | JSON type | required | description |
|--------|-----------|----------|---|
| allocs | array | y | an array of pairs of integers representing the starting offset and length of an allocation in sectors |

cache_tier: An object describing the cache tier. Identical format to **data_tier** except VDO layer is not supported.

flex_devs: An object with four keys that define the linear segments that make up each device in the Flex layer.

| key | JSON type | required | description |
|---------------------|-----------|----------|---|
| meta_dev | array | y | an array of pairs of integers representing the starting offset and length of an allocation in sectors that make up the metadata volume (MDV) |
| thin_meta_dev | array | y | an array of pairs of integers representing the starting offset and length of an allocation in sectors that make up the thin metadata device |
| thin_meta_dev_spare | array | y | an array of pairs of integers representing the starting offset and length of an allocation in sectors that make up the thin metadata spare device |
| thin_data_dev | array | y | an array of pairs of integers representing the starting offset and length of an allocation in sectors that make up the thin data device |

thinpool_dev: An object that defines properties of the thinpool device.

| key | JSON type | required | description |
|-----------------|-----------|--------------------|---|
| data_block_size | integer | y | the size in sectors of the thinpool data block |
| feature_args | array | since stratisd 3.1 | the feature args passed to the thin pool on setup |
| fs_limit | integer | since stratisd 3.1 | the maximum number of filesystems able to be created in this pool |
| enable_overprov | boolean | since stratisd 3.1 | indicates whether overprovisioning is allowed on this pool |

10.3.6 Metadata Volume (MDV)

The Metadata Volume is formatted with an XFS filesystem that is used by Stratis to store information on user-created thin filesystems (L5-L7). This information is stored in the filesystem as individual JSON files.

10.3.7 The MDA and Very Large Pools

Stratis pools with very large numbers of blockdevs will encounter two issues. First, updating the metadata on all blockdevs in the pool may become a performance bottleneck. Second, the default MDA size may become inadequate to contain the information required.

To solve the first issue, Stratis caps the number of blockdevs that receive updated metadata information. A reasonable value for this cap might be in the range of 6 to 10, and should try to spread metadata updates across path-independent blockdevs, if this can be discerned, or randomly. This limits excessive I/O when blockdevs are added or removed from the pool, but maximizes the likelihood that up-to-date pool metadata is retrievable in case of failure.

To solve the second issue, Stratis monitors how large its most recent serialized metadata updates are, and increases the size of MDA areas on newly added devices when a fairly low threshold – %50 – is reached in comparison to the available MDA region size. This ensures that by the time sufficient blockdevs have been added to the pool to be in danger of serialized JSON data being too large, there are enough blockdevs with enlarged MDA space that they can be used for MDA writes.

10.3.8 Metadata and Recovery

Bad things happen.

In order to recover from disk errors, Stratis uses checksums over the critical metadata, and writes duplicate copies to a single blockdev, as well as across multiple blockdevs, when possible. It takes this approach – copies – rather than

a mechanism that might make it possible to partially repair corrupted metadata for three reasons:

1. This metadata is relatively small.
2. Partially reconstructed information has limited value. This is due to the layered nature of Stratis. It's not sufficient to know some subset of the device mapping levels. Since they are layered, recovering only some layouts allows no data to be recovered without also knowing how others are mapped on top, and vice versa.
3. Stratis metadata on the block devices should require relatively few updates per day, since the changes it would reflect are blockdevs being added to the pool, or thinpool data device expansions. Infrequent updates reduces the likelihood of corruption⁵.

Filesystem metadata is stored on the Metadata Volume on an XFS filesystem. Partial data recovery of that information is possible.

In addition to Stratis-specific metadata, device-mapper layers such as thin, as well as XFS filesystems, all have their own metadata. Stratis would rely on running each of their specific repair/fsck tools in case they reported errors.

10.4 Cache Tier

The Cache Tier is a secondary optional stack that, if present, serves as a cache for the DataTier. If present, the Cache Tier sits directly underneath the Flex Layer. Its structure is similar to the lower levels of the Data Tier.

10.4.1 Requirements

1. Caching may be configured for write-back and write-through modes.
2. Stratis concatenates all cache blockdevs and uses the resulting device to cache the thinpool device. This lets all filesystems benefit from the cache.
3. Cache blocksize should match thinpool datablock size.
4. Removing cache tier comes with performance hit and “rewarming” phase

10.4.2 Cache Tier Metadata

Cache Tier Metadata Requirements

1. Identify all blockdevs that are part of the pool's cache tier and other cache-specific configuration parameters (e.g. WT/WB, block size, cache policy)
2. Cache tier supports up to 8 devices.

⁵citation needed?

10.5 Encryption

stratisd encrypts devices at the blockdev level. If Stratis devices are encrypted, the following conditions will hold:

- Each blockdev will be encrypted with a distinct and randomly generated MEK (Media Encryption Key).
- All blockdevs in a pool will be encrypted, or all blockdevs in a pool will be unencrypted. Stratis will support mixed usage for pools, where some pools are encrypted and others are not.
- A distinct passphrase (used to generate the KEK or Key Encryption Key) will be supported for each pool, although it will be possible to use the same passphrase for every pool, if desired.
- The user will be required to choose whether or not a pool is encrypted at pool creation time and must identify their choice by an additional argument in the CLI's "pool create" command. Encryption of an already existing pool will not be supported.
- Re-encryption will not be supported initially; this functionality will be considered and added in a later step.
- If a pool was encrypted on creation, then all blockdevs added to the data tier will be automatically encrypted with a randomly generated MEK and the pool's designated KEK.
- On any encrypted blockdev, the Stratis metadata will itself be encrypted; it will be inaccessible until the encrypted blockdev is opened.
- The use of a cache tier and of encryption will be mutually exclusive. If a pool is encrypted, an attempt to add a blockdev to the cache tier will be rejected.
- The default cipher specified by cryptsetup 2.1, `aes-xts-plain64`, is used to encrypt all encrypted devices. The MEK is 512 bits.

The above conditions require an implementation which makes use of the LUKS2 header. In particular, for a blockdev to be decrypted with its pool-specific KEK, it will be necessary to include information within the device header which allows the device to be identified as belonging to a particular Stratis pool. The LUKS2 header includes support for LUKS tokens, which will allow stratisd to identify the pool to which a device belongs; the LUKS1 header does not.

10.6 Block Device Characteristic Requirements (stratisd 3.4.0)

stratisd endeavors to enforce sufficient consistency in the characteristics of the block devices that make up a pool to ensure continuous proper operation of Stratis pools.

At present, `stratisd` takes into account the physical and the logical sector size of a block device, i.e, those values obtained by the `BLKBPSZGET` and the `BLKSSZGET` ioctls. `stratisd`'s requirements for creating new pools or pool caches or for adding block devices to an existing pool or its cache are quite stringent. It follows a more relaxed policy with pre-existing pools or caches.

10.6.1 Pre-existing pools and caches

With existing pools `stratisd` makes use of a rule intended to guard against changes in the logical and physical sector size presented by the cap device to the layers above. `stratisd` may automatically extend the cap device to accommodate pool usage. If the cap device is extended to make use of a block device which has a larger logical or physical sector size than the devices that it was using previously, the sector sizes exported by the cap device will change to the larger size. This can have the unfortunate effect of making XFS filesystems previously created above the cap device unmountable. To prevent this situation, `stratisd` enforces the following rule: If the cap device can be extended so that its logical or physical sector size could change, `stratisd` places the pool in “no_pool_changes” mode and logs a warning encouraging the user to migrate their data to a new pool. A pool in “no_pool_changes” mode can not take any action, including auto-extending.

With regard to existing pool caches, the danger of dynamically changing sector sizes does not exist. `stratisd` always makes use of all the block devices belonging to the cache when forming its cache device, so there is no check necessary for existing cache devices.

10.6.2 Newly created pools and caches

If the user wishes to create a new pool or a new cache it is required that all the block devices specified at creation have the same logical and physical sector size.

10.6.3 Adding block devices to an existing pool or to its cache

It is not possible to perform any operations on a pool that is in “no_pool_changes” mode, so it is not possible to add additional devices to such a pool's data or cache tier.

As a consequence of this rule, it can be assumed that all pools to which devices are being added can be assumed to have certain properties. In particular, both the data tier and the cache tier have achieved their *terminal sector sizes*. These are the respective sector sizes that the cap device would have if it were extended across all block devices that belong to the data tier and is the maximum of the respective sector sizes of all the individual block devices in the data tier. Since the cache always makes use of all its devices, it achieves its terminal sector sizes when constructed.

Taking these facts into account, the following rule is used when initializing a cache:

1. all the block devices specified for the cache must have the same logical and physical sector size.
2. the logical sector size of all the devices specified for the cache must be the same as the terminal logical sector size of the data tier.

and the following rule when adding devices to either the data or cache tier:

1. all the block devices specified must have the same logical and physical sector size
2. both sector sizes of all the devices specified must be the same as the respective terminal sector sizes of that tier

10.6.4 Notes

Because stratisd must support pools that were previously created without the restrictions of uniform logical and physical sector size that stratisd began imposing in the 3.4.0 release, these rules do not guarantee total uniformity of either physical or logical sector size in the devices that make up a pool or a cache. They guarantee only that the devices that extend the data or cache tier after stratisd 3.4.0 will all have the same logical and physical sector size.

11 Implementation Details

11.1 'stratis' command-line tool

Stratis' command-line tool is written in Python. Since it is only used after the system is booted by the administrator, Python's interpreted nature and overhead is not a concern.

11.2 stratisd

Stratisd needs to be implemented in a compiled language, in order to meet the requirement that it operate in a preboot environment. A small runtime memory footprint is also important.

stratisd is written in Rust. The key features of Rust that make it a good choice for stratisd are:

- Compiled with minimal runtime (no GC)
- Memory safety, speed, and concurrency
- Strong stdlib, including collections
- Error handling
- Libraries available for D-Bus, devicemapper, and JSON serialization
- FFI to C libs if needed

- Other alternatives considered were C and C++. Rust was preferred over them for increased memory safety and productivity reasons.

If stratisd terminates unexpectedly and is restarted, it needs to rebuild its knowledge of the running system. This includes not only re-enumerating blockdevs to find Stratis pool members, but also determining the current state of the devicemapper targets that make up pools. A restarting stratisd needs to handle if none, some, or all of the expected DM devices are present, and if present DM devices are working correctly, or in an error state.

11.3.1 Naming convention Requirements

- ### 11.3.2 Naming Convention

| Part | Name | Max length | Required | Description |
|------|-------------------|------------|----------|--|
| 1 | stratis-id | 7 | y | Universal DM differentiator: 'stratis' |
| 2 | format-version | 1 | y | Naming convention version: '1' |
| 3 | private | 7 | n | Optional indicator 'private' |
| 4 | pool-id or dev-id | 32 | y | ASCII hex UUID of the associated pool or, in the case of encryption, the block device |
| 5 | layer-name | 16 | y | Name of the Stratis layer this device is in |
| 6 | layer-role | 16 | y | Name of the role of the device within the layer |
| 7 | role-unique-id | 40 | n | Role-specific unique differentiator between multiple devices within the layer with the same role |

- The maximum length (adding 6 '-'s as separator) is 125, to stay within the DM name limit of 127 characters.
- “private” is included in names for DM devices that are internal and that should be excluded from content scanning by tools such as blkid.
- Characters for each part are drawn solely from the character classes '[a-z]' and '[0-9]' except that part 7 may also use the '-' character. These restrictions meet D-Bus and udev requirements⁶.)
- Encryption uses device UUIDs because there may be multiple encrypted devices in one pool so using the pool UUID would result in naming collisions

11.4 devicemapper minimum version

Stratisd devicemapper minor version 37 or greater, for DM event poll() support and support for event_nr in list_devices ioctl.

11.5 OS Integration: Boot and initrd

Since we want to allow Stratis to be used for system files, Stratis needs to run in the initrd preboot environment. This allows it to activate pools and filesystems so that they can be mounted and accessible during the transition to the main phase of operation.

The use of D-Bus is not possible in the preboot environment. Therefore, Stratis has an alternate IPC mechanism to be used in the initramfs. This can be accessed through the stratis-min and stratisd-min executables.

Stratis packages distribute a dracut module, systemd generator, and service file to automate set up of all needed pools, encrypted or unencrypted, during the boot process and `/etc/fstab` mount operations.

11.6 OS Integration: udev

The udev library “libudev” enables access to the udev device database. This allows library users to enumerate block devices on the system, and includes attributes describing their contents, such as what filesystem or volume manager signature was detected. (libudev uses libblkid for this, which recently had Stratis signature support added.) The primary benefit of this is to perform the time-consuming block device scan only once, and to alleviate library users from interpreting block device contents.

On boot, Stratis uses libudev to enumerate Stratis block devices on the system, reads the Stratis metadata from each, and activates pools that are complete. Later, during the main running phase, Stratis monitors udev events for newly-added block devices, so that if missing Stratis pool members are connected to complete a pool, the pool can be activated and used.

⁶See libdm/libdm-common.c `_is_whitelisted_char()` in the lvm2 code for more.

11.7 OS Integration: /dev entries

Stratis allows the user to create filesystems, which then can be mounted and used via `mount(8)` and the `fstab(5)`. Stratisd provides a udev rule that generates a `/dev/stratis` directory. It creates `/dev/stratis/<poolname>` for each pool present on the system, and `/dev/stratis/<poolname>/<filesystemname>` for each filesystem within the pool. Changes such as creations, removals, and renames are reflected in the entries under `/dev/stratis`. These entries give the user a well-known path to a device to use for mounting the Stratis filesystem. Filesystems may also be listed in `/etc/fstab` using XFS UUID. However, if the device is encrypted, it is recommended that users take advantage of the `stratis-fstab-setup@.service` systemd unit file to automate pool unlock prior to mounting.

11.8 Snapshots

Stratis's current snapshot implementation is characterized by a few traits:

- A snapshot and its origin are not linked in lifetime. i.e. a snapshotted filesystem may live longer than the filesystem it was created from.
- A snapshot of a filesystem is another filesystem.
- A filesystem may be snapshotted while it is mounted or unmounted.
- Each snapshot uses around half a gigabyte of actual backing storage, which is needed for the XFS filesystem's log.

These may change in the future.

11.9 Backstore Internals

The backstore is divided into two tiers: the data tier, and an optional cache tier. Each tier has its own set of physical block devices. The goal of each tier is to provide a single linear device that the flex layer (or another tier) can easily build on top of.

A tier is created with a certain feature set, which results in an internal layering of devices as needed to support those features. The features a tier supports are fixed at tier creation time. However, the block devices that make up the tier may change. New blockdevs may be added.

This requires each tier to support:

- `add_blockdev` (add a new blockdev to the tier)
- `blockdevs` (list/iterate)

The tier includes optional internal support for multiple features, which also are implemented using DM devices.

At the “bottom” of the tier are blockdevs. These blockdevs are mapped through layers that add value, such as encryption.

Each layer takes a list of blockdevs and converts it to a list of “better” blockdevs, whose total size is likely different.

While each intermediate layer may provide an array of blockdevs, the “cap” layer of the tier presents a single linear blockdev that maintains the location of each presented block and never shrinks, and hides the interior complexity of the tier from upper users.

The ordering of layers (from bottom to top) within a tier is:

1. blockdev
Blockdevs supply available space to the tier.
2. encryption
This layer provides optional encryption for all block devices available in the pool.
3. cap
If presented with more than one blockdev, or the blockdev has a nonzero offset, the “cap” layer will ensure the Tier presents a single blockdev with consistent block mapping for use above the tier by creating a Linear device that never relocates previously-mapped block ranges.

11.9.1 Demand-based allocations

Layers should not consume the entire space available to them when constructing devices, but instead grow existing mapped allocations (or create new ones) as the total demands of upper layers grow larger. This is preferred over a “greedy” strategy because it provides a better user experience to allow the amount of space allocated to both data and metadata to be calculated dynamically if requirements change.

11.9.2 Block device growth

The logical separation between the backstore and thin pool allows relatively simple support for growing block devices that can change in size like loopback devices or RAID arrays. Because the cap device abstracts away the complexity of the underlying block devices, newly exposed block device segments can be added to the cap device without any support needing to be added to the thin pool. The thin pool will simply see that more space is now available and allocate it lazily as needed.

11.10 Operation States

When encountering errors, Stratis must handle them if possible, but there are also errors that are severe enough to hamper Stratis’s ability to function. When these occur, instead of terminating, Stratis continues by transitioning to a less-capable operation state. This allows some measure of continued monitoring and enables its condition to be visible to the user through the API.

| Action availability state | Description |
|--------------------------------|--|
| <code>fully_operational</code> | All pool operations are available in this state. No restrictions are imposed. |
| <code>no_ipc_requests</code> | Pool operations triggered by an IPC request are disabled. This is often due to a failed IPC command that could not be fully rolled back. Manual resolution of the bad roll back state will allow the pool to resume fully operational state again. |
| <code>no_pool_changes</code> | Any operations that modify the state of the pool will be disabled. This includes IPC requests and background operations such as extending the thin pool and filesystem. |

11.11 Licensing

Currently, `stratisd` and all Rust libraries included in the `stratis-storage` organization meant for `stratisd` are licensed as MPLv2. This conclusion was reached after careful consideration of compatibility with other licenses in the open source ecosystem. MPLv2 allows some major benefits:

1. It is compatible with more permissive licenses in the open source ecosystem such as BSD and MIT licenses. Given the prevalence of more permissive licenses in the Rust ecosystem, this is an important consideration.
2. It is compatible with GPL code. This permits `stratisd` to incorporate GPL code and become effectively GPL without ever changing the MPLv2 license.
3. If GPL code is incompatible with the license of a dependency added later, MPLv2 allows the removal of GPL code and migration of the GPL code into a separate service to permit the addition of the conflicting dependency. This can all be done without relicensing.

After evaluating the options, the MPLv2 seemed to be the most flexible license that still fulfilled the requirements for this project.

References

- [1] Anne Mulhern. `justbytes` documentation. <http://pythonhosted.org/justbytes/>.
- [2] Anne Mulhern. The computation and representation of address ranges: With an introduction to the python `justbytes` library. https://mulhern.fedorapeople.org/justbytes_presentation.pdf, August 2016.

Appendices

A Encryption implementation details

Stratis uses `libcryptsetup` to manage FDE (full disk encryption) for each block device added to an encrypted pool.

A.1 On-disk format

Stratis uses the LUKS2 encryption format as the basis for the encryption implementation. The LUKS2 header contains information that can be used to identify a device as a Stratis encrypted device.

A.1.1 LUKS2 token format

LUKS2 tokens contain the necessary information to describe how to unlock the device. No private information is contained in the tokens. Stratis uses two tokens, one standard `cryptsetup` token which allows activating the device using a passphrase stored in the kernel keyring and another Stratis-defined token that contains activation information required by Stratis. Token IDs are statically assigned for each token for a number of reasons:

- Using static IDs, `stratisd` does not have to do a scan of all of the tokens followed by heuristics to recognize a token. Instead, it chooses the static ID, and if the format does not match what was expected, it is not treated as a Stratis encrypted device.
- As other activation methods are added, activation of a pool can specify one token ID to use for activation of all devices in the pool and expect that they will all be unlocked using the same mechanism.
- New tokens may be added without breaking changes to the assignment of existing token IDs.

The Stratis token has an ID of 0, the LUKS2 keyring token has an ID of 1, and the Clevis token has an ID of 2.

LUKS2 keyring token

The kernel keyring token contains information for LUKS2 integration with keys in the kernel keyring. This token is a standard token supported by `cryptsetup`, and details for the format can be found in the `cryptsetup` documentation. Interaction with this token is handled by standard `libcryptsetup` API methods.

Stratis token

The Stratis token is used for device identification and activation, and the values are set directly by Stratis. The format specification is as follows:

```
{
    "type": "stratis",
    "keyslots": [],
    "activation_name": <DEVICEMAPPER_NAME>,
    "pool_uuid": <POOL_UUID>,
    "device_uuid": <DEVICE_UUID>,
    "pool_name": <POOL_NAME>
}
```

See below for an explanation of each JSON value:

<DEVICEMAPPER_NAME>

This is the managed name that will show up in devicemapper when the device is activated using libcryptsetup. While the name can be seen on the system by querying devicemapper, managing encrypted Stratis devices outside of Stratis is not supported so this is considered an internal name.

<POOL_UUID>

This UUID corresponds to the Stratis pool that owns this block device. The pool UUID in the token matches the pool UUID in the encrypted Stratis metadata.

<DEVICE_UUID>

This UUID corresponds to the device UUID for this specific block device. The device UUID in the token matches the device UUID in the encrypted Stratis metadata.

<POOL_NAME>

This name is duplicated from the pool level metadata and updated when the pool name is changed to facilitate starting pools by name for encrypted devices.

A.1.2 Encrypted Stratis metadata format

Once the LUKS2 volume is unlocked, the encrypted Stratis metadata should be accessible through the unencrypted logical devicemapper device in exactly the same way as an unencrypted Stratis device.

A.2 Encrypted device creation

Stratis does not wipe the device prior to initializing it with a LUKS2 header. This means that an attacker can deduce the following from examining a disk that has been initialized using Stratis without any prior preparation:

- The amount of data currently stored on disk that is encrypted. For example, if a disk has sectors that were zeroed or contain unencrypted data previously stored on the disk at the end of an encrypted segment, this can give insight into how many encrypted blocks are stored on the device. To prevent this, the device should be wiped with random data prior to providing it to a Stratis pool.
- The contents of unencrypted data that was previously stored on the disk prior to initialization by Stratis. `cryptsetup`'s LUKS2 implementation does not overwrite all of the data on the disk by default, so without prior preparation, any sectors that have not been overwritten with encrypted data will still contain the data previously stored on the disk. To prevent this, the disk should be zeroed or wiped with random data.

A.3 Encrypted device discovery

Stratis identifies encrypted devices belonging to Stratis by their Stratis token. It does not attempt to activate any device until it receives a D-Bus command to activate all devices. When the command is received, `stratisd` attempts to unlock the devices using the LUKS2 keyring token previously set by `stratisd`. If activation of devices yields a set of devices that can form a complete pool, the pool is set up.

A.4 Encrypted device activation

Devices are activated with the activation name in the Stratis token. See A.1.1 for an explanation of the Stratis token. Device activation results in a new, activated device path with the canonical path name

`/dev/mapper/<activation_name>`

where the unencrypted data can be accessed. Because of the design and use of `libcryptsetup`, encrypted devices can also be activated outside of Stratis using `libcryptsetup` or the `cryptsetup` CLI as long as the required passphrase is in the kernel keyring.

A.5 Encrypted device destruction

Destroying an encrypted Stratis device does not wipe the entire device as the cost of this operation is linearly proportional with respect to disk size. Instead, Stratis uses `libcryptsetup` to destroy all of the keyslots, wiping all of the encrypted MEK (media encryption key) data in each keyslot. It then obtains the size of the LUKS2 metadata on this device and does an additional wipe of the remaining LUKS2 metadata. This provides the following device properties on pool destruction:

- The MEK data is destroyed so the data stored on the device will be unrecoverable.

- If this device is used when creating another pool later, Stratis will be able to reinitialize it and will consider this device unowned due to the wipe of the LUKS2 metadata.
- The encrypted data will be left on the device but will be inaccessible due to the destruction of the key.

Additional security may be achieved by zeroing the disk or overwriting it with random data using external tools.

A.6 Key consistency for encrypted pools

Stratis takes steps to ensure that the same passphrase used during initial creation of the pool is the passphrase that is used for adding encrypted block devices at a later time. `stratisd` runs a check prior to adding block devices to an encrypted pool to verify that the passphrase in the kernel keyring with the key description recorded in the LUKS2 metadata can unlock the block devices that have already been encrypted and added to the pool. This prevents the passphrase data associated with a key description from being accidentally or intentionally changed between pool creation and addition of encrypted block devices which would result in an unusable pool and loss of data on the next occasion when the pool must be set up.

A.7 Key management

Stratis provides facilities for key management. The kernel keyring is used as the backing store for the keys provided through the D-Bus API to allow proper access controls for passphrases. The architecture of key input has been carefully designed to avoid leaving keys in memory after they are no longer in use. The key is not directly sent over D-Bus; D-Bus traffic is not encrypted so this would leak the plaintext passphrase. Instead, the client side provides the server side with a file descriptor from which to read the passphrase so that no data is ever exposed in the D-Bus method call. When a user provides a key using the interactive mode in the CLI or D-Bus API, input buffering is turned off on the client side so the key is never stored in userspace memory. On the server side, `stratisd` reads the key into a memory block managed by `libcryptsetup` so that as soon as the memory is no longer in use, `libcryptsetup` will wipe the memory using a method that will not be optimized out by the compiler. All of this guarantees that the key data will only be available in one memory location while it is in use, and that the memory will be securely wiped after use.