Mission Statement
Safe cryptographic steganographic advanced filesystem

Arkadiusz Bulski

Abstract

Cameleonica is a prototype of a highly versatile filesystem and is to cover a wide range of safety and security and usability features. It aims to guarantee confidentiality, authenticity, plausible deniability, permanent deletion, versioning, snapshots, transactions, file and directory cloning, high throughput, low delays, internal compression, non-transparent compression and hashing, deduplication, departitioning, and serializability.

Mission statement sets a direction in which further development will tend to. Purposefully are omitted any technical details on how to achieve it. Features are mostly described through basic definitions and elaborate examples, not technical specifications. Usage scenarios showing obvious benefits to end users are presented. Scenarios show how different people benefit from different subsets of features.

Conceptual Design describes a wide range of theoretic concepts that could be incorporated into a new filesystem design. Potential benefits over existing schemes are presented with some reasons why these schemes did not or could not gain traction earlier. Expectations of their performance are based on both theoretic models and measured empirical evidence.

Preliminary design describes both on-disk and in-memory data structures and their methods for filesystem operations. This chapter is a full fledged technical specification.

Questions and Answers lists questions that were posted by reviewers, with responses.

Project is being hosted on GitHub, and can be found at github.com/arekbulski/Cameleonica. Issues can be used to post questions and suggestions.

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Introduction

Cameleonica is a safe cryptographic steganographic advanced filesystem.

This succinct description uses loaded terms. Let us expand them:

Cameleonica is a prototype of a highly versatile filesystem and is to cover a wide range of safety and security and usability features. It aims to guarantee confidentiality, authenticity, plausible deniability, permanent deletion, versioning, snapshots, transactions, file and directory cloning, high throughput, low delays, internal compression, non-transparent compression and hashing, deduplication, departitioning, and serializability.

These properties are more elaborately explained through definitions and examples:

Filesystem

is a data structure that maps a hierarchy of regular files and directories into a flat storage. Access to the files is governed by rules that make up so called semantics. Most semantics are already well defined by POSIX standard. The fact that open files can be removed and replaced while still being open is a notable example. There are also other, de-facto standards that are built upon POSIX. Linux man-pages define even more fancy semantics. For example, *fallocate* allows to remove a range of bytes without leaving a hole, stitching together both sides. Another example, *creat/open* can create anonymous temporary files that are not vulnerable to outside access since they do not have a name to be addressed with. Also temporary files are guaranteed to disappear after interruption. Replacing files is an atomic action, which is often used in modern software as means of ensuring that some consistent version remains on disk in case of a failure. All these semantics are interesting but are not the main selling point. They only build a foundation for a useful general purpose filesystem that is protected from at most interruption.

Cryptographic filesystem

is a filesystem that provides two attributes: confidentiality and authenticity. Confidentiality is a property that easily translates to filesystems. If a filesystem is encrypted, it should not reveal any information about it's file structure, names, sizes, content or usage quota until a valid password is provided. Authenticity is a property that guarantees that the files read now are same as the files written earlier. That is, a valid password must be provided before any changes can be made to the file structure. No file can be moved, truncated, or it's content changed without a valid password. Random or malicious changes to files are not allowed to remain undetected. If bytes being read were modified without a valid password, an error must be returned upon read. It is not acceptable for a read operation to return garbage bytes in this situation.

Steganographic filesystem

is a filesystem that provides more than one file structure using only one backend storage. Every file structure is encrypted with an independent valid password. Steganographic confidentiality is a property that demands that if one valid password is revealed, it does not aid in discovery of any other valid password or even existence thereof. In other words, existence of valid passwords remain concealed on top of their corresponding file structures. Steganographic confidentiality is a stronger notion than cryptographic confidentiality in this respect. Multiple independent valid passwords, or equivalently independent file structures, can exist at same time within a given filesystem. As a matter of contrast, cryptography usually deals with only one password at a time. More importantly, the mere existence of that one password is hardly a secret. In steganography, zero or one or more passwords may exist and their existence is a secret in it's own right.

Safe filesystem

is a filesystem that refuses to become unusable or lose access to already existing files in event of abrupt interruption. Modern filesystems are able to reliably recover from an unexpected power loss or system crash encountered at any point in time. This safety guarantee comes without any extra settings turned on. It is commonly expected from any popular filesystem to handle interruptions gracefully and reliably. However, commonly established semantics of what state is returned to after recovery are far from being acceptable. For example, once a file was opened for writing, usually a set of discrete changes is applied. An interrupted write can be partially successful, leaving content neither in the state before opening, neither in the state expected after a complete write. Often even individual file writes are not atomic. This outcome is unacceptable. Content from before changes started should be available for recovery. Another scenario is when a user copies a file overwriting the destination file. Old destination file gets truncated to zero before new content is written into it, which may take several minutes. After

interruption, user can expect old content to be gone while new content is only partially present, ending at undefined position. Even worse, eventual file size does not mean that all bytes up to that offset were persisted. Filesystems can persist file size before the content. This outcome is also unacceptable. Old content from before truncation should be available for recovery. Another scenario is when a program modifies a series of related files as supposedly one operation. Consider for example rotating pictures in a photo album. User could not only expect a rotation of a single image to be atomic, but could also expect the whole album to be processed seemingly at once. After interruption, user could demand the whole album to be reverted to original state. Mentioned problems are not new and can be solved using existing mechanisms. Snapshots are becoming quite popular lately, however they are too cumbersome to be of practical use. They have to be taken manually, often enough, and usually cover a whole volume at once. This is clearly not the right way to go. Versioning infrastructure should retain the state of file structure after every significant change, making save points automatically and transparently. Usable recovery scenario should be easily discoverable for any of mentioned scenarios. User should be able to recover from sets of changes made to sets of files.

Advanced filesystem

is a filesystem with outstanding usability. Usability can be meant as performance (sequential disk speeds, and instant copying), as security (deletions equivalent to permanent wiping), as introspectability and revertability (versioning, snapshots), as utilisation (lower disk usage), as integration (speeding up utilities). Let us briefly look at all these features.

Performance of modern filesystems is getting close to physical limitations of underlying hard-drives. Processing of big files would be expected to happen at high throughputs due to pre-allocation and runtime detection of a pattern. Processing of small files would be expected to happen at high rates due to log structured layout. To achieve this in the long term, file and free space fragmentation must be actively avoided by both adequate disk layout and regular defragmantation in the background.

Cloning files is found only on Btrfs. Hard-links were invented as means of instantaneous forking of files. This however only works in a shared-state fashion, where subsequent changes are also shared. It is possible to achieve similar performance characteristics for copying operation (cloning files), resulting in independently writable forks sharing an immutable copy of common data. Cloning files may be used to apply sets of changes to a file as atomic transactions. This operation is so beneficial that Linux even added a new syscall for cloning files.

Cloning directories is not found on any existing filesystem. Given a suitable architecture this should be achievable.

Secure deletion is another area where modern filesystems are lacking. Wiping files is not practical. User has to manually take action, and if he fails to do it right, unwanted evidence remains on disk basically forever. Performance of a wipe operation is usually comparable to writing few times more than the amount of data to be wiped, with current fragmentation. This makes wiping huge files problematic. Reliability is also a problem as filesystems do not always make guarantees whether overwriting is done in-place or copy-on-write. Above that, truncated file cannot be securely wiped as some data blocks are no longer reachable. Filesystems do not track data blocks that were used by a file. File removal could be made quick and reliable using basic cryptography.

Versioning is another functionality that is commonly missing. Users do often enough start modifying their documents without considering that they may later want to revert their changes, merely as a matter of changing their mind. Also, programs do not always apply changes in a safe, atomic manner while the user is not necessarily aware of it. This poses a risk of losing data, one way or another. Risk could be minimized by underlying filesystem by automatically creating a continuous history of changes, an ongoing list of save-points that keep being added in front of the list and being scrubbed away from the end of the list after some time.

Disk utilisation can be increased through transparent compression. Compression can happen transparently, with the user only noticing that he can store files with more total size than hard-disk capacity. User can explicitly disable compression on selected files, although the compressor

should notice at some point that gain is negligible and stop trying. Btrfs notably implements compression albeit without runtime skipping on uncompressible files.

Integration is a feature where system can process files on behalf of a user space process, but having more capabilities. Filesystem is in a position where it can do more or more efficiently and reliably because it has access to internal information that processes do not have.

Compressed representation of file content can be directly accessible to compressing software making re-compression unnecessary. Current filesystems use compression only internally and do not expose encoded representation to user processes. When a utility compresses a file, a compressed representation is read from disk, decompressed internally by the filesystem, only to be then handed over to the program that will re-compress it again, with perhaps the same algorithm. It would be beneficial for the filesystem to just hand over compressed representation. This could make compression software significantly faster, making it only disk bound.

Hashing can also be done on behalf of common utilities. Filesystem can compute checksums on file content and provide system utilities with result checksums instead of all the data necessary to compute it. Computation can both be done in advance when system is idle or doing scrubbing or defragmenting, on the fly during a sequential write, or on demand when a user process requests it. Once computed, results can be cached on disk and kept indefinitely for future use. System utilities can be modified to take advantage of filesystem provided computation when available and revert to usual method of reading file otherwise. Filesystem guarantees that cached checksum is correct even if other processes also contributed to it's computation, by concurrent requests. User space sharing of checksums would not be safe because programs could forget to change checksums, or change them out of sync with file itself, or purposefully corrupt it. Furthermore, checksum request can be computed on a particular revision, as if a temporary snapshot was created just for the purpose of checksumming, making sure that checksum is not affected by any writing being done while checksumming is in progress. Concurrent checksumming of a same file would not be possible on user space side, and correctness would not be possible at all.

Partitioning disks is very inflexible process. Production systems are often set up once and left running for many years, sometimes even decades, without repartitioning. If a decision is made that filesystems should have a different share of disk space, often the entire system is too big or under heavy load to be repartitioned. Filesystems should exist within partitions but not be constrained by early partitioning. This was solved by storage pools in [ZFS].

Disk backup is an important thing in system administration, however making copies of entire partitions is completely unacceptable. First, entire partition has to be read even if only a small fraction contains allocated data. Secondly, if the partition was not zeroed in advance then there is not much gained from compressing the backup image. This cannot be done if we back up a disk that was already used for a longer time. Thirdly, backup image can be prepared in a way that preserves shared structures, without duplicating clones, and also possibly defragments or compresses the data on the fly. For example, a fragmented file can end up in a contiguous extent in the backup image. This functionality is known as send/receive commands on Btrfs.

Deduplication is a feature not found in popular filesystems, most probably because not many people would benefit from it. Given a suitable architecture this could be easily added.

Usage scenarios

People with different needs can benefit from using a versatile filesystem. There are several reasons why someone might want to use any given feature. Provided below are possible scenarios of people benefiting from different subsets of functionality:

Graphic designer.

He works at an advertising company. Everyday he edits images and photographs provided by his agency. At regular meetings he exchanges materials with his coworkers, where everybody copy source materials from a shared drive and also copy their produced work to their superior's drive. Processing of medium sized files at high rate is beneficial, as it regularly saves time. After morning meeting, he started working on his last assignment. He would like to browse history of his changes to see what remains to be done. Regular snapshots and individual file versioning makes reviewing done work easy. He can now resume his work. While editing an image, his editor crashed. He would like to revert to a state few changes back but the image was saved after they were made and there is no undo possible after editor was closed. Even worse, editor crashed before saving was done, corrupting the only copy of the file. Filesystem keeps a continuous history of recent changes and fine grained undo is possible. He can revert to any state after a successful close operation. After a day full of work, he copies his files onto another drive, overwriting several files. Right after he started copying files power went off. After power was restored, some files were already partially overwritten and thus not usable. Replacing operation triggered a save-point however, and old version of entire file structure was quickly recovered.

Human rights activist.

She works for a local newspaper. Country in which they operate is ruled by an oppressive government. Her daily job activities revolve around gathering incoming reports and writing articles to be printed. She drives a lot around the country and encounters random checkpoints. She must protect her sources and cannot allow her notes to be seized by an opportunist militia soldier. If randomly searched, her laptop is encrypted and does not provide access to unauthorized persons. She refuses to decrypt it until a warrant is presented and her agency lawyer arrives. She is briefly questioned about her business and let go. After getting back home she gets detained by a security force and questioned about any involvement with anti-government organizations. She admits having no involvement. She is presented with a warrant to search her computers. She agrees to comply and provides a valid password that decrypts some documents on her laptop. To the auditors it is clear that the provided password is indeed valid and she complied with the order to decrypt her laptop. Her laptop is throughly checked and only expected agency documents are discovered. Her interrogators do not stop accusing her of being a suspected member and keep searching her laptop for incriminating evidence. Indeed, she was regularly in contact with rebel forces and her laptop contains illegally obtained documents. If these documents were found, or even a hint of their existence was found, she would likely be taken to jail. Secret documents are kept on a separate file structure which is unlocked by a different password that she did not disclose or even mention. Filesystem itself does not reveal how many more file structures exist on the hard disk, if any. Ultimately, no evidence is found on her computer showing that she hides any documents and she is cleared of suspicion.

Medical center maintenance staff.

He works at a major hospital that processes dozens of patients every day. His job is to maintain a database of medical records of current patients. Regularly he has to delete old records of former patients. Government regulations demand that these records are permanently purged when no longer needed. Medical center also has an obligation to guard privacy of it's patients and keep their records confidential. If these records would resurface later the center would get fined for breaking regulations or sued by patients for not providing privacy. He can rest assured that deleted files are permanently gone, as the filesystem guarantees it by design. Aside of regular file purging, there is a need to retire some hard-drives that were used for years. He needs to remove any remaining files from them before he can send them for disposal. Again, data needs to be purged from disks permanently or the center would be liable. He can rest assured that quick formatting done on the hard drives destroyed master keys permanently as the filesystem guarantees it. Also strong passphrase can be stored on a separate device like a pendrive, so even quick formatting is not needed.

Linux distro maintainer.

He works for a company maintaining a linux distro repository. Everyday he compiles and archives whole collections of source code and binaries. When he compiles, scripts often copy files which actually takes no space and no time. This takes away some time from compilation time. After a day worth of work, he sends a big disk image with upgrades. Big files are being copied at high throughput, which again saves time. Afterwards he needs to obtain sha1 checksums. Filesystem computed checksums already during copy operation. When he uses a standard command-line utility to obtain a checksum it gets results immediately from cache.

Computer forensics expert.

He works for FBI as a consultant. He is often being sent to crime-scenes to secure evidence. When a computer gets seized his job is to make disk images of confiscated hard-drives. Disk images take a huge amount of space. High throughput is necessary to make copies in acceptable amount of time. Also a fraction of the disk image is full of zero bytes allowing the filesystem to compress some of the data. Hash of the image gets calculated on the fly during the long process of sequential writing. Hash of the image then gets digitally signed and handed over to the court. After this is done, he needs to keep a copy in his possession until further notice. Court later demands evidence to be presented and jury needs to be assured that these copies were not modified after being obtained. The expert can remain calm as he was the only user with a password and the filesystem can guarantee that no one else could modify the files in his possession. If defense asks for a proof that the image presented in court is the same as the image obtained during a search, expert can present a hash computed by the filesystem or the image itself.

Software engineer.

He works for a major software vendor. His company has a policy that employees can bring work home only on encrypted devices. After work he took a copy of current project on a company laptop and drove back home. When shopping, his car got burglarized and the company laptop was stolen. Filesystem was encrypted and he can be sure that no company secrets fell into wrong hands. Company executives are relieved that there was no major loss and a new laptop was issued to the employee.

Note to the reader: (please add)

Conceptual Design
Ideas and Observations for a versatile filesystem

Arkadiusz Bulski

Introduction

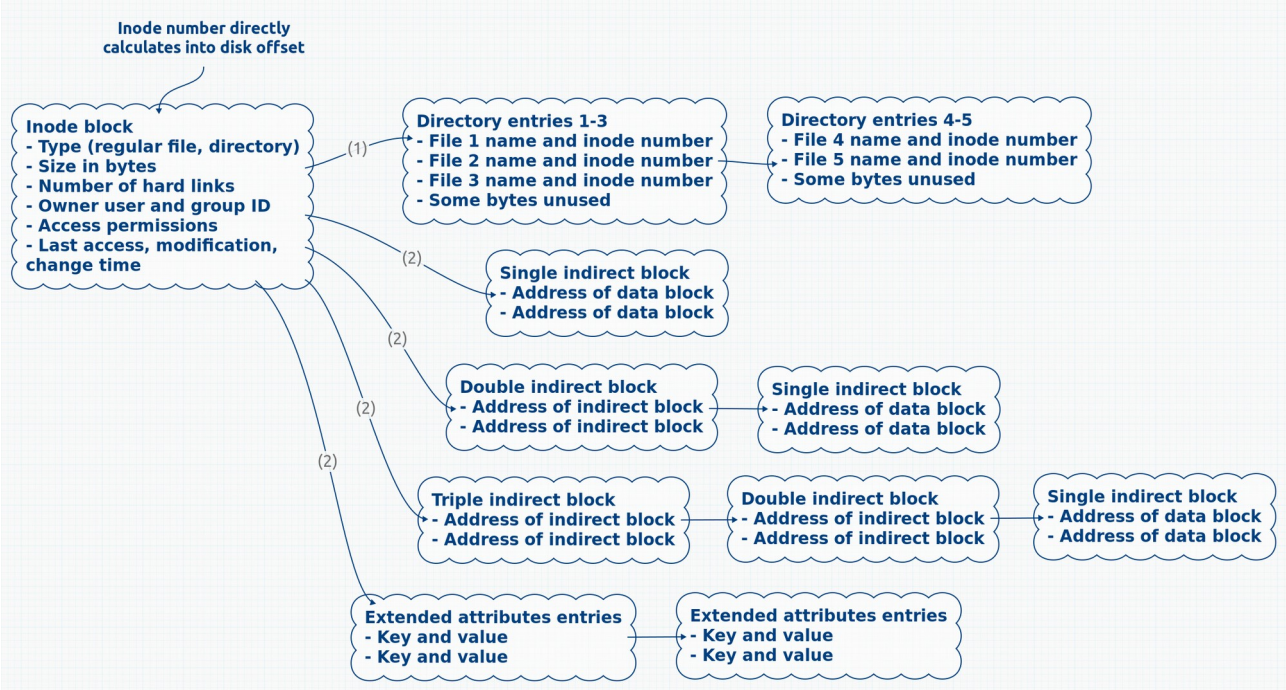
(This chapter is being expanded, but is mostly stable.)

When reading papers that describe filesystem designs, from the golden historical times of Unix development to contemporary times of Linux, one might come to a conclusion that evolution of filesystem designs was very incremental in nature and much effort was put into not making too many changes at once. Some designs like log-structured filesystem [Rosenblum91] seem to have been too radically different from mainstream designs that they have not gained much traction. For example, Ext4 [Mathur07] is an upgrade of Ext3 but it is somehow constrained by previous data formats. Switching from block to extent allocation is not that easy. B-trees were introduced per-directory but not filesystem wide. Offset fields were widened to 48 bits but they will have to be widened again at some point, instead of using variable length encoding. Ext3 was designed directly upon Ext2 with only one component added, a special file used for journaling. Journaling is slow as everything needs to be written to disk twice, and fragmentation is not actively avoided. Ext2 was built as analog to Fast File-System. Btrfs and ZFS seem to be examples of quite radical redesign from scratch rather than gradual evolution. It is possible that they did not gain wider adoption because of overly complex implementation (Btrfs has 120K sloc) and non portability (ZFS is on Solaris). This paper presents even more radical design ideas and hopefully will bring more features to the open source community.

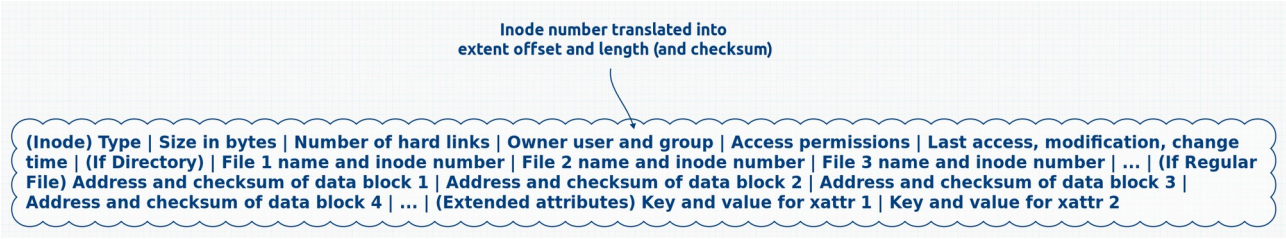
Inodes are not efficient.

Since the early days, filesystems were designed under a principle that data structures have to be broken down into fixed size blocks. This seems to have been due to the fact that hard disks require read and write operations to be carried out on 512 byte long, discrete blocks of data. In traditional designs most file operations can be done by processing one block at a time. Computers of the past often had little memory, [McKusi84] had maybe 8 MB, and caching complete sets of metadata was not feasible. Also changing metadata often ended up in writing just one block, which might have been seen as a compelling reason to use this approach. Furthermore hard disks guarantee that any given block is written atomically [Twee00], which was used for guaranteeing consistency after crash, for example in Ext2. All these reasons contributed to a decision that data structures had to be broken down into blocks.

To fully describe a single file, an amount of metadata needed almost always takes space of more than one block. Traditionally, as started in Fast File-System [McKusi84] and carried on in Ext2/Ext3, one main block (called inode) would hold most important data and point to further blocks, several blocks would point to where actual content is located (indirect blocks), some blocks would keep directory entries in case of a directory, and so on. For a large 1 GB file for example, assuming 4 KB blocks and 64 bit pointers, at least 512 blocks is needed. Certain operations such as copying or deleting file, or browsing directory necessarily requires all metadata blocks to be read. This was also noted in [Mathur07].



Instead, a *complete inode*, variable size structure could contain all metadata associated with a given file. In memory representation may remain similar to the one above but on disk format would be like one below. On disk structure always remains continuous. Size of entire metadata could easily go into hundreds of kilobytes for gigabyte sized files, depending on whether checksums are included with pointers alike [ZFS]. Below are presented arguments showing expected performance gains of complete inodes over classic inodes and indirect blocks.



Consider a range of possibilities, where all metadata blocks are either allocated in one continuous range (called an extent), are divided into subsets, or are divided into individual blocks. First approach we shall call the *extent approach* and it requires that all blocks are read from a continuous area on disk in one sweep and after changes are made all blocks are stored to another continuous area in one sweep. Last approach we shall call *block approach.* It is prevalent in modern filesystems. Space is allocated even one block at a time if allocation happens with long enough intervals, eventually leading to fragmentation of metadata.

Block approach seems efficient at first glance because changing one field requires only one block to be written to disk. To the contrary, extent approach may require rewriting the whole extent which takes many blocks. This kind of reasoning is flawed because it is focused on time of update operation but does not account for future read operations. Further analysis considers amortization of performance over most of lifespan of a file, and does not assume that any one operation must be carried out as fast as possible independently of other further operations.

It could be argued that extent approach, where all metadata is always loaded and stored in one sweep is better in every practical usage scenario. To show that, we need to recognize that magnetic hard disks have quite skewed performance characteristics. Flash based storage is considered separately. Representative hard disk is capable of ~120 MB/s of sustained

throughput and ~10 ms seek time to random location on average. Quick calculation shows that reading or writing an extent smaller than 1.2 MB is faster than literally one seek, on average.

This observation may seem counter intuitive. Filesystem designs so far seem to be based on the assumption that data needs to be processed in smallest chunks possible and only way to go is to process as small amount of them. It seems that the opposite approach of processing bigger chunks never gained traction. In traditional designs [OSTEP] directories put entries into individual data blocks, files put data locations into individual indirect blocks, and so on. In modern designs [Rodeh12] [ZFS] copy on write B-trees are replacing inodes and indirect blocks with leaf nodes but data is still being divided into small chunks. The issue being described here has not gone away.

Extent approach is shown to be better by considering total time spent on all operations throughout most of the lifetime of a file. Only metadata is counted towards the time spent on file operations. Both file content and parent directory metadata are excluded. At time zero file is assumed to already exist, with all content and metadata. It is assumed that file grew slowly enough for metadata blocks to be allocated individually, not being affected by deferred allocation. Blocks are allocated from entire disk, although smaller areas will also be investigated. A certain number of cycles is considered, where file is opened, several metadata blocks are accessed and then file gets closed. In each cycle some subset of metadata blocks is accessed, either read or written. Cached blocks are forgotten between cycles due to assumed long time intervals between cycles. Blocks are assumed to be 4 KB size. Suffixes like K M refer to thousands and millions of bytes.

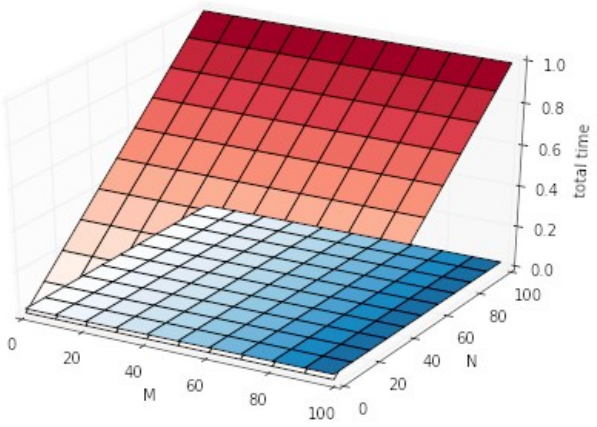
Reading or writing N blocks takes in total (assuming sequential and random pattern, referring to extent and block approach respectively):

$$R_1(N) = 0.010 + N \cdot 4\,K/120\,M = 0.010 + N \cdot 0.00003$$
$$R_N(N) = N \cdot (0.010 + 4\,K/120\,M) = N \cdot 0.01003$$

Simulation of entire lifespan is based on three variables, N is number of blocks accessed in each cycle, M is number of blocks total, and B is number of cycles. Only a subset of blocks is accessed during a cycle so N<M. Therefore total access time is (extent and block approach respectively):

$$T_1(N, M, B) = \sum_{i=1}^{B} R_1(M) + R_1(M)$$
$$T_N(N, M, B) = \sum_{i=1}^{B} R_N(N)$$

Plots show total time of extent approach (blue) and block approach (red) for least and most accessed files (N), and least and most sizable files (M).



There are cases where extent approach loses to block approach in comparison. Total times are compared through an inequality. Number of cycles cancels out.

$$T_N < T_1$$
$$B \cdot R_N(N) < B \cdot 2 \cdot R_1(M)$$
$$0.01003 \cdot N < 2 \cdot (0.01 + 0.00003 \cdot M)$$

$$N < 1.994 + 0.006 \cdot M$$
$$M > 166 \cdot N - 332$$

Last two inequalities show limits on how much metadata can be accessed during one cycle before block approach starts to lose advantage. Asymptotically, less than 1 in 166 metadata blocks could be accessed. For smallest files the limit is 2 blocks. Remember when earlier it was mentioned that a 1 GB file would require at least 512 metadata blocks? According to the limits, after opening at most 5 metadata blocks could be accessed before block approach would lose advantage and this includes the inode block. Is this really the kind of workload we are aiming to support?

When individual blocks are stored, time is gained on transfer time due to small block size but then more time is lost to seek time when blocks are read at next cycle. Disk characteristics make this tradeoff totally unfair. One seek takes as much time as transferring 1.2 MB which is a lot. For many files, complete metadata could be fit within that amount of space. Also, on desktops 90% of directories have less than 20 entries and mean file size is less than 189 KB [Agraw07] and 99.5% of directories have less than 20 entries and mean file size is less than 32 KB [Douceur99]. Additionally the extent approach requires one checksum to verify integrity while the block approach requires as many checksums as there are blocks.

Finally it should be admitted that the theoretical model above assumes most naive implementation of block approach where blocks are allocated individually (not grouped, as if allocations were separated by long time intervals) and non-preemptively (no space reserved in advance) from entire disk (space not divided into segments). It would be possible to allocate blocks in groups (deferred allocation), allocate space in advance, and also select blocks from small areas or segments (clustered allocation), increasing so called *spatial locality*. However, constructing a theoretical model that includes deferred allocation is outside of scope of this paper. Probabilistic distribution parameters are not known.

Secondly, disks can reorder outstanding operations to minimize total seek time, with technology called NCQ/TCQ. Model assumes that blocks are accessed without concurrency, one block after another. Some usage scenarios allow to anticipate which blocks will be subsequently accessed and disks would be able to take advantage of it. However, reordered and concurrent random disk operations will never be as fast as one contiguous disk operation.

Thirdly, seek times and rotational delays are quite expensive and the hardware trends are diverging. Delays and throughputs will be even more asymmetric in the future [Patterson].

Experimentally, average seek times measured on SAMSUNG HD154UI are as follows. Seek time is a function of area size over which seeks are made with uniform distribution. Code can be found in the repository.

Area size:	Seek time sequential:	Seek time concurrent:
1 MB	0.20 ms	0.01 ms
4 MB	0.44 ms	0.36 ms
16 MB	1.76 ms	1.30 ms

64 MB	4.53 ms	3.87 ms
256 MB	6.76 ms	7.59 ms
1 GB	8.61 ms	8.50 ms
4 GB	9.41 ms	9.20 ms
16 GB	10.93 ms	10.78 ms
64 GB	10.99 ms	10.85 ms
256 GB	12.19 ms	12.73 ms
1 TB	16.30 ms	15.72 ms

Above seek times are averages for single seeks. Formulas used for comparison between block and extent approach can be updated with any seek time from table above if clustered allocation is to be included. Sequential times mean that blocks are accessed one at a time, not that they are laid out in a contiguous area. For small files, metadata blocks could be clustered in small areas. For example, for 1 MB and 16 MB areas block approach works for at most 1 block access. For larger files, many blocks are needed so they have to be spread over larger areas, which leads to longer seek times. Concurrent times converge with sequential times as disk area gets larger. However, reordered and concurrent random disk operations will never be as fast as one contiguous disk operation.

SSD disks are not being considered in this design. Some design decisions are aimed to exploit asymmetric performance characteristics of hard drives, namely high throughputs but also high latencies. These mechanisms are counter productive on SSDs.

B-trees are not efficient.

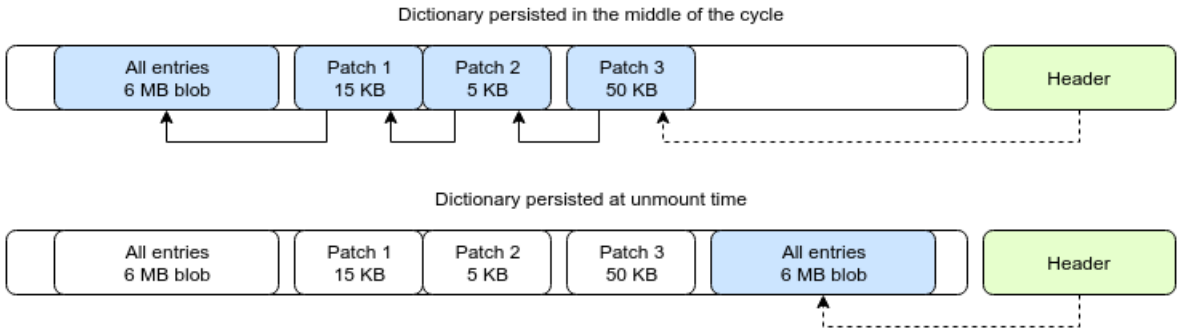
There is a trend among filesystem designs towards using both modified in-place [Mathur07] and copy on write B-trees [Rodeh12] [ZFS]. This trend might be easily explained by common expectation that filesystems should be able to handle huge numbers of files. Popular filesystems even explicitly advertise their ability to scale among main reasons why to choose them over the competition. B-trees are a good approach if a huge amount of keys is expected. Trees scale asymptotically with logarithmic complexity which means even billions of entries can be stored with only a few disk accesses needed to reach any given entry. This **asymptotic behavior** seems to have mislead everyone. It would be justified to use B-trees if billions of files were expected to be stored but that is a false assumption, at least in general case. Most computers hold on the order of 100'000 files [Agraw07]. That amount of dictionary entries can be stored and accessed more efficiently. In such a case, B-trees are suboptimal.

Second reason to use B-trees in the past is that memory needed to query and update trees is small, comparable to number of nodes from root to leaf. Computers of the past often had little memory, [McKusi84] had maybe 8 MB of memory. However, modern desktop computers have several gigabytes of memory and servers have tens of gigabytes of memory. Conserving memory is not justified anymore. Memory constrained devices like smartphones and embedded systems are not being considered.

Consider the two approaches described below, in the context of how many entries we expect to hold at any given time. As previously, we assume hard disks can sustain ~120 MB/s throughput and ~10 ms seek time on average.

First approach, entire dictionary is stored in a single extent. At mount time, entire dictionary is

loaded from disk in one sweep, kept in memory in entirety and entire time and regularly stored in entirety to disk as copy on write in one sweep. 1’000’000 entries dictionary would take 23 MB of disk space, assuming 64 bit keys and 128 bit values, and much less space if VarInt encoding was used. This amount of extents should be enough to store the files found on a typical desktop, which is 100K files [Agraw07] or 200K files [Douceur99]. Even better, small changesets (diffs) can be stored to disk every few seconds and entire dictionary can be stored only every few minutes. If filesystem gets unmounted successfully, only the final chunk containing the entire dictionary is going to be loaded at mount time, and if interrupted, about 100 patches need to be loaded from disk and combined. Either all patches were stored in one disk segment anyway, so only one disk sweep is needed to read them all, or readahead could be used to read them concurrently. Entire dictionary is being cached so all key lookups and changes are diskless. Storing blobs and diffs, after amortization becomes negligible. Following diagram shows deallocated space in white.



Second approach, B-trees as the contemporary alternative. Tree height is equivalent to amount of disk seeks. Assuming the root node is always in memory and nodes have 1480 entries (64 KB with 36 byte values and 64 bit pointers) then 1 seek gives a capacity of 2.2×10^6 entries, 2 seeks give 3.2×10^9 entries, 3 seeks gives 4.7×10^{12} entries, 4 seeks gives 7×10^{15} entries, and so on. Bitmaps can used to track unused nodes in allocated segments. This approach has its obvious benefits but one has to remember that most desktops have between 100K and 200K files. At this amount of entries, B-trees are not necessary and perform worse than an entire dictionary.

[Add a diagram for B-tree nodes.]

This argument is basically the same as for complete inodes. Importantly, these two approaches are not mutually exclusive. When entire dictionary grows over a limit the entries can be easily migrated into a B-tree, and when the tree becomes tiny then entries can be easily migrated to a dictionary. The filesystem can keep switching between these two representations.

Block allocation is not efficient.

Since the times of Fast File-System and up to about Ext4 and Btrfs, disk space was divided into blocks but grouped into clusters. There are few heuristics when assigning blocks to files that can increase overall performance. For one, same file can have blocks allocated in a row continuously or at least in close proximity. Large files are especially demanding of continuous allocation. Secondly, files that are supposed to be accessed together, for example if created by same application, can be allocated next to each other. This approach seems to be sub-optimal. As XFS documentation points out, fragmentation does not exist on filesystems containing small files and on filesystems containing large files. The problem only exists on filesystems containing both small and large files, because small deallocations must also satisfy large allocations. Eventually space always gets fragmented. At some point it becomes very difficult to find a large contiguous area while there is a lot of small free chunks. Problem is that seek time over small distances is quite significant, due to the settling phase. The right approach would be to actively counteract external fragmentation.

Log-structured filesystem invented by [Rosenblum91] solves the problem by allocating disk space from one huge circular log, while regularly moving files from the other end of the log and compacting space at same time. This approach has its own problems, that already continuous files, large or small, still need to be moved.

Segmented log-structure as described in this design aims to achieve the best of both worlds. Entire disk gets divided into separate segments which then get divided into extents. After some extents were deallocated or even internally deallocated, the segment is read in one sweep, compacted internally and possibly recompressed, and then stored to disk somewhere else. This approach has a problem of having a lot of segments that are half compact, as investigated by Rosenblum and Ousterhout. This is to be solved by redistributing extents so that there is not a 1-to-1 mapping of segments, but many partially filled segments turn into a few segments that are full. This means extents from one segment can be spread among different destination segments or even be split into separate extents.

(This requires expansion.)

Fsync is not efficient.

Files stored on computers become increasingly important as businesses and governments store ever more files of evermore importance on automated systems. At some point in the past, programs started using techniques that would ensure reasonable state after computer was interrupted which did and still does occur quite often. POSIX standard implies an approach that is being used to this day. Windows systems use an identical approach despite not recognizing POSIX. The well established approach replaces a file using following template:

```
int fd = creat("file.new", S_IRUSR|S_IWUSR);
write(fd, buf, len);
fsync(fd);
close(fd);
rename("file.new", "file");
```

This approach has been the expected way of achieving atomic changes to files and caused a lot of pain when people were depending on different guarantees than that of fsync. For example, Ext3 implemented fsync in a naive way that flushed all files to disk and not just the file of interest, which caused it to be slower than perhaps it should have been. At same time, Ext3 implemented non-POSIX behavior of persisting data blocks before related metadata which made the rename safe even without fsync. These two facts made fsync both slow and useless. As a result fsync was no longer needed for correctness and so people started skipping it. Later, ordering behavior was disabled to increase performance and fsync skipping code started corrupting files. This story has been described in LWN post POSIX vs Reality. Also, heavy reliance on fsync led to a famous major performance bug in Firefox.

Described behavior (and few others) is common in modern filesystems but it is not mandated by POSIX standard so applications should not rely on this property being always met. Refer to [Pillai13] for modern filesystem semantics that are common but are not part of the published POSIX standard. Notice that all of the behaviors they describe are met by a filesystem where all operations are both atomic and ordered, as proposed below. Article also describes how SQLite can increase performance by assuming specific filesystem behavior although user has to enable it manually. Also article shows bugs found in LevelDB, a predecessor to SQLite, that corrupted files because the same behavior was assumed but never verified. Both SQLite and LevelDB would be safe on a filesystem where all operations are atomic and ordered. How such a filesystem could be constructed is described below.

Following code is not safe on all filesystems but is representative of applications:

```
int fd = creat("file.new", S_IRUSR|S_IWUSR);
write(fd, buf, len);
fsync(fd);
close(fd);
rename("file.new", "file");
```

Whatever improvements to filesystems will be made in the future, it seems clear that applications will continue to use the approach established by POSIX and filesystems will have to cooperate. Inventing new APIs that ensure safety that also break existing code will not gain traction, no matter how fancy they seem. For example, Btrfs provides an interface to clone a file in zero-time, that allows to apply sets of changes and also changes to huge files in an atomic manner. This was integrated into *cp* command but databases like SQLite do not take advantage of this feature. Another example, Btrfs also provides a way to manage transactions spanning across files. This feature would seem useful if its own documentation have not outright discouraged using it, with warnings of deadlocks.

Below is described a new solution to the problem of ensuring consistency that keeps files correct whether the POSIX compliant approach is used or not while performance is approaching no use of fsync at all.

Consider a filesystem where all operations are both atomic and ordered. Above that fsync calls are implemented as no-op. Both codes above remain to keep files consistent. This is due to the fact that application developers (usually) use fsync not to persist data immediately but to persist data before metadata, which is what ordering behavior implies. Linux man pages define fsync as a means to persist data immediately but surprisingly this is not what POSIX strictly requires, rather it is just the mainstream interpretation. POSIX first defines fsync (in vague terms) as flushing buffers to a device but then explains in the notes, and explicitly, that if a filesystem can guarantee safety in a different way then that also counts as a valid implementation of fsync. Flushing buffers may be an obvious way to do it but are not the only way. Excerpt from POSIX documentation:

> *(DESCRIPTION) The fsync() function shall request that all data for the open file descriptor named by fildes is to be transferred to the storage device associated with the file described by fildes. The nature of the transfer is implementation-defined. The fsync() function shall not return until the system has completed that action or until an error is detected.*
>
> *(RATIONALE) The fsync() function is intended to force a physical write of data from the buffer cache, and to assure that after a system crash or other failure that all data up to the time of the fsync() call is recorded on the disk. […] It is **explicitly intended** that a null implementation is permitted. This could be valid in the case where the system cannot assure non-volatile storage under any circumstances or when the system is highly fault-tolerant and the functionality is not required. In the middle ground between these extremes, fsync() might or might not actually cause data to be written where it is safe from a power failure.*

Here is some historical background:

Persisting ordered operations used to be implemented though ordered persistence. Long time ago blocks were written one at a time (synchronous writes). Operating system buffered changes in memory (in the buffer cache) and was the only party that buffered. When hard disks started buffering writes themselves things got broken. System was no longer in a position to tell which blocks were already persisted on the platter and which were still pending. Immediate solution was to implement *flushing buffers* through so called *queue draining*. System withheld all future writes until disk reported that all outstanding writes completed, that write queue was empty.

When flushing buffers occurred quite often this approach basically defeated the purpose of installing buffers in hard disks in the first place.

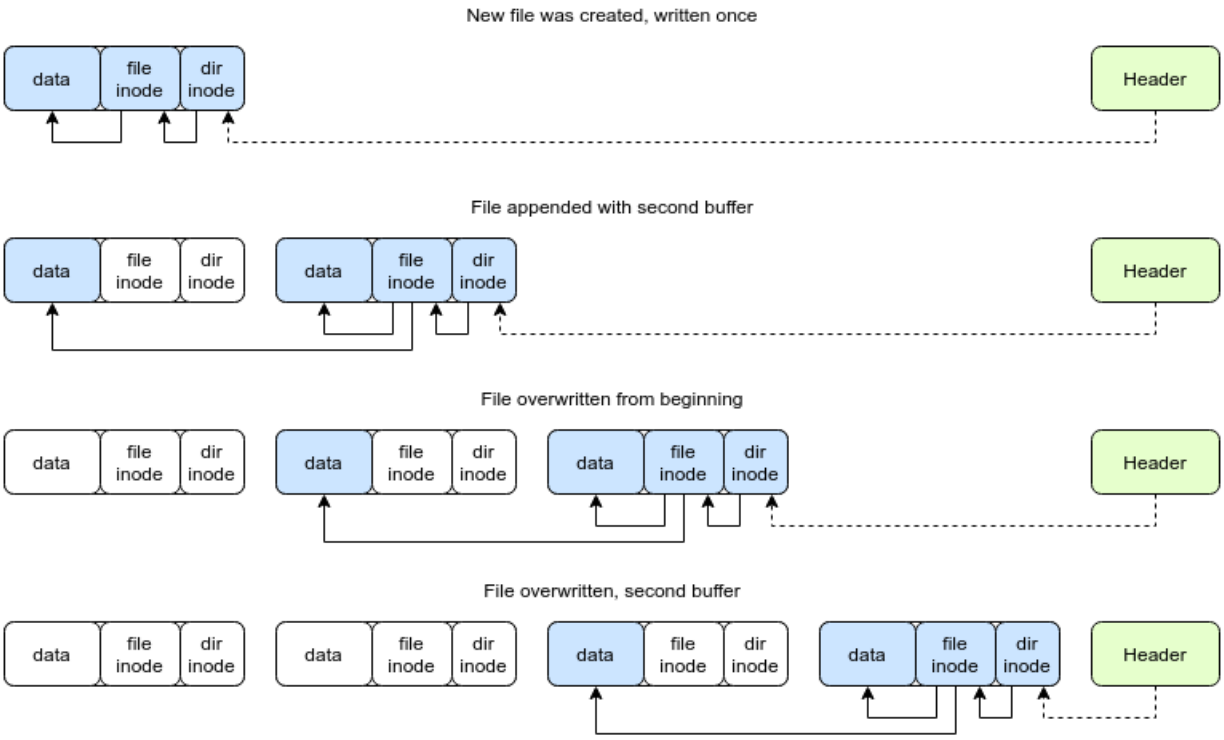
Later another major overhaul of disks took place. Up to this moment systems have reordered requests themselves. Buffer cache accumulated blocks to be written and system decided, without much help from the disk, in which order should the disk write them. It was more beneficial to process blocks in the order that minimized total time spent on jumping between locations on disk. Unfortunately, system was in no position to determine current orientation of the platter or current position of the head. The system made decisions based on some principle like elevator scheduling, not on exact state of the disk. Everything changed again when disks started to reorder requests themselves, with a technology called NCQ/TCQ. System was again no longer aware of what is the status of each request. System did not even know which of them will go to the platter first. The solution to ensuring order of writes was again the same, through withholding further writes.

Modern solution comes in form of two related mechanisms: explicit flushes and FUA requests. Flushes are writes that are weakly ordered, demanding that previously scheduled writes are completed before current writes. Previous requests can still be reordered between themselves, and so can future requests. Force Unit Access (FUA) requests can be reordered with any other request, imposing no ordering whatsoever, but disk reports immediately after they landed on the platter. FUA requests are also said to have priority over normal requests. System is no longer responsible for ensuring ordering. Instead the disk is being issued requests marked with these two flags. Topic is discussed on LWN The end of block barriers and Monolight Barriers, Caches, Filesystems.

Consider the following layout of a filesystem where all operations are atomic and ordered:

First sector contains the address of last persisted root inode, further sectors hold both data and metadata in any layout desired, be it log-structured or segments or blocks. Each operation puts new extents onto the disk, referencing previous extents. Everything that is being changed is stored copy on write, nothing is overwritten in place for safety reasons. Header points to a complete inode of root directory which points to complete inodes of files within the directory. File inodes point to data extents containing file content.

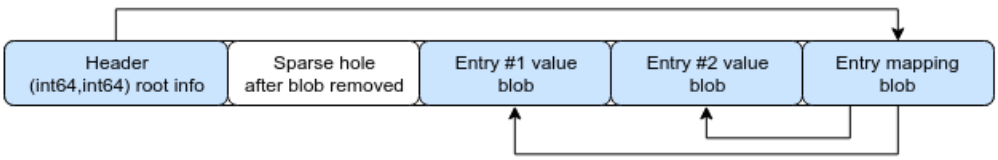
For example, a file write stores the data in a write buffer. After a short period the write buffer gets pushed to disk. File inode is updated with the location of the data extent. File inode then gets pushed to disk. Root directory then gets updated with new location of the file inode and itself gets pushed to disk. After these structures were sent do disk, disk operations get synced and the header is updated to point to latest location of the root directory inode. Note that only the header overwrite needs to be atomic. Other disk writes are neither atomic nor ordered. If the disk can implement a sync without withholding ongoing operations then checkpointing does not affect filesystem operations in any way. In summary, changes become durable in groups between checkpoints. Data can be sent continuously to disk for a long time before a checkpoint, even up to a minute if desired. Only one disk sync is triggered per checkpoint, regardless of fsync calls. No journaling is being employed so no data needs to be written twice. One might argue that inodes are written more than once but that is justified by shortening future reads to one seek anyway. Each inode gets serialized to a continuous extent and all dirty inodes can be laid out next to each other making entire checkpoint into a single sequential disk write followed by a single sync. Following diagram shows a log structured version, each after few operations:



Upgrades can be added. A dictionary that maps ids into disk offsets can be referenced from the header. Directories then associate file names and files associate data with extent ids instead of disk offsets. Changing an inode does not affect the inodes above in a path to the root anymore, instead only a dictionary entry translating the id gets updated. Furthermore, some structures are updated so frequently that patches (diffs) might be stored instead of full structures. That would make checkpointing more lightweight and could lead to more frequent checkpointing.

[Add a diagram for dictionary and inodes, more compact than just inodes.]

Simple key-value store can be implemented easily on an atomic ordered filesystem. First 128 bits hold extent info (which means offset and length) of a dictionary blob. The dictionary maps keys into extent infos of value blobs. Both the dictionary and the values are serialized into binary blobs and stored as contiguous extents. Value blobs are appended atomically to the file, and when database gets commited, dictionary blob also gets appended atomically and then header is overwritten atomically. This way, existing blobs cannot be damaged due to copy on write, header cannot be damaged due to atomicity, and current header is always consistent due to ordering. Reference implementation can be found in the repository.



Even simpler document store can be implemented when setcontents method is available. Only one entry can be stored at once, but it can be an arbitrarily complex data structure. Setcontents is a filesystem operation that truncates the file to zero and writes to it in one combined atomic operation. There is no reference implementation yet.

Cumulative representation is less useful.

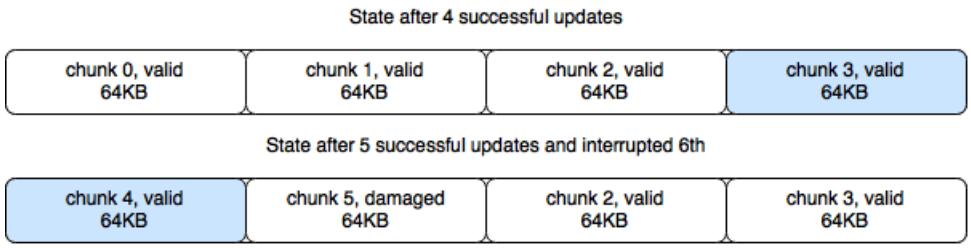
(This needs to be added entirely.)

Atomic sector overwrite is not necessary for consistency.

Many filesystems but also frameworks like SQLite guarantee consistency by depending on the underlying hard disk to overwrite sectors (512 bytes) atomically. There are some issues with this approach, although for many years so far this approach seems to have worked just fine. First, this simply moves responsibility down the chain. If possible, it is generally a good idea to implement a trait yourself than depend on other frameworks or hardware. This is because the framework below is by definition a responsibility of some other individual or organization. Many projects in the history of software got exposed to exploits or got broken due to bugs in borrowed code. And regarding hard disks specifically, there are some reasons to doubt whether atomic sector writes are indeed as real as advertised. Personal conversation with Stephen Tweedie is attached [Tweedie15], suggesting that each particular hardware system would have to be examined for this trait to exist or not. Therefore, a software solution breaking dependency on the hardware should be taken into consideration.

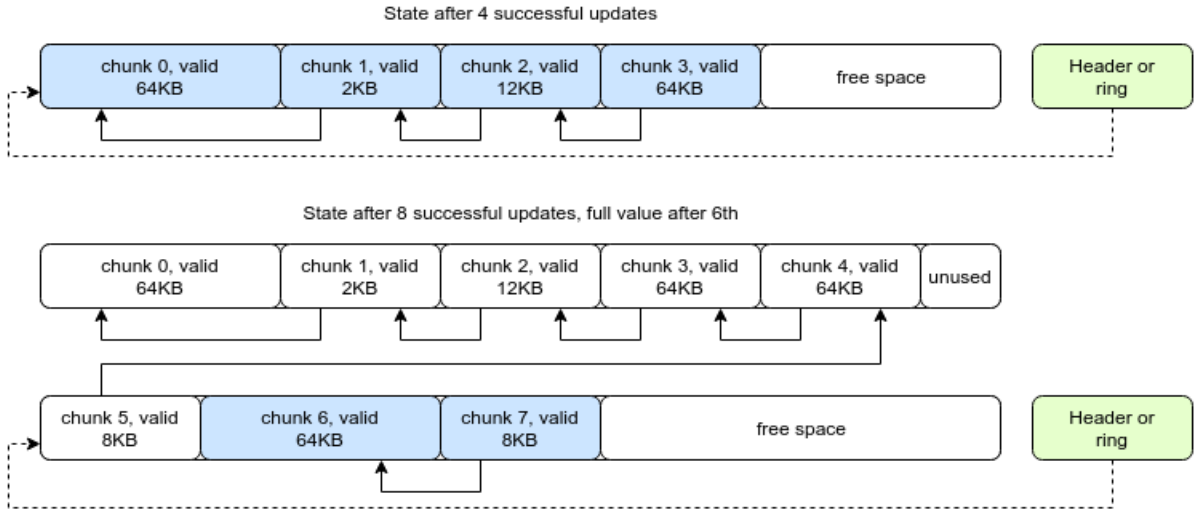
There are two ways to implement atomic changes on disk through software. Both no longer require the disk to have atomic sector writes. However, phantom writes, corrupted writes, and misplaced writes are not taken into account. Also a sector write must not damage anything outside that sector. This requirement is also being exploited by SQLite [Pillai13].

Ring is a disk extent that is sector aligned and long enough to contain some number of data chunks, 2 or more. Chunks need to be of fixed size and sector aligned. Each chunk has a format [checksum|generationid|data]. When the ring is being updated, a new chunk gets assigned an incremental unique id and both data and id get hashed. Then entire chunk gets stored to disk. When reloading, entire extent is read from disk and divided into chunks. Each chunk is checksummed, and from the valid ones the chunk with highest id is considered the current value. Writing another chunk requires the last index to be know, making this mechanism stateful.



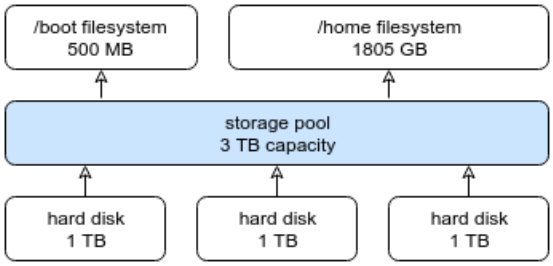
Chain is an disk extent that is sector aligned and contains a concatenation of variable sized chunks. Each chunk needs to be sector aligned. First chunk usually contains a large value and has a format [checksum|id|length|data] and further chunks contain small diffs and have same format. When the chain is being updated, a new chunk gets assigned an incremental unique id and all chunk fields get hashed. Since data field can be of variable size, the length field stores its size. When reloading, entire extent gets read from disk. First sector is parsed and given the length field, appropriate amount of bytes is verified by the checksum field. Length field needs to be rounded up to sector size. If valid, the base value was established. This also provides the offset where the next chunk begins. At some point, next offset goes outside the extent or a checksum fails. Valid chunks are summed (diffs are applied to base value) or simply the last value is taken. Writing another chunk requires the last offset to be know, making this mechanism stateful. Note that a chain is *one use only*, meaning it can be updated many times but at some point it gets full

and it becomes impossible to add further chunks. When a chain gets full, a new chain must be allocated and a ring can be used to switch between two or more chains, allowing the unused chains to be formatted and reused. Chains can also refer to previous chains thus creating a deque, however to enable removal indirect indexing must be used instead of direct pointers.



Volumes should not be synonymous with partitions.

Filesystems can and should be decoupled from disk partitions on which they reside. Zetabyte filesystem [ZFS] has a feature called storage pools. Hard disks are consolidated into pools of storage space, that later gets divided among many filesystems as they require it. This way a new filesystem can be added to a pool without disk repartitioning. Instead the storage pool allocates disk space to filesystems with time as filesystems grow. Likewise, a filesystem can be removed thus freeing its space back to the storage pool. Also filesystems can allocate segments from different disks to balance both free space and disk activity. Important files and metadata can be mirrored across different disks to increase resilience against disk failures.



Storage pool can be filesystem agnostic. A pool is made of block devices and divides its space among filesystems. Internal format of either filesystem is unknown to it. It is possible that after storage pools are implemented in the kernel, other filesystems might also embrace this layout.

(This needs to be expanded with some details.)

Encrypting disk blocks is not useful.

Encryption became a common feature that is not used only by geeks and criminals anymore. While in the past user would use some custom program to password-protect archives and store them away with other files on otherwise unencrypted media, today operating systems are

expected to offer encryption out of the box. In particular, systems are often installed on encrypted partitions and are supposed to boot off them. The problem is that initial code must be loaded before any decryption can be done. Some files need to be available in the clear before rest of them can be decrypted and booting sequence can proceed.

Linux uses a separate unencrypted /boot partition to start a booting process. Then a screen pops up asking the user to provide a password which decrypts a LUKS partition. There is a reason why one partition cannot be enough to boot a system. LUKS partitions are encrypted block-wise. There is no facility to keep selected blocks in the clear. Filesystems are mounted on arbitrary block devices and are unaware of how (or whether) underlying blocks are being encrypted.

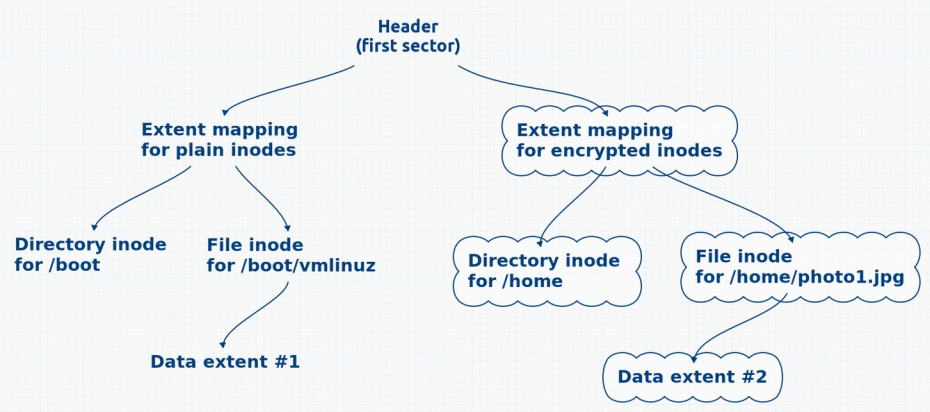
Only solution to booting from a partially encrypted filesystem seems to be encrypting selected data structures within the filesystem and not the entire block storage device underneath.

Consider a filesystem where encryption is applied to data structures like inodes and data extents, and not raw disk blocks. Each data structure is encrypted individually and initially free space is filled with random bytes. Header is stored at a known location and keeps two addresses in the clear: one pointing to unencrypted data structure and one pointing to encrypted data structure. Following one address would allow discovery of all files stored in the clear, while second address would allow discovery of encrypted files but only after password was provided.

Encrypted structures would be indistinguishable from free space so there is no way to tell how much data is stored aside of files stored in the clear. When encrypted blocks are freed they just become part of the garbage in the background. Freeing blocks from files stored in the clear should be followed by overwrite with random garbage, although erasing can be postponed, resulting in space being unavailable for time being. Biggest disadvantage is that entire block device should be filled with random bytes before being used, although that also can be postponed. Filesystem creation would happen instantaneously but several hours would pass before entire device is filled and full security is guaranteed. Until then, an examination would reveal that certain segments are not encrypted with high probability. Content would not be revealed, only whether it is encrypted or not and an upper bound on usage quota, and only for first few hours of operation. Eventually entire disk would become filled with random bytes mixed with encrypted bytes.

Writing files in the clear before unlocking would be impossible since without password there is no way to distinguish used space from free space to allocate from, unless space was reserved in advance. Then files like boot logs could be stored in the clear even before unlocking.

Following diagram shows an example of data structures on disk (clouds mean extents are encrypted, locations on disk are not represented):

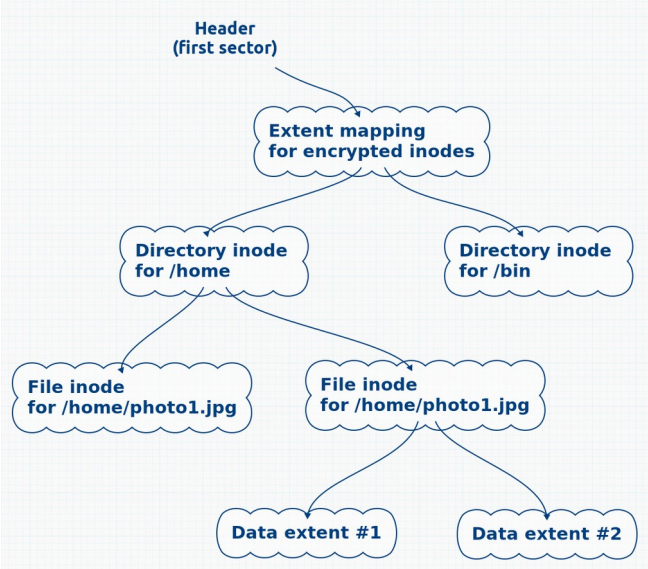


Overwriting files is not safe or efficient.

Wiping is an operation that renders a file unreadable, so as it is not possible to recover the content. Historically, and even to this day, this is achieved by overwriting content with zero or random bytes. This approach is definitely not fast or safe. Throughputs of modern hard disks is about 120 MB/s, and due to file fragmentation 8 ms of seek time per fragment will have to be added. For large or highly fragmented files this is going to take a long time. Also, magnetic force microscopy [Gutmann96] allows to recover overwritten data from disk platters, at least to some degree. To be sure, data should be overwritten up to 35 times. As for safety, files are being overwritten through the standard abstracted interface that provides no means of checking or changing how overwriting is effectuated. Modern filesystems like Btrfs tend to use copy on write strategy so overwriting files has no effect on already allocated blocks. Also when a file gets truncated, filesystem loses track of deallocated blocks. User space tools do not have an interface that would allow to query where these blocks are, or to allocate them specifically. Usually filesystems do not keep track of those blocks anyway.

Encrypted LUKS partitions are a partial solution, because they allow only to wipe entire filesystems and not individual files. However, the idea of keeping cryptographic keys in a header, that are used to encrypt subsequent blocks is a good idea that can be taken further.

Encrypting data structures within a filesystem, instead of data blocks within the block device underneath, is an approach that allows to efficiently and safely wipe files, and for that matter any other data structures that the filesystem is divided into, from individual data extents that compose file content to entire directories instead of directory trees. Principle is the same as in previous section, and also shown on diagram below. Header contains a key to a data structure that contains keys to further data structures which also contain keys to further data structures. This creates a tree of both cryptographic keys and data structures, and wiping of any key in the tree breaks decryptability of all data structures further down the branch.

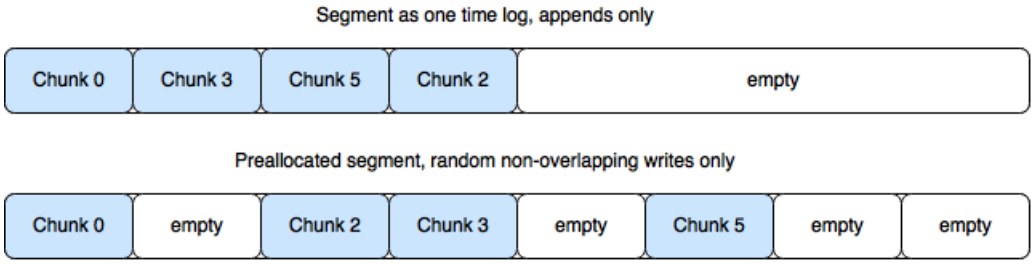


Strategies for data allocation are mutually exclusive.

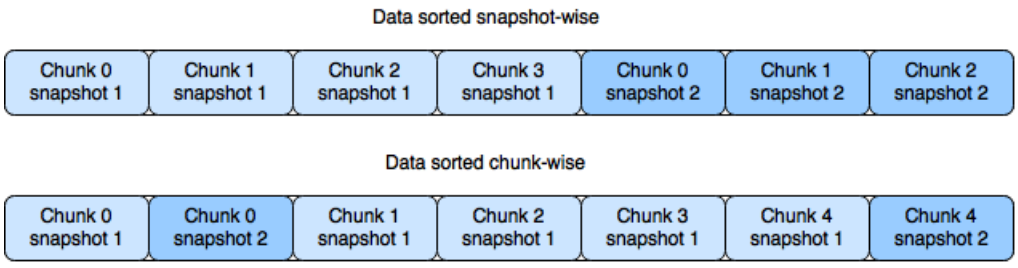
Segmented log structured filesystem is a layout where the entire disk is divided into segments, which are themselves one time logs. Filesystem selects an empty segment and appends data to it until that segment is full, and then selects a new segment. Concurrently, outdated segments can be read, compacted and defragmented internally, checksummed for integrity, recompressed, and finally stored to another location. Also, compacted segment could be split apart to fit into

previously compacted leftover free space. There are however some mutually exclusive strategies how to allocate data within the segments, and whether is it always a good idea to append only to one segment.

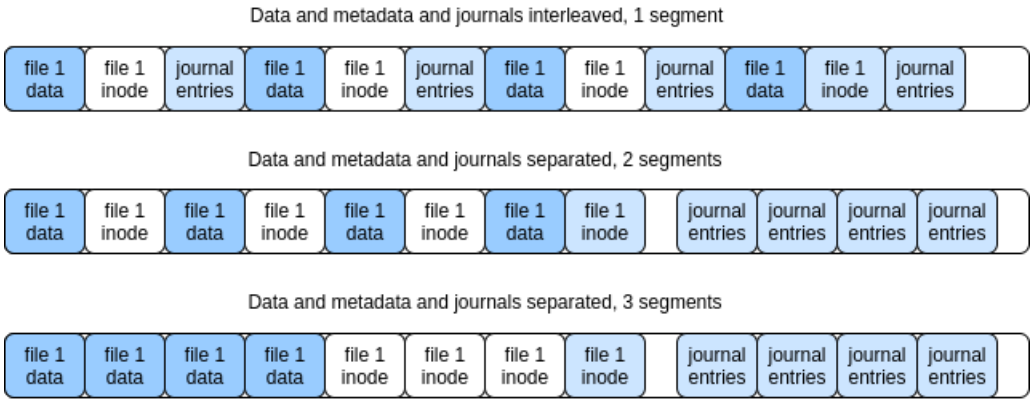
Consider the difference between how web browsers and torrent clients download files. Web browsers always download files sequentially. Therefore it is reasonable to lay buffers in same order. However, torrents are downloaded in a different way. Files are downloaded chunk wise in unpredictable order. That is, entire file gets divided into chunks, and each chunk is stored to disk exactly once. In this case, a better strategy is to preallocate the entire segment for this file and store chunks with random writes. There already exists a system interface which applications use to advise the filesystem on expected file size (fallocate). These two strategies have different performance goals. First approach has high throughput initially when storing chunks to disk, but all subsequent sequential file reads will cause random reads from disk. To the contrary, second approach is initially costly due to random writes to disk, but then reading the file is sequential on disk. There does not exist a strategy that has benefits of both. Strategy should be chosen per file. When fallocate is called on an empty file, it may be reasonable to assume that entire file will be written once, either sequentially or in random chunks, so allocating dedicated space of the requested size should be beneficial in both cases.



Another issue is how chunks from across different snapshots are laid out within the segment. If file get snapshotted, truncated to zero and overwritten in entirety, then first layout is more beneficial. However, if a file gets snapshotted and overwritten in only a small subset of chunks, then second layout is more beneficial. Which layout is better depends on how much a particular file is going to be overwritten. Applications do not report this to the filesystem, neither there seems to be an easy way to predict it for a particular file. During defragmentation this information is available, so layout can be optimized during defragmentation in anticipation of a read pattern. This topic was investigated by [Rodeh12].



Yet another issue is how journal entries are stored. If groups of journal entries are stored together with data and inodes they refer to, then each checkpointing operation requires only one seek but subsequent reading of journal entries then becomes slower due to caused fragmentation. On the other hand, if journal entries are stored in separate segments and data and perhaps even metadata are stored in another segments, then each checkpointing operation needs 2-3 seeks but both reading both journal and data, if files were large enough, becomes faster due to less fragmentation. First approach may be not as horrible as it looks, if the garbage collector is going to move these extents around soon enough. Third approach may happen as a result of explicit preallocation.



Conclusion is that there is always a tradeoff between performance during initial writing and performance during subsequent reading, due to fragmentation.

Design decisions for HDDs and SSDs are mutually exclusive.

(This needs to be added entirely.)

In place modification on disk is slow and hazardous.

(This needs to be added entirely.)

FUSE overhead is negligible.

(This needs to be added entirely.)

First few bytes of file should be easier to read.

When a directory is opened in Nautilus, all files within it are scanned with a *file* command that recognizes their type of content. This is a noticeable difference with Windows systems where file name extensions are used to determine mime type instead. Since *file* command is used often and probably uses only first few bytes, these bytes could also be stored within the inode. If a file gets queried with *stat* first, then the inode will still be in the cache to serve a read operation of first few bytes without any disk seeks. This is especially easy when complete inodes are used.

Behavior is based on assumptions, not history.

Filesystems can gather internal statistics about the files and other data structures, specifically the patters of how they were accessed in the past. For example, filesystem can easily find out which files are accessed immediately and frequently after boot. Then it can move these files and group them in some segment. At boot time, this segment would be read ahead of time to speed up boot process. If a file is no longer accessed at boot time, then filesystem can decide to move it away to make room for another file. This gain in speed used to be achieved by running some

additional application to log accessed files and another application to move files around Ext4 partition, and had to be run again after major changes to system files. There is no reason why this could not be handled by filesystem itself. Modern filesystems like Btrfs and ZFS provide very sophisticated features so a stance that filesystems need to be as simple as possible is no longer valid. Especially that Btrfs source reached ~120K sloc. Nowadays fast boot is mostly achieved by using solid state drives. While SSDs are bringing good performance characteristics, the problem of fast booting from hard drives will remain valid in foreseeable future.

Some patterns can be recognized in real time. For example, there is opportunity to use past patters during file reading and writing. Sequential pattern can be easily detected and lead to written buffers being laid out sequentially on disk or space being reserved in advance for the file in anticipation of further growth. Reading throughput can be increased by steady increase of prefetching, which is already implemented in ZFS. If previously written buffers were compressed with close to no gain, further compression for the file can be temporarily disabled to relieve the CPU.

Also when entire directory tree is being read, filesystem may read ahead other files and also do it concurrently in anticipation of incoming operations. For example, calling stat on entire directory entries list leads to this kind of pattern. Once few of directory entries were accessed, this might trigger an immediate read ahead of few or all of remaining entries.

When a file gets accessed more frequently than others it can be selected for defragmentation or compaction more often than other files or before other files.

Also since filesystem needs to do background scrubbing at some point, statistics can be built to predict peeks and valleys of user initiated disk activity. This way background operations may minimize impact on the foreground, user initiated activity.

Applications and operating systems often use internal statistics to find patterns like UX design efficiency. There is no reason why this could not be applied to filesystems as well.

Behavior is based on assumptions, not requests.

Future access patterns can also be anticipated by following explicit advice from the user or the application. For example, chromium and firefox executables always load a bunch of sqlite files. User could send an explicit advice that defines a set of files (let us call it a load set) to be kept together in one segment or to preload all of them at once whenever one of them is about to be loaded. This would certainly mitigate the well known Firefox performance bug.

Once defined data format is not flexible.

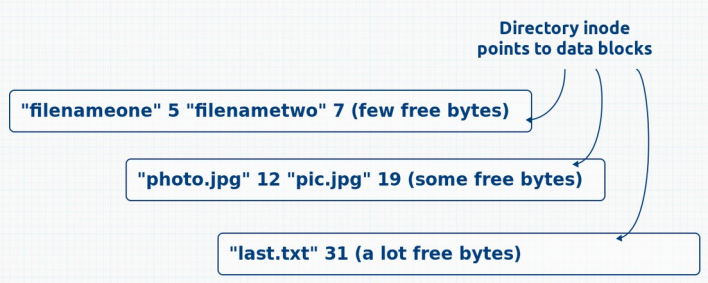
Specifications often define fixed data formats and leave no allowance for changing on-disk layout in the middle of its lifecycle. Once a new idea appears, usually a new but also fixed data format is created. Many filesystems implement tools for converting between versions offline, but that is probably being done by reading all metadata in one format and writing it in newer format. This means there is a need to take the filesystem offline and read/write a lot of blocks. There is usually no allowance made for dynamic change of data formats per file and in real time. This can be explained by the fact that filesystems are generally designed with fixed block length in mind. Even filesystems like Ext4 and Btrfs use fixed size blocks for metadata despite using variable size extents for file content. When metadata is being stored as variable size extents, layouts can change from file to file and at any point in time without a problem. Solution is to use a data format that prefixes a version number and interprets following bytes differently based on that number. This approach allows to change data structures within a filesystem in almost any

way without taking the filesystem offline, or redoing all other inodes.

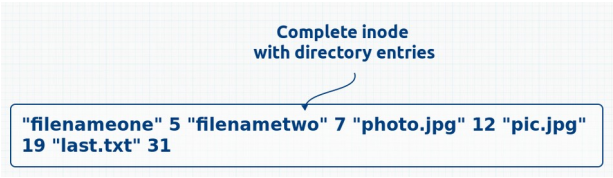
Blocks can store less than extents.

Earlier chapters discussed the issue of storing data structures like dictionaries and inodes in large single extents. While previous chapters were considering performance of disk devices this chapter is focused on compactness. Less bits are needed to store same data in variable size extent than in many individual blocks, leading to gain in disk utilization. The main reason why extents are more efficient is that blocks impose rigid boundaries between items. When data is divided into blocks, usually items should not be split between blocks.

For example, directory entries used to be grouped in blocks. File names are much shorter than a single block so they are being grouped. However, since file names are variable length each block has some unpredictable amount of space left unused.

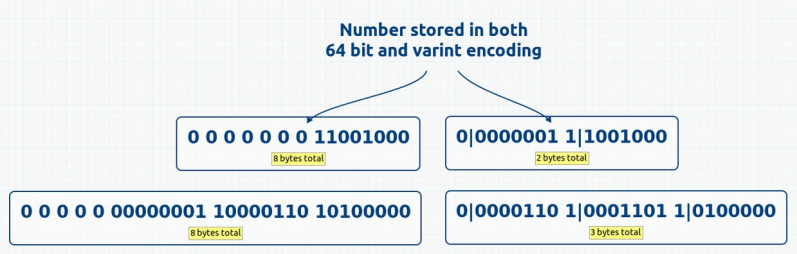


No doubt this approach was beneficial when memory was very limited. Iterating, querying, adding and removing entries requires processing only one block at a time. Consider using an extent instead. Items can be laid out next to each other without any blanks. At most, the extent could be aligned to block boundaries wasting only some fragment of the last block, called a *tail*. However if filesystem would allow extents to start and end at byte precise addresses then literally no byte would go to waste. This is the case with Btrfs filesystem.



Another example, dictionary that maps integers into arbitrary values can benefit from having all keys available when dictionary is being serialized into a blob. When keys are kept in separate blocks only few keys may be processed together. Keys can be arbitrarily reordered within the blob because deserialization process does not care. If keys are sorted in increasing order then instead of keys themselves only their pairwise differences need to be stored. Differences are smaller than entire keys. Small numbers can be encoded more efficiently using varint encoding which is explained below. Values may also varint encoded.

Normally a 64 bit number occupies exactly that much space, 8 bytes. Varint encoding divides a number into 7 bit chunks starting from least significant bits. 8th bit in each byte is used to signal whether more chunks follow. For example, numbers 200 and 100'000 are encoded as below.



Passwords are not usable.

Textual passwords have been and still are being used for protecting encrypted disks. However, passwords are hard to remember and almost always do not have enough entropy. Keyfiles were introduced as an alternative and became a moderate successor. However they are less secure because instead of losing a hard drive, the user is now concerned with losing the pendrive. Also pendrives are costly if more than one is needed, to share the keyfile with many people, inside an organization for example.

QR codes could be used as a third alternative. Aside of having the same benefits as keyfiles, namely having enough entropy, they are easy to handle (can be kept in the wallet or glued to a phone), are as hard to duplicate (shoulder surfing is not going to work), and distributing a hundred copies of these is inexpensive. A hundred pendrives would cost quite some money, compared to a hundred printouts. We already see QR codes being used for exchanging public keys in encrypted messengers, and for sharing WiFi passwords between smartphones. This could be yet another application of QR codes.

Please note that this particular feature is filesystem independed and not really part of this specification. It was intended as food for thought.

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Preliminary design
Layout and methods for a versatile filesystem

Arkadiusz Bulski

Introduction

This chapter is still being written and is therefore erroneous, inconsistent and incomplete. You may want to read it later after it is finished. Note that next chapter is written independently, and this chapter will probably be finished afterwards.

Data structure hierarchy

Storage pool is the highest data structure in hierarchy. Both hard disk partitions (also called backends) and filesystems (also called volumes) are each assigned to at most one pool. Each partition is divided into large, fixed size, sector aligned contiguous areas called segments. Default segment size is from 16 to 128 MB. Each segment has a unique id within a pool. When a new backend is added to a pool, it gets divided into segments and the segments are marked as uninitialized. Background process overwrites uninitialized segments with random bytes and only then marks them as unallocated. Optionally, the segments may also remain uninitialized. Whenever a volume requires more segments (new volume has none), the volume requests a free segment from the pool. Volumes can request either kind and be given either kind of segment depending on the pool. When a volume has too many segments or when a volume is destroyed, the segments are returned to the pool and marked as uninitialized.

Volume is the second data structure in hierarchy. A volume keeps track of allocated space within the segments allocated by the pool and locations of extents. Each file, directory, symlink, and groups of data chunks are stored as extents that are assigned unique incremental ids that are translated by the volume into physical disk locations and sizes.

File inode and directory inode are third in data structure hierarchy. Complete file and directory metadata are always contained in one continuous extent and referenced by a parent directory by id. Root directory inode has an id=1 by definition. When a file has many hard links, their parent directories reference the same file inode by id, and the file inode contains a list of parent ids. Symlink inodes are analogous.

Data extents are fourth in data hierarchy. Each file write creates data chunks that are first stored in a write buffer. After a few second window, chunks awaiting persistence are grouped in one continuous data extent and the extent is written to disk at sequential speed.

Extent map is a data structure that maps integer ids into physical locations and sizes on disk. Each extent gets assigned a unique incremental id. When an extent is modified or compacted, id remains the same but the location and size are updated to point to the new copy. Extents are always modified copy on write and the extent map needs to update references atomically.

Free extent map is a different data structure that keeps track of unused space within segments allocated by the pool. When a new extent needs to be persisted, it gets assigned free space from the free map. An empty segment can be split to satisfy an allocation request (and the remainder gets returned to the free map) or a partially filled segment can allocate more space (splitting it again) or a new segment can be requested from the pool (which should be avoided). Sequential

allocation from the same segment should be preferred over allocating across entire disk. This leads to both metadata changes and random file writes being persisted at sequential disk speed.

Journal is a data structure that keeps track of changes made to files within a volume with fine granularity down to individual file writes. When user changes a file or directory, the operation gets assigned a volume-wide unique incremental revision number and an entry is added at the end of the journal mentioning what was done and to which extents and at which revision. When the user wants to browse the revision history, the journal is scanned from the end backwards and presented to the user in a well formatted format. The user can select a particular revision to browse the volume as read only or revert the entire volume or just a selected file or directory. Journal is kept as a back-linked list of extents which are chains. Earliest extents can be removed to allow compacting process to reclaim space, while newest extents are used for adding more entries.

Data structure fields

Storage pool

is the top most structure. Every backend (disk) in the pool has the first segment used for 2 rings. First ring keeps a serialized blob of *diskdict* while the second ring contains a serialized blob of *pooldict* structure. Only one partition is needed to mount the pool. Its pooldict has a list of all other partitions. All rings are loaded at pool mount time and checked which one has the newest valid entry. The current pooldict is kept in memory until unmount. Other rings are also updated with the current value to ensure consistency. Whenever pooldict gets persisted, ring in each backend is updated with the new value. All segments in the pool are concatenated into a unified disk space with byte resolution. Pooldict translates disk space addresses into an open descriptor and offset within. New backends are assigned new byte ranges (ranges never being reused) and removed backends make byte ranges permanently inaccessible.

Diskdict contains:

- Checksum covering further fields, not keyed.
- Unique long random id of the backend. This is to ensure that disks are recognized properly when their system paths have changed.

Pooldict contains:

- Checksum covering further fields, not keyed.
- Unique long random id of the pool. This can be used to differentiate between pools.
- List of backends in the pool: their random ids, non unique labels for convenience, disk sizes, segment sizes, byte ranges in unified disk space, and bitmaps of unallocated and uninitialized segments.
- End of existing disk space ranges. This gets incremented when a new backend is added and is never decremented, even when a backend is removed.
- List of volumes in the pool: their random ids, unique names, non unique labels for convenience, extent infos (locations and sizes in unified disk space) of fsdict rings, bitmaps of allocated segments, encryption and authentication keys to fsdict if used, salted hash of an external key if these keys are also encrypted, selection of cryptographic algorithms.

Volume

always stores its extents within the segments allocated by the pool. Main responsibility of a volume is to allocate free space for new extents and to translate extent ids into physical

locations on disk. Also it manages a revision history (fine grained record of user made changes) and a list of snapshots (coarse grained history).

Fsdict contains:

- Checksum covering further fields, keyed from pooldict.
- Unique long random id of the volume. This can be attached to backup images and reused when restoring a volume from an image.
- Extent map, either an extent info of the chain containing an entire dictionary with diffs or a list of extent infos with their internal allocation bitmaps for B-tree fixed sized nodes, and a pointer to the root B-tree chunk, and the size of B-tree chunks.
- Root directory extent id. Alternatively it could be defined constant.
- Free extent set, as a list of extent infos. These can be used to satisfy allocation requests before the pool needs to allocate new segments. In memory representation can be more like a buddy allocator but on disk representation is a list.
- Unwiped extent set, as a list of extent infos. On encrypted volumes, inode extents end up on this list before they are passed to the free extent map. On unencrypted volumes, this list can be empty.
- Uncompacted extent set, as a list of extent ids. When the earliest journal entries are discarded, inodes mentioned in those entries are put onto this list. Duplicate ids are discarded.
- Journal, as a list of extent infos of chains containing journal entries. Earliest chain is used for compacting and newest chain is used for adding new entries.
- Earliest and newest revision number of the journal entries. The earliest revision is used to constrain compacting to revisions before the earliest remembered revision. The newest revision plus one is used for next operation.
- Snapshots, as a list of revision numbers and associated non-unique text labels. Version history feature uses the journal while the snapshots feature uses this one.
- Settings that were passed during volume creation or set online, for example, selection of encryption and authentication algorithms, RAID mode for new files, should fsync be ignored, is revision history enabled, amount of bytes for preallocation, amount of bytes to have always allocated from the pool, sector size, etc.
- Encryption and authentication keys and schemes to all mentioned data structures, independently for each external data structure.

Under volume

There are few data structures that are not contained but referenced, such as the journal, and the extent map (which switches between two representations).

Extent map chain chunk content:

- List of entries, each as variable size tuple containing: the key (extent id) and the value (extent info in unified disk space, and extent type). All fields are as varints. First chunk holds entire dictionary, and further chunks hold diffs. Removed entries are represented in diffs as null values assigned to their keys. Extent type can be either file inode, directory inode, symlink inode, or data.

Extent map B-tree chunk content:

- Concatenation of fixed size tuples each containing the key (extent id) and the value (extent info in unified disk space, and extent type). All fields are as uint64. Empty slots are represented by null keys. Extent type can be either file inode, directory inode, symlink inode, or data.

- Concatenation of fixed size pointers to other chunks, each in unified disk space.

Journal chunk content:

- List of variable length tuples, each having one of following formats. First field (revision number as varint) and second field (entry type as varint) are always varints and suggest how further fields are to be parsed. Value of of the second field is in parentheses.
  - (Initialized volume) No fields. This is used for informing the user.
  - (Mounted volume) No fields. This is used for informing the user.
  - (Opened file) Inode id of parent directory inode as varint, file inode id as varint, length of the path as varint, path as UTF8 encoded string.
  - (Created file) Inode id of parent directory inode as varint, length of the path as varint, path as UTF8 encoded string, owner and group as varints, and permissions as int. Since new inode carries same id as the journal entry there is no need to reference it.
  - (Written to file) Inode id as varint, buffer length as varint, offset within content space as varint. Since chunks carry same id as the journal entry there is no need to reference it. Other fields are merely for pretty printing.
  - (Appended to file) (same fields as file write)
  - (Truncated file) Inode id as varint. File's chunk map represents the truncation as one of the chunks but using a different type of entry does not require reading the inode to differentiate between chunks representing writes and truncations.
  - (Moved file) Inode id of source parent directory as varint, inode id of destination parent directory as varint, source path length as varint, source path as UTF8 encoded string, destination path length as varint, destination path as UTF8 encoded string. This also represents a renamed file.
  - (Removed file) File inode id as varint, parent directory inode id as varint, path length as varint, path as UTF8 encoded string.
  - (Created directory) Inode id of parent directory inode as varint, length of the path as varint, path as UTF8 encoded string in that many bytes, owner and group as varints, and permissions as int. Since new inode carries same id as the journal entry there is no need to reference it.
  - (Removed directory) Directory inode id as varint, parent directory inode id as varint, path length as varint, path as UTF8 encoded string, forced removal as byte boolean. Non empty directories can be removed, but for safety it requires root privileges.
  - (Unmounted volume) No fields. This is used for informing the user.

Extents

can be either of the few types: file inode, directory inode, symlink inode, data extent, or a special extent used for journals and extent maps. Depending on the type, the data structure is like the following:

File inode:

- Checksum covering further fields, keyed from any parent directory, parametrized by id.
- Unique volume wide id, as varint. This is the same id that is used by the extent map to translate into byte range. Also it is the revision number of the file creation operation.
- Hard links, as a set of extent ids as varints. These are ids of parent directory inodes that reference this file. Analogously directory inodes keep id of the file assigned to filename.
- Chunk map, as a list of tuples containing: revision number, byte range in content space, extent id of the data extent in which chunk is stored, byte range within that data extent (can be shorter due to compression, equal means no compression, zero means it was a

truncation). Some chunks represent file truncation and holes, and do not refer to any extent. Also some chunks refer to ownership or permission changes, or atime mtime ctime changes, or extended attributes changes, and therefore are interpreted differently. Adjacent entries can have same revision number if they represent different information but same operation.

- Ignored revisions, as a list of revision ranges. This is only used when reverting. Journal provides explanations of each revision and snapshots point to particular revisions.
- File size, owner and permissions, first 64 bytes of content, datetimes for atime mtime ctime for the newest revision. Those can be computed from the chunk map for any revision but newest values are cached here.
- Encryption and authentication keys and schemes to be used on data chunks.
- Padding bytes, needed for sector alignment and discarded during parsing.

In memory only:

- Is dirty, as a boolean flag. When set this means the inode needs to be persisted, even if there are no dirty data chunks.
- Dirty chunks, as a dict from chunk ids (which are also revision numbers) to byte buffers holding the data to be persisted. Newest entries in the chunk map refer to these buffers, they do not have on disk locations yet. This collection becomes empty after a checkpoint. Global cache may still keep these chunks for further read operations.
- Frozen at revisions, as a list of integers. When a file is opened at historical revision or is opened for hashing or compressed reading, the inode is withheld from compacting of enumerated revisions forward. Inode can be independently frozen at different revisions.

Directory inode:

- Checksum covering further fields, keyed from any parent directory, parametrized by id. Root directory is keyed from fsdict.
- Unique volume wide id. This is the same id that is used by the extent map to translate into extent info. Also it is the revision number of the dir creation operation.
- Entries map, as a list of tuples containing: revision number, filename, extent id, and type (regular file, dir, symlink). Some entries represent unlinking by associating filenames with null ids. Also some entries refer to ownership or permission change and therefore are interpreted differently.
- Ignored revisions, as a list of revision ranges. This is only used when reverting. Journal provides explanations of each revision and snapshots point to particular revisions.
- Link count (number of entries) and owner and permissions for the newest revision. Those can be computed from entries map for any revision but newest values are cached here.
- Datetimes for atime, mtime, ctime. These are not affected by revisioning or reverting.
- Encryption and authentication keys and schemes to be used on inodes.
- Padding bytes. These bytes are discarded during parsing.

In memory only:

- Is dirty, as a boolean flag. When set this means the inode needs to be persisted, because some fields were changed.
- Frozen at revisions, as a list of integers. When a file is opened at historical revision or is opened for hashing or compressed reading, the inode is withheld from compacting of enumerated revisions forward. Inode can be independently frozen at different revisions.

Symlink inode:

- Checksum covering further fields, keyed from any parent directory, parametrized by id.
- Unique volume wide id. This is the same id that is used by the extent map to translate into

extent info. Also it is the revision number of the link creation operation.

- Entries map, as a list of tuples containing: revision number, and target filename. Some entries represent unlinking by assigning null filenames. Also some entries refer to ownership or permission change and therefore are interpreted differently.
- Ignored revisions, as a list of revision ranges. This is only used when reverting. Journal provides explanations of each revision and snapshots point to particular revisions.
- Owner and permissions, and target for the newest revision. Those can be computed from the chunk map for any revision but newest values are cached here.
- Datetimes for atime, mtime, ctime. These are not affected by revisioning or reverting.
- Padding bytes. These bytes are discarded during parsing.

In memory only:

- Is dirty, as a boolean flag. When set this means the inode needs to be persisted, because some fields were changed.
- Frozen at revisions, as a set of integers. When a file is opened at historical revision or is opened for hashing or compressed reading, the inode is withheld from compacting of enumerated revisions forward. Inode can be independently frozen at different revisions.

Data extent:

- Algorithm selection, as varint. Implies length of checksum field.
- Checksum covering further fields, keyed from the file inode, parametrized by id.
- Unique incremental volume wide id, as varint. This is the same id that is used by the extent map to translate into byte range. Also it is the revision number of the fle write operation.
- Concatenation of variable size data chunks.
- Padding bytes. Extents must be sector aligned. Since the file inode keeps track of internal chunk structure, it does not matter how much bytes were added. Extent map keeps track of entire extent size. Chunks do not need padding.

Data chunk:

- Cheksum algorithm selection, as varint, implying length of checksum field.
- Checksum covering data field, keyed from the file inode, parametrized by id.
- Compression algorithm selection, as varint.
- Data, as bytes. Chunk map keeps track of the entire chunk size.

Some data structures

like diskdict, pooldict, and fsdict are stored in rings and the extent map, and journal entries as stored in chains. These two generic data structures are described below.

Ring extent:

- Concatenation of fixed size chunks.
- Padding bytes. The extent must be sector aligned. Sector size is externally provided.

Ring chunk:

- Checksum covering further fields, can be keyed or parametrized.
- Revision number. This is also the revision of checkpointing operation. When a ring holds few valid chunks (valid checksums) then revision number dictates which value is current. When a value is duplicated across few different rings, this number also dictates which

value is current.

- Length of data, in bytes.
- Data blob.

Chain extent:

- Concatenation of variable size chunks.

Chain chunk:

- Checksum covering further fields, can be keyed or parametrized.
- Revision number. This is also the revision of checkpointing operation. All valid chunks (that have valid checksum) from the beginning of the chain are considered part of the current value. When a value is duplicated across few different chains, this number also dictates which chain is most up to date.
- Length of data, in bytes.
- Length of padding, in bytes.
- Data blob.
- Padding bytes. Chunks must be sector aligned. Sector size is provided in fsdict.

User exposed methods

Regardless of implementation, in kernel, through FUSE or Dokan, a GUI application, or a base class in some programming language, the set of methods for manipulating files and directories is the same. Only one of the interfaces above needs to be truly implemented, as other can be mere wrappers.

Mounting a pool: User provides a list of paths to backends. Diskdict and pooldict is read from each listed backend. Newest valid value from all pooldict rings is taken as current. Each diskdict is checked against the random ids contained in the pooldict. This both sorts out which id goes to which path, and checks if all backends are present. If any backened mentioned in the pooldict is missing, mount fails, unless the user explicitly selected an override. Also some fields are checked for consistency, like if any segment was allocated more than once or if byte ranges are not overlapping. This is because this structure cannot be authenticated and malicious changes could be made when offline. Checksumming protects against accidental inconsistency. Pooldict is updated on each backend to current value, in case some rings were stale due to earlier interruption, unless mounted as read only. At this point mount is successful. File descriptors to backends are kept open, and current value of pooldict is kept in memory, until unmount.

Mounting a volume: Fsdict is loaded from all rings, and newest valid value is taken as current value. If the volume has access to many disks, then fsdict is duplicated in several rings, which are discoverable through pooldict. Each fsdict ring is updated to current value, in case some rings were stale due to earlier interruption, unless mounted as read only. If extent map is stored as entire dictionary, its chain is loaded and prepared for appending, if it is stored as B-tree, the root node is loaded. Last journal chain is loaded and prepared for appending. Mount is successful at this point. Current value of fsdict is kept in memory, until unmount.

Creating a file: Absolute path is computed. Root directory inode is loaded. Using its entry map, the inode for second path component is loaded. All inodes for intermediate path components are loaded. If any intermediate component does not exist in its parent directory or its inode has the wrong type, method fails. If the parent directory, which is the last intermediate inode, already contains an entry with the name, method fails. Revision number is recorded and

incremented. New file inode is created, the revision number is assigned as the id. Journal entry is added. Inode is retained in memory and considered dirty.

Opening a file: Absolute path is computed. All inodes for path components are loaded. If any component does not exist in its parent directory or its inode has the wrong type, method fails. If atime is to be updated, the inode field is changed and inode is considered dirty. A new handle is assigned, perhaps a new revision number, and the handle is associated with the inode. Journal entry is added. Inode is retained in memory until closed and persisted on disk.

If path is like "/dirname/filename?rev=21" then file is opened as read only, chunk map is filtered so only chunks up to specified revision are visible, stat fields are computed from the chunk map rather than taken from inode fields directly, and inode becomes frozen at specified revision or completely.

Writing to a file: Open handle is used to find the inode in memory. Revision number is recorded and incremented. New chunk is added to the chunk map, with id set to revision number, buffer size set as the buffer provided, and a pointer to the buffer. Data buffer is stored in memory for further persistence and read operations, and is considered dirty. Overwrites do not discard previous buffers. Other inode fields such as newest file size and mtime are updated.

Closing a file: Open handle is used to find the inode in memory. If file was opened for particular revision, then inode is thawed for that revision. Handle is invalidated. Dirty inode and data are not persisted immediately and remain in memory.

Removing a file: Absolute path is computed. All inodes for path components are loaded. If any component does not exist in its parent directory or its inode has the wrong type, method fails. Revision number is recorded and incremented. Parent directory inode entry map is added a new entry assigning the filename to null id. File inode is not changed. Extent map is not changed. Journal entry is added. Parent directory inode is marked dirty and remains in memory.

Checkpointing: This is an internal operation called whenever few seconds have passed or enough dirty inodes or data accumulated in memory. For each dirty file inode, all dirty data chunks are processed by compressor. Fsdict active options dictate which compressor is used, if any. If chunks are too big, they can be either split before being compressed or let the compressor split the compressed stream. Second alternative is preferred but requires a specialized compressor implementation. Compressed chunks are concatenated into a data extent or few extents depending on available free space, each chunk followed by its checksum. Inode chunk map is updated with new extent id (new revision number for each data extent) and offsets/lengths within extent. Inode is serialized and also allocated disk space by fsdict, preferably right next to the last allocation. Extent map is updated for both extents. Extent info of previous inode blob is returned back to fsdict as unwiped. Dirty journal entries are allocated chunks within last journal chain. If latest journal chain is almost full, entries can be split apart. Both data extents, inode extents, extent map (chain or B-tree) chunks, and journal chunks are sent to disk. Disk is synced, and then fsdict is serialized and stored to its rings. There is no second sync.

Background process: This is an internal operation called every few seconds during peek hours and called continuously during night hours. End of the journal is scanned. If the latest entry is older than active options dictate, this entry is removed and the affected inode gets loaded and inode chunk map has entries dropped accordingly. If that removes one or all chunks from a data extent, the inode fields are updated to remember that. If data extent had all chunks dropped then the extent can be deallocated immediately. Inode id is put into the awaiting compaction dict, with the number of bytes expected to be freed as value. After the journal was finished, a second phase is commenced. Inodes from the awaiting compaction are loaded, and their data extents are moved and compacted, if they contain any dropped chunks. Extents can also be split

and joined as part of defragmentation. Chunks can be recompressed if needed. Moved extents can be split or merged if needed. Extents are moved to a new segment. After all inodes were processed, third phase is commenced. Segments having most empty space or most small spaces are selected, loaded from disk, compacted and stored into new continuous segments. Extents can be split or merged if needed.

Conduits: Since FUSE does properly implement ioctl operations, not allowing data structures to be passed as parameters, alternative mechanism is going to be used for special operations. Each open() call having a path “?ioctl?” is going to return a descriptor connected to nothing. Writing to it represents a request with parameters passed as buffer, and blocks until that request completes. Reading from it returns the result of last operation. Several conduits can used concurrently, and each returns results of their requests.

[awaiting: creating snapshots, browsing revision history, reverting to a revision, ~~transactions~~, anonymous files, truncation, cloning files, ~~scrubbing process~~, ~~conduits for ioctl~~]

Questions and Answers
Topics that reviewers found unclear

Arkadiusz Bulski

asked by Thistle (pseudonym)
recorded on 2015-04-10

What control will a user have over wiping of files? Wiping of files is not practical? You mean manual wiping?

There are two different actions, regular deletion and permanent deletion. One is reversible and other is permanent. Practicality is meant as both performance and assurance. Wiping in general is a synonym to permanent removal but in this context it means a specific implementation, through overwriting of data in place. Historically, this is how it was done and is still being done. There are two major deficiencies with this approach. First problem, wiping is limited by hard disk performance and file sizes and fragmentation. Hard disks operate usually at maximum of about 120 MB/s assuming no seeks due to fragmentation. Overriding cannot proceed faster than that. And to be really sure, you should do that 35 times (Gutmann method). Second problem, this method is not safe. Data blocks that are no longer reachable by inode, due to truncates for example, cannot be overridden. In general it is not possible to find out which blocks used to belong to a selected file, much less allocate these blocks back to enable overwrite. Filesystems do not keep history of which blocks used to belong to a file. Once a block is deallocated, a track is gone. Also, copy on write mechanism can be applied to data writes, and if so, overwriting has no effect anyway. There is no common interface to find out whether underlying filesystem uses copy on write or not, nor to disable copy on write for a specific file before overwriting. Please also refer next question.

Will there be an option for non-permanent wiping in case a user accidentally wipes a file? What safety measures will be there to prevent accidental complete wiping of content? Or is that a risk users have to take?

There are two distinct actions. Regular deletion (called deletion) is an action that can be taken by non-privileged user. User processes are able to take this action without any user interaction. Therefore this kind of action is inspectable and undoable. Browsing history reveals any deletion and allows for recovery. Permanent deletion (called wiping) is a different action that requires root privileges. This kind of action is partially inspectable, as revision history reveals that some wiping has taken place but file content is not accessible anymore.

History of changes to files means that all versions of the file remain stored, or at least a history that can be viewed. Isn't that impractical in some cases of confidential files? An option to not save a file history?

History of changes is like a list of commits, states saved at some points in time, ordered chronologically. History can be browsed and every revision can be inspected for details but also every revision can be restored back. Confidentiality is not compromised because browsing past versions of files requires same level of access as browsing current version. Anyone having access to past history would necessarily have had access to current file in the first place. When user deletes a file, it will be recoverable as long as it is browsable in history. When user permanently deletes a file (as opposed to regularly deleting), it will not be recoverable even through past versions. Versioning as a feature can also be disabled. If so, regular deletion would make a file immediately inaccessible.

Deleted files are permanently gone, how would that be done? In comparison to saving file history...

Technically there are two ways of ensuring data is permanently gone, either through overriding data itself or overriding encryption keys that were used to encrypt said data. Second approach is much better since keys occupy only few bytes and overriding few bytes takes almost no time. This also erases data blocks no longer assigned to a file, due to truncate operations. Versioning is an independent feature. Different versions are encrypted with same encryption keys, allowing a swift permanent removal of entire history of a given file.

Legal questions, may use of the program encounter difficulties with existing laws in some countries?

Depending on your country of residence, you may be:

- forbidden from using cryptographic products in general
- required to get license or send notification before importing
- required to disclose cryptographic keys to authorities in advance
- asked to enter password and hand over your laptop
- asked if you have any other undisclosed encrypted partitions
- subpoenaed to produce keys or decrypted data itself
- jailed for long time or until your produce encryption keys

Lesson to learn here is that established law can put you in a position where technical solutions do not give you an easy and legal way out. Consider crossing US border with child pornography on your laptop (there was a famous real case). Officer asks you to mount all partitions and then asks if you have any hidden partitions on your laptop. Note that lying to a federal agent is a criminal offense in US. If you mount the hidden partition, jail, if you lie it does not exist, jail if caught, if you deny to answer, perhaps denial of entry into the country. Plausible deniability feature may let you lie your way out of the situation but it will not make it any more legal.

asked by Steven Balderrama
recorded on 2015-08-14

On mission document, page 3, I found top 3 things what lacks today in a filesystem: versioning, secure deletion and disk utilisation.

There are also other features but some are so specialized that clearly there will not be many people that will have a use for them. This project aims to deliver a versatile filesystem that will be useful to everybody.

Compression is great, but some files should not be compressed for performance.

Some files are almost impossible to compress, audio video formats are a good example. However, performance does not necessarily have to be negatively impacted. Methods like Gzip are meant to achieve high utilisation with little regard for performance but there are also other, less efficient, methods that are many times faster than a hard disk. Snappy developed by Google can compress ~250 MB/s and decompress ~500 MB/s per core at it's slowest, with worst case input data, and much more with more compressible data, while a hard disk can sustain only about ~120 MB/s transfer. Fragmentation lowers disk side of inequality even further. Direct Memory Access (DMA) allows to transfer data to disk in parallel to code execution so compression and disk operations can be done in parallel. The minimum of two throughputs then becomes a bottleneck. Compression is therefore CPU bound, and not disk bound. Processor load should be fractional and not impact user experience. Also, adaptive compression can be used. If during sequential writing compression gain is close to none, then further writes can skip compression in anticipation of no gain. Also, compression can be postponed till defragmantation so data is written raw during initial write and compressed in the background afterwards.

We sorta talked about performance. Since there is compression and encryption, how will that not hinder performance?

Compare throughput of modern hard disks to throughput of modern processors. Hard disks can sustain ~120 MB/s. Compression like Snappy can handle ~250 MB/s per core at least. Encryption using Salsa20 can handle ~400 MB/s per core. Lightweight hashing using SipHash can handle ~530 MB/s per core. All of the above can be achieved at a fraction of CPU load, and you can always disable some features to lower the CPU load. DMA allows to transfer data to disk in parallel to computation. Therefore, throughput becomes a function of the minimum of the two, which is equal to disk throughput. Refer to previous question.

And yes, versioning. How many times I have seen this, especially programmers who do not utilize software versioning. I have seen it even at my work now. Version control, is that what you mean?

There are two features that may be used to revert changes. Snapshots is a feature that saves state at explicitly chosen points in time, allowing to revert only to specific states that have been prepared in advance. This is the model of how version control software works. Commits are then the equivalent of snapshots. So this was the first feature. Continuous versioning is different than snapshots in that every operation creates a revision. As time progresses, old revisions become automatically compacted. So in summary, snapshots are manually created while versioning is automatic, and snapshots are kept forever while versions are only available for some period of time unless manually retained.

Lastly, you said about having it's own type of recovery. Explain in detail how it will recover or roll back.

Early filesystems like Fast File System and it's descendant Ext2 depended on running a program called *fsck* that scanned all inodes after an interruption. Later filesystems like Ext3 were using journaling to reapply a set of changed blocks. Later filesystems like Btrfs and ZFS started using copy on write and checksums. ZFS also uses intents. The state of the art solution would perhaps comprise of copy on write only. Initial idea of using intents was discarded.

Solution is described in Fsync chapter. Overwriting a file puts the data and the modified inode into new extents, doing copy on write. Their previous copies remain locked until a checkpoint. After all dirty data and inodes up to a specified revision were synced to disk, header is atomically updated to point to new extents, and then old locked extents get finally unallocated. Recovery is a noop since header always references extents that were completely synced to disk. Interrupting before or during a checkpoint only affects space that is considered unallocated anyway.

asked by Robert Węcławski
recorded on 2017-03-03

You wrote that this is a general purpose filesystem, but then that it only works on hard drives (not SSDs). Such a narrow application makes it not useful.

General purpose means that it meets minimum requirements of everyone and surpasses them for some, not that it beats every other filesystem on every benchmark. If I were designing one for SSDs then I would have made different design decisions, in fact the design would probably look the opposite of what it is. Then it would be inferior to popular filesystems on hard drives. Would you then complain that it does not work on HDDs?

Extents are not beneficial on SSDs, and are shortening their lifespan.

True but SSDs are not being considered, period.

Extents compaction is supposed to be delayed into the future, but what about servers running 24/7?

Some servers actually do experience peek hours, especially those hosting national and not international websites. Then more disk IO will be used on compaction during these non-peek hours. On servers running continuously compaction also runs continuously but at small IO rate. Also, note that pre-allocation can be used to avoid defragmentation entirely. Then only inodes remain to be compacted, which adds negligible overhead.

I think B-trees would cache better because the entire dictionary will be slow with large amount of files.

The dictionary representation switches over to a B-tree when the amount of entries grows so large that an entire dictionary becomes unusable. Dict representation is used only until it is still beneficial, and not a second longer.