



Ideas and Observations

Foundations for a versatile filesystem

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Abstract

Cameleonica is a prototype of a highly versatile filesystem. This paper describes a wide range of concepts that could be incorporated into popular filesystem designs. Both potential benefits and reasons why these features were not popularized earlier are presented. Expectations of their performance is based on theoretic models.

[work in progress]

Introduction

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. For example, Ext4 is an upgrade to Ext3 in sense that upgrade can be done in place.

[work in progress]

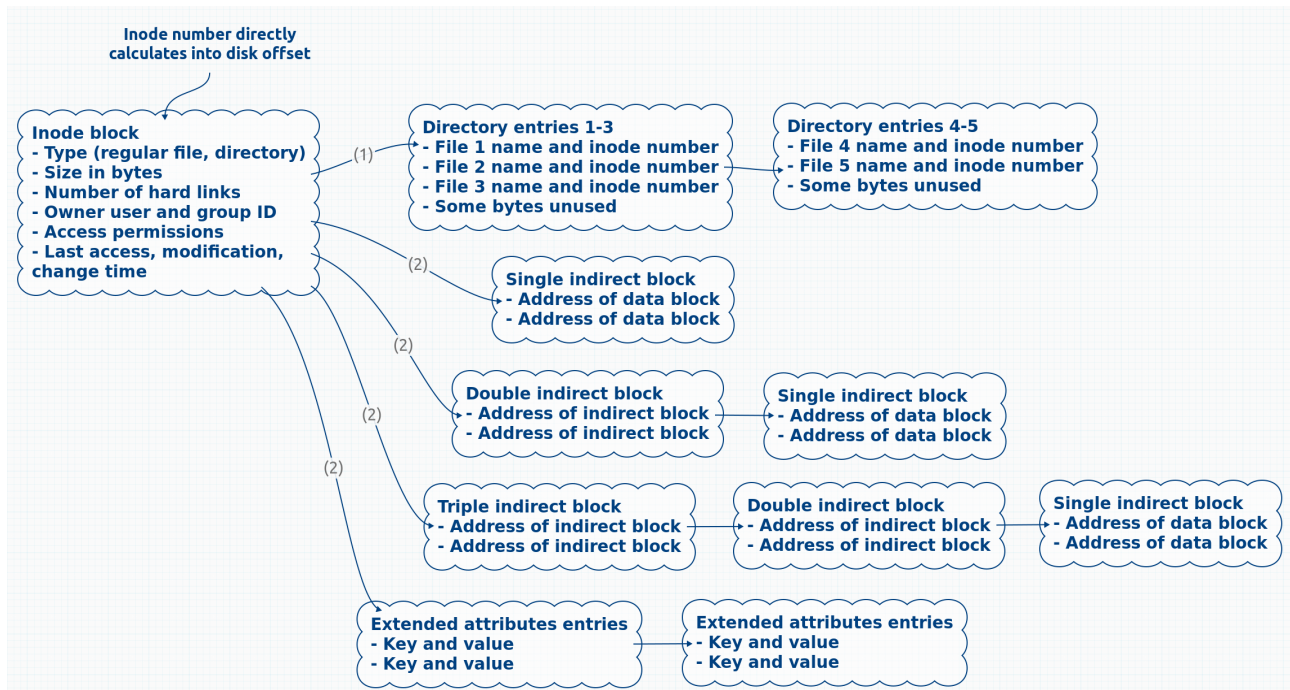
New ideas

Inodes are not efficient.

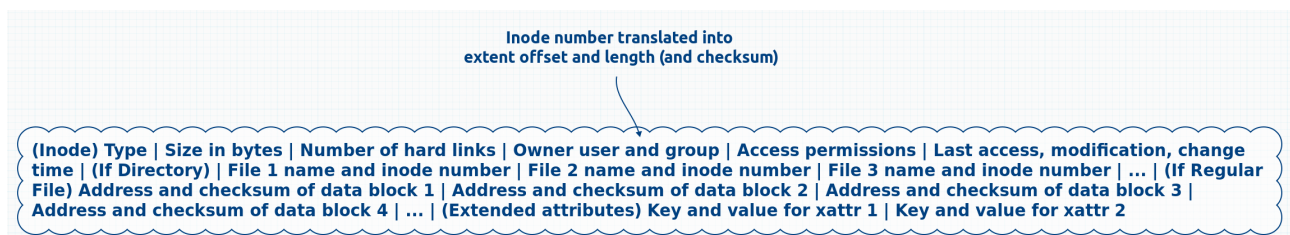
Since the early days, filesystems were designed under a principle that data structures have to be broken down into fixed size blocks. This seems to have been due to the fact that hard disks require read and write operations to be carried out on 512 byte long, discrete blocks of data. In traditional designs most 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 Ext2/3, 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.



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 per-block checksums are included. 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. This kind of reasoning is flawed because it does not account for future operations. Further analysis considers amortization of performance over most of lifespan of a file, and not assumes 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. Parent directory metadata is also 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. 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):

$$R_1(N) = 0.010 + N \cdot 4 \text{ K} / 120 \text{ M} = 0.010 + N \cdot 0.00003$$

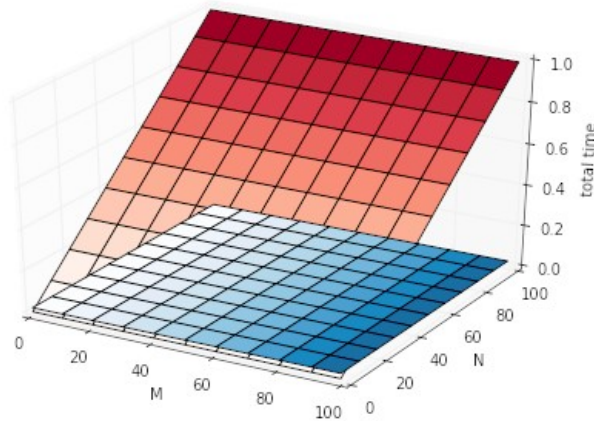
$$R_N(N) = N \cdot (0.010 + 4 \text{ K} / 120 \text{ M}) = N \cdot 0.01003$$

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.

$$\begin{aligned}
 T_N &< T_1 \\
 B \cdot R_N(N) &< B \cdot 2 \cdot R_1(M) \\
 0.01003 \cdot N &< 2 \cdot (0.01 + 0.00003 \cdot M) \\
 N &< 1.994 + 0.006 \cdot M \\
 M &> 166 \cdot N - 332
 \end{aligned}$$

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 exchange 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.

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 (as if allocations were separated by long time intervals) and non-preemptively (not in advance) from entire disk (independently from uniform distribution). It would be possible to allocate blocks in groups, close to each other whenever possible, increasing so called *spatial locality*. However, constructing a theoretical model that includes clustered allocation is outside of scope of this paper. 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, arguably neither issue would trump argument being made. Seek time and rotational delay are quite expensive, and considering hardware trends [Patterson] they will be even more expensive in the future.

Changes pending: Random seeks within a subset (maybe 1GB) would be more adequate. Manufacturers do not provide such data but it could be empirically measured.

Changes pending: SSD devices may be subject to the same argument, due to write amplification instead of seek time. Quantifying it is another matter.

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 points 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.

Second reason to use B-trees is that memory needed to query and update trees is small, comparable to number of nodes from root to leaf. 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 constitute an exception but that does not negate benefits on desktops and servers.

Consider a hybrid or rather a transitional approach. Initially all entries are loaded from one extent, kept in memory in entirety and the whole time, and occasionally stored to disk as one extent. If at some point amount of entries grows over a certain threshold, a transition to a B-tree representation is commenced, all entries (already in memory) are relocated into tree nodes and stored to disk in one sweep. The threshold can be chosen low enough so storing entire dictionary in one sweep is faster than analogous B-tree operation (few disk seeks). After transition, operations are carried out on the B-tree representation. If changes are being accumulated over some period of time then comparison is even more favorable. Intents (patches) can be stored to disk to persist individual operations instead of storing the entire dictionary every time. Intents are described in a later chapter on fsync.

The threshold would actually be very high. 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. Therefore a B-tree operation requiring 2 seeks or more takes on average more time than reading or writing an entire 1.2 MB in one sweep. A huge amount of entries can be stored in that amount of space.

Actually even more entries can be stored on disk than in memory. If for example entry keys are sorted then their pairwise differences can be stored instead. Smaller numbers can be encoded more compactly using varint encoding. This topic is further explained in a later chapter on extent efficiency.

This argument is basically the same as for inode extent. If mapping entries are considered as metadata of some special file then same theoretical model can be applied.

Fsync is not efficient.

Files stored on computers become increasingly important as businesses and governments store evermore 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 in it's work 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 result people started skipping on fsync. 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](#).

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 6 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 on his own accord. 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);
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. Not used anywhere. Another example, Btrfs also provides a way to manage transactions spanning across files. Would seem useful if its own documentation have not outright discouraged using it, warning 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, with respect to crash. Above that fsync calls are implemented as no-op.

The file replacing 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 a 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 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.

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 (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 queue was empty. When flushing buffers occurred quite often this approach basically defeated the purpose of installing buffers in disks in the first place.

Later another major overhaul of disks happened. Up to this moment systems 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. System was again no longer aware of what is the status of each request. The system did not even know which of them will go to the platter first. The solution to ensuring order of writes was 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 previously scheduled writes are completed before current. Previous requests can still be reordered between themselves, 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](#).

Here is a plausible implementation of a filesystem where all operations are atomic and ordered (but not durable) with respect to crash.

Consider a copy on write scheme where first sector contains address of last persisted block and address of root inode, further sectors contain a continuous cyclic stream of data and metadata similar to a log-structured filesystem.

Each operation puts more blocks into the stream in a sequential but asynchronous way. Ordered operations require that space on disk is allocated sequentially, so spatial ordering corresponds to chronology of operations, but actual disk writes need not be atomic nor ordered. These disk writes can be reordered and interleaved with previous and future disk operations. In most naive implementation, each operation appends full metadata of affected inodes to the log (storing complete inodes on each operation). However, considering that complete inodes are quite bulky, this approach is not good enough. Rather it provides a baseline upon which improvements will be made.

After the filesystem is sure that blocks up to a given point were persisted, it issues an atomic but also unordered write of the first sector (checkpointing), moving the address of last used block. Recovery is not strictly necessary so far because first sector reliably tells us how much data was persisted. Operations that happened between checkpoints are always lost. The window of changes that can get lost can be quite significant, depending on how many changes (or for how long) are accumulated between atomic writes of header. Modern filesystems make this sacrifice on regular basis. Losing few seconds worth of operations is commonly accepted.

Compactness can be achieved by storing intents instead of full structures. For example, in log structured filesystem a single file write could end up storing the data buffer, indirect blocks, file inode, parent directory data and inode, and so on up to root inode. Instead only the data buffer and an intent describing to which file this data belongs to would be enough. Inode has to be stored eventually but not before file write operation was persistent, neither between open-close cycles. Recovery involves doing a so called *roll forward*, scanning the log from last known end forward, looking for intents. Each intent carries a signature that verifies both intent integrity (checksum), data it references elsewhere in the log in case of file write operation (checksum) and that it represents actual intent, not stale bytes from whatever was stored on disk previously (generation number). On recovery, if complete inode was not saved properly then last complete copy is loaded, changes defined in intents have to be merged, incorporated into in-memory inode. Final complete copy is then stored. Complexity is added to recovery code but performance and utilisation gain may well be worth it.

Robustness can also be achieved in the sense that operations can become persistent as soon as their intents hit the disk. To maximize durability, that is shortening the time from operation returning success to being persistent, intents could be appended to log immediately after each operation, with each buffer in case of files writes. However, this approach also maximizes fragmentation because even between successive sequential file writes there is always an intent allocated in middle. On the other hand, garbage collection will eventually move the data, both defragmenting (joining buffers) and compacting it (getting rid of intents). If durability is a goal, this approach could be taken into consideration.

Avoided fragmentation together with compactness can be achieved by assigning global incremental generation numbers to each operation. Inodes affected by given operation are loaded from disk (if not yet present), operation is applied to in-memory inodes, and last generation number in each inode is updated to current operation. Before checkpointing, all in-memory inodes having last generation number less than some arbitrary generation are allocated in the log and sent to disk. Afterwards, first block is atomically updated. This approach allows to implement delayed allocation, coalescing sequential file writes and storing only one intent in total thus actively avoiding fragmentation and increasing compactness.

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. 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.

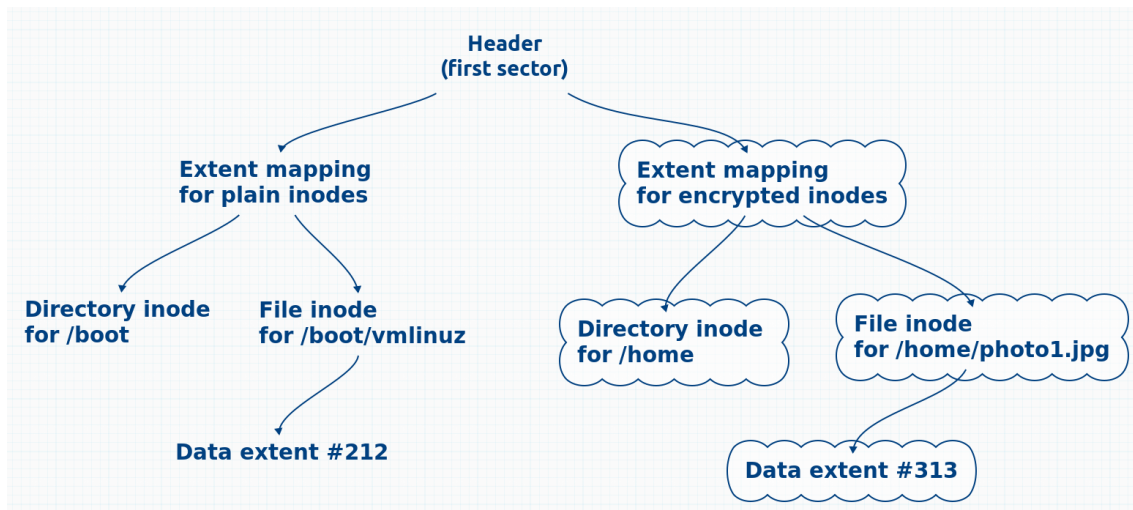
Only solution to booting from a (partially) encrypted filesystem seems to be encrypting filesystem itself and not the block storage device underneath.

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 be useful 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 allow to determine that a progressively shrinking fraction of blocks are not in use. Content would not be revealed, only an upper bound on usage quota, and only for first few hours of operation.

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.

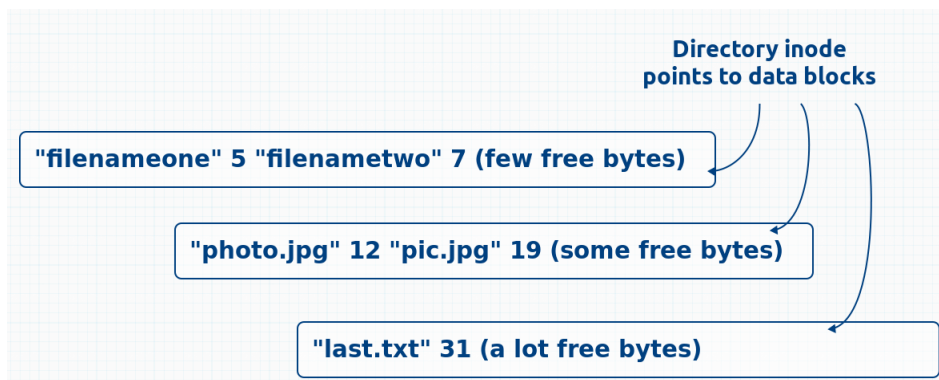
[work in progress]

Blocks can store less than extents.

Earlier chapters discussed the issue of storing data structures like dictionaries and inodes in single extents. While previous chapters were considering performance of disk devices this chapter is focused on compactness. Less bits are needed to store data in extent form than in individual blocks, leading to performance and space utilisation gain.

The main reason why extents are more efficient is that blocks impose rigid boundaries between data items stored inside. Items of variable size cannot be compactly laid out next to one another because boundaries between sets of items often not align with boundaries between blocks. When data is divided into blocks, usually items should not be split between blocks.

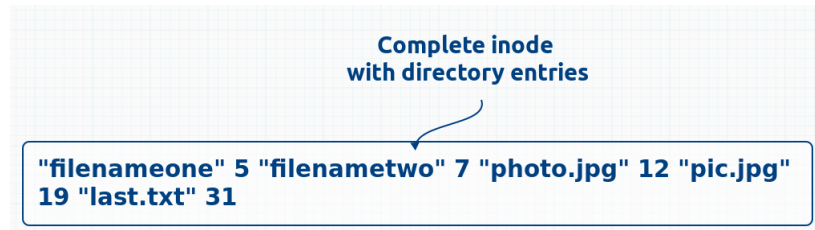
For example, directory entries used to be stored in data blocks like on a diagram below. File names are much shorter than a single block so they are being grouped to occupy as much space in each block as possible. However, since file names are variable length each block has some unpredictable amount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



No doubt this approach was beneficial when memory was heavily constrained. Listing and querying entries requires processing only one block at a time. Removing or changing an entry requires writing only one block to disk. New entries can be added to an existing block in place of

already removed entries, or can allocate a new block. All of these operations can be carried out with only one block in memory at a time, although keeping them in the buffer cache would be beneficial.

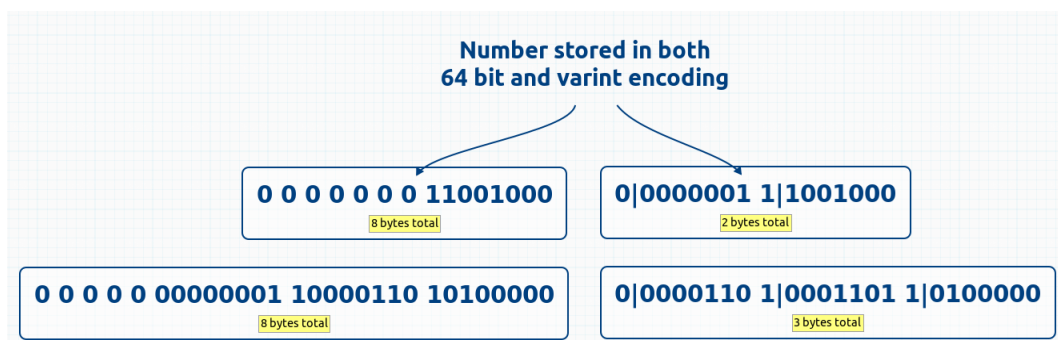
Consider using an extent instead. Items can be laid out next to each other with not even a byte wasted. At most, extent could be aligned to block boundaries wasting only some fragment of the last block, often called a *tail*. However if filesystem would allow extents to start and end at byte precise 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 binary blob (an extent). When keys are kept in separate blocks only few keys may be processed at once. Loading and storing entire dictionary each time becomes necessary when dictionary is supposed to always occupy a single extent.

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, on average and however else we choose to look at them. Small numbers can be encoded more efficiently using varint encoding which is explained right below. Values may be stored after each corresponding key and be also 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 is used to signal whether more chunks follow. For example, numbers 200 and 100'000 are encoded as below. Each byte is separated with a space and bits are concatenated with a pipe. Chunks are shown in binary system.



Varint encoding was developed by Google and used in their serialization framework [Protocol Buffers](#).

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Mission Statement

Safe cryptographic steganographic advanced filesystem

Arkadiusz Bulski

Abstract

Cameleonica is a prototype of a highly versatile filesystem. This paper explains what the project is about, what the mission statement is for the project, and what the ultimate end-goals are. Purposefully omitted are any technical details and means to ends. Overall project is mostly described through basic definitions and examples. Use cases showing obvious benefits are also presented.

[work in progress]

Introduction

Cameleonica is a safe cryptographic steganographic advanced filesystem.

This succinct definition best describes the overall project (and is the official description for the project on GitHub). That is however exactly because it uses loaded terms. Each of the terms carries a very elaborate meaning which will be discussed below. Above statement can be expanded into:

It aims to guarantee confidentiality, authenticity, plausible deniability, transactions, snapshots, versioning, instantaneous copying, permanent deletion, high performance, low delays, compression, and hashing.

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` can create an anonymous temporary file that can later be renamed and thus retained. 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.

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 its 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 its 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. **Filesystem can persist file size before the content, a phenomenon connected to deferred allocation in Ext4.** 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 (achieving speeds of underlying hardware), as functionality (instant copying), as security (deletions equivalent to permanent wiping), as introspectability (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 throughput close to

underlying device throughput. Processing of small files would be expected to happen at high rate due to write-back caches. To achieve that in the long term, file and free space fragmentation must be actively avoided.

Functionality of modern filesystems is mostly ancient. Paradigm of opening a file for writing, then applying a set of discrete changes, one at a time has not changed since the dawn of time. There is still room for improvement however. 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 even adding a new syscall (API) for cloning files would seem warranted.

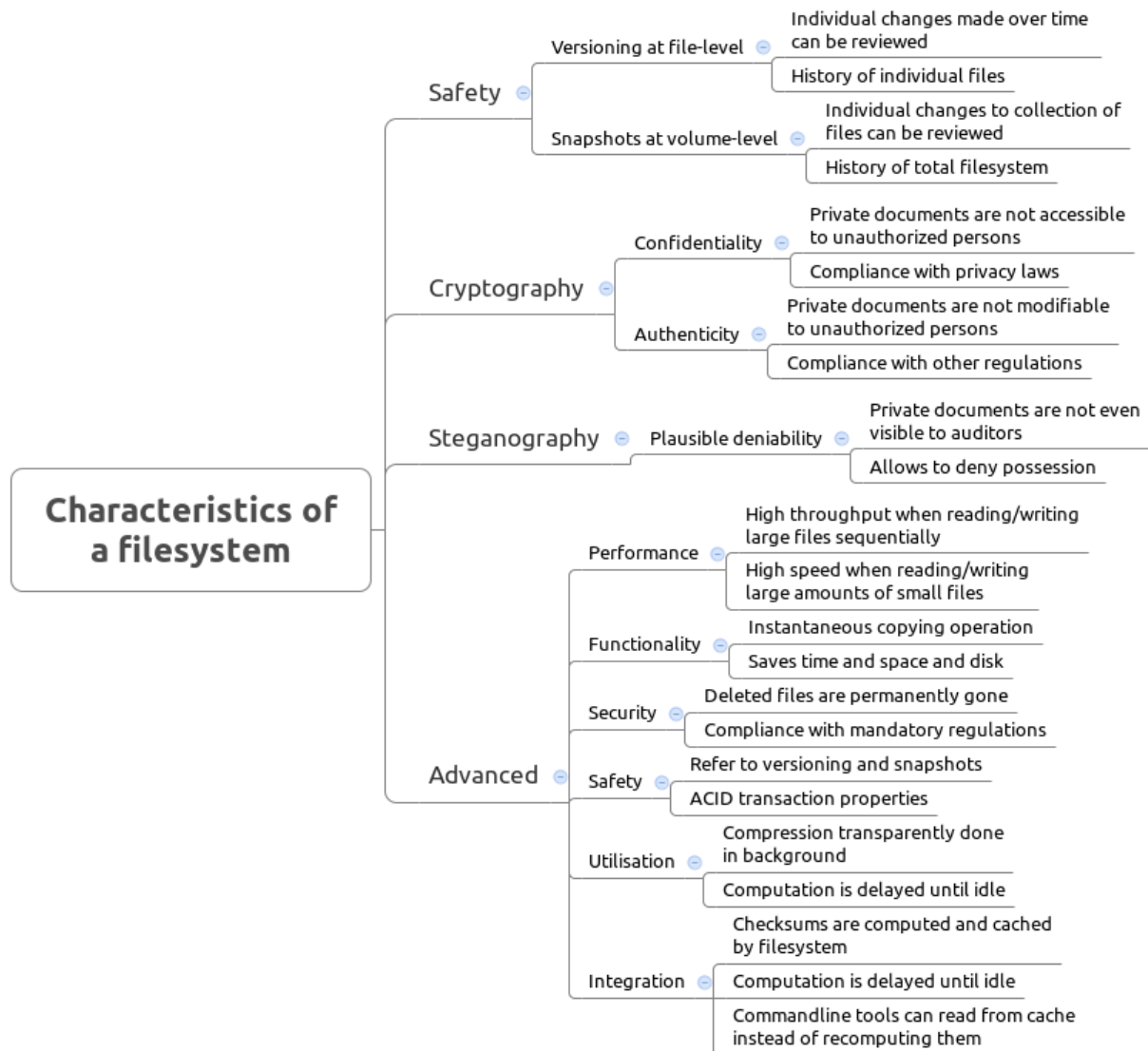
Secure deletion is another area where modern filesystems are lacking. Wiping files is not practical. User has to manually take action, and if he fails to do it right, unwanted evidence remains on disk basically forever. Performance of a wipe operation is usually comparable to writing few times more than the amount of data to be wiped. 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 compression of selected files. Compression can happen transparently, with the user only noticing that he can store files with more total size than hard-disk capacity. Furthermore, 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 handed over compressed representation. This could make compression software significantly faster.

Hashing can also be done on behalf of common utilities. Filesystem can compute checksums on file content and provide system utilities with checksums instead of all the data necessary to compute it. Computation can both be done in advance when system is idle, on the fly during a sequential write, or on demand when a user process requests it. Once computed, results can be cached 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.

Summary of the features and their applications:



Use cases

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. Her laptop is thoroughly 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 mentioned. 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.

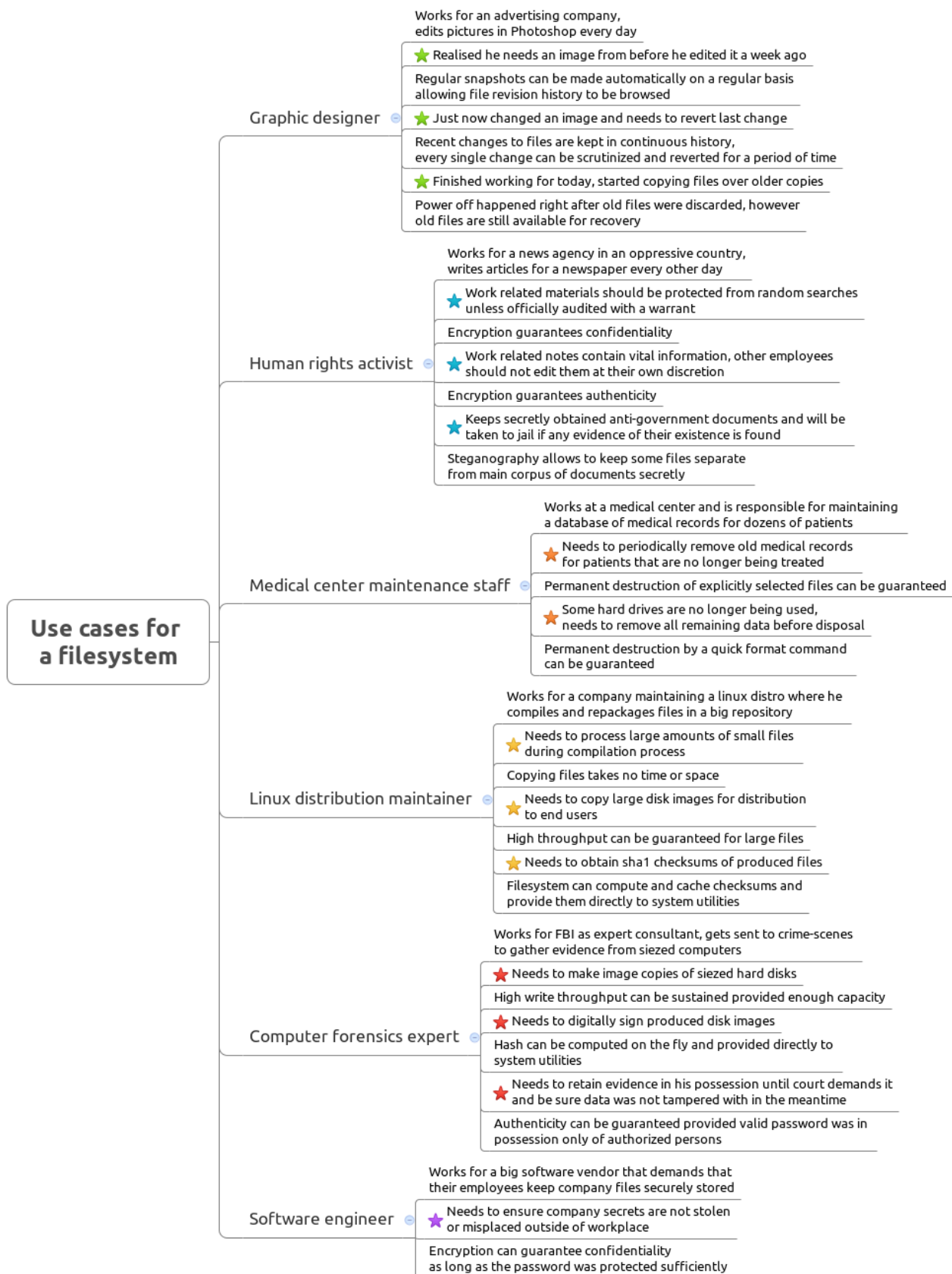
Medical center maintenance staff. He works at a major hospital that processes dozens of patients every day. His job is to maintain a database of medical records of current patients. Regularly he has to delete old records of former patients. Government regulations demand that these records are permanently purged when no longer needed. Medical center 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. He can rest assured that deleted files are permanently gone, as the filesystem guarantees it. Aside of regular tasks, 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

permanently or the center would be liable and would have to pay damages. He can rest assured that quick formatting done on the hard drives destroyed everything permanently as the filesystem guarantees it.

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.





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. Please refer to answer to next question.

Practicality is meant here 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 file content. Historically, this is how it was done and is still being done. There are two major deficiencies with this approach. First problem, wiping performance is limited by hard disk performance and file sizes and fragmentation. Hard disks operate usually at maximum of about 120 MB/s. 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 pointed to by inode, due to truncate operation for example, cannot be overridden. It is not possible to find out which blocks used to belong to a selected file. Copy on write mechanism can be applied to data, and if so, overwriting has no effect. There is no common interface to find out whether underlying filesystem uses COW or not.

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. User processes are normally not able to take this action. This kind of action is also 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 a list of snapshots, states saved at some points in time, ordered chronologically. History can be browsed and every snapshot can be inspected for details but also every snapshot 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 you 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.

Selective 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.

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 easily. 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. In the end, throughput becomes 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 recognized in advance. This is the model of how version control software works. Commits are then the equivalent of creating snapshots. So this was the first feature. Continuous versioning is similar to snapshots but has an important difference. Every change is automatically creating a temporary lightweight snapshot (a checkpoint) that gets stacked on top of previous changes. At the same time, changes from too far into the past become non-revertible. So in contrast, snapshots are manually created while versioning is automatic, and snapshots are kept forever while versions are only available for some period of time.

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. The state of the art solution would perhaps comprise of copy on write, checksums, and intents.

From user's perspective one thing should be noticeable: recovery should happen lazily. Mounting an interrupted filesystem should be achievable in sub-second time. Files that were not closed properly require maintenance and will be scrutinized either at opening or during routine scrubbing, whichever comes first. Maintenance should be carried out on individual files and be postponed preferably until after booting is complete. Further recovery can run in background. Unaffected files become accessible immediately.

This can be achieved by using copy on write, checksums, and intents. For example, when a write operation occurs the data is stored into a newly allocated extent and both its address and checksum are stored in an intent, which itself is stored at a known location. At mount, only intents need to be processed. Intents integrity are checked through their checksums and if they are good, extents they point to become reserved as if they were properly allocated. At this point filesystem is mounted and ready to go. When a file gets opened any remaining unverified intents referring to it must be processed. Intent holds a checksum to verify the data, if data is good then the intent is reapplied to inode, if not then data is deallocated and operation gets reverted.