# 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 but have not been incorporated into popular filesystem designs. Both potential benefits and reasons why these features were not popularized earlier are presented. Expectations of their performance are then justified.

## Introduction

When reading scientific papers that describe historical filesystem designs from the golden times of Unix development, 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 dramatical changes at any one time.

[work in progress]

## New ideas

**B-trees are not efficient.** We can see a trend within filesystem design towards using both modified in-place and copy-on-write B-trees. This trend might be easily explained by common expectation that filesystems should be able to handle billions of files, that they will be able to scale. 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 we expect huge amounts of keys to be stored. B-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 everybody. It would be justified to use B-trees if we expected billions of files to be stored, but that is a false assumption at least in general case. Most computers hold something on the order of 100'000 files. That amount of dictionary entries can be stored more efficiently by other means.

Consider a hybrid or rather a transitional approach. Initially all entries are loaded from one extent, kept in memory in entirety and all the time, and occasionally stored to disk as one extent. If at some point the amount of entries grows over a certain threshold, we commence a transition to a B-tree representation, we relocate all entries (already in memory) to tree nodes, and store all tree nodes to disk in one sweep. The threshold can be chosen low enough so storing entire collection in one sweep is faster than analogous B-tree operation (few disk seeks). Subsequent operations are carried out on a B-tree representation which is the compared alternative.

The threshold would actually be very high. We need to recognize that magnetic hard disks have quite disproportionate performance characteristics. Flash based disks are precluded due to reasons explained elsewhere. Representative hard disk is capable of ~120 MB/s of sustained throughput and ~10 ms seek time to random location. 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 would be slower than reading or writing an entire 1.2 MB in one sweep. A huge amount of entries can be stored in that amount of data.

Actually even more entries can be stored on disk than in memory. If for example entry keys are sorted then we can store their pairwise differences instead. Smaller numbers can be encoded more compactly using varint encoding as used in Protocol Buffers.

**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 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]. All these reasons contributed to a decision that data structures should be broken down into blocks.

To fully describe a single file, we need an amount of data that almost always takes space of more than one block. Traditionally, one main block (called inode) would hold most important data, several blocks would point to where actual content is located, some blocks would keep directory entries in case of a directory, and so on. For a large 1GB file for example, assuming 8KB blocks and 64 bit pointers, at least 128 blocks would be needed. Certain operations such as copying or deleting file, or browsing directory would necessarily require all metadata blocks to be read.

Consider now 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. Last situation is prevalent in modern filesystems. Space is allocated conservatively, one block at a time leading to fragmentation of metadata.

This approach seems efficient at first glance because changing one detail should require only one block to be written. This kind of reasoning is flawed because we do not consider the impact on further operations into account. We should consider amortizing performance over entire lifespan of a file.

It could be argued that first approach, where all metadata is always loaded and stored in one sweep is necessarily better in every possible usage scenario. To show that, we need to recognize that magnetic hard disks have quite disproportionate performance characteristics. Flash based disks are precluded due to reasons explained elsewhere. Representative hard disk is capable of ~120 MB/s of sustained throughput and ~10 ms seek time to random location. 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 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, directories put groups of entries into a linked list of blocks, files put data locations into indirect blocks, and so on. In modern designs like Btrfs, cow btrees are replacing linked lists but data is still being divided into small chunks.

To show first approach is better we will consider total time spent on all operations throughout a lifetime of a file. Only metadata is counted towards the time spent reading or writing. Parent directory metadata is also excluded. At time zero file metadata has no copy on disk. We let a certain number of cycles of the file being opened, changed several times and then closed. After each open, some of metadata blocks are read (in last approach) by necessity or all metadata blocks are read (in first approach) by design. Blocks need to be read before they can be changed. This is a simple fact, that if data is written in place then we need to know where to put it, and if data is copy-on-written then we need to deallocate previous data. Either way, we need to know metadata before changing it. Also cached blocks are forgotten between cycles due to assumed long time intervals. Each time file is opened we make a certain number of changes to metadata, where each change can be reflected in changing just one block on disk. These changes to metadata will be applied by overwriting their corresponding blocks on disk in place.

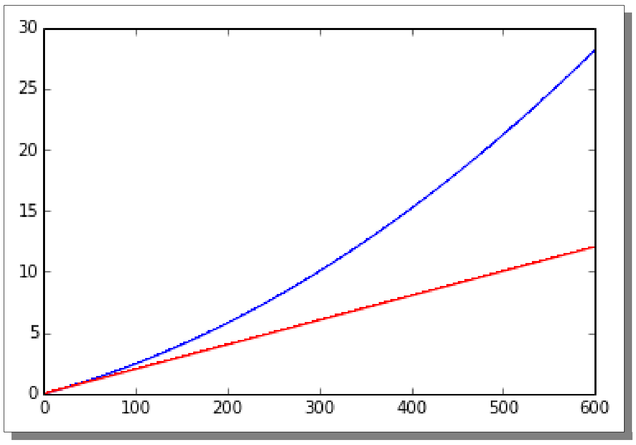
Reading or writing N blocks would take (first and last approach respectively):

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

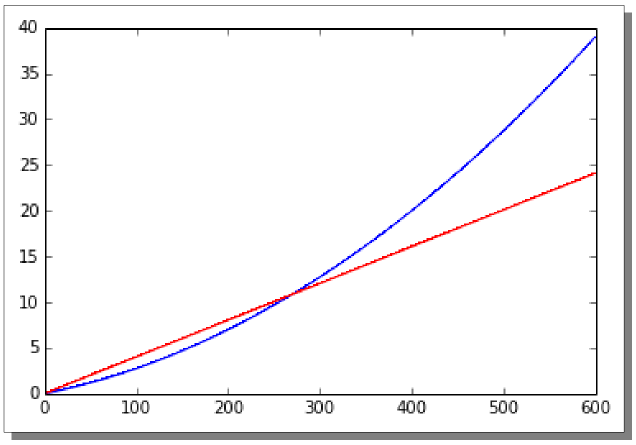
We will run simulations with two independent variables, N is number of changes in each cycle and M is number of cycles. After each cycle, the number of blocks will grow by N. Therefore total time would be:

$$T_1(N,M) = \sum_{i=0}^{M-1} R_1(N \cdot i) + R_1((N+1) \cdot i)$$
$$T_N(N,M) = \sum_{i=0}^{M-1} R_N(N) + R_N(N)$$

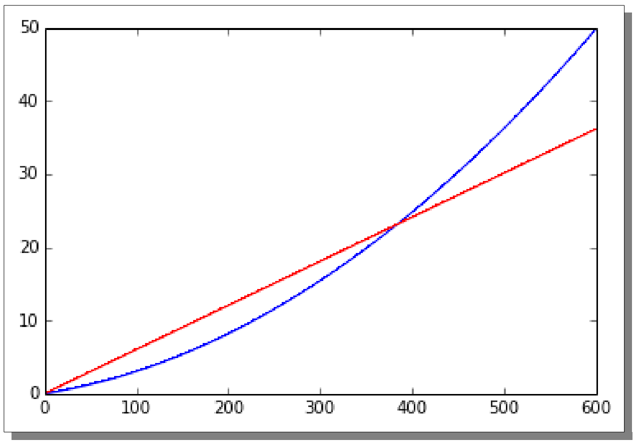
Plots show total time of extent-based (blue) and block-based (red) approach for least opened files. Files going through more cycles have even more disproportionate results in favor of extent-based approach.



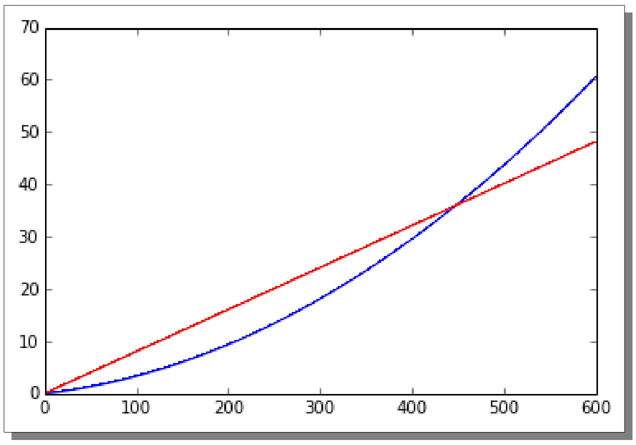
M=1



M=2



M=3



M=4

Extent-based approach clearly fails at one cycle. However, this case is invalidated for two reasons. One cycle does not mean that a file was written and then some time later deleted. Deleting a file requires reading all metadata as data blocks need to be deallocated. That would count as second cycle. One cycle refers to a file that was created, written, and unlinked before it was even closed properly. This is not a practical usage. More importantly, storing metadata may be easily deferred until it is closed, or as here unlinked, and therefore we can skip storing metadata on disk altogether.

In other cases extent-based approach outperforms the alternative approach up to a point where metadata size is under 270 4K blocks or 1.08 MB. This can be explained by a straightforward observation:

When we store individual blocks we gain on transfer time related to small block size but we pay for it with seek time the next time we read said blocks. Disk characteristics make this exchange totally unfair. One seek takes as much time as transferring 1.2 MB which for all practical purposes can fit complete metadata of any imaginable file, ever.

Conclusion: It is not worthwhile to pay a guy $100 bucks for him to recover our pennies lost behind a couch.

**Checksums are effective.**

For a long time filesystems depended on this feature to ensure ongoing consistency, in particular the Soft Updates method developed by McKusick and Ganger. Later on journaling became the way of ensuring consistency (as Steven Tweedie talks about Ext3) and today checksums are also becoming popular (with Btrfs and ZFS paving the way). As computational power and memory are now in abundance we see a shift in approaches to filesystem design. [McKusi99] [Bonw07] [McKusi84]

[work in progress]

## Bibliografia

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