

Formalising Filesystems in the ACL2 Theorem Prover: an Application to FAT32

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In this work, we present an approach towards constructing executable specifications of existing filesystems and verifying their functional properties in a theorem proving environment. We detail an application of this approach to the FAT32 filesystem.

We also detail the methodology used to build up this type of executable specification through a series of models which incrementally add features of the target filesystem. This methodology has the benefit of allowing the verification effort to start from simple models which encapsulate features common to many filesystems and which are thus suitable for reuse.

1 Introduction and overview

Filesystems are ubiquitous in computing, providing application programs a means to store data persistently, address data by names instead of numeric indices, and communicate with other programs. Thus, the vast majority of application programs directly or indirectly rely upon filesystems, which makes filesystem verification critically important. Here, we present a formalisation effort in ACL2 for the FAT32 filesystem, and a proof of the read-over-write properties for FAT32 system calls. By starting with a high-level abstract model and adding more filesystem features in successive models, we are able to manage the complexity of this proof, which has not, to our knowledge, been previously attempted. Thus, this paper contributes an implementation of several Unix-like system calls for FAT32, formally verified against an abstract specification and tested for binary compatibility by means of co-simulation.

In the rest of this paper, we describe these filesystem models and the properties proved, with examples; we proceed to a high-level explanation of these proofs and the co-simulation infrastructure; and further we offer some insights about the low-level issues encountered while working out the proofs.

2 Related work

Filesystem verification research has largely followed a pattern of synthesising a new filesystem based on a specification chosen for its ease in proving properties of interest, rather than faithfulness to an existing filesystem. Our work, in contrast, follows the FAT32 specification closely. In spirit, our work is closer to previous work which uses interactive theorem provers and explores deep functional properties than to efforts which use non-interactive theorem provers such as Z3 to produce fully automated proofs of simpler properties.

2.1 Interactive theorem provers

An early effort in the filesystem verification domain was by Bevier and Cohen [4], who specified the Synergy filesystem and created an executable model of the same in ACL2 [14], down to the level of processes and file descriptors. They certified their model to preserve well-formedness of their data structures through their various file operations; however, they did not attempt to prove read-over-write properties or crash consistency. Later, Klein et al. with the SeL4 project [23] used Isabelle/HOL [28] to verify a microkernel; while their microkernel design excluded file operations in order to keep their trusted computing base small, it did serve as a precursor to their more recent COGENT project [2]. Here the authors built a verifying compiler to translate a filesystem specification in their domain-specific language to C-language code, accompanied by a proof of the correctness of this translation. Elsewhere, the SibylFS project [29], again using Isabelle/HOL, provided an executable specification for filesystems at a level of abstraction that could function across multiple operating systems including OSX and Unix. The Coq prover [3] has been used to aid the development of FSCQ [6], a state-of-the-art filesystem built to have high performance and formally verified crash consistency properties.

2.2 Non-interactive theorem provers

Non-interactive theorem provers such as Z3 [8] have also been used to analyse filesystem models. Hyperkernel [27] is a recent effort which simplifies the xv6 [7] microkernel until the point where Z3 can verify its various properties with its SMT solving techniques. However, towards this end, all system calls in Hyperkernel are replaced with analogs which can terminate in constant time; while this approach is theoretically sound, it increases the chances of discrepancies between the model and the implementation which may diminish the utility of the proofs or even render them moot. A stronger effort in the same domain is Yggdrasil [31], which focusses on verifying filesystems with the use of Z3. While the authors have made substantial progress in terms of the number of filesystem calls they support and the crash consistency guarantees they provide, they are subject to the limits of SMT solving which prevent them from modelling filesystem features such as extents, which are essential to FAT32 and many other filesystems.

3 Program architecture

Modern filesystems, in response to the evolution of end users' needs over time, have developed a substantial amount of complexity in order to serve file operations in a fast and reliable manner. In order to address this complexity in a principled way, we choose to build our filesystem models incrementally, adding filesystem features in each new model and proving equivalence with earlier, simpler models.

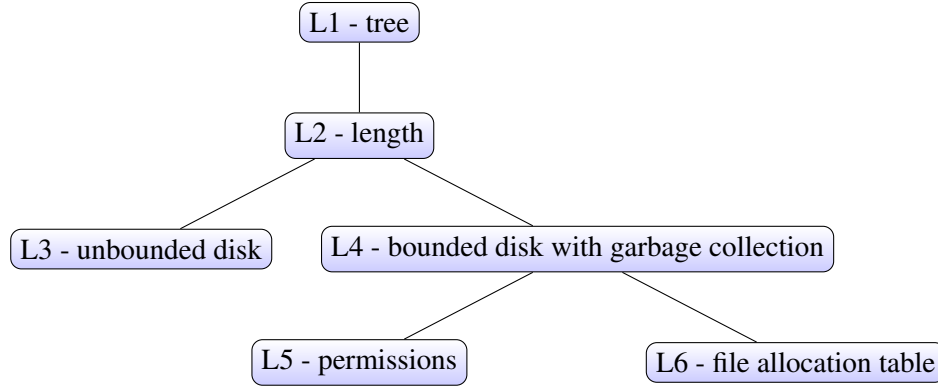
We have two concrete models for the FAT32 filesystem - M2, which is a faithful representation of a FAT32 disk image in the form of a stobj [5], and M1, which represents the state of the FAT32 filesystem as a directory tree. This allows us to address the practical details of updating a disk image in M2, which benefits from the efficient array operations ACL2 provides for stobjs, and abstract them away in M1 for easier reasoning without the syntactic constraints imposed on stobj arrays.

These concrete filesystem models are based upon abstract models L1 through L6. Incremental construction allows us to reuse read-over-write proofs for simpler models in more complex models. In the case of models L4 and L6, we are able to show a refinement relationship without stuttering [1]; however, for the other models we are able to reuse proofs without proving a formal refinement relation. These reuse relationships are summarised in figure 1. Much of the code and proof infrastructure is also

Table 1: Abstract models and their features

L1	The filesystem is represented as a tree, with leaf nodes for regular files and non-leaf nodes for directories. The contents of regular files are represented as strings stored in the nodes of the tree; the storage available for these is unbounded.
L2	A single element of metadata, <i>length</i> , is stored within each regular file.
L3	The contents of regular files are divided into blocks of fixed size. These blocks are stored in an external “disk” data structure; the storage for these blocks remains unbounded.
L4	The storage available for blocks is now bounded. An allocation vector data structure is introduced to help allocate and garbage-collect blocks.
L5	Additional metadata for file ownership and access permissions is stored within each regular file.
L6	The allocation vector is replaced by a file allocation table, matching the official FAT specification.

Figure 1: Refinement/reuse relationships between abstract models



shared between the abstract models and the concrete models by design. Details of the filesystem features introduced in the abstract models can be seen in table 1.

A design choice that arises in this work pertains to the level of abstraction: how operating-system specific do we want to be in our model? Choosing, for instance, to make our filesystem operations conform to the `file_operations` interface [30] provided by the Linux kernel for its filesystem modules would make our work less general, but avert us from having to recreate some of the filesystem infrastructure provided by the kernel. We, however, choose to implement a subset of the POSIX filesystem application programming interface, in order to enable us to easily compare the results of running filesystem operations on M2 and the Linux kernel’s implementation of FAT32, which in turn allows us to test our implementation’s correctness through co-simulation in addition to theorem proving. As a trade-off for this choice, we are required to implement process tables and file tables, which we do through a straightforward approach similar to that used in Synergy [4].

At the present moment, we have implemented the POSIX system calls `lstat` [17], `open` [20], `pread` [21], `pwrite` [22], `close` [15], `mkdir` [18] and `mknod` [19]. Wherever `errno` [16] is to be set by a system call, we abide by the Linux convention.

4 The FAT32 filesystem

FAT32 was initially developed at Microsoft in order to address the capacity constraints of the DOS filesystem. Microsoft’s specification for FAT32 [25], which we follow closely in our work, details the layout of data and metadata in a valid FAT32 disk image.

In FAT32 all files, including regular files and directory files, are divided into *clusters* (sometimes called *extents*) of a fixed size. The size of a cluster, along with other volume-level metadata, is stored in a *reserved area* at the beginning of the volume, and the clusters themselves are stored in a *data region* at the end of the volume. Between these two on-disk data structures, the volume has one or more redundant copies of the *file allocation table*.

The cluster size must be an integer multiple of the sector size, which in turn must be at least 512 bytes; these and other constraints on the fields of the reserved area are detailed in the FAT32 specification.

Directory files are for the most part treated the same way as regular files by the filesystem, but they differ in a metadata attribute, which indicates that the contents of directory files should be treated as sequences of directory entries. Each such directory entry is 32 bytes and contains metadata including name, size, first cluster index, and access times for the corresponding file.

The file allocation table is a table with one entry for each cluster in the data region; it contains a number of linked lists (*clusterchains*). It maps each cluster index used by a file to either the next cluster index for that file or a special end-of-clusterchain value.¹ This allows the contents of a file to be reconstructed by reading just the first cluster index from the corresponding directory entry, reconstructing the clusterchain using the table, and then looking up the contents of these clusters in the data region. Unused clusters are mapped to 0 in the table; this fact is used for counting and allocating free clusters.

We illustrate the file allocation table and data layout for a small example directory tree in figure 2. Here, /tmp is a subdirectory of the root directory (/). For the purposes of illustration, all regular files and directories in this example are assumed to span one cluster except for /vmlinuz which spans two clusters (3 and 4), and *EOC* refers to an “end of clusterchain” value. Also, as shown in the figure, the specification requires the first two entries in the file allocation table (0 and 1) to be considered reserved, and thus unavailable for clusterchains.

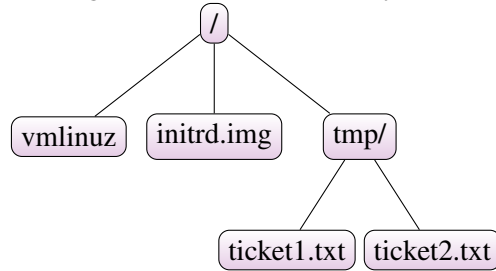
5 Proof methodology

Broadly, we characterise the filesystem operations we offer as either *write* operations, which do modify the filesystem, or *read* operations, which do not. In each model, we have been able to prove *read-over-write* properties which show that write operations have their effects made available immediately for reads at the same location, and also that they do not affect reads at other locations.

The first read-over-write theorem states that immediately following a write of some text at some location, a read of the same length at the same location yields the same text. The second read-over-write theorem states that after a write of some text at some location, a read at any other location returns exactly what it would have returned before the write. As an example, listings for the L1 versions of these theorems follow. Note, the hypothesis (`stringp (l1-stat path fs)`) stipulates that a regular file should exist at `path`, where `l1-stat` is a function for traversing a directory tree to look up a regular file or a directory at a given path (represented as a list of symbols, one for each subdirectory/file name).

¹ There is a range of end-of-clusterchain values in the specification, not just one. We support all values in the range.

Figure 2: A FAT32 directory tree



FAT index	FAT entry
0 (reserved)	
1 (reserved)	
2	<i>EOC</i>
3	4
4	<i>EOC</i>
5	<i>EOC</i>
6	<i>EOC</i>
7	<i>EOC</i>
8	<i>EOC</i>
9	0
⋮	⋮

	Directory entry in /
0	"vmlinuz", 3
32	"initrd.img", 5
64	"tmp", 6
⋮	⋮

	Directory entry in /tmp/
0	"ticket1", 7
32	"ticket2", 8
⋮	⋮

```

(defthm l1-read-over-write-1
  (implies (and (l1-fs-p fs)
                (stringp text)
                (symbol-listp path)
                (natp start)
                (equal n (length text))
                (stringp (l1-stat path fs))))
    (equal (l1-rdchs path (l1-wrchs path fs start text) start n) text)))

(defthm l1-read-over-write-2
  (implies (and (l1-fs-p fs)
                (stringp text2)
                (symbol-listp path1)
                (symbol-listp path2)
                (not (equal path1 path2))
                (natp start1)
                (natp start2)
                (natp n1)
                (stringp (l1-stat path1 fs))))
    (equal (l1-rdchs path1 (l1-wrchs path2 fs start2 text2) start1 n1)
      (l1-rdchs path1 fs start1 n1))))

```

By composing these properties, we can reason about executions involving multiple reads and writes, as illustrated in the following throwaway proof.

```

(thm
  (implies (and (l1-fs-p fs)
                (stringp text1)
                (stringp text2)
                (symbol-listp path1)
                (symbol-listp path2)
                (not (equal path1 path2))
                (natp start1)
                (natp start2)
                (stringp (l1-stat path1 fs))
                (equal n1 (length text1)))
    (equal (l1-rdchs path1
                    (l1-wrchs path2 (l1-wrchs path1 fs start1 text1)
                                   start2 text2)
                    start1 n1)
      text1)))

```

In L1, our simplest model, the read-over-write properties are proven from scratch. In each subsequent model, the read-over-write properties are proven as corollaries of equivalence proofs which establish the correctness of read and write operations in the respective model with respect to a previous model. A representation of such an equivalence proof can be seen in figures 3, 4 and 5, which respectively show the equivalence proof for l2-wrchs, the equivalence proof for l2-rdchs and the composition of these to obtain the first read-over-write theorem for model L2.

Figure 3: l2-wrchs-correctness-1

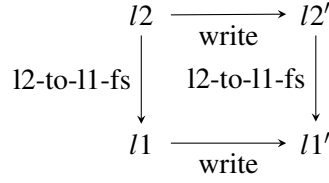
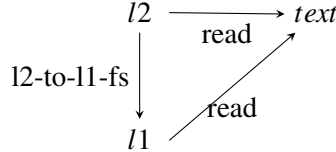


Figure 4: l2-rdchs-correctness-1



6 Proof and implementation details

We have come to rely on certain principles for the development of each new model and its corresponding proofs. We summarise these below.

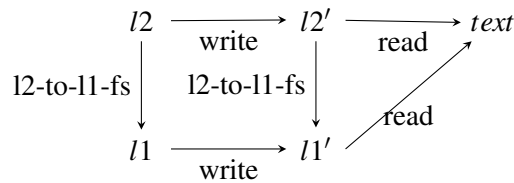
6.1 Invariants

As the abstract models grow more complex, with the addition of more auxiliary data the “sanity” criteria for filesystem instances become more complex. For instance, in L4, the predicate `l4-fs-p` is defined to be the same as `l3-fs-p`, which recursively defines the shape of a valid directory tree. However, we choose to require two more properties for a “sane” filesystem.

1. Each disk index assigned to a regular file should be marked as *used* in the allocation vector - this is essential to prevent filesystem errors.
2. Each disk index assigned to a regular file should be distinct from all other disk indices assigned to files - this does not hold true, for example, in filesystems with hardlinks. FAT32 is not such a filesystem, and we can use this fact to make our proofs easier.

These properties are invariants to be maintained across write operations; while not all of them are strictly necessary for a filesystem instance to be valid, they do simplify the verification of read-over-write properties by helping us ensure that write operations do not create an aliasing situation in which a regular file’s contents can be modified through a write to a different regular file.

Figure 5: l2-read-over-write-1



These properties, in the form of the predicates `indices-marked-listp` and `no-duplicatessp`, are packaged together into the `l4-stricter-fs-p` predicate, for which a listing follows. Here, `(boolean-listp alv)` is a type hypothesis for `alv`, the allocation vector.

```
(defun l4-stricter-fs-p (fs alv)
  (declare (xargs :guard t))
  (and (l4-fs-p fs)
        (boolean-listp alv)
        (let ((all-indices (l4-list-all-indices fs)))
          (and (no-duplicatessp all-indices)
                (indices-marked-p all-indices alv)))))
```

Similarly, for proof purposes we find it useful to package together certain invariants for the `stobj` `fat32-in-memory`, which we maintain while manipulating the `stobj` through input/output operations and file operations, in the predicate `compliant-fat32-in-memoryp` for which a listing follows. The constant `*ms-first-data-cluster*`, for instance, is 2, and the last clause of the conjunction helps us maintain an invariant about all cluster indices including the root cluster being greater than or equal to 2, which is stipulated in the FAT32 specification as previously noted and therefore necessary while reasoning about operations in the file allocation table.

```
(defund compliant-fat32-in-memoryp (fat32-in-memory)
  (declare (xargs :stobjs fat32-in-memory :guard t))
  (and (fat32-in-memoryp fat32-in-memory)
        (>= (bpb_bytsspersec fat32-in-memory) *ms-min-bytes-per-sector*)
        (>= (bpb_secperclus fat32-in-memory) 1)
        (>= (count-of-clusters fat32-in-memory)
              *ms-fat32-min-count-of-clusters*)
        (>= (bpb_rootclus fat32-in-memory) *ms-first-data-cluster*)))
```

M2, however, differs from previous models in that the predicate `compliant-fat32-in-memoryp` cannot be assumed to hold before the filesystem is initialised by reading a disk image. This also means that it is not straightforward to use an abstract `stobj` [11] for this purpose, using `compliant-fat32-in-memoryp` as an invariant.

6.2 Reuse

As noted earlier, in our abstract models, using a refinement methodology allows us to derive our read-over-write properties with little additional effort; more precisely, we are able to prove read-over-write properties simply with `:use` hints after having done the work of proving refinement through induction.

At a lower level, we are also able to benefit from refinement relationships between components of our different models. For example, such a relationship exists between the allocation vector used in L4 and the file allocation table used in L6. More precisely, by taking a file allocation table and mapping each non-zero entry to `true` and each zero entry to `false`, we obtain a corresponding allocation vector with exactly the same amount of available space. This is a refinement mapping which makes it a lot easier to prove that L4 itself is an abstraction of L6. This, in turn, means that the effort spent on proving the invariants described above for L4 need not be replicated for L6.

6.3 The FTY discipline

In the model M1 in particular, we use the FTY discipline and its associated library [32] to simplify our definitions for regular files, directory files, and other data types. This allows us to simplify as well as speed up our reasoning by eliminating many type hypotheses, and in particular allows us to prove read-over-write properties for M1 with a significantly smaller number of helper lemmas compared to our abstract models in which FTY is not used.

6.4 Allocation and garbage collection

In the development of our abstract models, L4 is the first to be bounded in terms of disk size; accordingly, data structures are needed for allocating free blocks on disk, including those which were previously occupied by other files. For simplicity, we choose to model the allocation vector used by the CP/M filesystem [26], which is a boolean array equal in size to the disk recording whether disk blocks are free or in use. Using this, we are able to prove that write operations succeed if and only if there is a sufficient number of free blocks available on the disk, and when we later model FAT32's file allocation table in L6, we are able to extend this result by proving a refinement relationship between these two allocation data structures as described earlier. While it is not straightforward to reuse this result for the file allocation table in M2, we are still able to benefit from reusing the allocation algorithms developed in L6 as well as the properties proved about them.

7 Stobjs and co-simulation

Previous work on executable specifications [10] has shown the importance of testing these on real examples, in order to validate that the behaviour shown matches that of the system being specified. In our case, this means we must validate our filesystem by testing it in execution against a canonical implementation of FAT32; in this case, we choose the implementation which ships with Linux kernel 3.10.

For each of our tests, we need to produce FAT32 disk images, which we do with the aid of the program `mkfs.fat` [13]. Further, we make use of this program's verbose mode (enabled through the `-v` command-line switch) for a simple yet fundamental co-simulation test. In the verbose mode, `mkfs.fat` emits an English-language summary of the fields of the newly created disk image; we use `diff` [9] to compare this summary against the output of an ACL2 program, based on our model, which reads the image and pretty-prints the FAT32 fields in the same format. This validates our code for constructing an in-memory representation of the disk image and also serves as a regression test during the process of modifying the model to support proofs and filesystem calls.

Further, we co-simulate `cp` [12], a simple program for copying files, by reproducing its functionality in an ACL2 program. This allows us to validate our code for reading and writing regular files and directories which span multiple clusters.

The quick execution of these co-simulation tests relies upon the use of stobjs. Since the file allocation table and data region (section 4) are large arrays which must be initialised whenever a new disk image is read, ACL2's efficient array operations turn out to be very helpful; this is also the case when we write back a disk image after performing a sequence of file operations. We have also developed a number of special-purpose macros for facilitating the generation of lemmas needed for reasoning about reads and writes to the fields of a stobj in the filesystem context; we expect these to continue to be useful as we work with abstract and concrete stobjs for modelling new filesystems.

8 Conclusion

This work formalises a FAT32-like filesystem and proves read-over-write properties through refinement of a series of models. Further, it proves the correctness of FAT32’s allocation and garbage collection mechanisms, and provides artefacts to be used in a subsequent realistic model of FAT32.

9 Future work

The FAT32 model is still a work in progress; the set of system calls is not yet complete and the translation functions between disk images, M2 instances and M1 instances are not yet verified. However, many of the techniques for these proofs have already been demonstrated in our abstract models. Once we have these, we intend to use them as a basis for reasoning about sequences of filesystem operations in a program, in a manner akin to proving properties of code on microprocessor models. This is a motivation for the pursuit of binary compatibility in our work.

While FAT32 is interesting of and by itself, it lacks features such as crash consistency, which most modern filesystems provide by means of journalling. We hope to reuse some artefacts of formalising FAT32 in order to verify a filesystem with journalling, such as ext4 [24].

We also hope to model the behaviour of filesystems in a multiprogramming environment, where concurrent filesystem calls must be able to occur without corruption or loss of data. Although we have not yet used abstract stobjs for the reasons described above in subsection 6.1, we plan to explore their use in facilitating our stobj reasoning.

Acknowledgments

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