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 re-use.

1 Introduction and overview

Filesystems are ubiquitous in computing, providing application programs a means to store data persistently, address data by a name instead of a numeric index, 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 an implementation of the FAT32 filesystem, and a proof of the read-over-write properties for this filesystem. 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 FAT32, a widely-used filesystem, 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 further we offer some insights about the low-level issues encountered while working 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 similarity 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.

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2.1 Interactive theorem provers

An early effort in the filesystem verification domain was by Bevier and Cohen [5], who specified the Synergy filesystem and created an executable model of the same in ACL2 [13], down to the level of processes and file descriptors. On the proof front, they certified their model to preserve well-formedness of their data structures through their various file operations; however, they did not attempt to prove, for instance, read-over-write properties or crash consistency. Later, Klein et al with the SeL4 project [16] used Isabelle/HOL [21] to verify a microkernel; while their design abstracted away 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 "verified compiler" of sorts, generating C-language code from specifications in their domain-specific in a manner guaranteed to avoid many common filesystem bugs. Elsewhere, the SibylFS project [23], 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 [4] has also been used, for instance, for FSCQ [6], a state-of-the art filesystem which was built to have high performance and formally verified crash consistency properties.

2.2 Non-interactive theorem provers

Non-interactive theorem provers such as Z3 [7] have also been used; Hyperkernel [20] is a recent effort which focusses on simplifying the xv6 microkernel until the point that Z3 can verify it 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 [25], which focusses on verifying filesystems with the use of Z3. While the authors make 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 essential filesystem features such as extents, which are central to many filesystems including FAT32.

3 Program architecture and performance considerations

We number our abstract filesystem models `L1` through `L6`, and our concrete models `M1` through `M2` (concrete). These models are constructed incrementally to allow for reuse of features in general, and a refinement relation where possible.

Starting with L1, an abstract model representing the directory structure as a tree, we add file metadata in `L2`. We branch off from `L2` into `L3`, a model with file contents broken up into blocks and stored in an external disk-like data structure, and `L4`, a model which also breaks file contents up into disk blocks, additionally with garbage collection through reference counting, and a fixed disk size bounding the total size of file contents. To implement the reference counter in `L4`, we use an allocation vector as in the CP/M filesystem, which happens to be the previous technology target of this work prior to FAT32. We are able to refine `L4` into `L6`, a filesystem with exactly the same properties but additionally featuring a FAT32-like file allocation table for allocation and garbage collection, since this data structure happens to refine the allocation vector.

`M1` is another tree model, which hews somewhat closely to the FAT32 specification; it is also used as the in-memory format for `M2`, a real model which reads and writes FAT32 disk images. The operations currently supported are `pread(2)`, `pwrite(2)`, and `stat(2)`. With these operations, we are able to

model the file operations used in standard disk utilities such as cat(1) and dd(1), with a view to writing formal specifications of these programs later.

In order to obtain reasonable execution performance, we implement `M2` as a single-threaded object. Most importantly, this allows us to model the file allocation table and data region, which are long arrays, as arrays in Common Lisp rather than as lists, which have poor performance for update operations on their elements because of the number of cons cells which must be created and garbage collected for each update. Array operations in single threaded objects are subject to certain syntactic restrictions to prevent copies of arrays from being created as usually happens with Lisp objects; to simplify the task of reading and writing disk images under these restrictions, we also create a library of useful macros.

We choose to implement a subset of the POSIX filesystem application programming interface. This allows 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. One trade-off for this choice is the necessity of emulating certain functionality provided by the Linux kernel to all filesystems; thus, we implement process tables and file tables through a straightforward approach similar to that used in Synergy [5].

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