Verifying filesystems in ACL2

Towards verifying file recovery tools

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Overview

1. Why we need a verified filesystem
2. Our approach
3. Progress so far
4. Future work

Why we need a verified filesystem

- Filesystems are everywhere.
- Yet they're poorly understood - especially by people who should.
- Modern filesystems have become increasingly complex, and so have the tools to analyse and recover data from them.
- It might be nice, it might be nice to verify that the filesystems and the tools actually provide the guarantees they claim to provide.

What we need

- Our filesystem should offer a set of operations that are sufficient for running a workload.
- However, as theorem proving researchers, we are loath to construct more operations than necessary - so what's the minimal set?
- We could attempt to emulate the VFS and replicate the operations for inodes, dentries, and files.
- That would mean 19 inode operations, 6 dentry operations and 22 file operations.

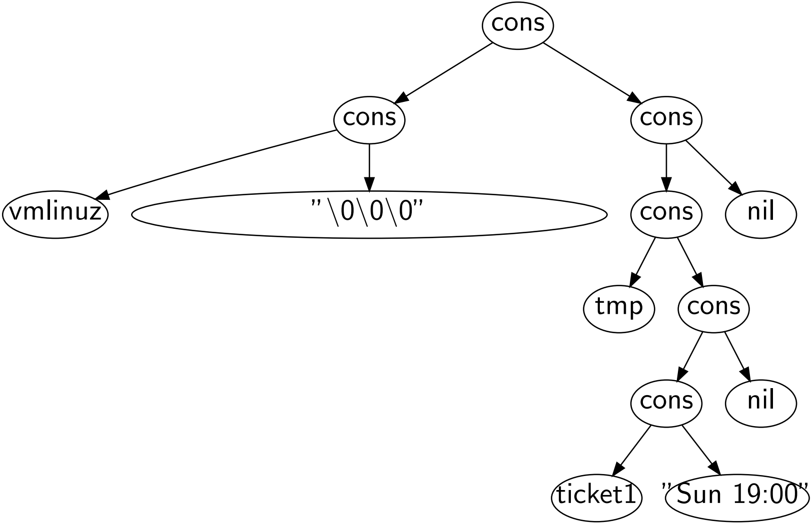
Minimal set of operations?

- There might be a better way, based on the Google file system.
- Here, we have a minimal set of operations:
  - `create`
  - `delete`
  - `open`
  - `close`
  - `read`
  - `write`
- Further, we could leave `open` and `close` for the time when we want to deal with multiprogramming and concurrency.
- Thus, we have a minimal set of filesystem operations which we can model.

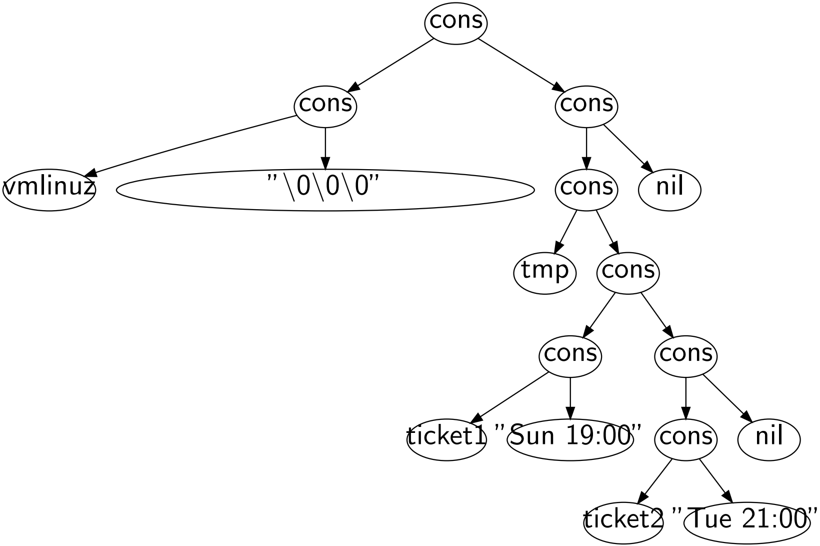
Modelling a filesystem

- What should the filesystem look like?
- We're used to thinking of the filesystem as a tree... how about that?
- Thinking along the lines of recursive datatypes, an `alist` containing only strings or similar `alist`s in its `strip-cdrs` could do the job.
- The `strip-cars` would contain the file/directory names.
- Next, we'll look at a running example where we see what it looks like to add/delete files from such a model.

Model 1

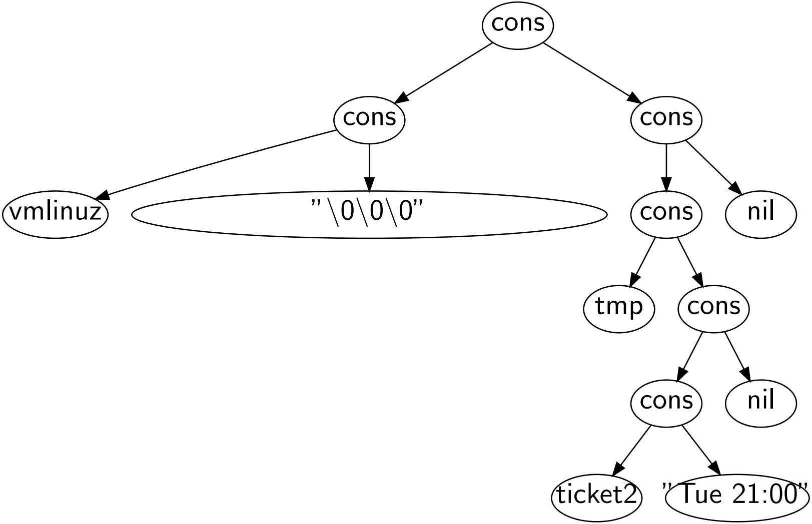

cons
cons
cons
vmlinuz
"\0\0\0"
cons
nil
tmp
cons
cons
nil
ticket1
"Sun 19:00"

Model 1

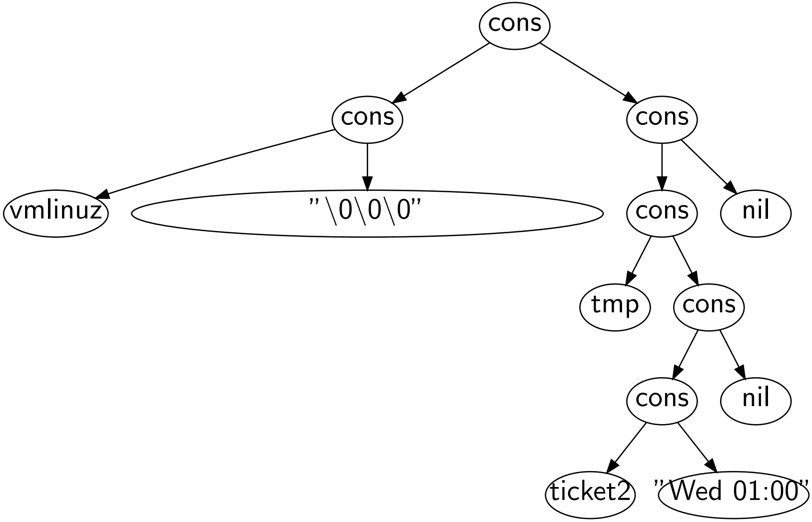


cons
cons
cons
vmlinuz
"\0\0\0"
cons
nil
tmp
cons
cons
cons
ticket1
"Sun 19:00"
cons
nil
ticket2
"Tue 21:00"

Model 1


cons
cons
cons
vmlinuz
"\0\0\0"
cons
nil
tmp
cons
cons
nil
ticket2
"Tue 21:00"

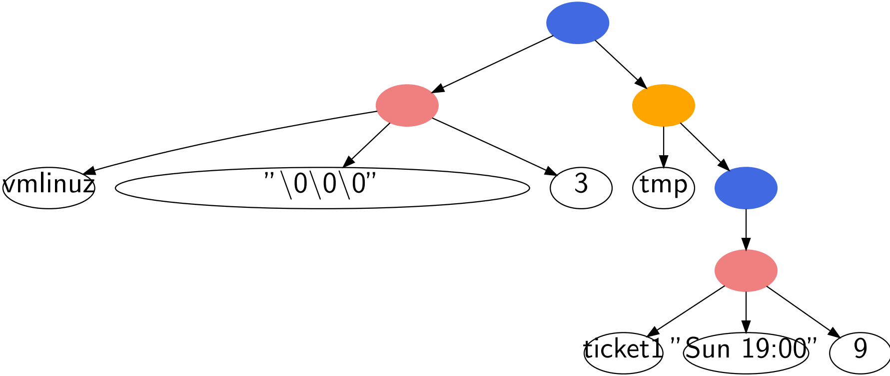
Model 1


cons
cons
cons
vmlinuz
"\0\0\0"
cons
nil
tmp
cons
cons
nil
ticket2
"Wed 01:00"

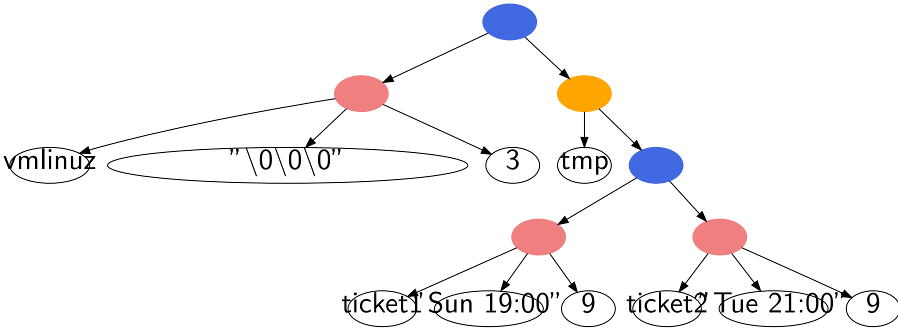
Model 2

- Model 1 can hold unbounded text files and nested directory structures.
- However, there's no metadata, either to provide additional information or to validate the contents of the file.
- With an extra field for length, we can create a simple version of fsck that checks file contents for consistency, and verify that create, delete etc preserve this notion of consistency.

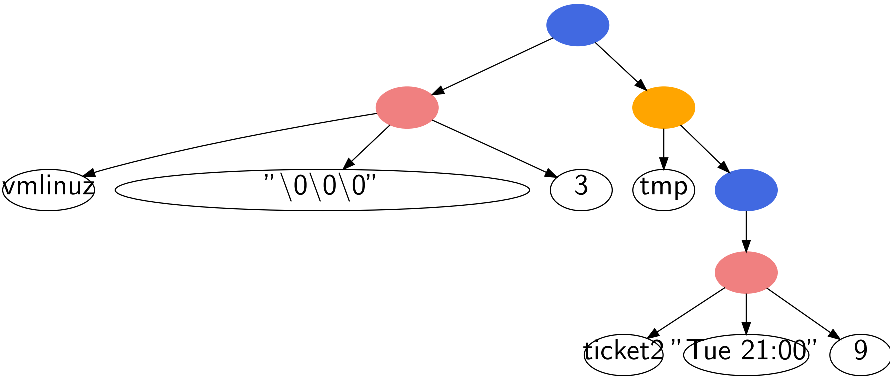
Model 2



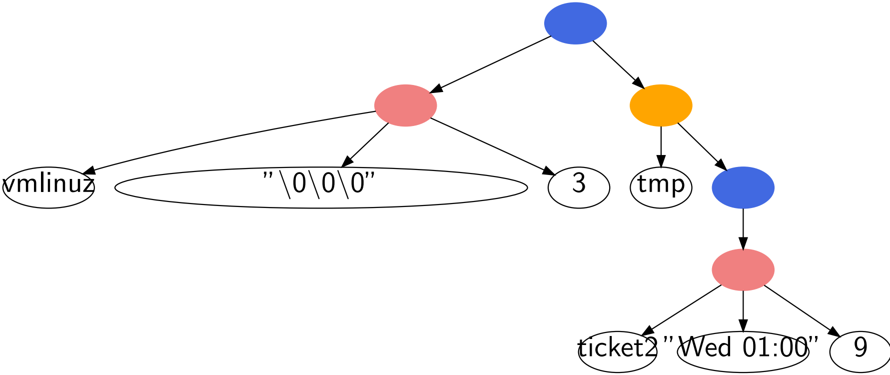
Model 2



Model 2



Model 2



Model 3

- As the next step, we would like to begin externalising the storage of file contents.
- It would also be good to break up file contents into "blocks" of a finite length.
  - Note: this would mean storing file length is no longer optional.

Model 3

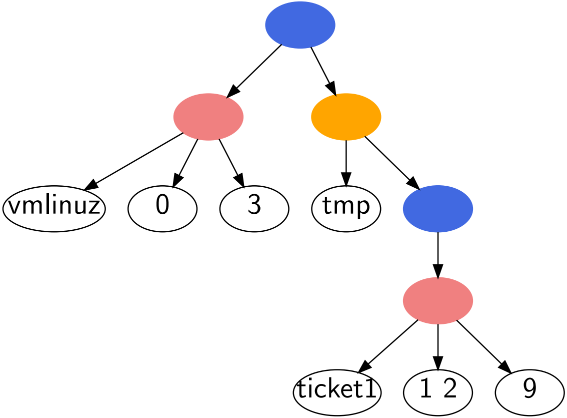


Table: Disk

\0\0\0
Sun 19:0
0

Model 3

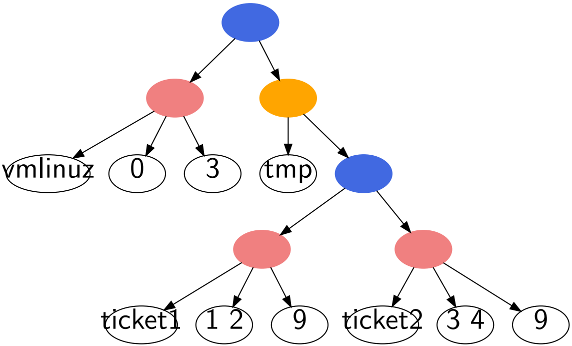


Table: Disk

\0\0\0
Sun 19:0
0
Tue 21:0
0

Model 3

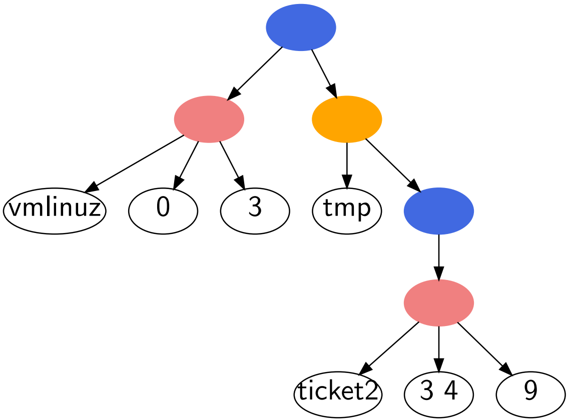


Table: Disk

\0\0\0
Sun 19:0
0

Model 3

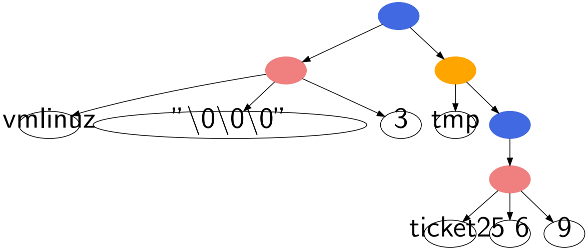


Table: Disk

\0\0\0
Sun 19:0
0
Tue 21:0
0
Wed 01:0
0

Proof approaches and techniques

- In the fourth model, we implement garbage collection in the form of an allocation vector.
- What guarantees do we need to show that a filesystem of this kind is consistent?

Model 4

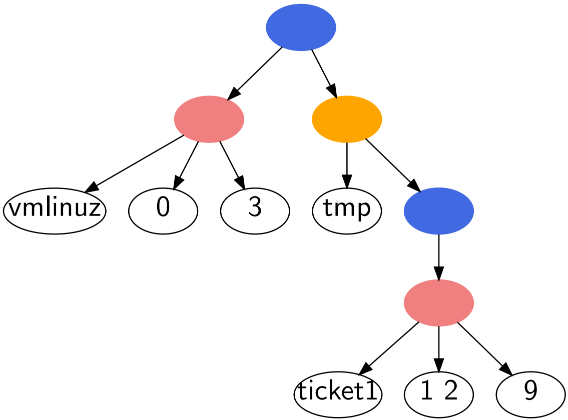


Table: Disk

\0\0\0
Sun 19:0
0

Model 4

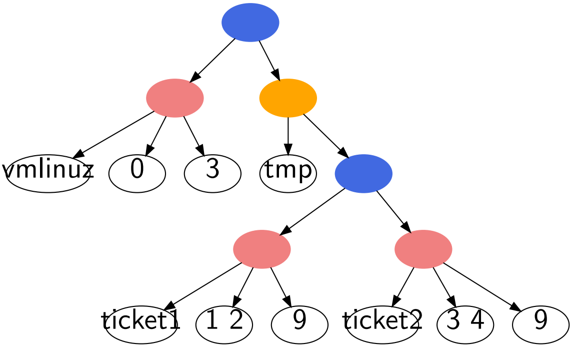


Table: Disk

\0\0\0
Sun 19:0
0
Tue 21:0
0

Model 4

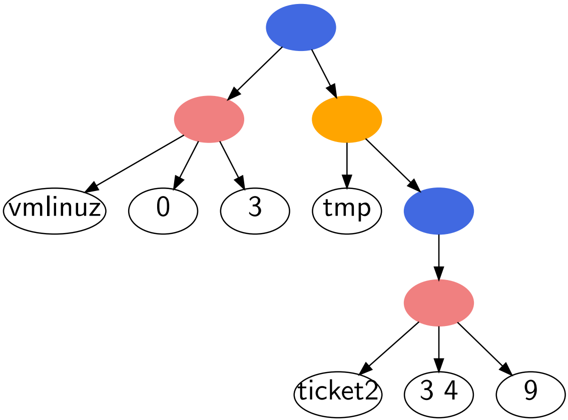


Table: Disk

\0\0\0
Sun 19:0
0

Model 4

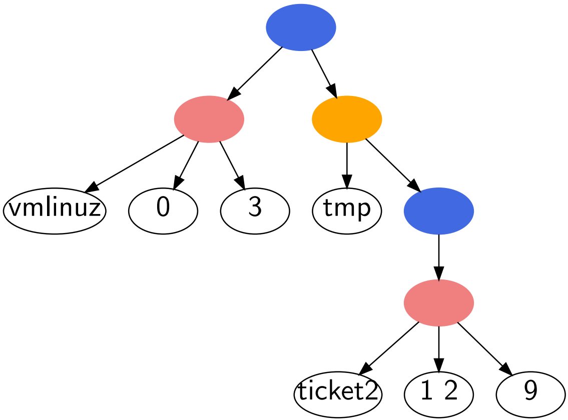


Table: Disk

\0\0\0
Wed 01:0
0

Proof approaches and techniques

- There are many properties that could be considered for correctness, but the read-over-write theorems from the first-order theory of arrays seem like a good place to start.
  1. Reading from a location after writing to the same location should yield the data that was written.
  2. Reading from a location after writing to a different location should yield the same result as reading before writing.
- For each of the models 1, 2 and 3, we have proofs of correctness of the two read-after-write properties, based on the proofs of equivalence between each model and its successor.

Proof approaches and techniques

1. For model 4, The disk and the allocation vector must be in harmony initially and updated in lockstep.
2. Every block referred to in the filesystem must be marked "used" in the allocation vector.
   What about the complementary problem - making sure unused blocks are unmarked?
3. If n blocks are available in the allocation vector, the allocation algorithm must provide n blocks when requested.
4. No matter how many blocks are returned by the allocation algorithm, they must be unique and disjoint with the blocks allocated to other files.

Future work

- Finish finitising the length of the disk and garbage collecting disk blocks that are left unused after a write or a delete operation.
- Possibly, add the system call open and close with the introduction of file descriptors.
  This would be a step towards the study of concurrent FS operations.
- Linearise the tree, leaving only the disk.
- Eventually emulate the CP/M filesystem as a convincing proof of concept, and move on to fsck and file recovery tools.

Related work

- In Haogang Chen's 2016 dissertation, the author uses Coq to build a filesystem (named FSCQ) which is proven safe against crashes.
- His implementation was exported into Haskell, and showed comparable performance to ext4 when run on FUSE.
- Our work is different - we're building verified models of actual filesystems with binary compatibility as the aim.