Specifying and Checking File System Crash-Consistency Models

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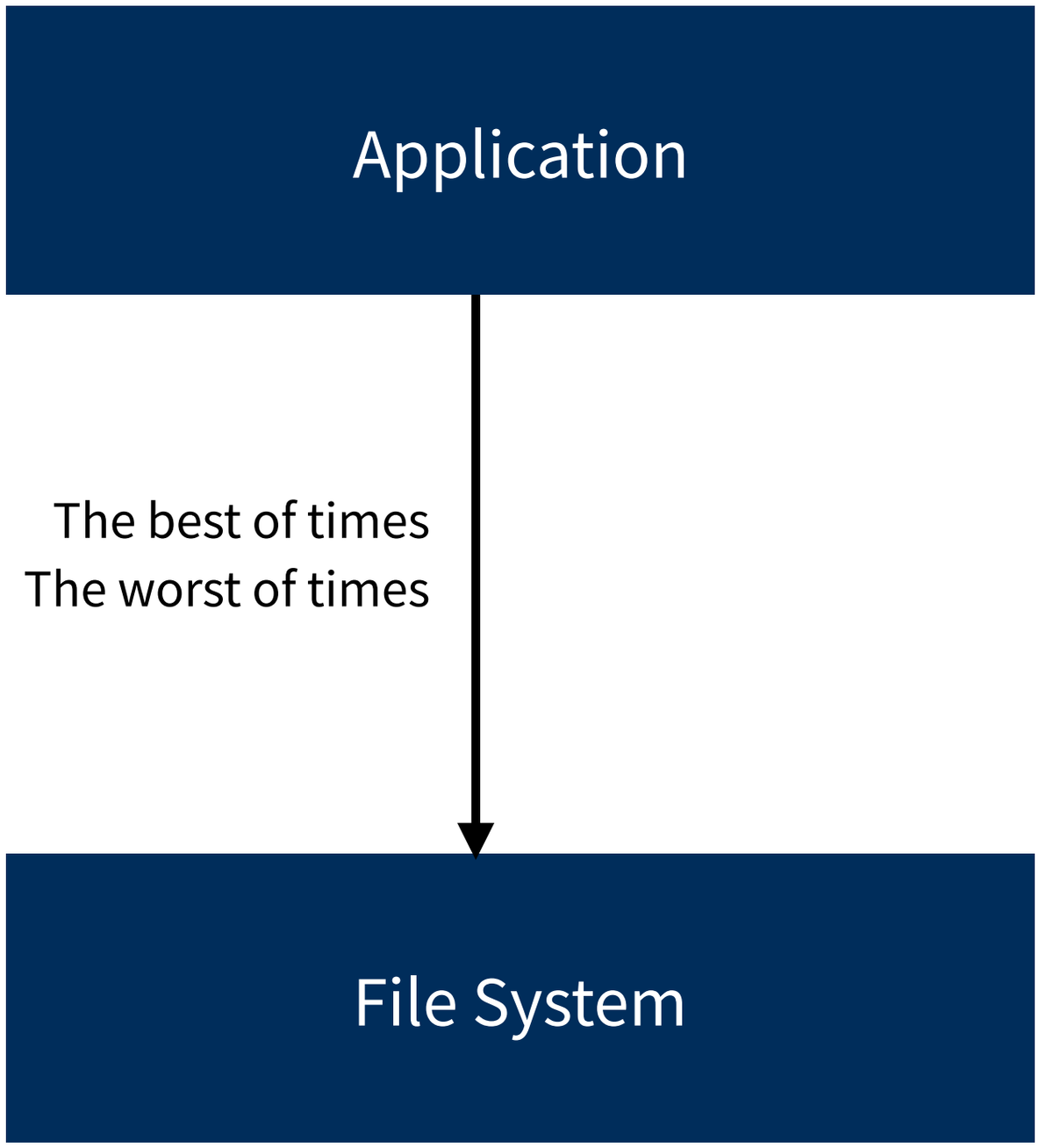
University of Washington

File systems persist our data

Application

File System

File systems persist our data



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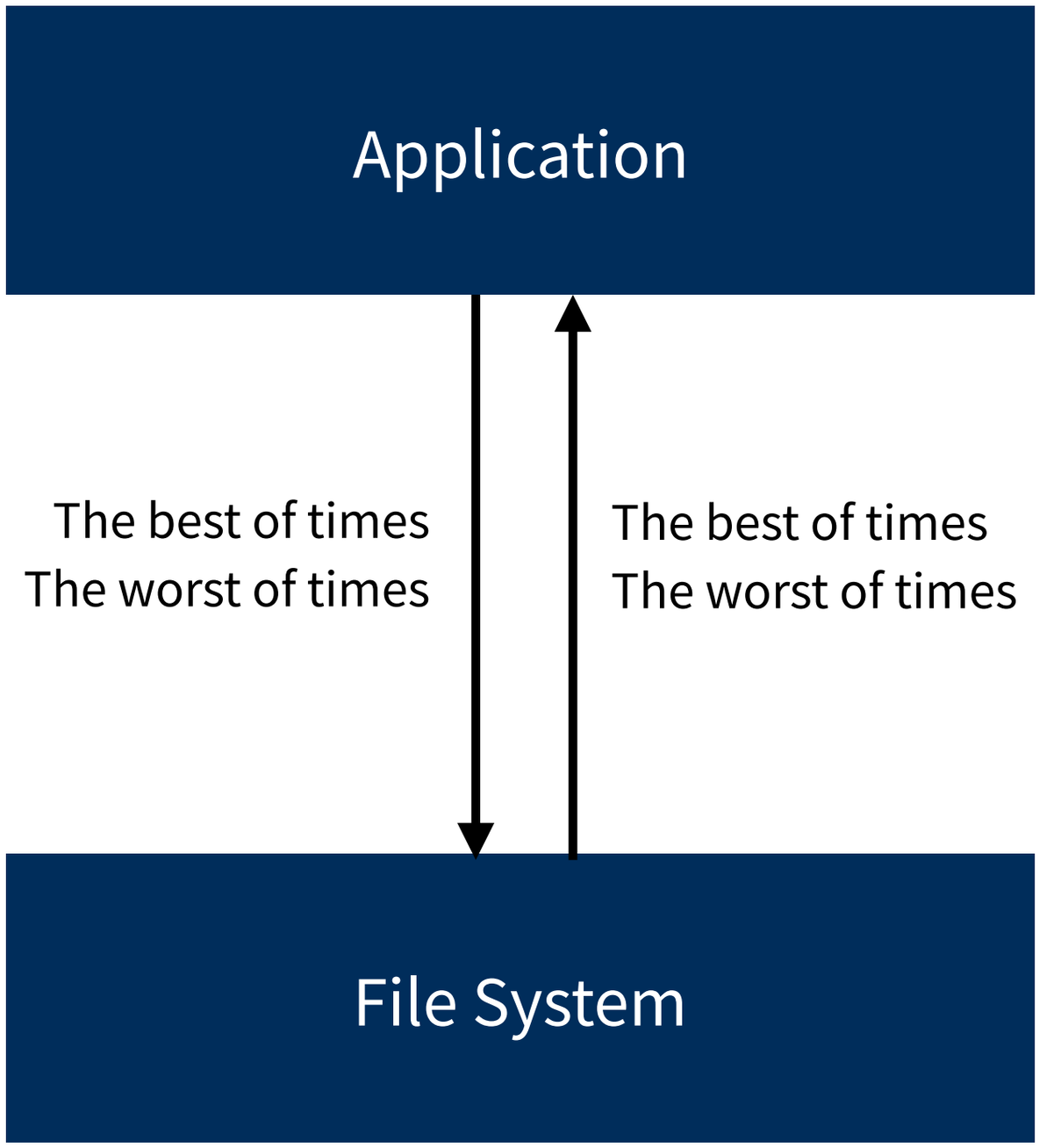

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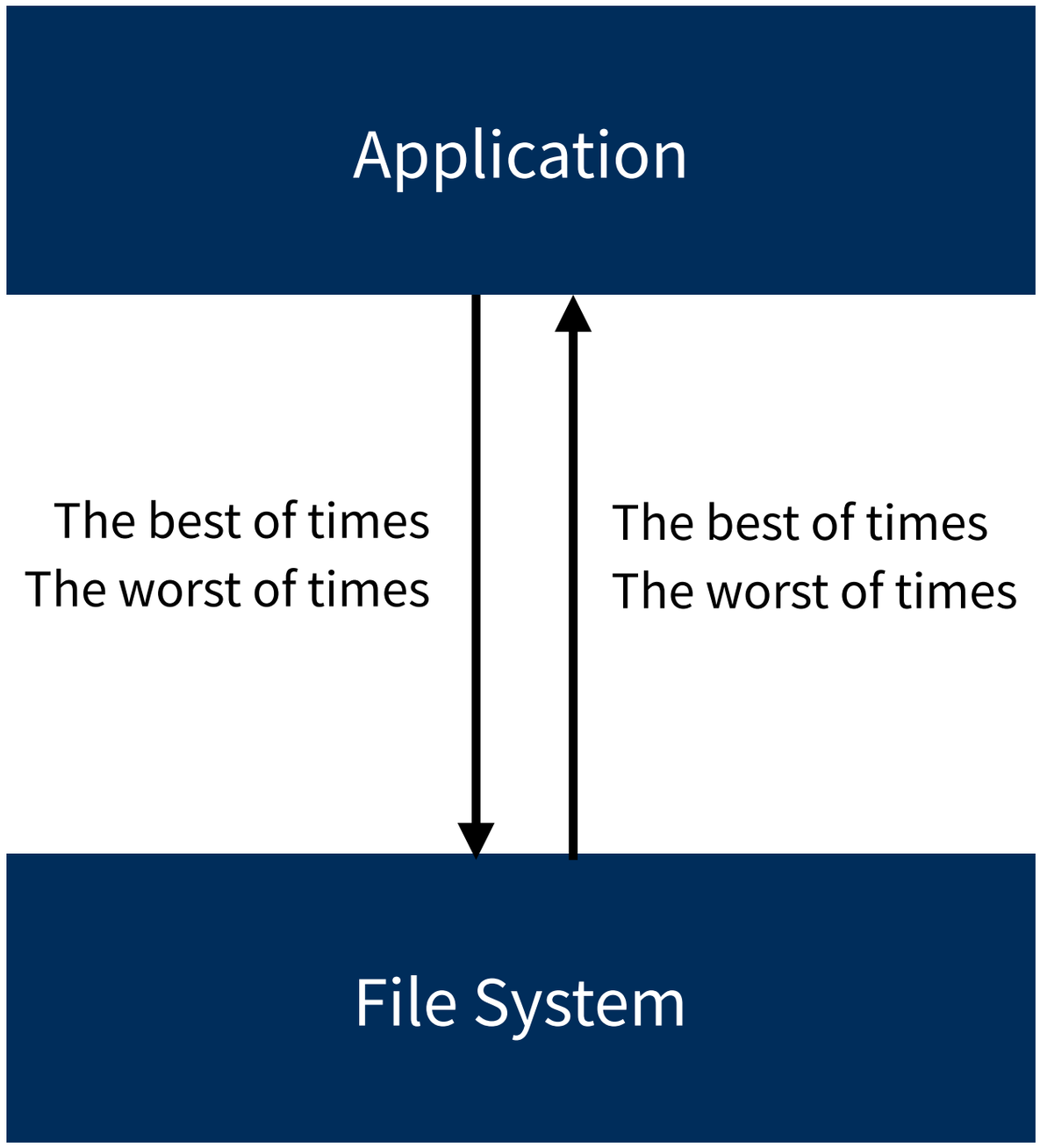

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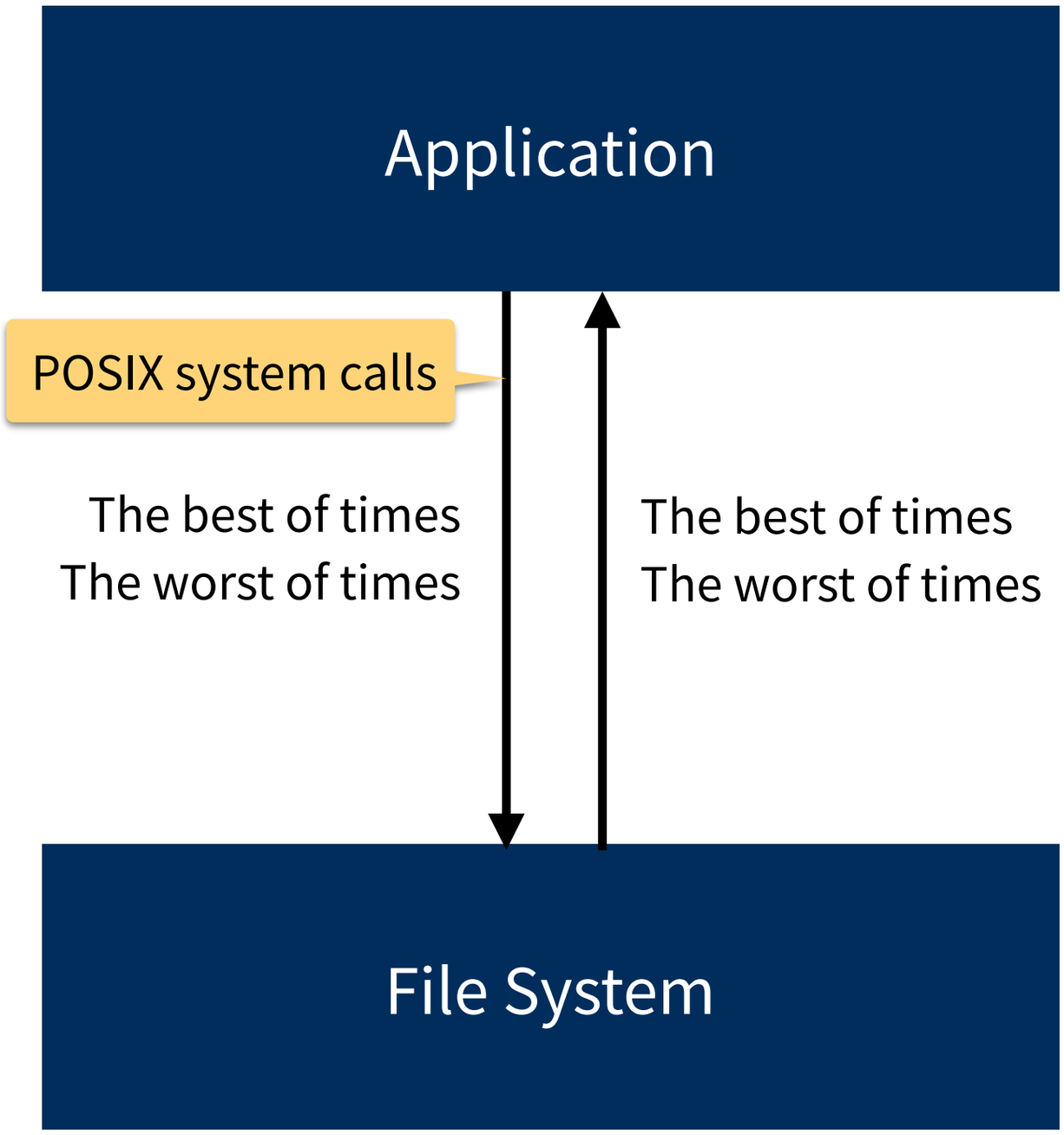

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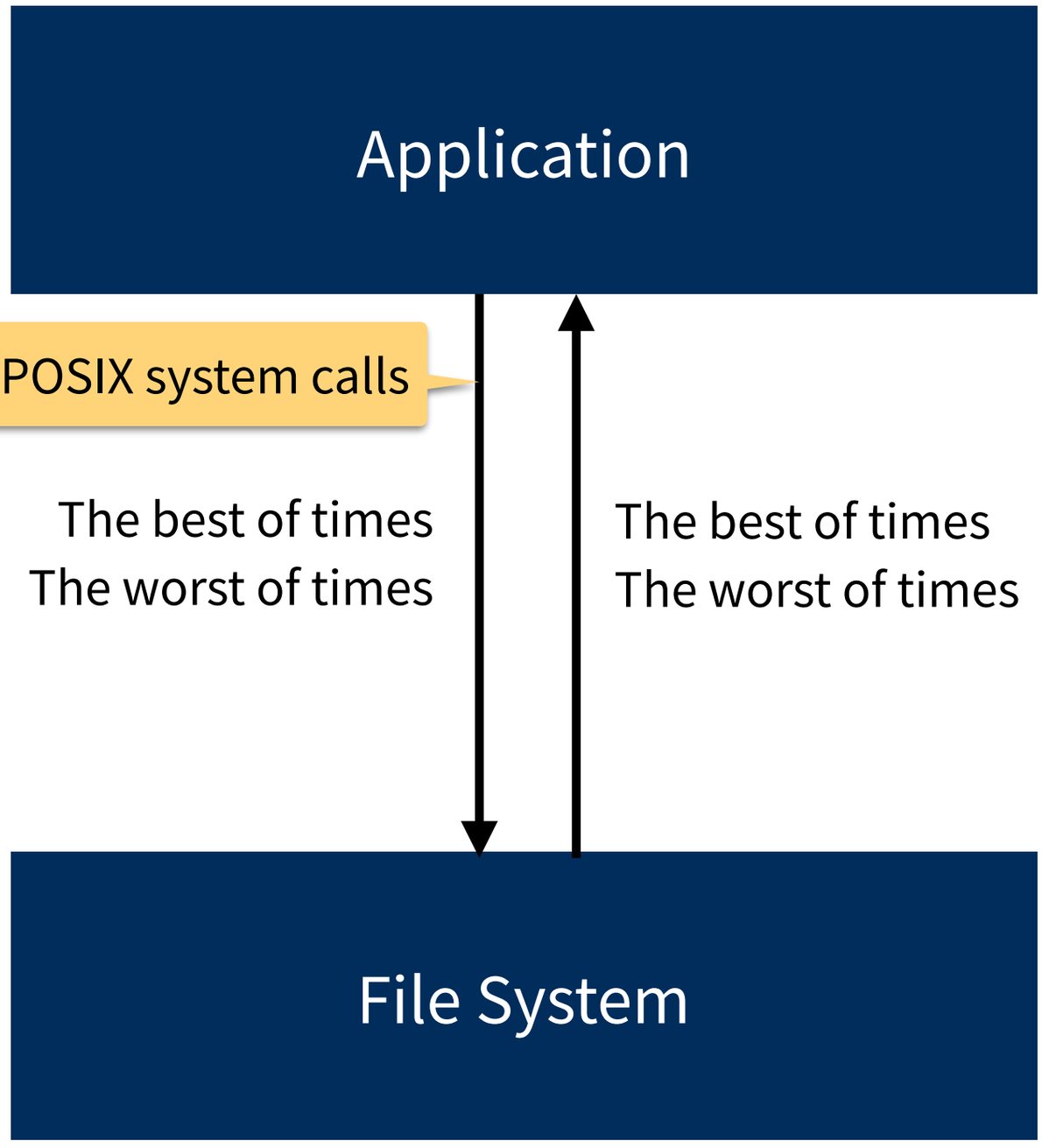


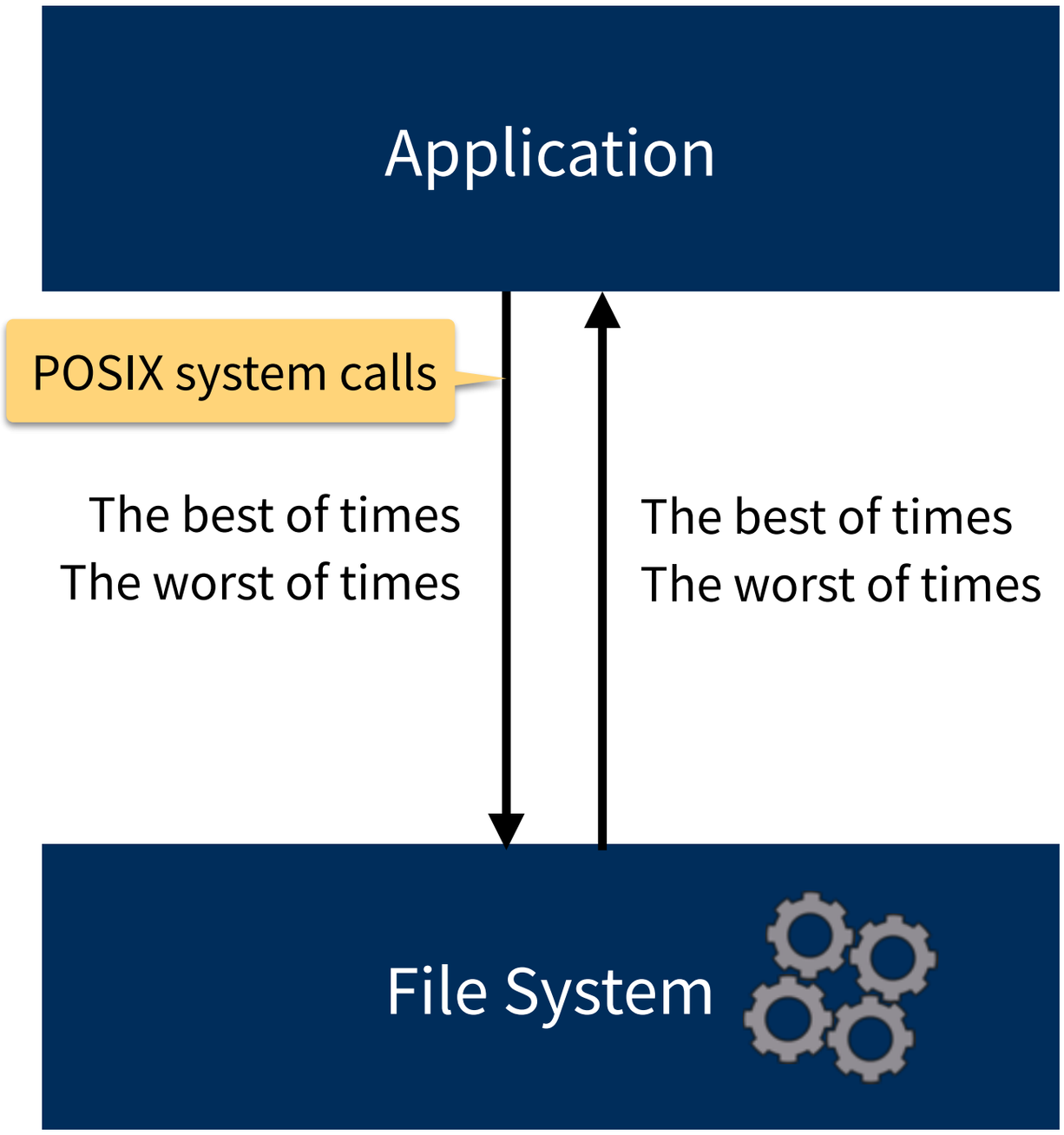
This provides **roughly the same level of guarantees** as ext3.

Linux kernel ext4 documentation

If the file system is inconsistent after a crash it is **usually** automatically checked and repaired when the system is rebooted

Proposed POSIX *fsync* documentation

But what if the system crashes?



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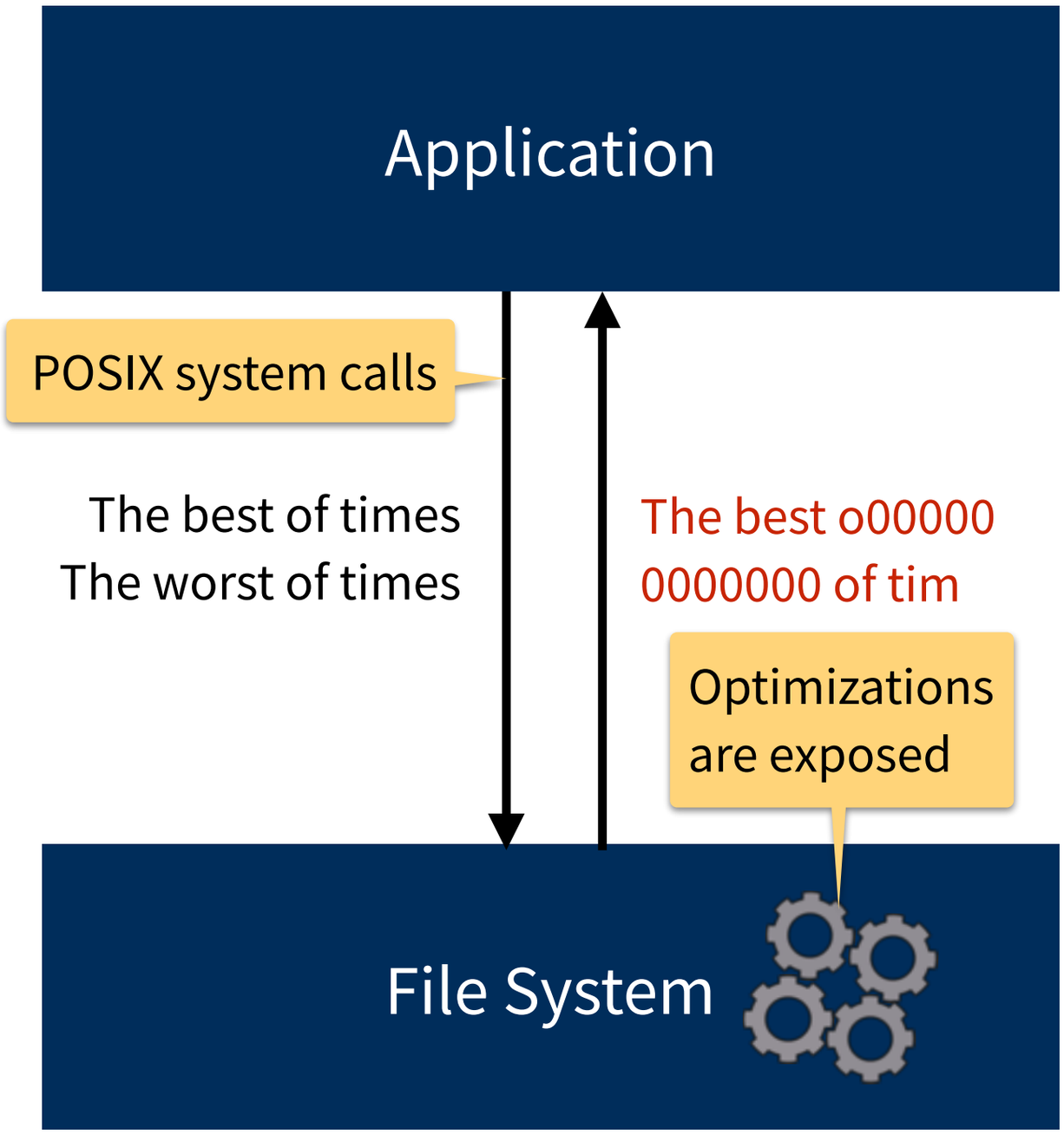

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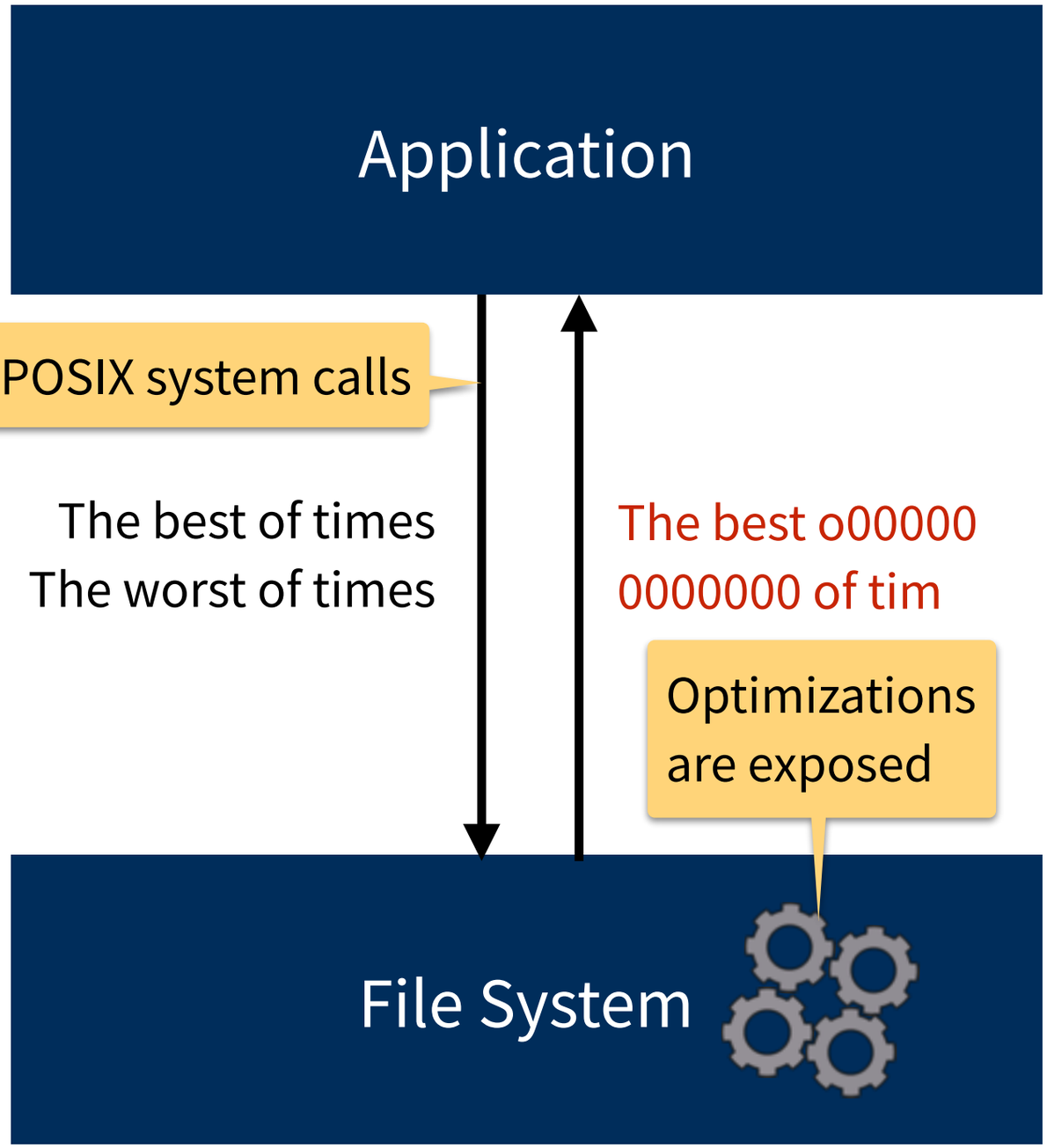


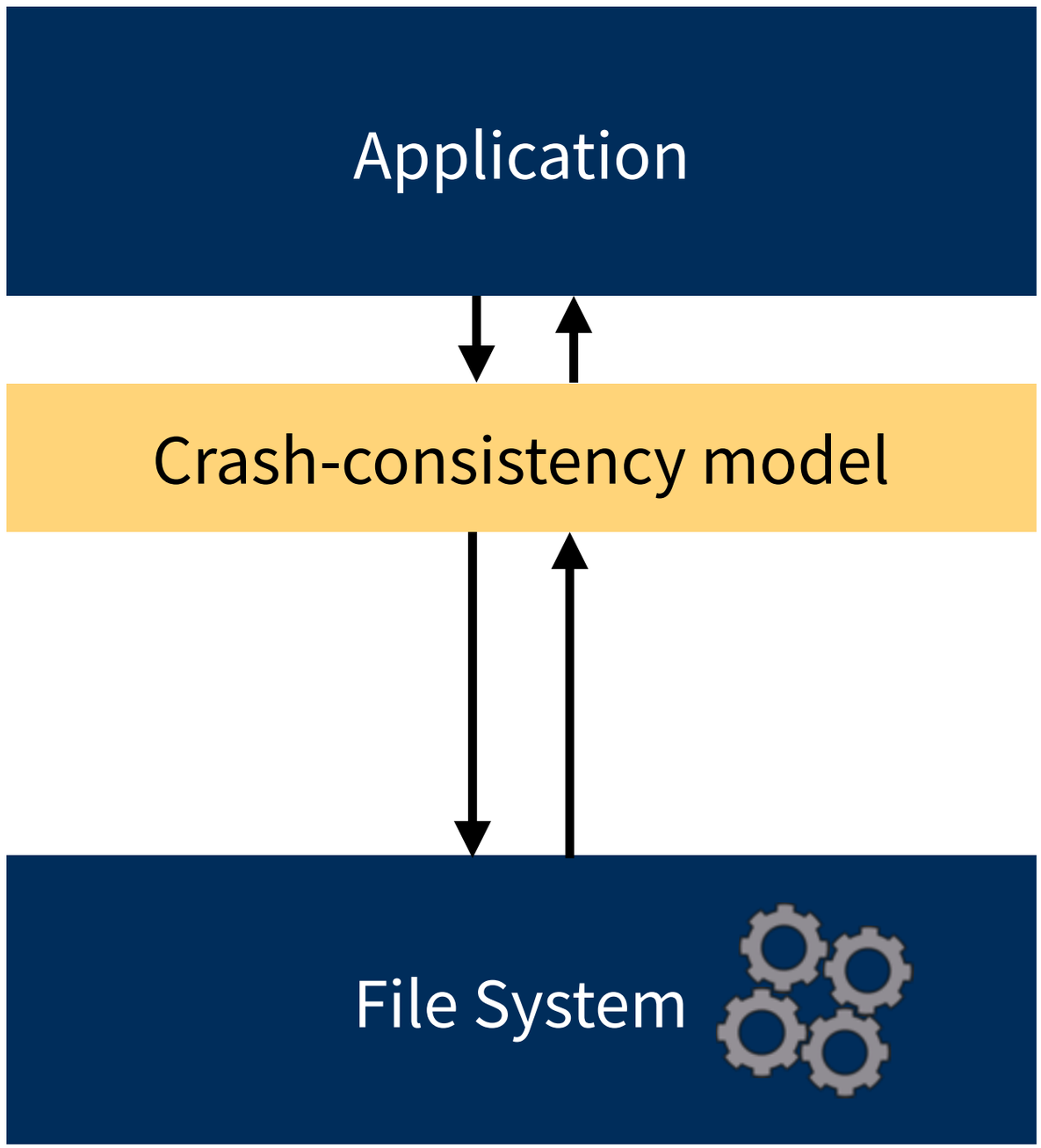
When gradually appending to a file, the content gets corrupted, causing **Chrome** to crash

ChromeOS “FS corruption on panic”, 2015

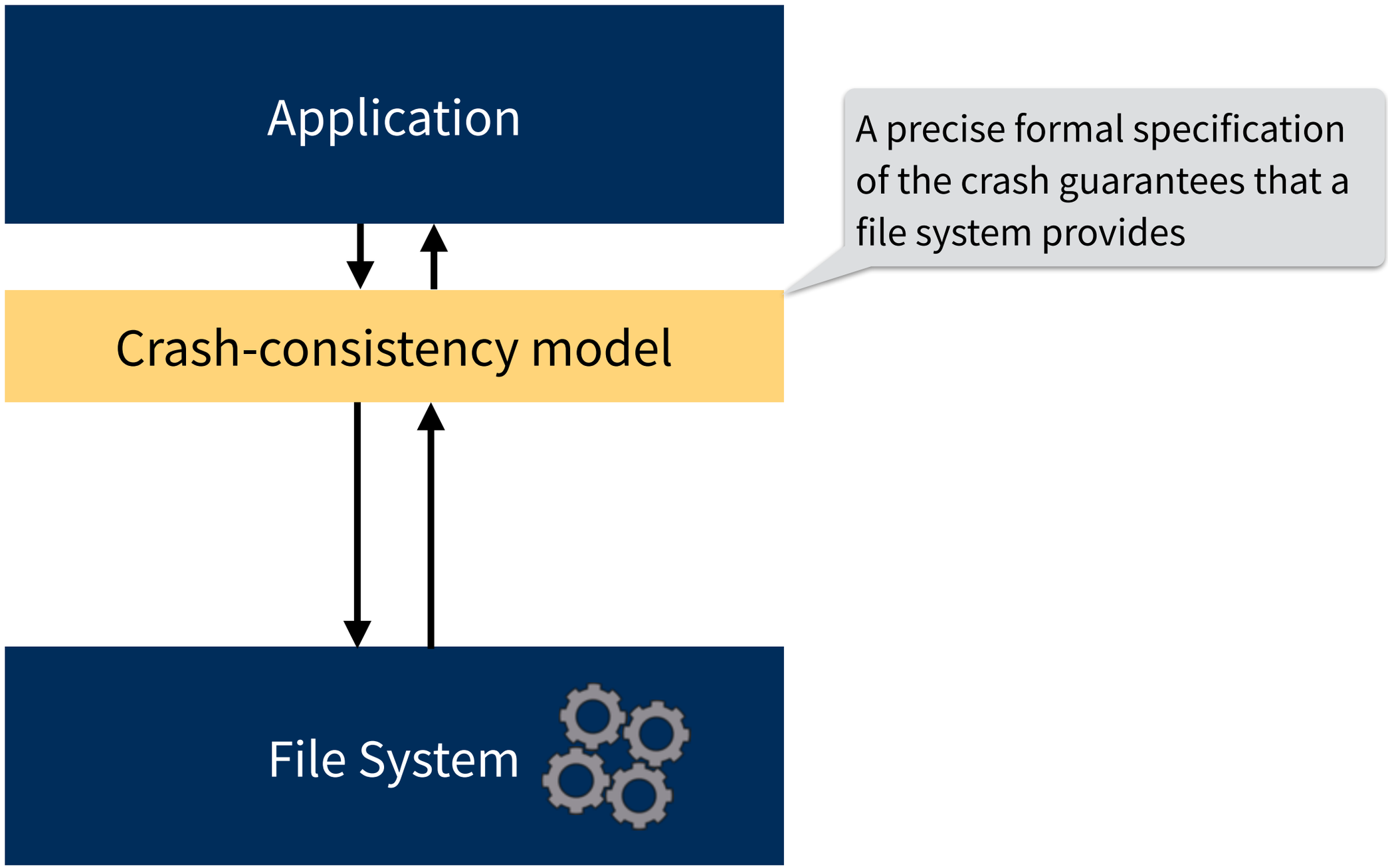
…some of the **KDE** core config files were reset. Also some of my **MySQL** databases were killed…

Ubuntu “ext4 data loss”, 2009

Crash-consistency models

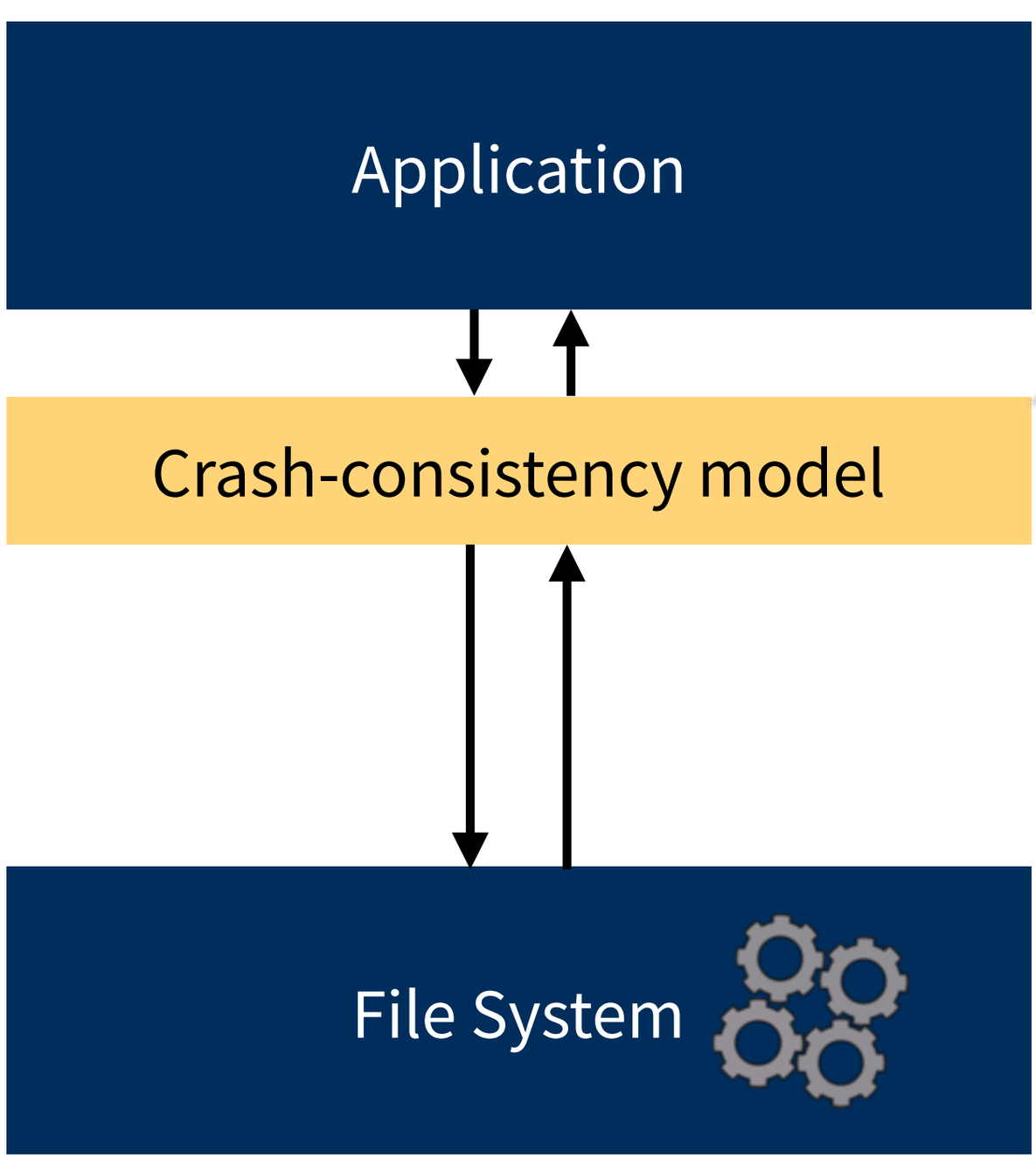


Crash-consistency models



A precise formal specification of the crash guarantees that a file system provides

Crash-consistency models



Just like a memory model!

A precise formal specification of the crash guarantees that a file system provides

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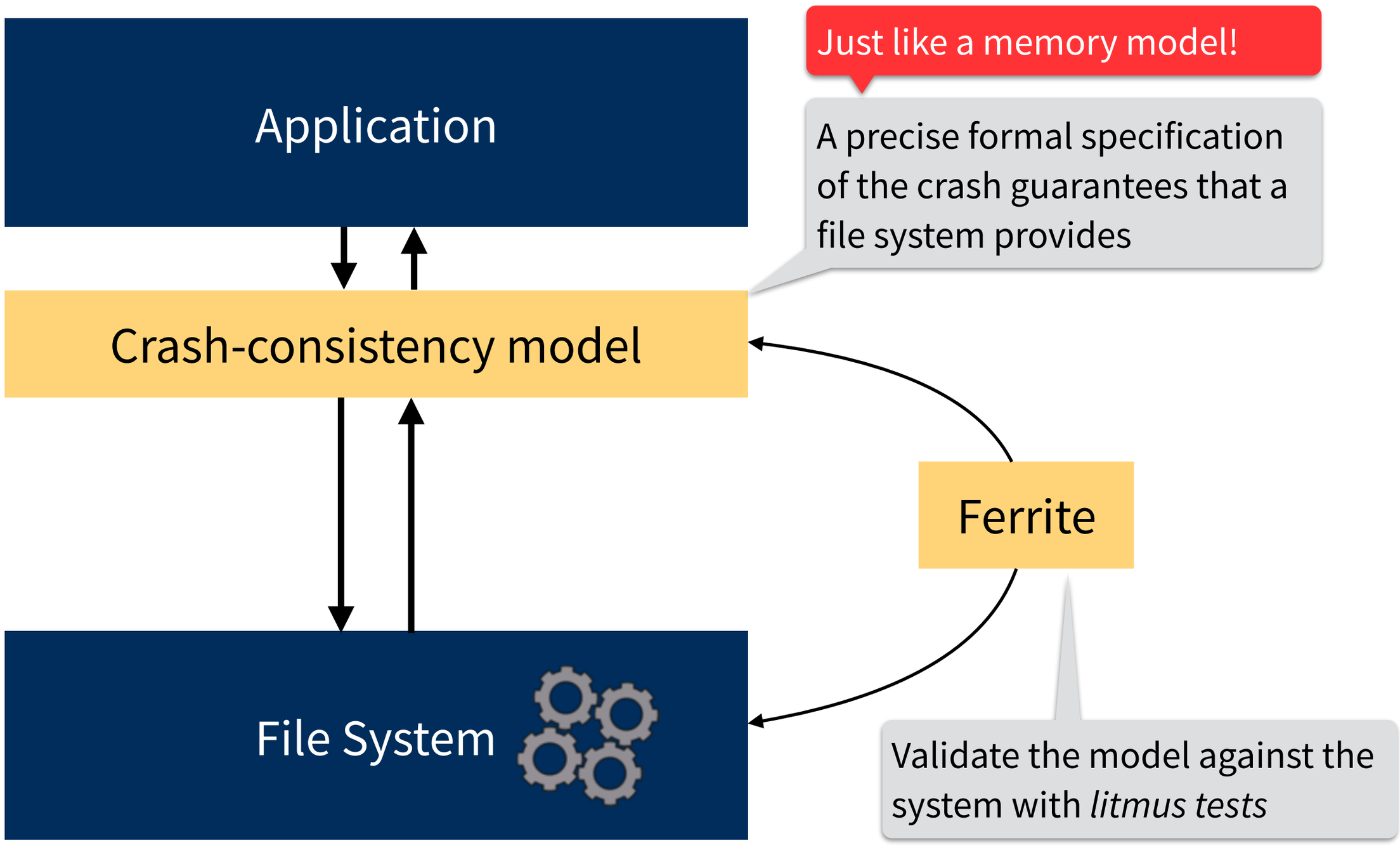

Crash behavior of modern file systems

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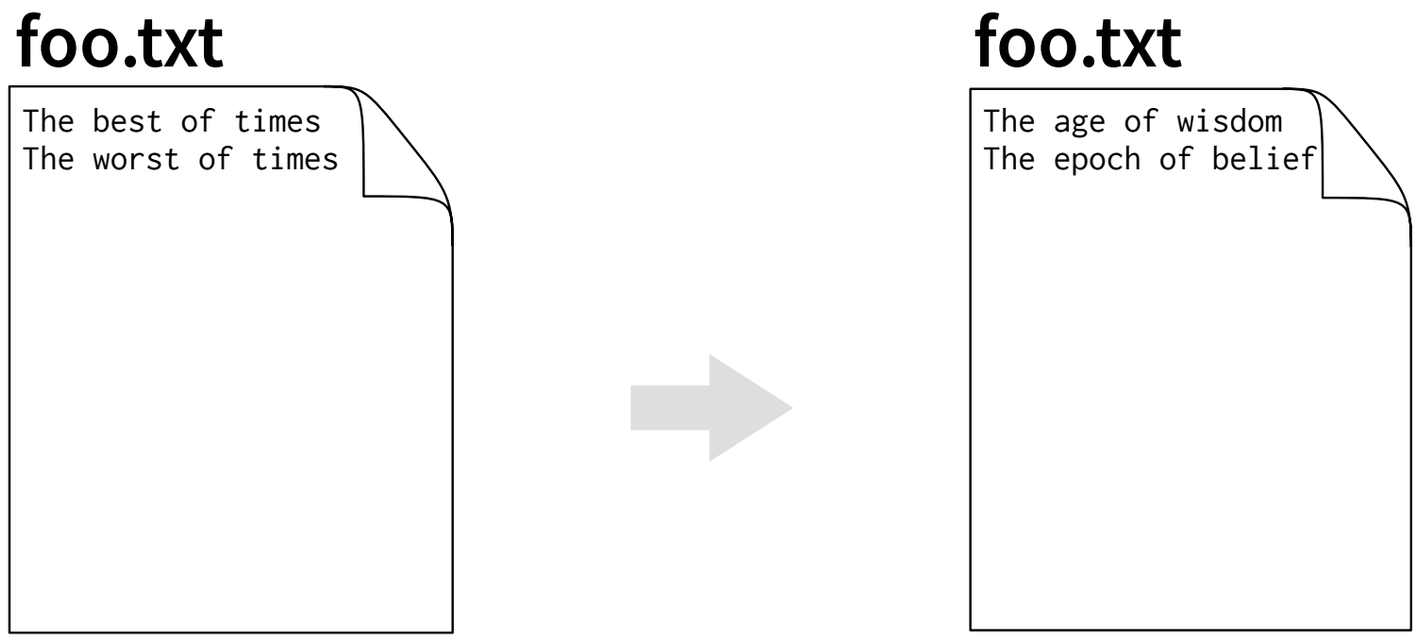
Replacing the contents of a file



Atomic replace via rename

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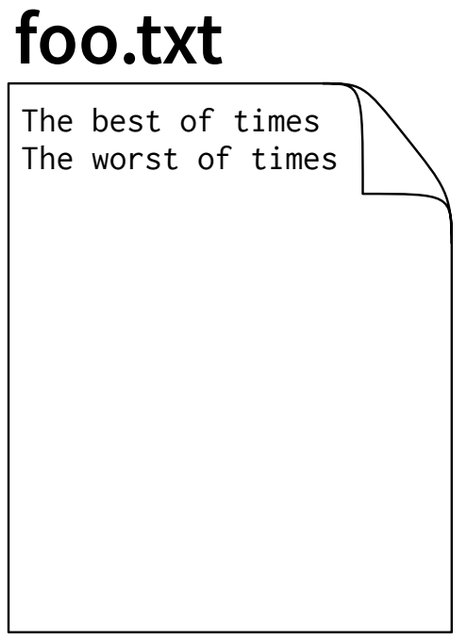

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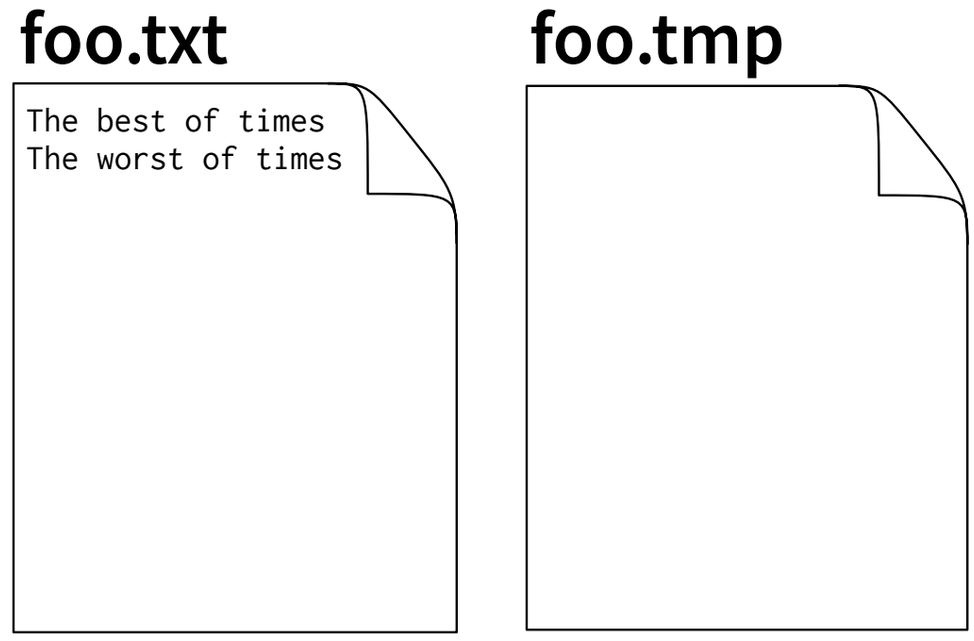

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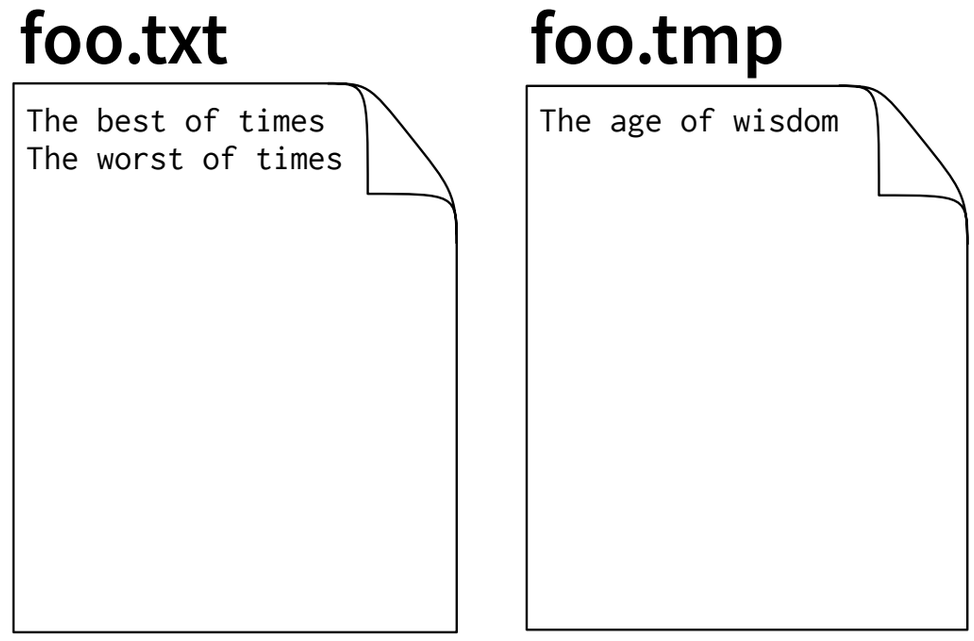

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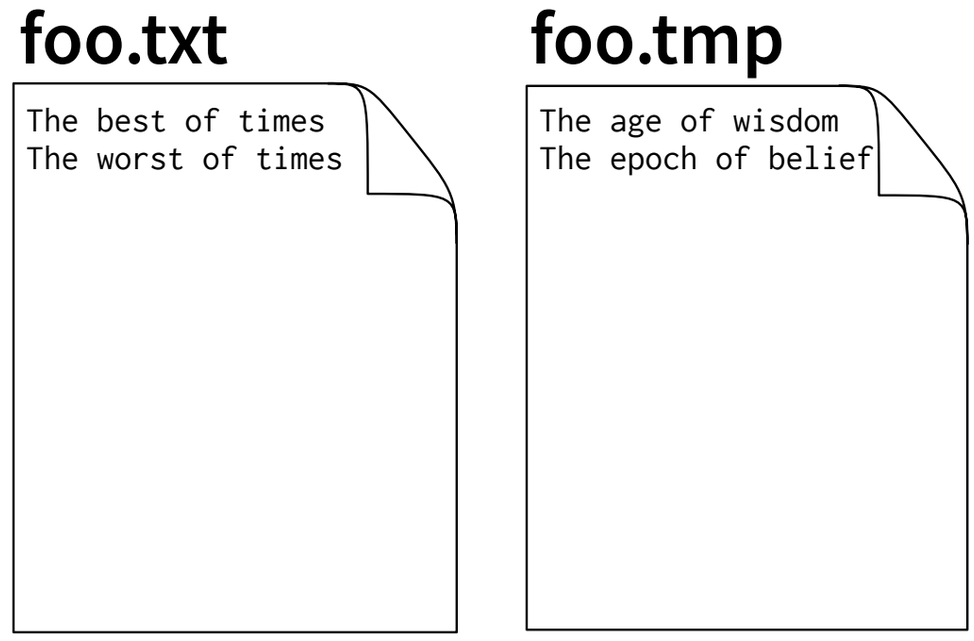

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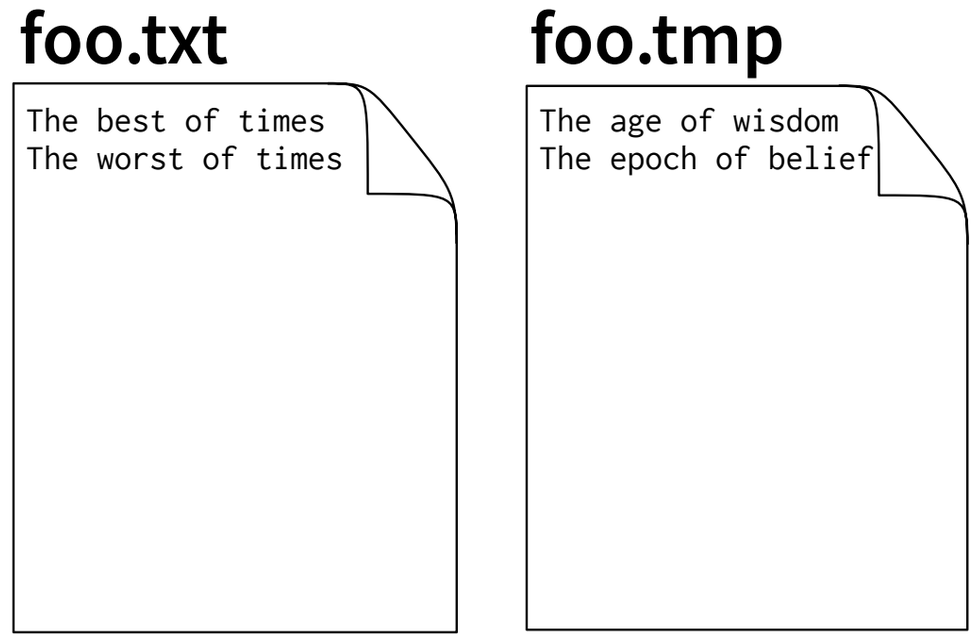

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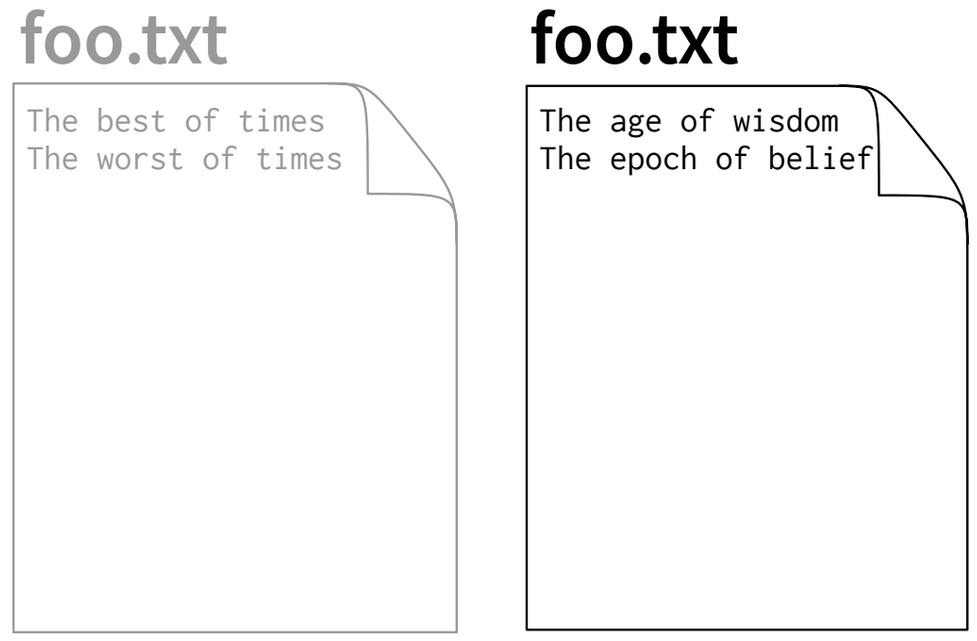

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Atomic replace via rename

File operations

create(“foo.tmp”)

rename(“foo.tmp”, “foo.txt”)

Writes

write(f, “The age of …”)

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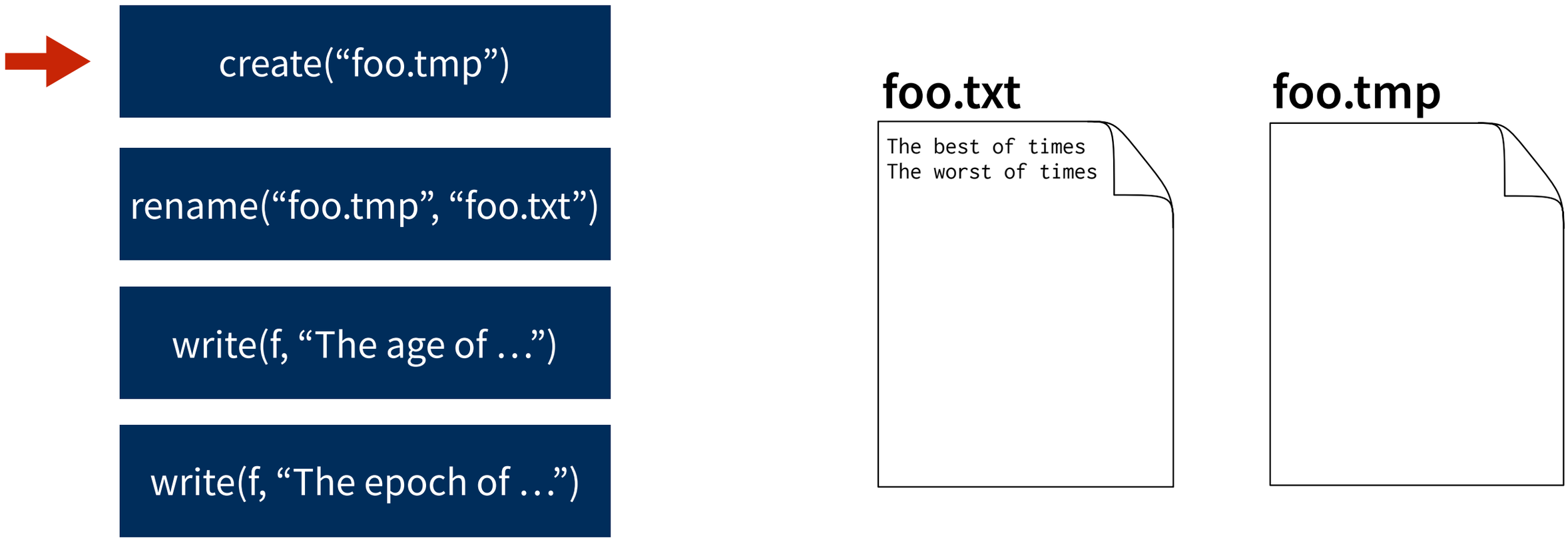

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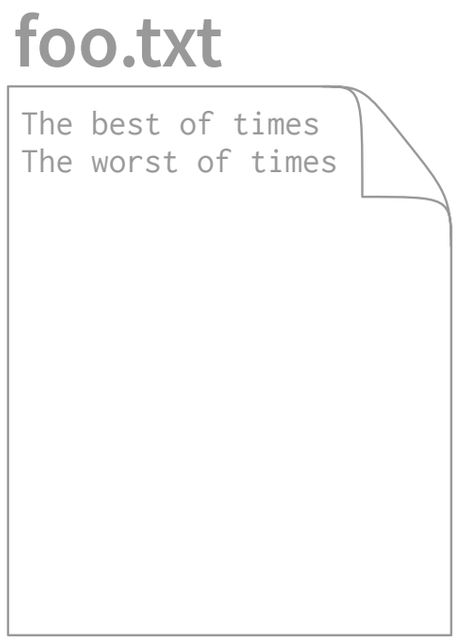

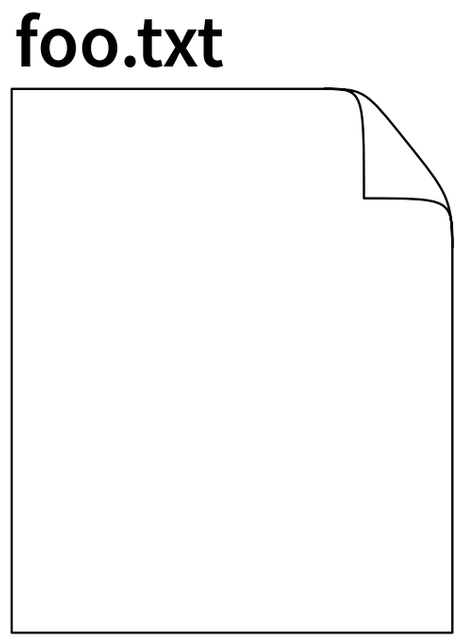

Atomic replace via rename

create(“foo.tmp”)

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Crash!

write(f, “The age of …”)

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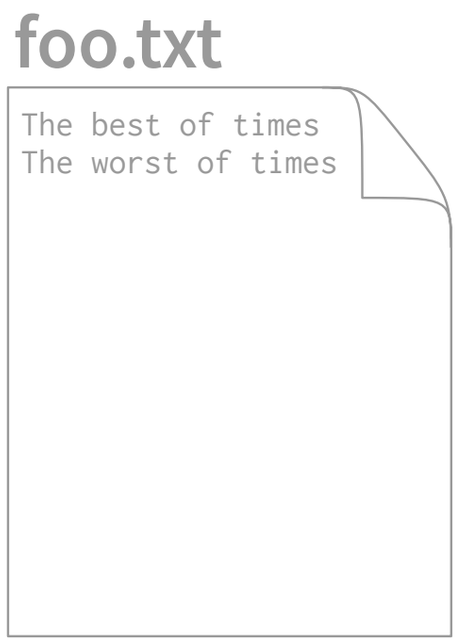

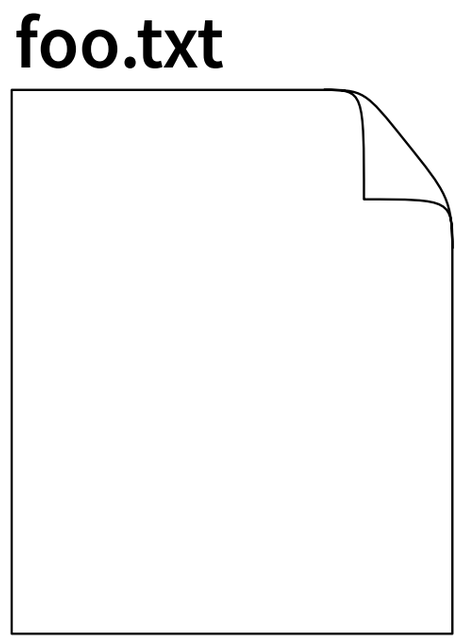

The storage stack

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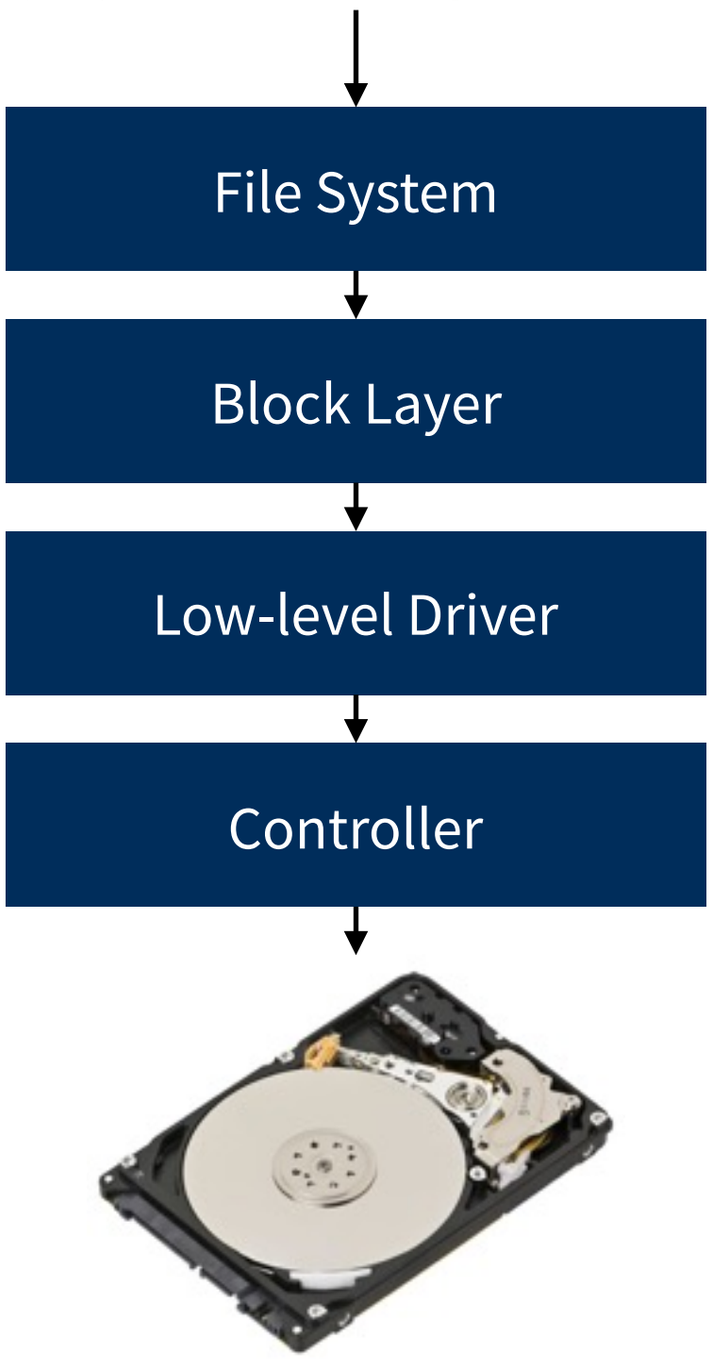

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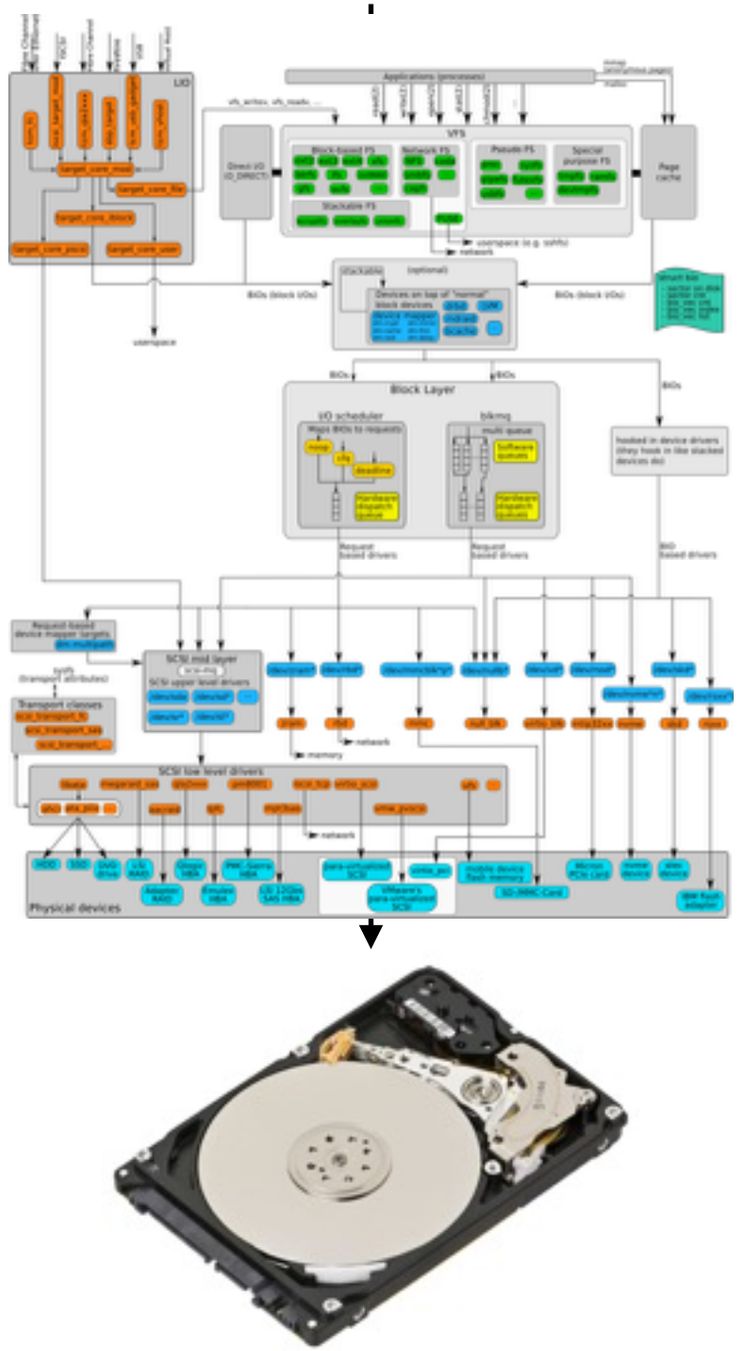

Diagram by Werner Fischer

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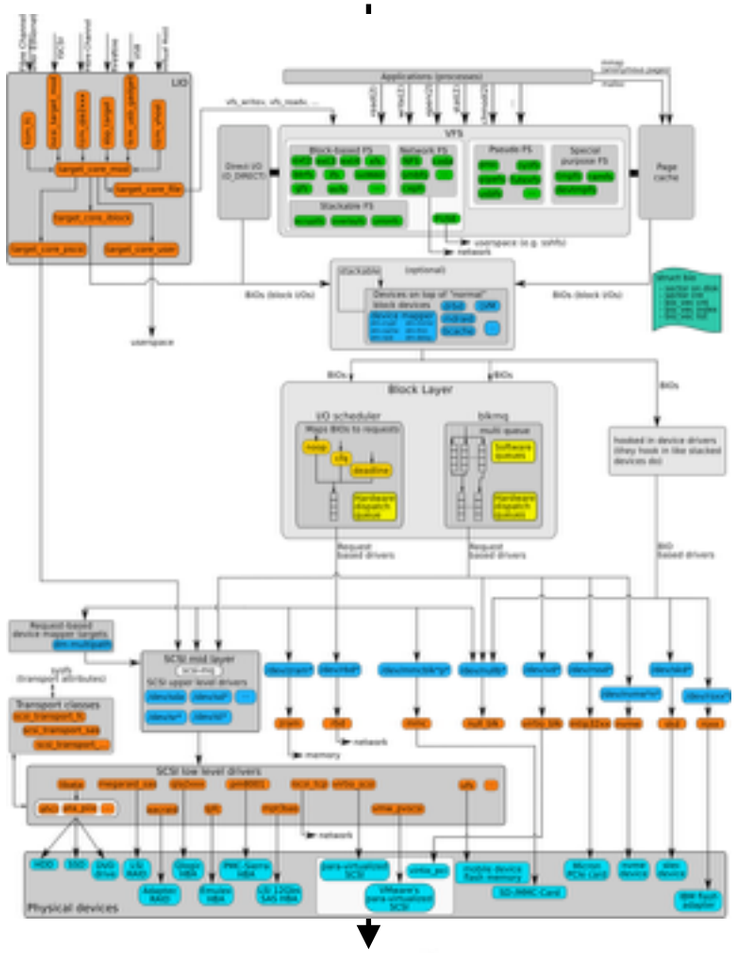

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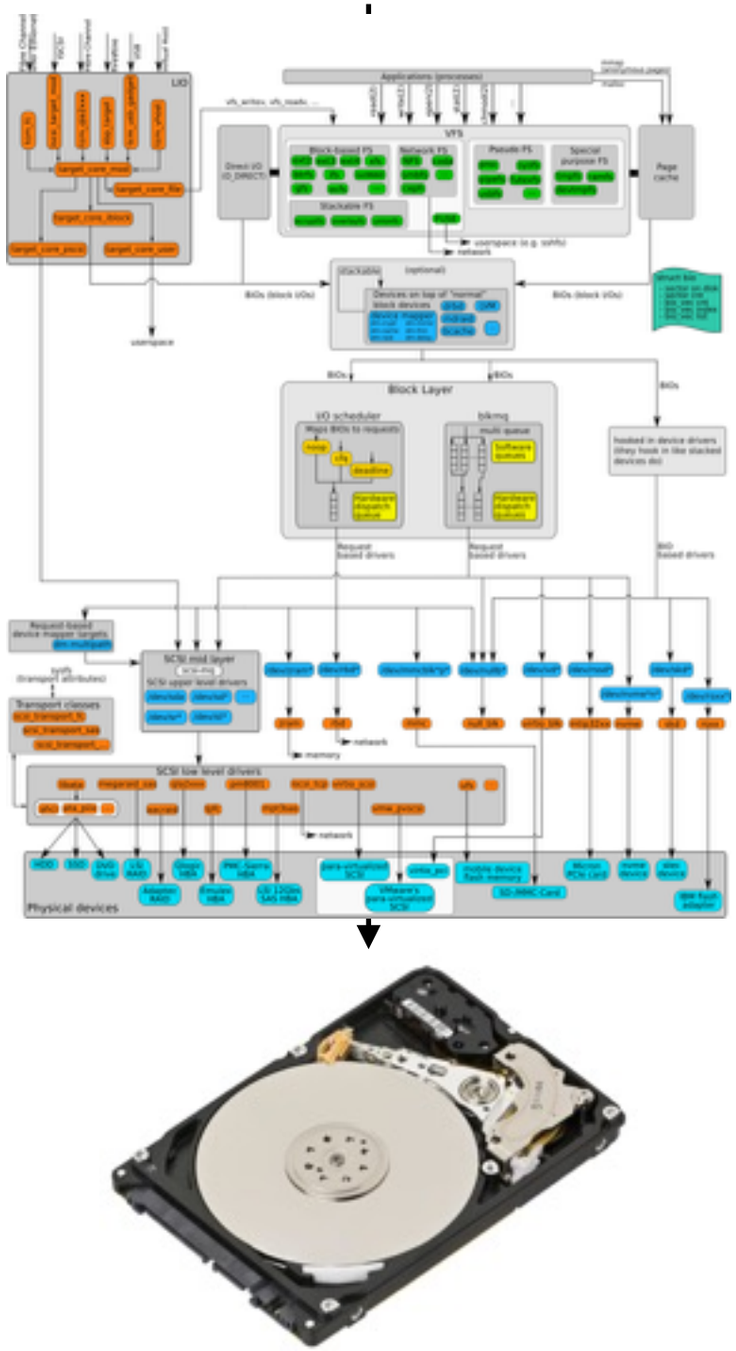

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Linux kernel ext4 documentation

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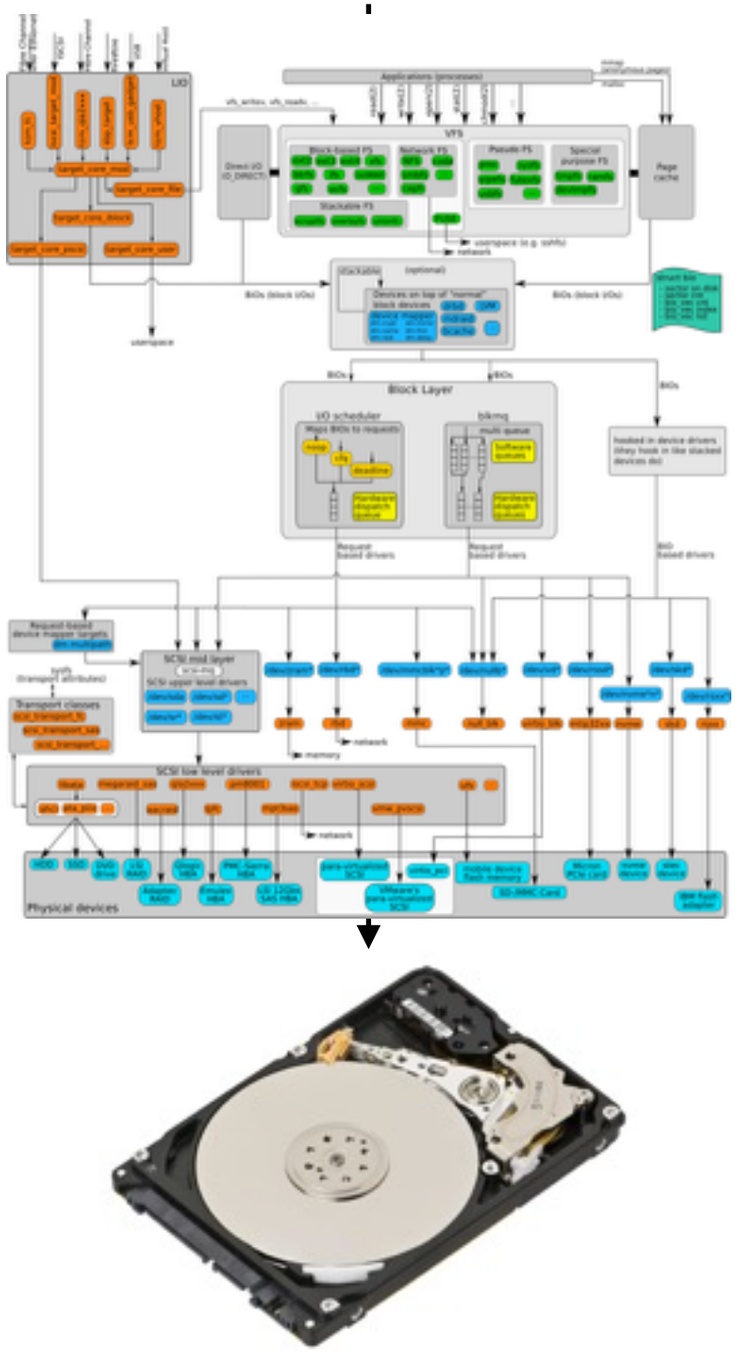

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Linux kernel ext4 documentation

The key aspects of `fsync()` are **unreasonable to test** in a test suite

POSIX specification for *fsync*

Existing work

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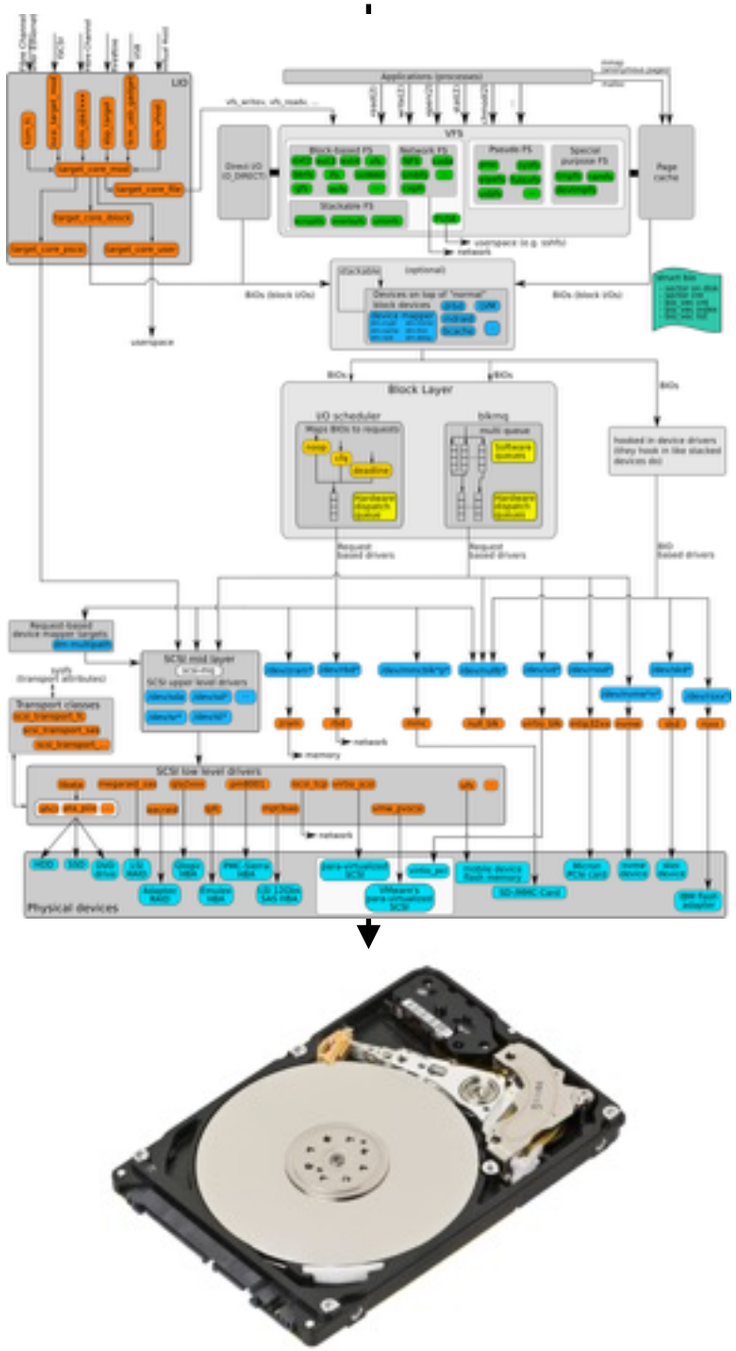

Formalize the existing POSIX interface (e.g. SibylFS [SOSP’15])

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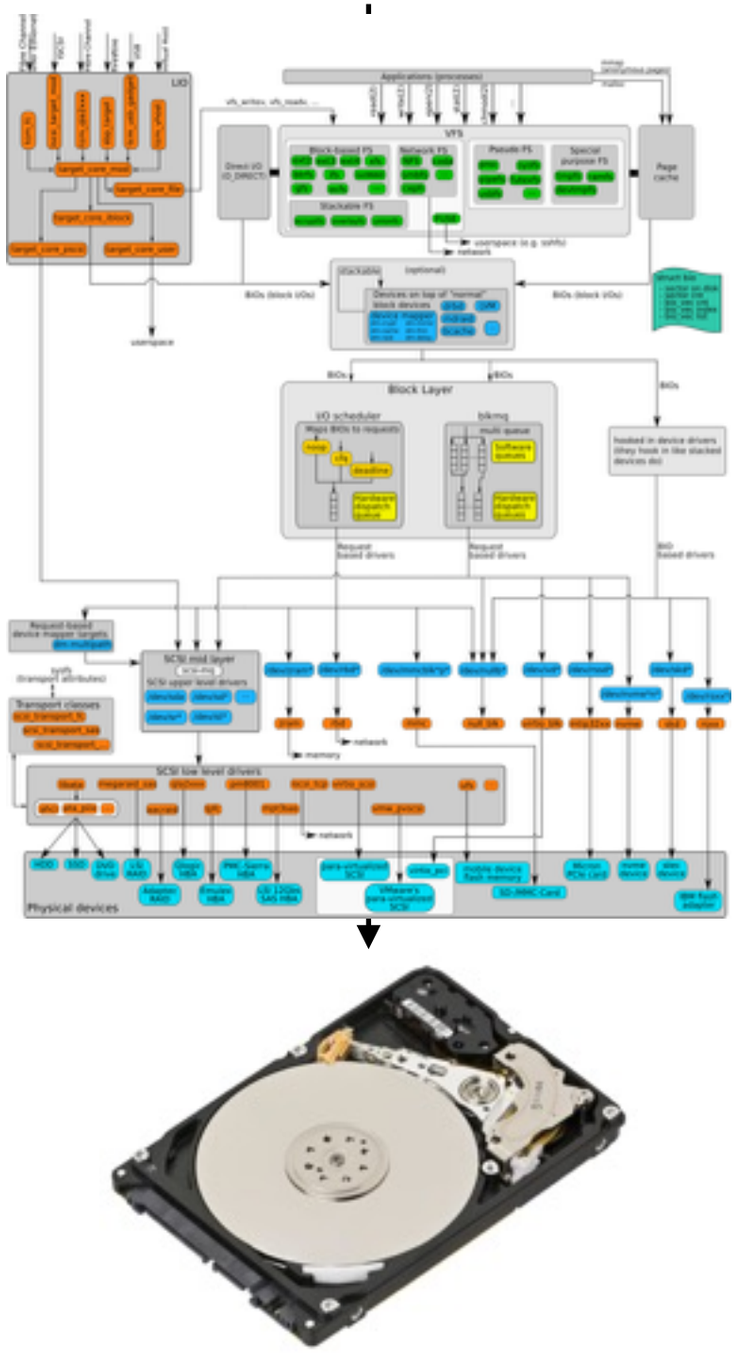

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Build a new crash-safe file system (e.g. FSCQ [SOSP’15])

- Comes with extremely high verification burden

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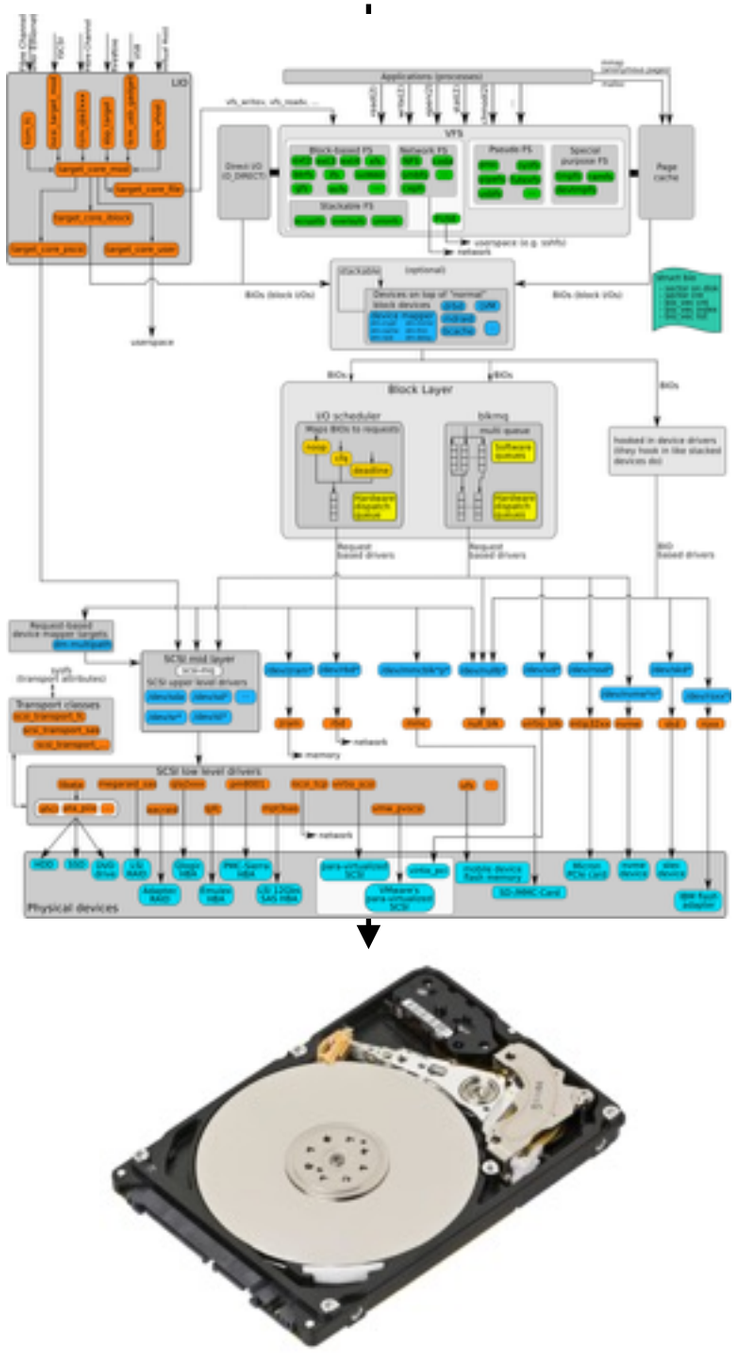

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Find bugs in existing file systems (e.g. eXplode [OSDI’06])

- Ours is a complementary problem: precisely specifying actual behavior

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Small programs that demonstrate allowed or forbidden behaviors of a file system across crashes

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Automated reasoning about crash safety

Litmus tests

Small programs that demonstrate allowed or forbidden behaviors of a file system across crashes

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  f = create(“file”)
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main:
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exists?:
  content(“file”) != old & content(“file”) != new
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(cannot crash)

Litmus tests

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Check whether some (possibly crashing) execution satisfies predicates

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Initial setup (cannot crash)

Main body (may crash at any point)

Check for behavior that may **surprise** application writers

Check whether some (possibly crashing) execution satisfies predicates

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Small programs that demonstrate allowed or forbidden behaviors of a file system across crashes

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Small programs that demonstrate allowed or forbidden behaviors of a file system across crashes

memory parallelism

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Small programs that demonstrate allowed or forbidden behaviors of a ~~file~~ system across ~~crashes~~

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Initially `A = B = 0`

Thread 1	**Thread 2**
`A = 1`	`B = 1`
`r1 = B`	`r2 = A`

Can `r1 = 0 & r2 = 0`?

Litmus tests

Small programs that demonstrate allowed or forbidden behaviors of a file system across crashes

	Litmus test		
	Prefix append	Atomic replace via rename	Atomic create via rename

Litmus tests

Small programs that demonstrate allowed or forbidden behaviors of a file system across crashes

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File system	Prefix append	Atomic replace via rename	Atomic create via rename
`ext4`	**Unsafe**	**Unsafe**	**Unsafe**

Litmus tests

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File system	Prefix append	Atomic replace via rename	Atomic create via rename
ext4	**Unsafe**	**Unsafe**	**Unsafe**
xfs	Safe	**Unsafe**	**Unsafe**
f2fs	**Unsafe**	**Unsafe**	**Unsafe**
nilfs2	Safe	**Unsafe**	**Unsafe**
btrfs	Safe	Safe	**Unsafe**
ufs2	**Unsafe**	**Unsafe**	**Unsafe**

Litmus tests

Small programs that demonstrate allowed or forbidden behaviors of a file system across crashes

File system	Prefix append
`ext4`	**Unsafe**
`xfs`	Safe
`f2fs`	**Unsafe**
`nilfs2`	Safe
`btrfs`	Safe
`ufs2`	**Unsafe**

> We suspect that most modern filesystems exhibit the safe append property.
>
> SQLite Atomic Commit documentation

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Ordering constraints on events in traces

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create(“foo.tmp”)

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A *trace* is a sequence of file system events generated by an execution of P

Formal specifications

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      rename(“file.tmp”, “file”)
```

create(“foo.tmp”)

write(f, “The epoch of …”)

rename(“foo.tmp”, “foo.txt”)

A *trace* is a sequence of file system events generated by an execution of P

A **crash-consistency model** is a *filter* on traces: it specifies which traces (and prefixes of traces) are allowed.

Formal specifications

```
P  =   f = create(“file.tmp”)
       write(f, new)
       close(f)
       rename(“file.tmp”, “file”)
```

create(“foo.tmp”)

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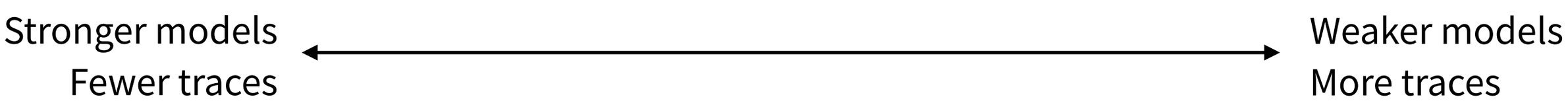

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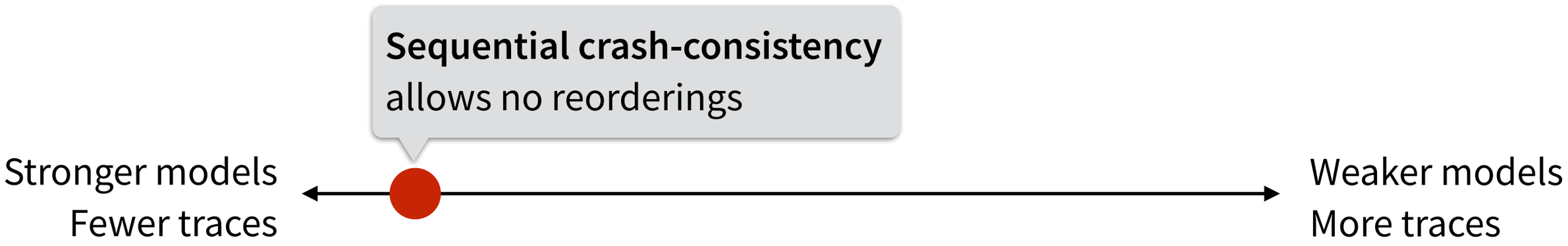

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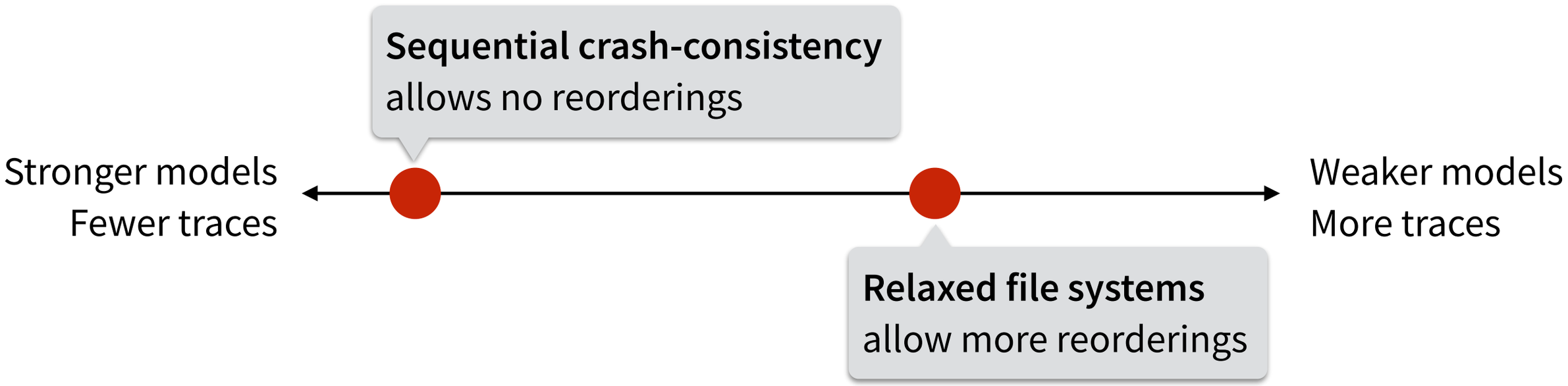

ext4 crash-consistency

```
P =  f = create(“file.tmp”)
     write(f, new)
     close(f)
     rename(“file.tmp”, “file”)
```

create(“foo.tmp”)

write(f, “The epoch of …”)

rename(“foo.tmp”, “foo.txt”)

Definition 7 (ext4 Crash-Consistency). Let t_P be a valid trace and τ_P the corresponding canonical trace. We say that t_P is ext4 *crash-consistent* iff $e_i \leq_{t_P} e_j$ for all events e_i, e_j such that $e_i \leq_{\tau_P} e_j$ and at least one of the following conditions holds:

1. e_i and e_j are metadata updates to the same file: $e_i = \mathit{setattr}(f, k_i, v_i)$ and $e_j = \mathit{setattr}(f, k_j, v_j)$.
2. e_i and e_j are writes to the same block in the same file: $e_i = \mathit{write}(f, a_i, d_i)$, $e_j = \mathit{write}(f, a_j, d_j)$, and $\mathit{sameBlock}(a_i, a_j)$, where *sameBlock* is an implementation-specific predicate.
3. e_i and e_j are updates to the same directory: $\mathit{args}(e_i) \cap \mathit{args}(e_j) \neq \emptyset$, where $\mathit{args}(\mathit{link}(i_1, i_2)) = \{i_1, i_2\}$, $\mathit{args}(\mathit{unlink}(i_1)) = \{i_1\}$, and $\mathit{args}(\mathit{rename}(i_1, i_2)) = \{i_1, i_2\}$.
4. e_i is a write and e_j is an extend to the same file: $e_i = \mathit{write}(f, a_i, d_i)$ and $e_j = \mathit{extend}(f, a_j, d_j, s)$.

ext4 crash-consistency

```
P =  f = create(“file.tmp”)
     write(f, new)
     close(f)
     rename(“file.tmp”, “file”)
```

create(“foo.tmp”)

write(f, “The epoch of …”)

rename(“foo.tmp”, “foo.txt”)

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ext4 crash-consistency: allows traces that respect ordering of:

1. Metadata updates to the same file
2. Same-block writes
3. Same-directory operations
4. Write-append operations

Crash-consistency models

Like memory consistency models but for describing file system crashes

Litmus tests	Formal specifications
Small programs that demonstrate allowed or forbidden behaviors of a file system across crashes	Axiomatic descriptions of crash consistency using first order logic
Documentation for application developers	**Automated reasoning** about crash safety

Crash behavior of
modern file systems

Crash-consistency models

Litmus tests & formal specifications

Ferrite: developing
crash-consistency models

Building crash-safe
applications

Crash behavior of
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applications

The storage stack is complex

```
write(f, “The age of …”)
write(f, “The epoch of …”)
```

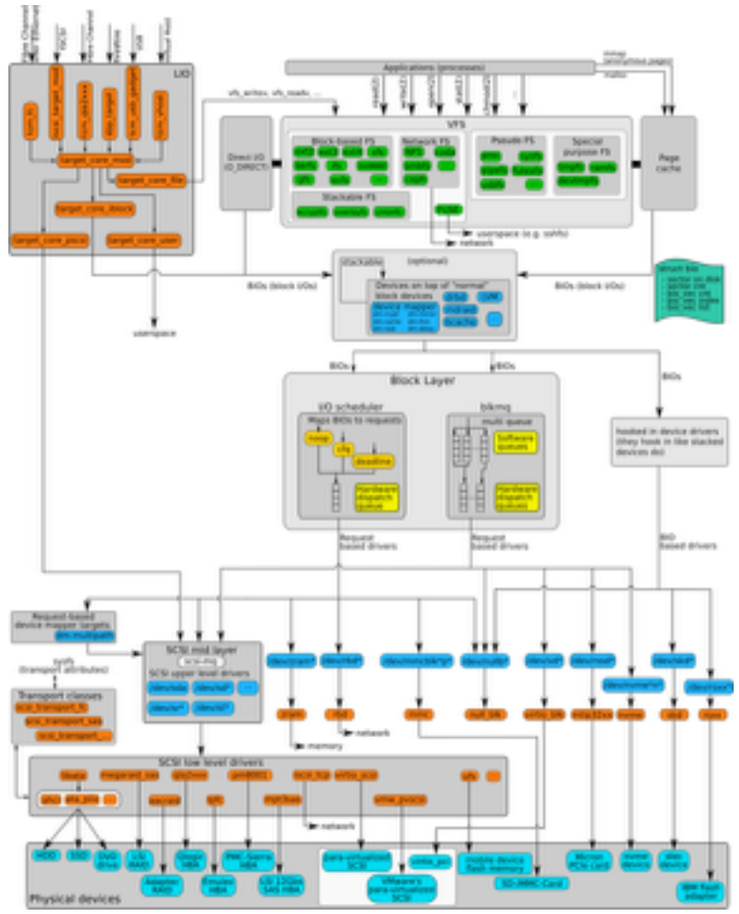

Diagram by Werner Fischer

Building models with Ferrite

Ferrite

Litmus tests

File System
(via QEMU)

Building models with Ferrite

Litmus tests

System calls

File System
(via QEMU)

Ferrite

Building models with Ferrite

Ferrite

Litmus tests

System calls

File System
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Storage stack

Building models with Ferrite

Ferrite

Litmus tests

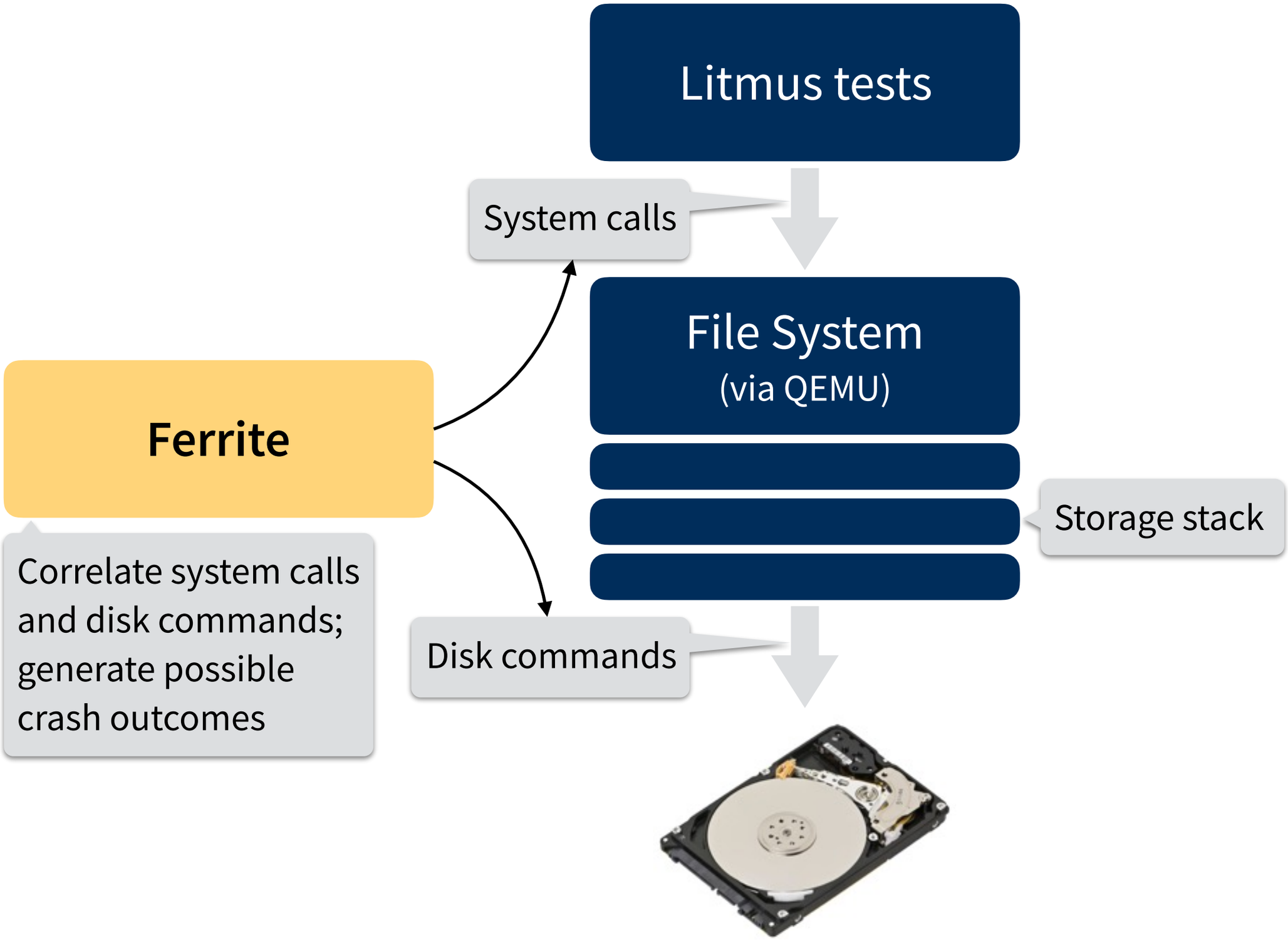
System calls

File System
(via QEMU)

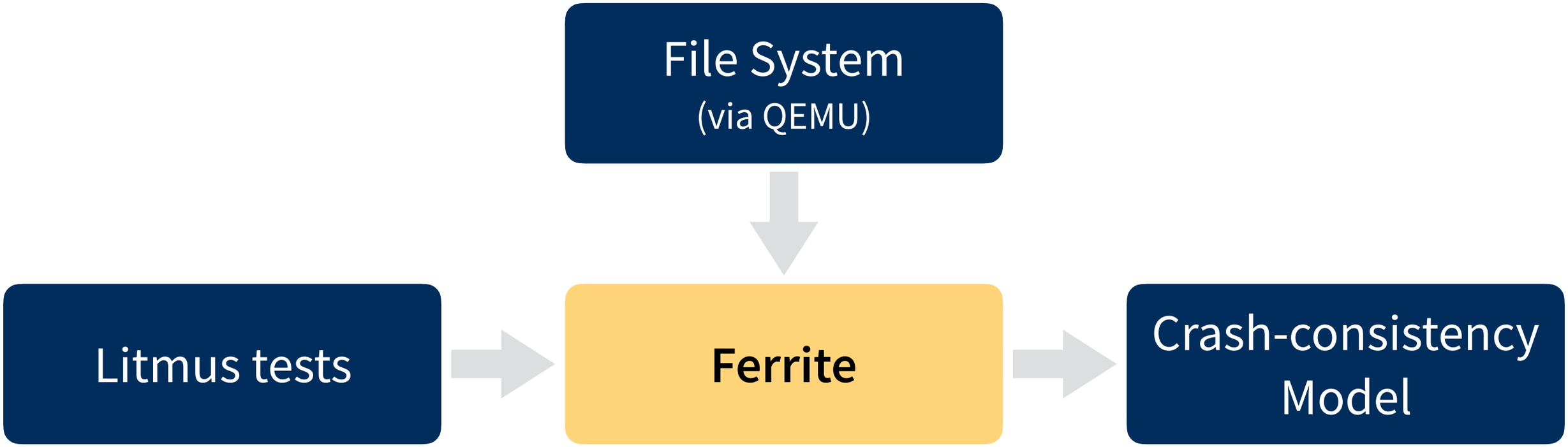
Storage stack

Disk commands

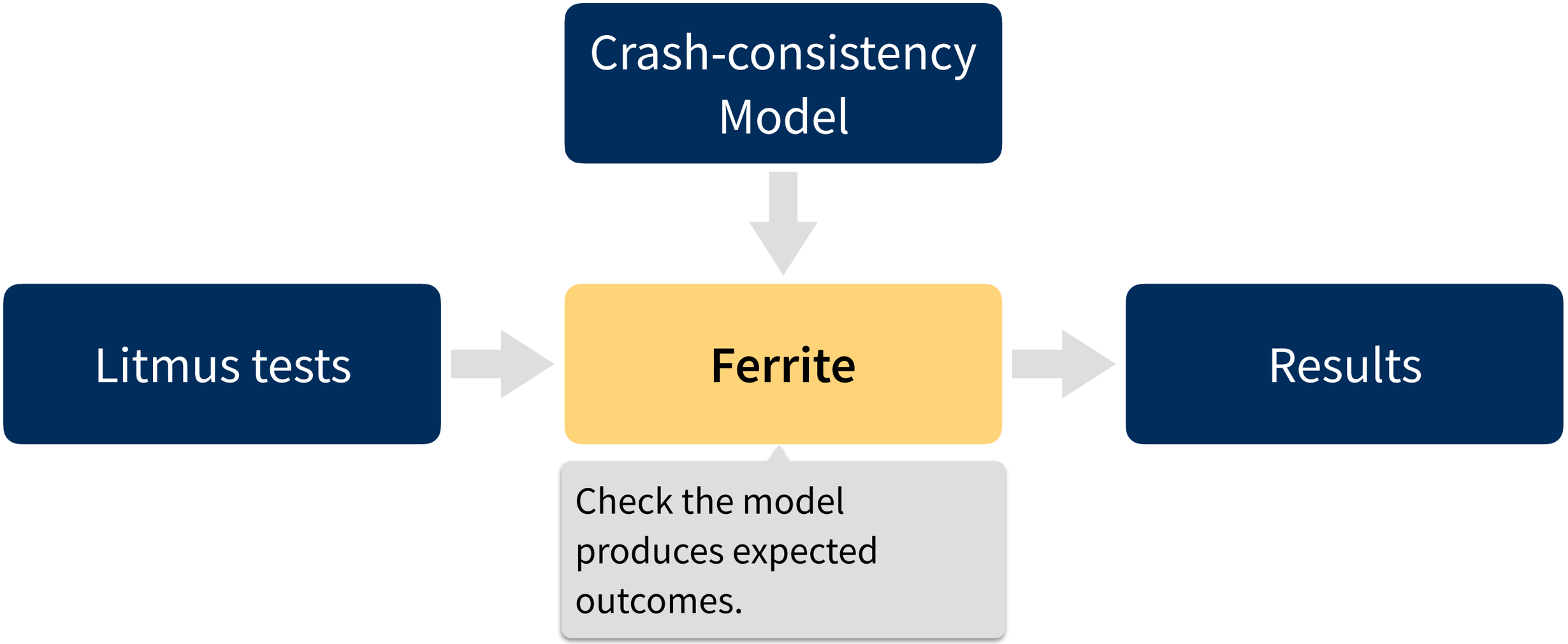
Building models with Ferrite



Building models with Ferrite



Checking models with Ferrite



Crash behavior of
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Crash-consistency models

Litmus tests & formal specifications

Ferrite: developing
crash-consistency models

Building crash-safe
applications

Crash behavior of
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Automating crash consistency

```
initial:
  f = create(“file”)
  write(f, old)

main:
  f = create(“file.tmp”)
  write(f, new)
  close(f)
  rename(“file.tmp”, “file”)
```

```
exists?:
  content(“file”) != old & content(“file”) != new
```

Automating crash consistency

```
initial:
  f = create(“file”)
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main:
  fsync(f)
  f = create(“file.tmp”)
  fsync(f)
  write(f, new)
  fsync(f)
  close(f)
  fsync(f)
  rename(“file.tmp”, “file”)
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Synthesizing crash consistency


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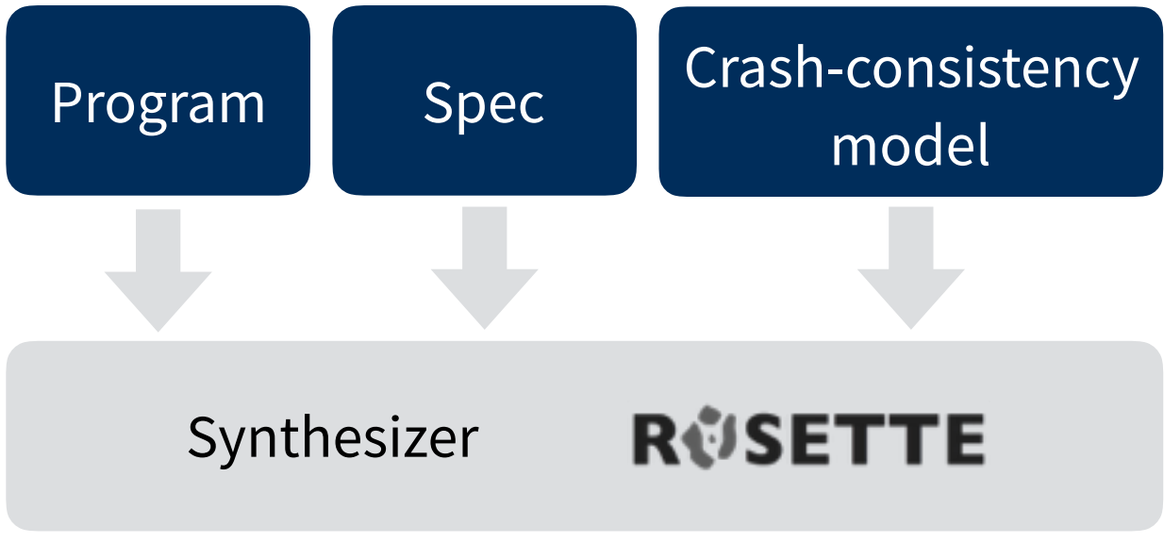


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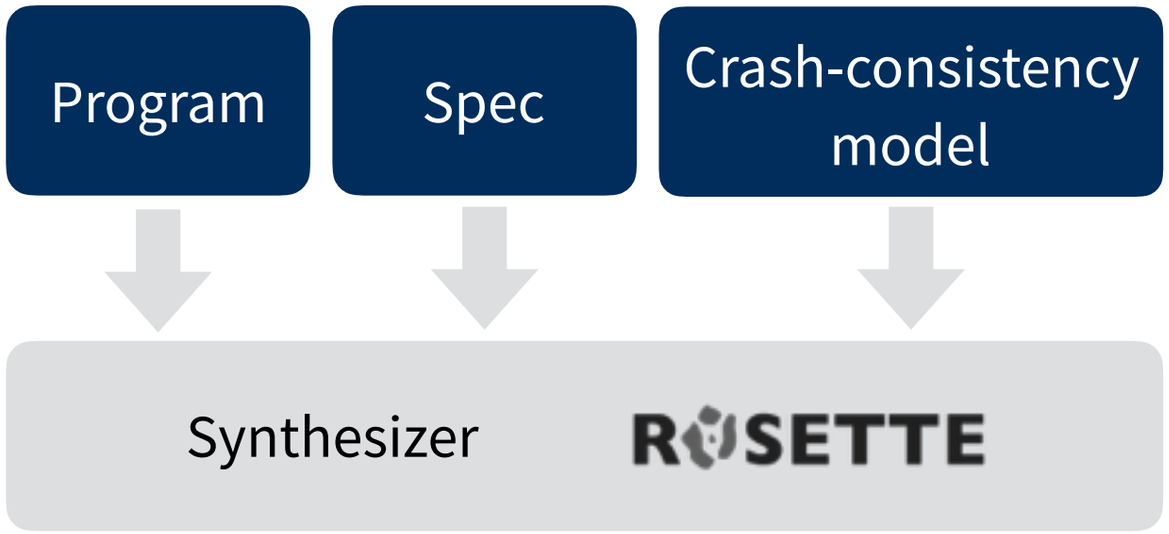

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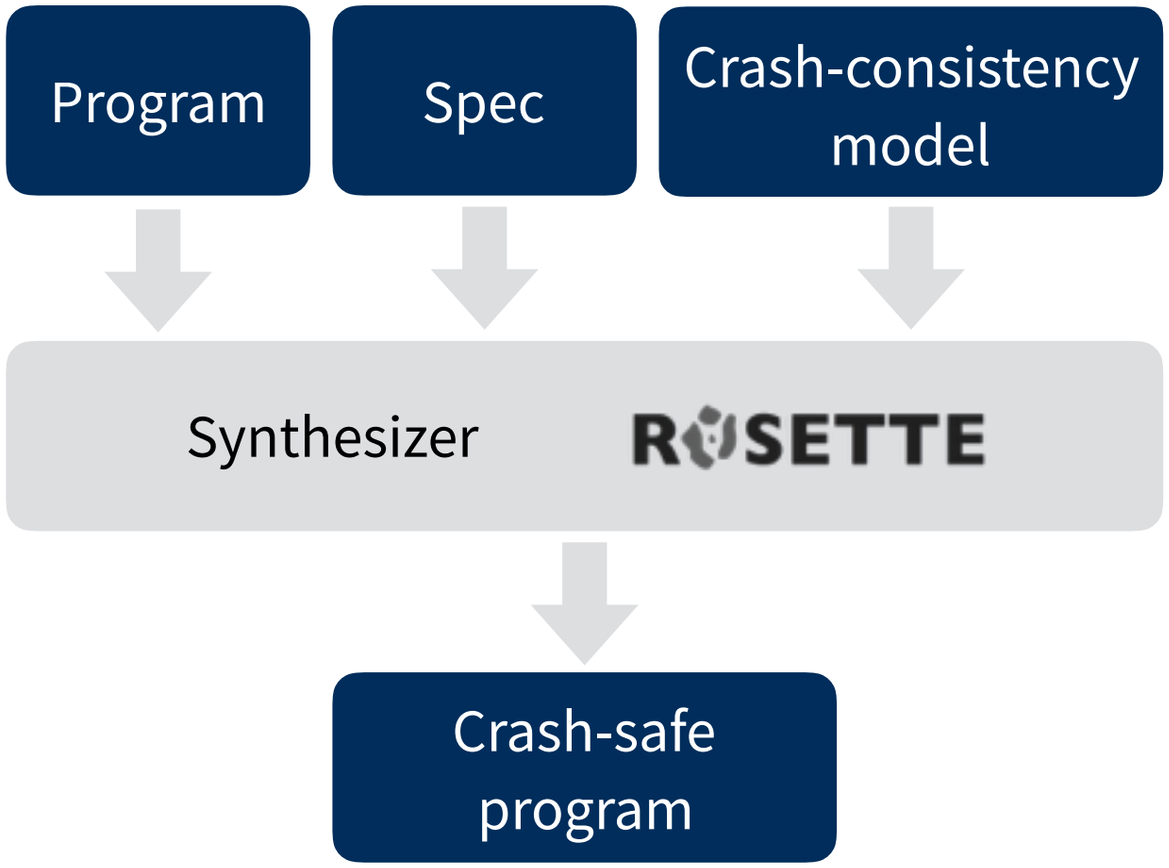

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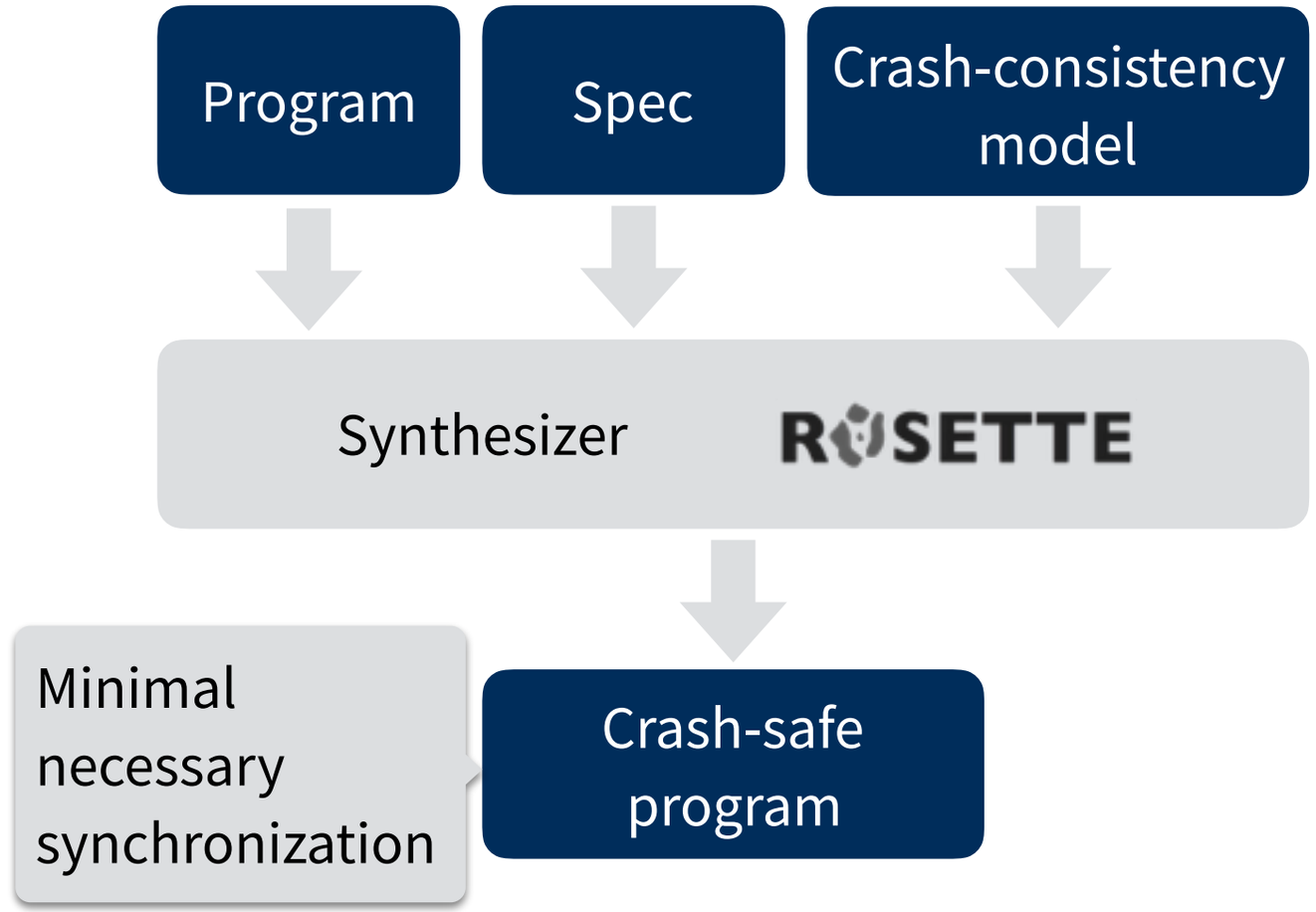
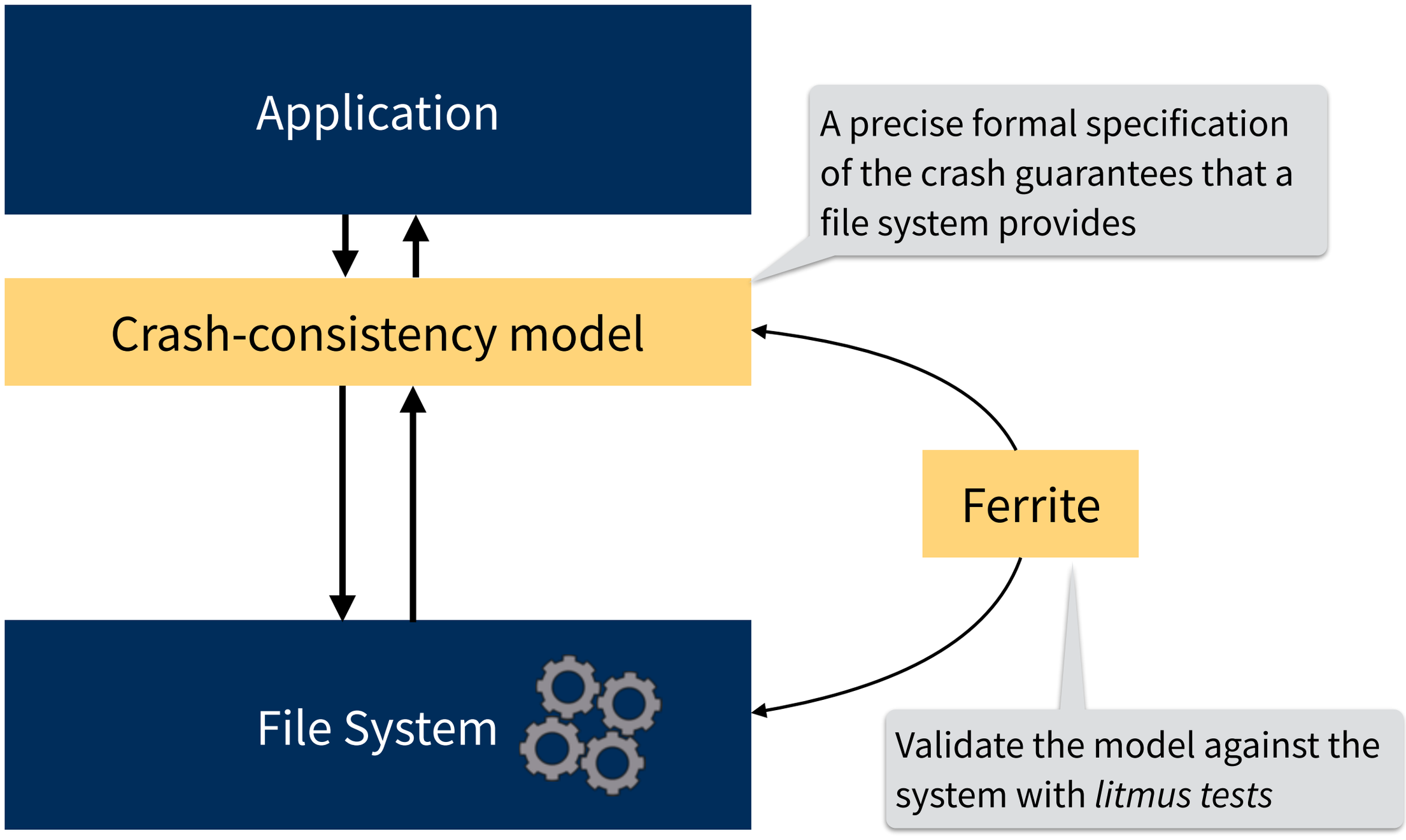


Crash-consistency models



Crash-consistency models

A DNA-Based Archival Storage System
Wednesday, right before lunch