Lightweight Application-Level Crash Consistency on Transactional Flash Storage

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Georgia Institute of Technology
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Application's data is not consistent after random failures

Mobile Phone

Bank Account

Hang while booting

Financial loss

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Mobile Phone

Bank Account

Power Outage
Hardware Errors
Software Panics (OS, Device Driver)

Hang while booting

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Example: inserting records in two databases

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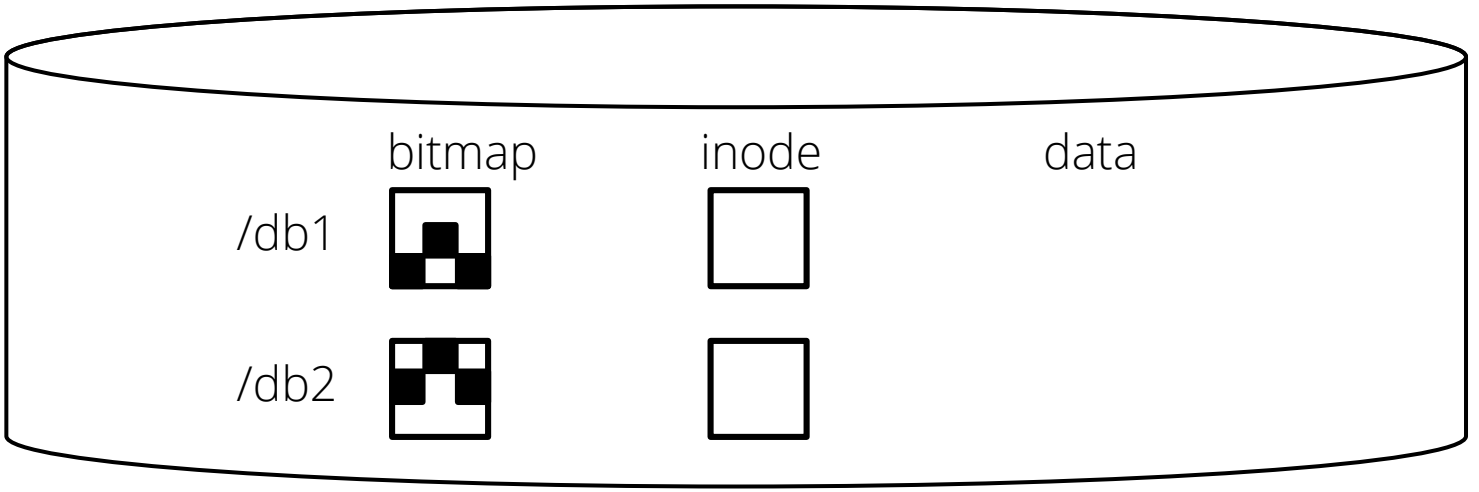

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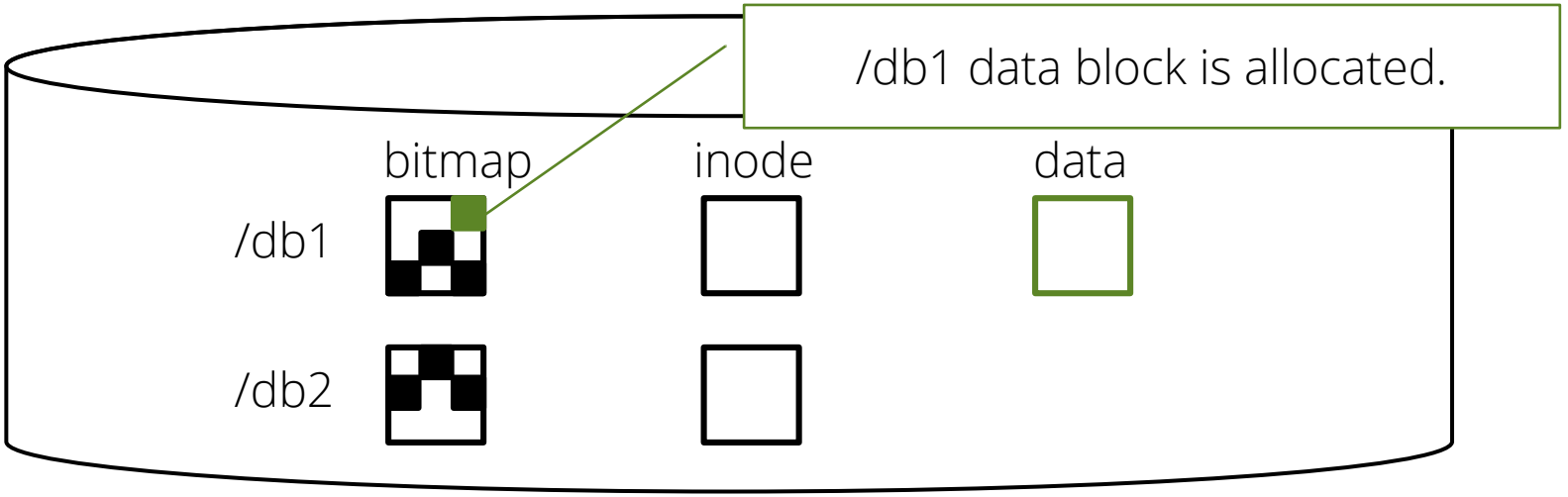

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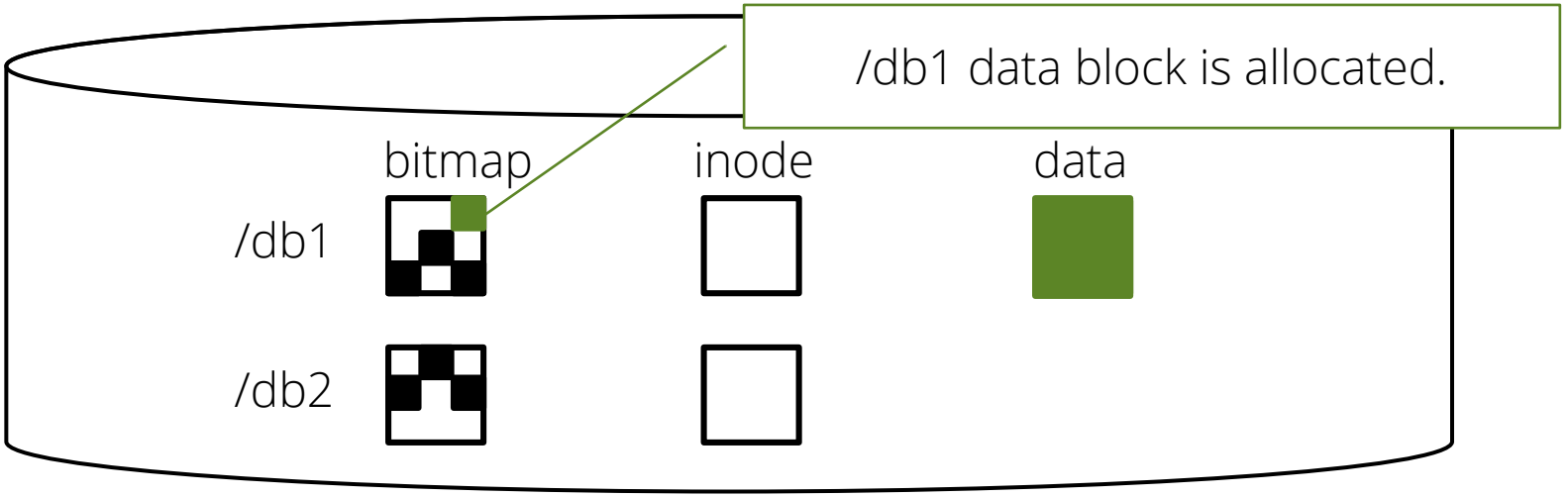

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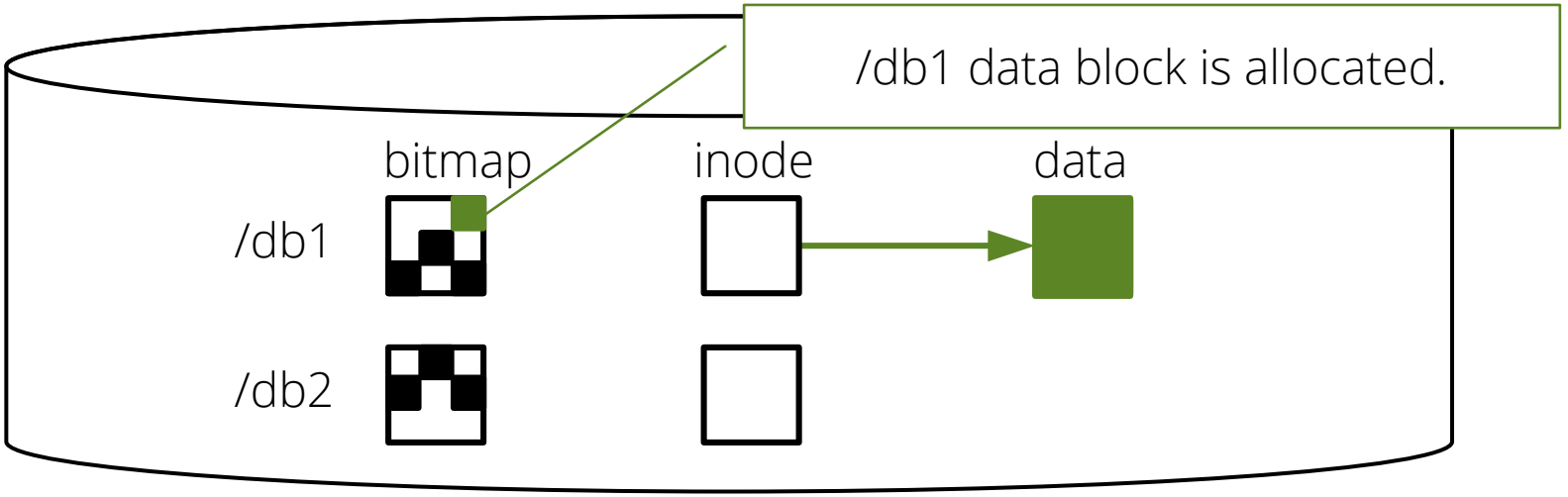

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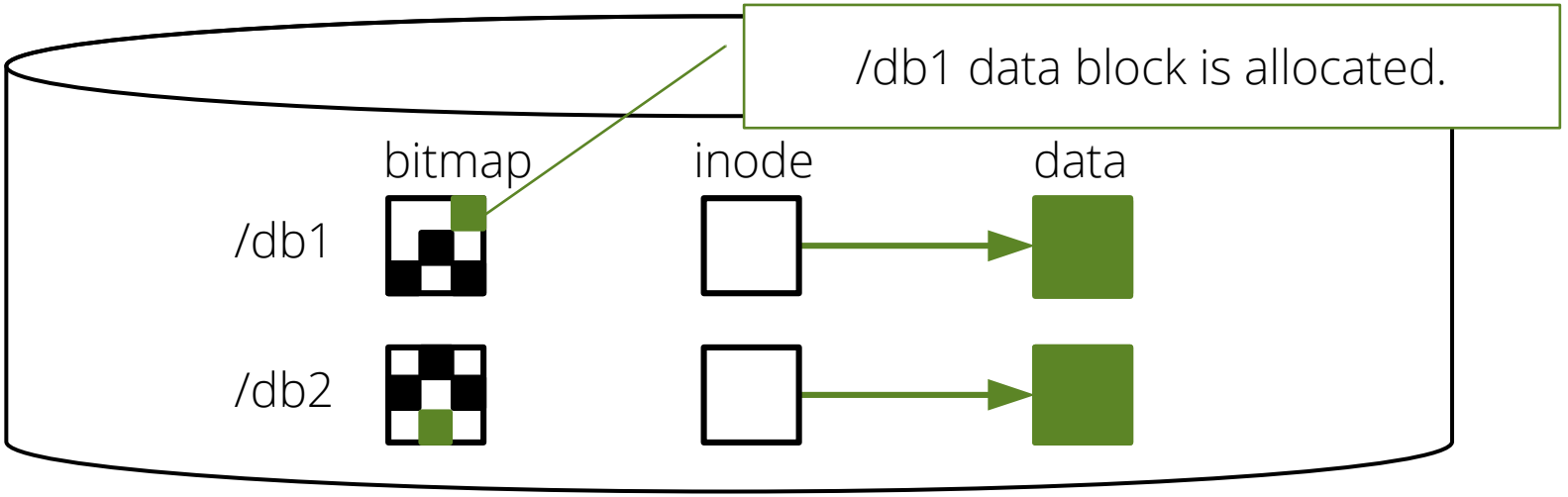

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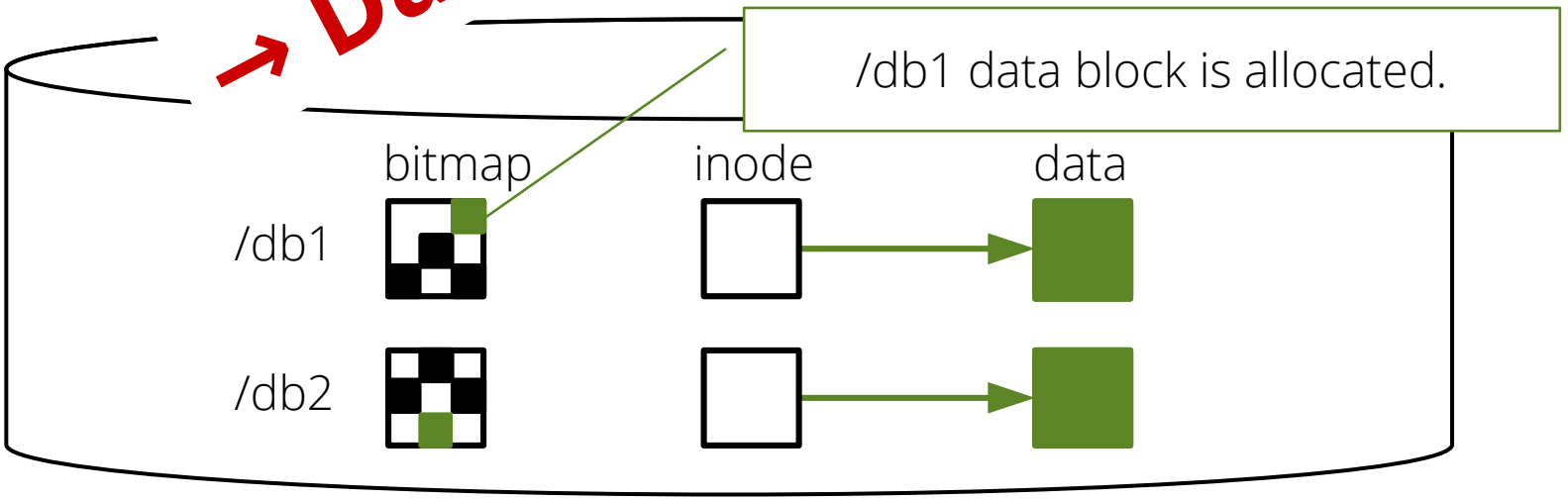
File System

For each database:
- Allocates [illegible]
- Fills [illegible] data (data)
- [illegible] block (inode)

Random failures?
→ Data corruption!

Storage Device



How to Achieve Crash Consistency : The Case of SQLite

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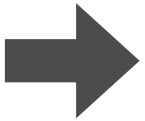

Logging (i.e., journaling) & Crash Recovery

"Write logs first before writing data in place"

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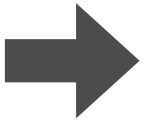

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: for each DB and their master

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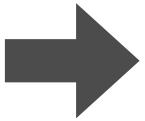

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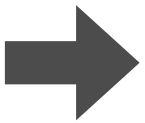

Logging (i.e., journaling) & Crash Recovery

"Write logs first before writing data in place"

Ordering & durability
: 11 fsync()

Maintaining three log files
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: 3 create() & 3 unlink()

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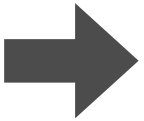

```
// create master journal
open(/master.jnl);
write(/master.jnl, "/db1,/db2");
fsync(/master.jnl);
fsync(/);
// update db1
open(/db1.jnl);
write(/db1.jnl, "old");
fsync(/db1.jnl);
fsync(/);
write(/db1.jnl, "master.jnl");
fsync(/db1.jnl);
write(/db1, "new");
fsync(/db1);
```

```
// update db2
open(/db2.jnl);
write(/db2.jnl, "old");
fsync(/db2.jnl)
fsync(/);
write(/db2.jnl, "master.jnl");
fsync(/db2.jnl);
write(/db2, "new");
fsync(/db2);
// clean up journals
unlink(/master.jnl);
fsync(/);
unlink(/db1.jnl);
unlink(/db1.jnl);
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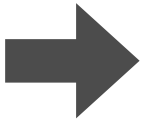

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open(/db1.jnl);
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fsync(/db1.jnl);
fsync(/);
write(/db1.jnl, "master.jnl");
fsync(/db1.jnl);
write(/db1, "new");
fsync(/db1);
```

```
// update db2
open(/db2.jnl);
write(/db2.jnl, "old");
fsync(/db2.jnl)
fsync(/);
write(/db2.jnl, "master.jnl");
fsync(/db2.jnl);
write(/db2, "new");
fsync(/db2);
// clean up journals
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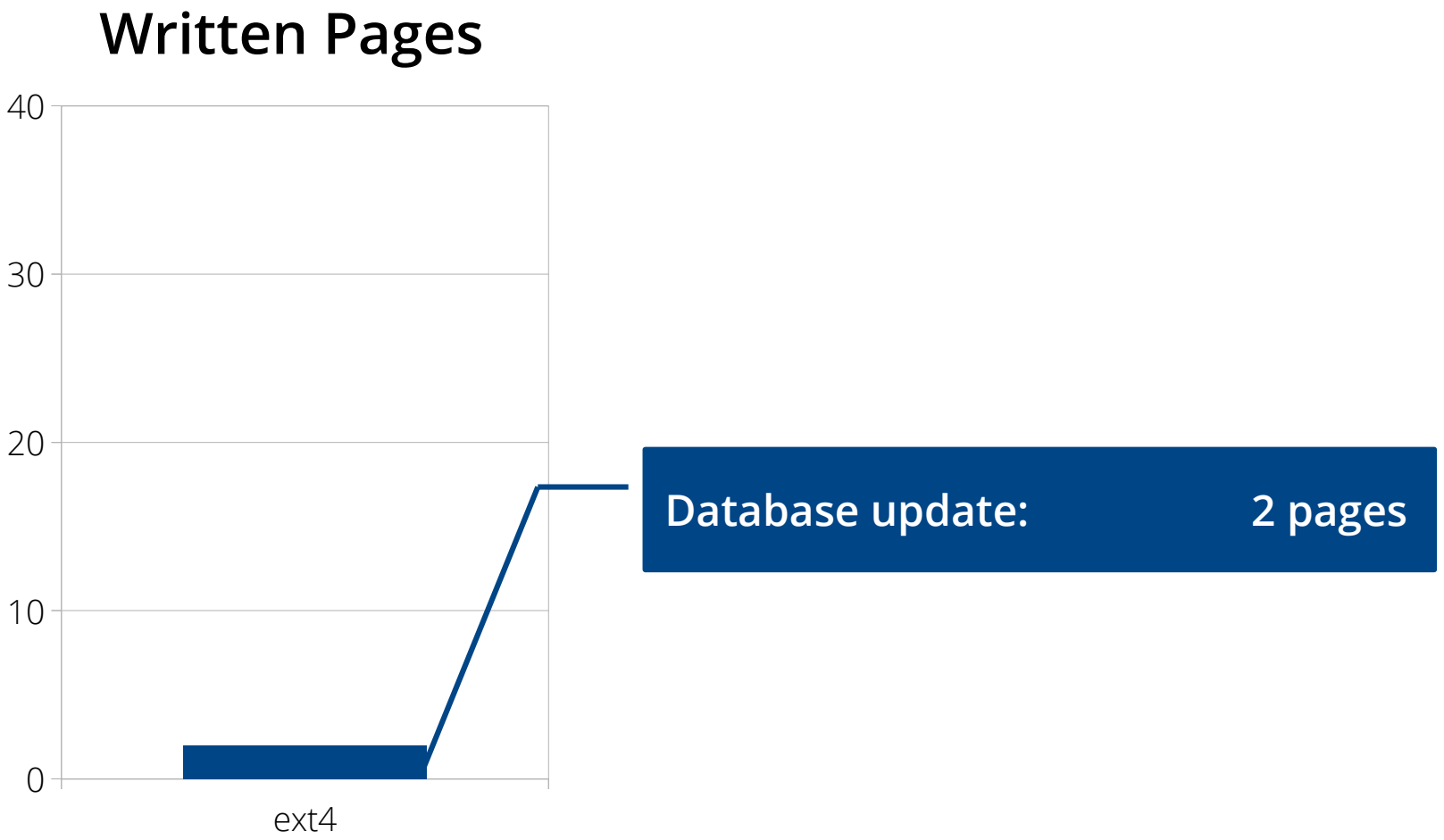
Cost of Crash Consistency : The Case of SQLite



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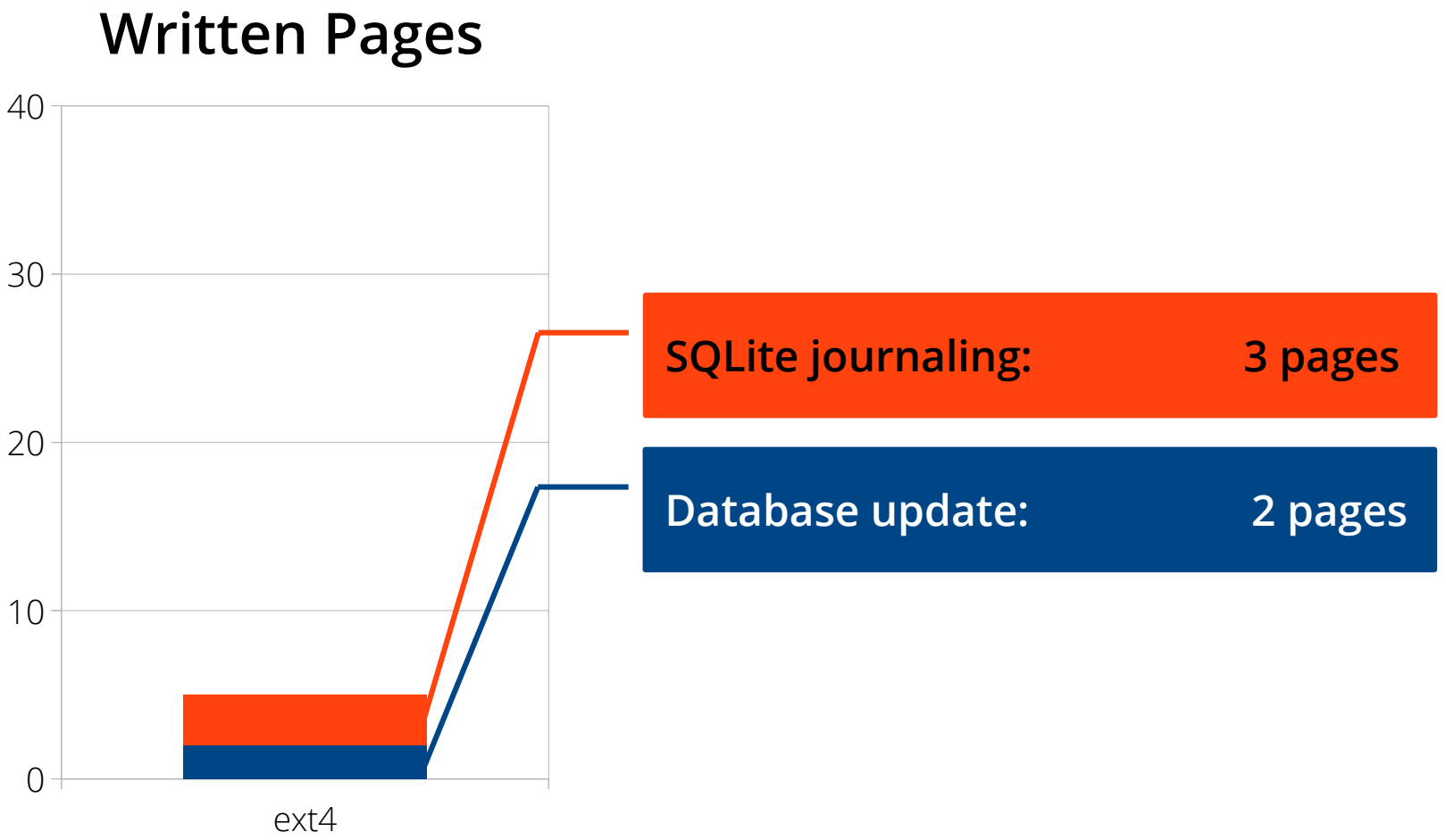

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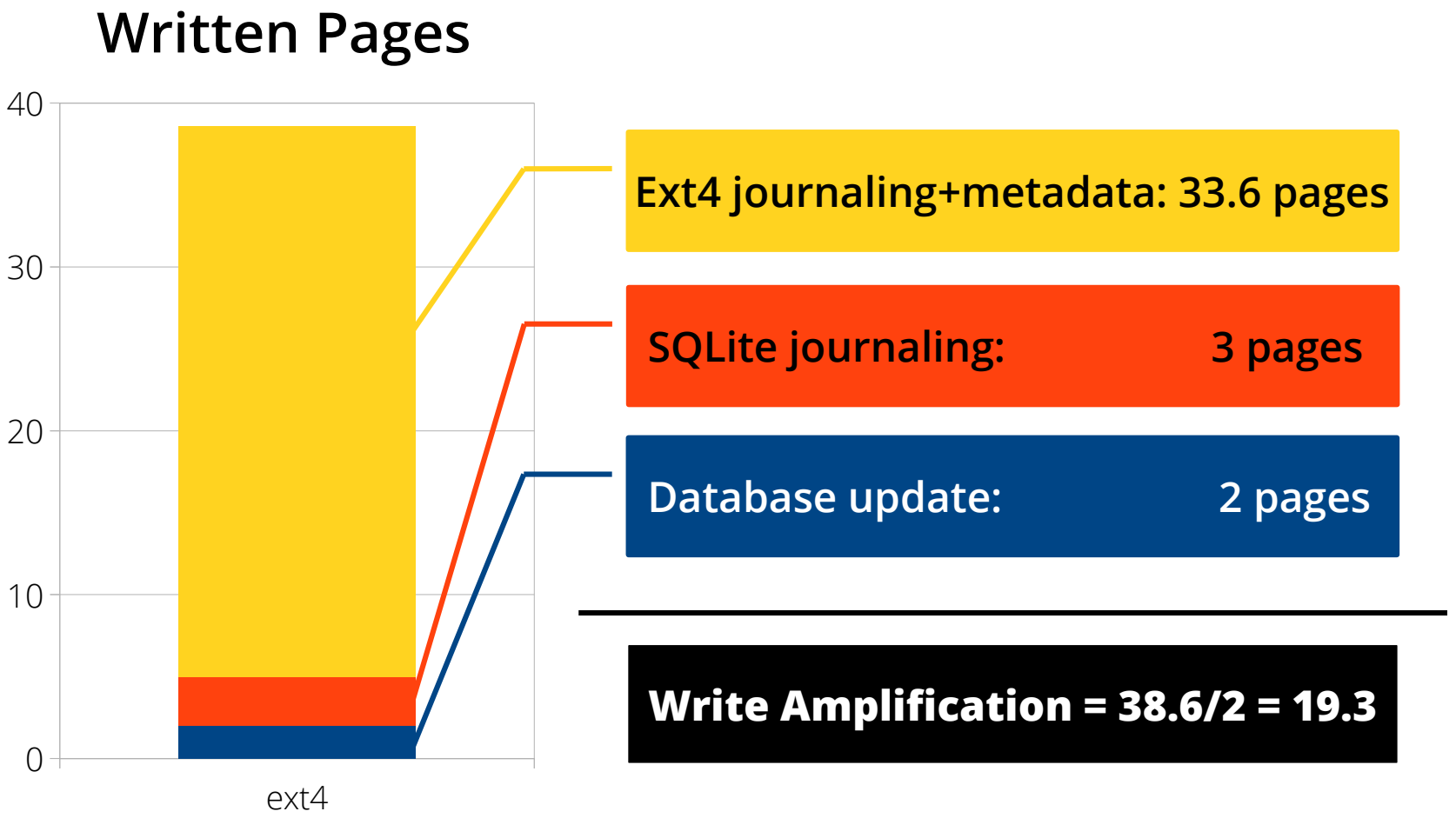

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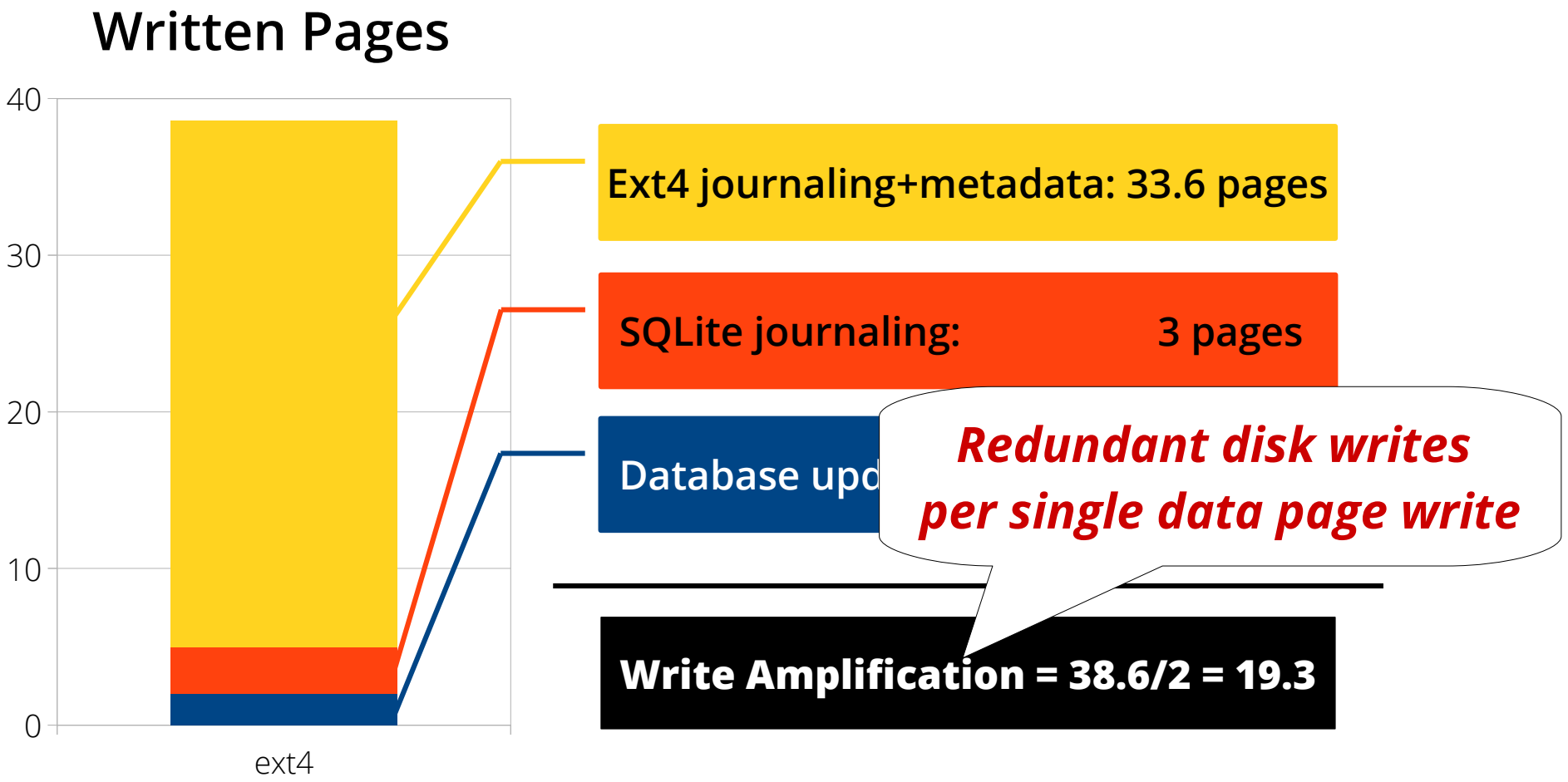

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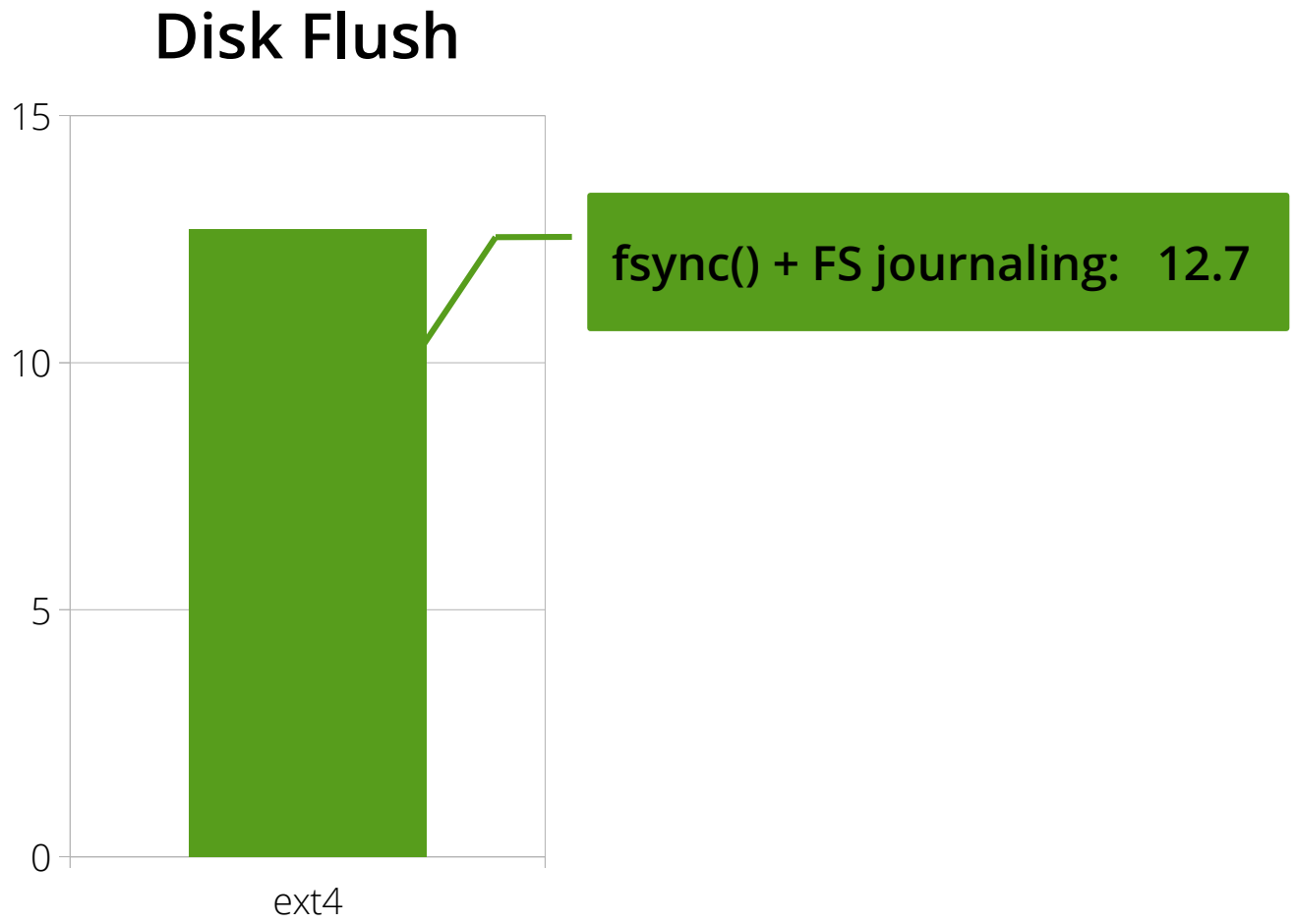
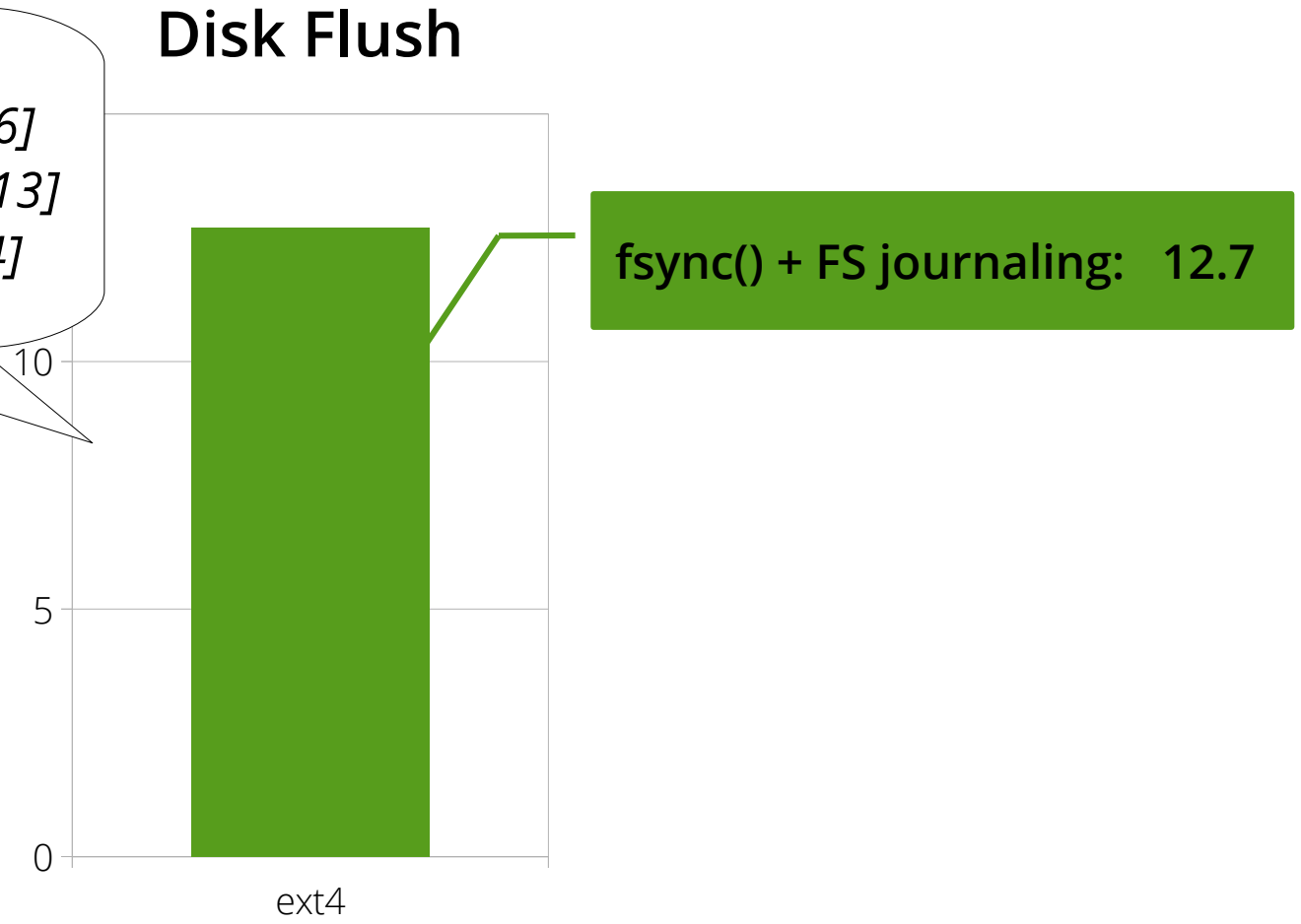


Cost of Crash Consistency : The Case of SQLite

Notoriously slow!

xsyncfs [Nightingale:OSDI06]
OptFS [Chidambaram:SOSP13]
DuraSSD [Kang:SIGMOD14]
...



Problem: complex, redundant software stack for crash consistency

How can we **simplify** mechanisms for **application crash consistency**?

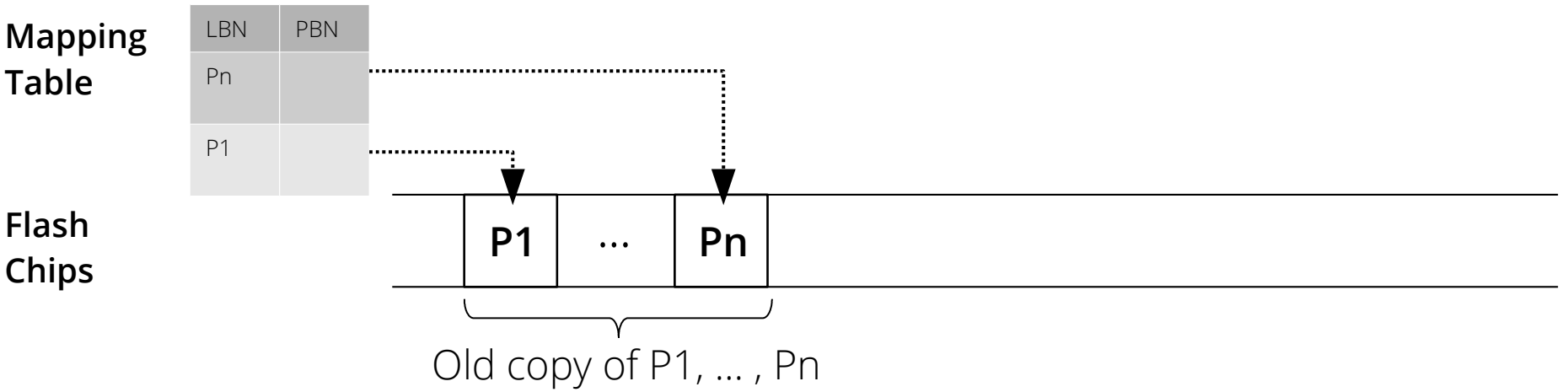
Problem: complex, redundant software stack for crash consistency

How can we simplify mechanisms for application crash consistency?

*Can we use **atomic updates of multi pages** provided by **transactional flash**?*

Transactional Flash 101

- NAND Flash SSD
  - No in-place update
  - Log-structured write
  - Mapping table: logical address → physical address



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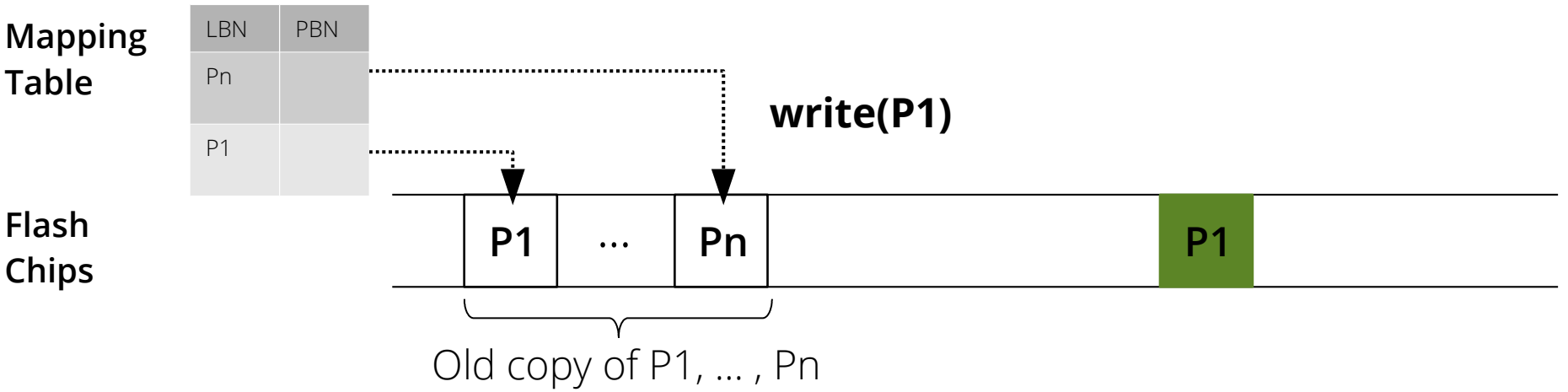

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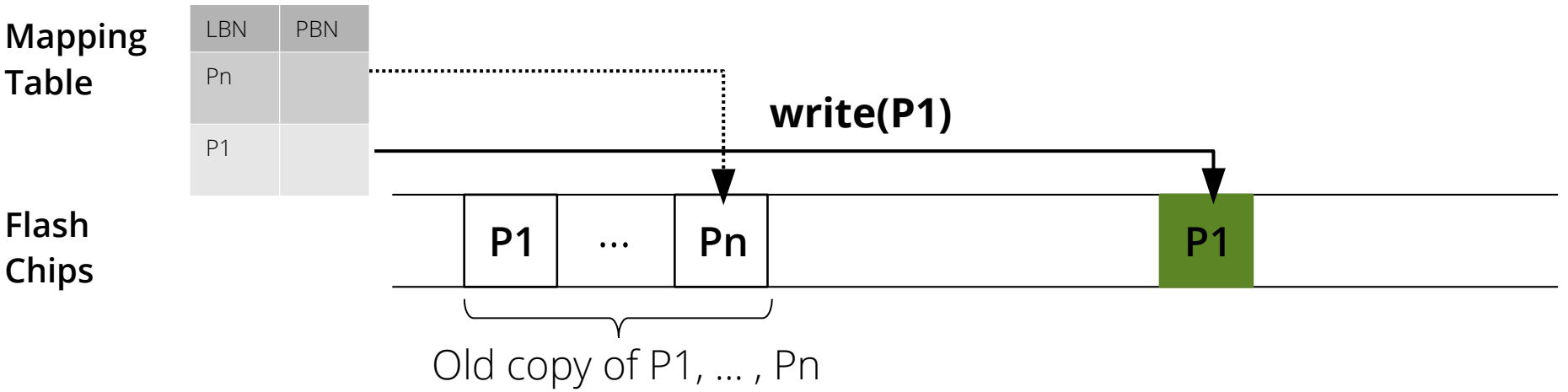

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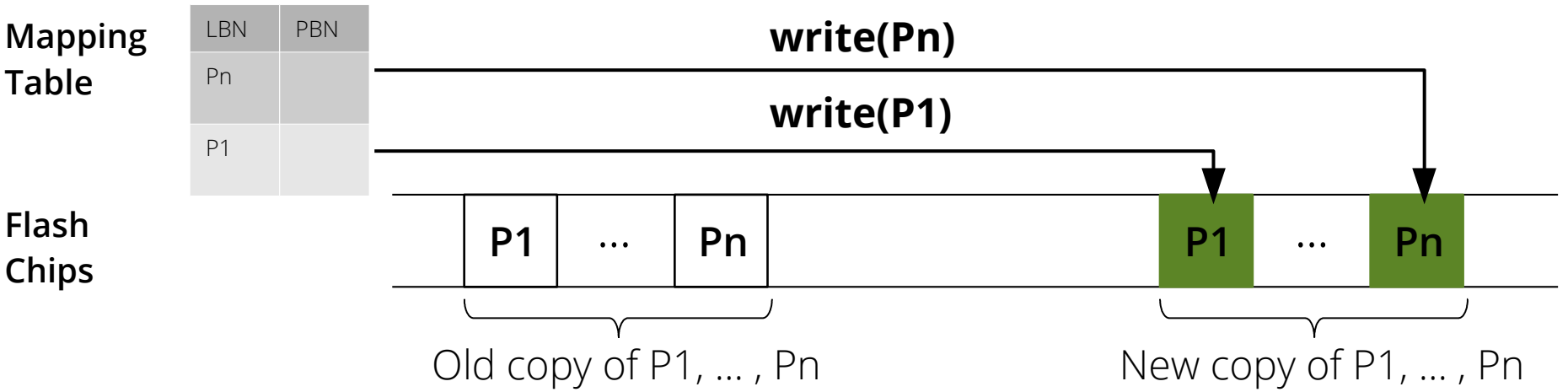

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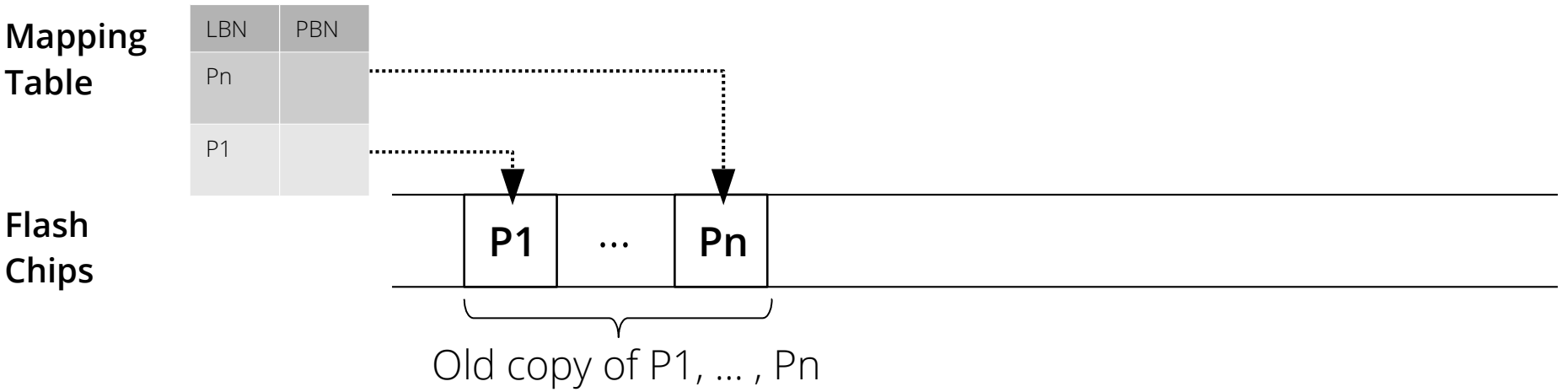
    - write(txid, page), commit(txid), abort(txid)
  - H/W implementation or S/W emulation



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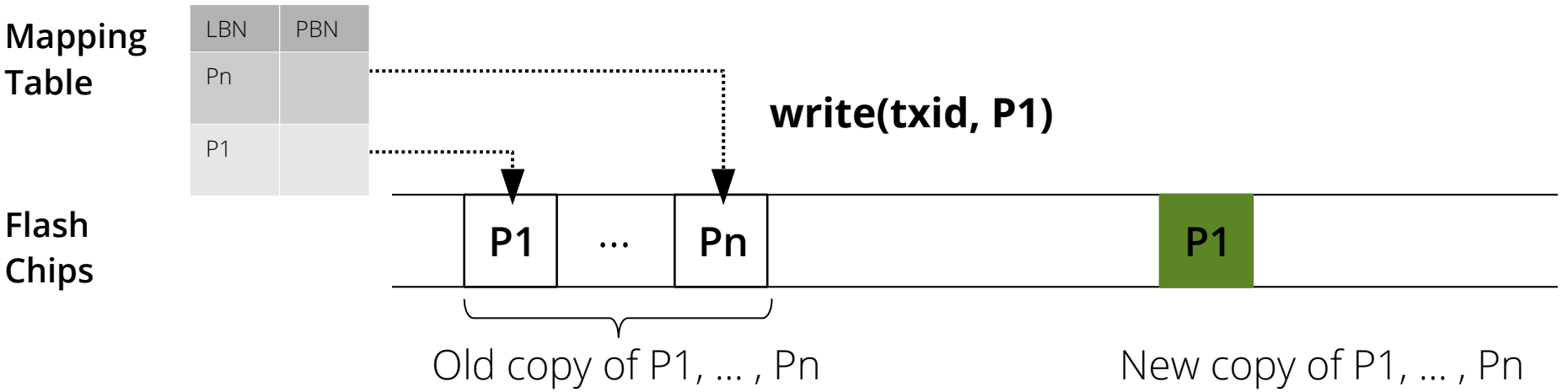

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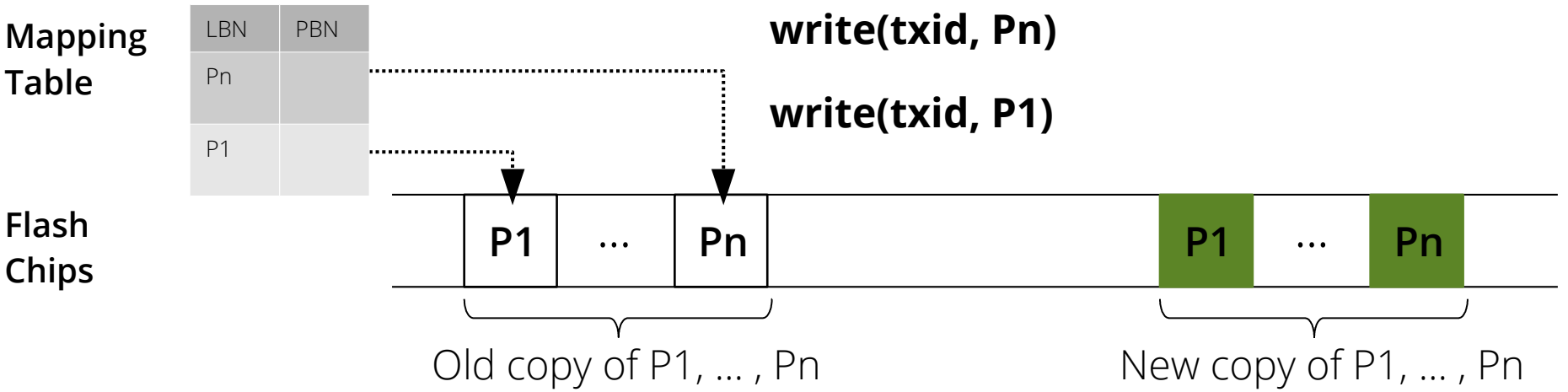

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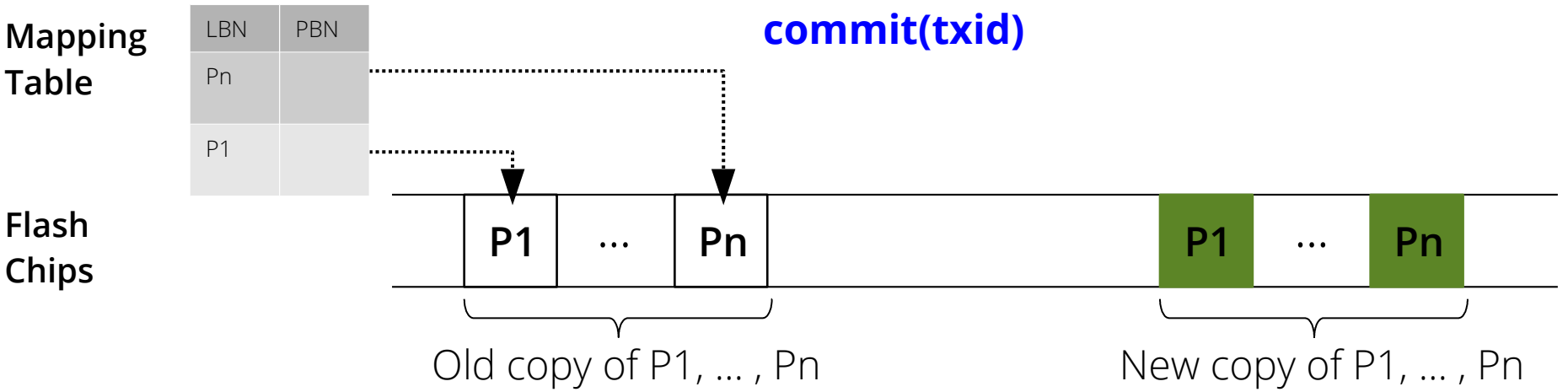

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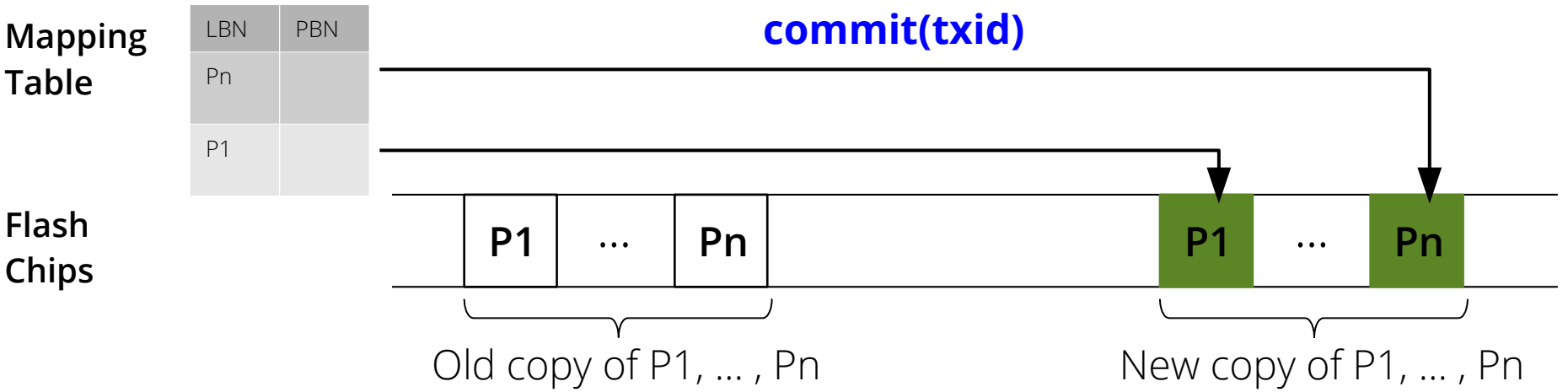

Our Solution: CFS, a new file system using transactional flash

Simplifying

applications' crash consistency

using atomic multi-page write

of transactional flash

Our Solution: CFS

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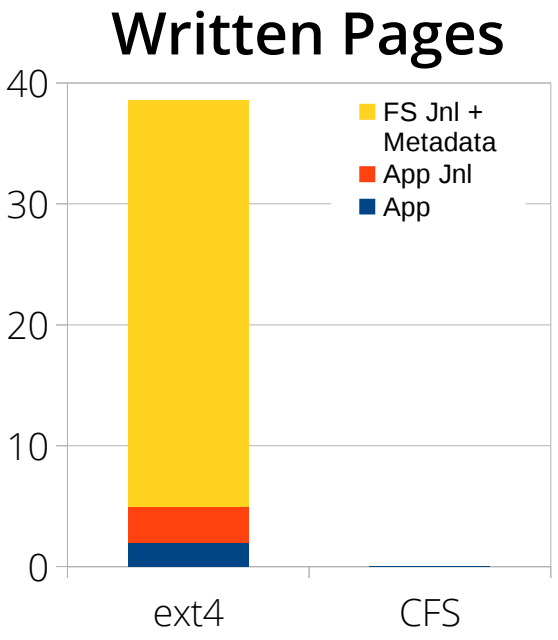

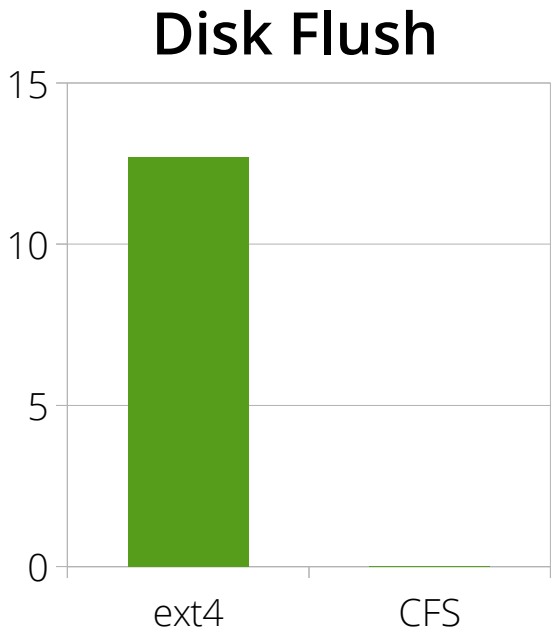

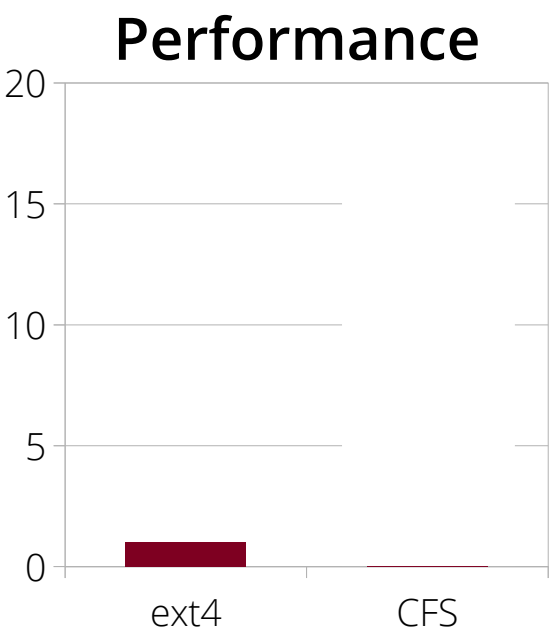

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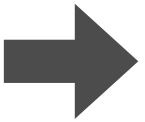

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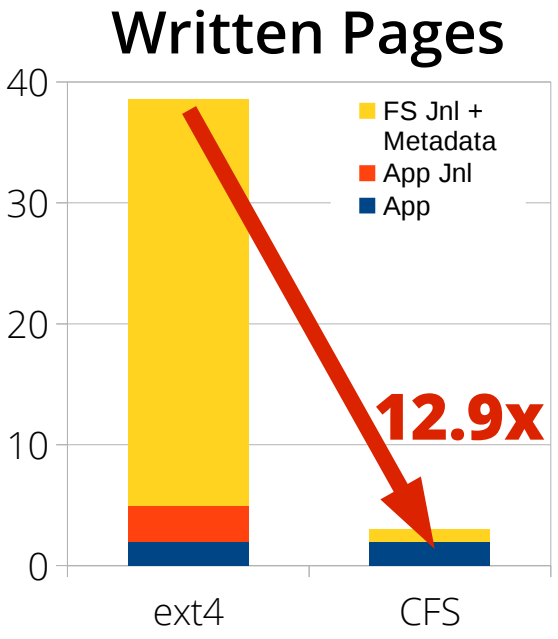
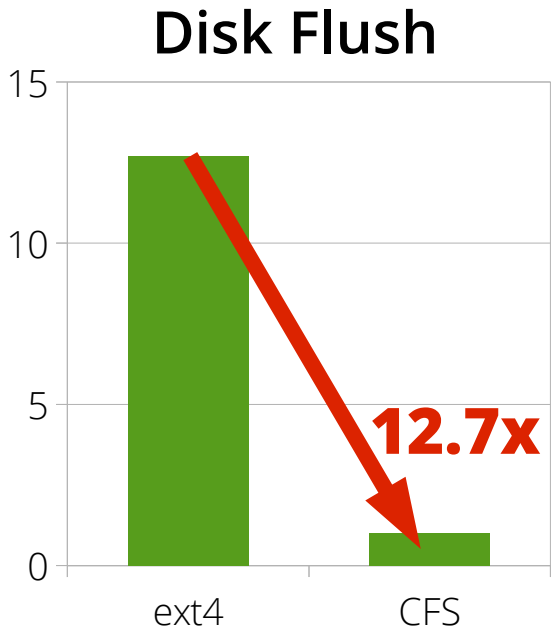
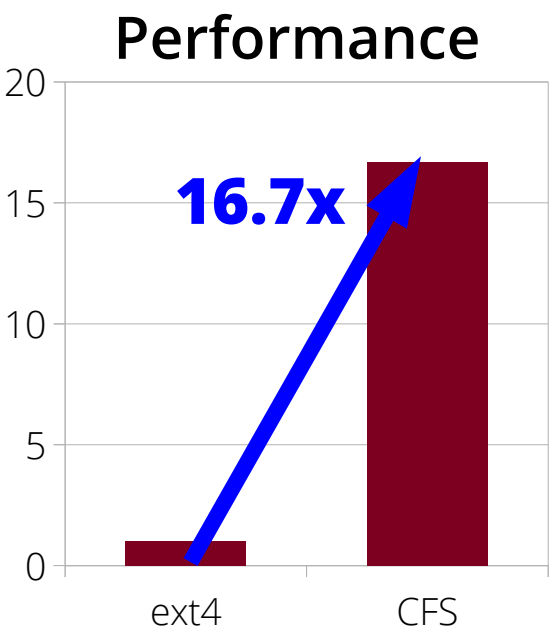


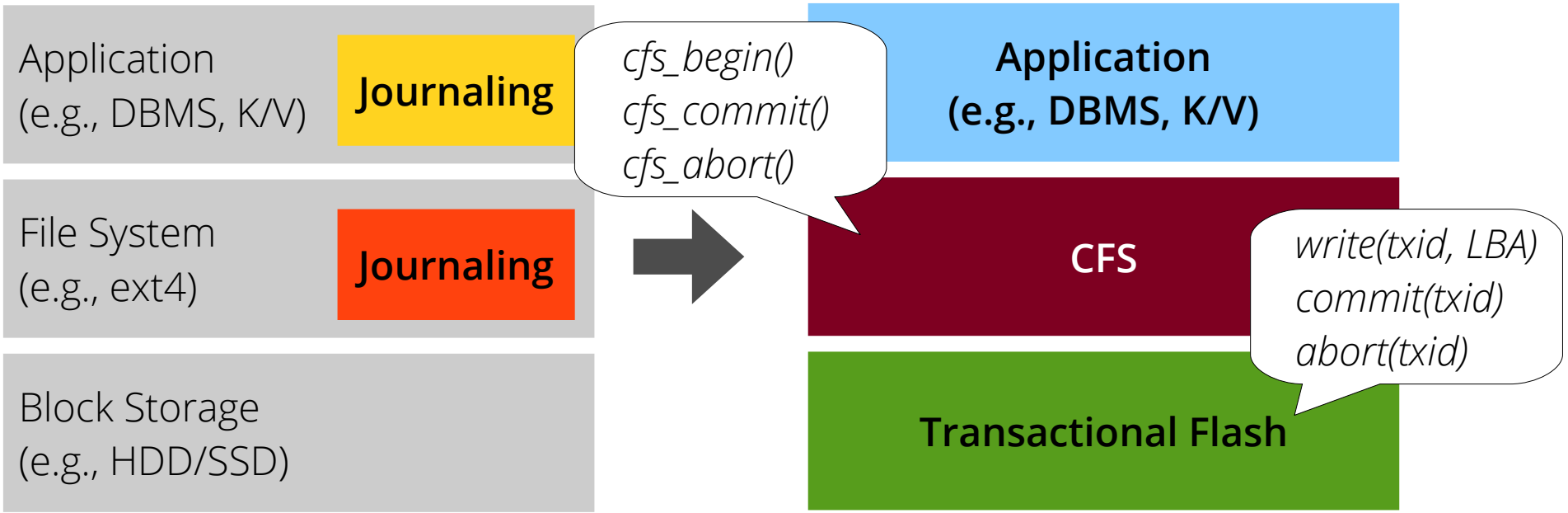




Outline

- Introduction
- **CFS Design**
- Evaluation
- Conclusion

CFS Architecture



Removing redundant journaling with new primitives provided by transactional flash

Four Challenges

1. Finding a set of pages for atomic updates
2. File system metadata consistency in every case
3. Concurrency control among atomic updates
4. Legacy application support without any modification

#1. Unit of Atomic Write
: Atomic Propagation Group

Application

+ cfs_begin();

write(/db1, “new”);

write(/db2, “new”);

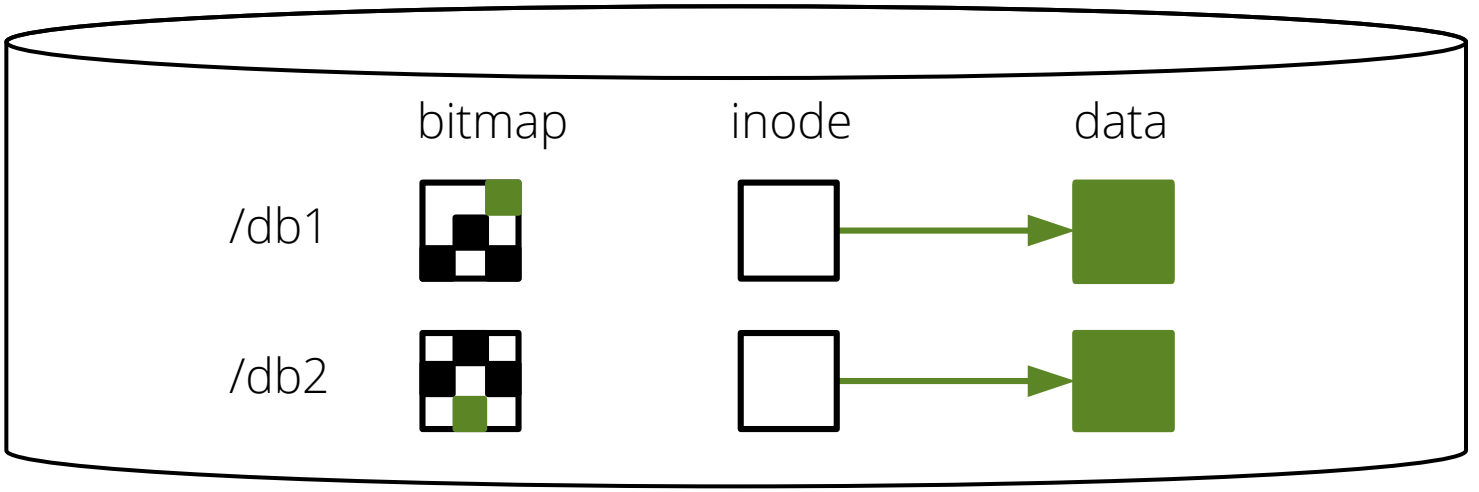
+ cfs_commit();

File System

For each database

- Allocates new data block (bitmap)
- Fills data block with user data (data)
- Sets location of data block (inode)

Transactional Flash



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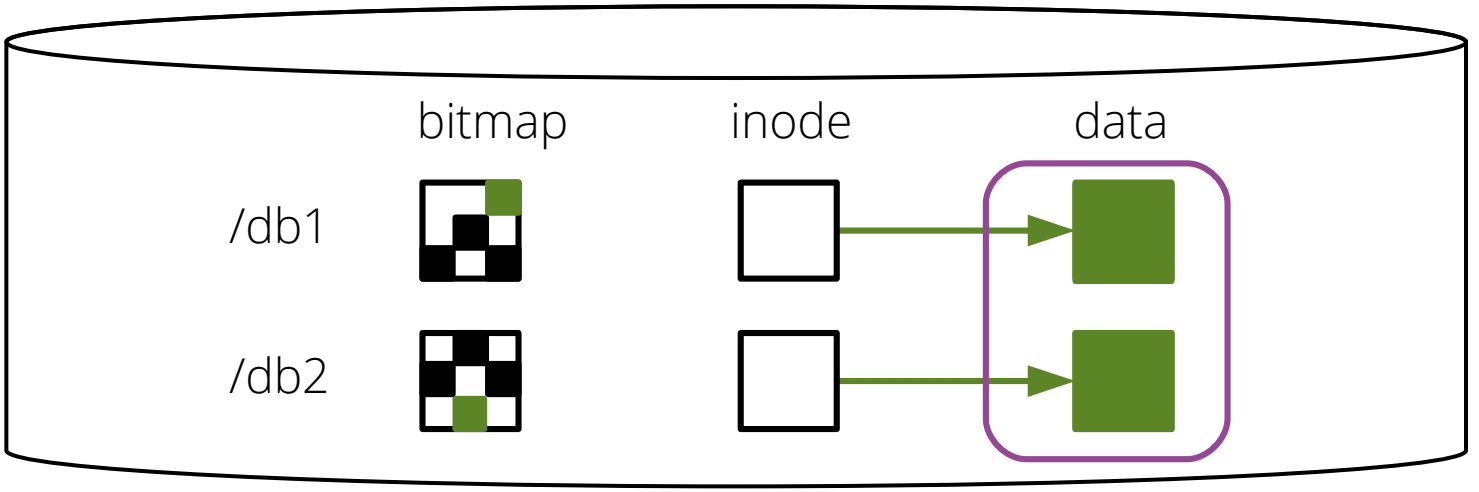

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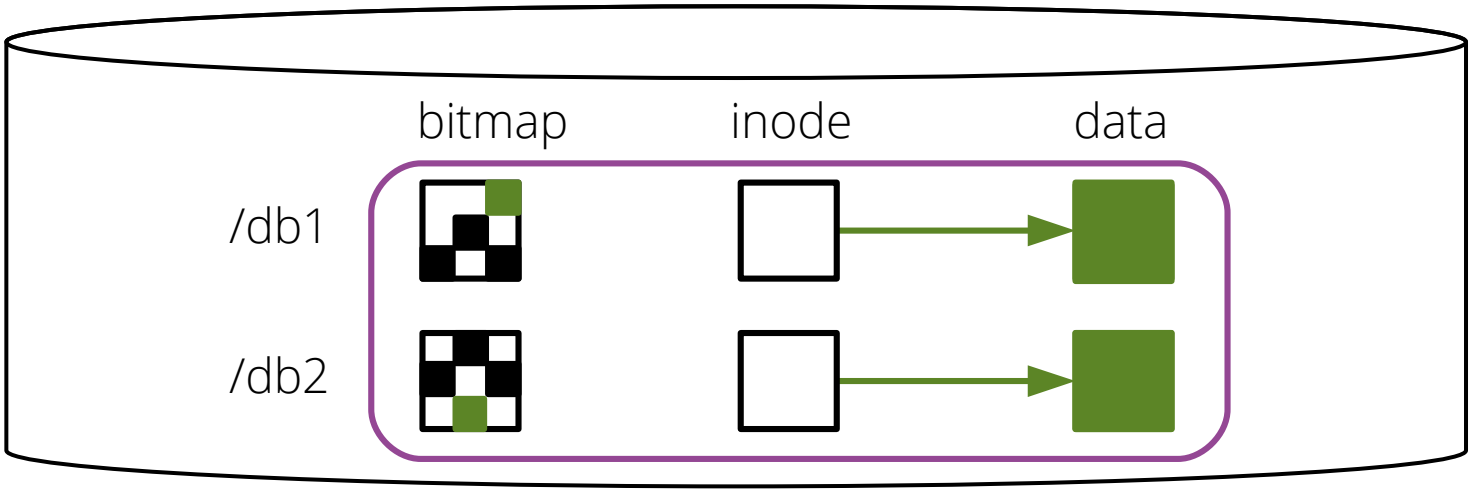

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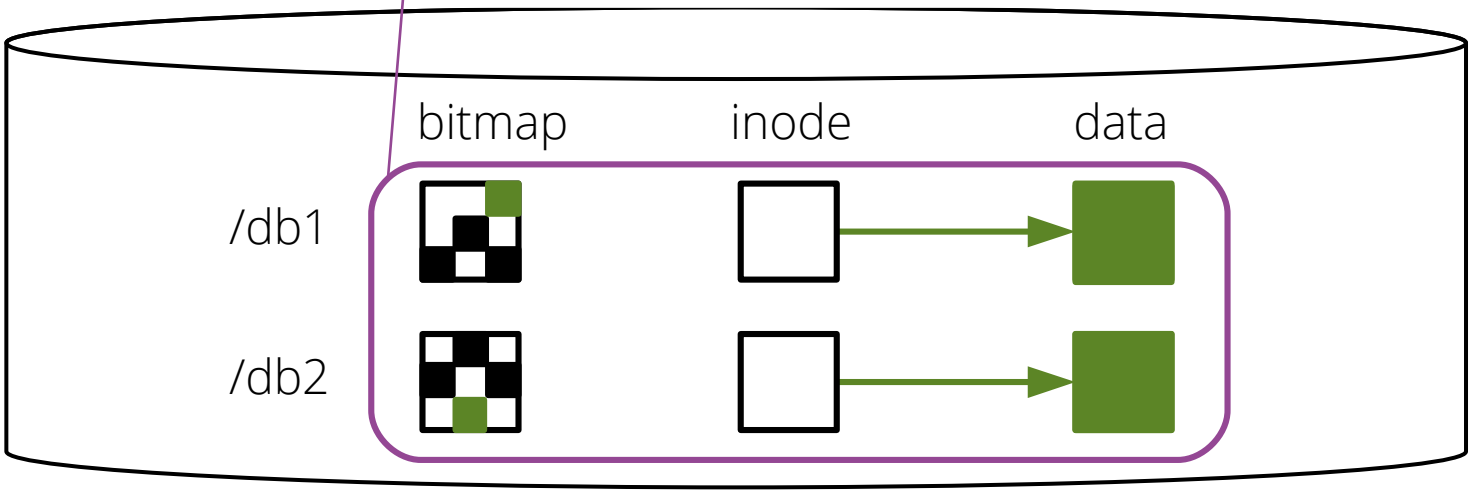
+ cfs_commit();
```

- Updated data and file system metadata pages need to be atomically updated.
- Use atomic multi-page write operations

→ Atomic Propagation Group

Transactional Flash

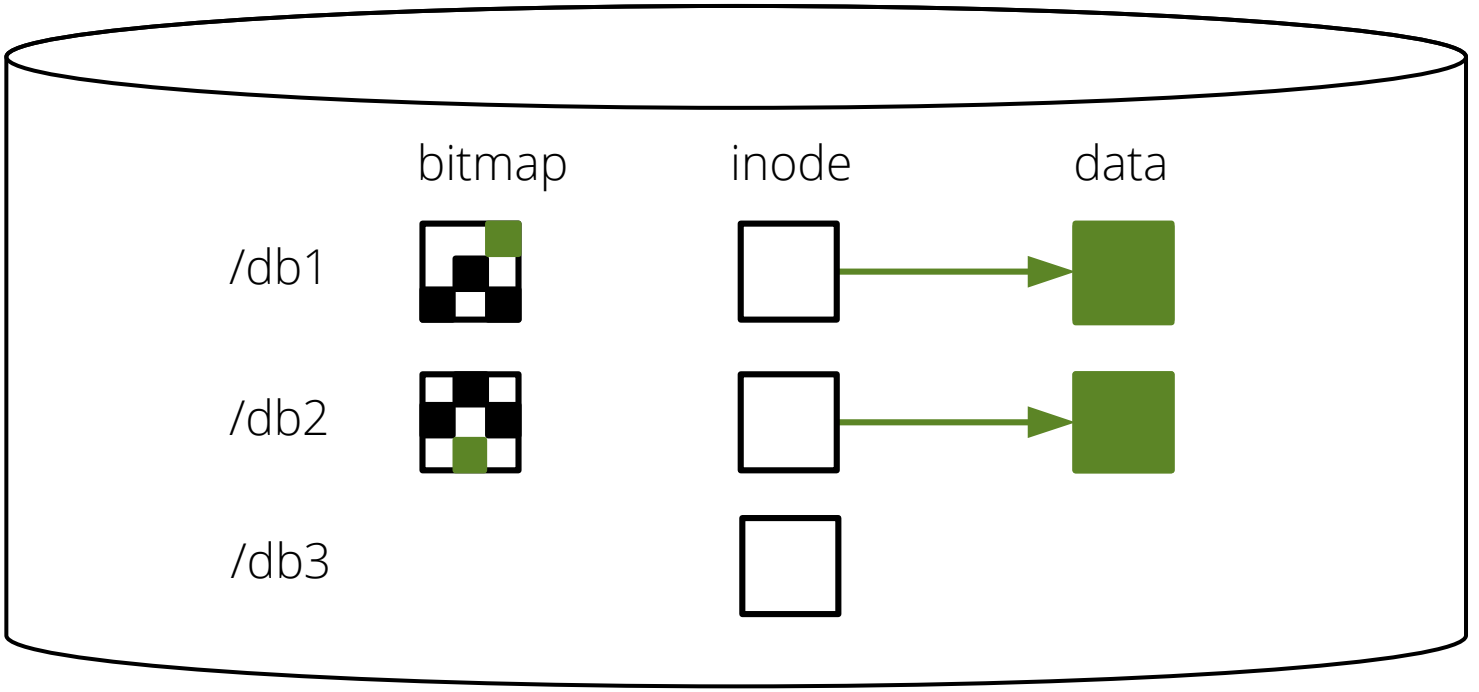


Example: Two apps. are running

Application

```
+ cfs_begin();
  write(/db1, "new");
  write(/db2, "new");
+ cfs_commit();
```

Transactional Flash



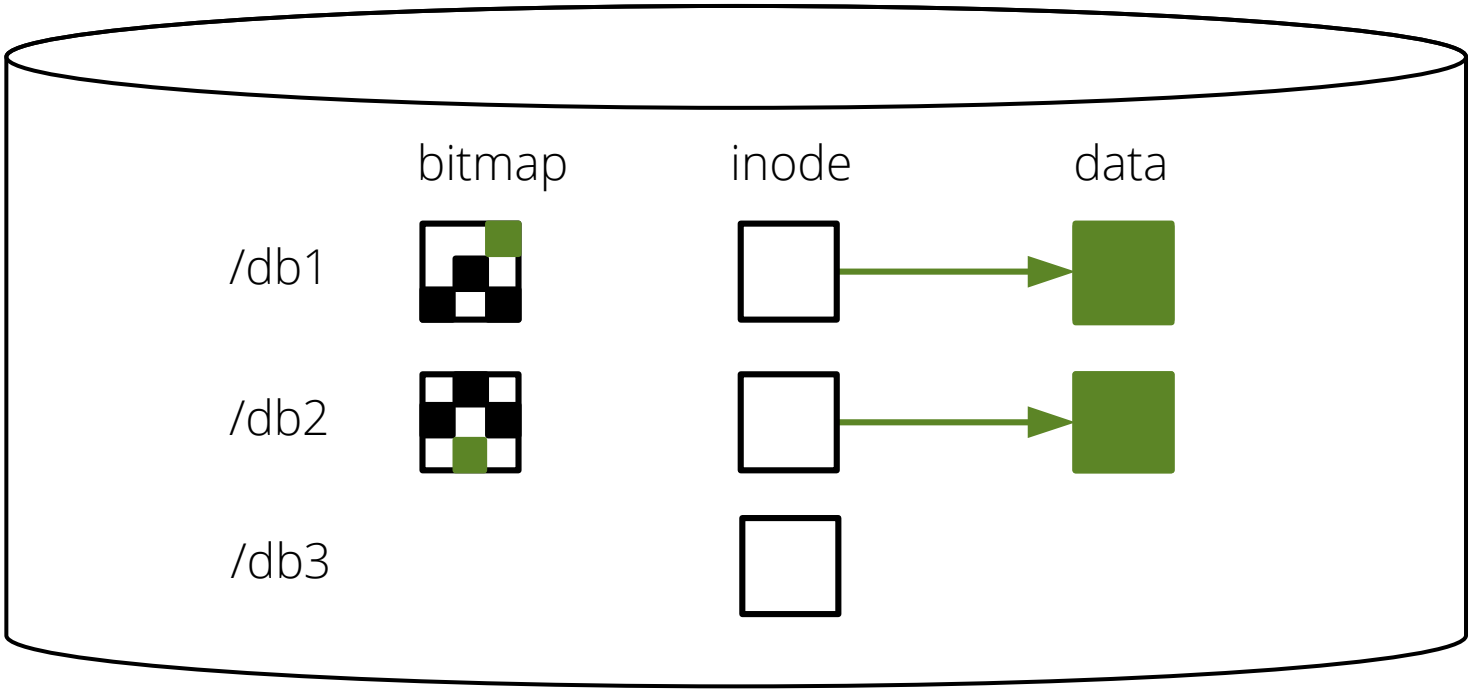
Example: Two apps. are running

Application

```
+ cfs_begin();
  write(/db1, "new");
  write(/db2, "new");
+ cfs_commit();
```

```
+ cfs_begin();
  write(/db3, "new");
  ...
```

Transactional Flash



Example: Two apps. are running

Application

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  write(/db1, "new");
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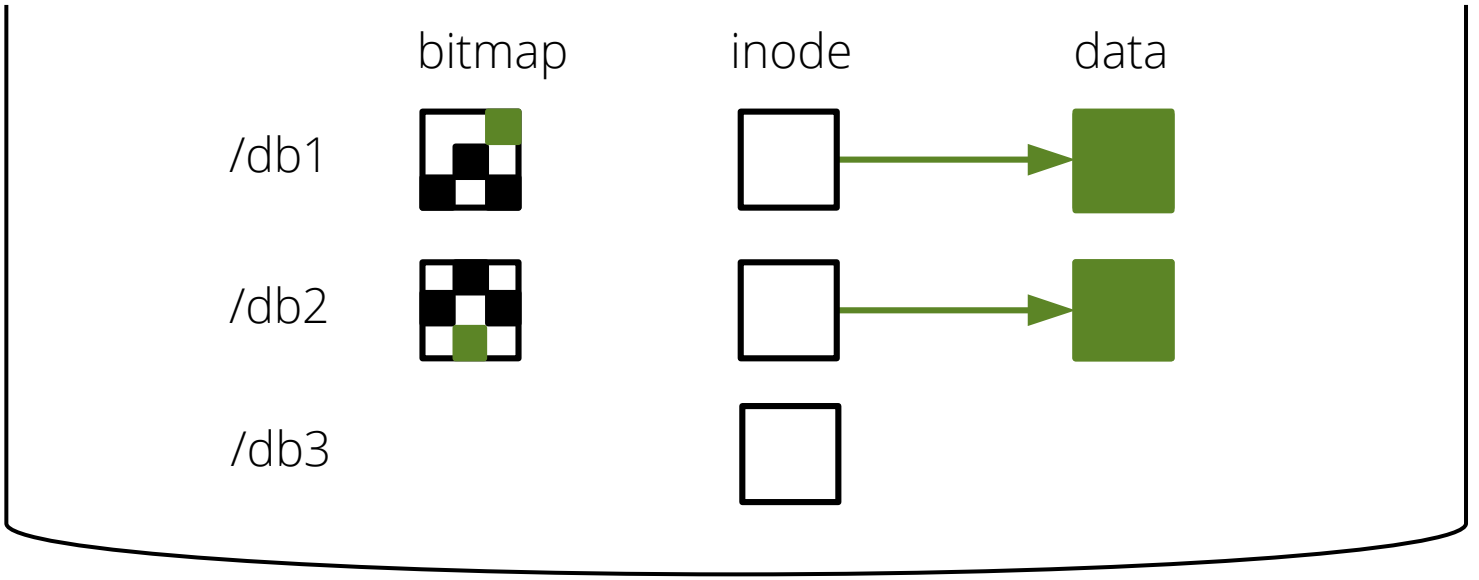
+ cfs_commit();
```

```
+ cfs_begin();
  write(/db3, "new");
  ...
```

What if /db3 bitmap locates in the /db2 bitmap?

Transactional Flash



Example: Two apps. are running

Application

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  write(/db3, "new");
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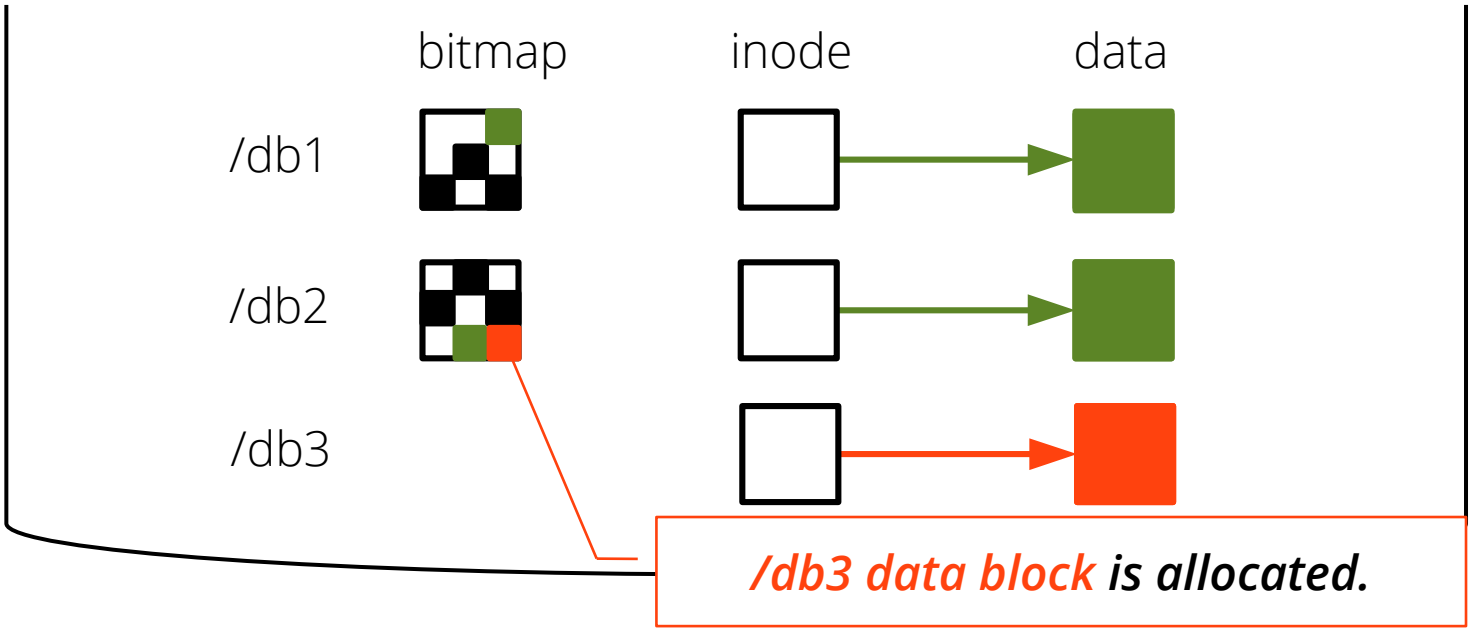

Example: Two apps. are running

Application

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  write(/db1, "new");
  write(/db2, "new");
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```

```
+ cfs_begin();
  write(/db3, "new");
  ...
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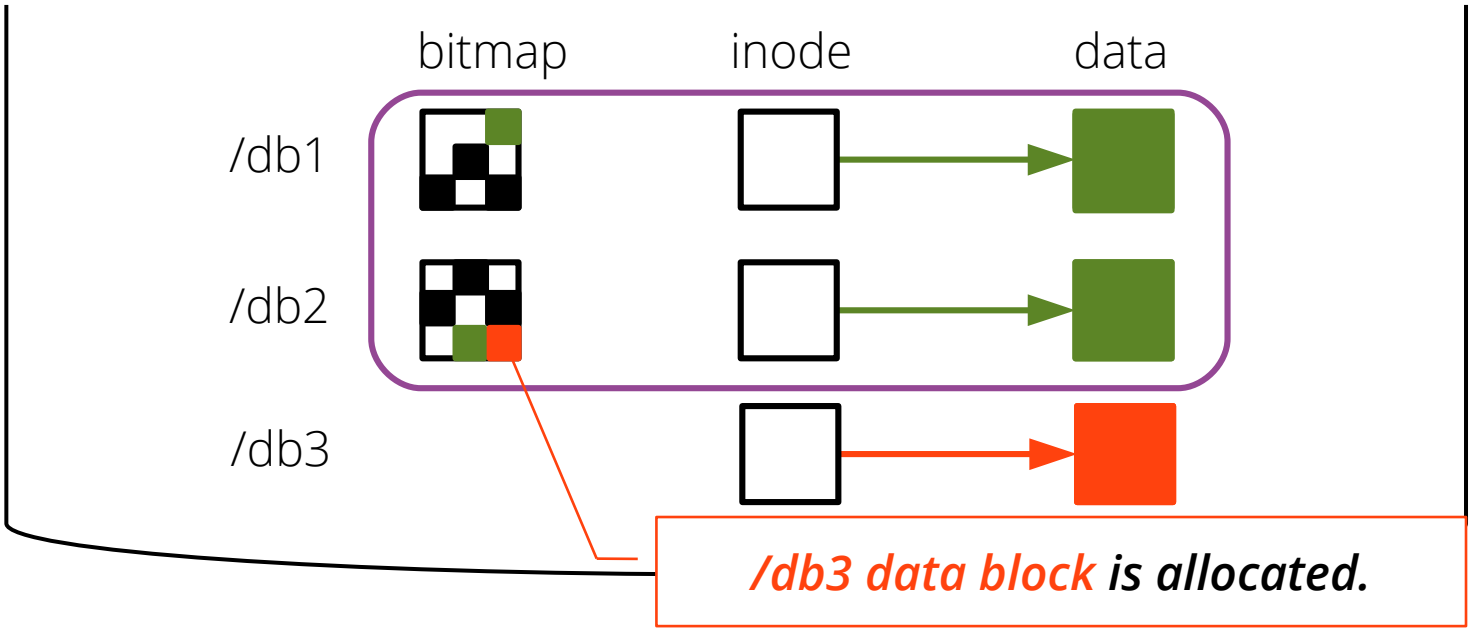
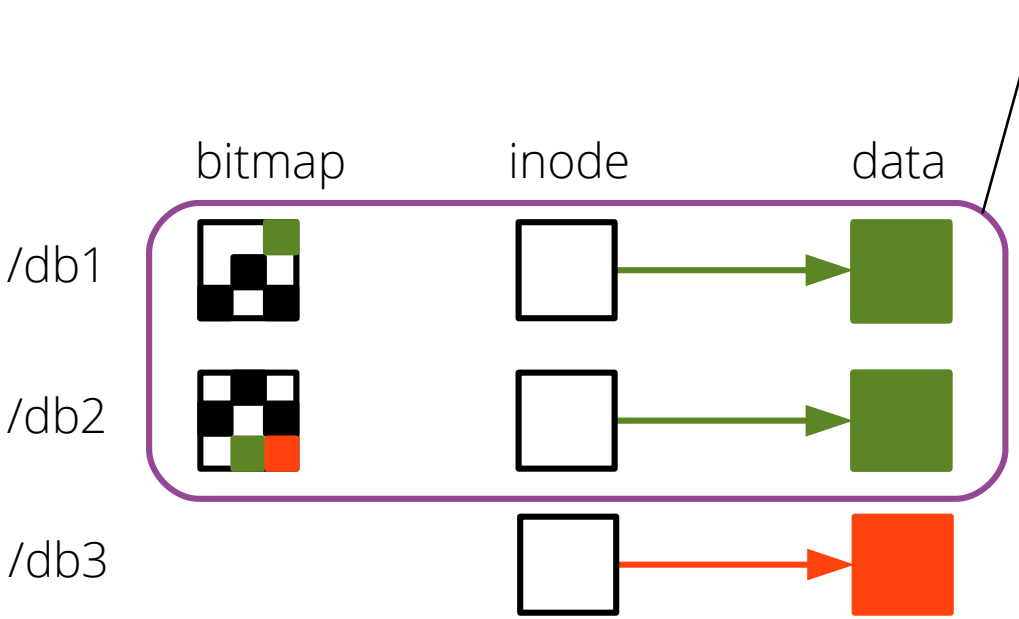
What if /db3 bitmap locates in the /db2 bitmap?

Transactional Flash



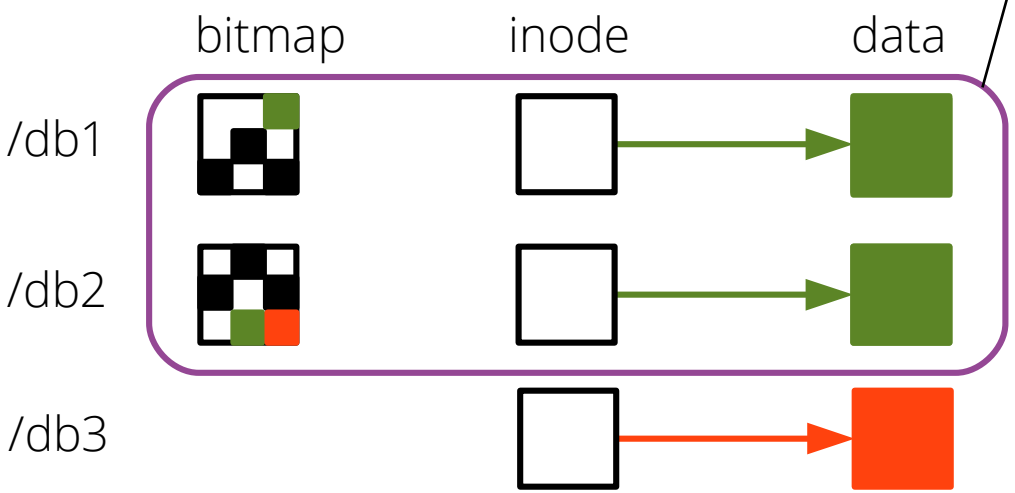
Problem: entangled disk pages



1. cfs_commit()

- /db1 and /db2 are persistent

Problem: entangled disk pages



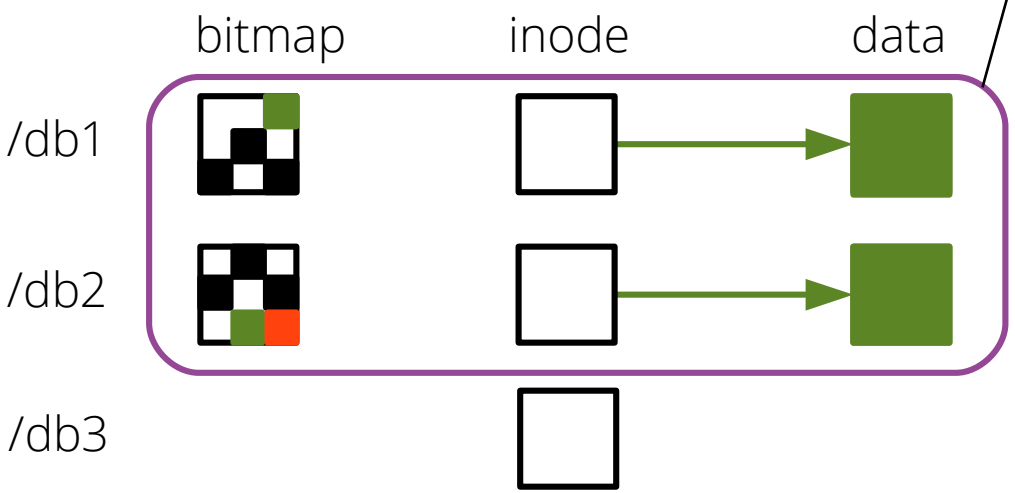
1. cfs_commit()

- /db1 and /db2 are persistent

2. Sudden Power Outage

- /db3 changes are lost.

Problem: entangled disk pages



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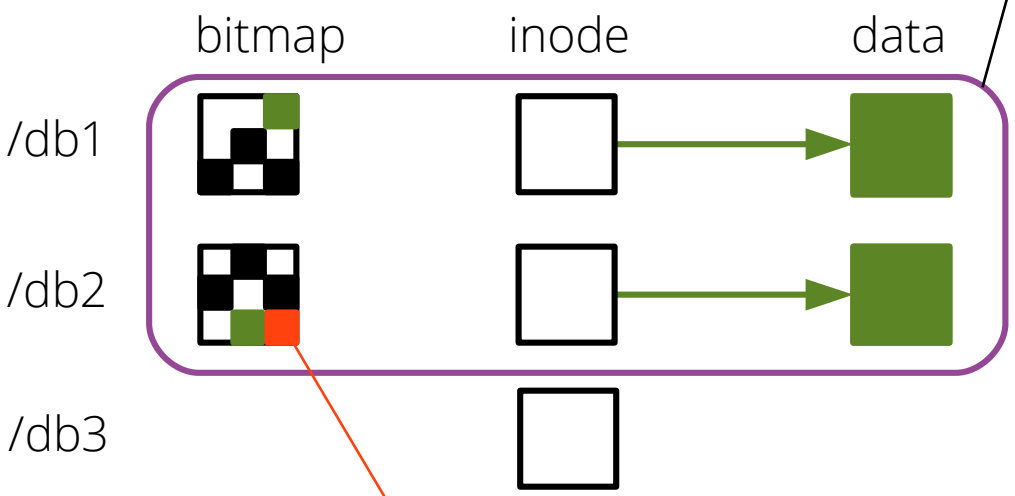


1. cfs_commit()

- /db1 and /db2 are persistent

2. Sudden Power Outage

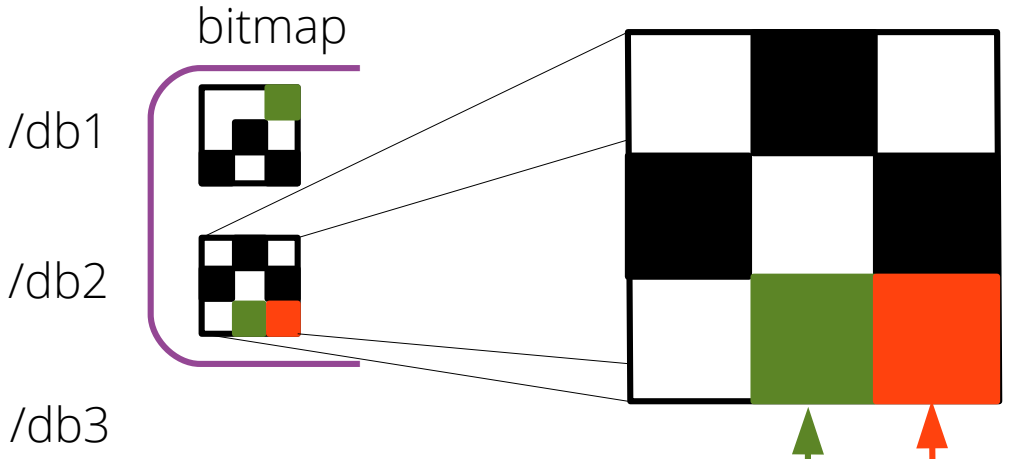
- /db3 changes are lost.

~~*/db3 data block*~~ ***is allocated.***

Incorrect bitmap

- Free block is marked as allocated.

Problem: entangled disk pages



False Sharing of Metadata Pages

```
+ cfs_begin();
  write(/db1, "new");
  write(/db2, "new");
+ cfs_commit();
```

```
+ cfs_begin();
  write(/db3, "new");
  ...
- sudden power outage
```

#2. Metadata False Sharing : In-Memory Metadata Logging

- Operational Logging for in-memory metadata change
  - *toggle_bit(free_block_bitmap, LBA)*
  - *sub(free_block_count, 1)*
- Maintain two versions of in-memory metadata to selectively propagate only relevant changes to storage
  - Memory version: on-going modification
  - Storage version: committed version, used for storage IO

REDO or UNDO operational logs

```
cfs_commit() {
  storage version += REDO(logs);
  write(txid, storage version);
  commit(txid);
}
```

```
cfs_abort() {
  memory version -= UNDO(logs);
  abort(txid);
}
```

Example: Two apps. are running

In-Memory Metadata

bitmap

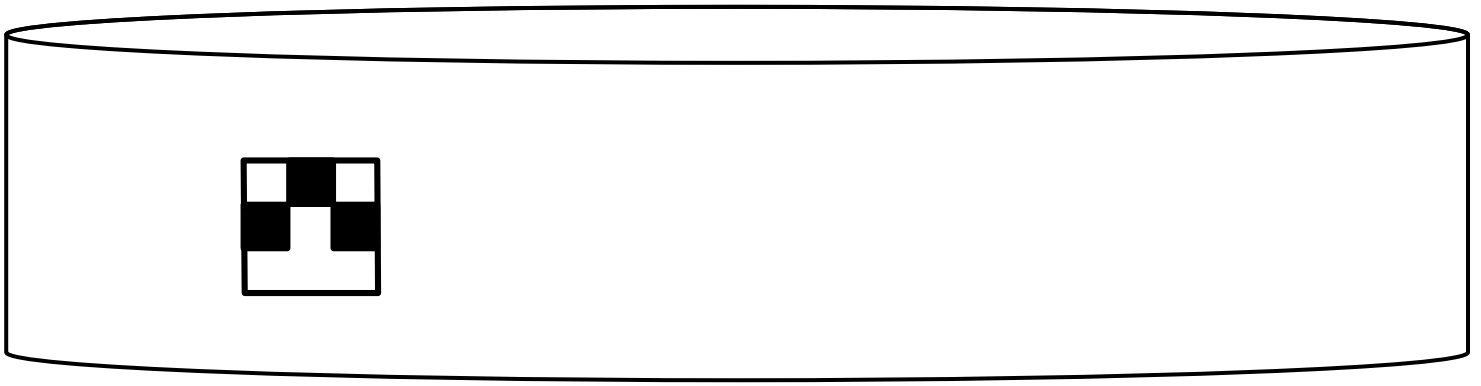
Memory Version

Storage Version

Operational Log for Atomic Propagation Group

App 1	App 2
Turn on a bit	Turn on a bit

Transactional Flash



Example: Two apps. are running

In-Memory Metadata

bitmap

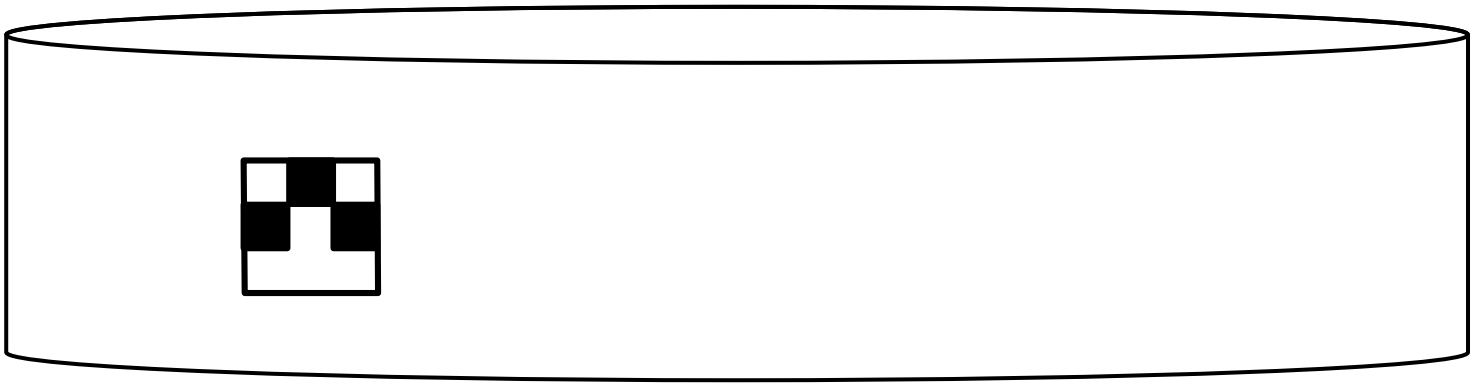
Memory Version

Storage Version

Operational Log for Atomic Propagation Group

App 1	App 2
Turn on a bit	Turn on a bit
cfs_commit()	

Transactional Flash



Example: Two apps. are running

In-Memory Metadata

bitmap

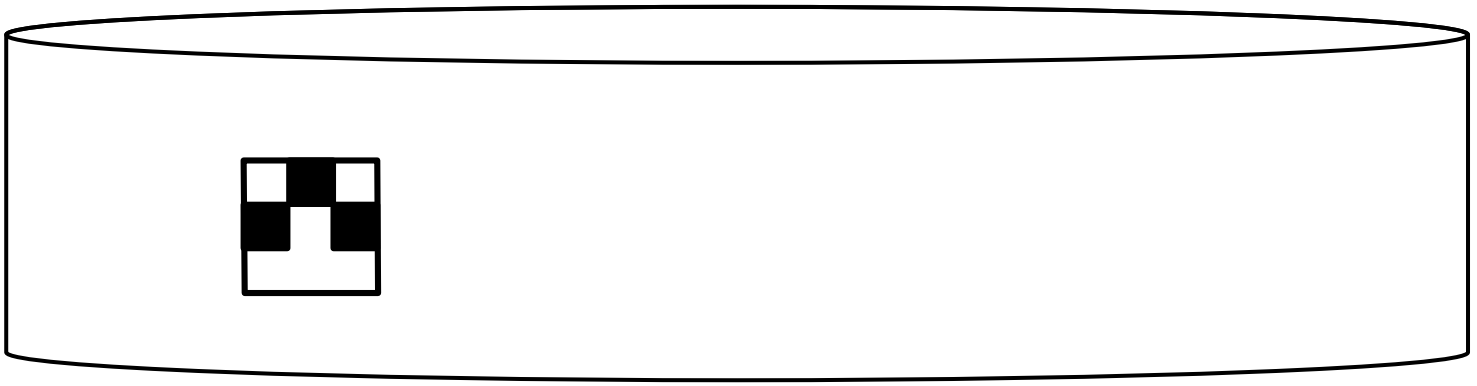
Memory Version

Storage Version

Operational Log for Atomic Propagation Group

App 1	App 2
✅ Turn on a bit	Turn on a bit
cfs_commit()	

Transactional Flash



Example: Two apps. are running

***Bitmap for db3* is not written.**

Operational Log
for Atomic Propagation Group

App 1	App 2
✅ Turn on a bit	Turn on a bit
✅ cfs_commit()	

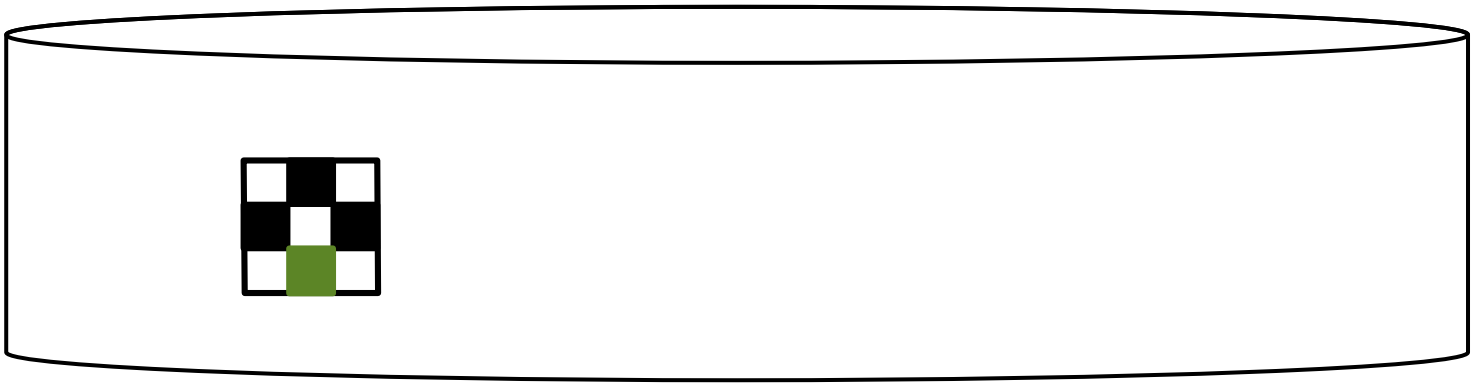
In-Memory Metadata

bitmap

Memory Version

Storage Version

Transactional Flash



Example: Two apps. are running

Bitmap for db3 ***is not written.***

Operational Log
for Atomic Propagation Group

App 1	App 2
✅ Turn on a bit	Turn on a bit
✅ cfs_commit()	cfs_abort()

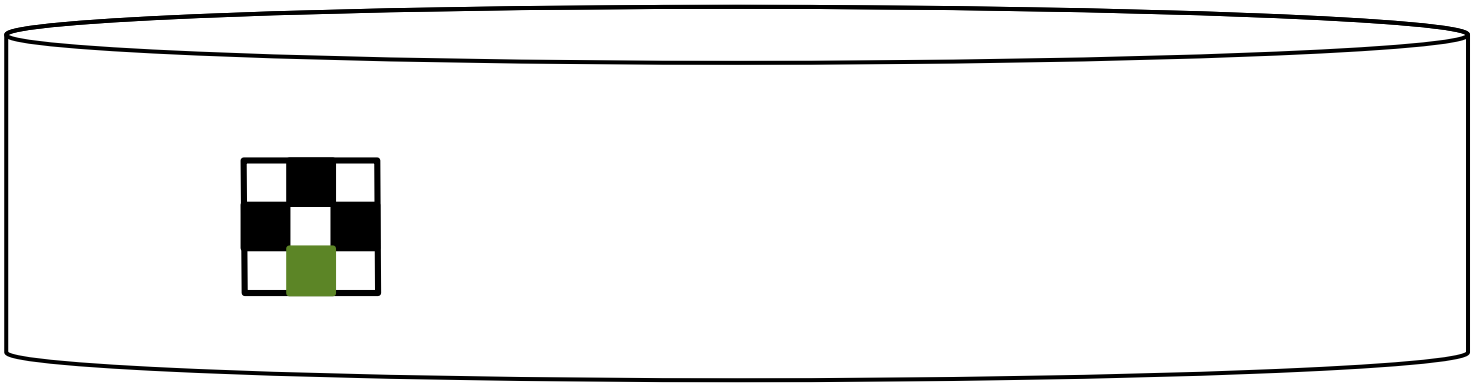
In-Memory Metadata

bitmap

Memory Version

Storage Version

Transactional Flash



Example: Two apps. are running

***Bitmap for db3* is reverted.**

In-Memory Metadata

bitmap

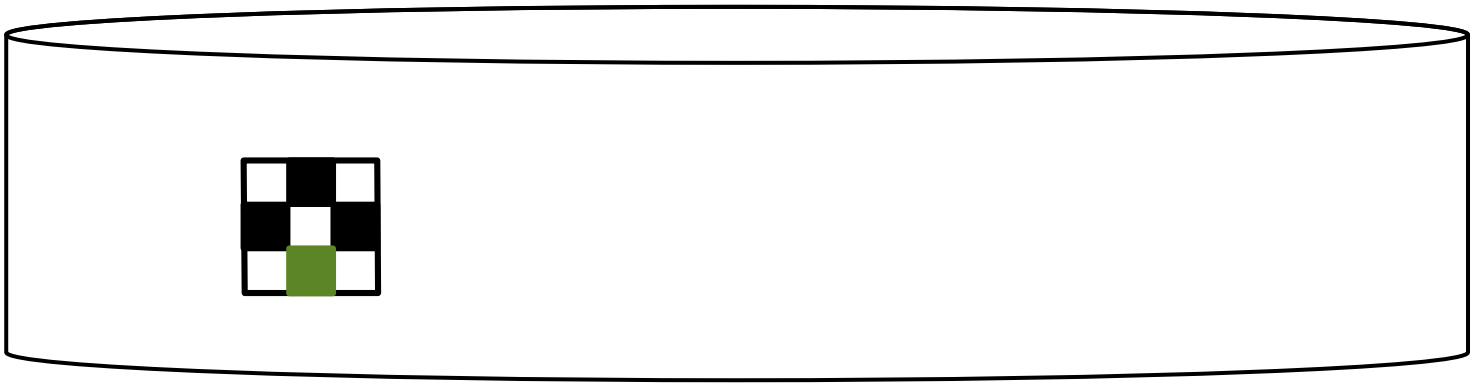
Memory Version

Storage Version

Operational Log for Atomic Propagation Group

App 1	App 2
Turn on a bit	Turn on a bit
cfs_commit()	cfs_abort()

Transactional Flash



Example: Two apps. are running

***Bitmap for db3* is reverted.**

In-Memory Metadata

bitmap

Memory Version

Storage Version

Operational Log for Atomic Propagation Group

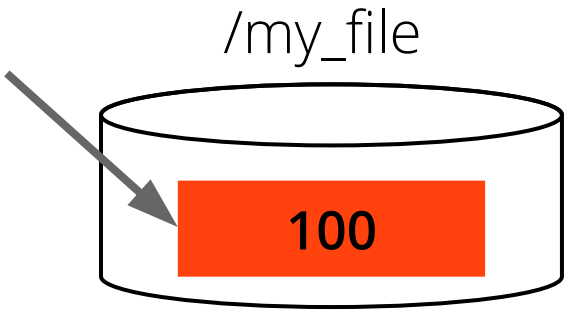
App 1	App 2
Turn on a bit	Turn on a bit
cfs_commit()	cfs_abort()

Transactional Flash

Selective Propagation of Metadata Change

#3. Isolation? Concurrency Control? : Leave It to Application

```
cfs_begin();
write(/my_file, “200”);
...
```



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cfs_begin();
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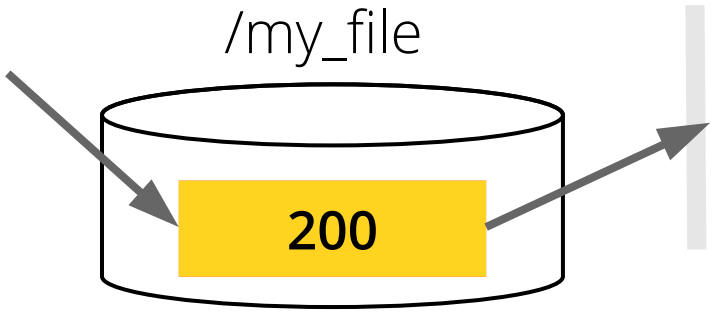
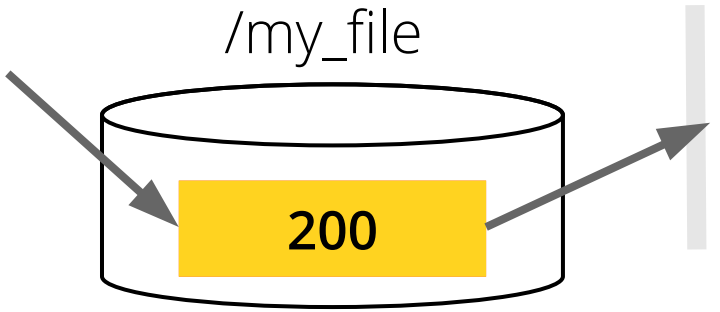



```
cfs_begin();
val = read(/my_file);
…
```

#3. Isolation? Concurrency Control? : Leave It to Application

```
cfs_begin();
write(/my_file, “200”);
…
```

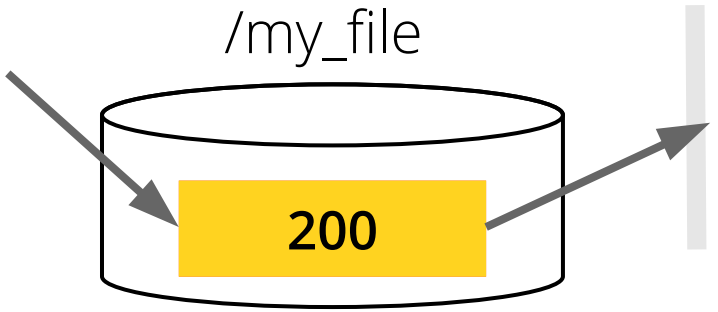



```
cfs_begin();
val = read(/my_file);
…
```

What *val* should be either of *100* or *200*?

#3. Isolation? Concurrency Control? : Leave It to Application

```
cfs_begin();
write(/my_file, “200”);
…
```

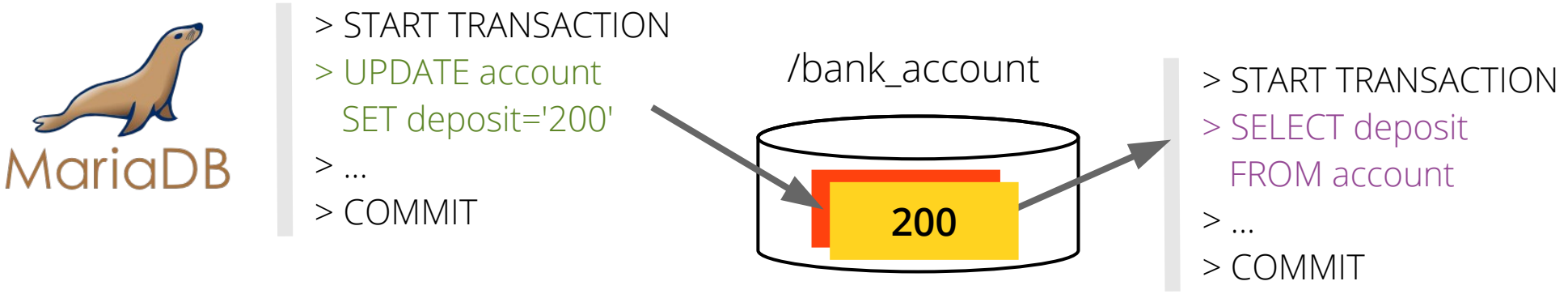



```
cfs_begin();
val = read(/my_file);
…
```

What *val* should be either of *100* or *200*?

It depends on application semantics.

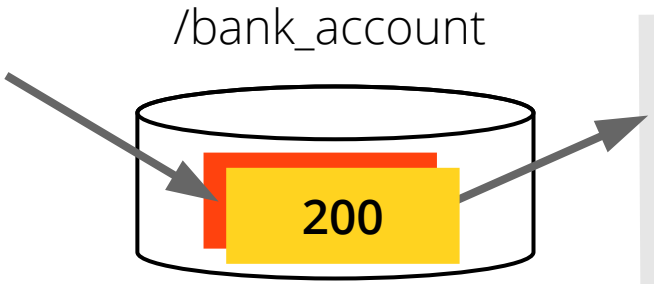
#3. Isolation? Concurrency Control? : Leave It to Application



Deposit of bank account must be 200.

#3. Isolation? Concurrency Control? : Leave It to Application

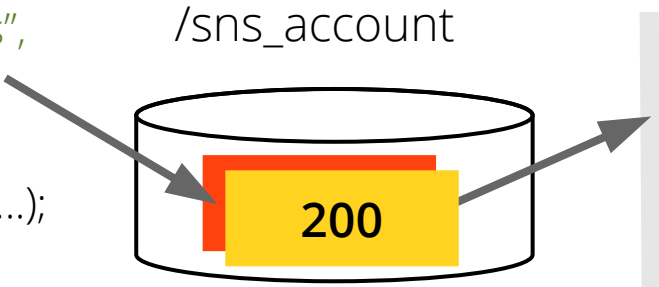

```
> START TRANSACTION
> UPDATE account
  SET deposit='200'
> ...
> COMMIT
```




```
> START TRANSACTION
> SELECT deposit
  FROM account
> ...
> COMMIT
```

Deposit of bank account must be 200.


```
KV→begin_transaction(...);
KV→set("account.likes",
        "200");
...
KV→end_transaction(...);
```




```
KV→begin_transaction(...);
KV→get("account.deposit");
...
...
KV→end_transaction(...);
```

Likes of SNS account can be either of 100 or 200.

#3. Isolation? Concurrency Control? : Leave It to Application

- Isolation and crash-consistency are orthogonal.
  - Even the SQL standard defines four different isolation levels.
- CFS does not provide its own concurrency control mechanism.
  - If needed, use existing synchronization primitives (e.g., mutex, RW lock, etc).

#4. Legacy Application Support

- System-Wide Atomic Propagation Group
  - Every update from legacy applications belongs.
  - Automatically committed by sync() or page flusher

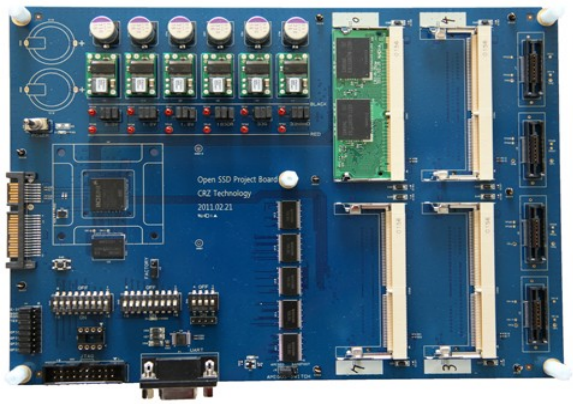
CFS supports legacy applications without any modification.

Outline

- Introduction
- CFS Design
- **Evaluation**
- Conclusion

Implementation

- CFS
  - 5.8k LoC modification of ext4 on Linux 3.10
  - Capture logs by inserting 182 places in ext4
- Transactional Flash
  - OpenSSD: 8KB, 128 pages/block, 8GB w/ SATA2
  - X-FTL/SSD [Kang:SIGMOD'13]



Real Application & Workloads

Mobile Database

+ RLBench
+ Facebook

SQL Database

+ SysBench
+ LinkBench

Key/Value Store

+ kctreetest
+ db_bench

Text Editor

Package Installer

Real Application & Workloads

Mobile Database

+ RLBench
+ Facebook

Text Editor

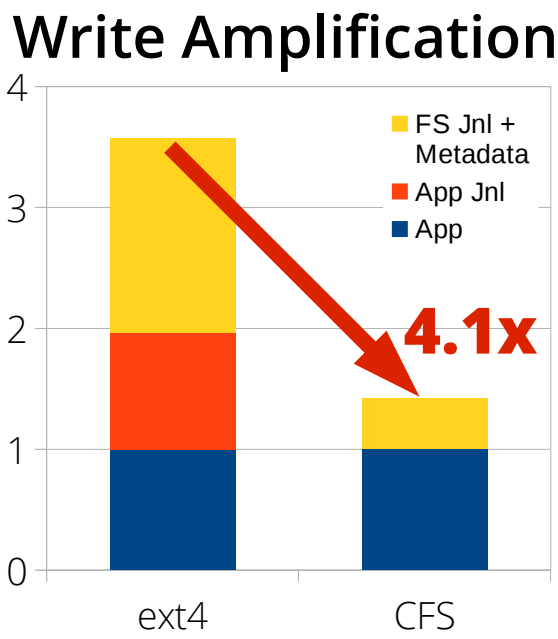
CFS is easy-to-use!
: 317 LoC changes out of 3.5 million

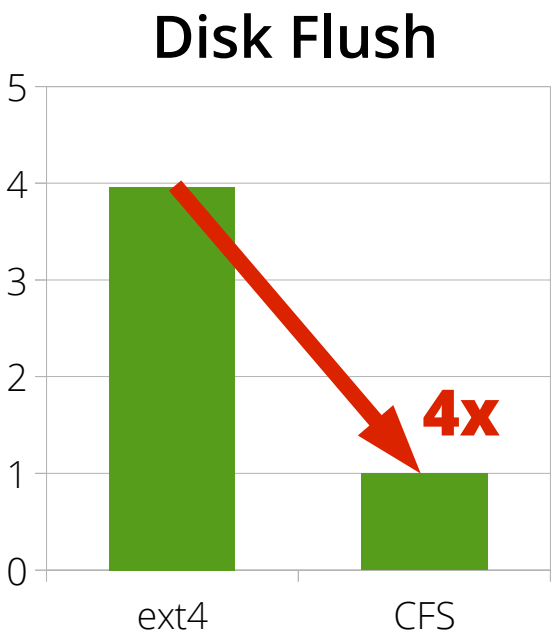
Key/Value Store

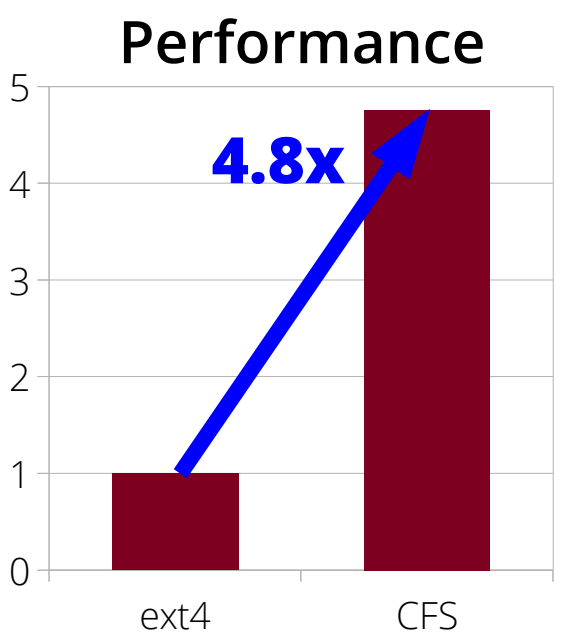
+ kctreetest
+ db_bench

Package Installer

SQLite
+ Facebook App. SQL Trace



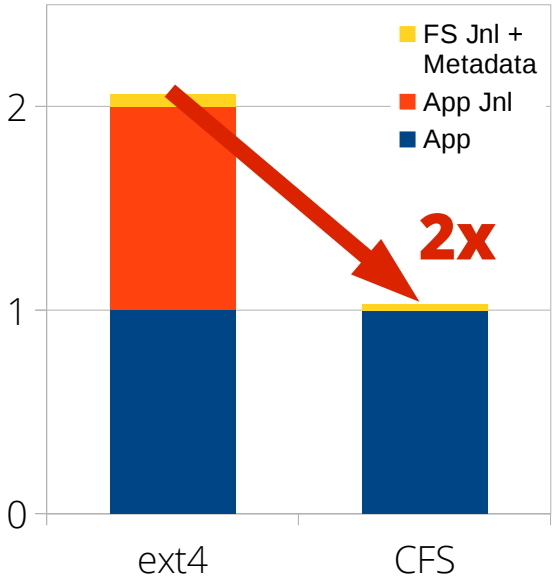




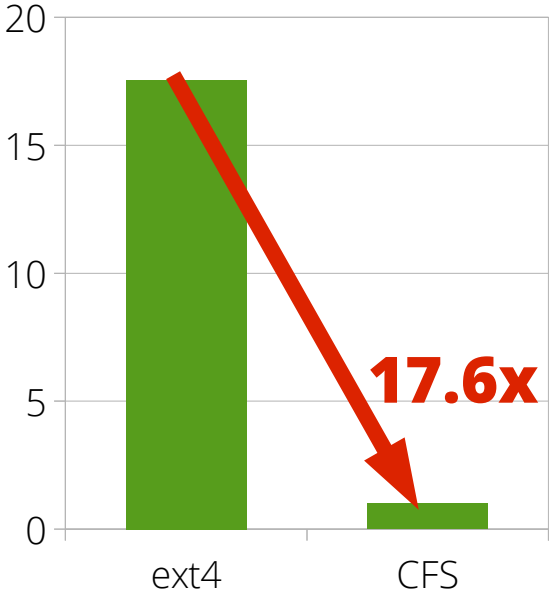
Ext4: ordered journal mode
SQLite: rollback journal mode

MariaDB
+ LinkBench

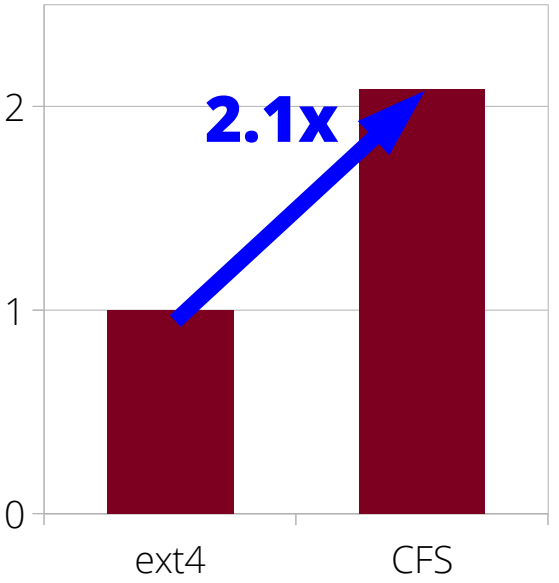
Write Amplification



Disk Flush

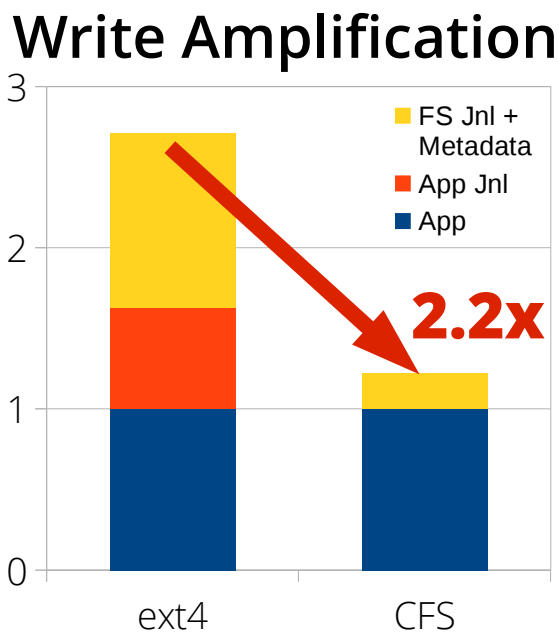


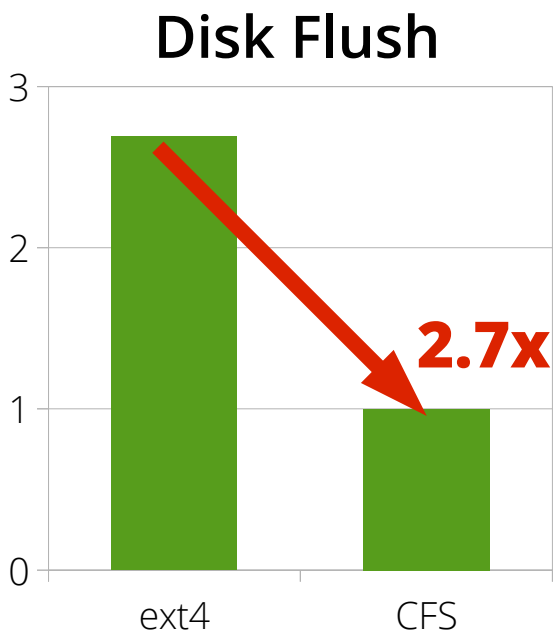
Performance

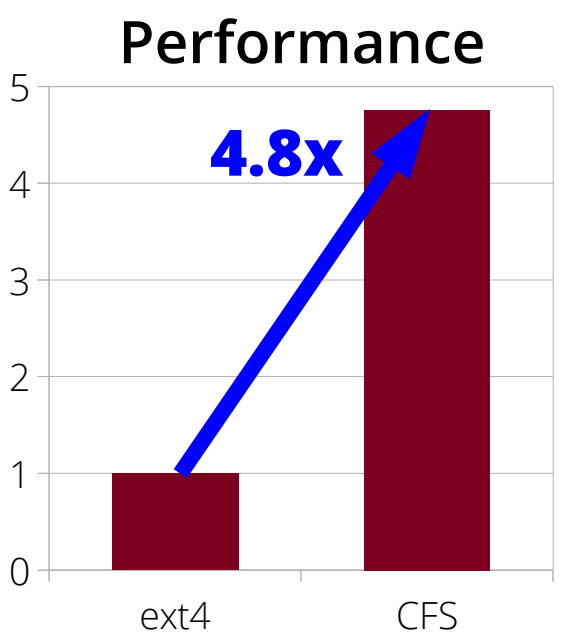


Ext4: ordered journal mode

KyotoCabinet
+ db_bench







Ext4: ordered journal mode

Conclusion

- Current mechanisms for crash consistency is complex, slow, and error-prone.
- CFS simplifies application's crash consistency using transactional flash.
  - Atomic propagation group
  - In-memory metadata logging
- Our evaluation shows
  - Less write: 2 ~ 4x ↓
  - Less disk flush: 3 ~ 17x ↓
  - Higher performance: 2 ~ 5x ↑

Thank you!

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Georgia Institute of Technology
[†]Sungkyunkwan University

Questions?