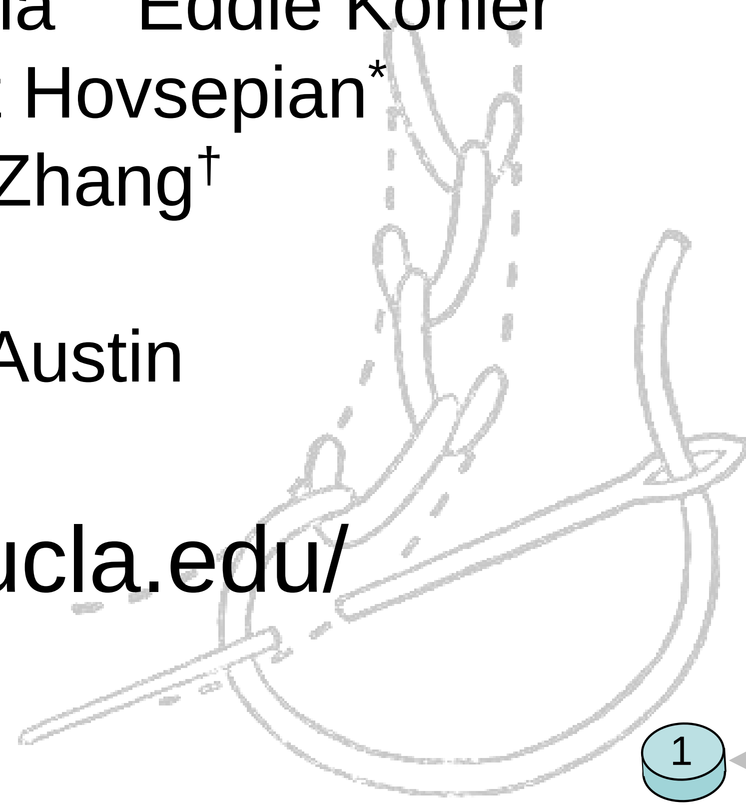
Generalized File System Dependencies

Christopher Frost[*] Mike Mammarella[*] Eddie Kohler[*]
Andrew de los Reyes[†] Shant Hovsepian[*]
Andrew Matsuoka[‡] Lei Zhang[†]

[*]UCLA [†]Google [‡]UT Austin

http://featherstitch.cs.ucla.edu/



Supported by the NSF, Microsoft, and Intel.

Featherstitch Summary

- A new architecture for constructing file systems
- The generalized dependency abstraction
  - Simplifies consistency code within file systems
  - Applications can define consistency requirements for file systems to enforce

File System Consistency

- Want: don’t lose file system data after a crash
- Solution: keep file system consistent after every write
  - Disks do not provide atomic, multi-block writes
- Example: journaling

- Enforce *write-before relationships*

File System Consistency Issues

- Durability features vs. performance
  - Journaling, ACID transactions, WAFL, soft updates
  - Each file system picks one tradeoff
  - Applications get that tradeoff plus sync
- Why no extensible consistency?
  - Difficult to implement
  - Caches complicate write-before relations
  - Correctness is critical

> “Personally, it took me about 5 years to thoroughly understand soft updates and I haven't met anyone other than the authors who claimed to understand it well enough to implement it.” – Valerie Henson

> FreeBSD and NetBSD have each recently attempted to add journaling to UFS.
> Each declared failure.

The Problem

Can we develop a simple, general mechanism
for implementing *any* consistency model?

Yes! With the *patch* abstraction in Featherstitch:

- File systems specify low-level write-before requirements
- The buffer cache commits disk changes, obeying their order requirements

Featherstitch Contributions

- The *patch* and *patchgroup* abstractions
  - Write-before relations become explicit and file system agnostic
- Featherstitch
  - *Replaces* Linux's file system and buffer cache layer
  - ext2, UFS implementations
  - Journaling, WAFL, and soft updates, implemented using just patch arrangements
- Patch optimizations make patches practical

Patches

Problem

Patches for file systems

Patches for applications

Patch optimizations

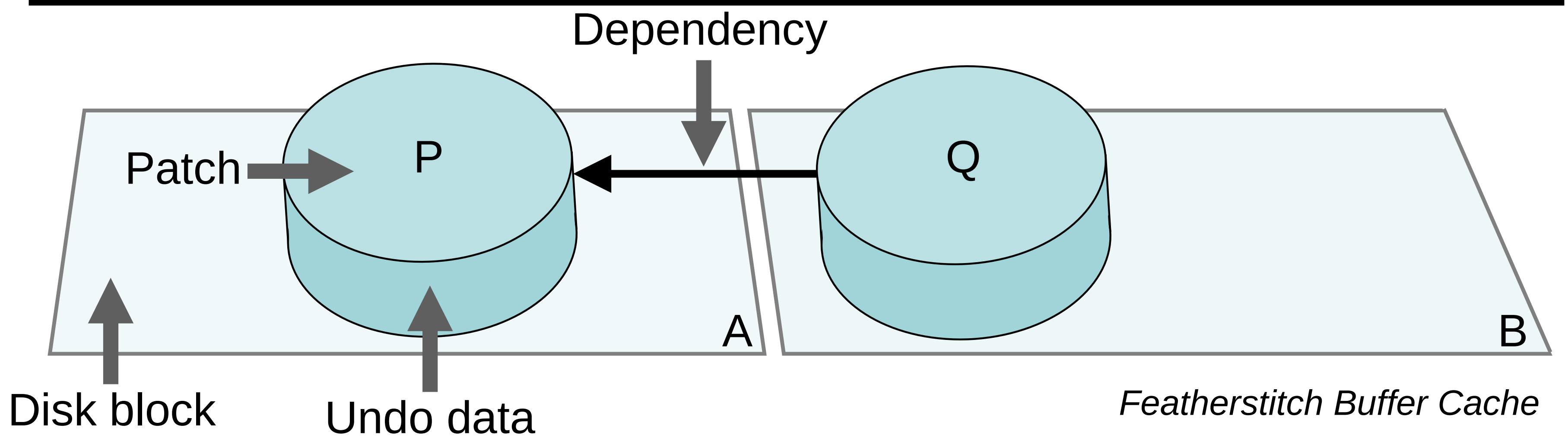
Evaluation

Patch Model

A patch represents:

- a disk data change
- any dependencies on other disk data changes

patch_create(block* **block**, int **offset**, int **length**, char* **data**, patch* **dep**)



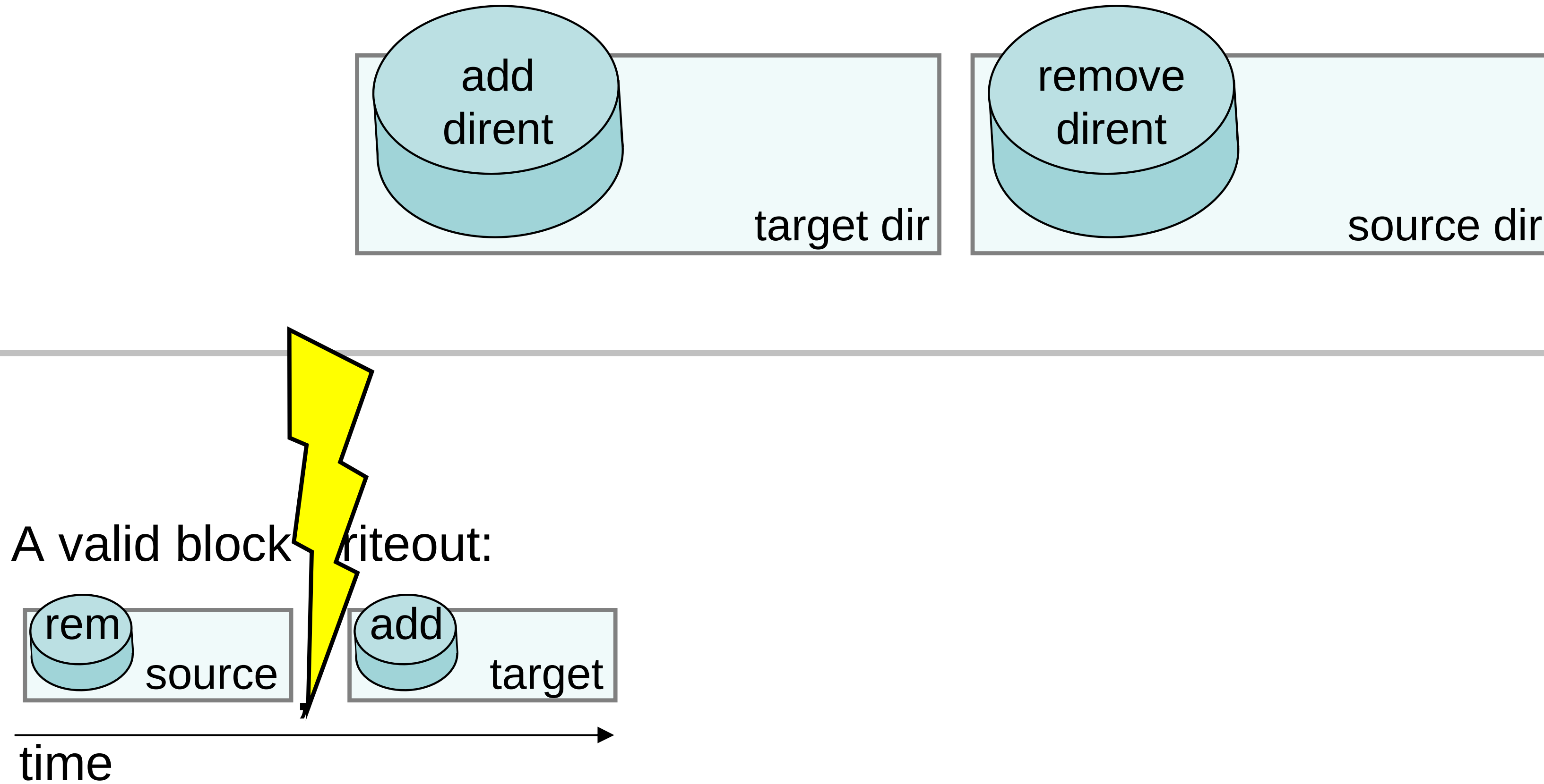
Benefits:

- separate write-before specification and enforcement
- explicit write-before relationships

Base Consistency Models

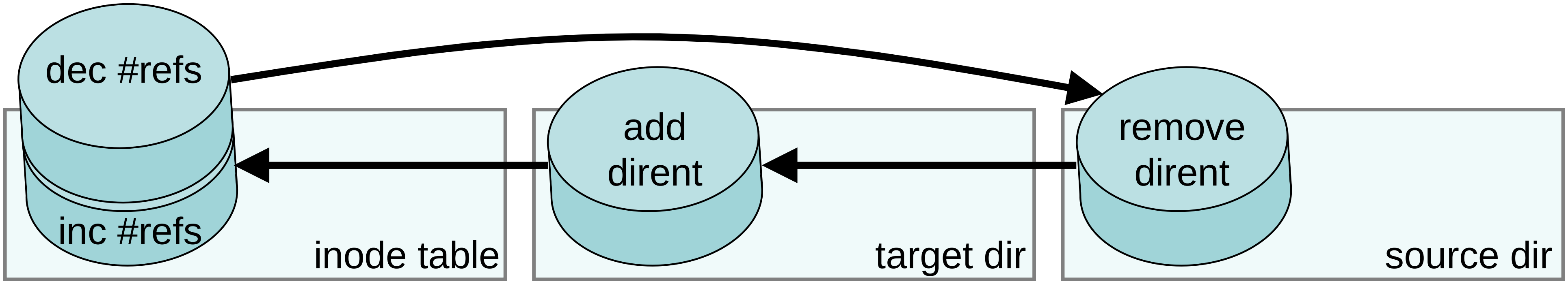
- Fast
  - Asynchronous
- Consistent
  - Soft updates
  - Journaling
- Extended
  - WAFL
  - Consistency in file system images
- All implemented in Featherstitch

Patch Example: Asynchronous rename()



File lost.

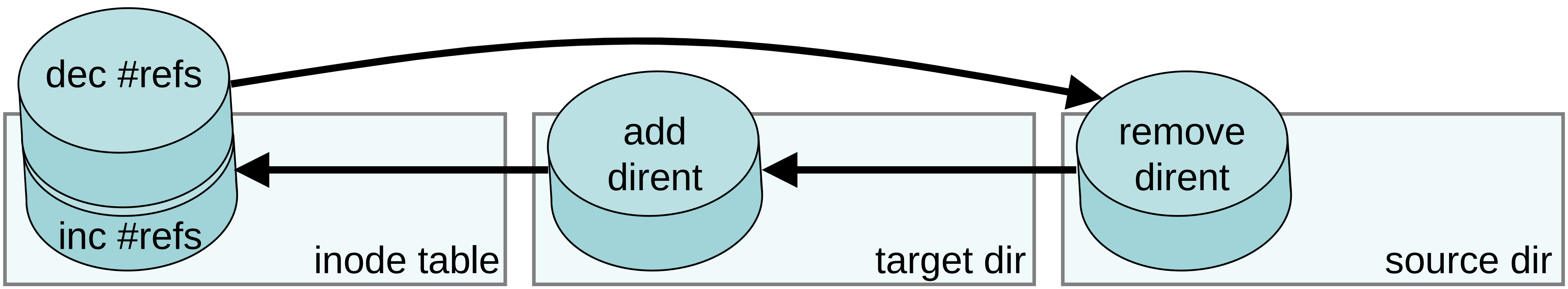
Patch Example: rename() With Soft Updates



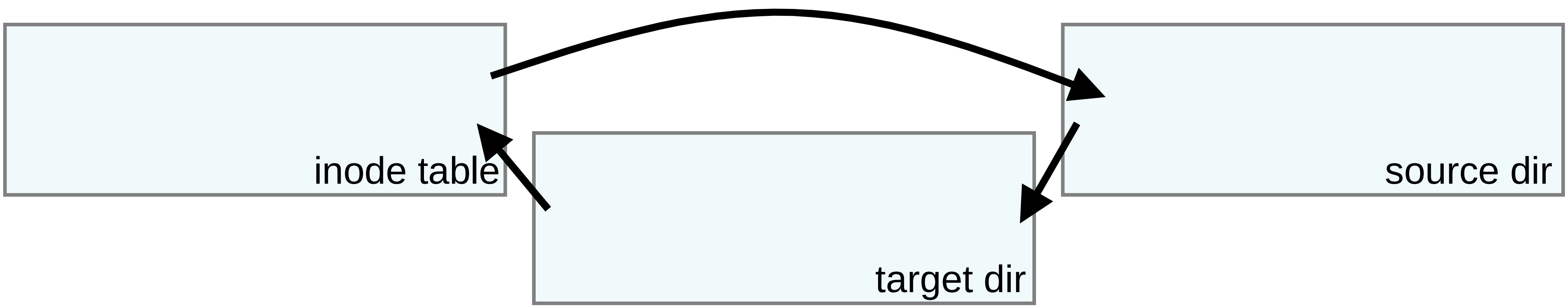
A valid block writeout:

time

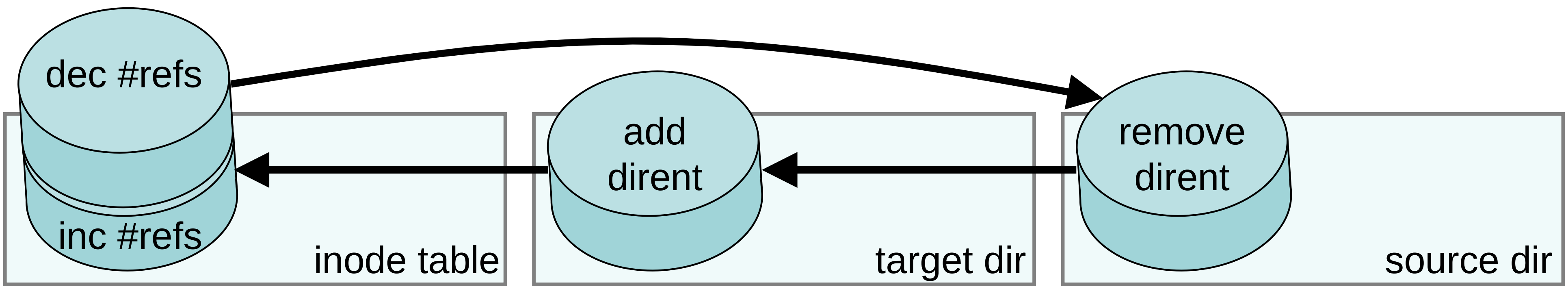
Patch Example: rename() With Soft Updates



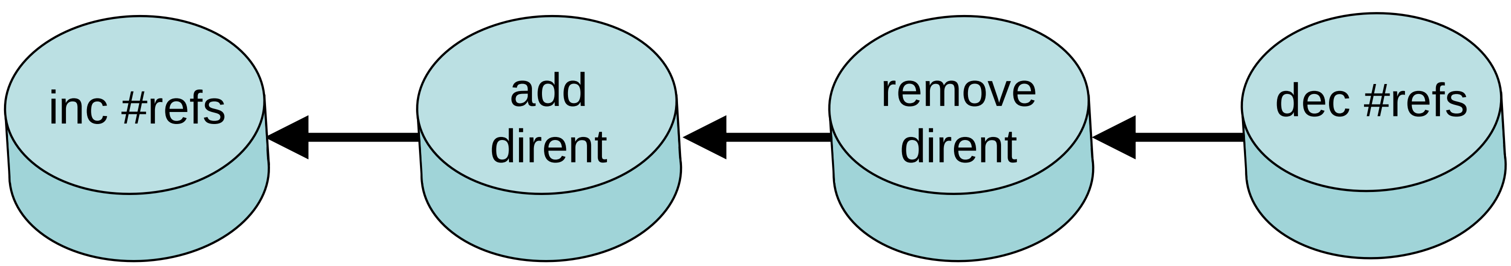
Block level cycle:



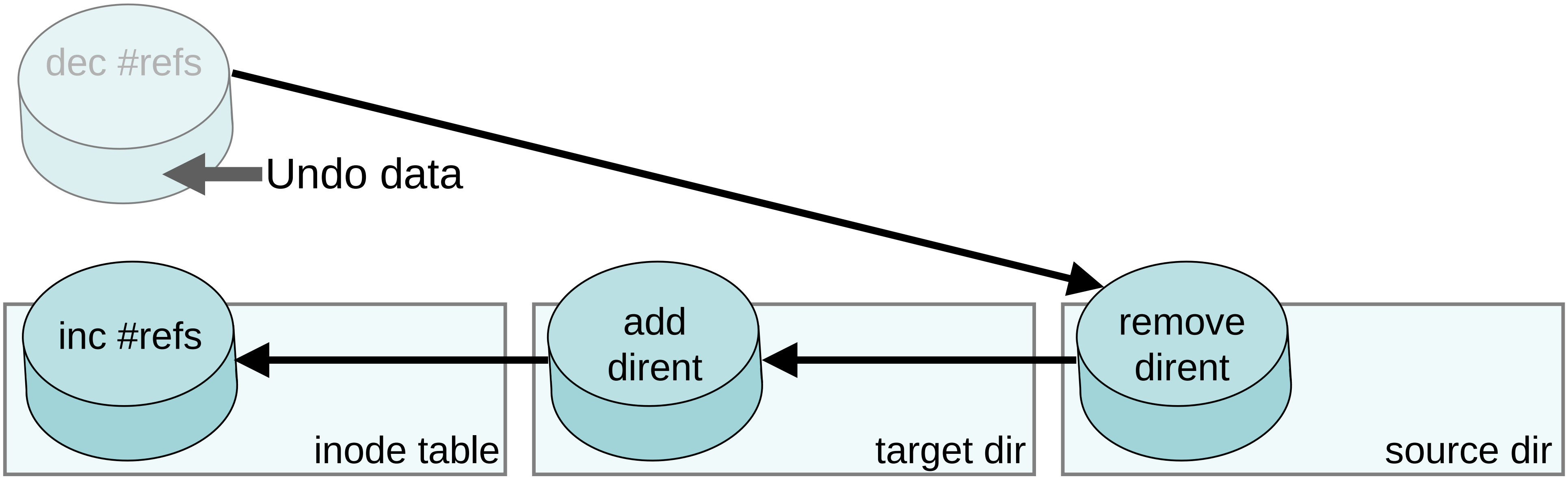
Patch Example: rename() With Soft Updates



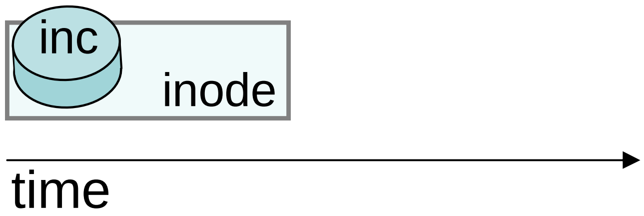
Not a *patch level* cycle:



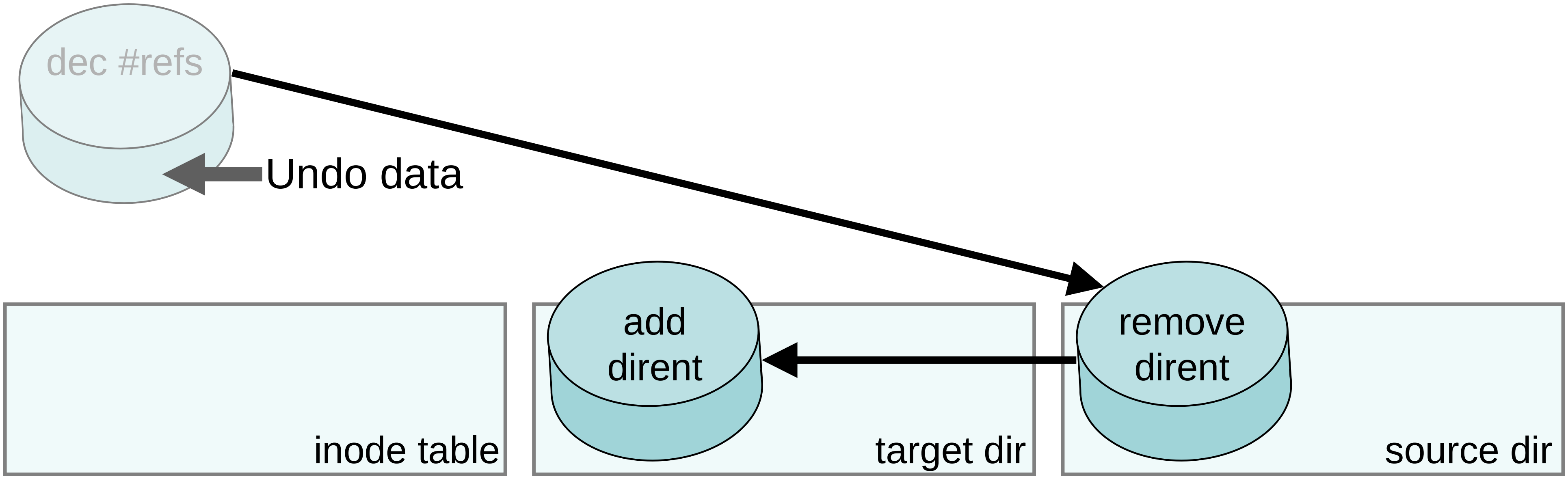
Patch Example: rename() With Soft Updates



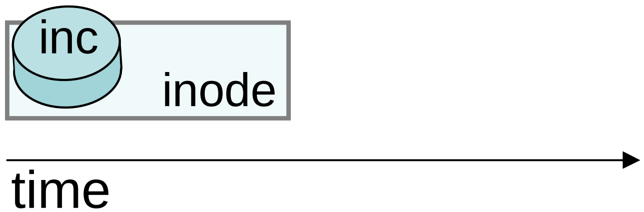
A valid block writeout:



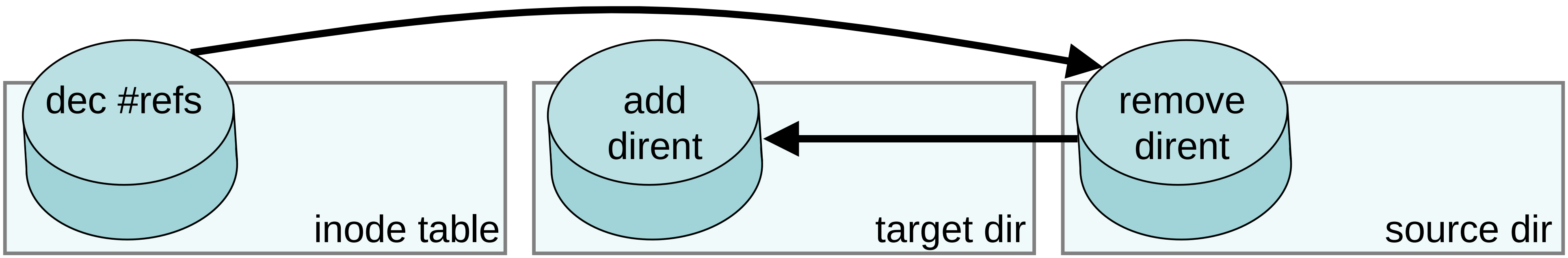
Patch Example: rename() With Soft Updates



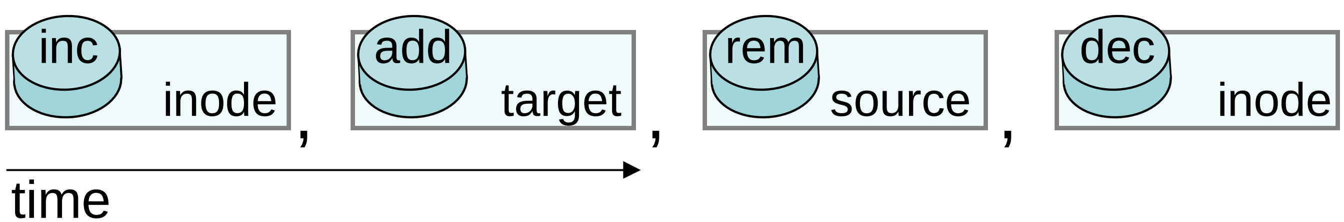
A valid block writeout:



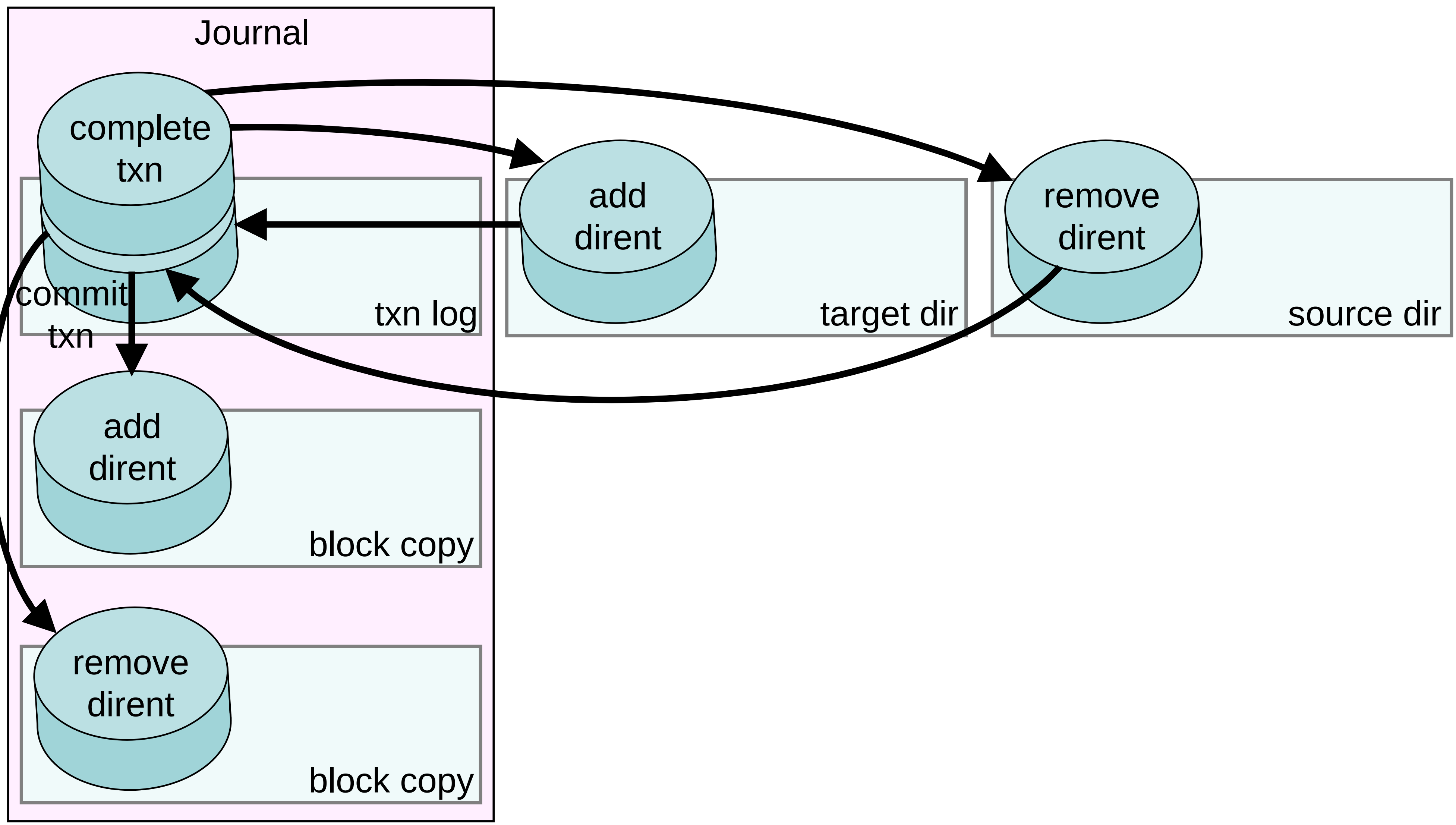
Patch Example: rename() With Soft Updates



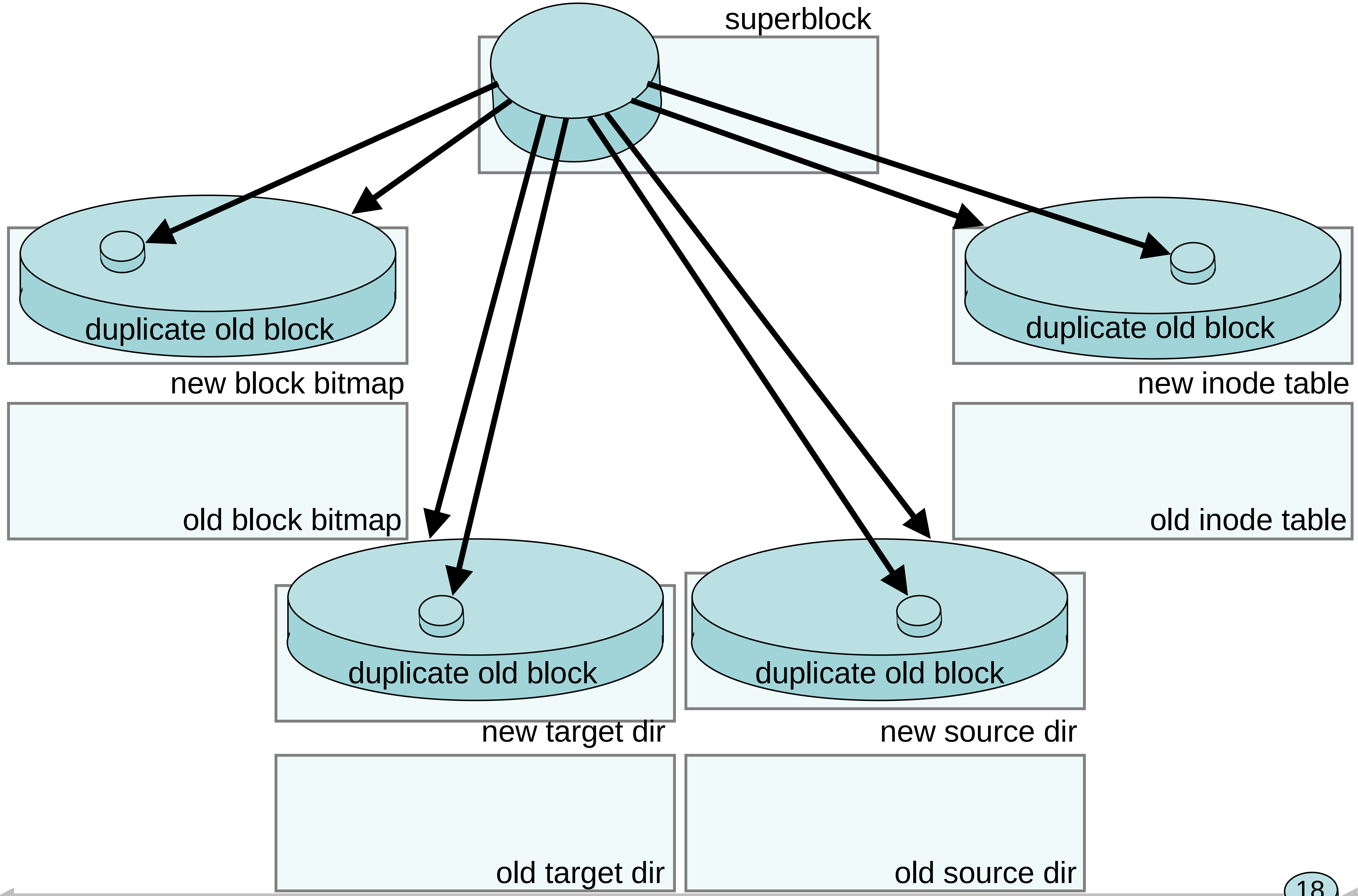
A valid block writeout:



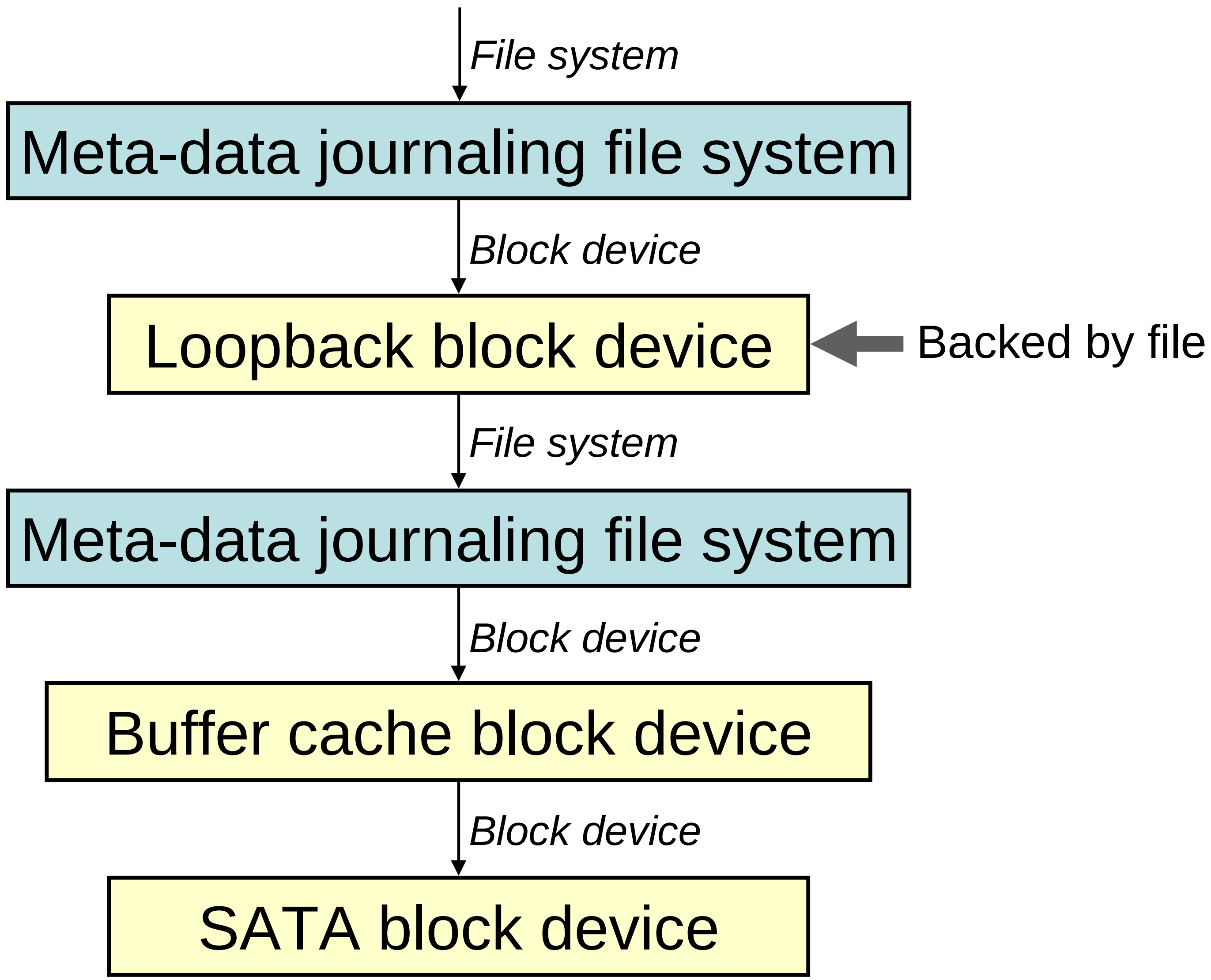
Patch Example: rename() With Journaling



Patch Example: rename() With WAFL



Patch Example: Loopback Block Device



Meta-data journaling file system obeys file data requirements

Patchgroups

Problem

Patches for file systems

Patches for applications

Patch optimizations

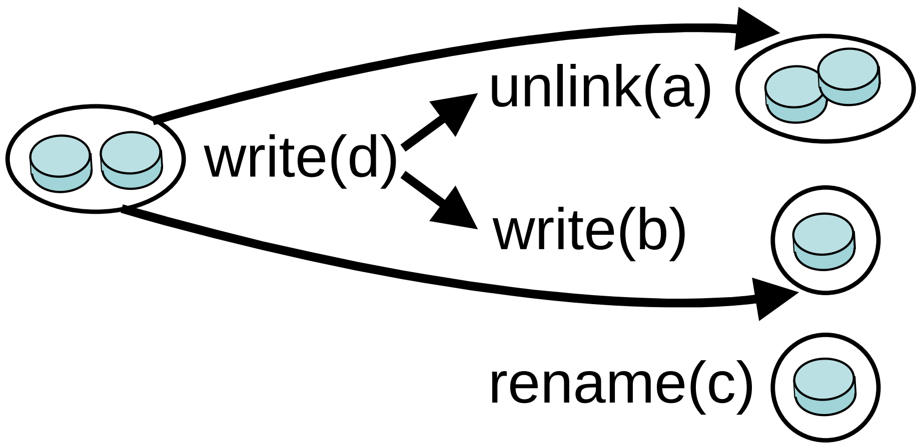
Evaluation

Application Consistency

- Application-defined consistency requirements
  - Databases, Email, Version control
- Common techniques:
  - Tell buffer cache to write to disk immediately (fsync et al)
  - Depend on underlying file system (e.g., ordered journaling)

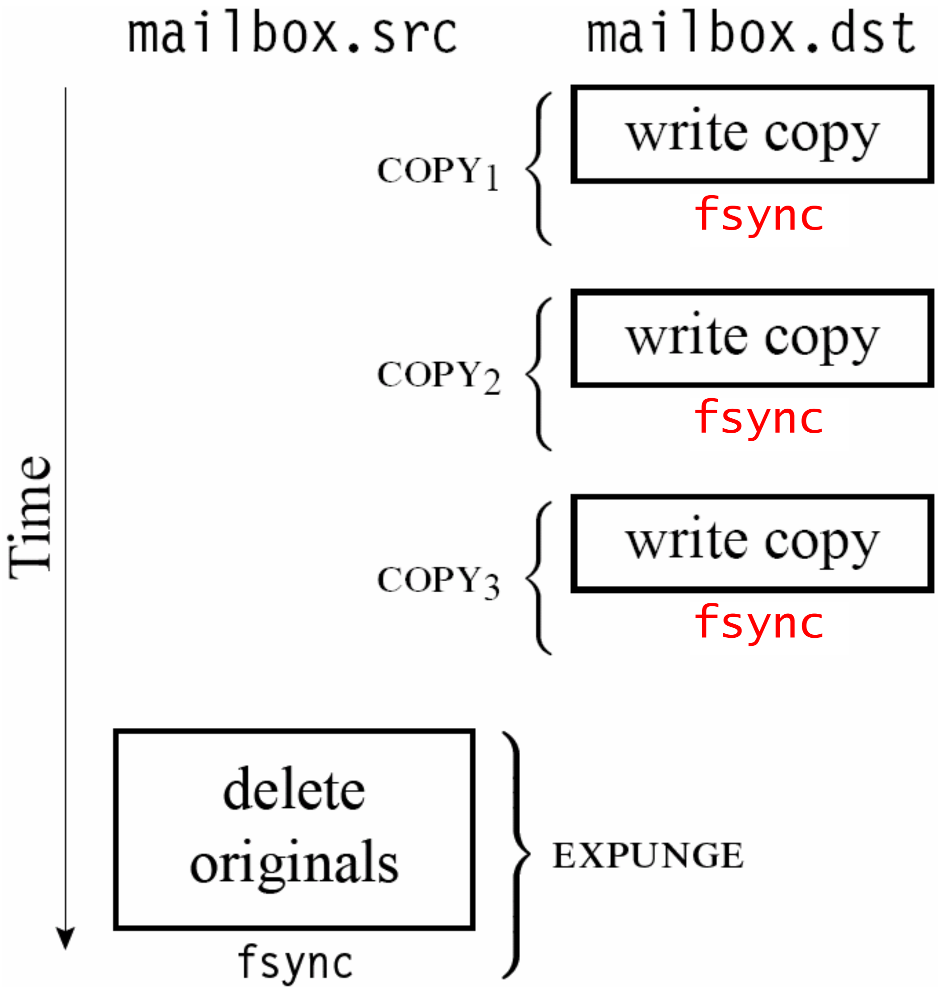
Patchgroups

- Extend patches to applications: *patchgroups*
  - Specify write-before requirements among system calls

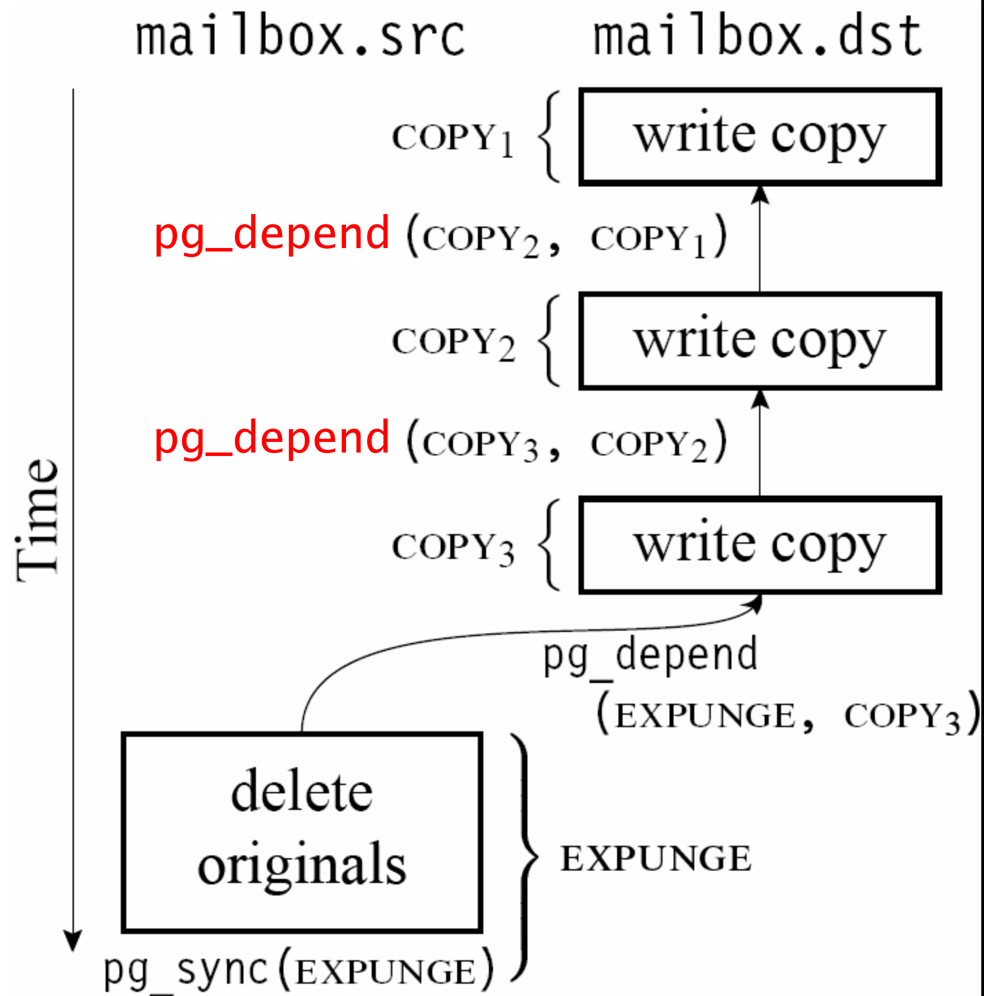


- Adapted gzip, Subversion client, and UW IMAP server

Patchgroups for UW IMAP



Unmodified UW IMAP



Patchgroup UW IMAP

Patch Optimizations

Problem

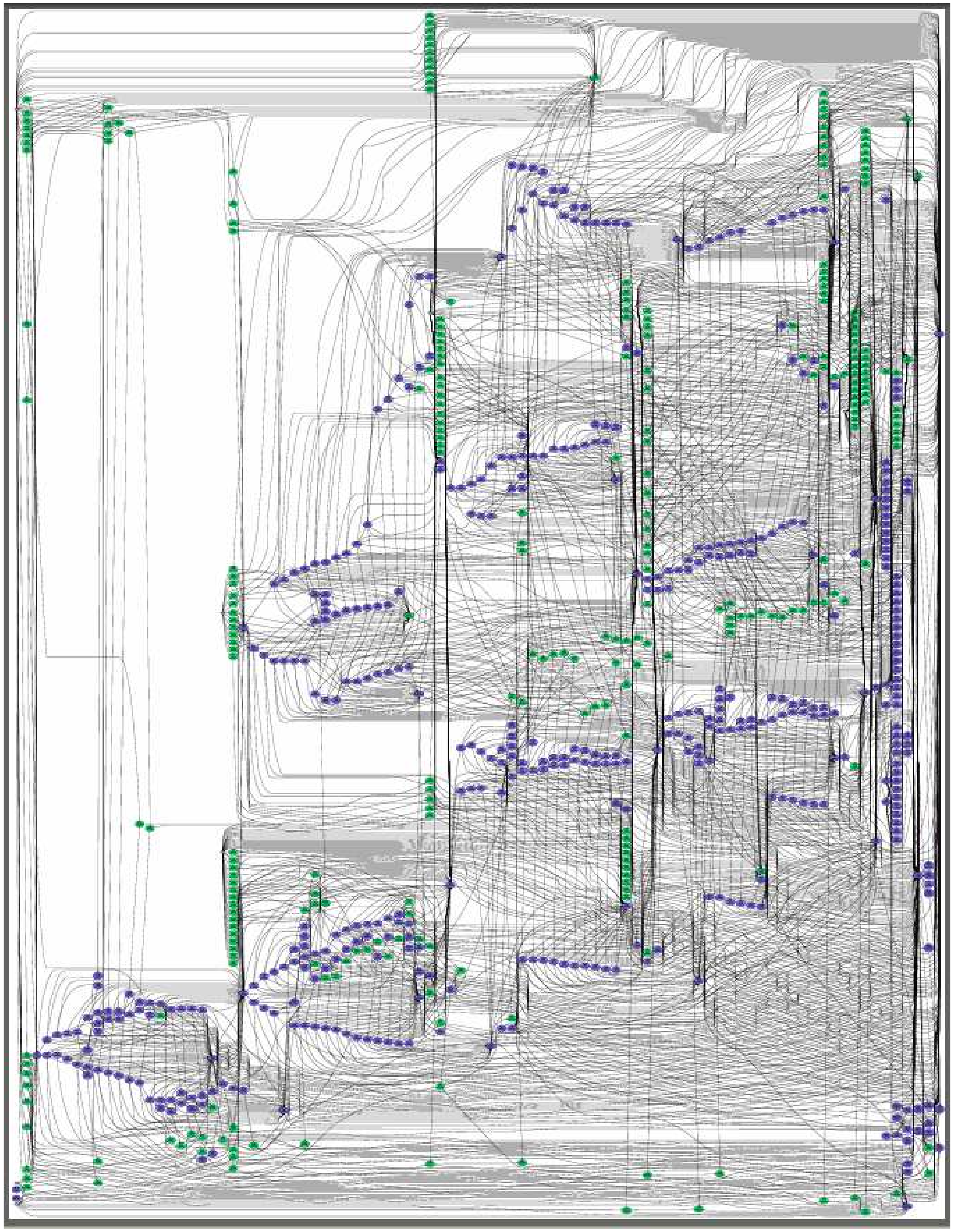
Patches for file systems

Patches for applications

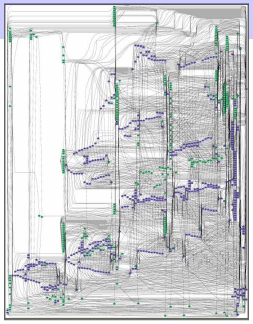
Patch optimizations

Evaluation

Patch Optimizations



Patch Optimizations



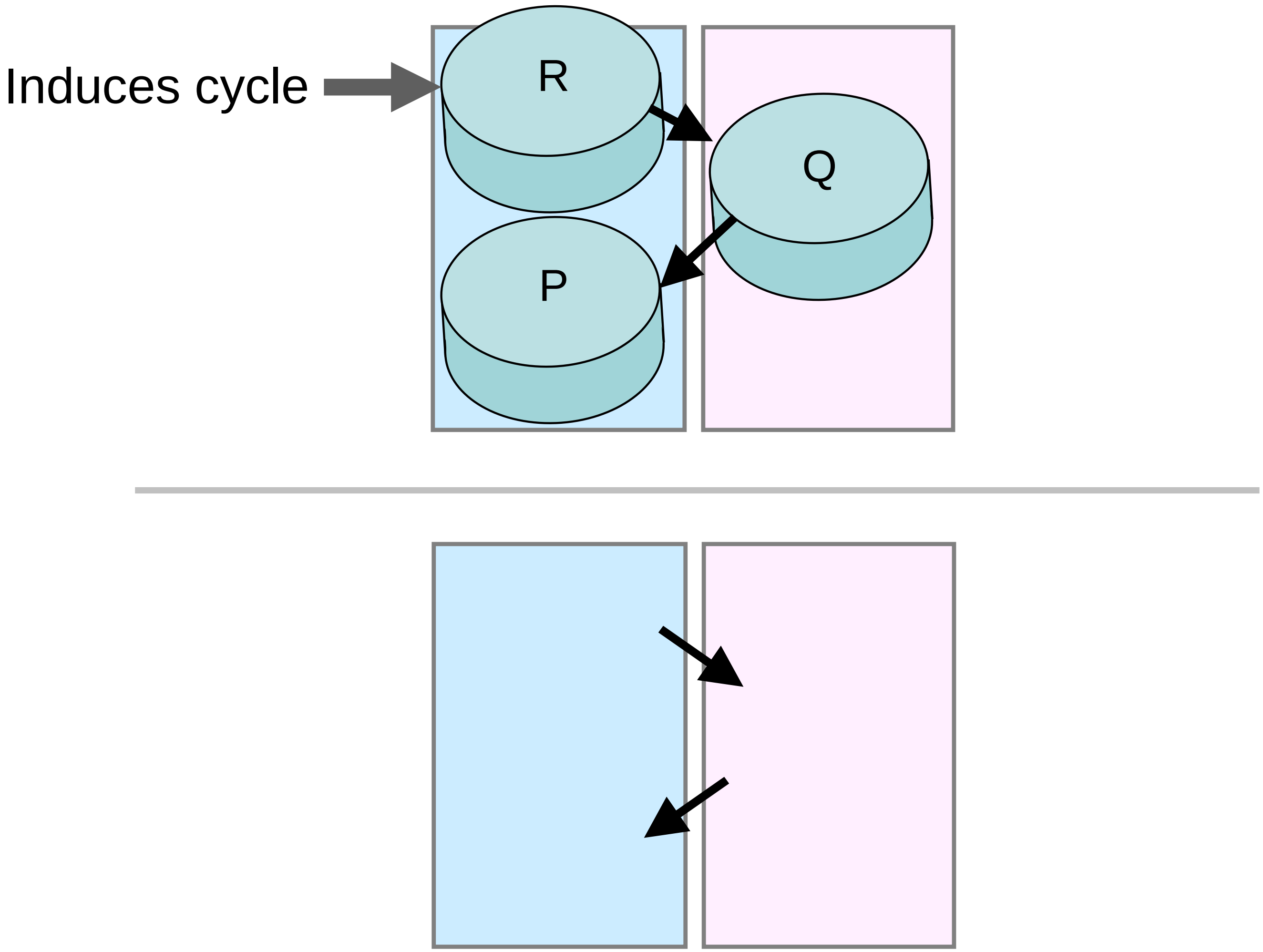
- In our initial implementation:
  - Patch manipulation time was the system bottleneck
  - Patches consumed more memory than the buffer cache
- File system agnostic patch optimizations to reduce:
  - Undo memory usage
  - Number of patches and dependencies
- Optimized Featherstitch is not much slower than Linux ext3

Optimizing Undo Data

- Primary memory overhead: unused (!) undo data
- Optimize away unused undo data allocations?
  - Can't detect "unused" until it's too late
- Restrict the patch API to reason about the future?

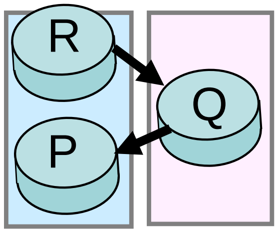
Optimizing Undo Data

Theorem: A patch that must be reverted to make progress must *induce a block-level cycle*.

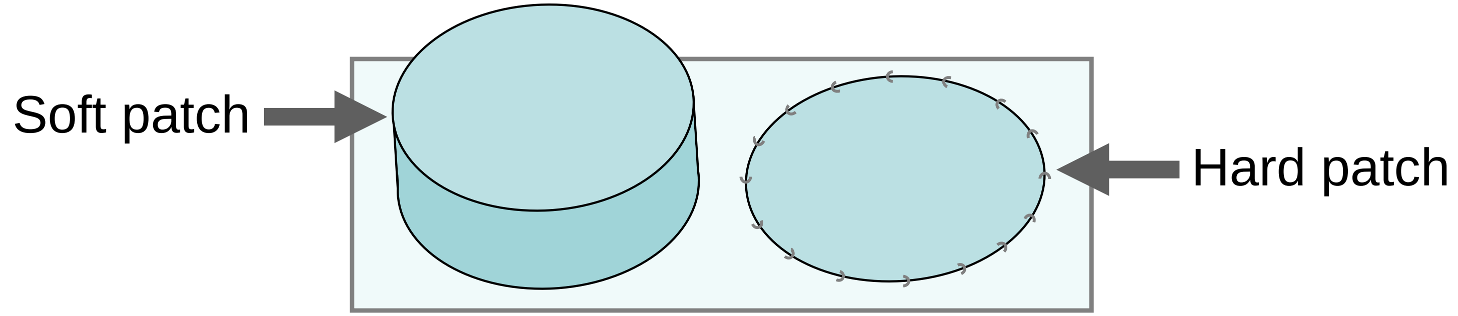


Hard Patches

- Detect block-level cycle inducers when allocating?
  - Restrict the patch API: supply all dependencies at patch creation*
- Now, any patch that will need to be reverted must induce a block-level cycle at creation time

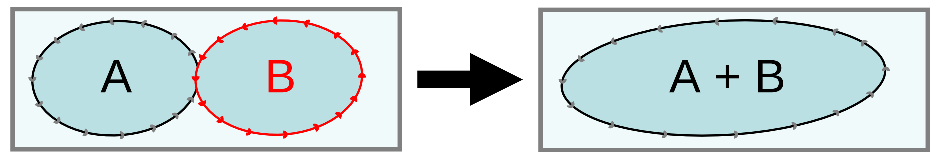


- We call a patch with undo data omitted a **hard patch**. A **soft patch** has its undo data.

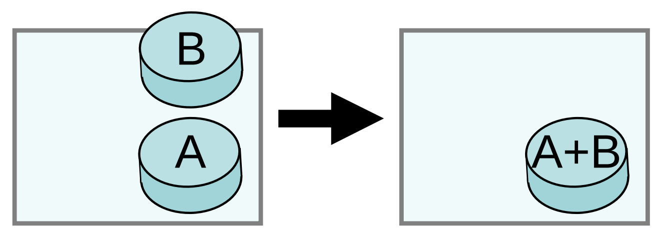


Patch Merging

- Hard patch merging



- Overlap patch merging



Evaluation

Problem

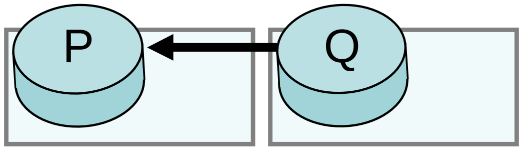
Patches for file systems

Patches for applications

Patch optimizations

Evaluation

Efficient Disk Write Ordering



- Featherstitch needs to efficiently:
  - Detect when a write becomes durable
  - Ensure disk caches safely reorder writes

- SCSI TCQ or modern SATA NCQ
  + FUA requests or WT drive cache

- Evaluation uses disk cache safely for both Featherstitch and Linux

Evaluation

- Measure patch optimization effectiveness
- Compare performance with Linux ext2/ext3
- Assess consistency correctness
- Compare UW IMAP performance

Evaluation: Patch Optimizations

PostMark

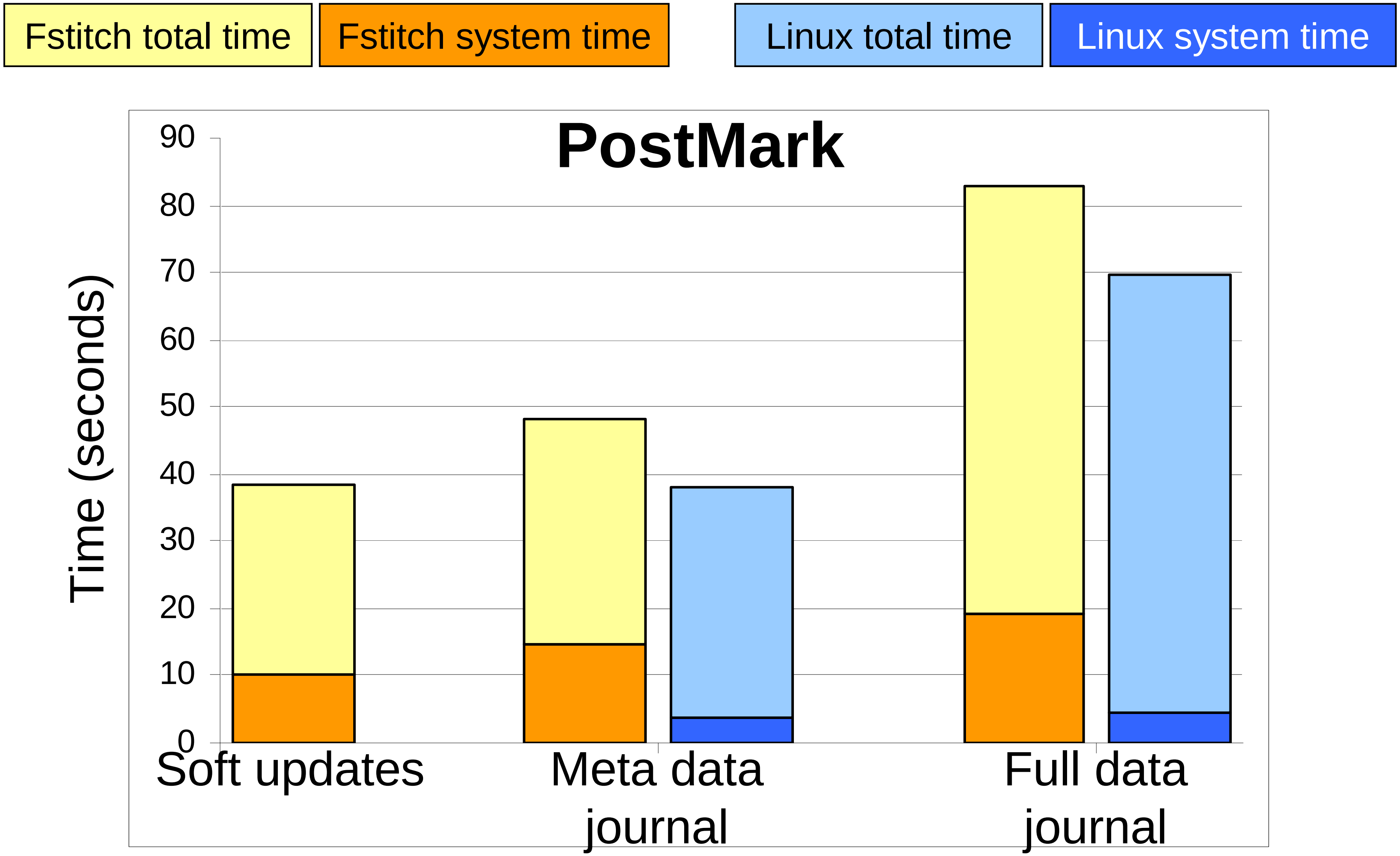
Optimization	# Patches	Undo data	System time
None	4.6 M	3.2 GB	23.6 sec
Hard patches	2.5 M	1.6 GB	18.6 sec
Overlap merging	550 k	1.6 GB	12.9 sec
Both	675 k	0.1 MB	11.0 sec

Evaluation: Patch Optimizations

PostMark

Optimization	# Patches	Undo data	System time
None	4.6 M	3.2 GB	23.6 sec
Hard patches	2.5 M	1.6 GB	18.6 sec
Overlap merging	550 k	1.6 GB	12.9 sec
Both	675 k	0.1 MB	11.0 sec

Evaluation: Linux Comparison



- Faster than ext2/ext3 on other benchmarks
  - Block allocation strategy differences dwarf overhead

Evaluation: Consistency Correctness

- Are consistency implementations correct?
- Crash the operating system at random
- Soft updates:
  - Warning: High inode reference counts (expected)
- Journaling:
  - Consistent (expected)
- Asynchronous:
  - Errors: References to deleted inodes, and others (expected)

Evaluation: Patchgroups

- Patchgroup-enabled vs. unmodified UW IMAP server benchmark: move 1,000 messages

- Reduces runtime by 50% for SU, 97% for journaling

Related Work

- Soft updates [Ganger ’00]
- Consistency research
  - WAFL [Hitz ‘94]
  - ACID transactions [Gal ’05, Liskov ’04, Wright ’06]
- Echo and CAPFS distributed file systems [Mann ’94, Vilayannur ’05]
- Asynchronous write graphs [Burnett ’06]
- xsyncfs [Nightingale ’05]

Conclusions

- Patches provide new write-before abstraction
- Patches simplify the implementation of consistency models like journaling, WAFL, soft updates
- Applications can precisely and explicitly specify consistency requirements using patchgroups
- Thanks to optimizations, patch performance is competitive with ad hoc consistency implementations

Featherstitch source:

http://featherstitch.cs.ucla.edu/

Thanks to the NSF, Microsoft, and Intel.