Fast, Transparent Filesystem Microkernel Recovery with Ananke

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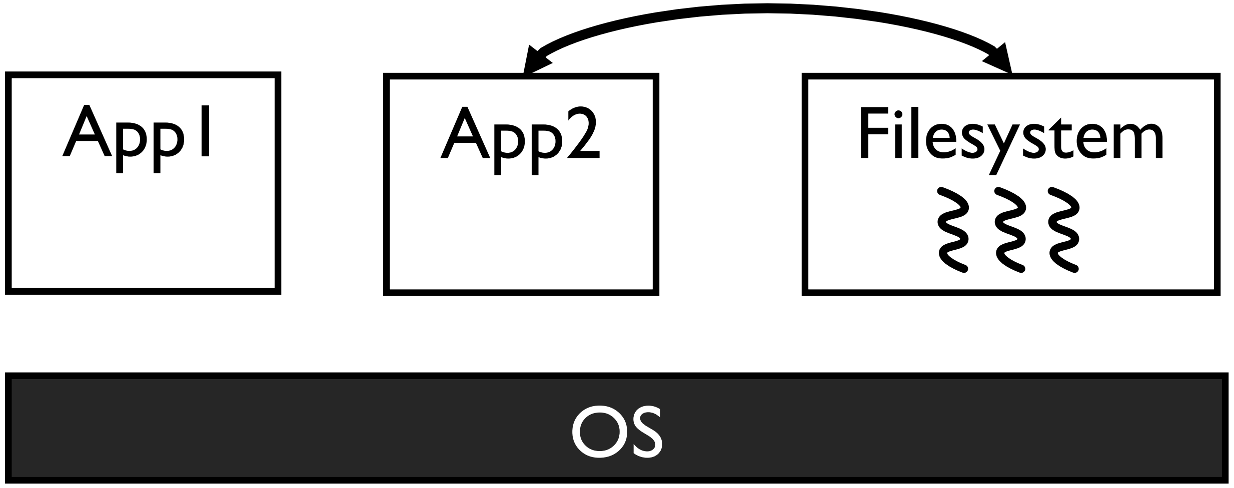
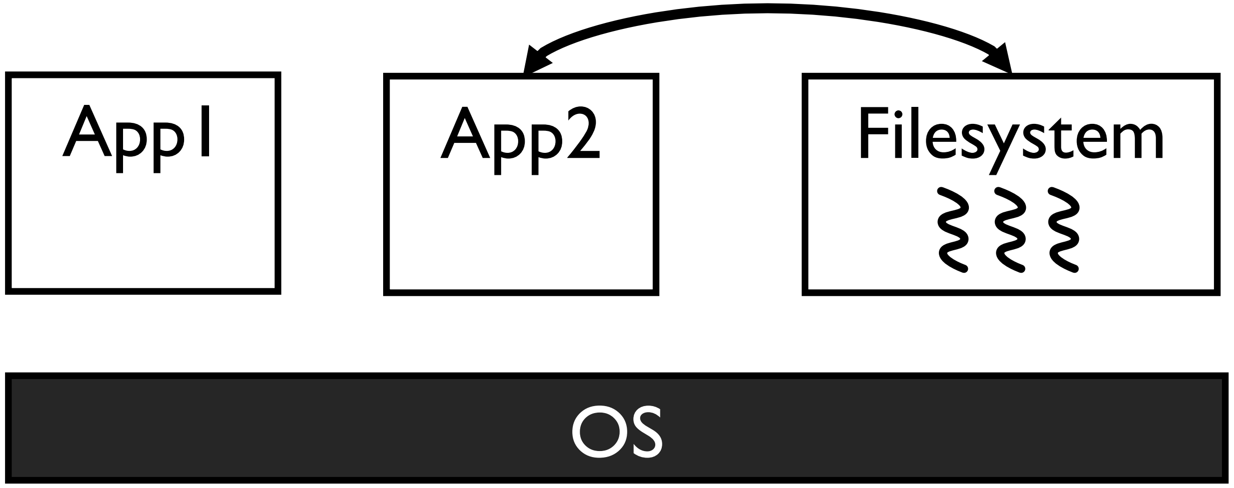
Filesystem Microkernels



Filesystems service as a user-space process

- No OS involvement

Benefits of Filesystem Microkernels



Filesystems service as a user-space process

- Better performance for modern IO devices and CPUs
- Easy to develop and upgrade
- Better fault isolation

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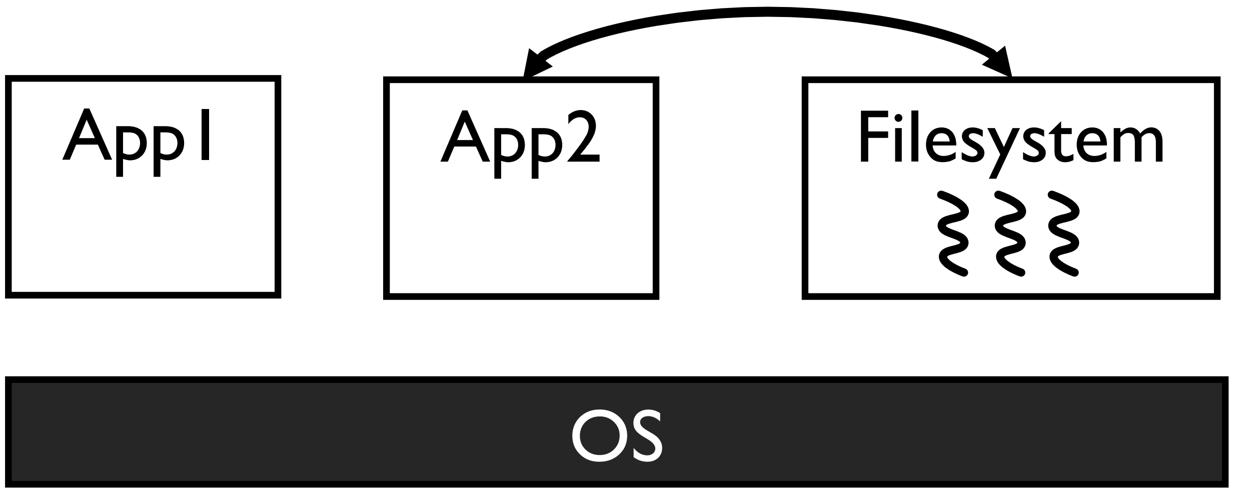
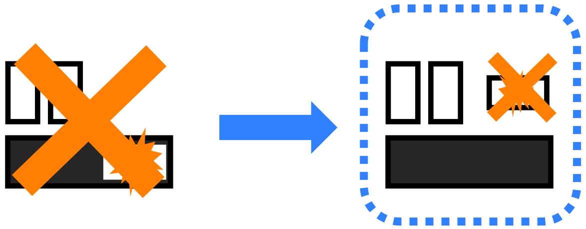


Filesystems service as a user-space process

- Better performance for modern IO devices and CPUs
- Easy to develop and upgrade
- Better fault isolation

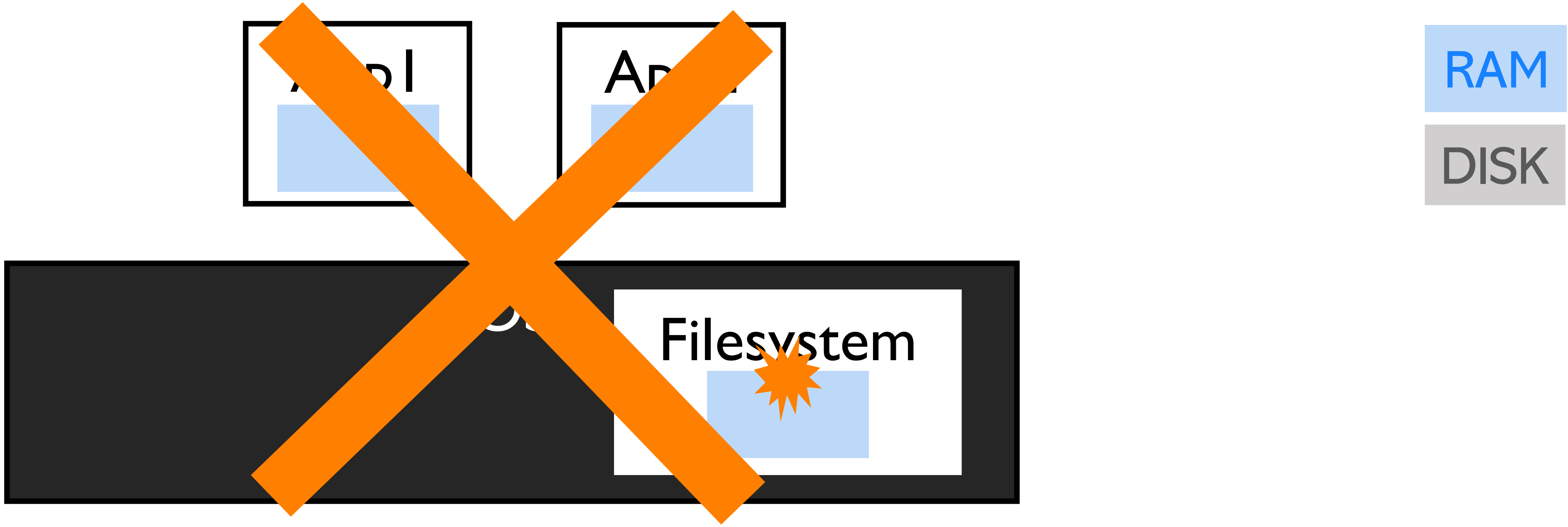
Systems: *uFS* (SOSP '21), *Hongmeng* (OSDI '23)



A new paradigm of crash recovery

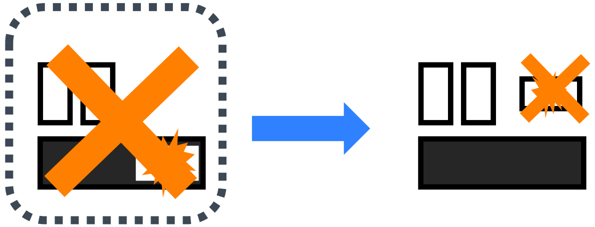
process crash recovery

Kernel Filesystem Failure ➡ Full-system Crash



OS and all applications crash (i.e., full-system crash)

Applications also lose their progress



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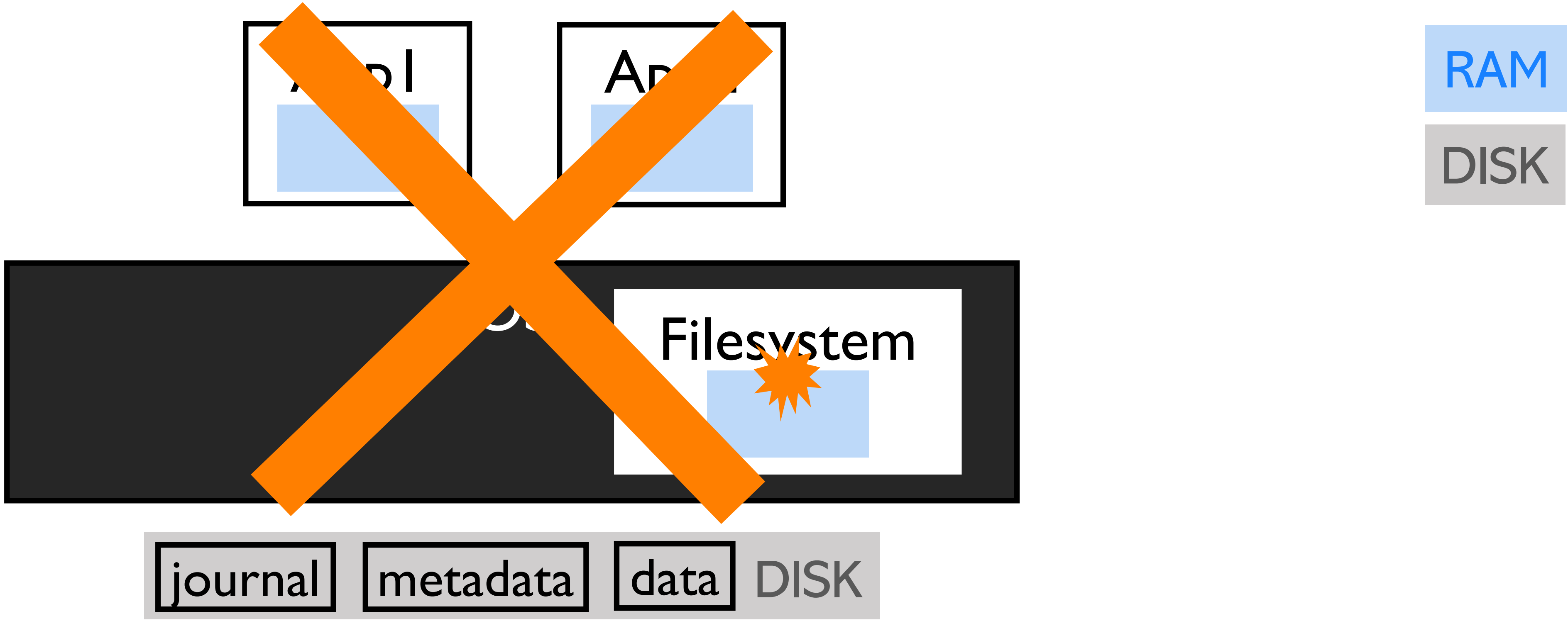
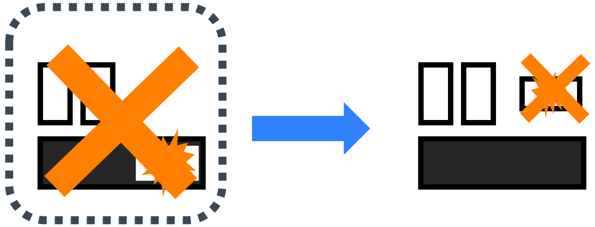
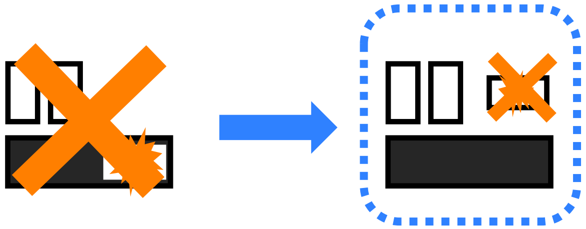


Filesystem crash is treated the same as power failure

Full-system crash recovery only utilizes on-disk states





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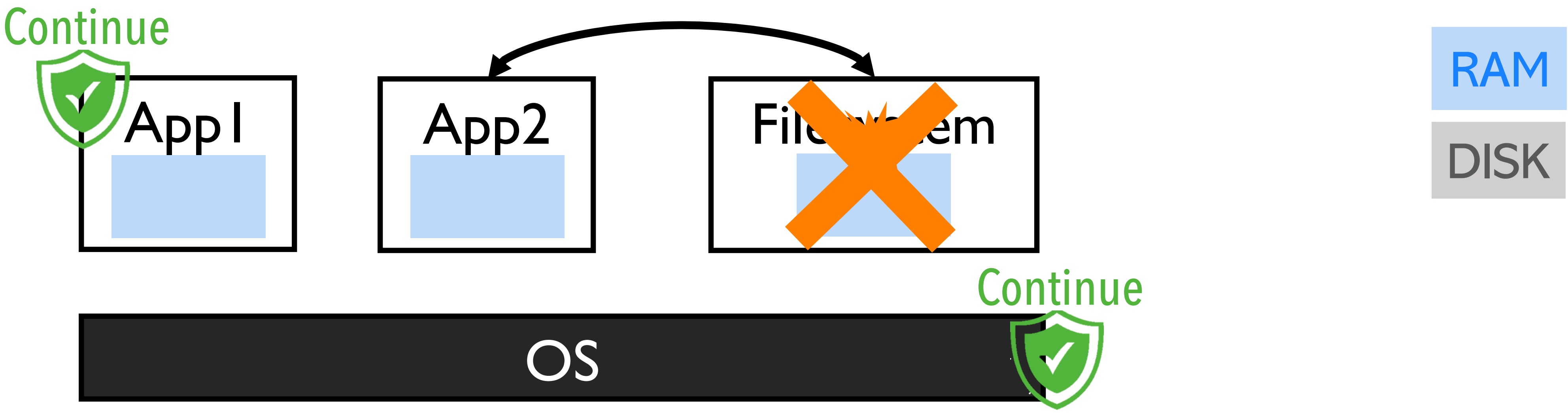
Microkernel Filesystem Failure ➡ Process Crash

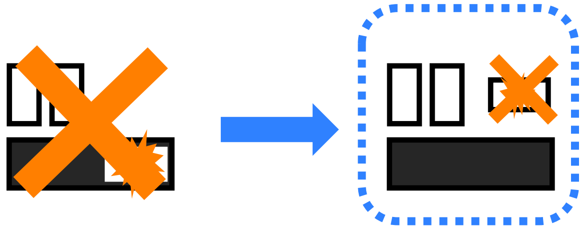


A new crash model

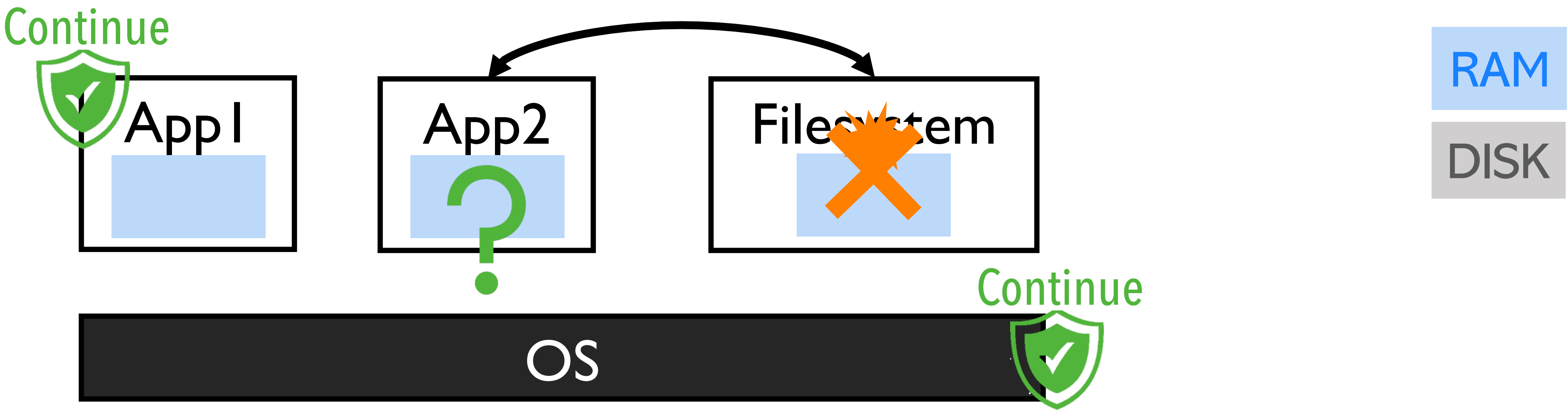
- Process crash, not full-system crash

Opportunities to continue

- Monolithic OS and some apps naturally continue



Microkernel Filesystem Failure ➡ Process Crash



A new crash model

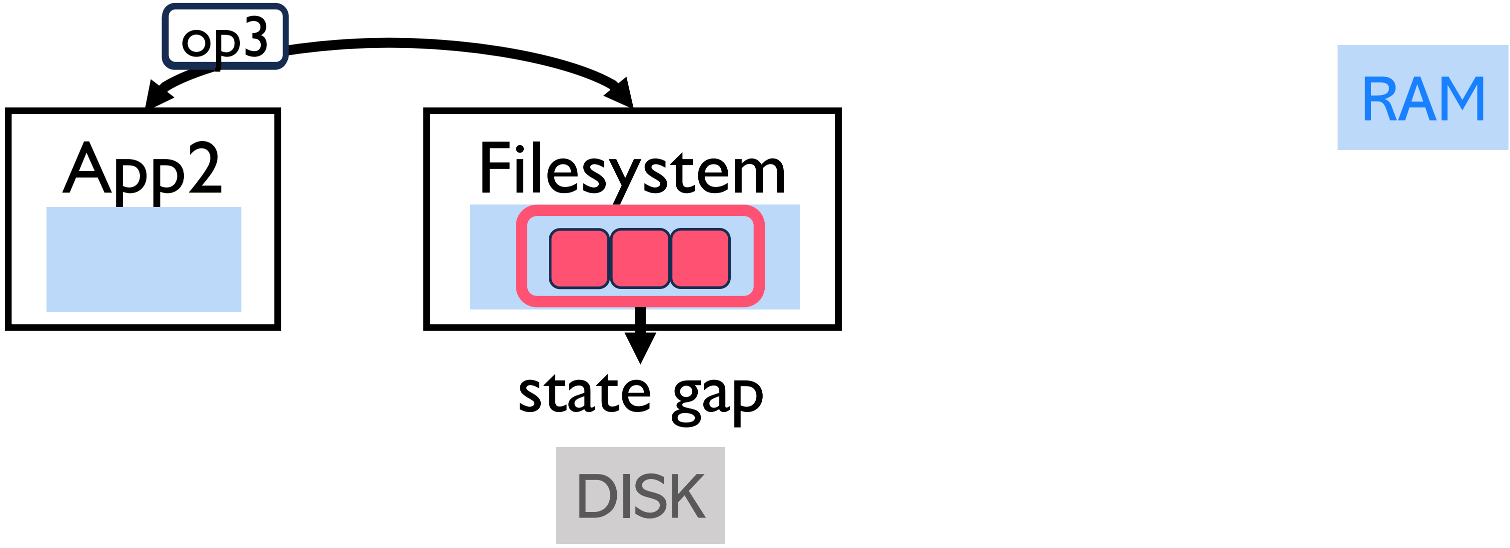
- Process crash, not full-system crash

Opportunities to continue

- Monolithic OS and some apps naturally continue

Can filesystem applications also continue?

Main Challenge: Recover the State Gap

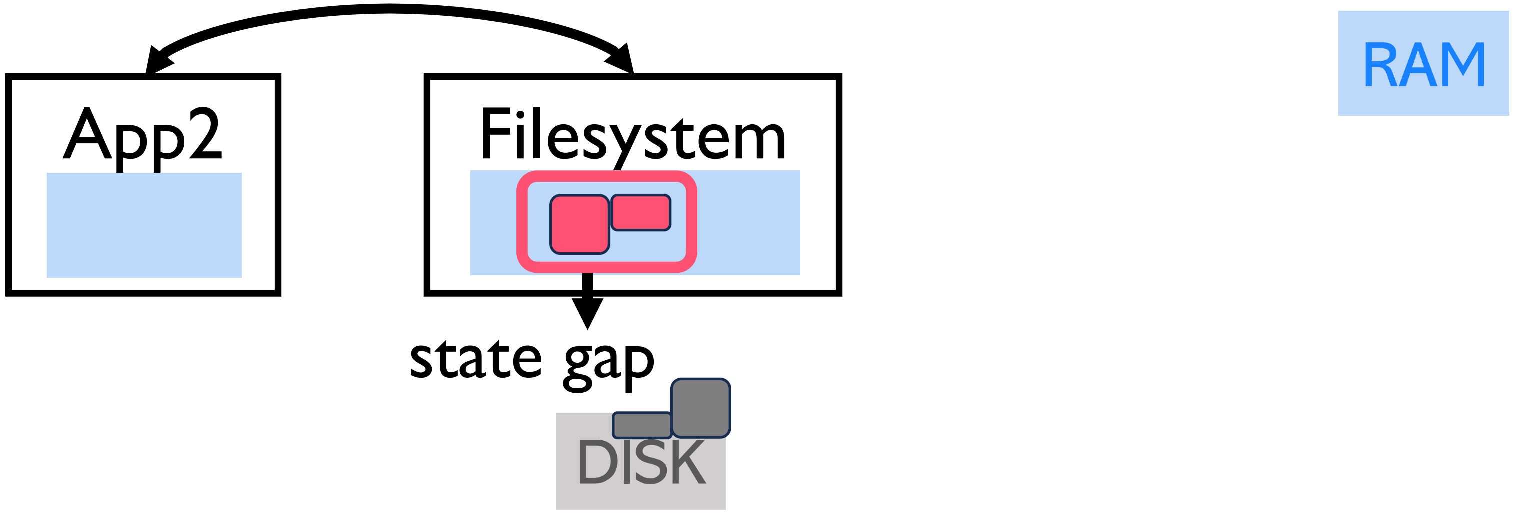


Filesystems buffer update in memory

State gap

- Difference between <u>on-disk states</u> and <u>application view</u>

Main Challenge: Recover the State Gap

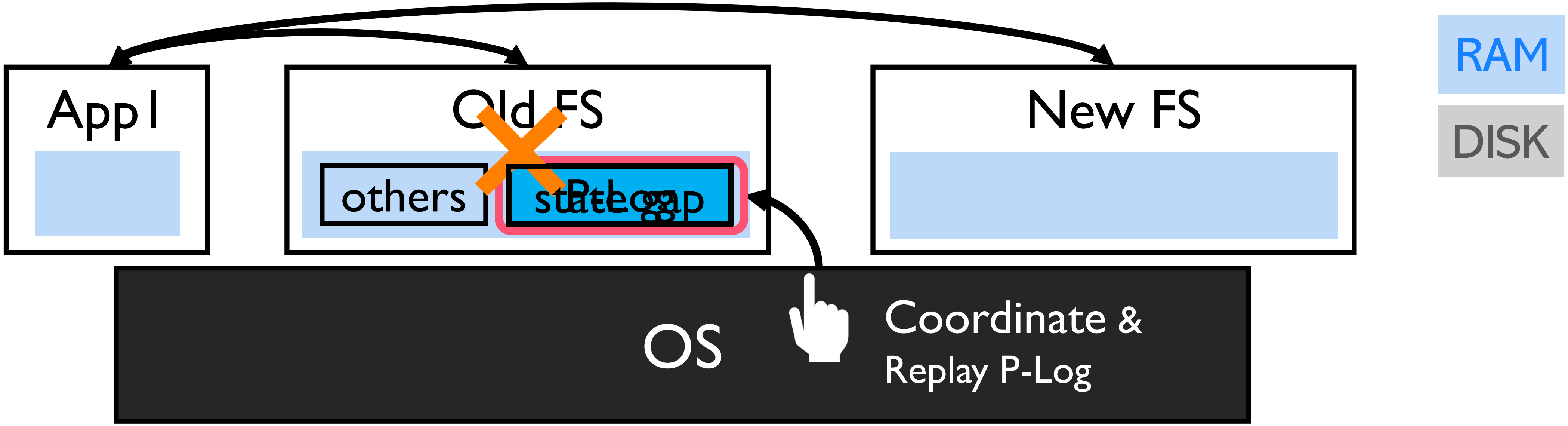


Filesystems buffer update in memory

State gap

- Difference between on-disk states and application view
- **Changes erratically**

Ananke: A Filesystem Microkernel that Supports Process Crash Recovery



P-Log: In-memory Data Structure

- Log the operations and other information

Ananke: A Filesystem Microkernel that Supports Process Crash Recovery

Novel mechanisms

- P-Log and AIM algorithm
- Kernel-coordinated speculative restart
- Lightweight detection of corruption

Ananke: A Filesystem Microkernel that Supports Process Crash Recovery

Novel mechanisms

- P-Log and AIM algorithm
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- Lightweight detection of corruption

Implemented in uFS, a state-of-the-art filesystem microkernel

- Add ~4K LoC

Ananke: A Filesystem Microkernel that Supports Process Crash Recovery

Achieved fast and transparent recovery

- Failure transparency
  - Over 30,000 fault injection experiments
- Low common-path overhead
  - <2% in most cases
- Fast recovery
  - <400ms even for challenging workloads

Outline

- Introduction
- Challenges
- P-Log and AIM
- Evaluation
- Conclusion

Ananke: A Filesystem Microkernel that Supports Process Crash Recovery

Principled process crash recovery

- Challenges
  - Recover State Gap
  - Low Overhead
  - Robustness of Recovery

Ananke: A Filesystem Microkernel that Supports Process Crash Recovery

Principled process crash recovery

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Recover State Gap

Low Overhead

Robustness of Recovery

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Novel mechanisms

- **P-Log and AIM algorithm**
- Kernel-coordinated speculative restart
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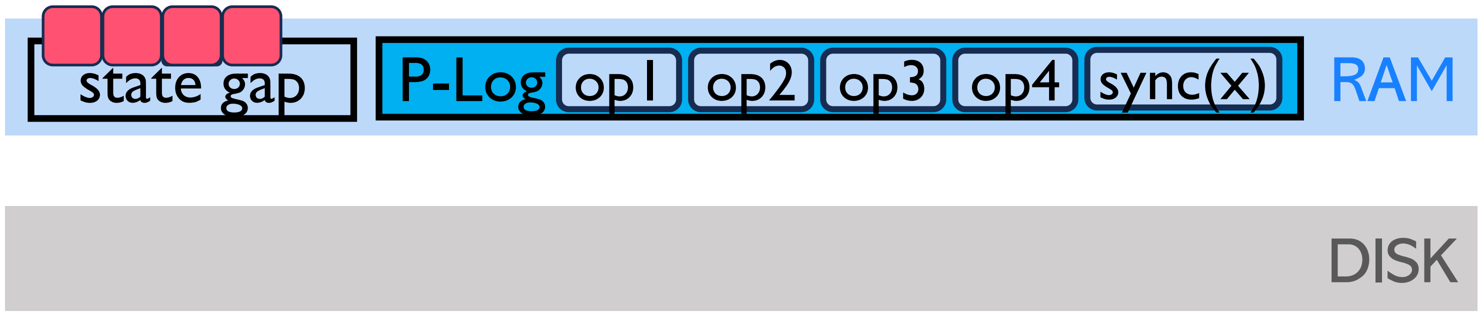
Recover State Gap

Low Overhead

Robustness of Recovery

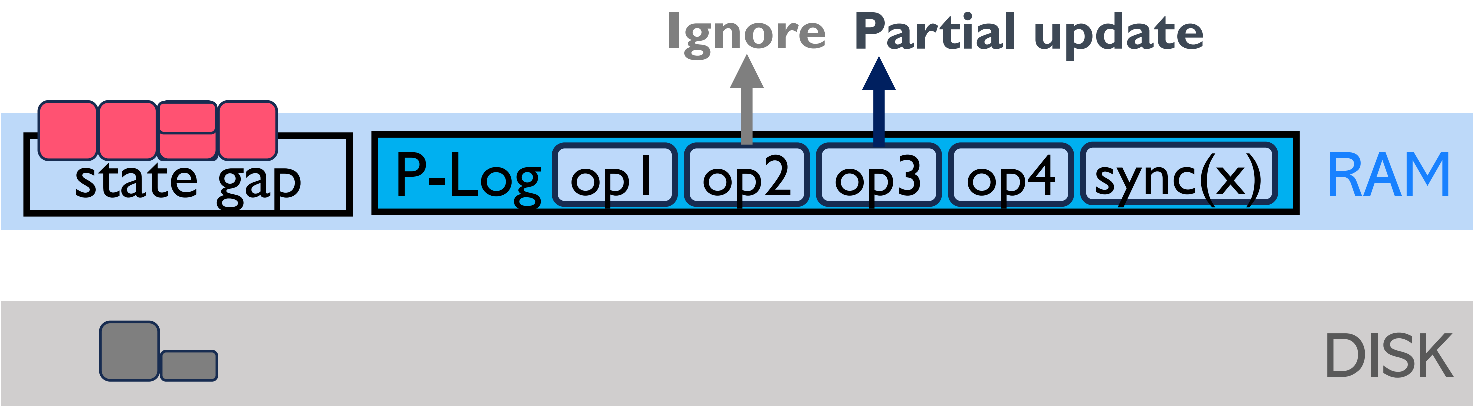
P-Log: In-memory Log for Process Crash Recovery



P-Log

- Log the operations and other information

P-Log: Challenge to Recover the State Gap



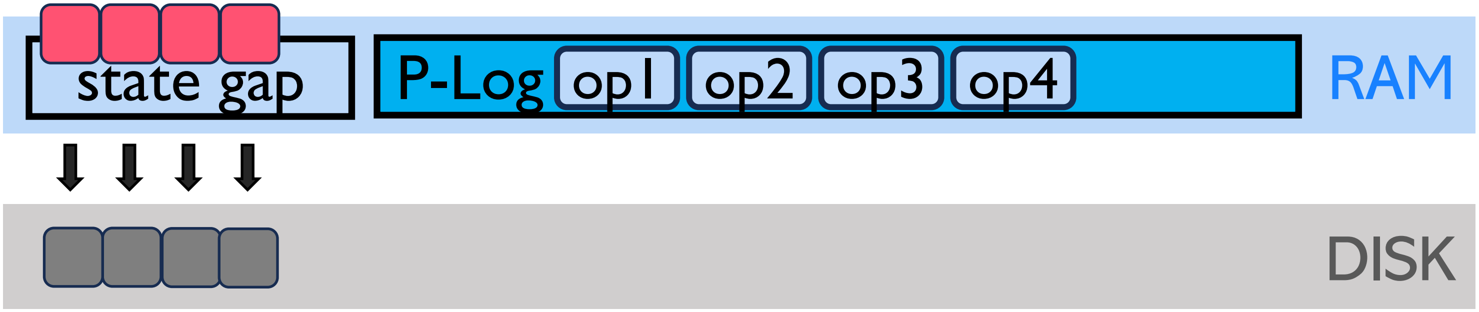
P-Log

- Log the operations and other information
- **Naively replaying is not sufficient**
  - An operation's update may have been durable
  - Part of an operation's update needs to be recovered

Trade-off: Fast, Transparent Recovery vs. Low Common-path Overhead

Incorrect due to the loss of state gap
Manual efforts and long recovery time

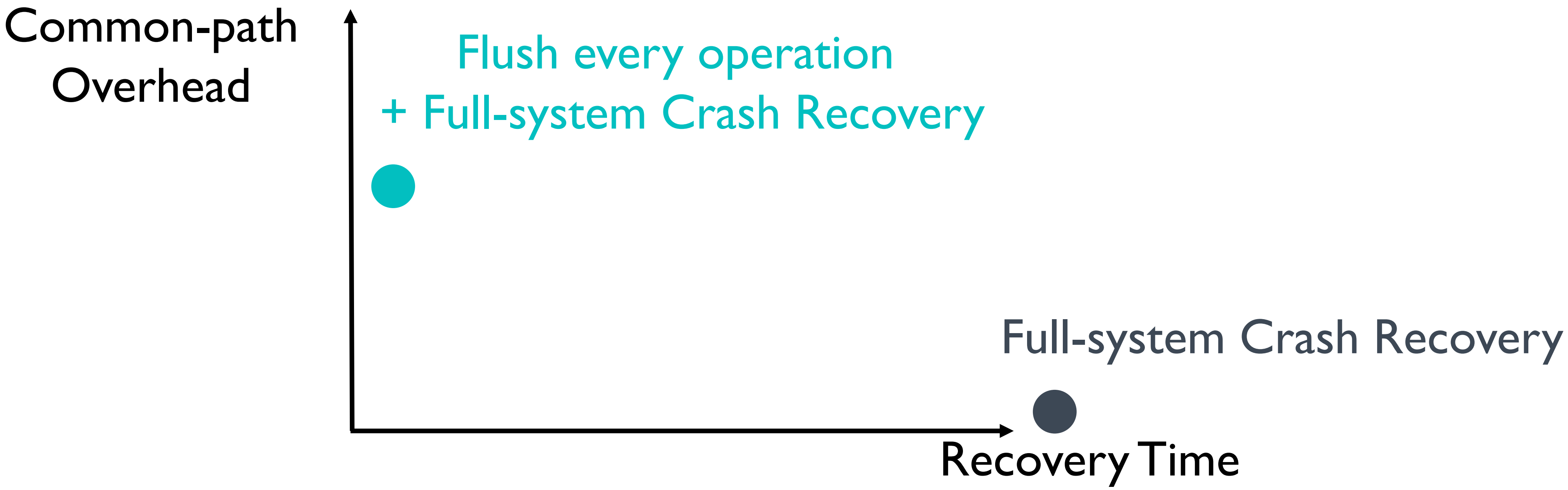
P-Log: Challenge to Recover the State Gap



P-Log

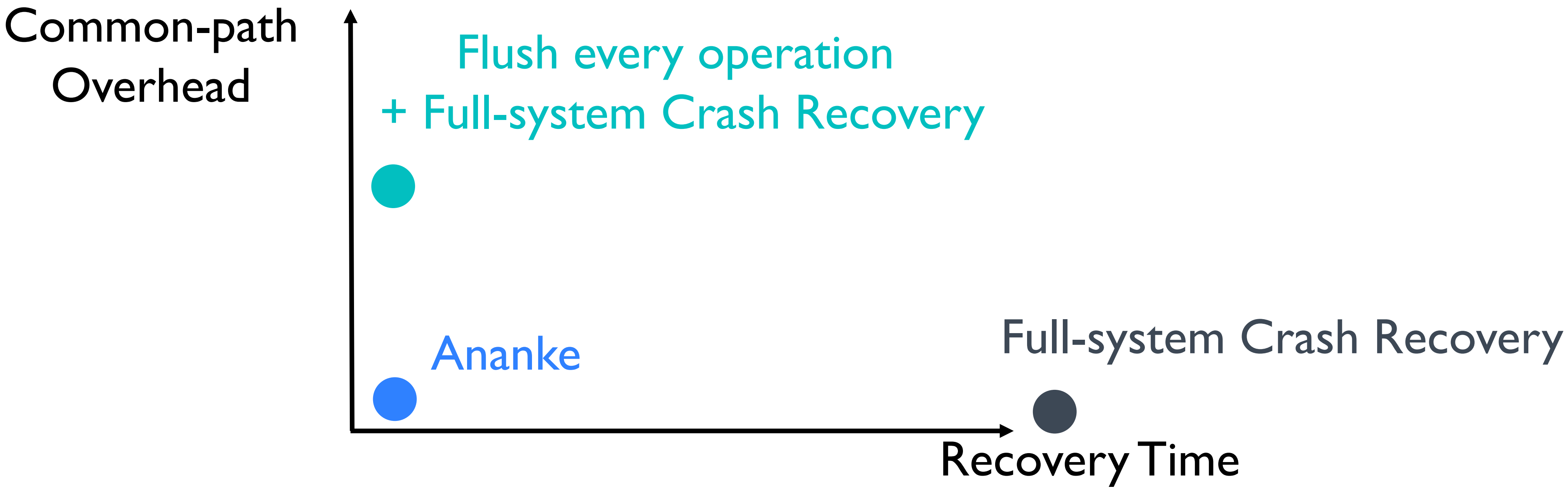
- Log the operations and other information
- **Control the common-path overhead**
  - Extra flushes can simplify the state gap, but incurs large overhead

Fast, Transparent Recovery AND Low Common-path Overhead



Large common-path overhead

Fast, Transparent Recovery AND Low Common-path Overhead

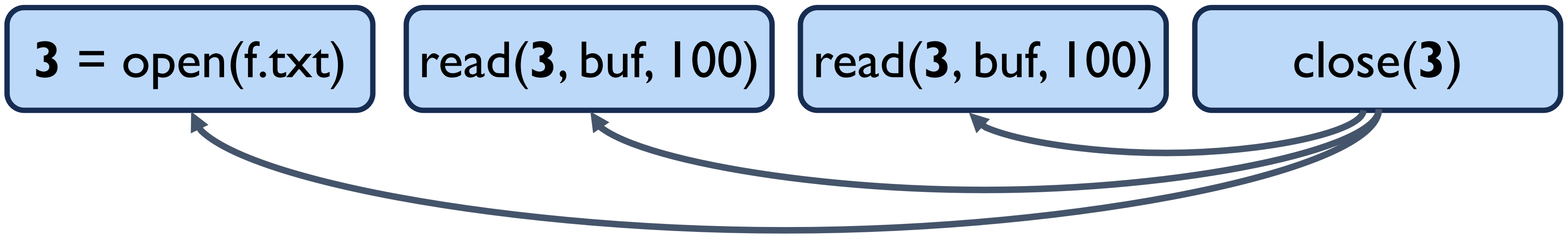


P-Log and AIM: recover the state gap without incurring extra flushes

Recover the Exact State Gap

❶ Subsequent operations may remove some (or all) of the changes from the state gap

- close() removes fd



remove the **fd**, and thus updates of several previous operations

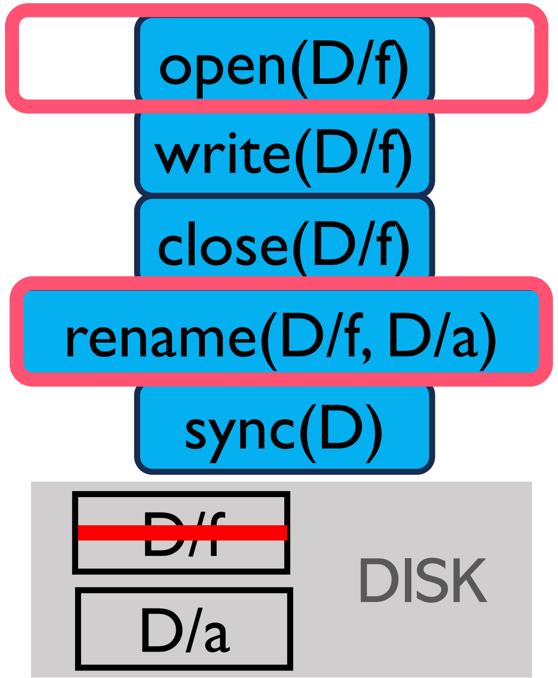
Recover the Exact State Gap

❶ Subsequent operations may remove some (or all) of the changes from the state gap

- close() removes an fd
- fsync()/sync()/background sync

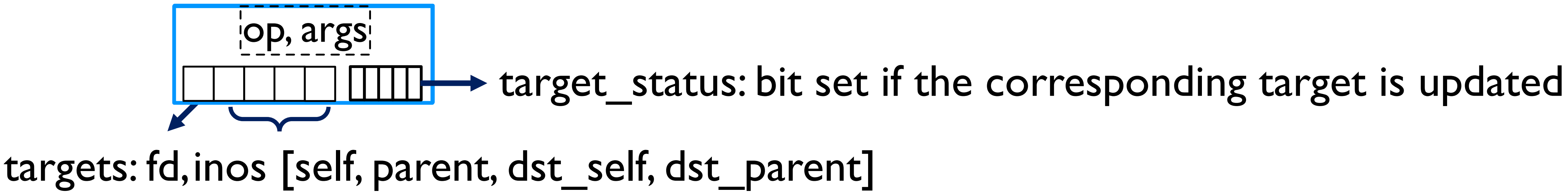
Recover the Exact State Gap

1. Subsequent operations may remove some (or all) of the changes from the state gap
2. Subsequent operations may alter the preconditions



Re-execute: open(D/f) cannot find it

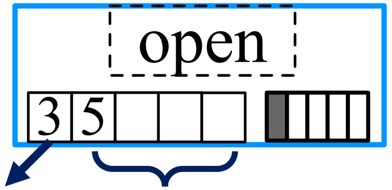
P-Log: In-memory Per-Core Log



A P-Log entry contains an array to record possible targets

- file descriptor and involved inodes (inos)

P-Log: In-memory Per-Core Log

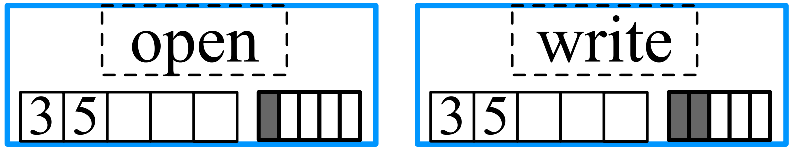


targets: fd, inos [self, parent, dst_self, dst_parent]

Workload

- 3 = open(f), write(3, “xx"), fsync(3), close(3)
- (file inode number = 5)

P-Log: In-memory Per-Core Log



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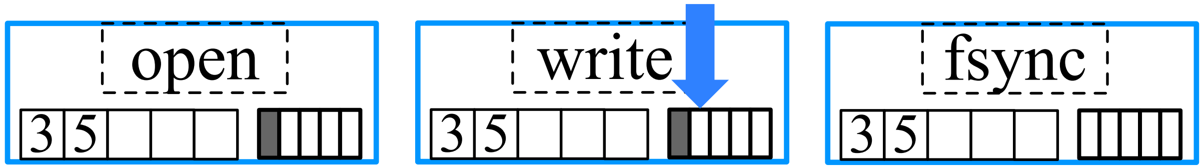

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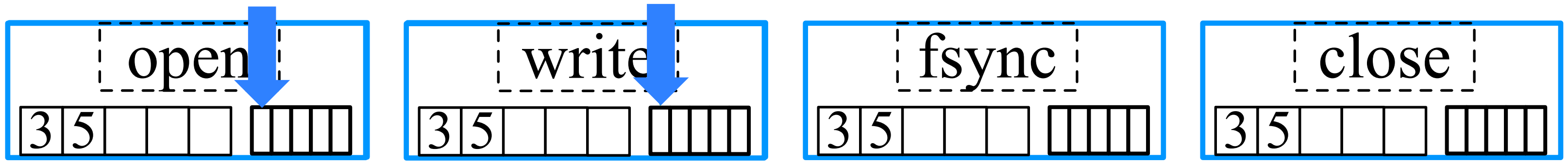

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AIM (Act, Ignore, Modify) A I M

Transform P-Log entries into actions that can be executed by the original filesystem implementation

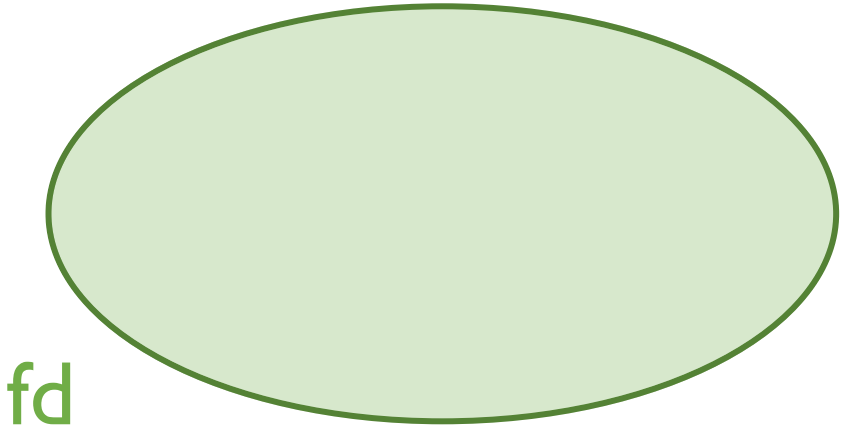
Ignore or not

- Ignore: a logged operation needs to be ignored

Act or Modify

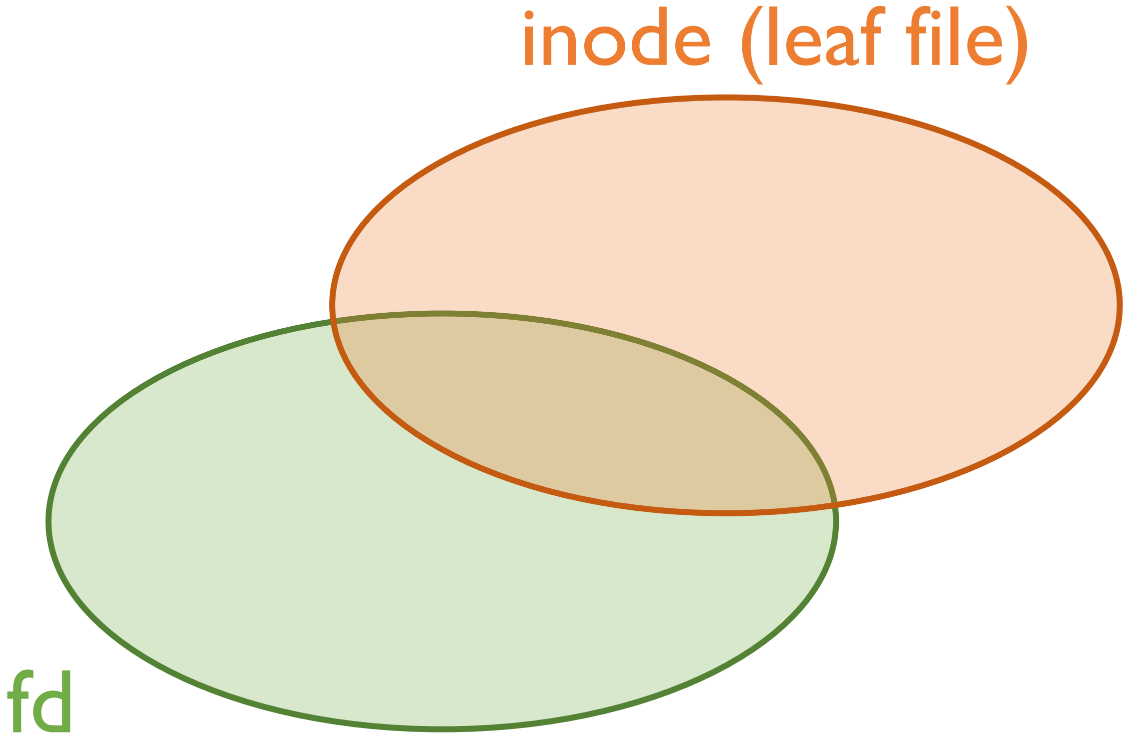
- Act: an operation will be directly replayed
- Modify: needs to take actions for an operation, but in a modified form
  - E.g., another operation type, different parameters

Intuition behind P-Log and AIM



Applications change filesystem states upon three abstractions

Intuition behind P-Log and AIM



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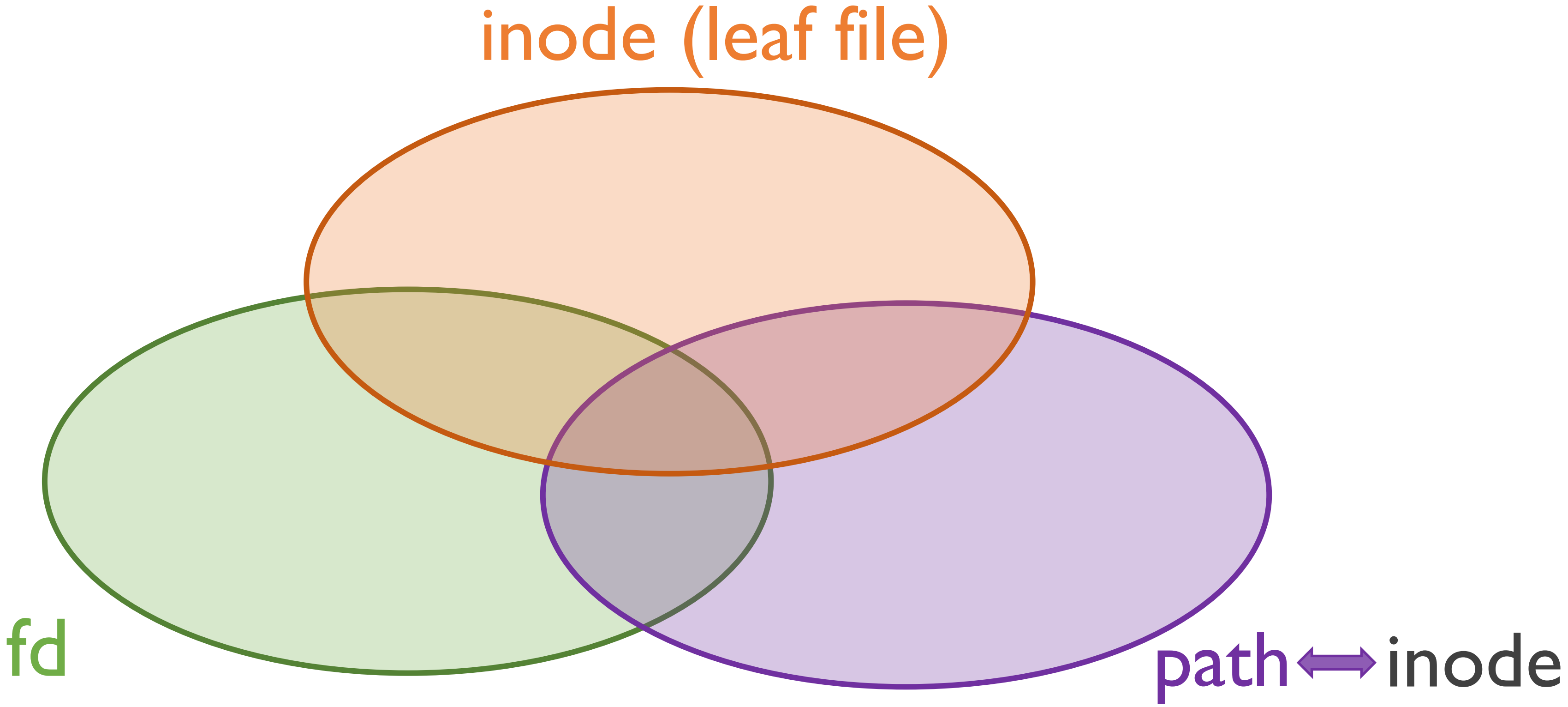

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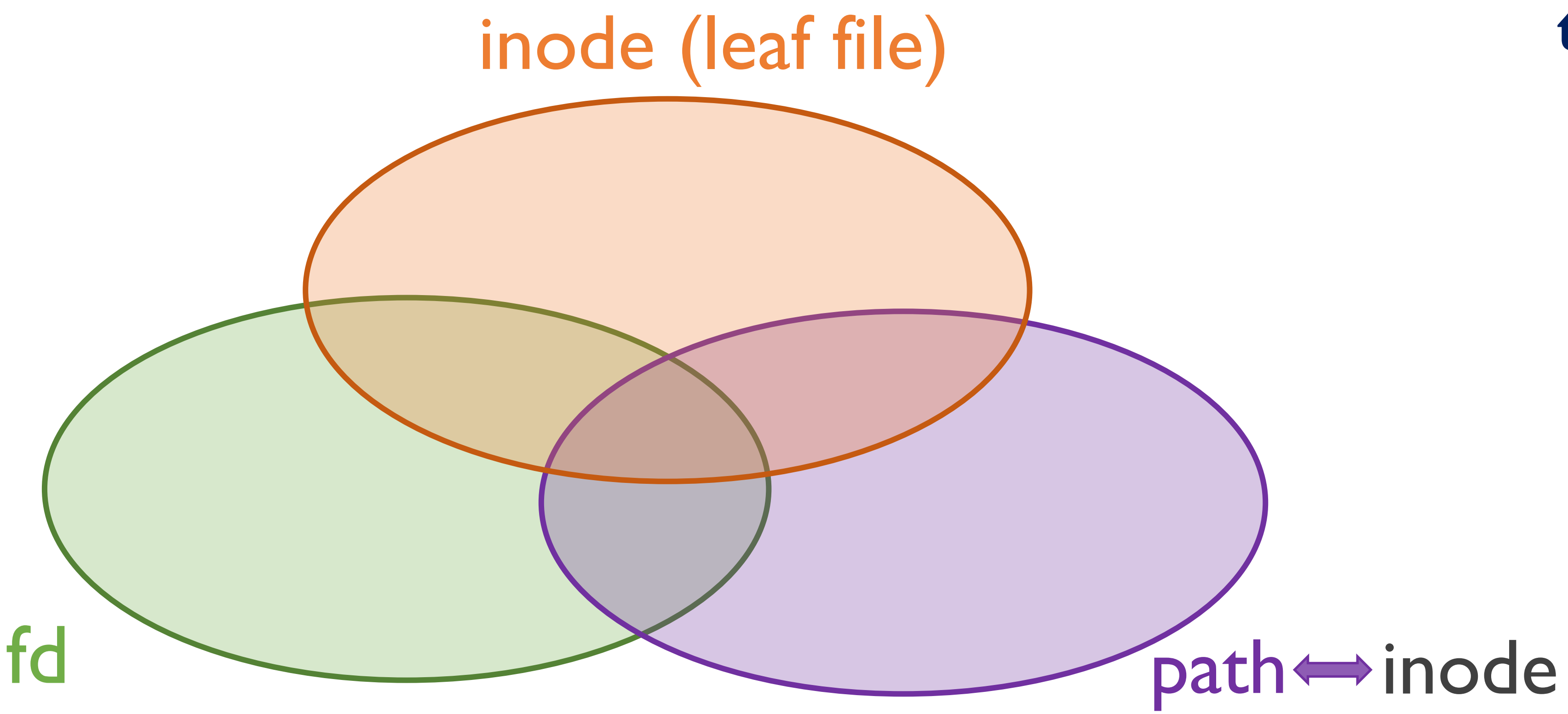
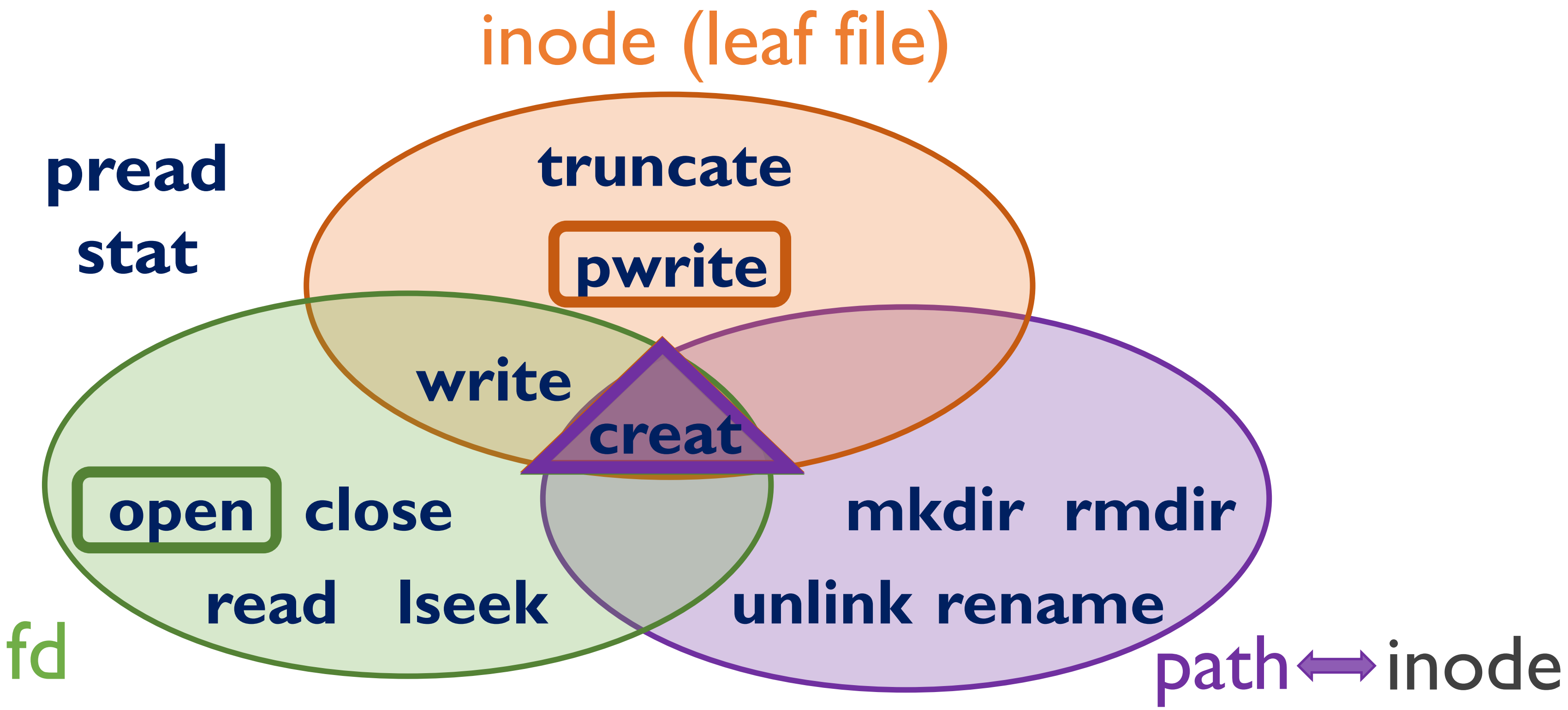


stat
pread
truncate
write
creat
mkdir
rmdir
unlink
rename
open
close
read
lseek

Applications change filesystem states upon three abstractions

- Use Filesystem APIs

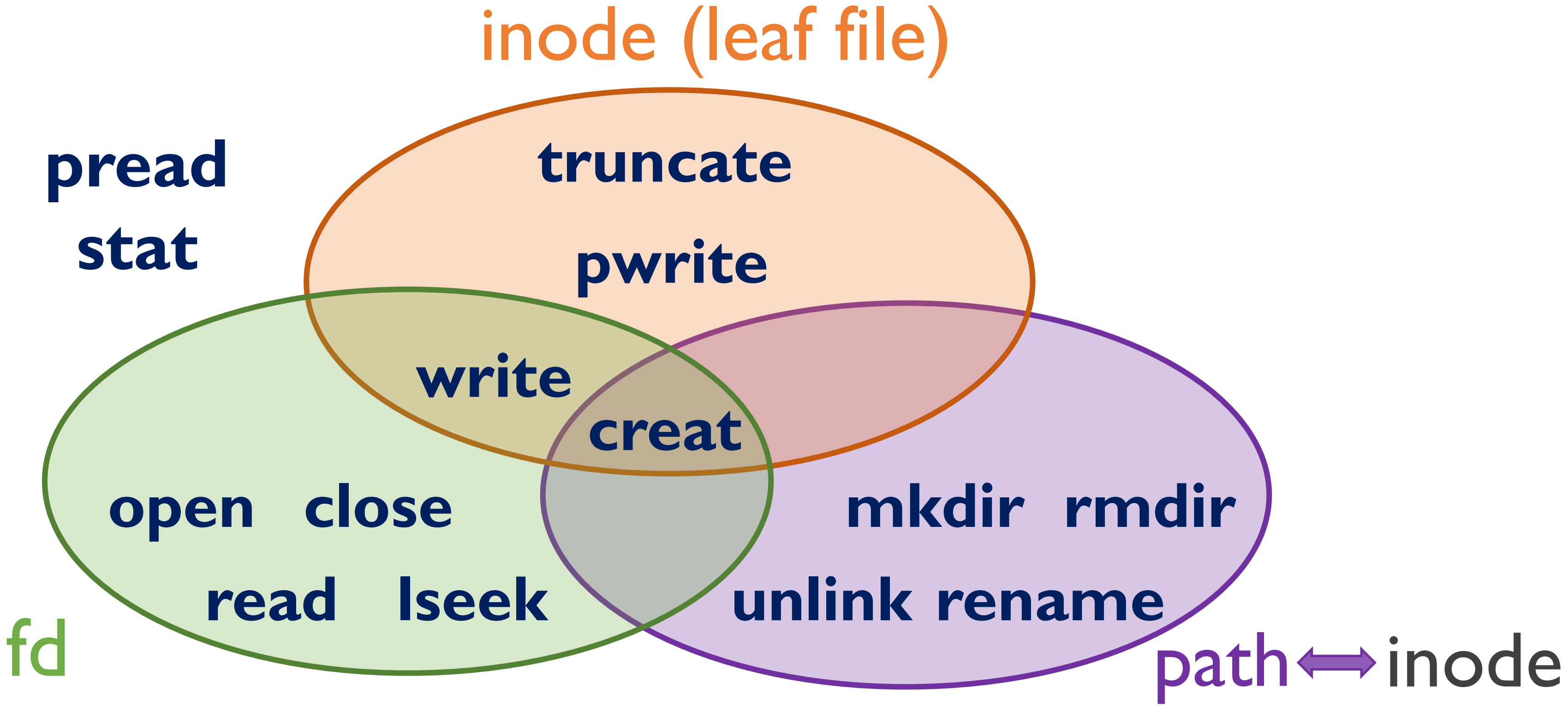
Intuition behind P-Log and AIM

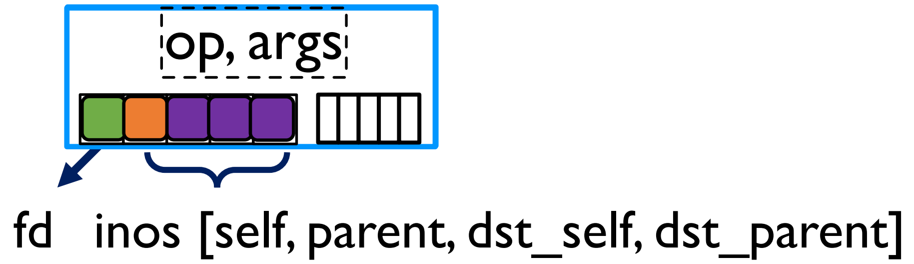


Applications change filesystem states upon three abstractions

- Use Filesystem APIs

Checking the Bit Can Decide: How Much of an Operation's Update are in the State Gap





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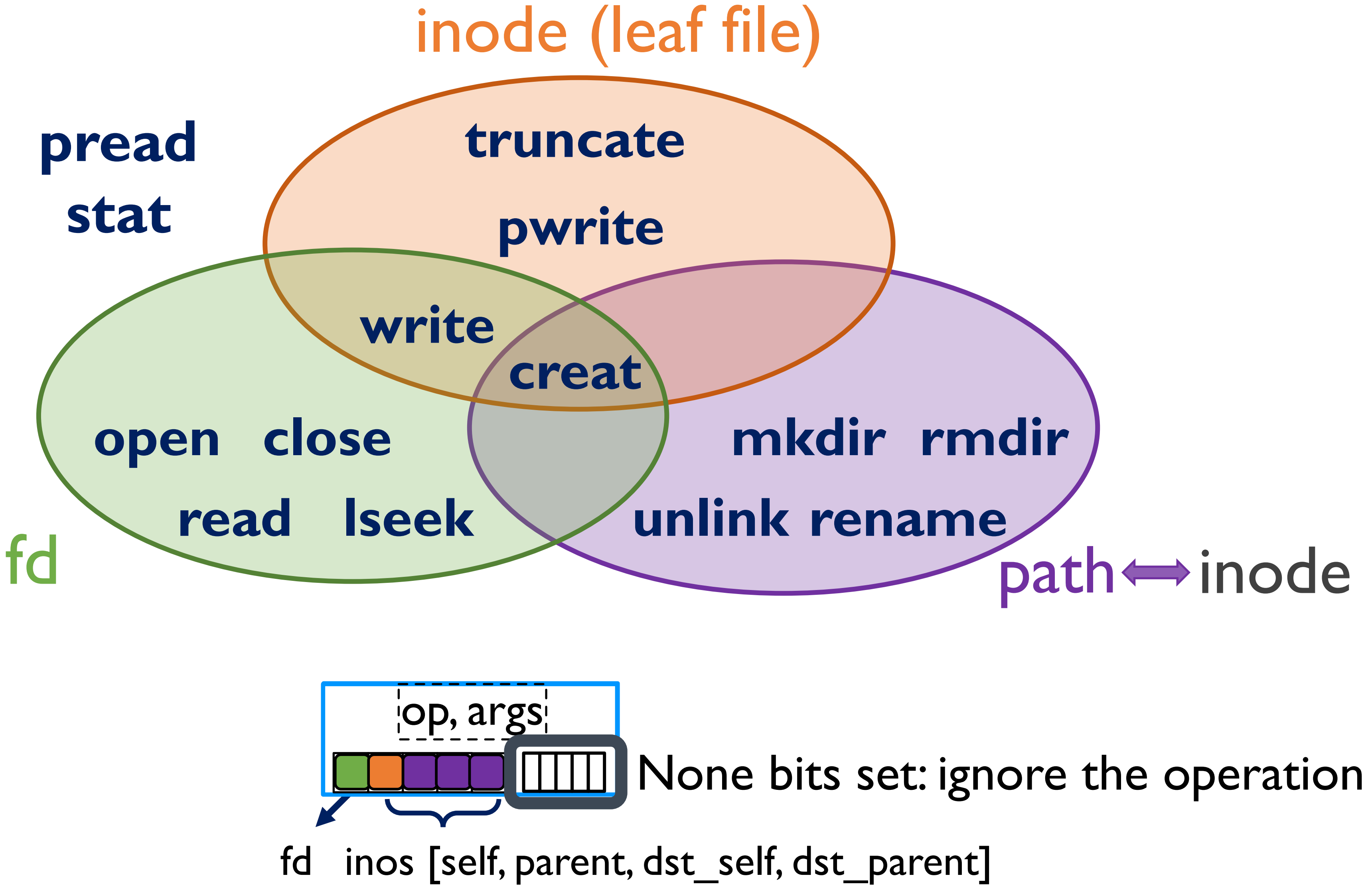

AIM (Act, Ignore, Modify) A I M

Transform p-log into actions that can be executed by the original filesystem implementation

Ignore or not (Checking the bits & Fast in the common path)

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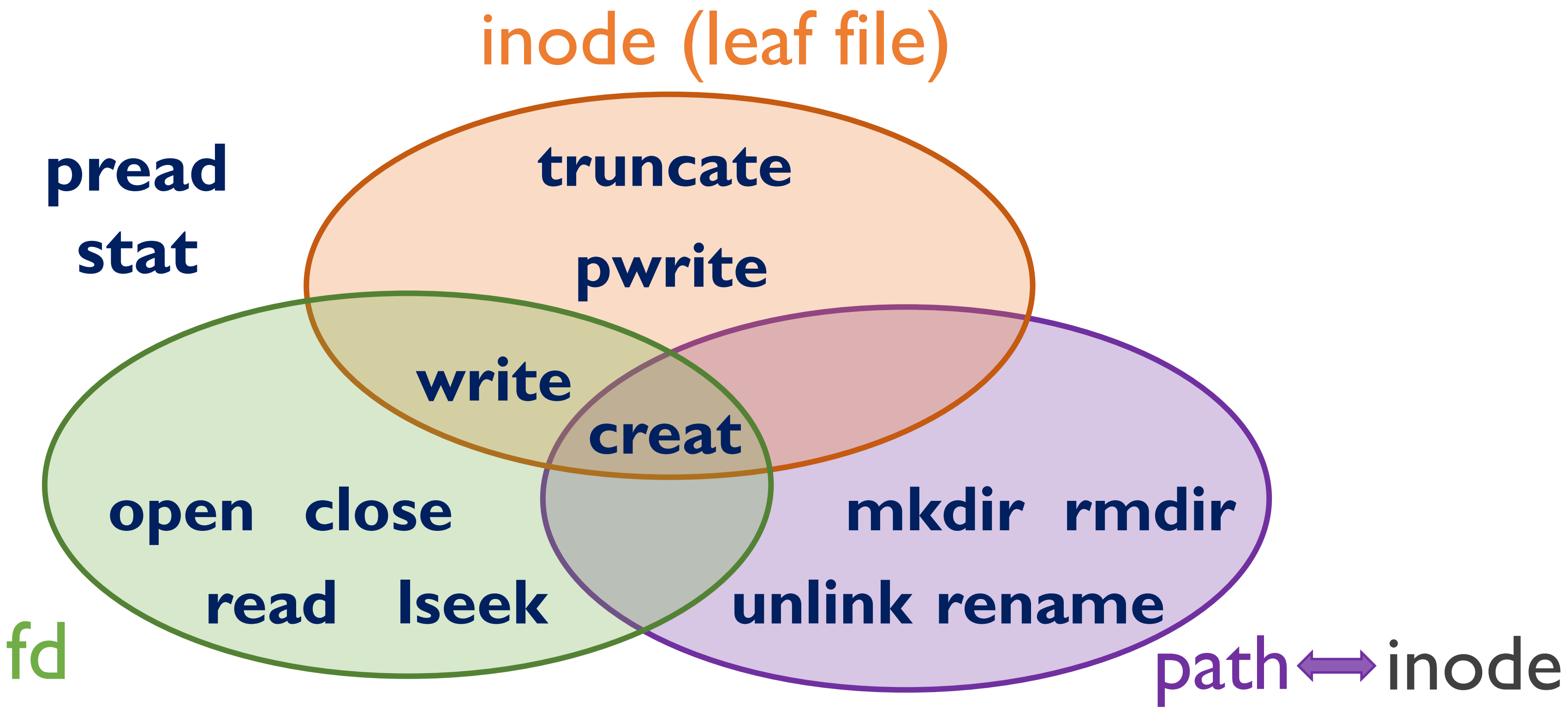
Modify: Decide the Resulting Form during Recovery



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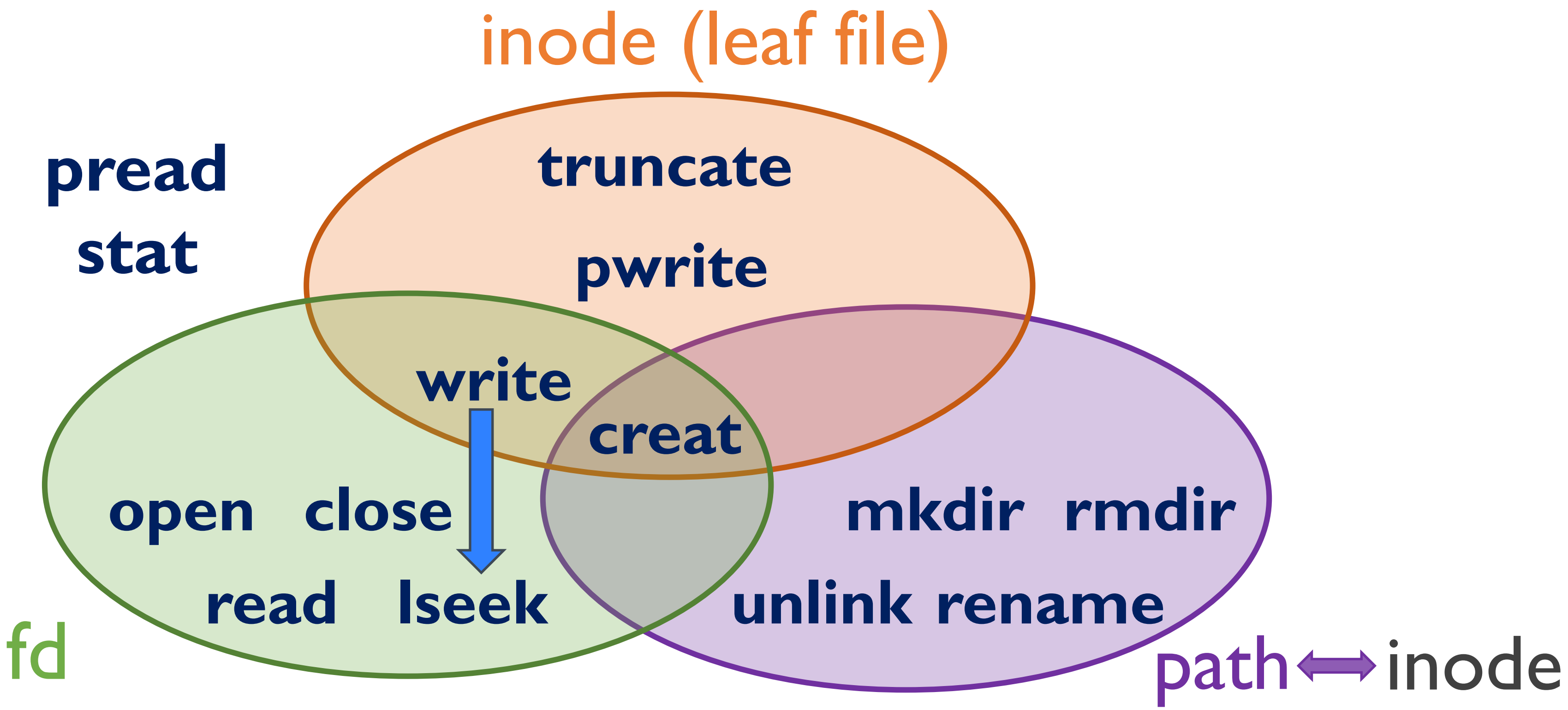

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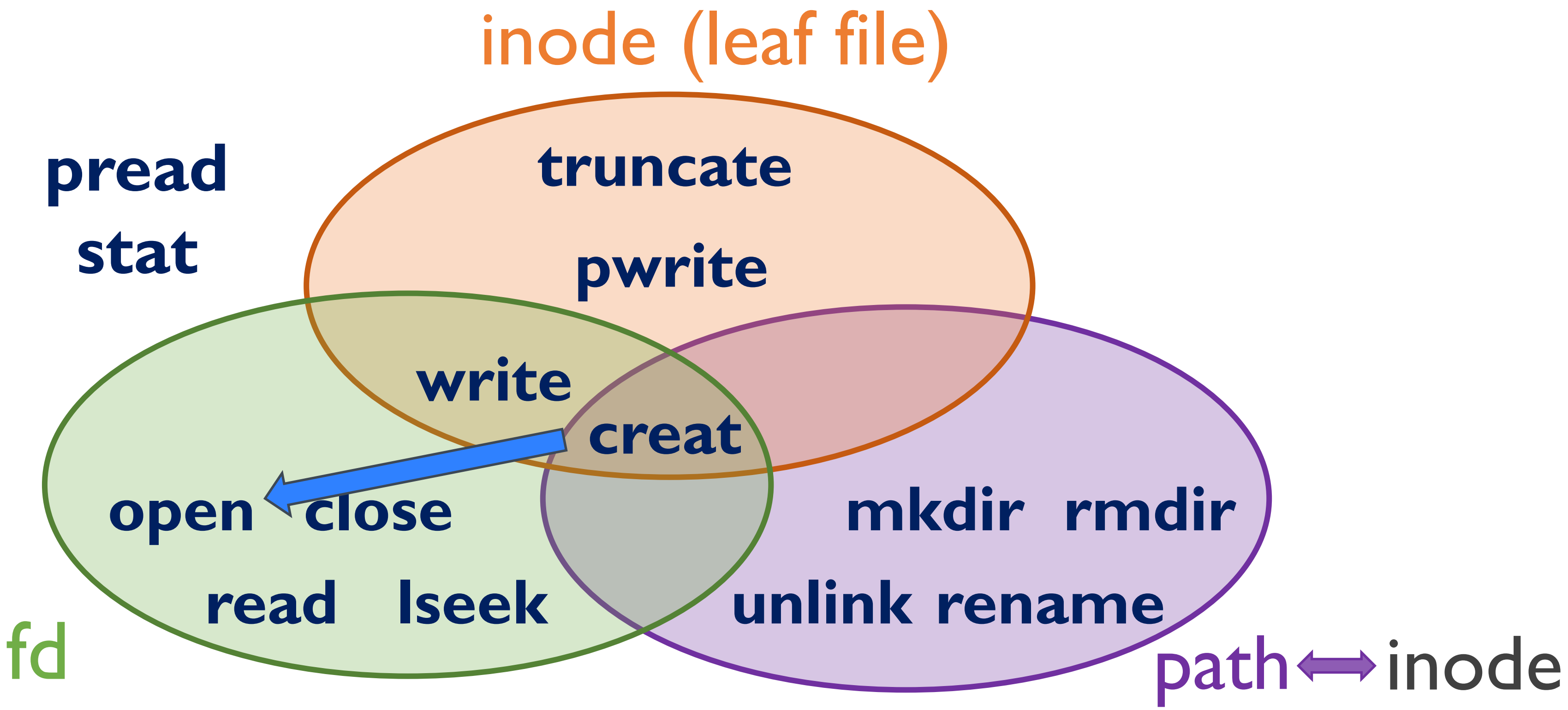

AIM (Act, Ignore, Modify) A I M

Transform P-Log entries into actions that can be executed by the original filesystem implementation

Ignore or not (Checking the bits & Fast in the common path)

- Ignore: a logged operation needs to be ignored

Act or Modify (During recovery)

- Act: an operation will be directly replayed
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AIM (Act, Ignore, Modify) A I M

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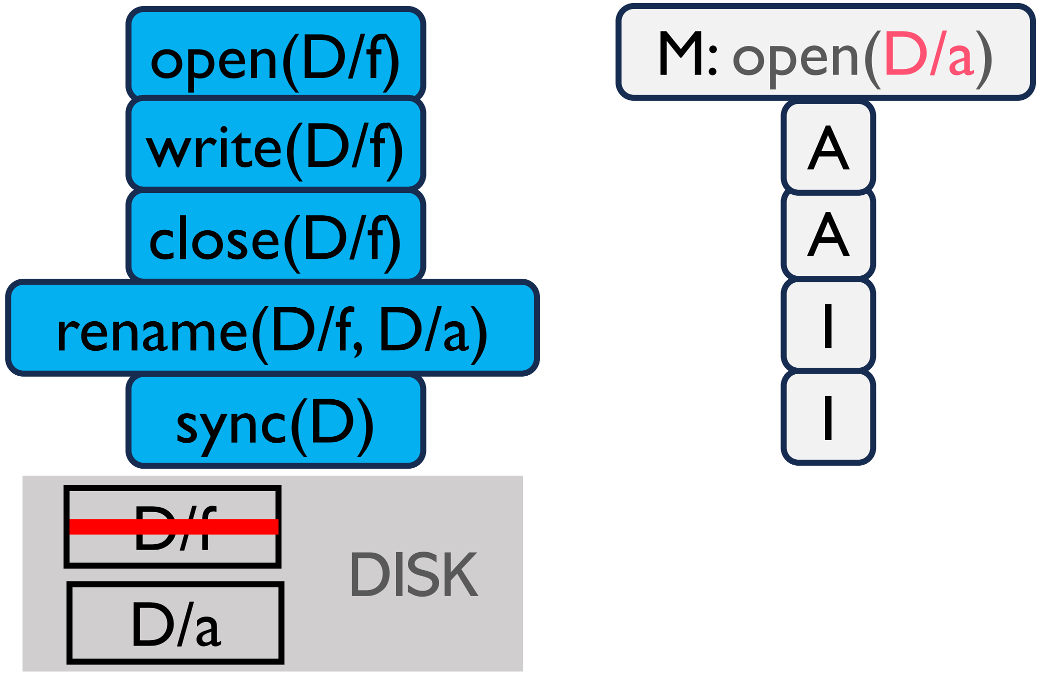

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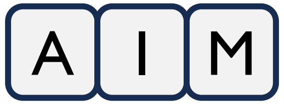

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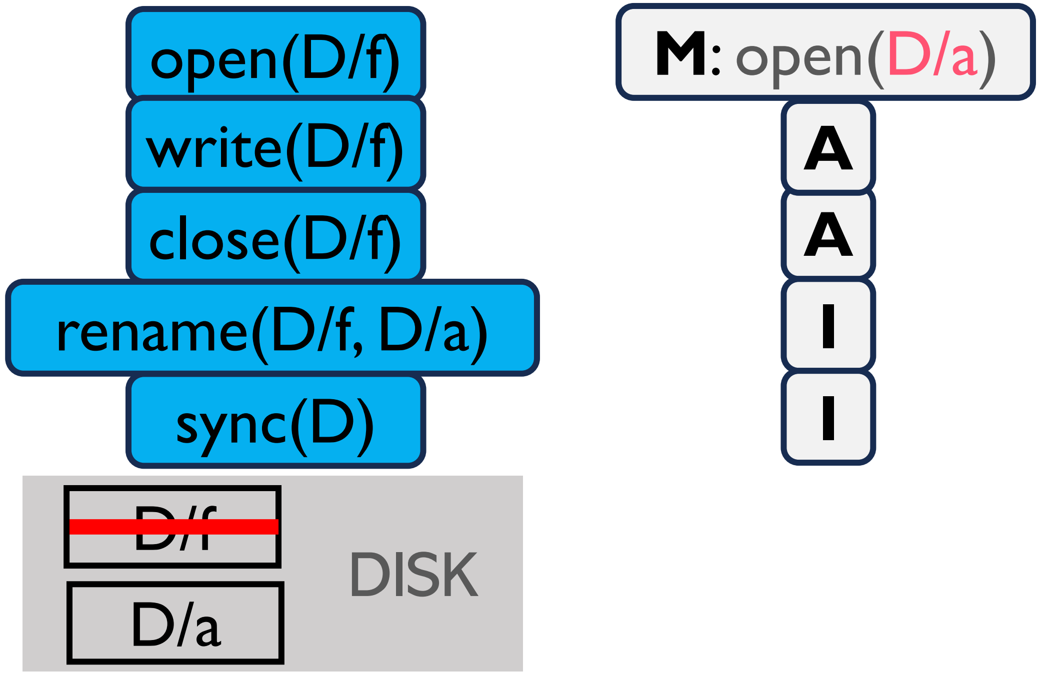

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- Evaluation
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Evaluation

Failure transparency

- Over 30,000 fault injection experiments under various applications, covering different state gap
- Over 3,000 Memory corruption experiments

Fast recovery

Low overhead in common-path

- Performance overhead & memory overhead

Empirical Evaluation of Recovering the State Gap

Five real-world applications

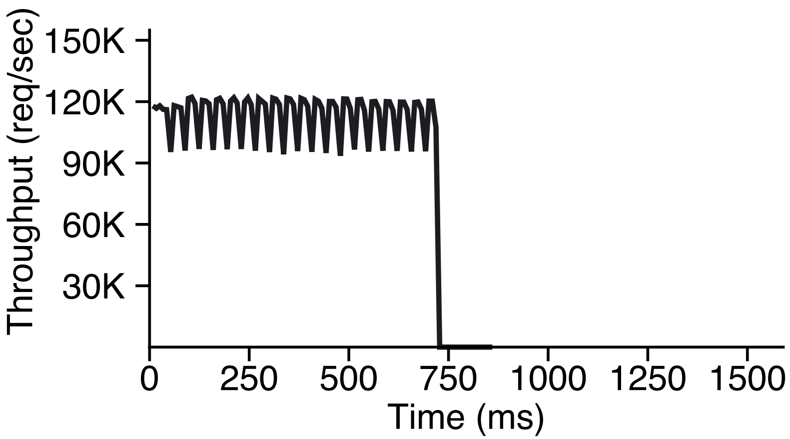
- Sort, copy, unzip, SQLite, LevelDB
- Inject a process crash after each operation in sequences

Over 30,000 cases

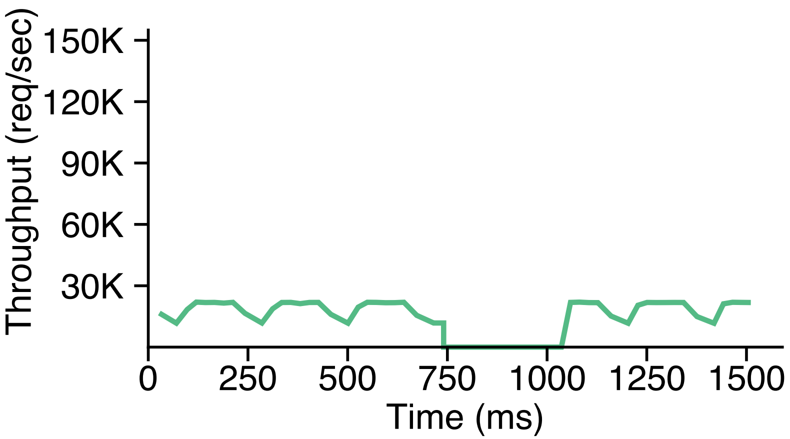
- Provide failure transparency

Fast, Transparent Recovery & Low Overhead During Normal Execution

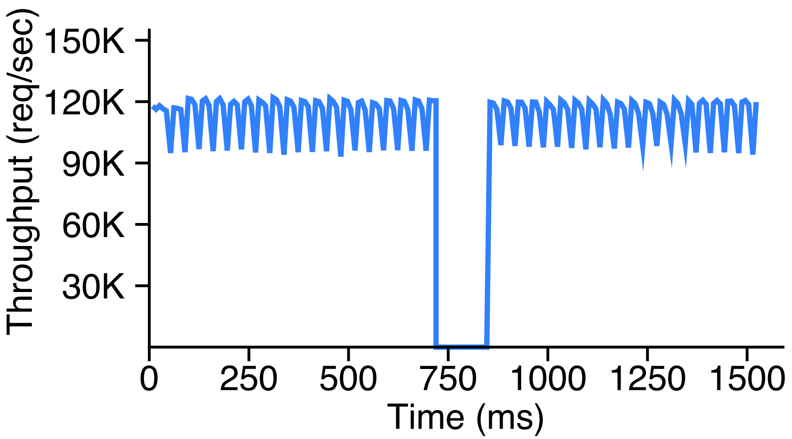
Workload: LevelDB (load)



full-system crash recovery



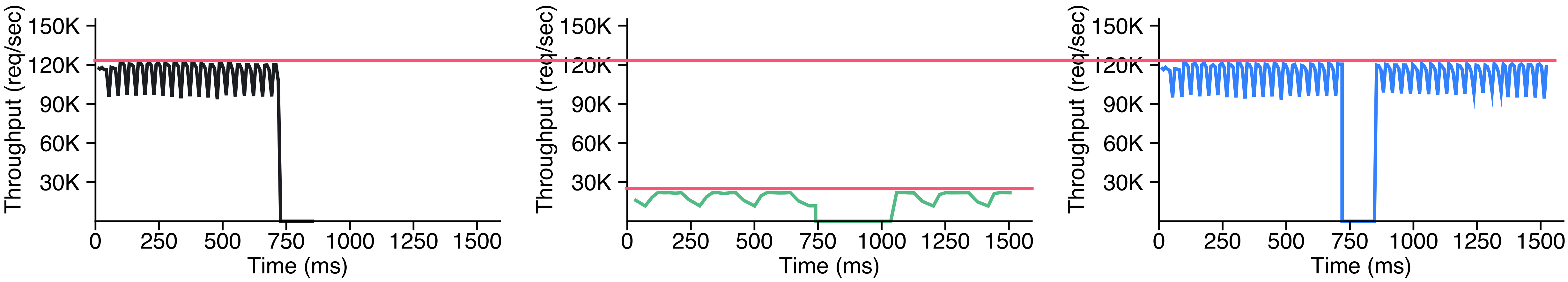
full-system crash recovery + flush every operation



full-system crash recovery + process crash recovery (Ananke)

Low Overhead in the Common Path

Workload: LevelDB (load)



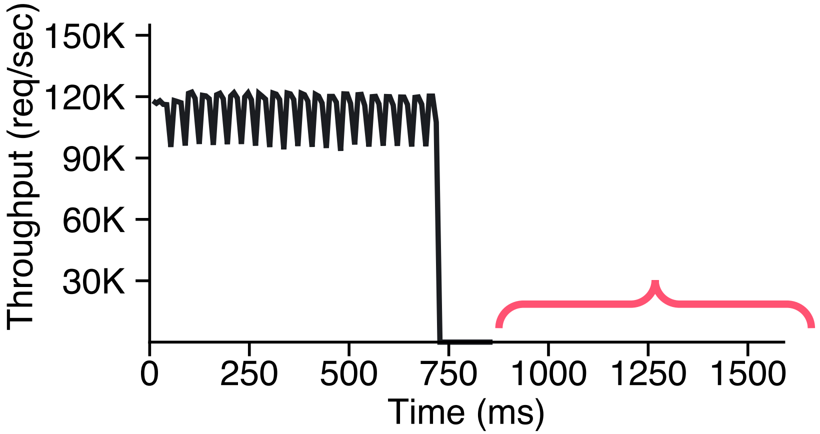
full-system crash recovery

full-system crash recovery + flush every operation

full-system crash recovery + process crash recovery (Ananke)

Fast, Transparent Recovery

Workload: LevelDB (load)



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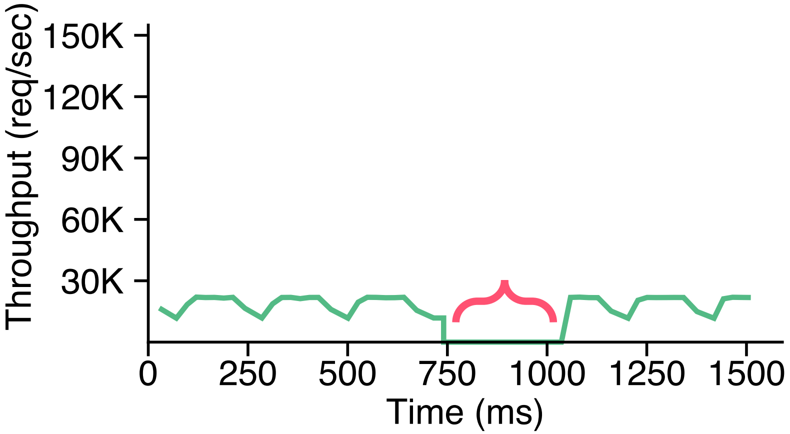

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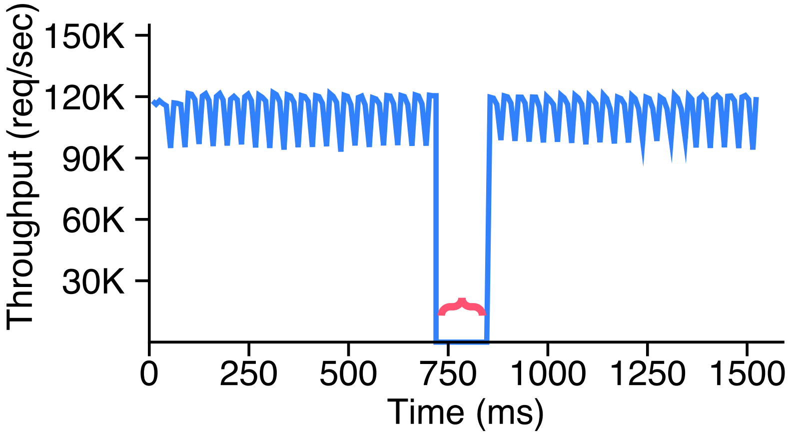

full-system crash recovery + process crash recovery (Ananke)

Conclusion

Ananke: fast, transparent filesystem process crash recovery

- Implemented in uFS—a state-of-the-art filesystem microkernel
- Novel mechanisms:
  - P-log and AIM to recover state gap
  - Others to improve recovery performance and robustness
- Thorough evaluation: fault injection and overhead analysis

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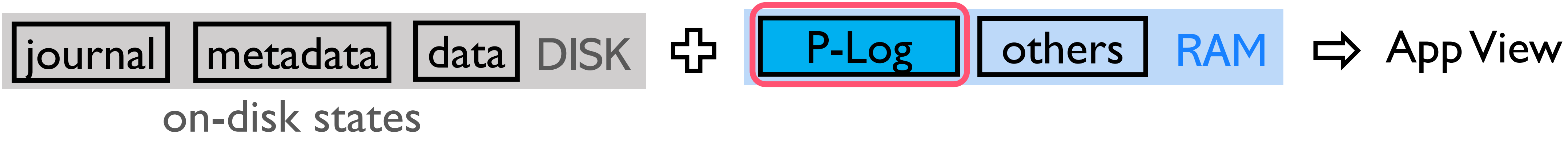
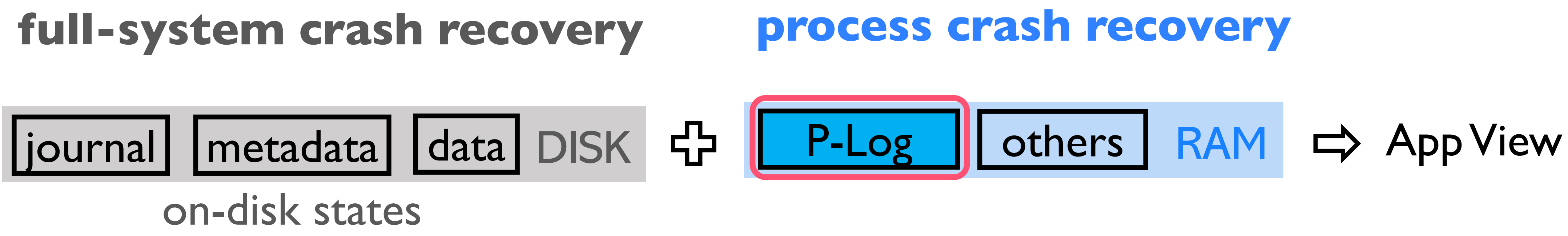


Conclusion

Separate **process crash recovery** from **full-system crash recovery**

- Filesystem process crash is not the same as power-failure
  - Opportunity for transparent recovery
- Improve the guarantee of local filesystem services



Ananke and Process Crash Recovery

See the paper (or email me: jingliu3@microsoft.com) for:

- Principles and challenges for process crash recovery
- Detailed design of P-log and AIM
- Correctness and performance evaluation under various applications

Thank you for listening!