Improving Server Applications with System Transactions

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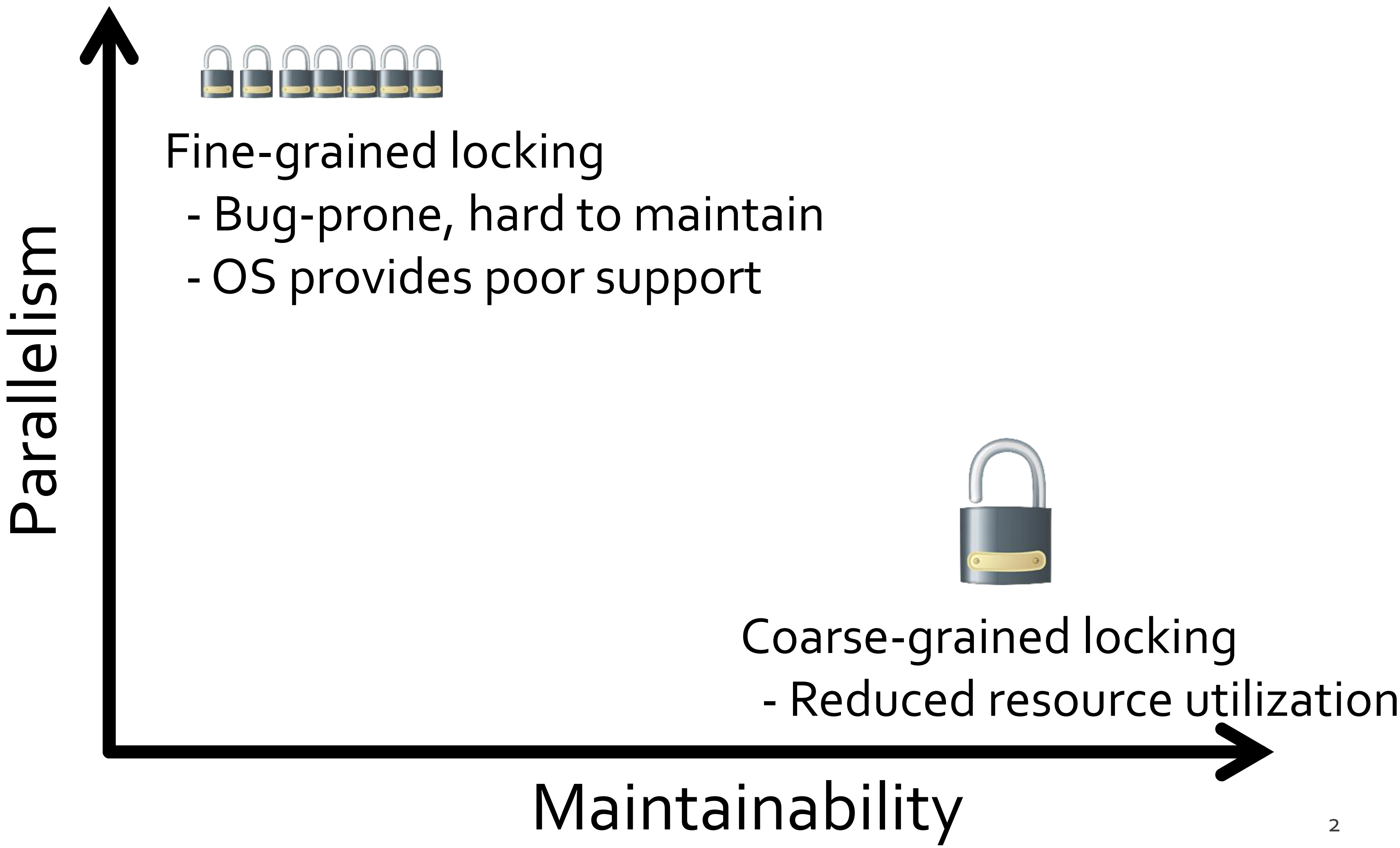
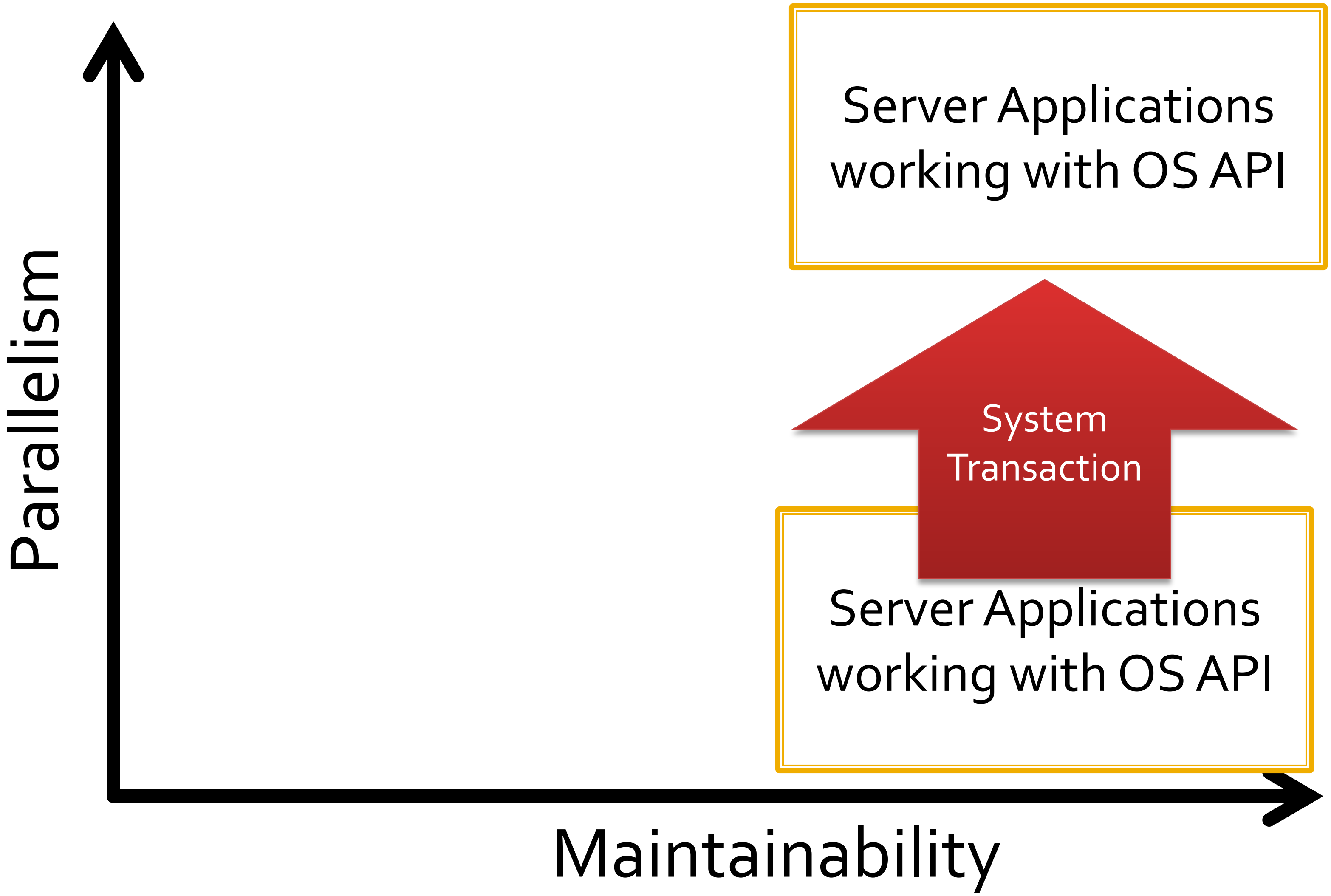
Poor OS API Support for Concurrency



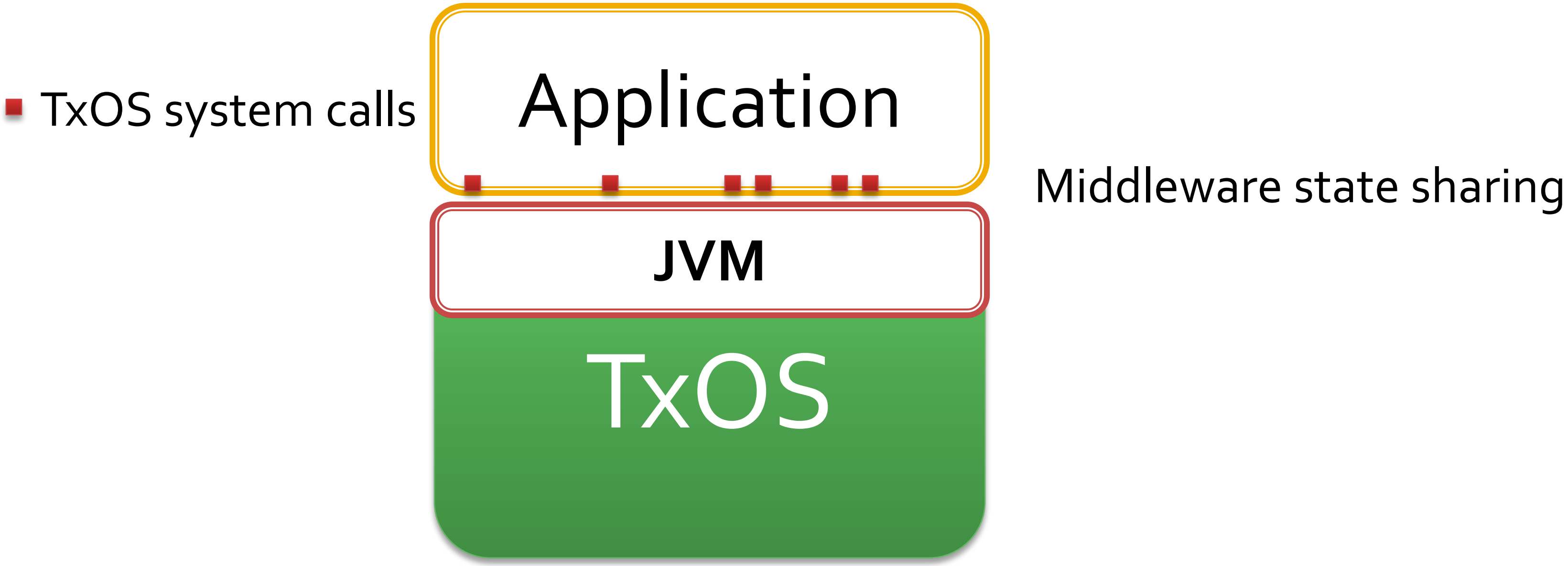
System Transaction Improves OS API Concurrency



Improving System Transactions

- TxOS provides operating system transaction
  [Porter et al., SOSP 2009]
  - Transaction for OS objects (e.g., files, pipes)

Middleware state sharing with multithreading



Improving System Transactions

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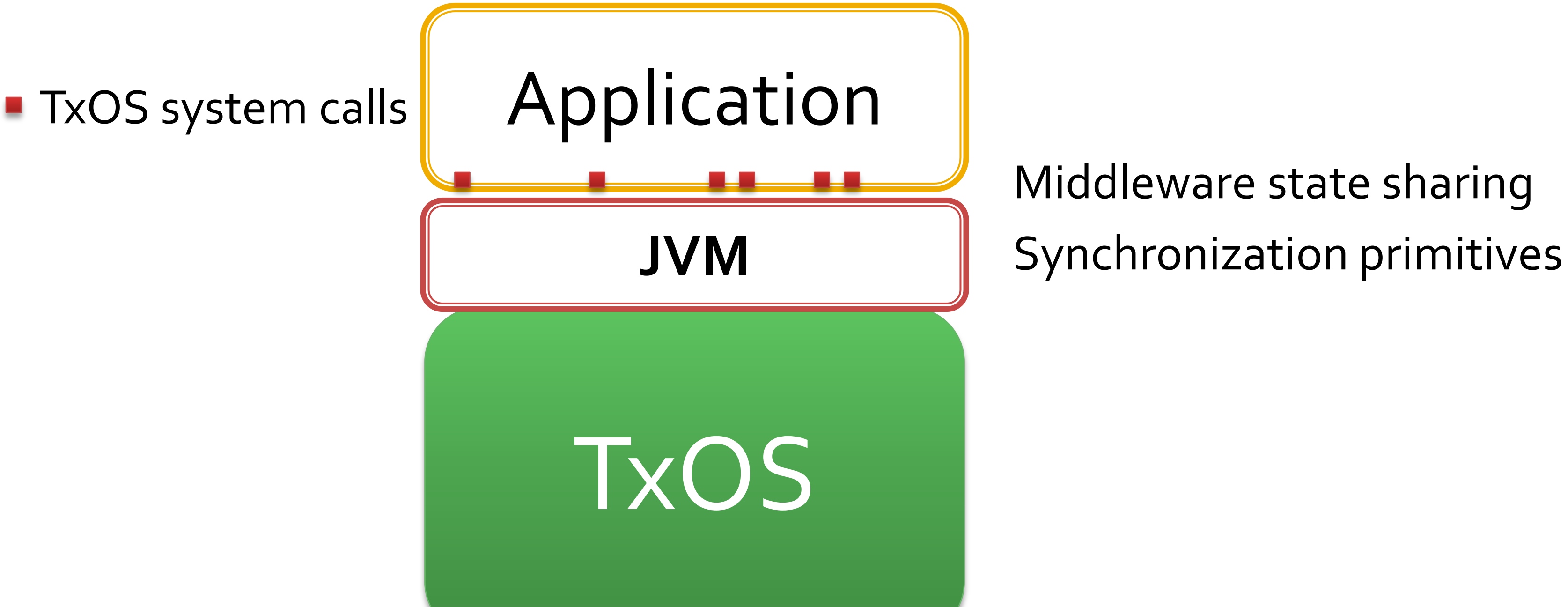
  - Transaction for OS objects (e.g., files , pipes)

Synchronization in legacy code



Improving System Transactions

- TxOS provides operating system transaction
  [Porter et al., SOSP 2009]

Up to 88% throughput improvement

At most 40 application line changes

- TxOS system calls

Application

JVM

TxOS+

Middleware state sharing

Synchronization primitives

TxOS+: pause/resume, commit ordering, and more

Outline

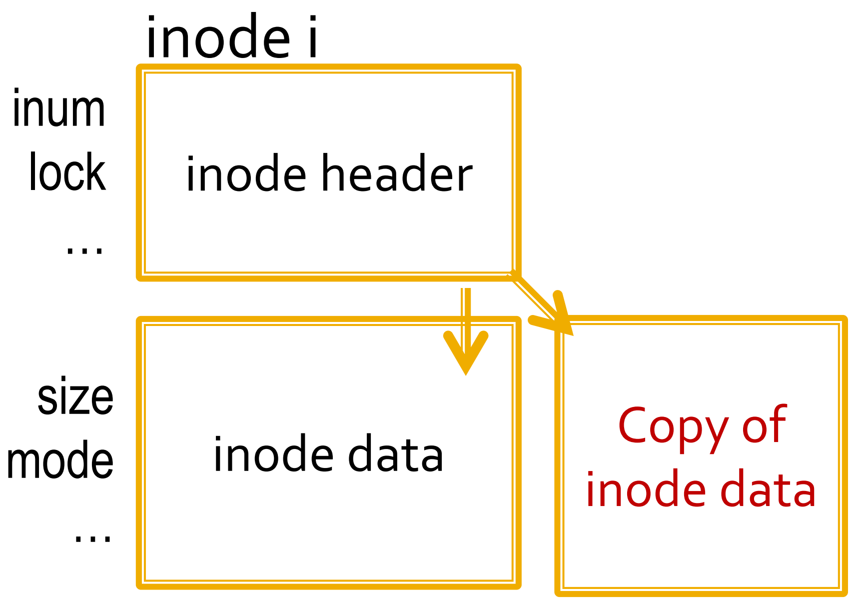
- Background: system transaction
- System transactions in action
- Challenges for rewriting applications
- Implementation and evaluation

Background: System Transaction

- Transaction Interface and semantics
  - System calls: xbegin(), xend(), xabort()
  - ACID semantics
    - Atomic – all or nothing
    - Consistent – one consistent state to another
    - Isolated – updates as if only one concurrent transaction
    - Durable – committed transactions on disk
  - Optimistic concurrency control
- Fix synchronization issues with OS APIs

Background: System Transaction

- Lazy versioning: speculative copy for data



xbegin();	←
write(f, buf);	← Conflict!
xend();	← Abort / Commit

- **TxOS requires no special hardware**

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Applications Parallelized with OS Transactions

- **Parallelizing applications that synchronize on OS state**
- Example 1: State-machine replication
  - Constraint: Deterministic state update
- Example 2: IMAP Email Server
  - Constraint: Consistent file system operations

Example 1: Parallelizing State-machine Replication

- Core component of fault tolerant services
  - e.g., Chubby, Zookeeper, Autopilot
- Replicas execute the same sequence of operations
  - Often **single-threaded** to avoid non-determinism
- **Ordered transaction**
  - Makes parallel OS state updates deterministic
  - Applications determine commit order of transactions

Example 2: Parallelizing IMAP Email Servers

- **Everyone has concurrent email clients**
  - Desktop, laptop, tablets, phones, ...
  - Need concurrent access to stored emails
- **Brief history of email storage formats**
  - mbox: single file, file locking
  - Lockless Maildir
  - Dovecot Maildir: return of file locking

mbox: Database Without Parallelism

- mbox
  - **Single file** mailbox of email messages

~/.mbox

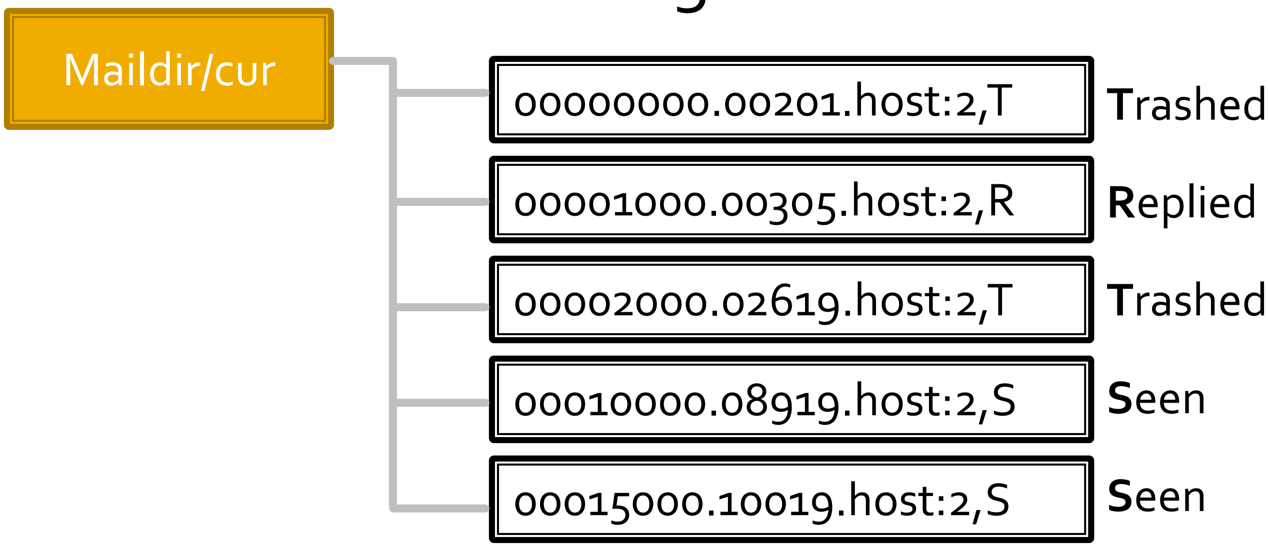
```
From MAILER-DAEMON Wed Apr 11 09:32:28 2012
From: Sangman Kim <sangmank@cs.utexas.edu>
To: EuroSys 2012 audience
Subject: mbox needs file lock. Maildir hides message.
.....
From MAILER-DAEMON Wed Apr 11 09:34:51 2012
From: Sangman Kim <sangmank@cs.utexas.edu>
To: EuroSys 2012 audience
Subject: System transactions good, file locks bad!
....
```

  - Synchronization with file-locking
    - One of fcntl(), flock(), lock file (.mbox.lock)
    - Very coarse-grained locking

Maildir: Parallelism Through Lockless Design

- Maildir: Lockless alternative to mbox
  - Directories of message files
  - Each file contains a message
  - Directory access with no synchronization (originally)

- Message filenames contain flags



Messages Hidden with Lockless Maildir

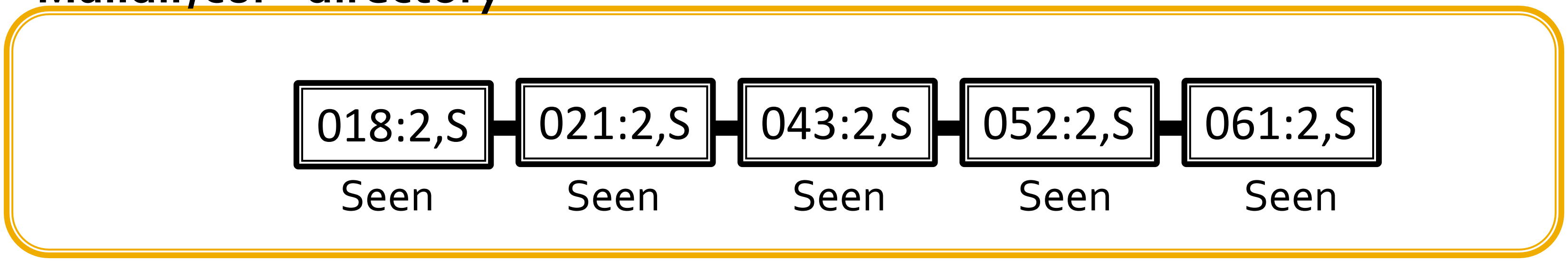
PROCESS 1 (LISTING)

```
while (f = readdir(“Maildir/cur”)):
    print f.name
```

PROCESS 2 (MARKING)

```
if (access(“043:2,S”)):
    rename(“043:2,S”, “043:2,R”)
```

“Maildir/cur” directory



Messages Hidden with Lockless Maildir

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while (f = readdir("Maildir/cur")):
    print f.name
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PROCESS 2 (MARKING)

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if (access("043:2,S")):
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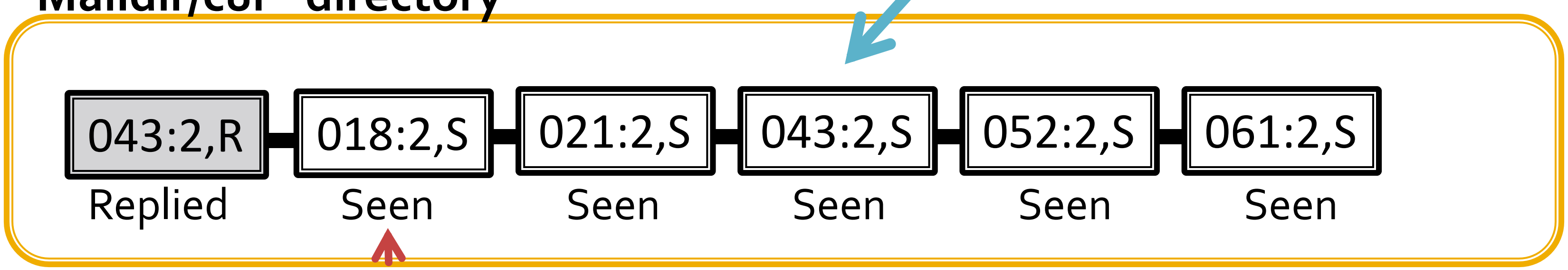
"Maildir/cur" directory



Process 1 Result

018:2,S
021:2,S
052:2,S
061:2,S

Message missing!

Return of The Coarse-grained File Locking

- Maildir synchronization
  - Lockless

    > *"certain anomalous situations may result"*
    >
    > – Courier IMAP manpage

  - File locks
    - Per-directory coarse-grained locking
    - Complexity of Maildir, performance of mbox
  - **System transactions**

Maildir Parallelized with System Transaction

PROCESS 1 (MARKING)

```
xbegin()
if (access("XXX:2,S")):
    rename("XXX:2,S",
   "XXX:2,R")
xend()
```

PROCESS 2 (MESSAGE LISTING)

```
xbegin()
while (f = readdir("Maildir/cur")):
    print f.name
xend()
```

Consistent directory accesses with better parallelism

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- Background: system transaction
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- Challenges for rewriting applications
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Challenges of Rewriting Applications

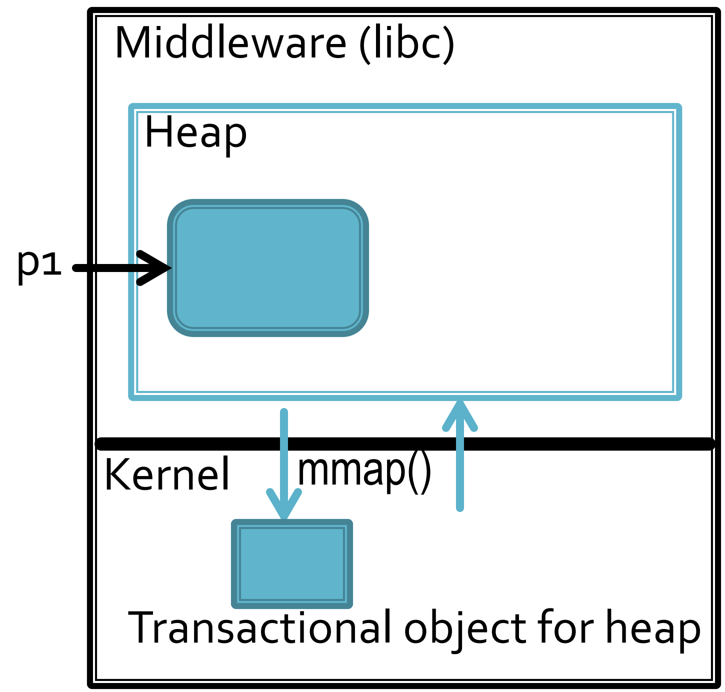
1. Middleware state sharing
2. Deterministic parallel update for system state
3. Composing with other synchronization primitives

Middleware and System Transaction

- Problem with memory management
  - Multiple threads share the same heap

In Transaction

Thread 1	Thread 2
→ xbegin();	
→ p1 = malloc();	
	p2 = malloc();
xabort();	
	*p2 = 1;

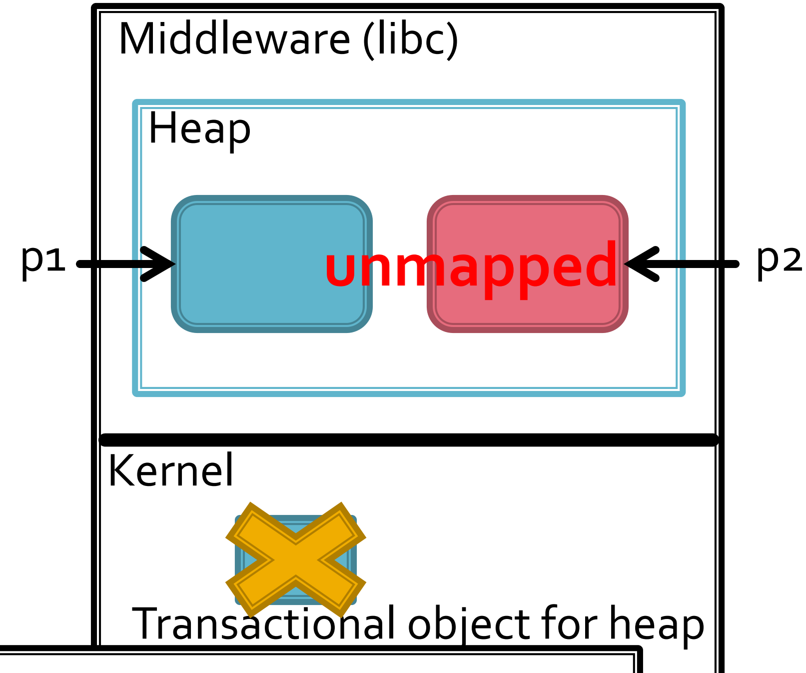


Middleware and System Transaction

- Problem with memory management
  - Multiple threads share the same heap

In Transaction

Thread 1	Thread 2
xbegin(); p1 = malloc();	
	→ p2 = malloc();
→ xabort();	
	→ *p2 = 1; **FAULT!**



Certain middleware actions should not roll back

Two Types of Actions on Middleware State

USER-INITIATED ACTION

- User changes system state
  - Most file accesses
  - Most synchronization

MIDDLEWARE-INITIATED

- System state changed as side effect of user action
  - malloc() memory mapping
  - Java garbage collection
  - Dynamic linking
- Middleware state shared among user threads
  - Can't just roll back!

Handling Middleware-Initiated Actions

- Transaction pause/resume
  - Expose state changes by **middleware-initiated actions** to other threads
  - Additional system calls
    - **xpause(), xresume()**
  - Limited complexity increase
    - We used pause/resume 8 times in glibc, 4 times in JVM
    - Only used in application for debugging

Pause/Resume In JVM Execution

Java code	JVM Execution
SysTransaction.begin();	xbegin();
files = dir.list();	files = dir.list();
	xpause()
	VM operations (garbage collection)
	xresume()
SysTransaction.end();	xend();

Other Challenges for Maturing TxOS

- 17,000 lines of kernel changes
  - Transactionalizing file descriptor table
  - Handling page lock for disk I/O
  - Memory protection
  - Optimization with directory caching
  - Reorganizing data structure
  - and more

- Details in the paper

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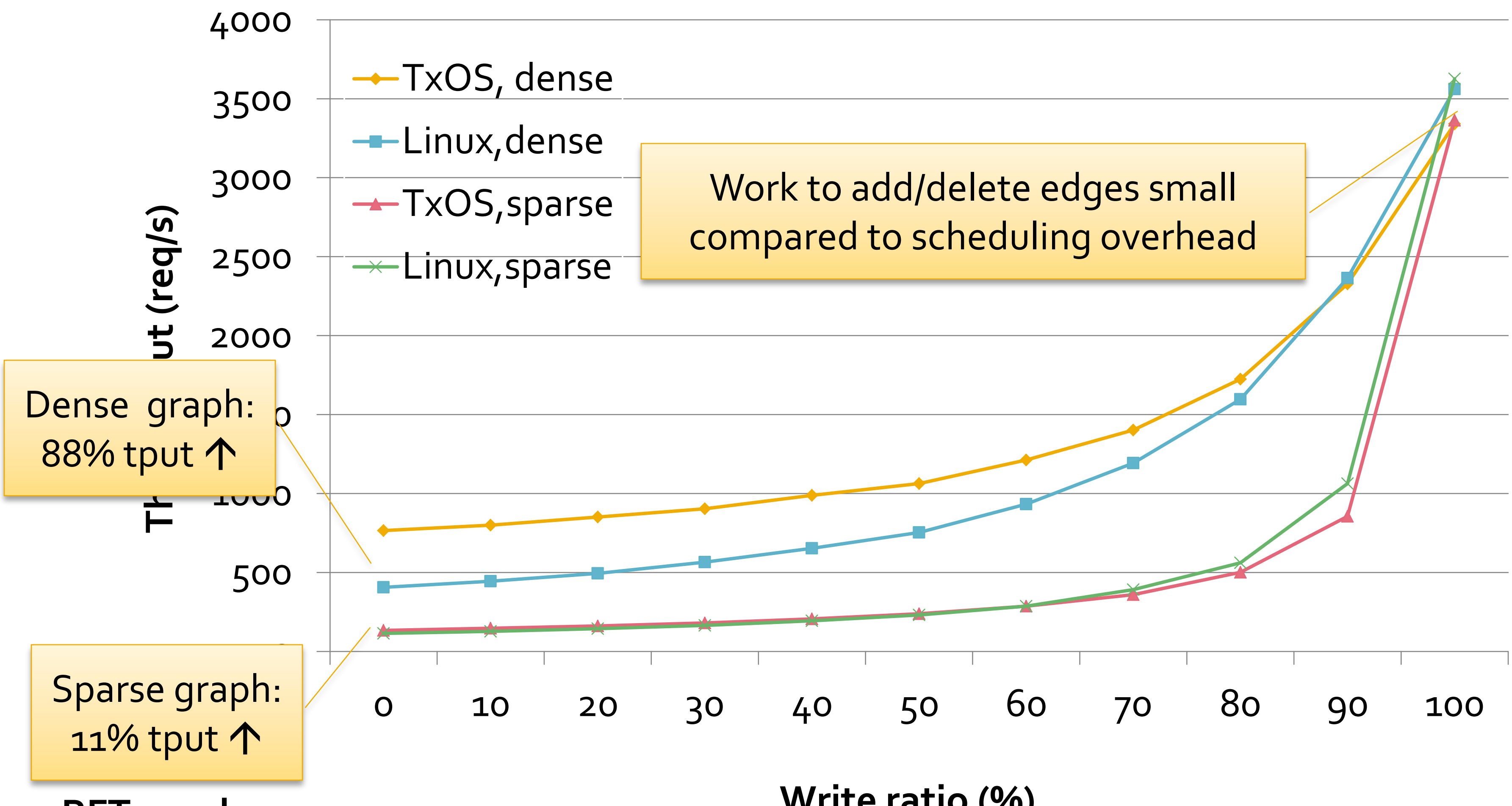
Application 1: Parallelized BFT Application

- Implemented in UpRight BFT library
- Fault tolerant routing backend
  - Graph stored in a file
  - Compute shortest path
  - Edge add/remove
- Ordered transactions for deterministic update

Minimal Application Code Change

Component	Total LOC	Changed LOC
Routing application	1,006	18 **(1.8%)**
Upright Library	22,767	174 **(0.7%)**
JVM	496,305	384 **(0.0008%)**
glibc	1,027,399	826 **(0.0008%)**

Deterministic State Update with Better Throughput



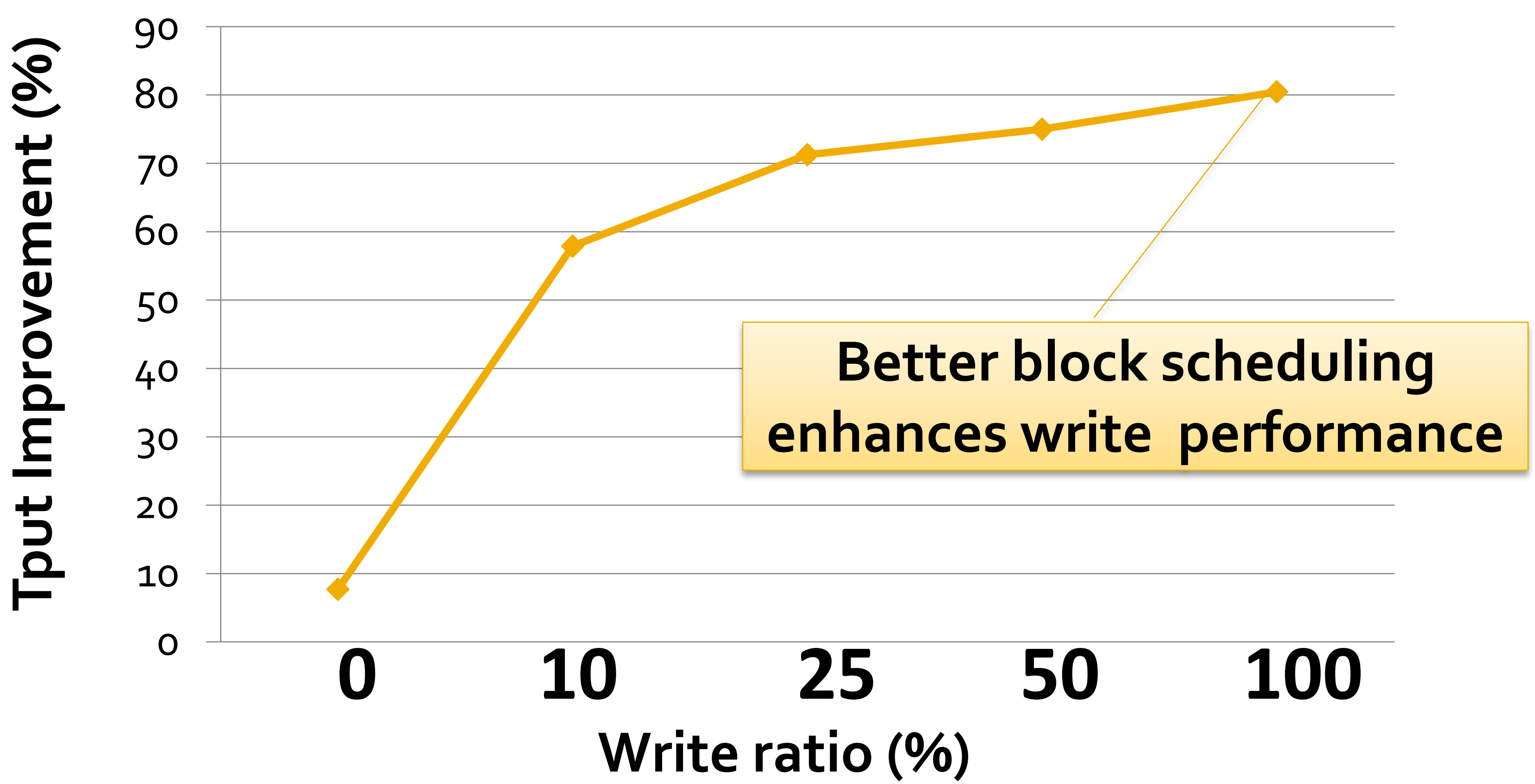
BFT graph server

Application 2: Dovecot Maildir access

- Dovecot mail server
  - Uses directory lock files for maildir accesses
- Locking is replaced with system transactions
  - Changed LoC: 40 out of 138,723
- Benchmark: Parallel IMAP clients
  - Each client executes operations on a random message
    - Read: message read
    - Write: message creation/deletion
    - 1500 messages total

Mailbox Consistency with Better Throughput

- Dovecot benchmark with 4 clients



Conclusion: OS Transactions Improve Server Performance

- System transactions parallelize tricky server applications
  - Parallel Dovecot maildir operations
  - Parallel BFT state update
- System transaction improves throughput with few application changes
  - Up to 88% throughput improvement
  - At most 40 changed lines of application code