

TxLinux: Managing Transactional Memory in an Operating System

Chris Rossbach, Owen Hofmann, Don Porter,
Hany Ramadan, Aditya Bhandari, Emmett Witchel
University of Texas at Austin

Hardware Transactional Memory is a reality

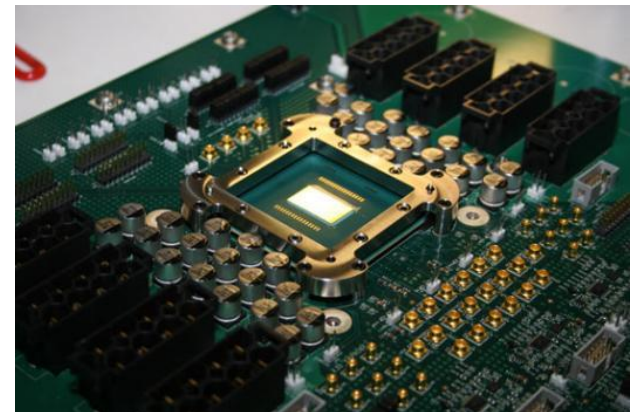
- ▶ Sun “Rock” supports HTM
- ▶ Solaris 10 takes advantage of HTM support



Parallel Programming Predicament

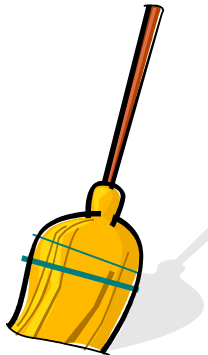
- ▶ Challenge: taking advantage of multi-core
- ▶ Parallel programming is difficult with locks:
 - Deadlock, convoys, priority inversion
 - Conservative, poor composability
 - Lock ordering complicated
 - Performance-complexity tradeoff
- ▶ Transactional Memory in the OS
 - Benefits user programs
 - Simplifies programming

Intel's snazzy 80
core chip →

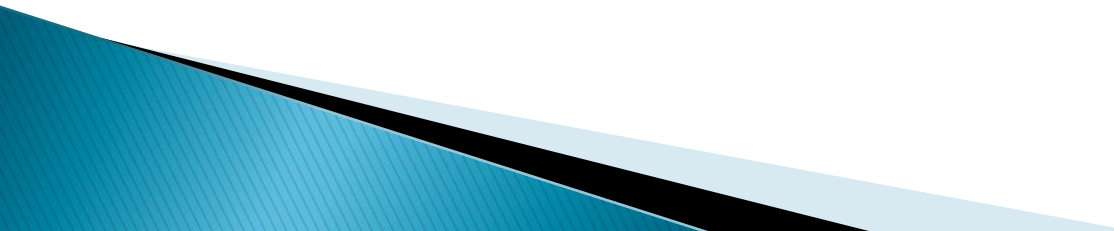


mm/filemap.c lock ordering

```
/*
 * Lock ordering:
 * ->i_mmap_lock          (vmtruncate)
 * ->private_lock        (__free_pte->__set_page_dirty_buffers)
 * ->swap_lock           (exclusive_swap_page, others)
 * ->mapping->tree_lock
 * ->i_mutex
 * ->i_mmap_lock          (truncate->unmap_mapping_range)
 * ->mmap_sem
 * ->i_mmap_lock
 * ->page_table_lock or pte_lock  (various, mainly in memory.c)
 * ->mapping->tree_lock  (arch-dependent flush_dcache_mmap_lock)
 * ->mmap_sem
 * ->lock_page           (access_process_vm)
 * ->mmap_sem
 * ->i_mutex              (msync)
 * ->i_mutex
 * ->i_alloc_sem          (various)
 * ->inode_lock
 * ->sb_lock              (fs/fs-writeback.c)
 * ->mapping->tree_lock  (__sync_single_inode)
 * ->i_mmap_lock
 * ->anon_vma.lock        (vma_adjust)
 * ->anon_vma.lock
 * ->page_table_lock or pte_lock  (anon_vma_prepare and various)
 * ->page_table_lock or pte_lock
 * ->swap_lock           (try_to_unmap_one)
 * ->private_lock        (try_to_unmap_one)
 * ->tree_lock           (try_to_unmap_one)
 * ->zone.lru_lock        (follow_page->mark_page_accessed)
 * ->zone.lru_lock        (check_pte_range->isolate_lru_page)
 * ->private_lock        (page_remove_rmap->set_page_dirty)
 * ->tree_lock           (page_remove_rmap->set_page_dirty)
 * ->inode_lock           (page_remove_rmap->set_page_dirty)
 * ->inode_lock           (zap_pte_range->set_page_dirty)
 * ->private_lock        (zap_pte_range->__set_page_dirty_buffers)
 * ->task->proc_lock
 * ->dcache_lock          (proc_pid_lookup)
 */
```



Outline

- ▶ Motivation
 - ▶ TM Primer
 - ▶ TM and Lock cooperation
 - OS can use TM to **handle output commit**
 - ▶ TM and Scheduling
 - OS can use TM to **eliminate priority inversion**
 - ▶ Related Work
 - ▶ Conclusion
- 

Hardware TM Primer

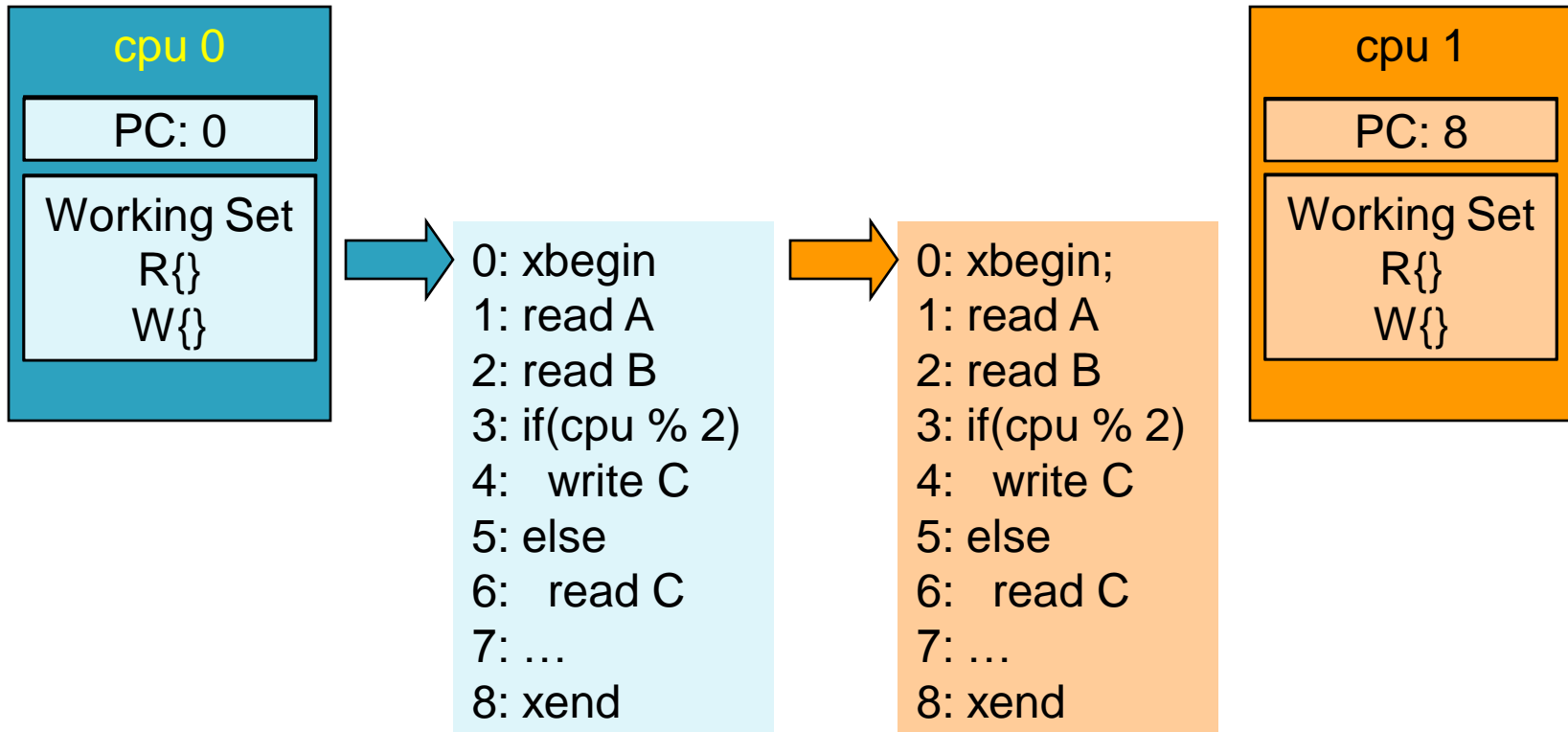
Key Ideas:

- ▶ Critical sections execute concurrently
- ▶ Conflicts are detected dynamically
- ▶ If conflict serializability is violated, rollback

Key Abstractions:

- ▶ Primitives
 - **xbegin, xend, xretry**
 - **xpush, xpop**
 - **xcas, xtest, xgettxid**
- ▶ Conflict
 - $\emptyset \neq \{W_a\} \cap \{R_b \cup W_b\}$
- ▶ Contention Manager
 - Need flexible policy

Hardware TM basics: example



CONFLICT
Assume Contention
manager decides cpu1
wins:
C is in the read set of
cpu0, and in the write
set of cpu1
cpu0 rolls back
cpu1 commits

Conventional Wisdom 'Transactionalization'

- ▶ xspinlocks
 - spin_lock() -> xbegin
 - spin_unlock() -> xend
- ▶ Basis of our first transactionalization of Linux
 - 9 subsystems (profile-guided selection)
 - 30% of dynamic lock calls
 - 6 developers * ~1 year
- ▶ Issues:
 - I/O (output commit)
 - idiosyncratic locking (e.g. runqueue)

Locks and Transactions must Cooperate!

- ▶ Legacy code
- ▶ I/O
 - Nested critical section may do I/O
 - Beware low memory (page faults!)
- ▶ Critical sections may defy transactionalization
- ▶ Programmer flexibility
 - Tx performs well when actual contention is rare
 - Locks perform better when contention is high.

Cxspinlocks

- ▶ **C**ooperative **T**ransactional **S**pinlock
- ▶ Critical sections use locks **OR** transactions
 - Most critical sections attempt transactions
 - Rollback and lock if a crit sec attempts I/O
 - Locks optimize crit sec that always does I/O
- ▶ Contention manager involved in lock acquisition
- ▶ “Informing Transactions”
 - **xbegin** must return a reason for retry
- ▶ One developer * 1 month to convert

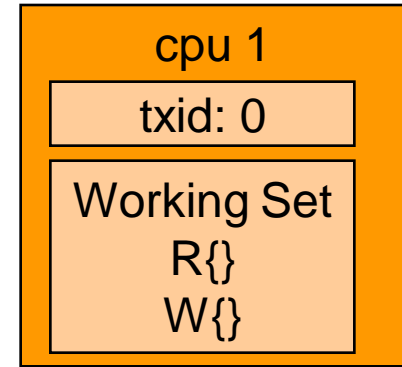
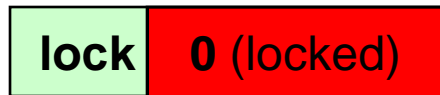
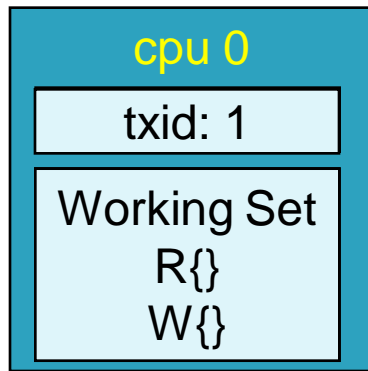
Cxspinlock API

cx_optimistic: <i>Use transactions, restart on I/O attempt</i>	cx_exclusive <i>Acquire a lock, using contention manager</i>	cx_end <i>Release a critical section</i>
<pre>void cx_optimistic(lock){ status = xbegin; if(status==NEED_EXCL){ xend; if(gettxid) xrestart(NEED_EXCL); else cx_exclusive(lock); return; } while(!xtest(lock,1)); }</pre>	<pre>void cx_exclusive(lock){ while(1) { while(*lock != 1); if(xcas(lock, 1, 0)) break; } }</pre>	<pre>void cx_end(lock){ if(xgettxid) { xend; } else { *lock = 1; } }</pre>

`NEED_EXCL ==` need exclusive.

Returned from `xbegin` when hardware detects I/O in a transaction.

cxspinlock action zone



```
void cx_optimistic(lock){
    status = xbegin;
    if(status==NEED_EXCL){
        xend;
        if(gettxid)
            xrestart(NEED_EXCL);
        else
            cx_exclusive(lock);
        return;
    }
    while(!xtest(lock,1));
}
```



```
void cx_exclusive(lock){
    if(xgettxid)
        xrestart(NEED_EXCL);
    while(1) {
        while(*lock != 1);
        if(xcas(lock, 1, 0))
            break;
    }
}
```

Conversely, if CM decides that cpu0 wins, `xcas` fails, and cpu1 will spin until lock leaves cpu0's working set.

cxspinlock action zone: I/O



```
...  
cx_optimistic(lock);  
do_useful_work();  
if(arcane_condition)  
    perform_io();  
cx_end();  
...
```

The `cx_exclusive` call results in the critsec being entered with a lock to protect I/O

lock	0 (locked)
arcane_condition	1

```
void cx_exclusive(lock){  
    while(1) {  
        while(*lock != 1);  
        if(xcas(lock, 1, 0))  
            break;  
    }  
}  
  
return;  
}  
while(!xtest(lock,1));  
}
```

Experimental Setup

- ▶ Implemented HW(MetaTM) as x86 extensions
- ▶ Simulation environment
 - Simics 3.0.27 machine simulator
 - 16k 4-way tx L1 cache; 4MB 4-way L2; 1GB RAM
 - 1 cycle/inst, 16 cyc/L1 miss, 200 cyc/L2 miss
 - 16 & 32 processors
- ▶ Benchmarks
 - **pmake, bonnie++, MAB, configure, find**

TxLinux Performance

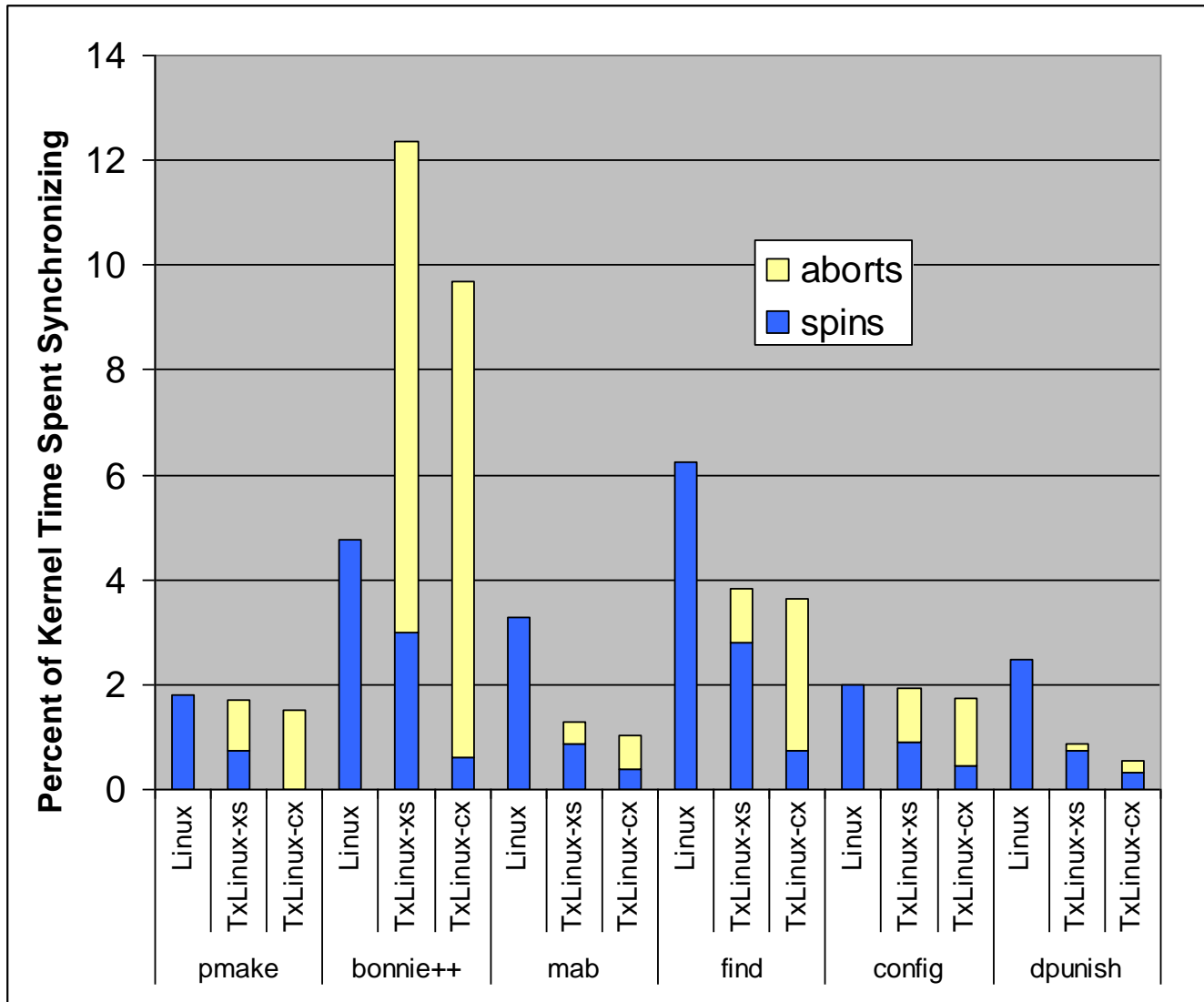
▶ TxLinux with xspinlocks

- 16 cpus -> 2% slowdown over Linux
 - Pathological backoff in bonnie++
 - 16 cpus -> 1.9% speed up excluding bonnie++
- 32 cpus -> 2% speedup over Linux

▶ TxLinux with cxspinlocks

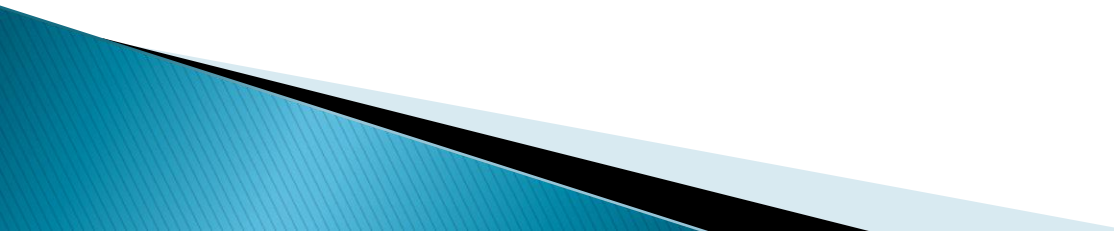
- 16 cpus -> 2.5% speedup over Linux
- 32 cpus -> 1% speedup over Linux

Reducing Synchronization Overhead

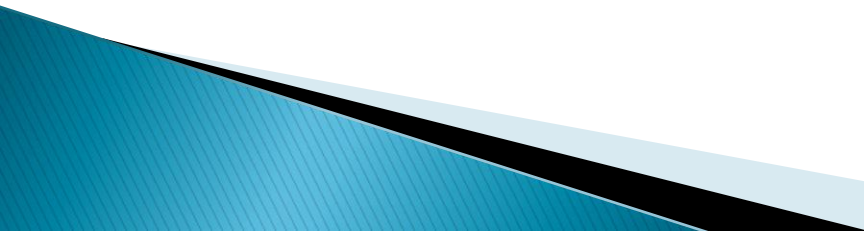


- 16 cpus
- 1-12% sync
- xs 34% lower
- cx 40% lower

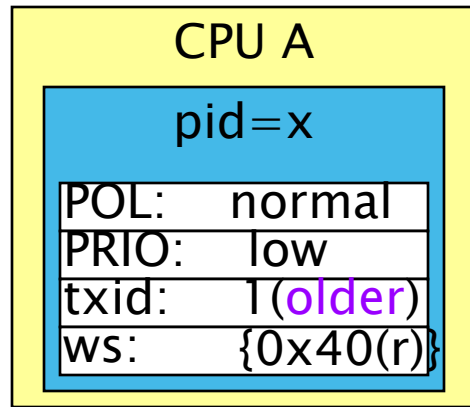
Outline

- ▶ Motivation
 - ▶ TM Primer
 - ▶ TM and Lock cooperation
 - OS can use TM to handle output commit
 - ▶ **TM and Scheduling**
 - OS can use TM to eliminate priority inversion
 - ▶ Related Work
 - ▶ Conclusion
- 

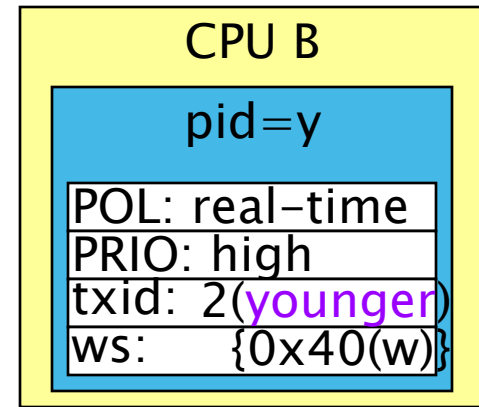
Transactions and Scheduling

- ▶ Transaction Restarts can *waste* a lot of work
 - ▶ Contention Management and OS scheduler *can* work at cross purposes
 - HW policies avoid livelock
 - But HW policies ignore OS goals
 - e.g. timestamp
 - ▶ OS requires better contention management
- 

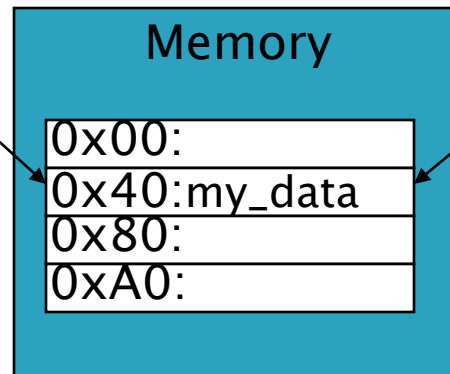
A problem with *timestamp* policy



1. x,A starts tx:1
3. x,A reads 0x40



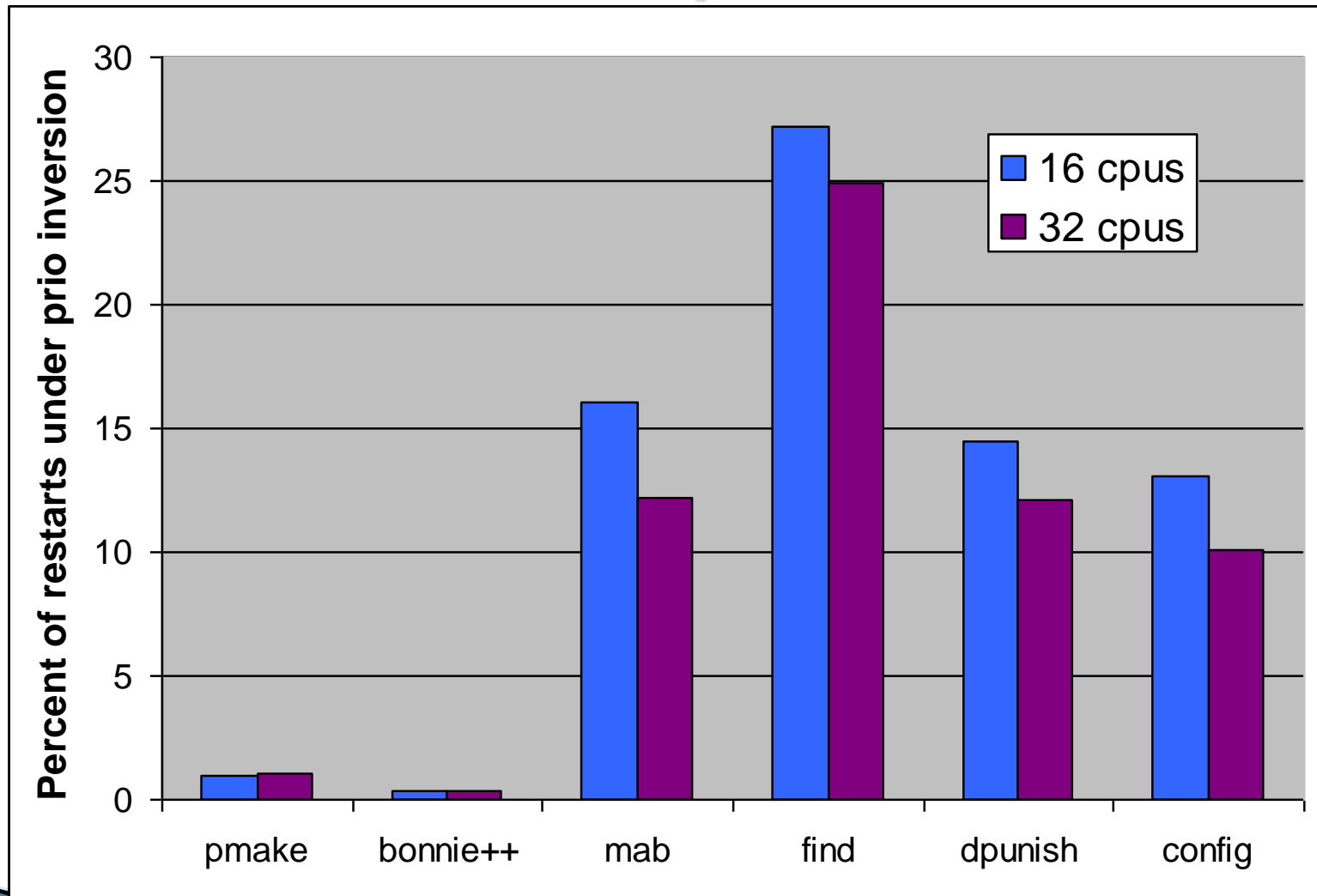
2. y,B starts tx:2
4. y,B writes 0x40



CONFLICT!

Low priority, non-real-time process wins conflict!

Inversion in the presence of Tx



9% conflicts → priority inversion
0.02% → policy inversion

Scheduling-Aware Transactions

- ▶ OS communicates priority to TM HW
- ▶ *os-prio* contention management policy
 - decides in favor of higher priority process
 - default to other policies when necessary
- ▶ Eliminates 100% of priority inversion
 - Better than priority-inversion avoidance for locks
- ▶ Negligible performance cost (<1%)

Related Work

- ▶ **Hardware Transactional Memory**
 - TCC [Hammond 04], LogTM[-SE] [Moore 06], VTM [Rajwar 05], UTM [Ananian 05] HASTM, PTM, HyTM, RTM
- ▶ **Dynamic selection of synchronization**
 - Speculative Lock Elision, TLR [Rajwar 01,02]
 - Reconciling Locks and Transactions [Welc 06]
- ▶ **I/O in Transactions**
 - Suspend [Moravan 06, Zilles 06]
 - Guarantee Completion [Blundell 07]
- ▶ **Scheduling**
 - HW support for inversion free spinlocks [Akgul 03]
 - Linux RT patch, Solaris 10

Conclusions

- ▶ Lock and Transactions need to cooperate
 - negligible performance cost
 - cxspinlock API simplifies conversion to tx
- ▶ The cxspinlock API enables I/O in tx
- ▶ Transactions can reduce sync overhead
 - but beware new pathologies
- ▶ Priority inversion can be *eliminated* with TM
- ▶ **Release: www.metatm.net**

(Special thanks to Sun Microsystems for the student scholarship!)