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

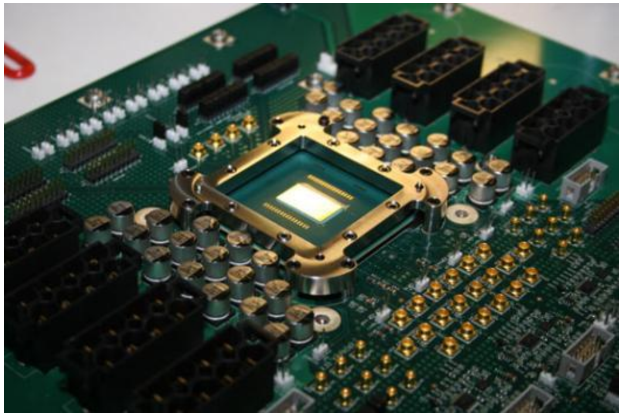
Hardware Transactional Memory is a reality

- Sun "Rock" supports HTM
- Solaris 10 takes advantage of HTM support

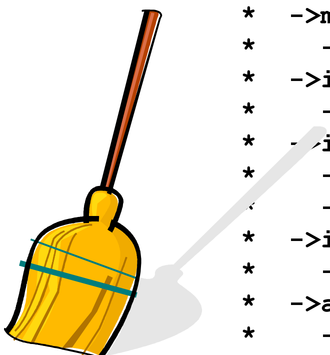
Parallel Programming Predicament

- 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
  - $\varnothing \neq \{W_a\} \cap \{R_b \cup W_b\}$
- Contention Manager
  - Need flexible policy

Hardware TM basics: example

cpu 0

PC: 0

Working Set
R{}
W{}

```
0: xbegin
1: read A
2: read B
3: if(cpu % 2)
4:   write C
5: else
6:   read C
7: …
8: xend
```

```
0: xbegin;
1: read A
2: read B
3: if(cpu % 2)
4:   write C
5: else
6:   read C
7: …
8: xend
```

cpu 1

PC: 8

Working Set
R{}
W{}

CONFLICT:

C is in the read set of cpu0, and in the write set of cpu1

Assume contention manager decides cpu1 wins:

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

- Cooperative Transactional Spinlock
- 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: *Use transactions, restart on I/O attempt*	cx_exclusive *Acquire a lock, using contention manager*	cx_end *Release a critical section*

`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){`
	`  while(1) {`
	`    while(*lock != 1);`
	`    if(xcas(lock, 1, 0))`
	`       break;`
	`  }`
	`}`
		`void cx_end(lock){`
		` if(xgettxid) {`
		`   xend;`
		` } else {`
		`   *lock = 1;`
		` }`
		`}`

NEED_EXCL == need exclusive.
Returned from xbegin when hardware detects I/O in a transaction.

cxspinlock action zone

cpu 0

txid: 1

Working Set
R{}
W{}

lock | **0** (locked)

cpu 1

txid: 0

Working Set
R{}
W{}

```
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();
…
```

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));
}
```

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

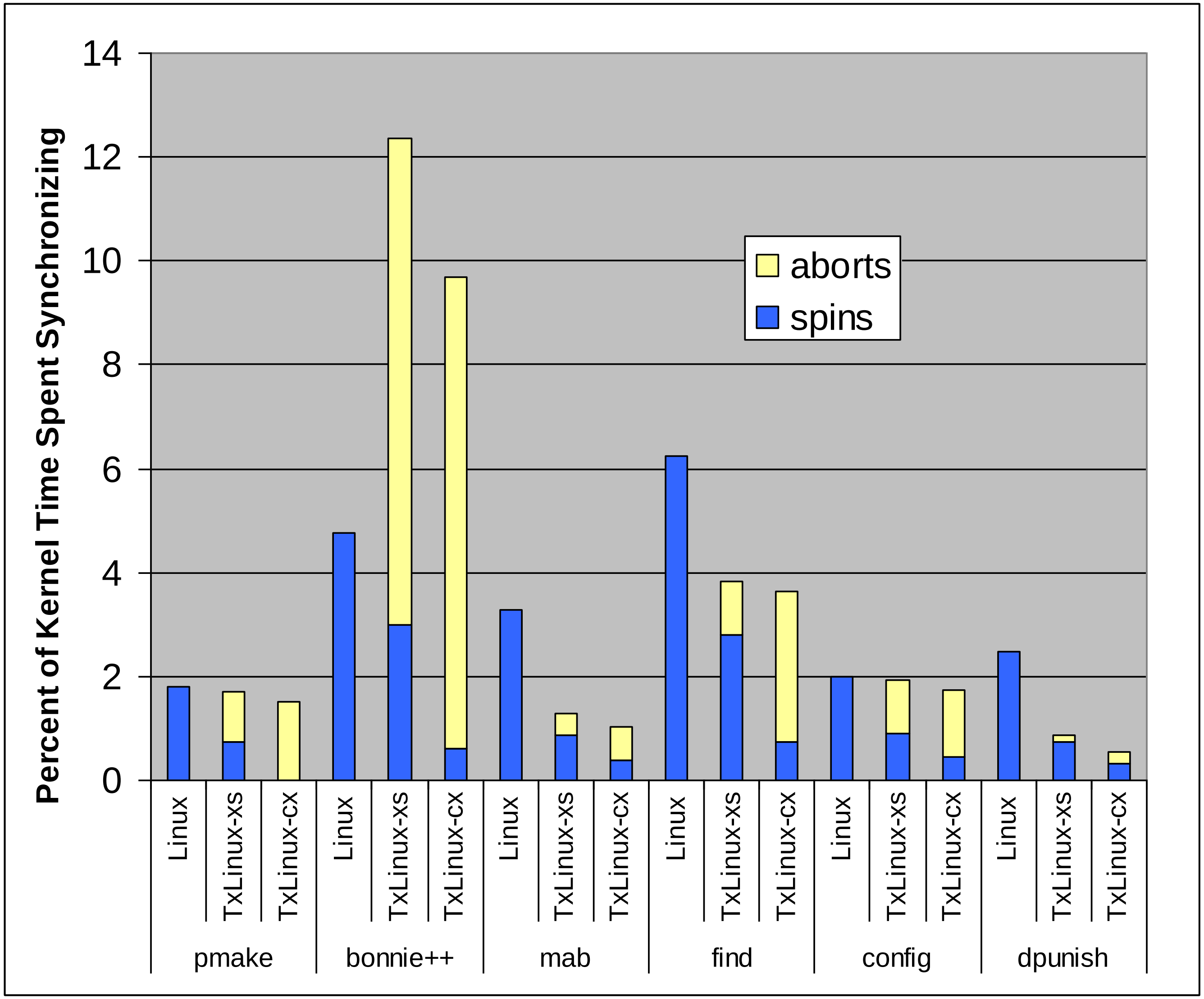
Experimental Setup

- 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

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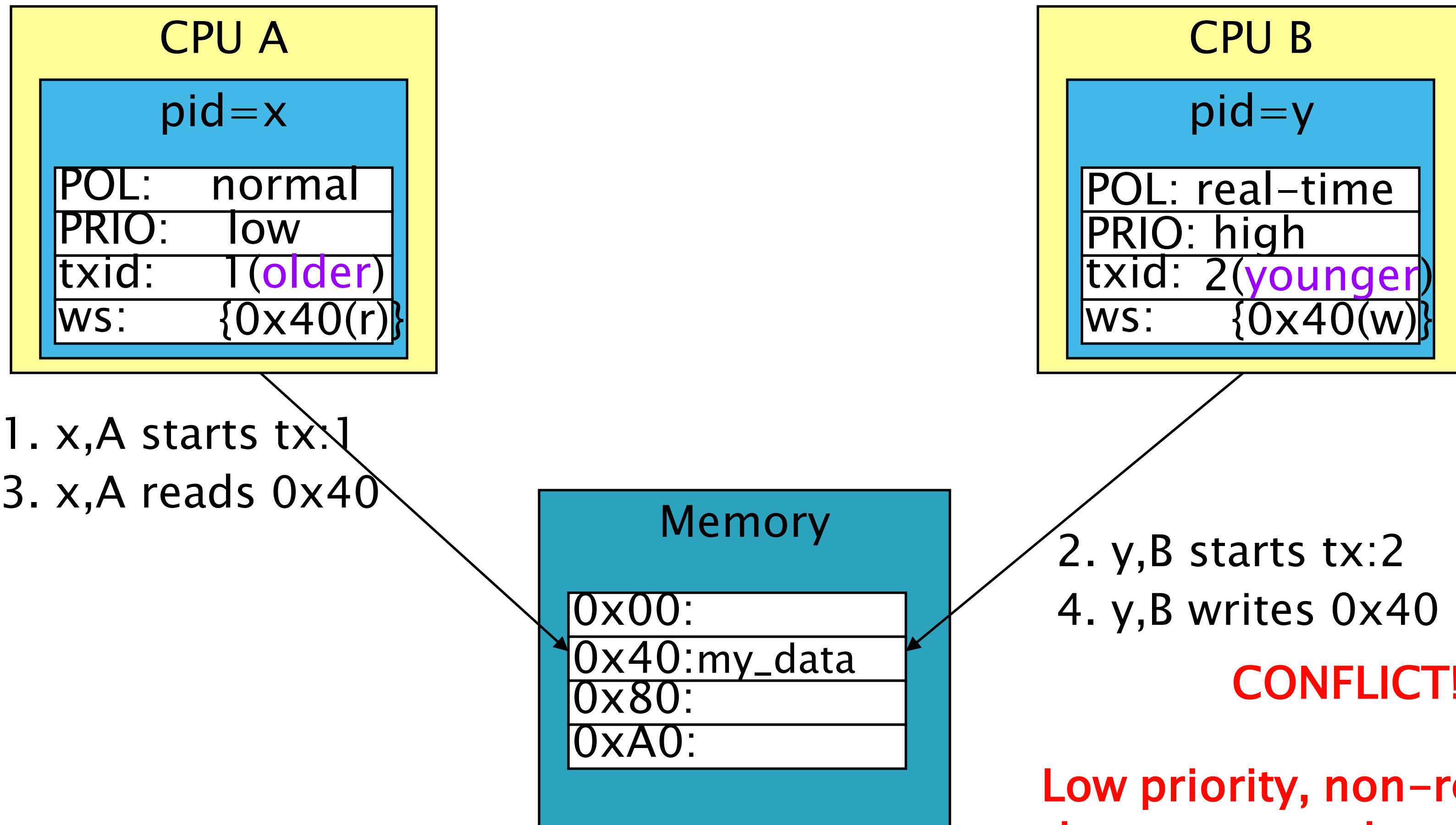
Transactions and Scheduling

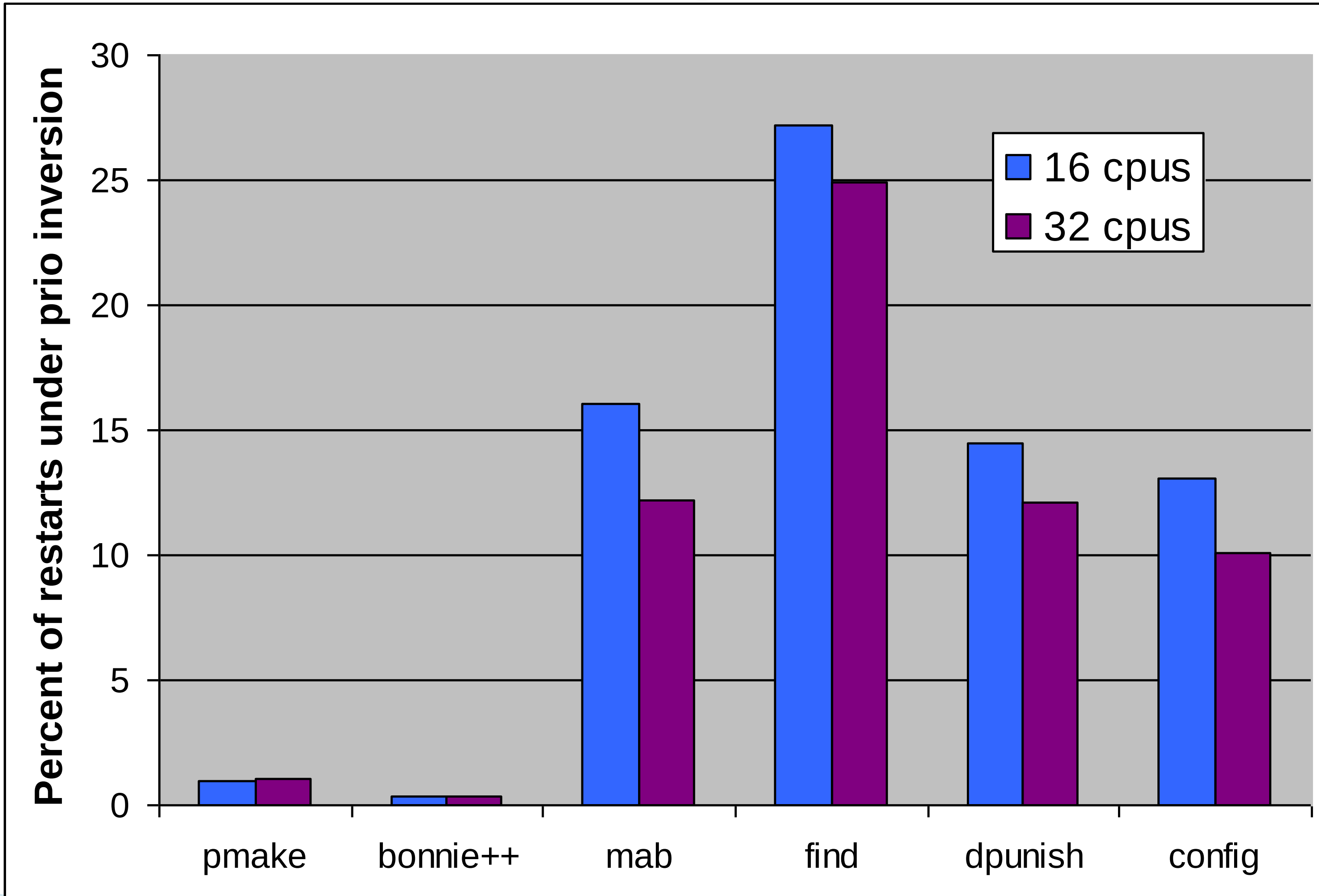
- Transaction Restarts can ***waste*** a lot of work
- Contention Management and OS scheduler ***can*** work at cross purposes
  - HW policies avoid livelock
  - But HW policies ignore OS goals
  - e.g. timestamp
- OS requires better contention management

A problem with *timestamp* policy



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

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