SMP, Multicore, Memory Ordering & Locking

Never Stand Still

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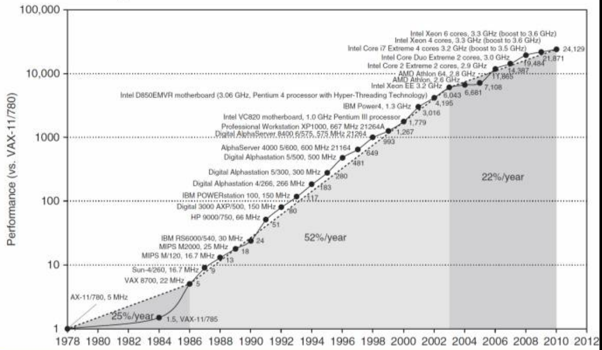
CPU performance increases are



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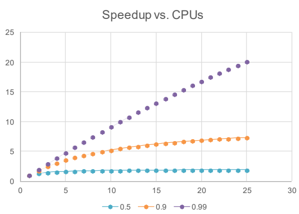
Multiprocessor System

- A single CPU can only go so fast
  - Use more than one CPU to improve performance
  - Assumes
    - Workload can be parallelised
    - Workload is not I/O-bound or memory-bound

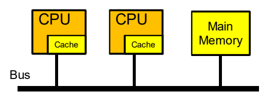
Amdahl's Law



- Given:
  - Parallelisable fraction P
  - Number of processor N
  - Speed up S
- $S(N) = \frac{1}{(1-P)+\frac{P}{N}}$
- $S(\infty) = \frac{1}{(1-P)}$
- Parallel computing takeaway:
  - Useful for small numbers of CPUs (N)
  - Or, high values of P
    - *Aim for high P values by design*

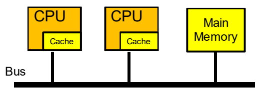
Types of Multiprocessors (MPs)

- Classic symmetric multiprocessor (SMP)
  - Uniform Memory Access
    - Access to all memory occurs at the same speed for all processors.
  - Processors with local caches
    - Separate cache hierarchy
    - ⇒ Cache coherency issues



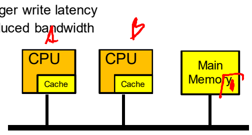
Cache Coherency

- What happens if one CPU writes to address 0x1234 (and it is stored in its cache) and another CPU reads from the same address (and gets what is in its cache)?
  - Can be thought of as managing replication and migration of data between CPUs



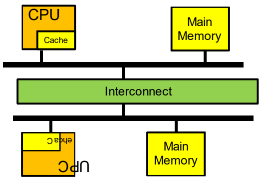
Memory Model

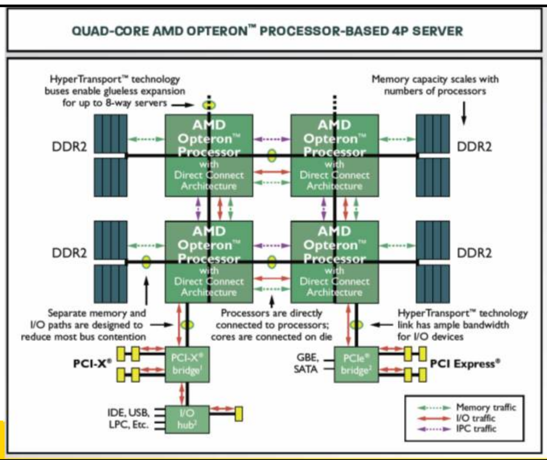
- A read produces the result of the last write to a particular memory location?
  - Approaches that avoid the issue in software also avoid exploiting replication for cooperative parallelism
    - E.g., no mutable shared data.
  - For classic SMP a hardware solution is used
    - Write-through caches
    - Each CPU snoops bus activity to invalidate stale lines
    - Reduces cache effectiveness – all writes go out to the bus.
      - Longer write latency
      - Reduced bandwidth



Types of Multiprocessors (MPs)

- NUMA MP
  - Non-uniform memory access
    - Access to some parts of memory is faster for some processors than other parts of memory
  - Provides high-local bandwidth and reduces bus contention
    - Assuming locality of access





Cache Coherence

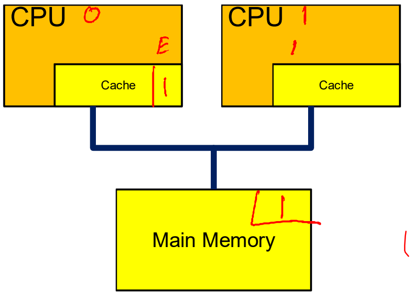
- Snooping caches assume
  - write-through caches
  - cheap "broadcast" to all CPUs
- Many alternative cache coherency models
  - They improve performance by tackling above assumptions
  - We'll examine MESI (four state)
  - 'Memory bus' becomes message passing system between caches

Example Coherence Protocol MESI

Each cache line is in one of four states

- Modified (M)
  - The line is valid in the cache and in only this cache.
  - The line is modified with respect to system memory—that is, the modified data in the line has not been written back to memory.
- Exclusive (E)
  - The addressed line is in this cache only.
  - The data in this line is consistent with system memory.
- Shared (S)
  - The addressed line is valid in the cache and in at least one other cache.
  - A shared line is always consistent with system memory. That is, the shared state is shared-unmodified; there is no shared-modified state.
- Invalid (I)
  - This state indicates that the addressed line is not resident in the cache and/or any data contained is considered not useful.

Example



MESI (with snooping/broadcast)

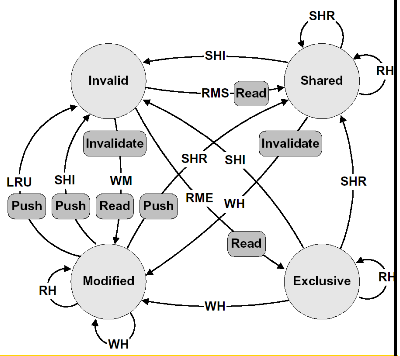
- Events

RH = Read Hit
RMS = Read miss, shared
RME = Read miss, exclusive
WH = Write hit
WM = Write miss
SHR = Snoop hit on read
SHI = Snoop hit on invalidate
LRU = LRU replacement

- Bus Transactions

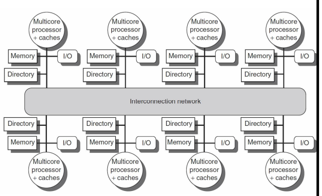
Push = Write cache line back to memory
Invalidate = Broadcast invalidate
Read = Read cache line from memory

- Performance improvement via write-back caching
  - Less bus traffic



Directory-based coherence

- Each memory block has a home node
- Home node keeps directory of caches that have a copy
  - E.g., a bitmap of processors per cache line
- Pro
  - Invalidation/update messages can be directed explicitly
    - No longer rely on broadcast/snooping
- Con
  - Requires more storage to keep directory
    - E.g. each 256 bits of memory (cache line) requires 32 bits (processor mask) of directory



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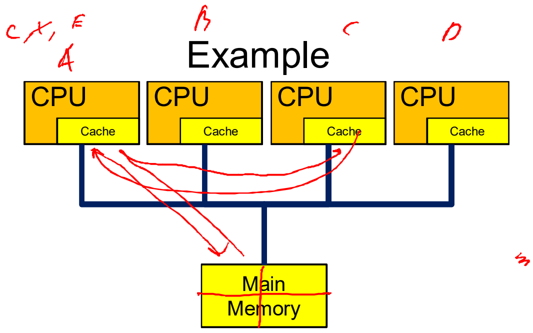
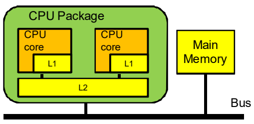
Example



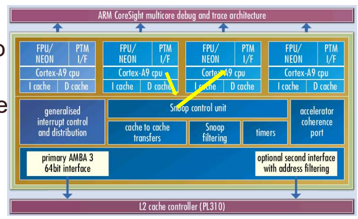
Chip Multiprocessor (CMP)

- *Chip Multiprocessor (CMP)*
  - per-core L1 caches
  - shared lower on-chip caches
  - usually called "*multicore*"
  - "reduced" cache coherency issues
    - Between L1's, L2 shared.



ARM MPCore: Cache-to-Cache Transfers

- Cache lines can migrate between L1 caches belonging to different cores without involving the L2
- Clean lines – DDI (Direct Data Intervention)
- Dirty Lines – ML (Migratory Lines)



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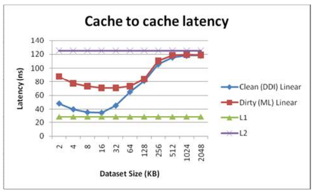
Cache to Cache Latency

- Significant benefits achievable if the working set of the application partitioned between the cores can be contained within the sum of their caches
- Helpful for streaming data between cores
  - may be used in conjunction with interrupts between cores



- Though dirty lines have higher latency they still have ≈ 50% performance benefit

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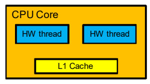
ARM techcon³ DESIGN TO THE POWER OF THREE

Simultaneous multithreading (SMT)

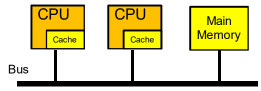
- D.M. Tullsen, S.J. Eggers, and H.M. Levy, "Simultaneous Multithreading: Maximizing On-Chip Parallelism," In 22nd Annual International Symposium on Computer Architecture, June, 1995
- replicated functional units, register state
- interleaved execution of several threads
  - As opposed to extracting limited parallelism from instruction stream.
- fully shared cache hierarchy
- no cache coherency issues
- (called *hyperthreading* on x86)



Summary

- Hardware-based cache coherency:
  - provide a consistent view of memory across the machine.
  - Read will get the result of the last write to the memory hierarchy

Memory Ordering



- Example: a tail of a critical section

```
/* assuming lock already held */
/* counter++ */
load r1, counter
add r1, r1, 1
store r1, counter
/* unlock(mutex) */
store zero, mutex
```

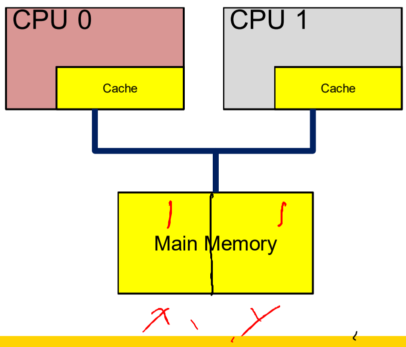
- Relies on all CPUs seeing update of counter before update of mutex
- Depends on assumptions about ordering of stores to memory

Memory Models: Strong Ordering

- Sequential consistency
  - the result of any execution is the same as if the operations of all the processors were executed in some sequential order, and the operations of each individual processor appear in this sequence in the order specified by its program
- Traditionally used by many architectures
- Assume X = Y = 0 initially

CPU 0	CPU 1
`store 1, X` `load r2, Y`	`store 1, Y` `load r2, X`

Example



Potential interleavings

- At least one CPU must load the other's new value
  - Forbidden result: X=0,Y=0

```
store 1, X
load r2, Y
store 1, Y
load r2, X
X=1,Y=0
```

```
store 1, X
store 1, Y
load r2, Y
load r2, X
X=1,Y=1
```

```
store 1, X
store 1, Y
load r2, X
load r2, Y
X=1,Y=1
```

```
store 1, Y
load r2, X
store 1, X
load r2, Y
X=0,Y=1
```

```
store 1, Y
store 1, X
load r2, X
load r2, Y
X=1,Y=1
```

```
store 1, Y
store 1, X
load r2, Y
load r2, X
X=1,Y=1
```

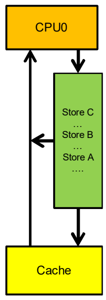
Realistic Memory Models

- Modern hardware features can interfere with store order:
  - write buffer (or store buffer or write-behind buffer)
  - instruction reordering (out-of-order execution)
  - superscalar execution and pipelining
- Each CPU/core keeps its own data consistent, but how is it viewed by others?

Write-buffers and SMP

- Stores go to *write buffer* to hide memory latency
  - And cache invalidates
- Loads read from write buffer if possible

```
CPU 0
store r1, A
store r2, B
store r3, C
load  r4, A
```

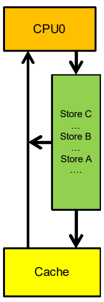


Write-buffers and SMP

- When the buffer eventually drains, what order does CPU1 see CPU0's memory updates?

```
CPU 0
store r1, A
store r2, B
store r3, C
```

```
CPU 1
```



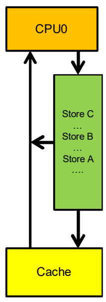
What happens in our example?

Total Store Ordering (e.g. x86)

- Stores are guaranteed to occur in FIFO order

```
CPU 0
store 1, A
store 2, B
store 3, C
```

```
CPU 1 sees
A=1
B=2
C=3
```

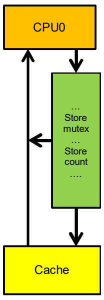


Total Store Ordering (e.g. x86)

- Stores are guaranteed to occur in FIFO order

```
/* counter++ */
  load r1, count
  add r1, r1, 1
  store r1, counter
/* unlock(mutex) */
store zero, mutex
```

```
CPU 1 sees
count updated
mutex = 0
```



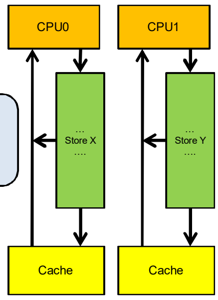
Total Store Ordering (e.g. x86)

- Assume X = Y = 0 initially

CPU 0
```
store 1, X
load r2, Y
```

CPU 1
```
store 1, Y
load r2, X
```

What is the problem here?



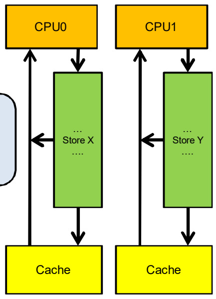
Total Store Ordering (e.g. x86)

- Stores are buffered in write-buffer and don't appear on other CPU in time.
- Can get X=0, Y=0!!!!
- Loads can "appear" re-ordered with preceding stores

CPU 0
```
store 1, X
load r2, Y
```

CPU 1
```
store 1, Y
load r2, X
```

```
load r2, Y
load r2, X
store 1, X
store 1, Y
```

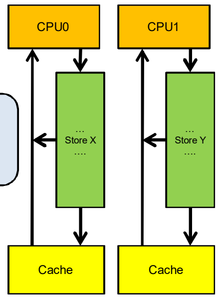


Memory "fences" or "barriers"

- The provide a "fence" between instructions to prevent apparent re-ordering
- Effectively, they drain the local CPU's write-buffer before proceeding.

CPU 0
```
store 1, X
fence
load r2, Y
```

CPU 1
```
store 1, Y
fence
load r2, X
```



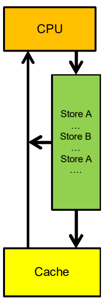
Total Store Ordering

- Stores are guaranteed to occur in FIFO order
- Atomic operations?

CPU 0
```
ll r1, addr1
sc r1, addr1
```

CPU 1
```
ll r1, addr1
sc r2, addr1
```

- Need hardware support, e.g.
  - atomic swap
  - test & set
  - load-linked + store-conditional
- Stall pipeline and drain (and bypass) write buffer
- Ensures addr1 held exclusively



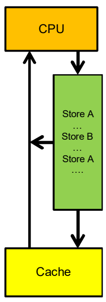
Partial Store Ordering (e.g. ARM MPcore)

- All stores go to write buffer
- Loads read from write buffer if possible
- *Redundant stores are cancelled or merged*

```
CPU 0
store BUSY, addr1
store VAL, addr2
store IDLE, addr1
```

```
CPU 1 sees
addr2 = VAL
addr1 = IDLE
```

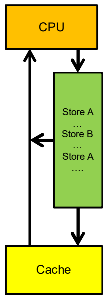
- Stores can appear to overtake (be re-ordered) other stores
- Need to use *memory barrier*



Partial Store Ordering (e.g. ARM MPcore)

- The barriers prevent preceding stores appearing after successive stores
  - Note: Reality is a little more complex (read barriers, write barriers), but principle similar.

```
load r1, counter
add r1, r1, 1
store r1, counter
barrier
store zero, mutex
```



- Store to counter can overtake store to mutex
  - i.e. update move outside the lock
- Need to use *memory barrier*
- Failure to do so will introduce subtle bugs:
  - Critical section “leaking” outside the lock

MP Hardware Take Away

- Each core/cpu sees sequential execution of own code
- Other cores see execution affected by
  - Store order and write buffers
  - Cache coherence model
  - Out-of-order execution
- Systems software needs understand:
  - Specific system (cache, coherence, etc..)
  - Synch mechanisms (barriers, test_n_set, load_linked – store_cond).

…to build cooperative, correct, and scalable parallel code

MP Hardware Take Away

- Existing sync primitives (e.g. locks) will have appropriate fences/barriers in place
  - In practice, correctly synchronised code can ignore memory model.
- However, racey code, i.e. code that updates shared memory outside a lock (e.g. lock free algorithms) must use fences/barriers.
  - You need a detailed understanding of the memory coherence model.
  - Not easy, especially for partial store order (ARM).

Memory ordering for various Architectures

Type	Alpha	ARMv7	PA-RISC	POWER	SPARC RMO	SPARC PSO	SPARC TSO	x86	x86 oostore	AMD64	IA-64	zSeries
Loads reordered after loads	Y	Y	Y	Y	Y				Y		Y	
Loads reordered after stores	Y	Y	Y	Y	Y				Y		Y	
Stores reordered after stores	Y	Y	Y	Y	Y	Y			Y		Y	
Stores reordered after loads	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Atomic reordered with loads	Y	Y		Y	Y						Y	
Atomic reordered with stores	Y	Y		Y	Y	Y					Y	
Dependent loads reordered	Y											
Incoherent instruction cache pipeline	Y	Y		Y	Y	Y	Y	Y	Y		Y	Y

Concurrency Observations

- Locking primitives require exclusive access to the “lock”
  - Care required to avoid excessive bus/interconnect traffic

Kernel Locking

- Several CPUs can be executing kernel code concurrently.
- Need mutual exclusion on shared kernel data.
- Issues:
  - Lock implementation
  - Granularity of locking (i.e. parallelism)

Mutual Exclusion Techniques

- Disabling interrupts (CLI — STI).
  - Unsuitable for multiprocessor systems.
- Spin locks.
  - Busy-waiting wastes cycles.
- Lock objects (locks, semaphores).
  - Flag (or a particular state) indicates object is locked.
  - Manipulating lock requires mutual exclusion.

Hardware Provided Locking Primitives

- `int test_and_set(lock *);`
- `int compare_and_swap(int c, int v, lock *);`
- `int exchange(int v, lock *)`
- `int atomic_inc(lock *)`
- `v = load_linked(lock *) / bool store_conditional(int, lock *)`
  - LL/SC can be used to implement all of the above

Spin locks

```
void lock (volatile lock_t *l) {
  while (test_and_set(l)) ;
}
void unlock (volatile lock_t *l) {
  *l = 0;
}
```

- Busy waits. Good idea?

Spin Lock Busy-waits Until Lock Is Released

- Stupid on uniprocessors, as nothing will change while spinning.
  - Should release (yield) CPU immediately.
- Maybe ok on SMPs: locker may execute on other CPU.
  - Minimal overhead (if contention low).
  - Still, should only spin for short time.
- Generally restrict spin locking to:
  - *short* critical sections,
  - unlikely to (or preferably can't) be contended by the same CPU.
  - local contention can be prevented
    - by design
    - by turning off interrupts

Spinning versus Switching

- Blocking and switching
  - to another process takes time
    - Save context and restore another
    - Cache contains current process not new
      - » Adjusting the cache working set also takes time
    - TLB is similar to cache
  - Switching back when the lock is free encounters the same again
- Spinning wastes CPU time directly
- Trade off
  - If lock is held for less time than the overhead of switching to and back

  ⇒ It's more efficient to spin

Spinning versus Switching

- The general approaches taken are
  - Spin forever
  - Spin for some period of time, if the lock is not acquired, block and switch
    - The spin time can be
      - Fixed (related to the switch overhead)
      - Dynamic
        - » Based on previous observations of the lock acquisition time

Interrupt Disabling

- Assume no local contention by design, is disabling interrupt important?
- Hint: What happens if a lock holder is preempted (e.g., at end of its timeslice)?
- All other processors spin until the lock holder is re-scheduled

Alternative to spinning: Conditional Lock (TryLock)

```
bool cond_lock (volatile lock t *l) {
   if (test_and_set(l))
       return FALSE; //couldn't lock
   else
       return TRUE; //acquired lock
}
```

- Can do useful work if fail to acquire lock.
- **But** may not have much else to do.
- Starvation: May never get lock!

Another alternative to spinining.

```
void mutex lock (volatile lock t *l) {
   while (1) {
       for (int i=0; i<MUTEX N; i++)
           if (!test and set(l))
               return;
       yield();
   }
}
```

- Spins for limited time only
  - assumes enough for other CPU to exit critical section
- Useful if critical section is shorter than N iterations.
- Starvation possible.

Common Multiprocessor Spin Lock

```
void mp_spinlock (volatile lock t *l) {
   cli(); // prevent preemption
   while (test and set(l)) ; // lock
}
void mp unlock (volatile lock t *l) {
   *l = 0;
   sti();
}
```

- Only good for short critical sections
- Does not scale for large number of processors
- Relies on bus-arbitrator for fairness
- Not appropriate for user-level
- Used in practice in small SMP systems

Need a more systematic analysis

Thomas Anderson, "The Performance of Spin Lock Alternatives for Shared-Memory Multiprocessors", *IEEE Transactions on Parallel and Distributed Systems*, Vol 1, No. 1, 1990

Compares Simple Spinlocks

- Test and Set

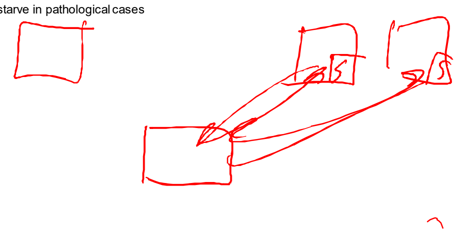
```
void lock (volatile lock_t *l) {
   while (test_and_set(l)) ;
}
```

- Test and Test and Set

```
void lock (volatile lock_t *l) {
   while (*l == BUSY || test_and_set(l)) ;
}
```

test_and_test_and_set LOCK

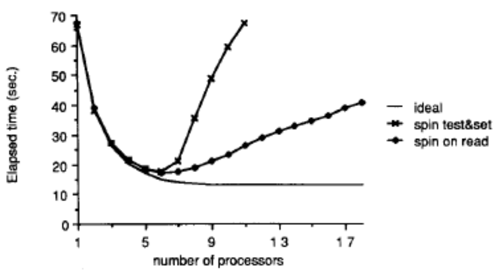
- Avoid bus traffic contention caused by test_and_set until it is likely to succeed
- Normal read spins in cache
- Can starve in pathological cases



Benchmark

```
for i = 1 .. 1,000,000 {
  lock(l)
  crit_section()
  unlock()
  compute()
}
```

- Compute chosen from uniform random distribution of mean 5 times critical section
- Measure elapsed time on Sequent Symmetry (20 CPU 30386, coherent write-back invalidate caches)



Results

- Test and set performs poorly once there is enough CPUs to cause contention for lock
  - Expected
- Test and Test and Set performs better
  - Performance less than expected
  - Still significant contention on lock when CPUs notice release and all attempt acquisition
- Critical section performance degenerates
  - Critical section requires bus traffic to modify shared structure
  - Lock holder competes with CPU that missed as they test and set
    - o lock holder is slower
  - Slower lock holder results in more contention

Idea

- Can inserting delays reduce bus traffic and improve performance
- Explore 2 dimensions
  - Location of delay
    - o Insert a delay after release prior to attempting acquire
    - o Insert a delay after each memory reference
  - Delay is static or dynamic
    - o Static – assign delay "slots" to processors
      - Issue: delay tuned for expected contention level
    - o Dynamic – use a back-off scheme to estimate contention
      - Similar to ethernet
      - Degrades to static case in worst case.

Examining Inserting Delays

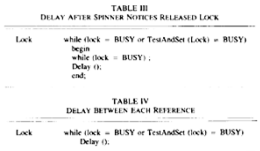


TABLE III
DELAY AFTER SPINNER NOTICES RELEASED LOCK

```
Lock      while (lock = BUSY or TestAndSet (Lock) = BUSY)
            begin
            while (lock = BUSY) ;
            Delay ();
            end;
```

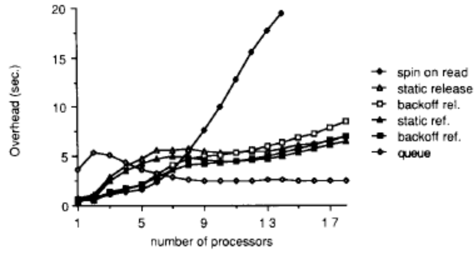
TABLE IV
DELAY BETWEEN EACH REFERENCE

```
Lock      while (lock = BUSY or TestAndSet (lock) = BUSY)
              Delay ();
```

Queue Based Locking

- Each processor inserts itself into a waiting queue
  - It waits for the lock to free by spinning on its own separate cache line
  - Lock holder frees the lock by “freeing” the next processors cache line.

Results



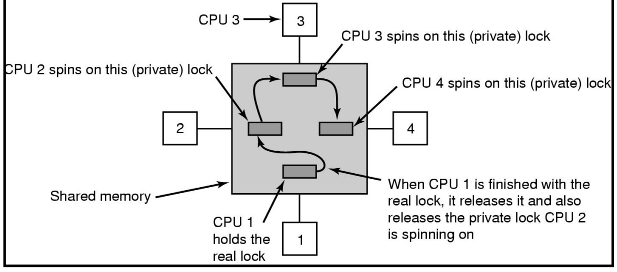
Results

- Static backoff has higher overhead when backoff is inappropriate
- Dynamic backoff has higher overheads when static delay is appropriate
  - as collisions are still required to tune the backoff time
- Queue is better when contention occurs, but has higher overhead when it does not.
  - Issue: Preemption of queued CPU blocks rest of queue (worse than simple spin locks)

- John Mellor-Crummey and Michael Scott, “Algorithms for Scalable Synchronisation on Shared-Memory Multiprocessors”, *ACM Transactions on Computer Systems,* Vol. 9, No. 1, 1991

MCS Locks

- Each CPU enqueues its own private lock variable into a queue and spins on it
  - No contention
- On lock release, the releaser unlocks the next lock in the queue
  - Only have bus contention on actual unlock
  - No starvation (order of lock acquisitions defined by the list)



MCS Lock

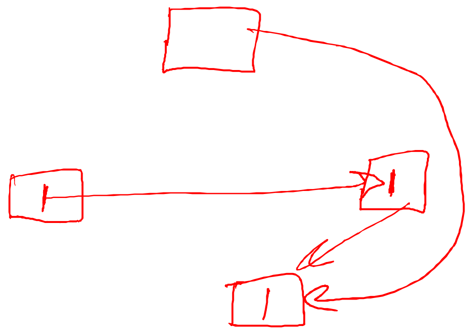
- Requires
  - compare_and_swap()
  - exchange()
    - o Also called fetch_and_store()

```
type qnode = record
    next : ^qnode
    locked : Boolean
type lock = ^qnode

// parameter I, below, points to a qnode record allocated
// (in an enclosing scope) in shared memory locally-accessible
// to the invoking processor

procedure acquire_lock (L : ^lock, I : ^qnode)
    I->next := nil
    predecessor : ^qnode := fetch_and_store (L, I)
    if predecessor != nil       // queue was non-empty
        I->locked := true
        predecessor->next := I
        repeat while I->locked               // spin

procedure release_lock (L : ^lock, I: ^qnode)
    if I->next = nil        // no known successor
        if compare_and_swap (L, I, nil)
            return
            // compare_and_swap returns true iff it swapped
        repeat while I->next = nil           // spin
    I->next->locked := false
```

Sample MCS code for ARM MPCore

```
void mcs_acquire(mcs_lock *L, mcs_qnode_ptr I)
{
    I->next = NULL;
    MEM_BARRIER;
    mcs_qnode_ptr pred = (mcs_qnode*) SWAP_PTR( L, (void *)I);
    if (pred == NULL)
    {           /* lock was free */

        MEM_BARRIER;
        return;
    }
    I->waiting = 1; // word on which to spin
    MEM_BARRIER;
    pred->next = I; // make pred point to me
}
```

Selected Benchmark

- Compared
  - test and test and set
  - Anderson's array based queue
  - test and set with exponential back-off
  - MCS

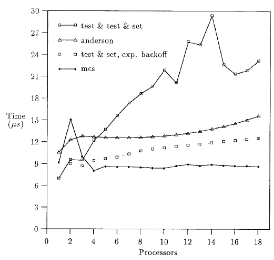
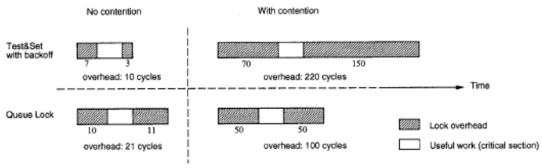


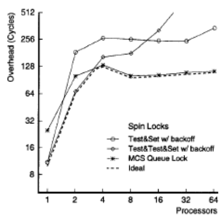
Fig. 17. Performance of spin locks on the Symmetry (empty critical section).

Confirmed Trade-off

- Queue locks scale well but have higher overhead
- Spin Locks have low overhead but don't scale well
- What do we use?

- Beng-Hong Lim and Anant Agarwal, “Reactive Synchronization Algorithms for Multiprocessors”, *ASPLOS VI*, 1994





Idea

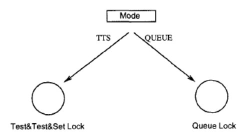
- Can we dynamically switch locking methods to suit the current contention level???

Issues

- How do we determine which protocol to use?
  - Must not add significant cost
- How do we correctly and efficiently switch protocols?
- How do we determine when to switch protocols?

Protocol Selection

- Keep a “hint”
- Ensure both TTS and MCS lock a never free at the same time
  - Only correct selection will get the lock
  - Choosing the wrong lock with result in retry which can get it right next time
  - Assumption: Lock mode changes infrequently
    - hint cached read-only
    - infrequent protocol mismatch retries



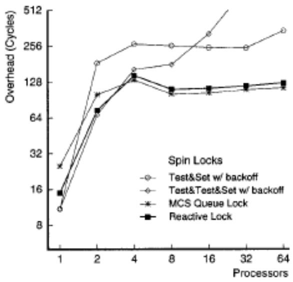
Changing Protocol

- Only lock holder can switch to avoid race conditions
  - It chooses which lock to free, TTS or MCS.

When to change protocol

- Use threshold scheme
  - Repeated acquisition failures will switch mode to queue
  - Repeated immediate acquisition will switch mode to TTS

Results



The multicore evolution and operating systems

Frans Kaashoek

Joint work with: Silas Boyd-Wickizer, Austin T. Clements, Yandong Mao, Aleksey Pesterev, Robert Morris, and Nickolai Zeldovich

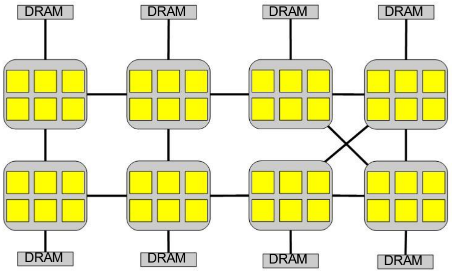
MIT

- **Non-scalable locks are dangerous.** Silas Boyd-Wickizer, M. Frans Kaashoek, Robert Morris, and Nickolai Zeldovich. *In the Proceedings of the Linux Symposium, Ottawa, Canada, July 2012.*

How well does Linux scale?

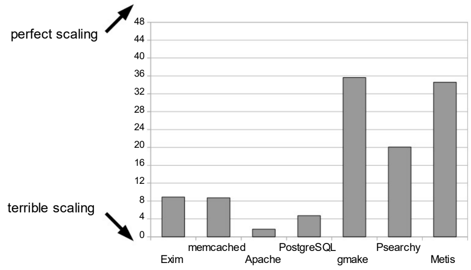
- Experiment:
  - Linux 2.6.35-rc5 (relatively old, but problems are representative of issues in recent kernels too)
  - Select a few inherent parallel system applications
  - Measure throughput on different # of cores
  - Use tmpfs to avoid disk bottlenecks
- Insight 1: Short critical sections can lead to sharp performance collapse

Off-the-shelf 48-core server (AMD)



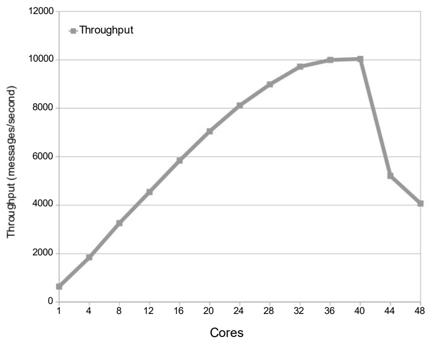
- Cache-coherent and non-uniform access
- An approximation of a future 48-core chip

Poor scaling on stock Linux kernel

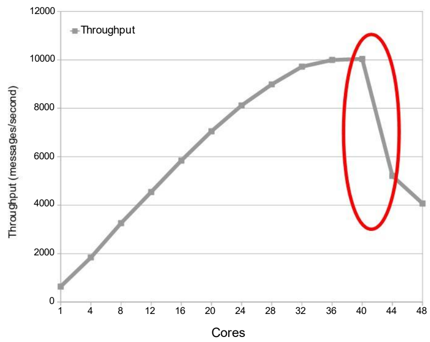


Y-axis: (throughput with 48 cores) / (throughput with one core)

Exim on stock Linux: collapse



Exim on stock Linux: collapse



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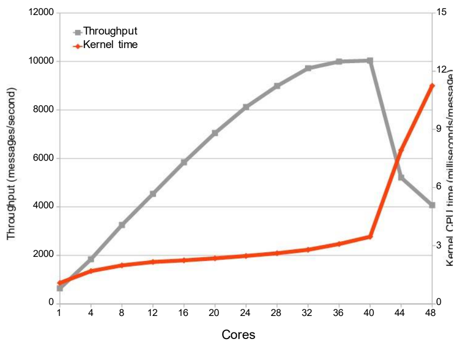

Oprofile shows an obvious problem

	samples	%	app name	symbol name
40 cores: 10000 msg/sec	2616	7.3522	vmlinux	radix_tree_lookup_slot
	2329	6.5456	vmlinux	unmap_vmas
	2197	6.1746	vmlinux	filemap_fault
	1488	4.1820	vmlinux	__do_fault
	1348	3.7885	vmlinux	copy_page_c
	1182	3.3220	vmlinux	unlock_page
	966	2.7149	vmlinux	page_fault

	samples	%	app name	symbol name
48 cores: 4000 msg/sec	13515	34.8657	vmlinux	lookup_mnt
	2002	5.1647	vmlinux	radix_tree_lookup_slot
	1661	4.2850	vmlinux	filemap_fault
	1497	3.8619	vmlinux	unmap_vmas
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Bottleneck: reading mount table

- Delivering an email calls sys_open
- sys_open calls

```
struct vfsmount *lookup_mnt(struct path *path)
{
        struct vfsmount *mnt;
        spin_lock(&vfsmount_lock);
        mnt = hash_get(mnts, path);
        spin_unlock(&vfsmount_lock);
        return mnt;
}
```

Bottleneck: reading mount table

- sys_open calls:

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Bottleneck: reading mount table

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}
```

Serial section is short. Why does it cause a scalability bottleneck?

What causes the sharp performance collapse?

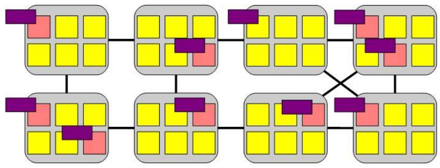
- Linux uses ticket spin locks, which are non-scalable
  - So we should expect collapse [Anderson 90]
- But why so sudden, and so sharp, for a short section?
  - Is spin lock/unlock implemented incorrectly?
  - Is hardware cache-coherence protocol at fault?

Scalability collapse caused by non-scalable locks [Anderson 90]

```
void spin_lock(spinlock_t *lock)
{
    t = atomic_inc(lock->next_ticket);
    while (t != lock->current_ticket)
        ;   /* Spin */
}
```

```
void spin_unlock(spinlock_t *lock)
{
    lock->current_ticket++;
}
```

```
struct spinlock_t {
    int current_ticket;
    int next_ticket;
}
```



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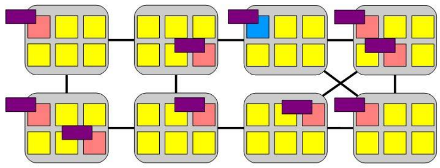

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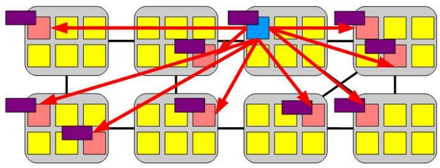

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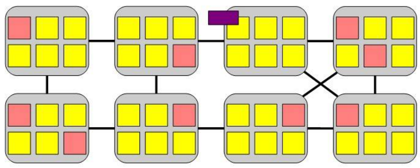

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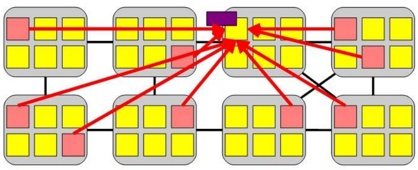

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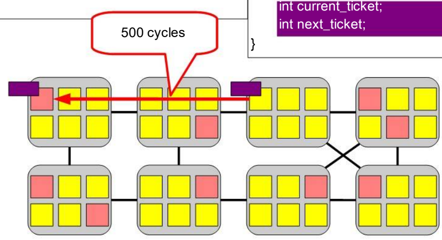

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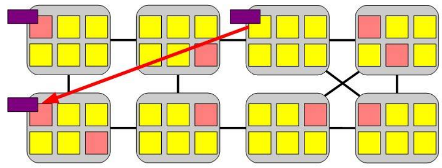

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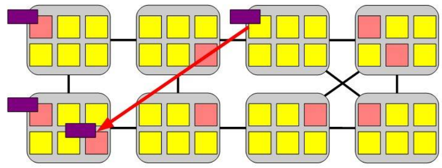

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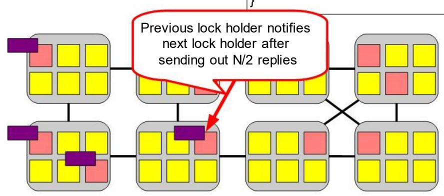
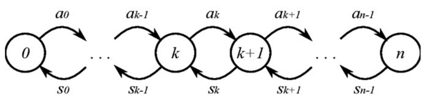
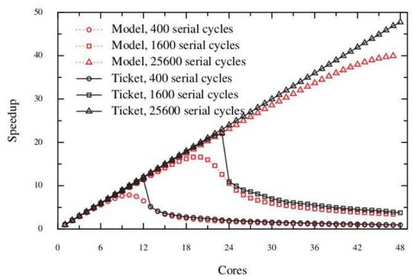


Why collapse with short sections?



- Arrival rate is proportional to # non-waiting cores
- Service time is proportional to # cores waiting (*k*)
  - As *k* increases, waiting time goes up
  - As waiting time goes up, *k* increases
- System gets stuck in states with many waiting cores

Short sections result in collapse

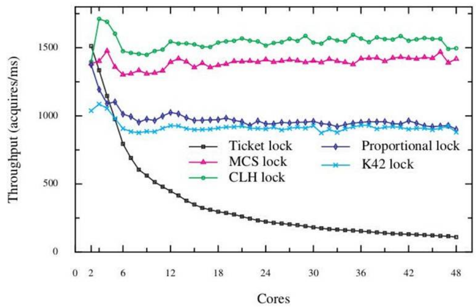


- Experiment: 2% of time spent in critical section
- Critical sections become "longer" with more cores
- Lesson: non-scalable locks fine for long sections

Avoiding lock collapse

- Unscalable locks are fine for long sections
- Unscalable locks collapse for short sections
  - Sudden sharp collapse due to "snowball" effect
- Scalable locks avoid collapse altogether
  - But requires interface change

Scalable lock scalability



- It doesn't matter much which one
- But all slower in terms of latency

Avoiding lock collapse is not enough to scale

- "Scalable" locks don't make the kernel scalable
  - Main benefit is avoiding collapse: total throughput will not be lower with more cores
  - But, usually want throughput to keep increasing with more cores