## 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

1

## 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

2

## 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)) ;
}
```

3

## 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

4

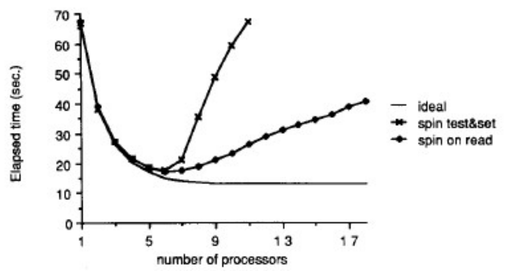
## Benchmark

```
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)

5




6

## 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
  - lock holder is slower
- Slower lock holder results in more contention

UNSW

7

## Idea

Can inserting delays reduce bus traffic and improve performance

Explore 2 dimensions

- Location of delay
  - Insert a delay after release prior to attempting acquire
  - Insert a delay after each memory reference
- Delay is static or dynamic
  - Static – assign delay “slots” to processors
    - Issue: delay tuned for expected contention level
  - Dynamic – use a back-off scheme to estimate contention
    - Similar to ethernet
    - Degrades to static case in worst case.

UNSW

8

## Examining Inserting Delays

TABLE III
DELAY AFTER SPINNER NOTICES RELEASED LOCK

| | |
|---|---|
| Lock | while (lock = BUSY or TestAndSet (Lock) = BUSY)<br>begin<br>while (lock = BUSY) ;<br>Delay ();<br>end; |

TABLE IV
DELAY BETWEEN EACH REFERENCE

| | |
|---|---|
| Lock | while (lock = BUSY or TestAndSet (lock) = BUSY)<br>Delay (); |

UNSW

9

## Queue Based Locking

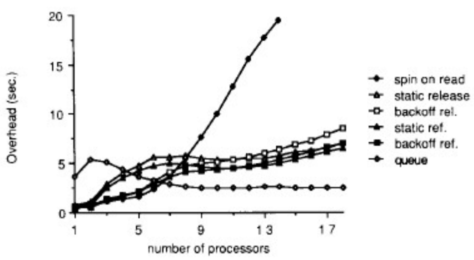
Each processor inserts itself into a waiting queue

- 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.

UNSW

10

## Results




UNSW

11

## 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)

UNSW

12

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

13

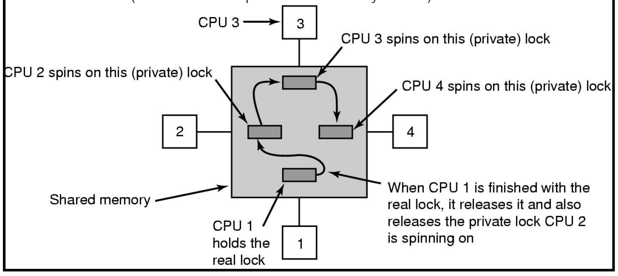
## MCS Locks

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 livelock (order of lock acquisitions defined by the list)




14

## MCS Lock

Requires

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

15

```
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
```

16

17

## 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
}
```

18

## Selected Benchmark

Compared

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

19

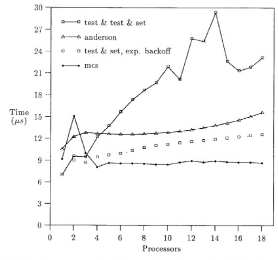



Fig. 17. Performance of spin locks on the Symmetry (empty critical section).

20

## Confirmed Trade-off

Queue locks scale well but have higher overhead

Spin Locks have low overhead but don't scale well

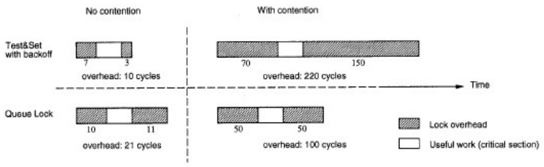
What do we use?

21

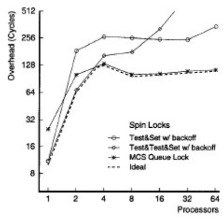
Beng-Hong Lim and Anant Agarwal, "Reactive Synchronization Algorithms for Multiprocessors", *ASPLOS VI*, 1994



22




23




24

## Idea

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

25

## 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?

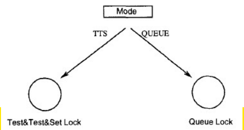
26

## 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




27

## Changing Protocol

Only lock holder can switch to avoid race conditions

- It chooses which lock to free, TTS or MCS.

28

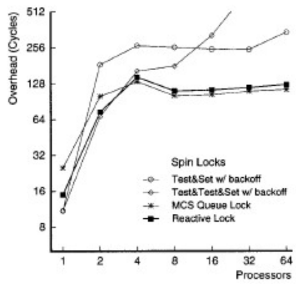
## When to change protocol

Use threshold scheme

- Repeated acquisition failures will switch mode to queue
- Repeated immediate acquisition will switch mode to TTS

29

## Results




30

# 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*

31

**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.*

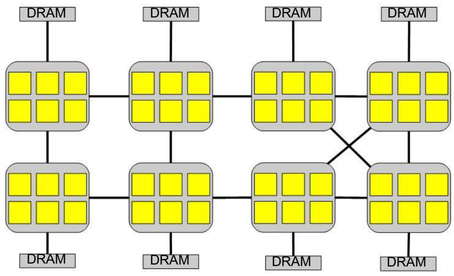
32

## 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

33

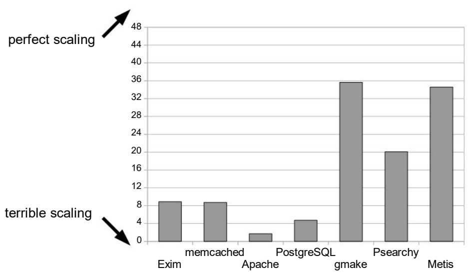
## Off-the-shelf 48-core server (AMD)




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

34

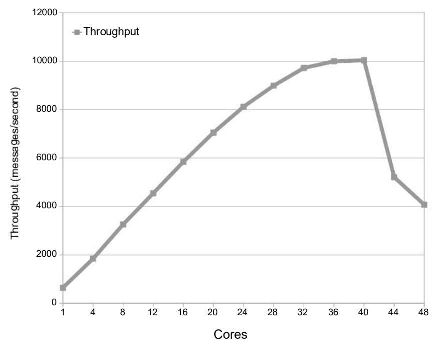
## Poor scaling on stock Linux kernel




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

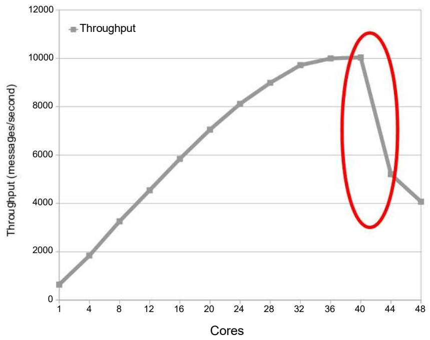
35

## Exim on stock Linux: collapse



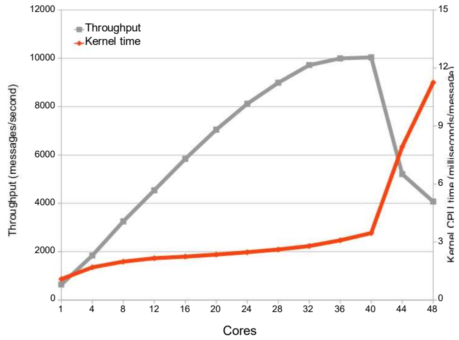

36

## Exim on stock Linux: collapse




37

## Exim on stock Linux: collapse




38

## 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 |
| | 1026 | 2.6469 | vmlinux | __do_fault |
| | 914 | 2.3579 | vmlinux | atomic_dec |
| | 896 | 2.3115 | vmlinux | unlock_page |

39

## 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 |
| | 1026 | 2.6469 | vmlinux | __do_fault |
| | 914 | 2.3579 | vmlinux | atomic_dec |
| | 896 | 2.3115 | vmlinux | unlock_page |

40

## 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 |
| | 1026 | 2.6469 | vmlinux | __do_fault |
| | 914 | 2.3579 | vmlinux | atomic_dec |
| | 896 | 2.3115 | vmlinux | unlock_page |

41

## 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;
}
```

42

## Bottleneck: reading mount table

- 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;
}
```

43

## Bottleneck: reading mount table

- 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;
}
```

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

44

## 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?

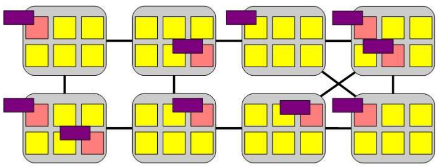
45

## 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;
}
```



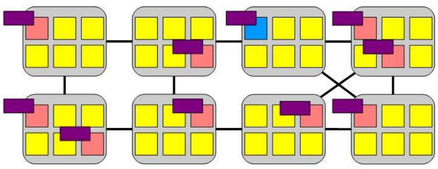
46

## 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;
}
```



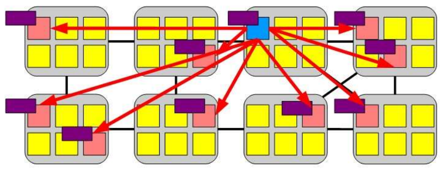
47

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

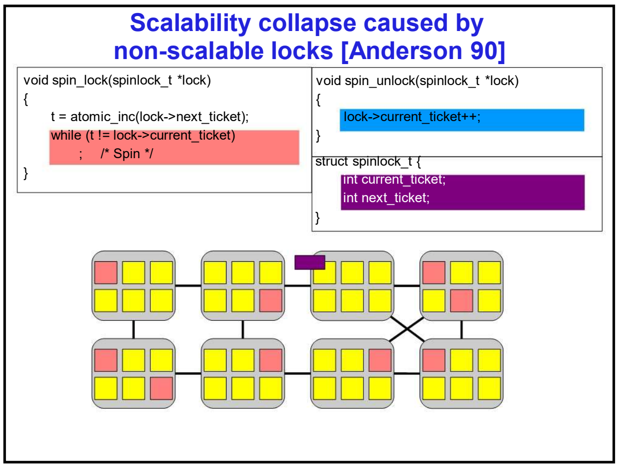
```
void spin_lock(spinlock_t *lock)
{
    t = atomic_inc(lock->next_ticket);
    while (t != lock->current_ticket)
        ;   /* Spin */
}
```

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

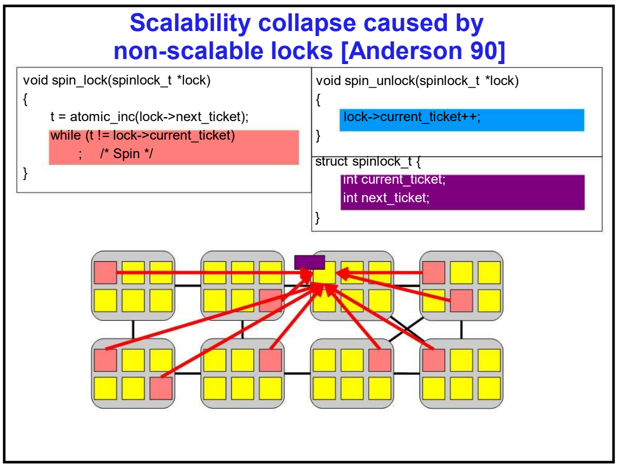
```
struct spinlock_t {
    int current_ticket;
    int next_ticket;
}
```



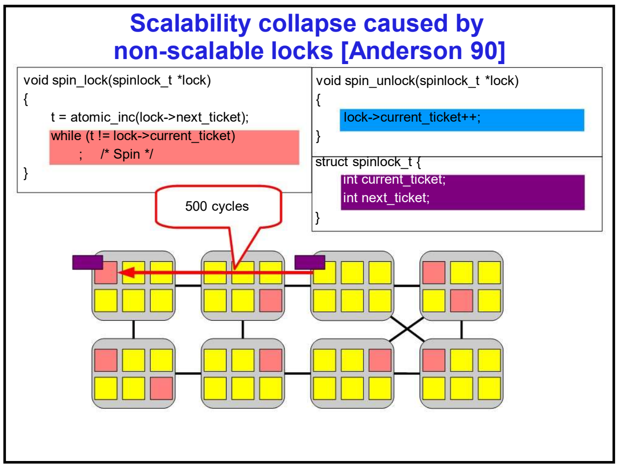
48



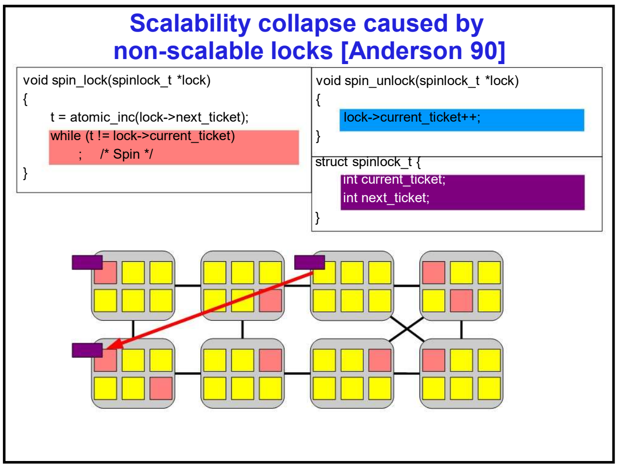

49



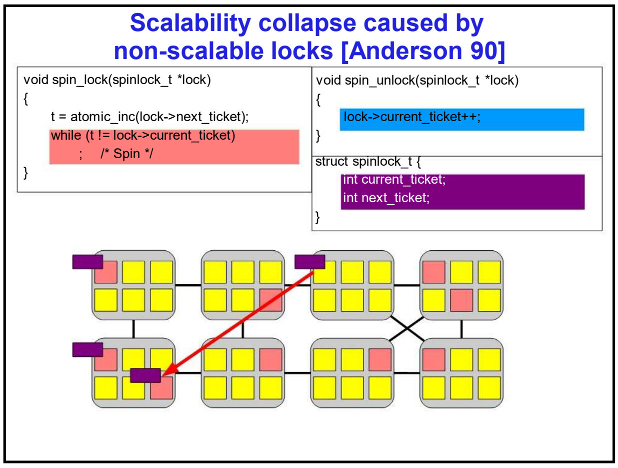

50



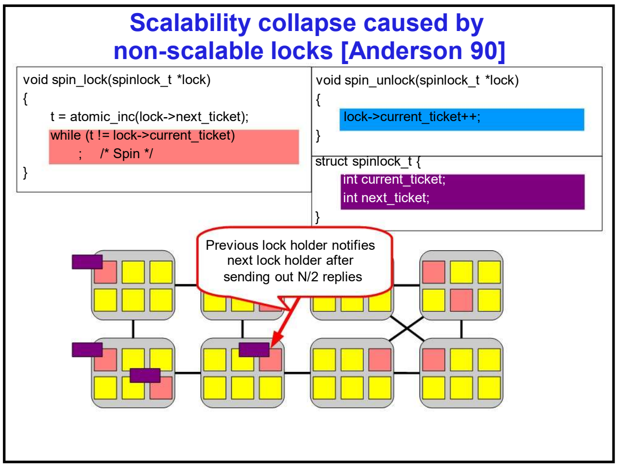

51




52

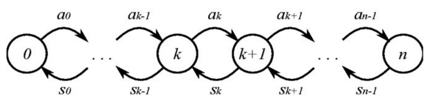



53




54

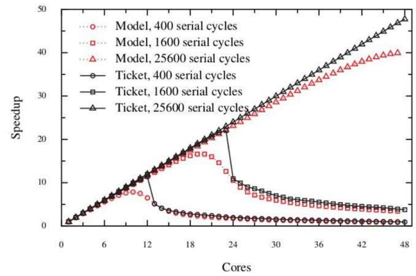
## Why collapse with short sections?




- 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

55

## 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

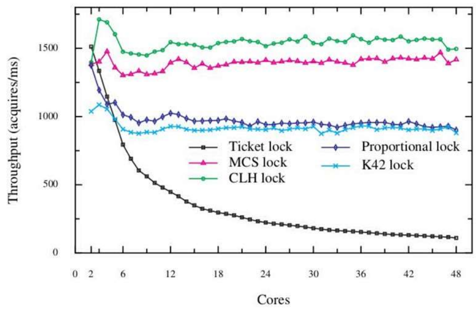
56

## 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

57

## Scalable lock scalability




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

58

## 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

59