Effective Synchronization on Linux/NUMA Systems

by

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This presentation and the corresponding paper may be found at
http://oss.sgi.com/projects/page_fault_performance/gelato

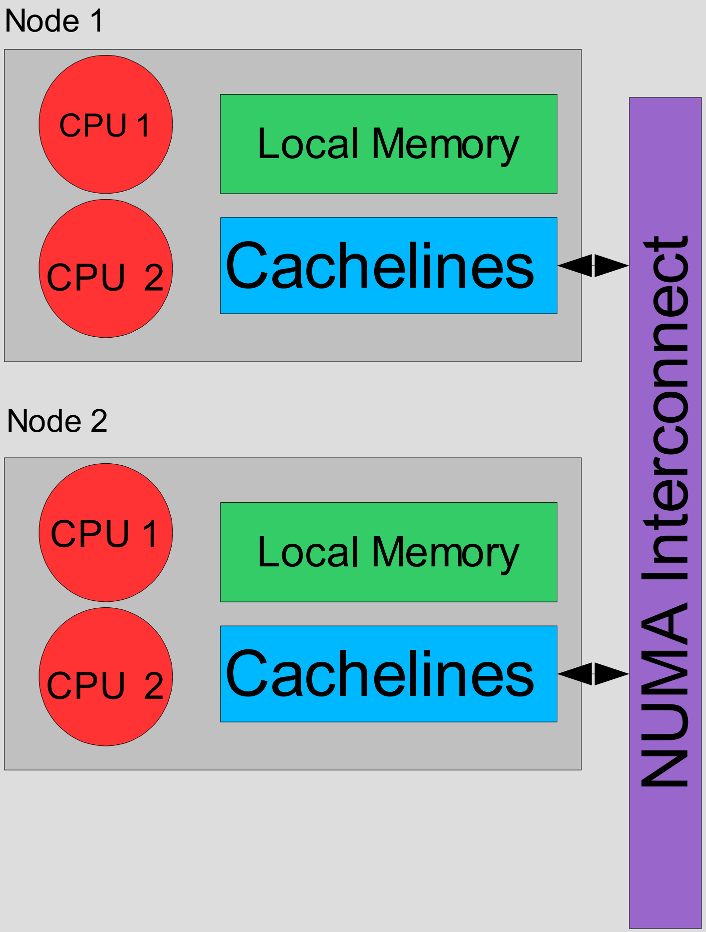
Effective locking is necessary for satisfactory performance on large Itanium based NUMA systems. Synchronization of parallel executing streams on NUMA machines is currently realized in the Linux kernel through a variety of mechanisms which include atomic operations, locking and ordering of memory accesses. Various synchronization methods may also be combined in order to increase performance.

Introduction

- Limits on processor clock rate
  - Future: *Multi-Core* and *NUMA* everywhere
  - Parallelism Itanium / Multi-Core
- *Synchronization Methods*
  - Critical Component for concurrency
  - Determines viable hardware scaling
- Outline
  - Existing synchronization on Linux / Itanium
  - Reasons for issues with lock contention arises
  - Hierachical Backoff Locks on large NUMA systems.

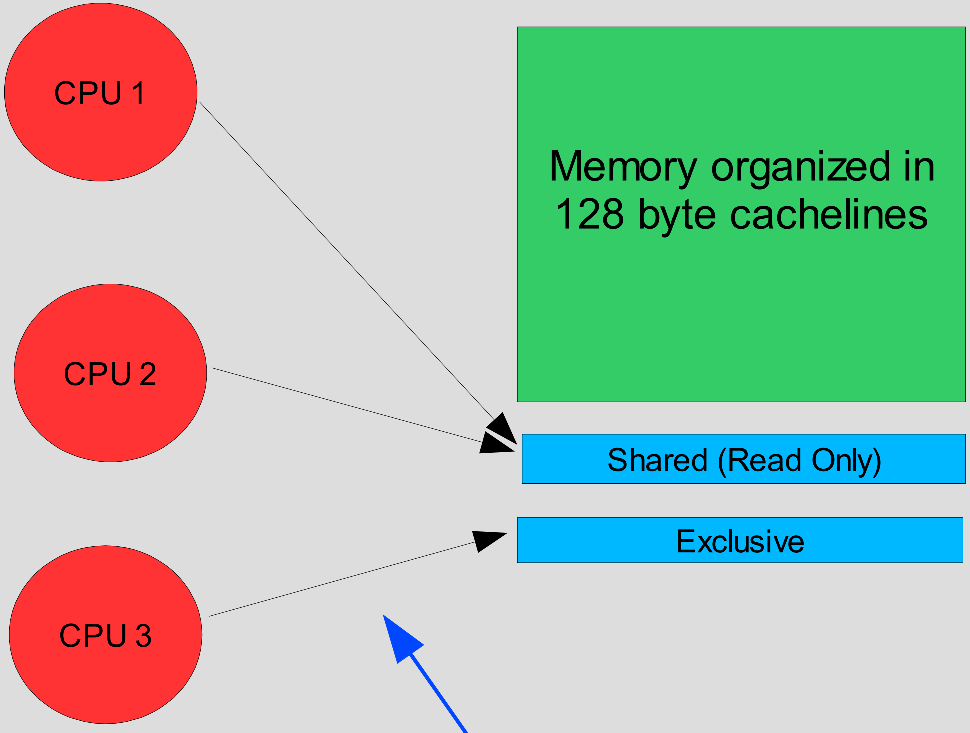
Basic Atomicity

- NUMA Multiprocessor Systems
  - NUMA interconnect
  - Hardware consistency protocol
- Node
  - Processor/ Memory
- Cache Line
- MESI type
  - Coherent view of memory
  - In Hardware



Cache Lines

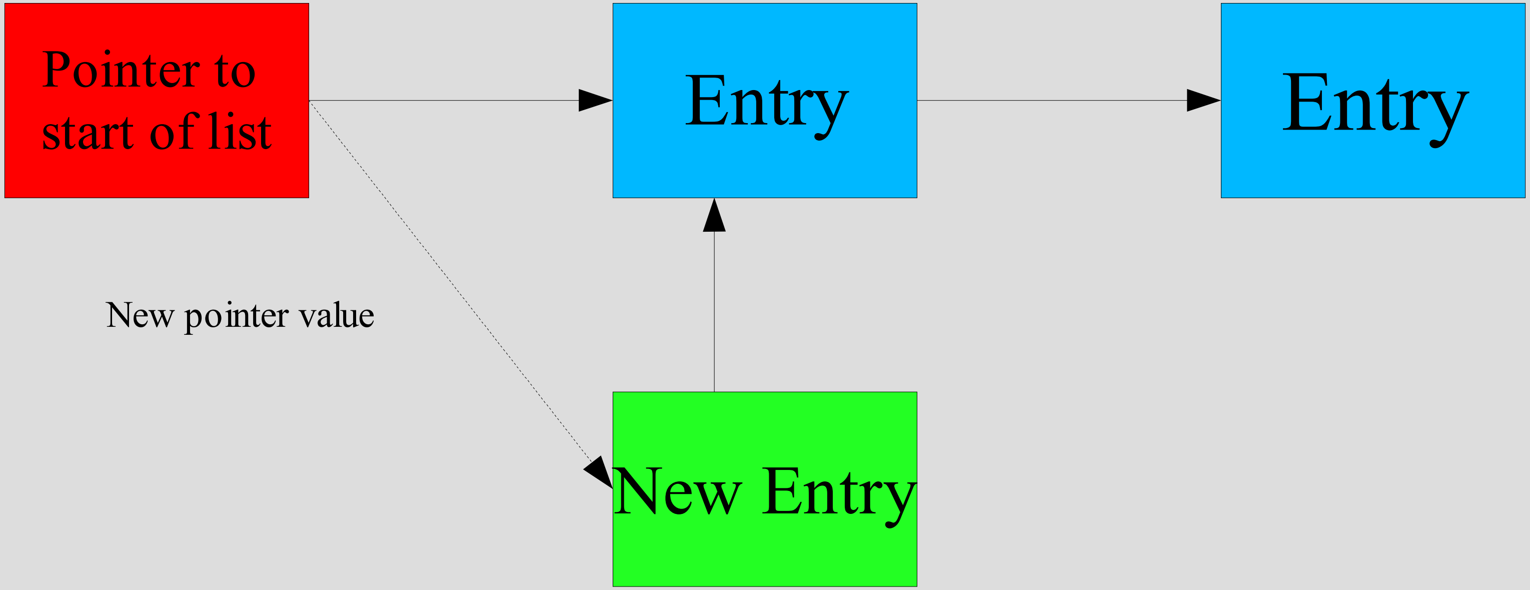
- Modes of Cachelines
  - Shared
  - Exclusive
- Cache Lines
  - Efficiency
  - Optimization
  - Bouncing
- Special Operations
  - Read Modify Write



Memory organized in 128 byte cachelines

Atomic Operations can be performed on a cacheline if a cpu has exclusive ownership of a cache line

Atomic Loads and Stores



- 64 bit atomic operations
  - Alignment issues
- RCU functions in the Linux kernel
- A lockless insertion of a list element

Barriers and Acquire/Release

- Itanium Memory accesses
  - Unordered by nature
  - Necessity of ordering memory accesses
  - Memory Fence
  - Instructions with acquire / release semantics
  - Write and Read barriers
- Semaphore instructions
  - Necessity
  - Efficiency vs. atomic loads / stores

Linux RCU Lockless List Manipulation

- In include/linux/list.h
  - list_add_rcu(*struct list_head *new, *head*)
  - list_del_rcu(*struct list_head *entry*)
  - list_for_each_entry_rcu(..)
- Single writer/ multiple readers
  - Deferral of freeing objects
    - rcu_read_lock
    - rcu_read_unlock

```
void __list_add_rcu(struct list_head * new,
     struct list_head * prev, struct list_head * next)
{
       new->next = next;
       new->prev = prev;
       smp_wmb();
       next->prev = new;
       prev->next = new;
}

void list_add_rcu(struct list_head *new,
             struct list_head *head)
{
       __list_add_rcu(new, head, head->next);
}
```

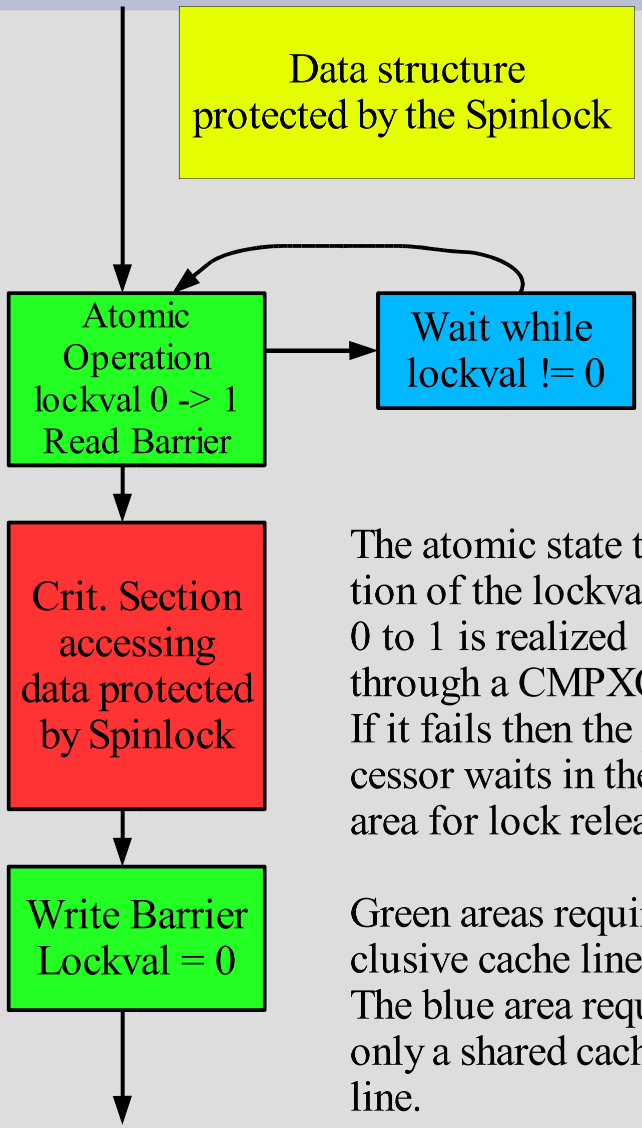
- Write exclusive requires a regular lock

Itanium Semaphore Instructions

- Read Modify Write cycles
  - exclusive cacheline
  - Non-speculative
  - Pipeline stalls
  - Acquire or release semantics
- Single processor effects a certain state change

Compare and Exchange	CMPXCHG
Fetch and add	FETCHADD
Exchange	XCHG

The Spinlock Implementation



The atomic state transition of the lockval from 0 to 1 is realized through a CMPXCHG. If it fails then the processor waits in the blue area for lock release.

Green areas require exclusive cache lines
The blue area requires only a shared cache line.

- Protected Data
- Critical Sections
- Locking
- Unlocking
- Exclusive Cache line use vs. Shared Cache line
- Bouncing Cachelines
- Spinlocks under contention

Spinlock Examples

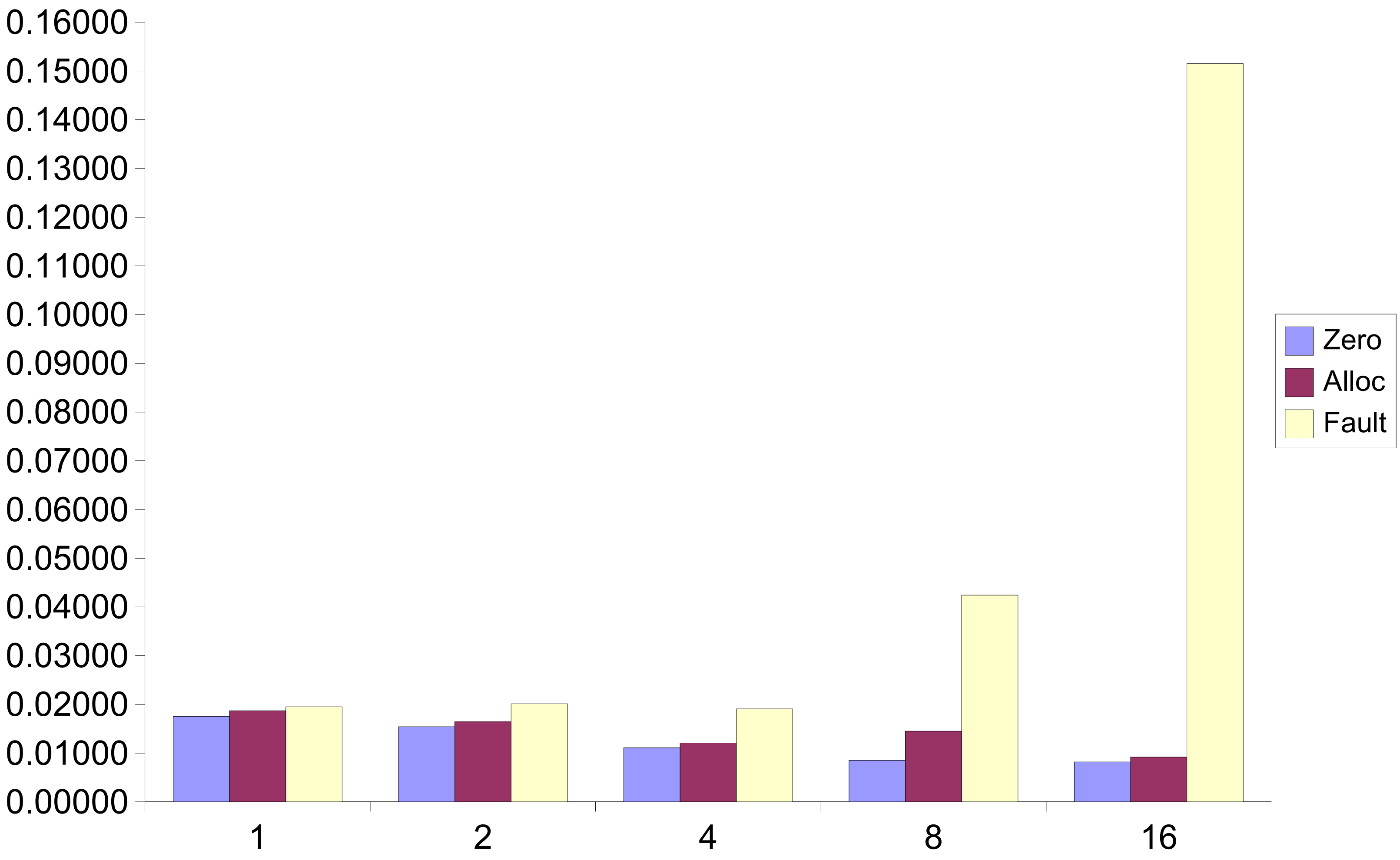
- Spinlock Functions

```
spin_lock(spinlock_t *lock);
spin_unlock(spinlock_t *lock);
```

- Sample Use

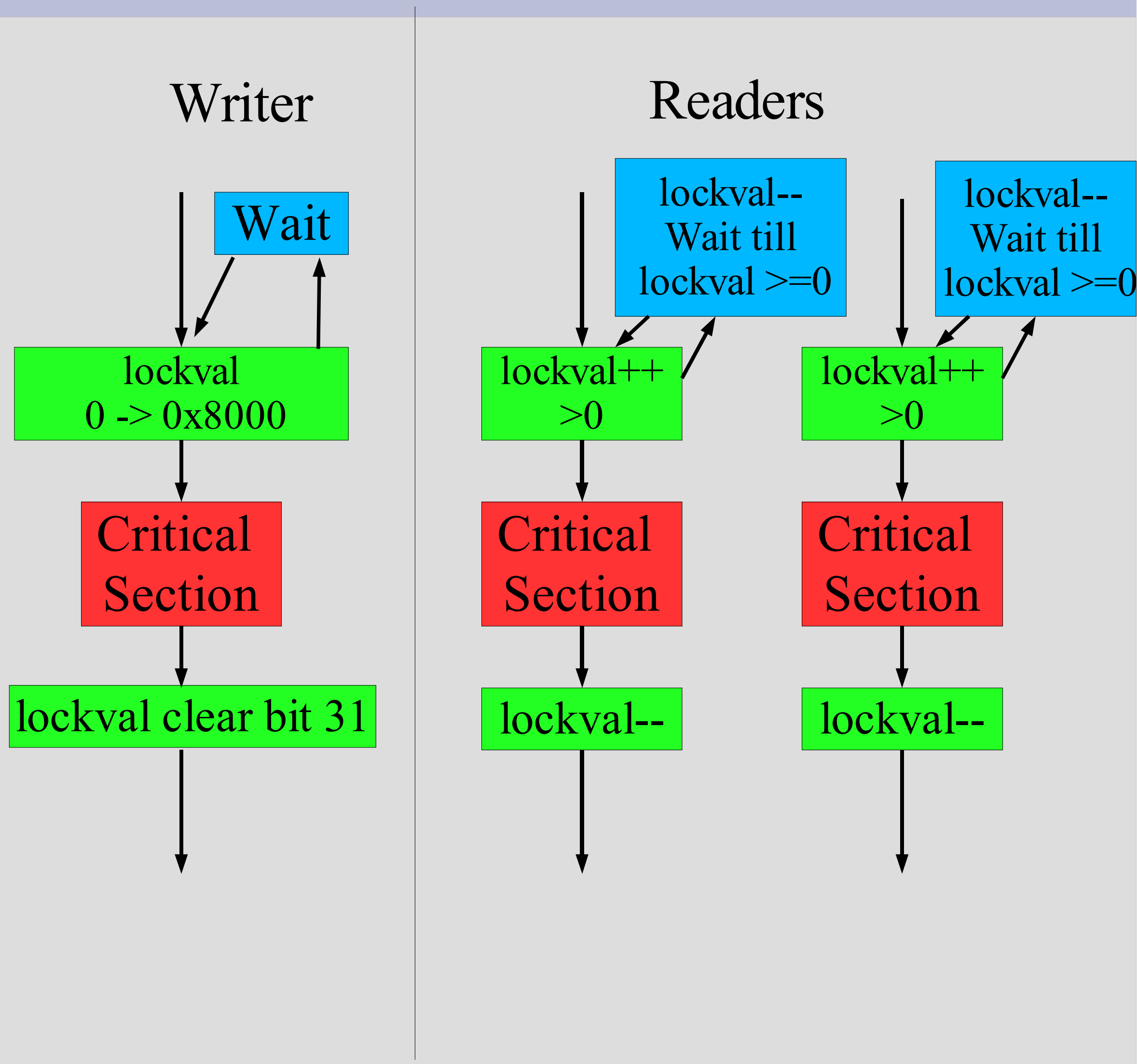
```
spin_lock(&mmlist_lock);
list_add(&dst_mm->mmlist, &src_mm->mmlist);
spin_unlock(&mmlist_lock);
```

Time in the Page Fault Handler



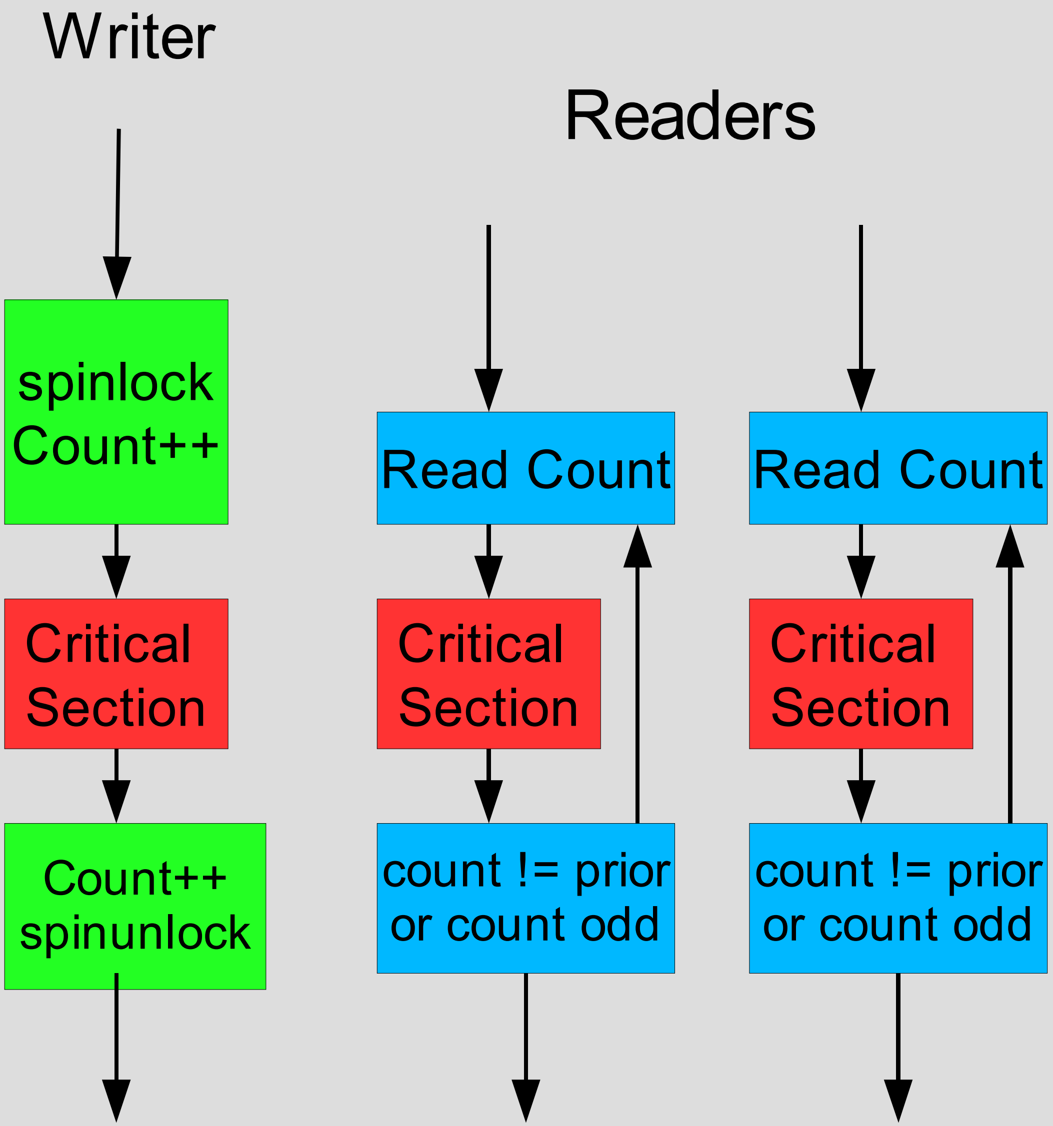
Reader/Writer Spinlocks

- Lock value
  - >0 -> nr readers
  - <0 writer
  - 0 free
- Needs
  - 2x Cmpxchg
  - 2x Fetchadd
  - Clear Bit 31 (byte store instead?)
- Performance worse than regular spinlock



Sequence locks

- Most scalable lock
  - Is this a “lock”?
  - no write for readers
- Effort
  - Writer
    - 2xCmpxchg
2xFetchadd
  - Reader
    - 2x barrier
- Critical section
- Time access



Atomic Variables and Usage Counters

- Use of “atomic_t”
- Explicit use of memory barriers
- Usage counters and atomic_dec_and_test
- Risk of cache line bouncing due to counter increments and decrements

- Effort
  - High
    - Increment
    - Decrement
    - Add
  - Low
    - Assignment
    - Store
    - Loads
  - Very high
    - Bit Operations

Example of atomic_dec_and_test

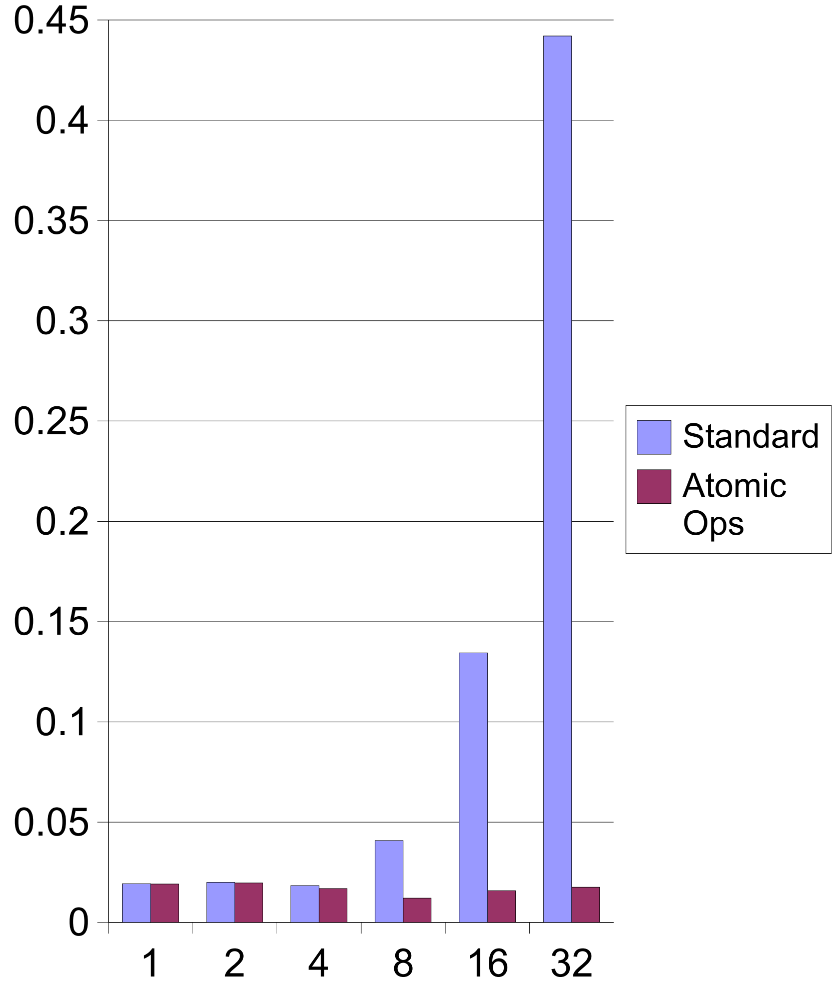
```
/*
 * Decrement the use count and release all resources for an mm.
 */
void mmput(struct mm_struct *mm)
{
        if (atomic_dec_and_test(&mm->mm_users)) {
                exit_aio(mm);
                exit_mmap(mm);
                if (!list_empty(&mm->mmlist)) {
                        spin_lock(&mmlist_lock);
                        list_del(&mm->mmlist);
                        spin_unlock(&mmlist_lock);
                }
                put_swap_token(mm);
                mmdrop(mm);
        }
}
EXPORT SYMBOL GPL(mmput);
```

Per CPU “Atomicity”

- Guaranteed if one processor is accessing variables reserved for its own use.
- Disabling interrupts, preemption to guaranteed non interference by interrupts or the process being moved to another processor.
- Splitting of counters per cpu to avoid atomic operations
- Counter coherency issues

Combining Techniques

- Earlier example of rcu locks and spinlocks
- Page Fault Patches
  - Page table spinlock
  - Mmap_sem
  - Limited atomic operations
- Redefining a spinlock
  - Do not modify only populate
- Severity of changing lock semantics

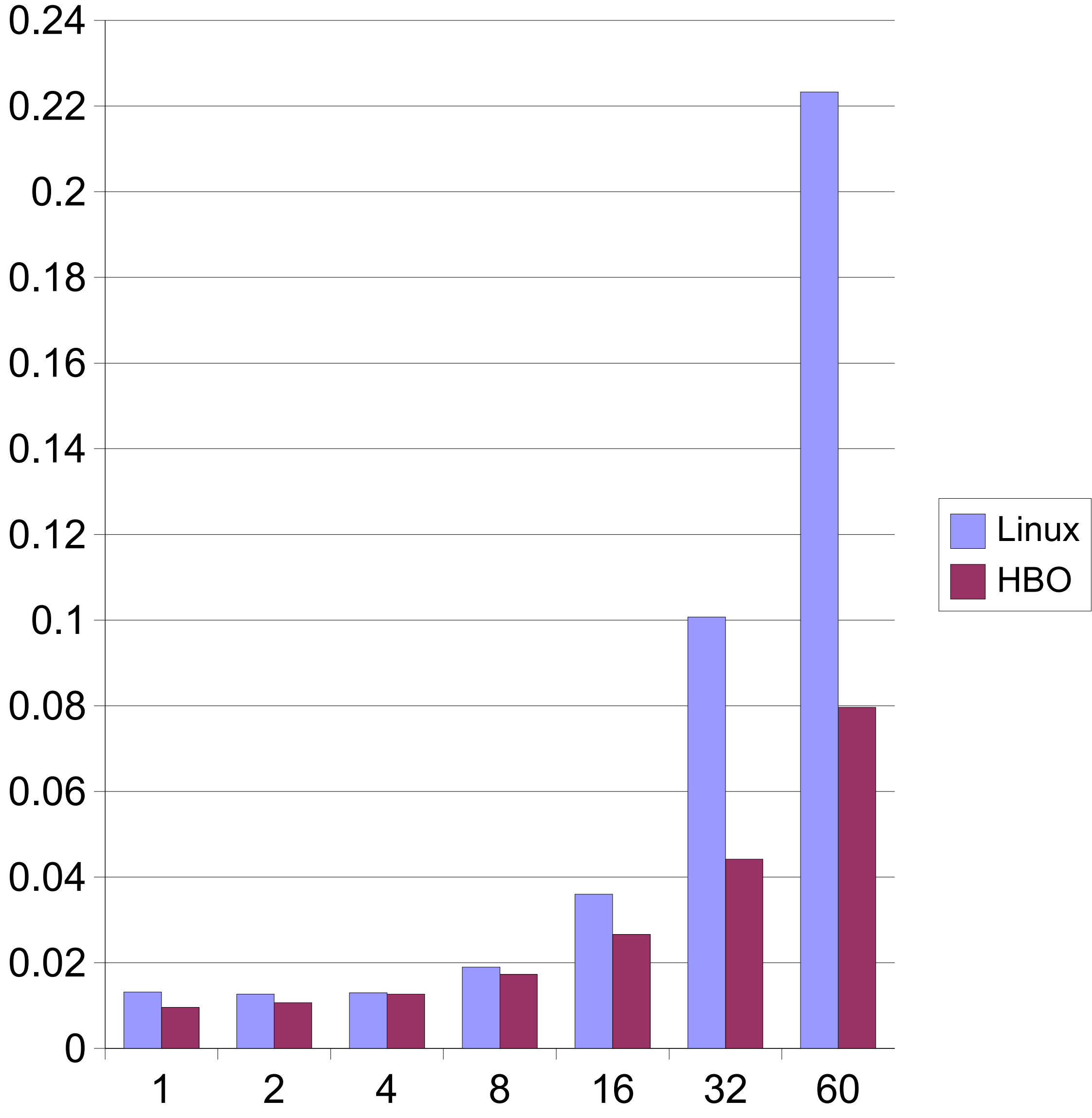


Other Locking Approaches

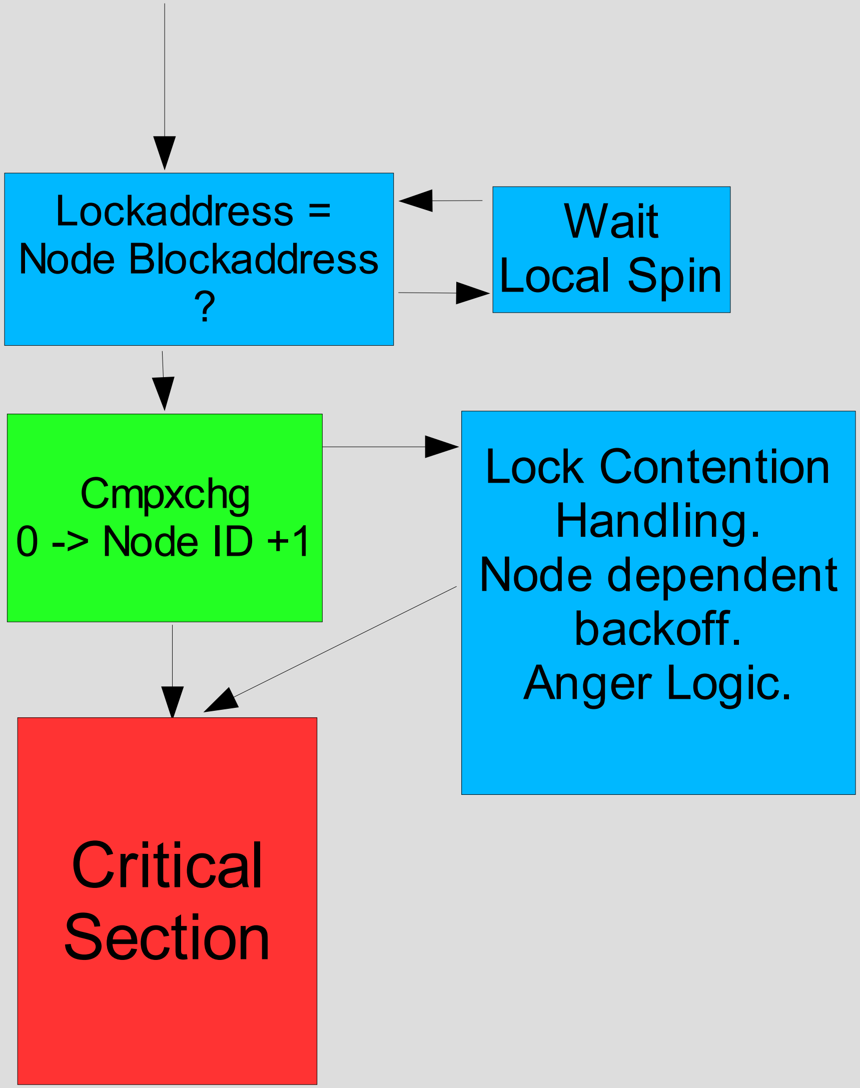
- Backoff Algorithms
  - Obvious choice
  - Simple Backoff
  - Ethernet style exponential backoff
- Queue locks
  - Access ordering
  - Slow typical combined with simple spinlock
  - Fairness addressed
  - MCS
    - John Stultz MCS Queue implementation for Linux
- Locking based on Hardware features
  - Bypass cache coherency protocol

Hierarchical BackOff Locks

- HBO
  - NUMA aware backoff
  - Limit off node contention
  - Starvation and Anger Levels
- Disadvantages
  - Additional load operation
  - Complexity of contention handling



HBO Details



- Contention handling
  - Backoff
    - On node -> 4 microsecond backoff
    - Off node -> 7 microseconds
    - 50% backoff increase on failure
  - Off node
    - Set blockaddress
  - Anger Level
    - After 50 retries set remote blockaddress