Synchronization

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(Based on slides by Don Porter and Mike Ferdman)

What is Synchronization?

- Code on multiple CPUs coordinate their operations
- Examples:
  - Locking provides mutual exclusion
    - CPU A locks CPU B's run queue to steal tasks
      - Otherwise CPU B may start running a task that CPU A is stealing
  - Threads wait at barrier for completion of computation
  - Coordinating which CPU handles an interrupt

Why Linux Synchronization?

- A modern OS kernel is one of the most complicated parallel programs you can study
  - Other than perhaps a database
- Includes most common synchronization patterns
  - And a few interesting, uncommon ones

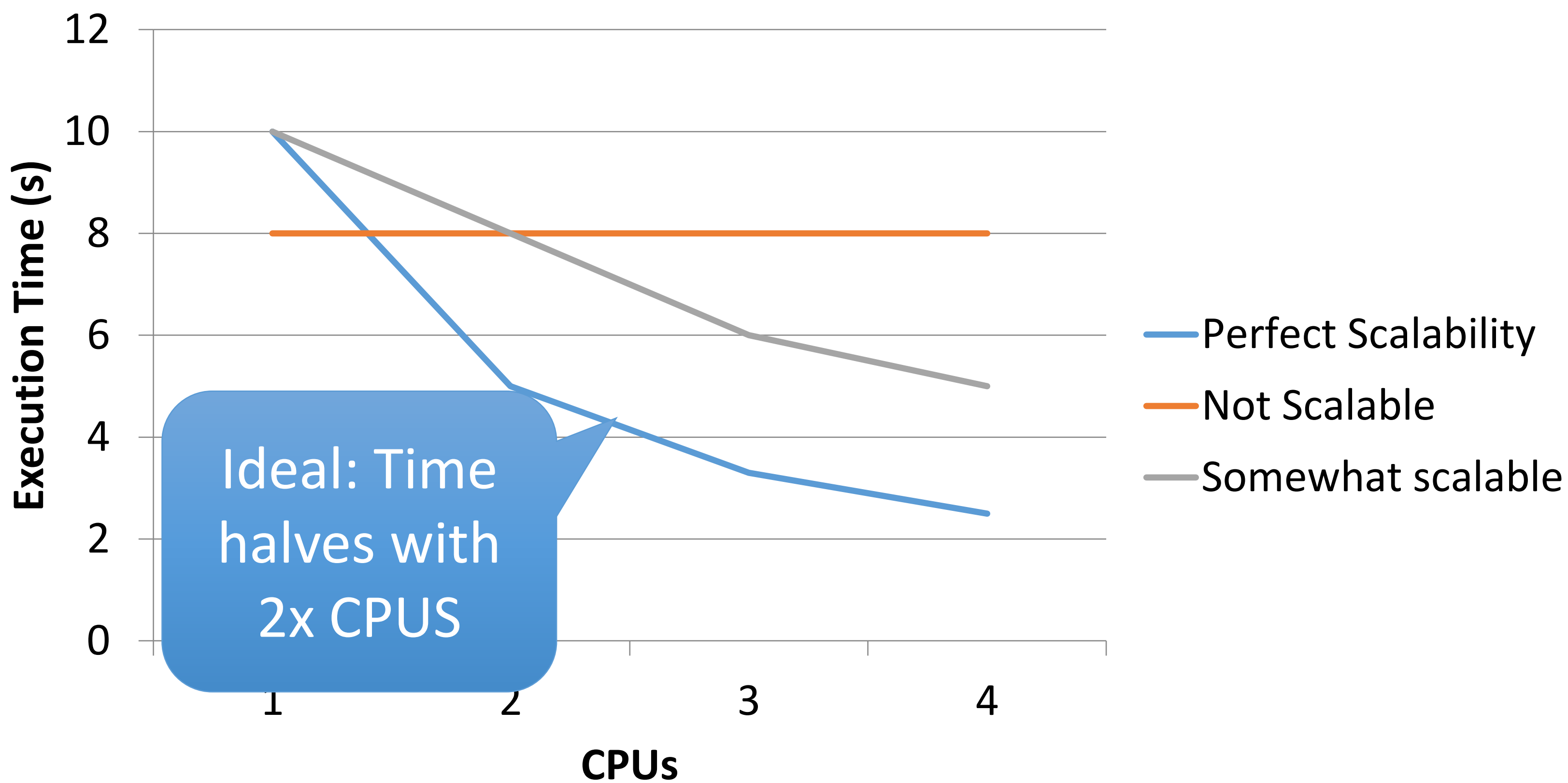
Kernel Locking History

- Traditionally, didn't worry about it
  - Most machines were single processor
- Eventually started supporting multi-processors
  - Called kernels "SMP" around this time
  - Typically had a few (one?) lock
    - Called "***Giant***" lock
- Giant lock became a bottleneck
  - Switches to fine-grained locking
    - With many different types of locks
- Grew tools to dynamically detect/fix locking bugs
  - E.g., FreeBSD "WITNESS" infrastructure

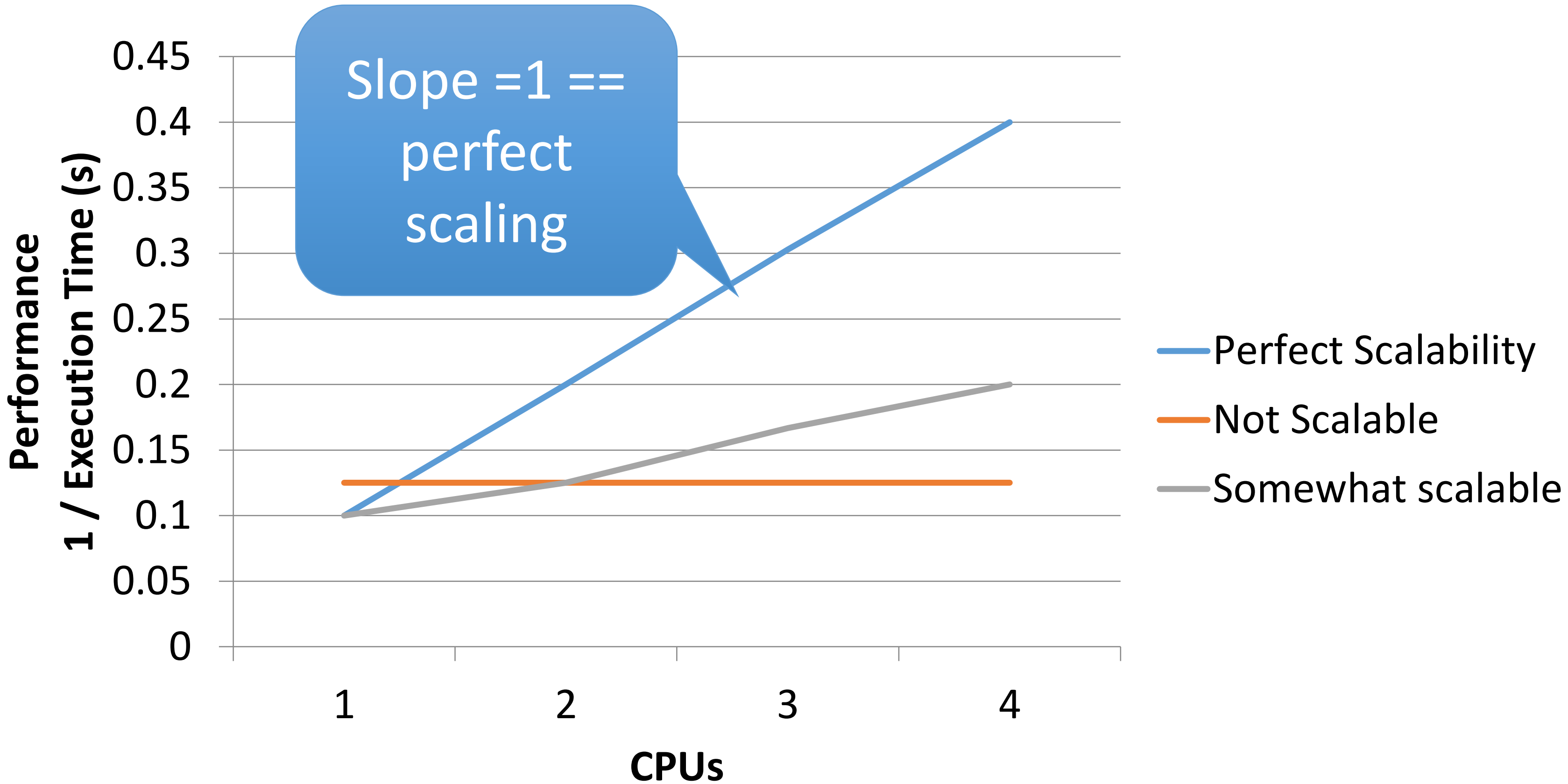
Performance Scalability

- How much more work can this software complete in a unit of time if I give it another CPU?
  - Same: No scalability---extra CPU is wasted
  - 1 -> 2 CPUs doubles the work: Perfect scalability
- Most software isn't scalable
- Most scalable software isn't perfectly scalable

Performance Scalability



Performance Scalability (more visually intuitive)



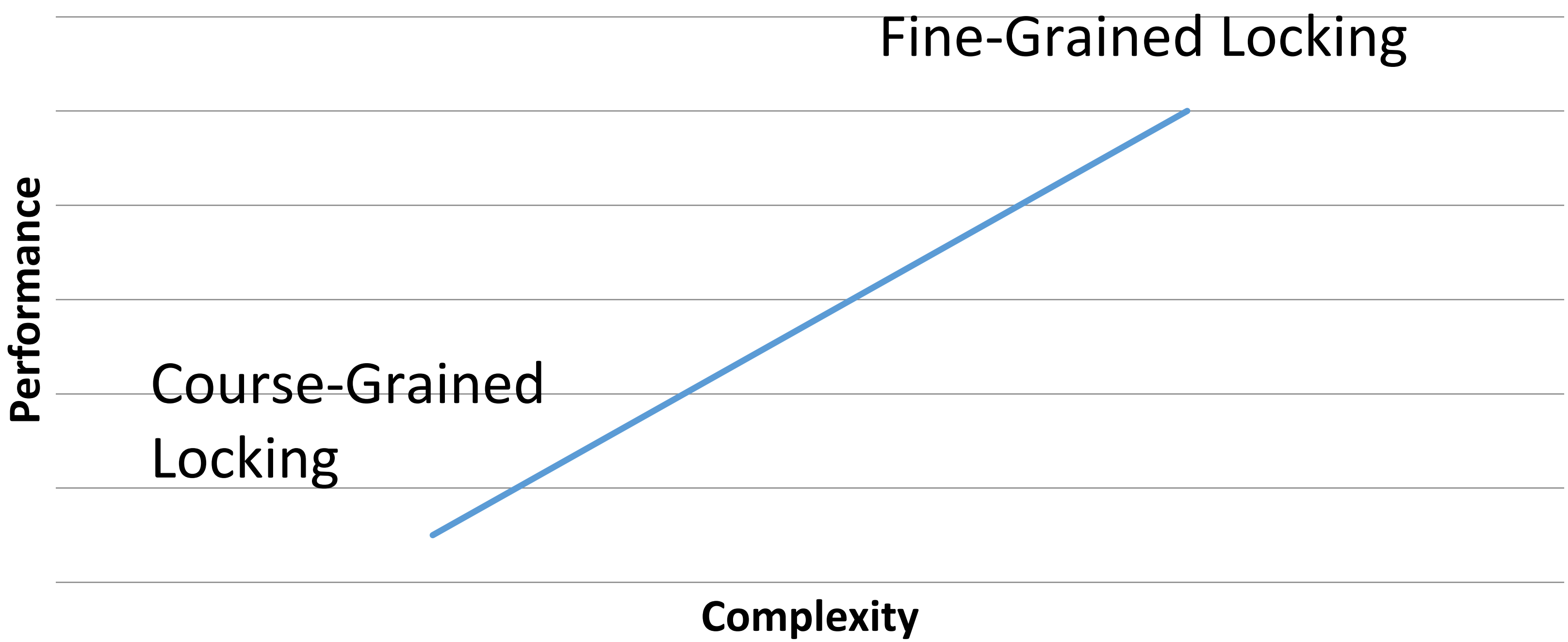
Coarse-Grained Locking

- A single lock for everything
  - Idea: Before touching any shared data, grab the lock
  - Problem: completely unrelated operations ***serialized***
    - Adding CPUs doesn't improve performance

Fine-Grained Locking

- Many “little” locks for individual data structures
  - Goal: Unrelated activities hold different locks
    - Hence, adding CPUs improves performance
  - Cost: complexity of coordinating locks

Current Reality



- Unsavory trade-off between complexity and performance scalability

How Do Locks Work?

- Locks are addresses in ***shared memory***
  - To check if locked, read value from location
  - To unlock, write value to location to indicate unlocked
  - To lock, write value to location to indicate locked
    - If already locked, keep reading value until unlock observed
- Use hardware-provided ***atomic instruction***
  - Determines who wins under contention
  - Requires waiting strategy for the loser(s)
- Also need a waiting strategy for the loser(s)

Atomic Instructions

- Regular memory accesses don't work

```
lock: movq [lock],%rax
cmpq %rax,1
je lock                    ;# "spin" lock
movq 1,[lock]
```

Other CPU may "`movq 1,[lock]`" at this time

- ***Atomic Instructions*** guarantee atomicity
  - Perform ***Read, Modify, and Write*** together (RMW)
  - Many flavors in the real world (***lock*** prefix on x86)
    - ***Compare and Swap*** (CAS)
    - ***Fetch and Add***
    - ***Test and Set***
    - ***Load Linked / Store Conditional***

Atomic Instruction Examples

- Atomic increment/decrement
  - $x = x \pm 1$
  - Used for reference counting
  - Some variants also return the value x was set to by this instruction (useful if another CPU immediately changes the value)
- Compare and swap
  - if (x == y) {x = z; return 1;} else {return 0;}
  - Used for many lock-free data structures

Atomic Instructions + Locks

- Most lock implementations have some sort of counter
- Say initialized to 1
- To acquire the lock, use an atomic decrement
  - If you set the value to 0, you win! Go ahead
  - If you get < 0, you lose. Wait ☹
  - Atomic decrement ensures that only one CPU will decrement the value to zero
- To release, set the value back to 1

Waiting Strategies

- Spinning
  - Poll lock in a busy loop
  - When lock is free, try to acquire it
- Blocking
  - Put process on wait queue and go to sleep
    - CPU may do useful work
  - Winner (lock holder) wakes up loser(s)
    - After releasing lock
  - Same thing as used to wait on I/O

Which Strategy to Use?

- Expected waiting time vs. time of 2 context switches
  - If lock will be held a long time, blocking makes sense
  - If the lock is only held momentarily, spinning makes sense
- Adaptive sometimes works
  - Try to spin a bit
    - If successful, great
    - If unsuccessful, block
  - Can backfire (if spin is never successful)

Linux Lock Types

- Non-blocking: spinlocks, seqlocks, completions
- Blocking: mutex, semaphore

Linux Spinlock (simplified)

```
1: lock; decb slp->slock     // Locked decrement of lock var
   jns 3f                    // Jump if not set (result is zero) to 3
2: pause                     // Low power instruction, wakes on
                             // coherence event
   cmpb $0,slp->slock        // Read the lock value, compare to zero
   jle 2b                    // If less than or equal (to zero), goto 2
   jmp 1b                    // Else jump to 1 and try again
3:                           // We win the lock
```

Rough C Equivalent

```
while (0 != atomic_dec(&lock->counter)) {
        do {
                // Pause the CPU until some coherence
                // traffic (a prerequisite for the counter
                //  changing) saving power

        } while (lock->counter <= 0);
}
```

Reader/Writer Lock

- If everyone is reading, no need to block
  - Everyone reads at the same time
- Writers require mutual exclusion
  - For anyone to write, wait for all readers to give up lock

Linux RW-Spinlock

- Low 24 bits count active readers
  - Unlocked: 0x01000000
  - To read lock: atomic_dec_unless(count, 0)
    - 1 reader: 0x:00ffffff
    - 2 readers: 0x00fffffe
    - Etc.
    - Readers limited to 2^24
- 25th bit for writer
  - Write lock – CAS 0x01000000 -> 0
    - Readers will fail to acquire the lock until we add 0x1000000

Readers Starving Writers

- Constant stream of readers starves writer
- We may want to prioritize writers over readers
  - For instance, when readers are polling for the write

Seqlock

- Explicitly favor writers, potentially starve readers
- Idea:
  - An explicit write lock (one writer at a time)
  - Plus a version number – each writer increments at beginning and end of critical section
- Readers: Check version number, read data, check again
  - If version changed, try again in a loop
  - If version hasn't changed and is even, neither has data

Seqlock Example

70

% Time for CSE 506

30

% Time for All Else

0

Version

Lock

Invariant:
Must add up to 100%

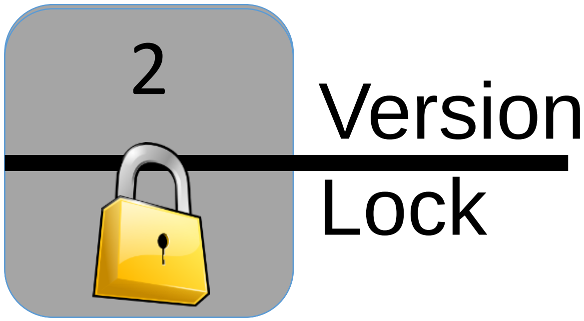
Seqlock Example

80

% Time for CSE 506

20

% Time for All Else



What if reader executed now?

```
Reader:
do {
    v = version;
    a = cse506;
    b = other;
} while (v % 2 == 1  &&
         v != version);
```

```
Writer:
    lock();
    version++;
    other = 20;
    cse506 = 80;
    version++;
    unlock();
```

Seqlock

- Explicitly favor writers, potentially starve readers
- Idea:
  - An explicit write lock (one writer at a time)
  - Plus a version number – each writer increments at beginning and end of critical section
- Readers: Check version number, read data, check again
  - If version changed, try again in a loop
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Semaphore

- A counter of allowed concurrent processes
  - A mutex is the special case of 1 at a time
- Plus a wait queue
- Implemented similarly to a spinlock, except spin loop replaced with placing oneself on a wait queue

Lock Composition

- Need to touch two data structures (A and B)
  - Each is protected by its own lock
- What could go wrong?
  - Deadlock!
  - Thread 0: lock(a); lock(b)
  - Thread 1: lock(b); lock(a)
- How to solve?
  - Lock ordering

Lock Ordering

- A code convention
- Developers gather, eat lunch, plan order of locks
  – Potentially worse: gather, drink beer, plan order of locks
- Nothing prevents violating convention
  – Research topics on making this better:
    - Finding locking bugs
    - Automatically locking things properly
    - Transactional memory

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)
 */
```