```
Handout for CS 372H
Class 8
9 February 2012

1. How can we implement lock, acquire(), and release()?

    1a. Here is A BADLY BROKEN implementation:

        struct Lock {
          int locked;
        }

        void [BROKEN] acquire(Lock *lock) {
          while (1) {
            if (lock->locked == 0) { // C
              lock->locked = 1;    // D
              break;
            }
          }
        }

        void release (Lock *lock) {
          lock->locked = 0;
        }

        What's the problem? Two acquire()s on the same lock on different
        CPUs might both execute line C, and then both execute D. Then
        both will think they have acquired the lock. This is the same
        kind of race that we were trying to eliminate in insert().  But
        we have made a little progress: now we only need a way to
        prevent interleaving in one place (acquire()), not for many
        arbitrary complex sequences of code.

    1b. Here's a way that is correct but only sometimes appropriate:
        Use an atomic instruction on the CPU. For example, on the x86,
        doing
                "xchg addr, %eax"
        does the following:

        (i)   freeze all CPUs' memory activity for address addr
        (ii)  temp = *addr
        (iii) *addr = %eax
        (iv)  %eax = temp
        (v)   un-freeze memory activity

        /* pseudocode */
        int xchg_val(addr, value) {
            %eax = value;
            xchg (*addr), %eax
        }

        struct Lock {
          int locked;
        }

        /* bare-bones version of acquire */
        void acquire (Lock *lock) {
          pushcli();    /* what does this do? */
          while (1) {
            if (xchg_val(&lock->locked, 1) == 0)
              break;
          }
        }

        /* optimization in acquire; call xchg_val() less frequently */
        void acquire(Lock* lock) {
            pushcli();
            while (xchg_val(&lock->locked, 1) == 1) {
                while (lock->locked) ;
            }
        }
```



```
        void release(Lock *lock){
           xchg_val(&lock->locked, 0);
           popcli();    /* what does this do? */
        }

        The above is called a *spinlock* because acquire() spins.

        The spinlock above is great for some things, not so great for
        others. The main problem is that it *busy waits*: it spins,
        chewing up CPU cycles. Sometimes this is what we want (e.g., if
        the cost of going to sleep is greater than the cost of spinning
        for a few cycles waiting for another thread or process to
        relinquish the spinlock). But sometimes this is not at all what we
        want (e.g., if the lock would be held for a while: in those
        cases, the CPU waiting for the lock would waste cycles spinning
        instead of running some other thread or process).


    1c. Here's an object that does not involve busy waiting; it can work
    as the list_lock mentioned above. Note: the "threads" here
    can be user-level threads, kernel threads, or threads-inside-kernel.
    The concept is the same in all cases.

        struct Mutex {
            bool is_held;           /* true if mutex held */
            thread_id owner;        /* thread holding mutex, if locked */
            thread_list waiters;    /* queue of thread TCBs */
            Lock wait_lock;         /* as in 1b */
        }

        Now, instead of acquire(&list_lock) and release(&list_lock) as
        abve, we'd write, mutex_acquire(&list_mutex) and
        mutex_release(&list_mutex). The implementation of the latter two
        would be something like this:

        void mutex_acquire(Mutex *m) {

            acquire(&m->wait_lock);   /* we spin to acquire wait_lock */
            while (m->is_held) {     /* someone else has the mutex */
                m->waiters.insert(current_thread)
                release(&m->wait_lock);
                schedule();   /* run a thread that is on the ready list */
                acquire(&m->wait_lock);   /* we spin again */
            }
            m->is_held = true;      /* we now hold the mutex */
            m->owner = self;
            release(&m->wait_lock);
        }

        void mutex_release(Mutex *m) {

            acquire(&m->wait_lock);    /* we spin to acquire wait_lock */
            m->is_held = false;
            m->owner = 0;
            wake_up_a_waiter(m->waiters); /* select and run a waiter */
            release(&m->wait_lock);

        }

        [Please let me (MW) know if you see bugs in the above.]

    NOTE: Unfortunately, insert() with these locks is correct only if
    there are some constraints on the order in which the CPU carries out
    memory reads and writes. For example, if insert() were executed so
    that the read at A appeared to another processor (and to memory) to
    be executed before the acquire(), then insert() would be incorrect
    even with locks.

    How do we get the required guarantee? Answer: by ensuring that neither
    the programmer nor the processor reorders instructions with respect to
    the acquire().
```

2. Terminology

To avoid confusion, we will use the following terminology in this course (you will hear other terminology elsewhere):

--A "lock" is an abstract object that provides mutual exclusion

--A "spinlock" is a lock that works by busy waiting, as in 6b

--A "mutex" is a lock that works by having a "waiting" queue and then protecting that waiting queue with atomic hardware instructions, as in 6c. The most natural way to "use the hardware" is with a spinlock, but there are others, such as turning off interrupts, which works if we're on a single CPU machine.

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3. Producer/consumer example [also known as bounded buffer]

3a. Recall buggy implementation

```
/*
"buffer" stores BUFFER_SIZE items
"count" is number of used slots. a variable that lives in memory
"out" is next empty buffer slot to fill (if any)
"in" is oldest filled slot to consume (if any)
*/

 void producer (void *ignored) {
     for (;;) {
         /* next line produces an item and puts it in nextProduced */
         nextProduced = means_of_production();
         while (count == BUFFER_SIZE)
             ; // do nothing
         buffer [in] = nextProduced;
         in = (in + 1) % BUFFER_SIZE;
         count++;
     }
 }

 void consumer (void *ignored) {
     for (;;) {
         while (count == 0)
            ; // do nothing
         nextConsumed = buffer[out];
         out = (out + 1) % BUFFER_SIZE;
         count--;
         /* next line abstractly consumes the item */
         consume_item(nextConsumed);
     }
 }
```

--Review: what's the problem?
--Answer: count++ and count-- might compile to, respectively:

```
reg1 <-- count      # load
reg1 <-- reg1 + 1   # increment register
count <-- reg1      # store

reg2 <-- count      # load
reg2 <-- reg2 - 1   # decrement register
count <-- reg2      # store
```

--Review: why not use instructions like "addl $0x1, _count"?
--Answer: not atomic if there are multiple CPUs.

--Review: so why not use "LOCK addl $0x1, _count"?
--Answer: we could do that here, but LOCK won't save us every time

--Review: so use general-purpose approach to protecting critical sections: locks (or mutexes).

```
3b. Producer/consumer [bounded buffer] using mutexes

  Mutex mutex;

  void producer (void *ignored) {
      for (;;) {
          /* next line produces an item and puts it in nextProduced */
          nextProduced = means_of_production();

          acquire(&mutex);
          while (count == BUFFER_SIZE) {
             release(&mutex);
             yield(); /* or schedule() */
             acquire(&mutex);
          }

          buffer [in] = nextProduced;
          in = (in + 1) % BUFFER_SIZE;
          count++;
          release(&mutex);
      }
  }

  void consumer (void *ignored) {
      for (;;) {

          acquire(&mutex);
          while (count == 0) {
             release(&mutex);
             yield(); /* or schedule() */
             acquire(&mutex);
          }

          nextConsumed = buffer[out];
          out = (out + 1) % BUFFER_SIZE;
          count−−;
          release(&mutex);

          /* next line abstractly consumes the item */
          consume_item(nextConsumed);
      }
  }
```



```
3c. Producer/consumer [bounded buffer] using mutexes and condition
variables

     Mutex mutex;
     Cond nonempty;
     Cond nonfull;

     void producer (void *ignored) {
         for (;;) {
             /* next line produces an item and puts it in nextProduced */
             nextProduced = means_of_production();

             acquire(&mutex);
             while (count == BUFFER_SIZE)
                cond_wait(&nonfull, &mutex);

             buffer [in] = nextProduced;
             in = (in + 1) % BUFFER_SIZE;
             count++;
             cond_signal(&nonempty, &mutex);
             release(&mutex);
         }
     }

     void consumer (void *ignored) {
         for (;;) {

             acquire(&mutex);
             while (count == 0)
                cond_wait(&nonempty, &mutex);

             nextConsumed = buffer[out];
             out = (out + 1) % BUFFER_SIZE;
             count−−;
             cond_signal(&nonfull, &mutex);
             release(&mutex);

             /* next line abstractly consumes the item */
             consume_item(nextConsumed);
         }
     }


    Question: why does cond_wait need to both release the mutex and
    sleep? Why not:

       while (count == BUFFER_SIZE)  {
           release(&mutex);
           cond_wait(&nonfull);
           acquire(&mutex);
       }
```

```
3d.  Producer/consumer [bounded buffer] with semaphores

    Semaphore mutex(1);             /* mutex initialized to 1 */
    Semaphore empty(BUFFER_SIZE);  /* start with BUFFER_SIZE empty slots */
    Semaphore full(0);             /* 0 full slots */

    void producer (void *ignored) {
         for (;;) {
             /* next line produces an item and puts it in nextProduced */
             nextProduced = means_of_production();

            /*
             * next line diminishes the count of empty slots and
             * waits if there are no empty slots
             */
             sem_down(&empty);
             sem_down(&mutex);  /* get exclusive access */

             buffer [in] = nextProduced;
             in = (in + 1) % BUFFER_SIZE;

             sem_up(&mutex);
             sem_up(&full);   /* we just increased the # of full slots */
         }
     }

     void consumer (void *ignored) {
         for (;;) {

             /*
              * next line diminishes the count of full slots and
              * waits if there are no full slots
              */
             sem_down(&full);
             sem_down(&mutex);

             nextConsumed = buffer[out];
             out = (out + 1) % BUFFER_SIZE;

             sem_up(&mutex);
             sem_up(&empty);   /* one further empty slot */

             /* next line abstractly consumes the item */
             consume_item(nextConsumed);
         }
     }

    Semaphores *can* (not always) lead to elegant solutions (notice
    that the code above is fewer lines than 3c) but they are much
    harder to use.

    The fundamental issue is that semaphores make implicit (counts,
    conditions, etc.) what is probably best left explicit. Moreover,
    they *also* implement mutual exclusion.

    For this reason, you should not use semaphores. This example is
    here mainly for completeness and so you know what a semaphore
    is. But do not code with them. Solutions that use semaphores in
    this course will receive no credit.
```



```
4. Example of a monitor: MyBuffer

    // This is pseudocode that is inspired by C++.
    // Don’t take it literally.

    class MyBuffer {
      public:
        MyBuffer();
        ~MyBuffer();
        void Enqueue(Item);
        Item = Dequeue();
      private:
        int count;
        int in;
        int out;
        Item buffer[BUFFER_SIZE];
        Mutex* mutex;
        Cond* nonempty;
        Cond* nonfull;
    }

    void
    MyBuffer::MyBuffer()
    {
        in = out = count = 0;
        mutex = new Mutex;
        nonempty = new Cond;
        nonfull = new Cond;
    }

    void
    MyBuffer::Enqueue(Item item)
    {
        mutex.acquire();
        while (count == BUFFER_SIZE)
            cond_wait(&nonfull, &mutex);

        buffer[in] = item;
        in = (in + 1) % BUFFER_SIZE;
        ++count;
        cond_signal(&nonempty, &mutex);
        mutex.release();
    }

    Item
    MyBuffer::Dequeue()
    {
        mutex.acquire();
        while (count == 0)
            cond_wait(&nonempty, &mutex);

        Item ret = buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        --count;
        cond_signal(&nonfull, &mutex);
        mutex.release();
        return ret;
    }
```

```
    int main(int, char**)
    {
        MyBuffer buf;
        int dummy;
        tid1 = thread_create(producer, &buf);
        tid2 = thread_create(consumer, &buf);
        thread_join(tid1);

        // never reach this point
        return −1;
    }

    void producer(void* buf)
    {
        MyBuffer* sharedbuf = reinterpret_cast<MyBuffer*>(buf);
        for (;;) {
            /* next line produces an item and puts it in nextProduced */
            Item nextProduced = means_of_production();
            sharedbuf−>Enqueue(nextProduced);
        }
    }

    void consumer(void* buf)
    {
        MyBuffer* sharedbuf = reinterpret_cast<MyBuffer*>(buf);
        for (;;) {
            Item nextConsumed = sharedbuf−>Dequeue();

            /* next line abstractly consumes the item */
            consume_item(nextConsumed);
        }
    }
```

Key point: *Threads* (the producer and consumer) are separate from *shared object* (MyBuffer). The synchronization happens in the shared object.

5. Readers/writers

```
    state variables:
        AR = 0;  // # active readers
        AW = 0;  // # active writers
        WR = 0;  // # waiting readers
        WW = 0;  // # waiting writers

        Condition okToRead = NIL;
        Condition okToWrite = NIL;
        Mutex mutex = FREE;

    Database::read() {
        startRead();  // first, check self into the system
        Access Data
        doneRead();   // check self out of system
    }

    Database::startRead() {
        acquire(&mutex);
        while((AW + WW) > 0){
            WR++;
            wait(&okToRead, &mutex);
            WR−−;
        }
        AR++;
        release(&mutex);
    }

   Database::doneRead() {
        acquire(&mutex);
        AR−−;
        if (AR == 0 && WW > 0) { // if no other readers still
          signal(&okToWrite, &mutex);   // active, wake up writer
        }
        release(&mutex);
    }

    Database::write(){  // symmetrical
        startWrite();  // check in
        Access Data
        doneWrite();  // check out
    }

    Database::startWrite() {
        acquire(&mutex);
        while ((AW + AR) > 0) { // check if safe to write.
                                // if any readers or writers, wait
            WW++;
            wait(&okToWrite, &mutex);
            WW−−;
        }
        AW++;
        release(&mutex);
    }

    Database::doneWrite() {
        acquire(&mutex);
        AW−−;
        if (WW > 0) {
            signal(&okToWrite, &mutex); // give priority to writers
        } else if (WR > 0) {
            broadcast(&okToRead, &mutex);
        }
        release(&mutex);
    }
```

NOTE: what is the starvation problem here?

6. Shared locks

```
    struct sharedlock {
      int i;
      Mutex mutex;
      Cond c;
    };

    void AcquireExclusive (sharedlock *sl) {
      acquire(&sl->mutex);
      while (sl->i) {
        wait (&sl->c, &sl->mutex);
      }
      sl->i = -1;
      release(&sl->mutex);
    }

    void AcquireShared (sharedlock *sl) {
      acquire(&sl->mutex);
      while (sl->i < 0) {
        wait (&sl->c, &sl->mutex);
      }
      sl->i++;
      release(&sl->mutex);
    }

    void ReleaseShared (sharedlock *sl) {
      acquire(&sl->mutex);
      if (!--sl->i)
        signal (&sl->c, &sl->mutex);
      release(&sl->mutex);
    }

    void ReleaseExclusive (sharedlock *sl) {
      acquire(&sl->mutex);
      sl->i = 0;
      broadcast (&sl->c, &sl->mutex);
      release(&sl->mutex);
    }
```

QUESTIONS:

A. There is a starvation problem here. What is it? (Readers can keep writers out if there is a steady stream of readers.)

B. How could you use these shared locks to write a cleaner version of the code in item 5., above? (Though note that the starvation properties would be different.)

13. [12 points] Consider the function `doublecheck_alloc()` below, which is intended to be invoked from multiple threads on a multiprocessor machine. Its purpose is to avoid a mutex acquisition in the common case that `ptr` is already initialized. The requirements for this function are:

(i) `doublecheck_alloc()` must call `alloc_foo()` no more than once over the whole execution.

(ii) A caller of `doublecheck_alloc()` must, after the function returns, observe `ptr` as non-zero.

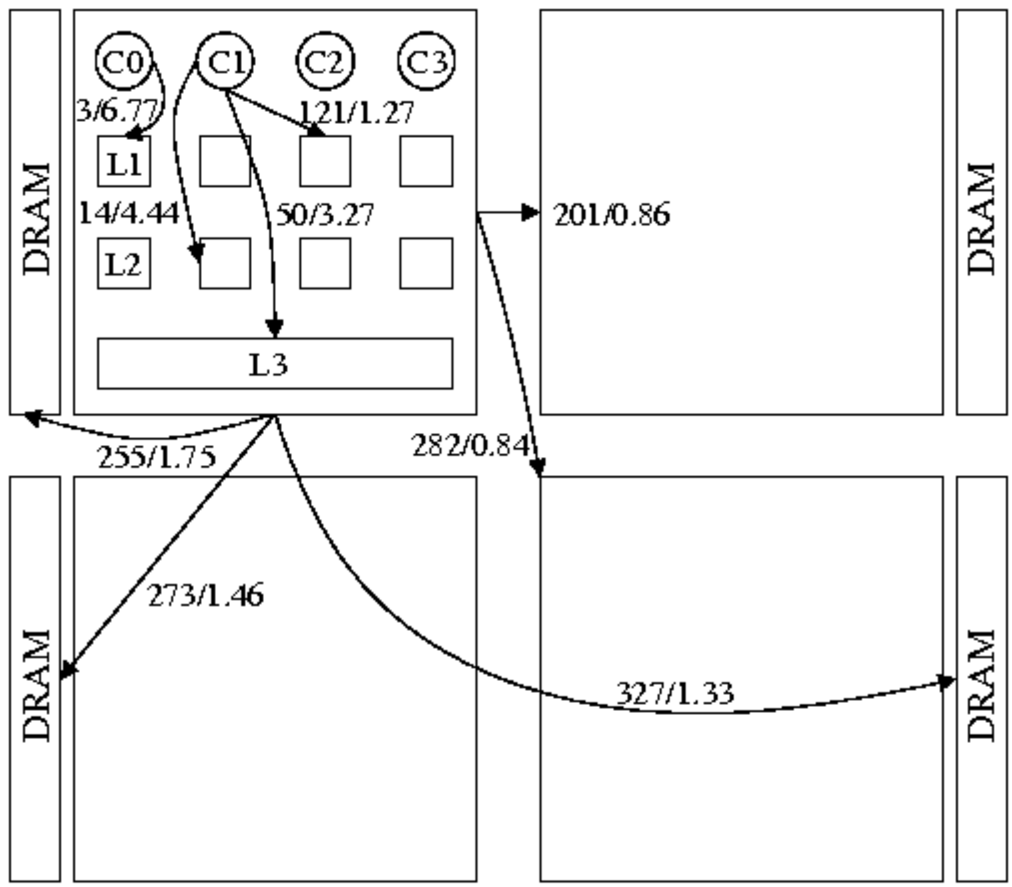
The machine does **not** offer sequential consistency. Thus, a processor is not guaranteed to see the memory operations of another processor in program order. However, each of `mutex_acquire()` and `mutex_release()` is implemented correctly; in particular, each of them internally contains a memory barrier (`mfence` on the x86). Recall that `mfence` ensures that all memory operations before the `mfence` barrier appear to all processors to have executed before all memory operations after the `mfence` barrier.

On the other hand, the compiler **preserves** program order (it does not reorder instructions).

```
struct foo {
    int abc;
    int def;
};
static int ready = 0;
static mutex_t mutex;
static struct foo* ptr = 0;

void
doublecheck_alloc()
{
    if (!ready) {    /* <-- accesses shared variable w/out holding mutex */
        mutex_acquire(&mutex);
        if (!ready) {
            ptr = alloc_foo();  /* <-- sets ptr to be non-zero */
            ready = 1;
        }
        mutex_release(&mutex);
    }
    return;
}
```

The above code certainly violates our coding standards, but this problem is about whether it violates requirements **(i)** and **(ii)**, above. The questions are given on the next page.



The AMD 16-core system topology. Memory access latency is in cycles and listed before the backslash. Memory bandwidth is in bytes per cycle and listed after the backslash. The measurements reflect the latency and bandwidth achieved by a core issuing load instructions. The measurements for accessing the L1 or L2 caches of a different core on the same chip are the same. The measurements for accessing any cache on a different chip are the same. Each cache line is 64 bytes, L1 caches are 64 Kbytes 8-way set associative, L2 caches are 512 Kbytes 16-way set associative, and L3 caches are 2 Mbytes 32-way set associative.

[Reprinted with permission from S. Boyd-Wickizer et al. Corey: An Operating System for Many Cores. Proceedings of Usenix Symposium on Operating Systems Design and Implementation (OSDI), December 2008.]

A. CAS / CMPXCHG

Useful operation: compare−and−swap, known as CAS. Says: "atomically check whether a given memory cell contains a given value, and if it does, then replace the contents of the memory cell with this other value; in either case, return the original value in the memory location".

On the X86, we implement CAS with the CMPXCHG instruction, but note that this instruction is not atomic by default, so we need the LOCK prefix.

Here's pseudocode:

```
int cmpxchg_val(int* addr, int oldval, int newval) {
    LOCK: // remember, this is pseudocode
    int was = *addr;
    if (*addr == oldval)
        *addr = newval;
    return was;
}
```

Here's inline assembly:

```
uint32_t cmpxchg_val(uint32_t* addr, uint32_t oldval, uint32_t newval) {
    uint32_t was;
    asm volatile("lock cmpxchg %3, %0"
                 : "+m" (*addr), "=a" (was)
                 : "a" (oldval), "r" (newval)
                 : "cc");
    return was;
}
```

B. MCS locks

Citation: Mellor−Crummey, J. M. and M. L. Scott. Algorithms for Scalable Synchronization on Shared−Memory Multiprocessors, ACM Transactions on Computer Systems, Vol. 9, No. 1, February, 1991, pp.21−65.

Each CPU has a qnode structure in *local* memory. Here, local can mean local memory in NUMA machine or its own cache line that other CPUs are not allowed to cache (i.e., the cache line is in exclusive mode):

```
typedef struct qnode {
    struct qnode* next;
    bool someoneelse_locked;
} qnode;

typedef qnode* lock;  // a lock is a pointer to a qnode
```

−−The lock itself is literally the *tail* of the list of CPUs holding or waiting for the lock.

−−While waiting, a CPU spins on its local "locked" flag. Here's the code for acquire:


```
    // lockp is a qnode**. I points to our local qnode.
    void acquire(lock* lockp, qnode* I) {

        I->next = NULL;
        qnode* predecessor;

        // next line makes lockp point to I (that is, it sets *lockp <−− I)
        // and returns the old value of *lockp. Uses atomic operation
        // XCHG. see earlier in handout (or earlier handouts)
        // for implementation of xchg_val.

        predecessor = xchg_val(lockp, I);    // "A"
        if (predecessor != NULL) { // queue was non−empty
            I->someoneelse_locked = true;
            predecessor->next = I;           // "B"
            while (I->someoneelse_locked) ;    // spin
        }
        // we hold the lock!
    }
```

What's going on?

−−If the lock is unlocked, then *lockp == NULL.

−−If the lock is locked, and there are no waiters, then *lockp points to the qnode of the owner

−−If the lock is locked, and there are waiters, then *lockp points to the qnode at the tail of the waiter list.

−−Here's the code for release:

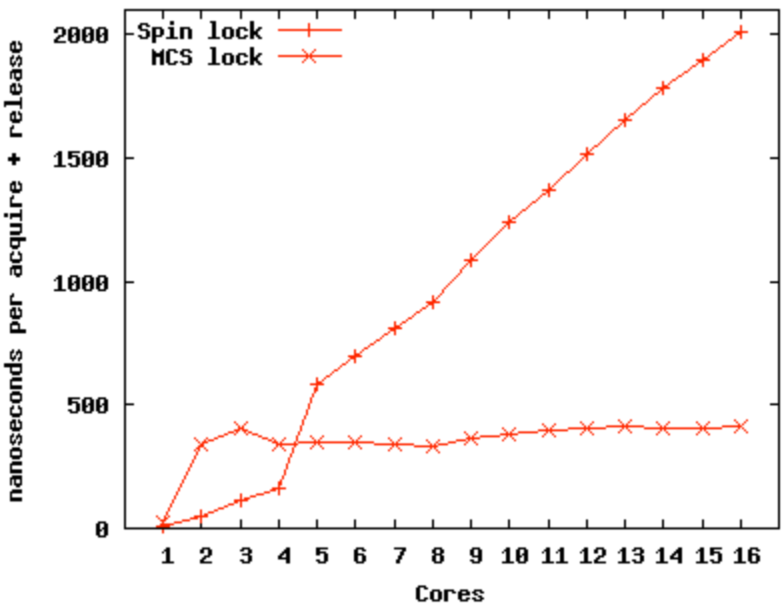
```
    void release(lock* lockp, qnode* I) {
        if (!I->next)   { // no known successor
            if (cmpxchg_val(lockp, I, NULL) == I) {     // "C"
                // swap successful: lockp was pointing to I, so now
                // *lockp == NULL, and the lock is unlocked. we can
                // go home now.
                return;
            }
            // if we get here, then there was a timing issue: we had
            // no known successor when we first checked, but now we
            // have a successor: some CPU executed the line "A"
            // above. Wait for that CPU to execute line "B" above.
            while (!I->next) ;
        }
        // handing the lock off to the next waiter is as simple as
        // just setting that waiter's "someoneelse_locked" flag to false
        I->next->someoneelse_locked = false;
    }
```

What's going on?

−−If I−>next == NULL and *lockp == I, then no one else is waiting for the lock. So we set *lockp == NULL.

−−If I−>next == NULL and *lockp != I, then another CPU is in acquire (specifically, it executed its atomic operation, namely line "A", before we executed ours, namely line "C"). So wait for the other CPU to put the list in a sane state, and then drop down to the next case:

−−If I−>next != NULL, then we know that there is a spinning waiter (the oldest one). Hand it the lock by setting its flag to false.



Time required to acquire and release a lock on a 16-core AMD machine when varying number of cores contend for the lock. The two lines show Linux kernel spin locks and MCS locks (on Corey). A spin lock with one core takes about 11 nanoseconds; an MCS lock about 26 nanoseconds.

[Reprinted with permission from S. Boyd-Wickizer et al. Corey: An Operating System for Many Cores. Proceedings of Symposium on Operating Systems Design and Implementation (OSDI), December 2008.]

```
Performance v complexity trade-off with locks

/*
 *      linux/mm/filemap.c
 *
 * Copyright (C) 1994-1999  Linus Torvalds
 */

/*
 * This file handles the generic file mmap semantics used by
 * most "normal" filesystems (but you don't /have/ to use this:
 * the NFS filesystem used to do this differently, for example)
 */
#include <linux/config.h>
#include <linux/module.h>
#include <linux/slab.h>
#include <linux/compiler.h>
#include <linux/fs.h>
#include <linux/aio.h>
#include <linux/capability.h>
#include <linux/kernel_stat.h>
#include <linux/mm.h>
#include <linux/swap.h>
#include <linux/mman.h>
#include <linux/pagemap.h>
#include <linux/file.h>
#include <linux/uio.h>
#include <linux/hash.h>
#include <linux/writeback.h>
#include <linux/pagevec.h>
#include <linux/blkdev.h>
#include <linux/security.h>
#include <linux/syscalls.h>
#include "filemap.h"
/*
 * FIXME: remove all knowledge of the buffer layer from the core VM
 */
#include <linux/buffer_head.h> /* for generic_osync_inode */

#include <asm/uaccess.h>
#include <asm/mman.h>

static ssize_t
generic_file_direct_IO(int rw, struct kiocb *iocb, const struct iovec *iov,
        loff_t offset, unsigned long nr_segs);

/*
 * Shared mappings implemented 30.11.1994. It's not fully working yet,
 * though.
 *
 * Shared mappings now work. 15.8.1995  Bruno.
 *
 * finished 'unifying' the page and buffer cache and SMP-threaded the
 * page-cache, 21.05.1999, Ingo Molnar <mingo@redhat.com>
 *
 * SMP-threaded pagemap-LRU 1999, Andrea Arcangeli <andrea@suse.de>
 */

/*
 * 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)
 */

/*
 * Remove a page from the page cache and free it. Caller has to make
 * sure the page is locked and that nobody else uses it - or that usage
 * is safe.  The caller must hold a write_lock on the mapping's tree_lock.
 */
void __remove_from_page_cache(struct page *page)
{
        struct address_space *mapping = page->mapping;

.............

[point of this item on the handout: fine-grained locking leads to complexity]
```