Readers-Writers Problem

- **Multiple threads may access data**
  - *Readers* – will only observe, not modify data
  - *Writers* – will change the data
- **Goal: allow multiple readers or one single writer**
  - Thus, lock can be *shared* amongst concurrent readers
- **Can implement with other primitives (next slide)**
  - Keep integer `i` – # or readers or -1 if held by writer
  - Protect `i` with mutex
  - Sleep on condition variable when can't get lock

Implementing shared locks

```
struct sharedlk {
  int i;     /* # shared lockers, or -1 if exclusively locked */
  mutex_t m;
  cond_t c;
};

void AcquireExclusive (sharedlk *sl) {
  lock (sl->m);
  while (sl->i) { wait (sl->m, sl->c); }
  sl->i = -1;
  unlock (sl->m);
}

void AcquireShared (sharedlk *sl) {
  lock (sl->m);
  while (sl->i < 0) { wait (sl->m, sl->c); }
  sl->i++;
  unlock (sl->m);
}
```


shared locks (continued)

```
void ReleaseShared (sharedlk *sl) {
  lock (sl->m);
  if (!--sl->i) signal (sl->c);
  unlock (sl->m);
}

void ReleaseExclusive (sharedlk *sl) {
  lock (sl->m);
  sl->i = 0;
  broadcast (sl->c);
  unlock (sl->m);
}
```

- **Note: Must deal with starvation**

Review: Test-and-set spinlock

```
struct var {
  int lock;
  int val;
};

void atomic_inc (var *v) {
  while (test_and_set (&v->lock))
    ;
  v->val++;
  v->lock = 0;
}

void atomic_dec (var *v) {
  while (test_and_set (&v->lock))
    ;
  v->val--;
  v->lock = 0;
}
```


Review: Test-and-set on alpha

- `ldl_l` **– load locked**
  `stl_c` **– store but sets reg to 0 if not atomic w.** `ldl_l`

```
_test_and_set:
     ldq_l   v0, 0(a0)          # v0 = *lockp (LOCKED)
     bne     v0, 1f             # if (v0) return
     addq    zero, 1, v0        # v0 = 1
     stq_c   v0, 0(a0)          # *lockp = v0 (CONDITIONAL)
     beq     v0, _test_and_set  # if (failed) try again
     mb
     addq    zero, zero, v0     # return 0
1:
     ret     zero, (ra), 1
```

- **Note: Alpha memory consistency weaker than S.C.**
- ***Memory barrier* instruction,** `mb`**, is there to compensate**
  - Also need `mb` before releasing spinlock

Relaxed consistency model

- **Suppose no sequential consistency & don't compensate**
  - E.g., say we omit `mb` instruction on alpha?
- **Hardware could violate program order**

```
   PROGRAM ORDER                      VIEW ON OTHER CPU
read/write: v->lock = 1;              v->lock = 1;
      read: v->val;
     write: v->val = read_val + 1;
     write: v->lock = 0;              v->lock = 0;
                                      /* danger */
                                      v->val = read_val + 1;
```

- **If** `atomic_inc` **called where** `danger`**, bad** `val` **results**

Relaxed consistency (continued)

- **Use memory barriers to preserve program order of memory accesses with respect to locks**
- **`mb` in `test_and_set` preserves program order**
  - All ops before `mb` in program order appear before on *all CPUs*
  - All ops after `mb` in program order appear after on *all CPUs*
- **Many examples in this lecture assume S.C.**
  - Useful on non-S.C. hardware, but must add barriers
- **Dealing w. memory consistency important**
  - E.g., see [Howells] for how Linux deals
- **Fortunately need not overly complicate code**
  - If you do locking right, only need to add a few barriers
  - Code will be easily portable to new CPUs

Cache coherence

- **Performance requires caches**
- **Sequential consistency requires cache coherence**
- **Barrier & atomic ops require cache coherence**
- **Bus-based approaches**
  - "Snoopy" protocols, each CPU listens to memory bus
  - Use write through and invalidate when you see a write
  - Or have ownership scheme (e.g., Pentium MESI bits)
  - Bus-based schemes limit scalability
- **Cache-Only Memory Architecture (COMA)**
  - Each CPU has local RAM, treated as cache
  - Cache lines migrate around based on access
  - Data lives only in cache

cc-NUMA

- **Previous slide had *dance hall* architectures**
  - Any CPU can "dance with" any memory equally
- **An alternative: Non-Uniform Memory Access**
  - Each CPU has fast access to some "close" memory
  - Slower to access memory that is farther away
  - Use a directory to keep track of who is caching what
- **Originally for machines with many CPUs**
  - But AMD Opterons integrated mem. controller, essentially NUMA
  - Now intel CPUs are like this, too
- **cc-NUMA = cache-coherent NUMA**
  - Can also have non-cache-coherent NUMA, though uncommon
  - BBN Butterfly 1 has no cache at all
  - Cray T3D has local/global memory

NUMA and spinlocks

- **Test-and-set spinlock has several advantages**
  - Simple to implement and understand
  - One memory location for arbitrarily many CPUs
- **But also has disadvantages**
  - Lots of traffic over memory bus (especially when > 1 spinner)
  - Not necessarily fair (same CPU acquires lock many times)
  - Even less fair on a NUMA machine
  - Allegedly Google had fairness problems even on Opterons
- **Idea 1: Avoid spinlocks altogether**
- **Idea 2: Reduce bus traffic with better spinlocks**
  - Design lock that spins only on local memory
  - Also gives better fairness

Recall producer/consumer (lecture 3)

```
/* PRODUCER */
for (;;) {
  /* produce item, put
     in nextProduced */

  mutex_lock (&mutex);
  while (count == BUF_SIZE)
    cond_wait (&nonfull,
               &mutex);

  buffer [in] = nextProduced;
  in = (in + 1) % BUF_SIZE;
  count++;
  cond_signal (&nonempty);
  mutex_unlock (&mutex);
}
```

```
/* CONSUMER */
for (;;) {
  mutex_lock (&mutex);
  while (count == 0)
    cond_wait (&nonempty,
               &mutex);

  nextConsumed =  buffer[out];
  out = (out + 1) % BUF_SIZE;
  count--;
  cond_signal (&nonfull);
  mutex_unlock (&mutex);

  /* use item in
     nextConsumed */
}
```


Eliminating locks

- **One use of locks is to coordinate multiple updates of single piece of state**
- **How to remove locks here?**
  - Factor state so each variable only has a single writer
- **Producer/consumer example revisited**
  - Assume for example you have sequential consistency
  - Assume one producer, one consumer
  - Why do we need `count` variable, written by both?
    To detect buffer full/empty
  - Have producer write `in`, consumer write `out`
  - Use `in`/`out` to detect buffer state
  - But note next example busy-waits, which is less good

Lock-free producer/consumer

```
void producer (void *ignored) {
    for (;;) {
        /* produce an item and put in nextProduced */

        while (((in + 1) % BUF_SIZE) == out)
            ; // do nothing
        buffer [in] = nextProduced;
        in = (in + 1) % BUF_SIZE;
    }
}

void consumer (void *ignored) {
    for (;;) {
        while (in == out)
            ; // do nothing
        nextConsumed =  buffer[out];
        out = (out + 1) % BUF_SIZE;

        /*  consume the item in nextConsumed */
    }
}
```


Non-blocking synchronization

- **Design algorithm to *avoid critical sections***
  - Any threads can make progress if other threads are preempted
  - Which wouldn't be the case if preempted thread held a lock
- **Requires atomic instructions available on some CPUs**
- **E.g., atomic compare and swap:** `CAS (mem, old, new)`
  - If `*mem == old`, then set `*mem = new` and return true, else false
- **Can implement many common data structures**
  - Stacks, queues, even hash tables
- **Can implement any algorithm on right hardware**
  - Need operation such as atomic compare and swap (has property called *consensus number* $= \infty$ [Herlihy])
  - Seldom used because inefficient (lots of retries), but entire cache kernel written w/o locks using double CAS [Greenwald]

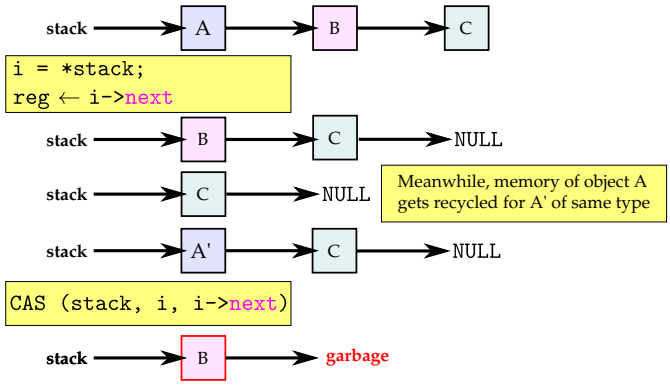
Example: stack

```
struct item {
  /* data */
  struct item *next;
};
typedef struct item *stack_t;

void atomic_push (stack_t *stack, item *i) {
  do {
    i->next = *stack;
  } while (!CAS (stack, i->next, i));
}

item *atomic_pop (stack_t stack) {
  item *i;
  do {
    i = *stack;
  } while (!CAS (stack, i, i->next));
  return i;
}
```


Wait-free stack issues



- **"ABA" race in pop if other thread pops, re-pushes i**
  - Can be solved by counters or hazard pointers to delay re-use

Benign races

- **Can also eliminate locks by having race conditions**
- **Sometimes "cheating" buys efficiency…**
- **Care more about speed than accuracy**

```
hits++;  // each time someone accesses web site
```

- **Know you can get away with race**

```
if (!initialized) {
  lock (m);
  if (!initialized) {
    initialize ();
    initialized = 1;
  }
  unlock (m);
}
```


Read-copy update [McKenney]

- **Some data is read way more often than written**
- **Routing tables**
  - Consulted for each packet that is forwarded
- **Data maps in system with 100+ disks**
  - Updated when disk fails, maybe every 10^{10} operations
- **Optimize for the common case of reading w/o lock**
  - E.g., global variable: `routing_table *rt;`
  - Call `lookup (rt, route);` with no locking
- **Update by making copy, swapping pointer**
  - E.g., `routing_table *nrt = copy_routing_table (rt);`
  - Update `nrt`
  - Set global `rt = nrt` when done updating
  - All `lookup` calls see consistent old or new table

Garbage collection

- **When can you free memory of old routing table?**
  - When you are guaranteed no one is using it—how to determine
- **Definitions:**
  - *temporary variable* – short-used (e.g., local) variable
  - *permanent variable* – long lived data (e.g., global `rt` pointer)
  - *quiescent state* – when all a thread's temporary variables dead
  - *quiescent period* – time during which every thread has been in quiescent state at least once
- **Free old copy of updated data after quiescent period**
  - How to determine when quiescent period has gone by?
  - E.g., keep count of syscalls/context switches on each CPU
  - Can't hold a pointer across context switch or user mode (Preemptable kernel complicates things slightly)

MCS lock

- **Idea 2: Build a better spinlock**
- **Lock designed by Mellor-Crummey and Scott**
  - Goal: reduce bus traffic on cc machines, improve fairness
- **Each CPU has a `qnode` structure in local memory**

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

  - Local can mean local memory in NUMA machine
  - Or just its own cache line that gets cached in exclusive mode
- **A lock is just a pointer to a `qnode`**

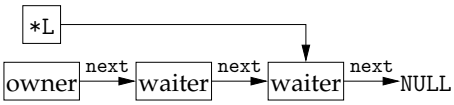
```
typedef qnode *lock;
```

- **Lock is list of CPUs holding or waiting for lock**
- **While waiting, spin on *your local* `locked` flag**

MCS Acquire

```
acquire (lock *L, qnode *I) {
  I->next = NULL;
  qnode *predecessor = I;
  XCHG (predecessor, *L); /* atomic swap */
  if (predecessor != NULL) {
    I->locked = true;
    predecessor->next = I;
    while (I->locked)
      ;
  }
}
```

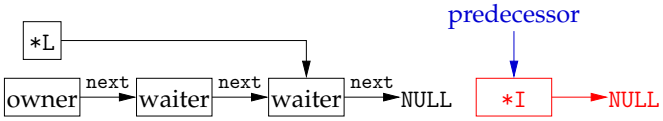
- **If unlocked, `L` is `NULL`**
- **If locked, no waiters, `L` is owner's `qnode`**
- **If waiters, `*L` is tail of waiter list:**



MCS Acquire

```
acquire (lock *L, qnode *I) {
  I->next = NULL;
  qnode *predecessor = I;
  XCHG (predecessor, *L); /* atomic swap */
  if (predecessor != NULL) {
    I->locked = true;
    predecessor->next = I;
    while (I->locked)
      ;
  }
}
```

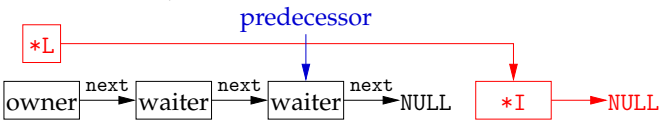
- **If unlocked, `L` is `NULL`**
- **If locked, no waiters, `L` is owner's `qnode`**
- **If waiters, `*L` is tail of waiter list:**



MCS Acquire

```
acquire (lock *L, qnode *I) {
  I->next = NULL;
  qnode *predecessor = I;
  XCHG (predecessor, *L); /* atomic swap */
  if (predecessor != NULL) {
    I->locked = true;
    predecessor->next = I;
    while (I->locked)
      ;
  }
}
```

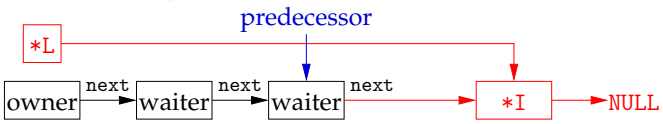
- **If unlocked, `L` is `NULL`**
- **If locked, no waiters, `L` is owner's `qnode`**
- **If waiters, `*L` is tail of waiter list:**



MCS Acquire

```
acquire (lock *L, qnode *I) {
  I->next = NULL;
  qnode *predecessor = I;
  XCHG (predecessor, *L); /* atomic swap */
  if (predecessor != NULL) {
    I->locked = true;
    predecessor->next = I;
    while (I->locked)
      ;
  }
}
```

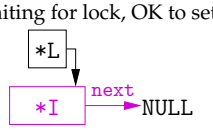
- **If unlocked, `L` is `NULL`**
- **If locked, no waiters, `L` is owner's `qnode`**
- **If waiters, `*L` is tail of waiter list:**



MCS Release w. CAS

```
release (lock *L, qnode *I) {
  if (!I->next)
    if (CAS (*L, I, NULL))
      return;
  while (!I->next)
    ;
  I->next->locked = false;
}
```

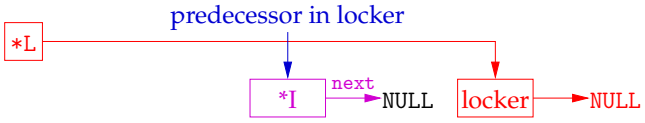
- **If `I->next` NULL and `*L == I`**
  - No one else is waiting for lock, OK to set `*L = NULL`



MCS Release w. CAS

```
release (lock *L, qnode *I) {
  if (!I->next)
    if (CAS (*L, I, NULL))
      return;
  while (!I->next)
    ;
  I->next->locked = false;
}
```

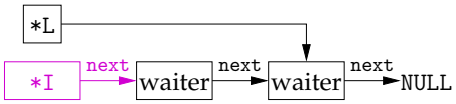
- **If `I->next` NULL and `*L != I`**
  - Another thread is in the middle of `acquire`
  - Just wait for `I->next` to be non-NULL



MCS Release w. CAS

```
release (lock *L, qnode *I) {
  if (!I->next)
    if (CAS (*L, I, NULL))
      return;
  while (!I->next)
    ;
  I->next->locked = false;
}
```

- **If `I->next` is non-NULL**
  - `I->next` oldest waiter, wake up w. `I->next->locked = false`



MCS Release w/o CAS

- **What to do if no atomic compare & swap?**
- **Be optimistic—read `*L` w. two `XCHG`s:**
  1. Atomically swap NULL into `*L`
     - If old value of `*L` was `I`, no waiters and we are done
  2. Atomically swap old `*L` value back into `*L`
     - If `*L` unchanged, same effect as `CAS`
- **Otherwise, we have to clean up the mess**
  - Some "userper" attempted to acquire lock between **1** and **2**
  - Because `*L` was `NULL`, the userper succeeded
    (May be followed by zero or more waiters)
  - Stick old list of waiters on to end of new last waiter

MCS Release w/o C&S code

```
release (lock *L, qnode *I) {
  if (I->next)
    I->next->locked = false;
  else {
    qnode *old_tail = NULL;
    XCHG (*L, old_tail);
    if (old_tail == I)
      return;

    qnode *userper = old_tail;
    XCHG (*L, userper);
    while (I->next == NULL)
      ;
    if (userper != NULL) {
      /* Someone changed *L between 2 XCHGs */
      userper->next = I->next;
    }
    else
      I->next->locked = false;
  }
}
```


Kernel support for synchronization

- **Locks must interact with scheduler**
  - For processes or kernel threads, must go into kernel (expensive)
  - Common case is you can acquire lock—how to optimize?
- **Idea: only go into kernel if you can't get lock**

```
struct lock {
  int busy;
  thread *waiters;
};
void acquire (lock *lk) {
  while (test_and_set (&lk->busy)) {    /* 1 */
    atomic_push (&lk->waiters, self);   /* 2 */
    sleep ();
 }
}
void release (lock *lk) {
  lk->busy = 0;
  wakeup (atomic_pop (&lk->waiters));
}
```

Race condition

- **Unfortunately, previous slide not safe**
  - What happens if release called between lines 1 and 2?
  - `wakeup` called on `NULL`, so `acquire` blocks
- ***futex* abstraction solves the problem [Franke]**
  - Ask kernel to sleep only if memory location hasn't changed
- `void futex (int *uaddr, FUTEX_WAIT, int val...);`
  - Go to sleep only if `*uaddr == val`
  - Extra arguments allow timeouts, etc.
- `void futex (int *uaddr, FUTEX_WAKE, int val...);`
  - Wake up at most `val` threads sleeping on `uaddr`
- `uaddr` **is translated down to offset in VM object**
  - So works on memory mapped file at different virtual addresses in different processes

Transactions

- **A *transaction* T is a collection of actions with**
  - *Atomicity* – all or none of actions happen
  - *Consistency* – T leaves data in valid state
  - *Isolation* – T's actions all appear to happen before or after every other transaction T'
  - *Durability** – T's effects will survive reboots
  - Often hear mnemonic *ACID* to refer to above
- **Transactions typically executed concurrently**
  - But *isolation* means must *appear* not to
  - Must roll-back transactions that use others' state
  - Means you have to record all changes to undo them
- **When deadlock detected just abort a transaction**
  - Breaks the dependency cycle