1 Cache coherence – the hardware view

2 Synchronization and memory consistency review

3 C11 Atomics

4 Avoiding locks
Important memory system properties

- Coherence – concerns accesses to a single memory location
  - Must obey program order if access from only one CPU
  - There is a total order on all updates
  - There is bounded latency before everyone sees a write

- Consistency – concerns ordering across memory locations
  - Even with coherence, different CPUs can see writes at different times
  - Sequential consistency is what matches our intuition (As if instructions from all CPUs interleaved on one CPU)
  - Many architectures offer weaker consistency
  - Yet well-defined weaker consistency can still be sufficient to implement [thread API contract from concurrency lecture](#)
Multicore Caches

- Performance requires caches
  - Divided into chunks of bytes called lines (e.g., 64 bytes)
  - Caches create an opportunity for cores to disagree about memory

- Bus-based approaches
  - “Snoopy” protocols, each CPU listens to memory bus
  - Use write through and invalidate when you see a write bits
  - Bus-based schemes limit scalability

- Modern CPUs use networks (e.g., hypertransport, QPI)
  - CPUs pass each other messages about cache lines
MESI coherence protocol

- **Modified**
  - One cache has a valid copy
  - That copy is dirty (needs to be written back to memory)
  - Must invalidate all copies in other caches before entering this state

- **Exclusive**
  - Same as Modified except the cache copy is clean

- **Shared**
  - One or more caches (and memory) have a valid copy

- **Invalid**
  - Doesn’t contain any data
Core and Bus Actions

- **Core**
  - Read
  - Write
  - Evict (modified? must write back)

- **Bus**
  - Read: without intent to modify, data can come from memory or another cache
  - Read-exclusive: with intent to modify, must invalidate all other cache copies
  - Writeback: contents put on bus and memory is updated
cc-NUMA

- Old machines used *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 esoteric machines with many CPUs
  - But AMD and then Intel integrated memory controller into CPU
  - Faster to access memory controlled by the local socket (or even die)

- cc-NUMA = cache-coherent NUMA
  - Rarely see non-cache-coherent NUMA (BBN Butterfly 1, Cray T3D)
Real World Coherence Costs

- See [David] for a great reference. Xeon results:
  - 3 cycle L1, 11 cycle L2, 44 cycle LLC, 355 cycle local RAM

- If another core in same socket holds line in modified state:
  - load: 109 cycles (LLC + 65)
  - store: 115 cycles (LLC + 71)
  - atomic CAS: 120 cycles (LLC + 76)

- If a core in a different socket holds line in modified state:
  - NUMA load: 289 cycles
  - NUMA store: 320 cycles
  - NUMA atomic CAS: 324 cycles

- But only a partial picture
  - Could be faster because of out-of-order execution
  - Could be slower because of interconnect contention or multiple hops
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 (today)

Idea 2: Reduce bus traffic with better spinlocks (Wednesday)
- Design lock that spins only on local memory
- Also gives better fairness
1. Cache coherence – the hardware view

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3. C11 Atomics

4. Avoiding locks
Amdahl’s law

\[ T(n) = T(1) \left( B + \frac{1}{n}(1 - B) \right) \]

- Expected speedup is limited when only part of a task is sped up
  - \( T(n) \): the time it takes \( n \) CPU cores to complete the task
  - \( B \): the fraction of the job that must be serial

- Even with massive multiprocessors, \( \lim_{n \to \infty} = B \cdot T(1) \)
  - Places an ultimate limit on parallel speedup

- Problem: synchronization increases serial section size
mutex_t m;

lock(&m);
start = cnt + 1; /* critical section */
unlock(&m);

- Only one thread can hold a mutex at a time
  - Makes critical section atomic
- Recall thread API contract
  - All access to global data must be protected by a mutex
  - Global = two or more threads touch data and at least one writes
- Means must map each piece of global data to one mutex
  - Never touch the data unless you locked that mutex
- But many ways to map data to mutexes
Locking granularity

- Consider a global hash table and two lookup implementations:

  ```c
  struct list *hash_tbl[1021];
  ```

  **coarse-grained locking**

  ```c
  mutex_t m;
  :
  mutex_lock(&m);
  struct list_elem *pos = list_begin (hash_tbl[hash(key)]);
  /* ... walk list and find entry ... */
  mutex_unlock(&m);
  ```

  **fine-grained locking**

  ```c
  mutex_t bucket[1021];
  :
  int index = hash(key);
  mutex_lock(&bucket[index]);
  struct list_elem *pos = list_begin (hash_tbl[index]);
  /* ... walk list and find entry ... */
  mutex_unlock(&bucket[index]);
  ```

- Which implementation is better?
Locking granularity (continued)

- Fine-grained locking admits more parallelism
  - E.g., imagine network server looking up values in hash table
  - Parallel requests will usually map to different hash buckets
  - So fine-grained locking should allow better speedup

- When might coarse-grained locking be better?
Locking granularity (continued)

- Fine-grained locking admits more parallelism
  - E.g., imagine network server looking up values in hash table
  - Parallel requests will usually map to different hash buckets
  - So fine-grained locking should allow better speedup

- When might coarse-grained locking be better?
  - Suppose you have data global that applies to whole hash table

```c
struct hash_table {
    size_t num_elements;    /* num items in hash table */
    size_t num_buckets;     /* size of buckets array */
    struct list *buckets;  /* array of buckets */
};
```

- Read `num_buckets` each time you insert
- Check `num_elements` each insert, possibly expand buckets & rehash
- Single global mutex would protect these fields

- Can you avoid serializing lookups to hash table?
Readers-writers problem

- Recall a mutex allows access in only one thread
- But a data race occurs only if
  - Multiple threads access the same data, and
  - At least one of the accesses is a write
- How to allow multiple readers or one single writer?
  - Need lock that can be shared amongst concurrent readers
- Can implement using other primitives (next slides)
  - 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

```c
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);
}
```
Implementing shared locks (continued)

```c
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);
}

• Any issues with this implementation?
```
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);
}

• Any issues with this implementation?
  - Prone to starvation of writer (no bounded waiting)
  - How might you fix?
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;
}

• Is this code correct without sequential consistency?
• Suppose no sequential consistency (& don’t compensate)

• Hardware could violate program order

Program order on CPU #1
v->lock = 1;
register = v->val;
v->val = register + 1;
v->lock = 0;

View on CPU #2
v->lock = 1;
v->lock = 0;
/* danger */;
v->val = register + 1;

• If atomic_inc called at /* danger */, bad val ensues!
void atomic_inc (var *v) {
    while (test_and_set (&v->lock))
        ;
    v->val++;
    /* danger */
    v->lock = 0;
}

• Must ensure all CPUs see the following:
  1. v->lock = 1 ran before v->val was read and written
  2. v->lock = 0 ran after v->val was written

• How does #1 get assured on x86?
  - Recall test_and_set uses xchgl %eax,(%edx)

• How to ensure #2 on x86?
void atomic_inc (var *v) {
    while (test_and_set (&v->lock))
    ;
    v->val++;
    /* danger */
    v->lock = 0;
}

• Must ensure all CPUs see the following:
  1. v->lock = 1 ran before v->val was read and written
  2. v->lock = 0 ran after v->val was written

• How does #1 get assured on x86?
  - Recall test_and_set uses xchgl %eax,(%edx)
  - xchgl instruction always “locked,” ensuring barrier

• How to ensure #2 on x86?
void atomic_inc (var *v) {
    while (test_and_set (&v->lock))
        ;
    v->val++;
    asm volatile ("sfence" ::: "memory");
    v->lock = 0;
}

• Must ensure all CPUs see the following:
  1. v->lock = 1 ran before v->val was read and written
  2. v->lock = 0 ran after v->val was written

• How does #1 get assured on x86?
  - Recall test_and_set uses xchgl %eax,%edx
  - xchgl instruction always “locked,” ensuring barrier

• How to ensure #2 on x86?
  - Might need fence instruction after, e.g., non-temporal stores
  - Definitely need compiler barrier
asm volatile (\textit{template-string} : \textit{outputs} : \textit{inputs} : \textit{clobbers});

- Tells compiler to put \textit{template-string} in assembly language output
  - Expands $\%0$, $\%1$, \ldots (a bit like printf conversion specifiers)
  - Use "%%" for a literal % (e.g., "%%cr3" to specify $\%cr3$ register)
- \textit{inputs}/\textit{outputs} specify parameters as "\textit{constraint}" (\textit{value}), e.g.:
  \begin{verbatim}
  int outvar, invar = 3;
  asm ("movl \%1, \%0" : "=r" (outvar) : "r" (invar));
  /* now outvar == 3 */
  \end{verbatim}
- \textit{clobbers} lists other state that get used/overwritten
  - Special value "\texttt{memory}" prevents reordering with loads & stores
  - Serves as \textit{compiler barrier}, as important as hardware barrier
- \textit{volatile} indicates side effects other than result
  - Otherwise, gcc might optimize away if you don’t use result
**Correct spinlock on alpha**

- Recall implementation of `test_and_set` on alpha (with much weaker memory consistency than x86):

  ```assembly
  _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
  ```

- **Memory barrier** instruction `mb` (like `mfence` but more important)
  - All processors will see that everything before `mb` in program order happened before everything after `mb` in program order

- Need barrier before releasing spinlock as well:

  ```c
  asm volatile ("mb" ::: "memory");
  v->lock = 0;
  ```
Memory barriers/fences

• Fortunately, consistency need not overly complicate code
  - If you do locking right, only need a few fences within locking code
  - Code will be easily portable to new CPUs

• Most programmers should stick to mutexes

• But advanced techniques may require lower-level code
  - Later this lecture will see some wait-free algorithms
  - Also important for optimizing special-case locks
    (E.g., linux kernel rw_semaphore, ...)

• Algorithms often explained assuming sequential consistency
  - Must know how to use memory fences to implement correctly
  - E.g., see [Howells] for how Linux deals with memory consistency

• Next: How C11 allows portable low-level code
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Atomics and portability

- Lots of variation in atomic instructions, consistency models, compiler behavior
  - Changing the compiler or optimization level can invalidate code
- Different CPUs today: Your laptop is x86, your cell phone is ARM
  - x86: Total Store Order Consistency Model, CISC
  - arm: Relaxed Consistency Model, RISC
- Could make it impossible to write portable kernels and applications
- Fortunately, the C11 standard has builtin support for atomics
  - Enable in GCC with the \texttt{--std=gnu11} flag (now the default)
- Also available in C++11, but won’t discuss today
• C guarantees coherence, but not consistency

• Within a thread, many evaluations are \textit{sequenced}
  - E.g., in “\texttt{f1(); f2();}”, evaluation of \texttt{f1} is sequenced before \texttt{f2}

• Across threads, some operations \textit{synchronize with} others
  - E.g., releasing mutex \texttt{m} synchronizes with a subsequent acquire of \texttt{m}

• Evaluation \textit{A happens before B}, which we’ll write \texttt{A \rightarrow B}, when:
  - \texttt{A} is sequenced before \texttt{B} (in the same thread),
  - \texttt{A} synchronizes with \texttt{B},
  - \texttt{A} is dependency-ordered before \texttt{B} (ignore for now), or
  - There is another operation \texttt{X} such that \texttt{A \rightarrow X \rightarrow B}.

\footnote{Except chain of \texttt{\rightarrow} cannot end: \ldots, dependency-ordered, sequenced before}
• C11 says behavior of a *data race* is undefined
  - A write conflicts with a read or write of same memory location
  - Two conflicting operations race if not ordered by happens before
  - Undefined can be anything (delete all your files, …)
• Spinlocks (& mutexes using spinlocks) synchronize across threads
  - Synchronization adds happens before arrows, avoiding data races
• Yet hardware supports other means of synchronization
• C11 atomics provide direct access to synchronized lower-level operations
  - E.g., can get compiler to issue `lock` prefix in some cases
C11 Atomics: Basics

- Include new `<stdatomic.h>` header
- New `_Atomic` type qualifier: e.g., `_Atomic int foo;
  - Convenient aliases: atomic_bool, atomic_int, atomic_ulong,...
  - Must initialize specially:
    ```c
    #include <stdatomic.h>
    Atomic_int global_int = ATOMIC_VAR_INIT(140);
    Atomic_int *dyn = malloc(sizeof(*dyn));
    atomic_init(dyn, 140);
    ```
- Compiler generates read-modify-write instructions for atomics
  - E.g., +=, -=, |=, &=, ^=, ++, -- do what you would hope
  - Act atomically and synchronize with each other
- Also functions including `atomic_fetch_add`, `atomic_compare_exchange_strong`,...
Locking and atomic flags

- Implementations might use spinlocks internally for most atomics
  - Could interact badly with interrupt/signal handlers
  - Can check if ATOMIC_INT_LOCK_FREE, etc., macros defined
  - Fortunately modern CPUs don’t require this

- `atomic_flag` is a special type guaranteed lock-free
  - Boolean value without support for loads and stores
  - Initialize with: `atomic_flag mylock = ATOMIC_FLAG_INIT;`
  - Only two kinds of operation possible:
    - `__Bool atomic_flag_test_and_set(volatile atomic_flag *obj);`
    - `void atomic_flag_clear(volatile atomic_flag *obj);`
  - Above functions guarantee sequential consistency (atomic operation serves as memory fence, too)
enum memory_order { /*...*/ };

_Bool atomic_flag_test_and_set_explicit(
    volatile atomic_flag *obj, memory_order order);
void atomic_flag_clear_explicit(
    volatile atomic_flag *obj, memory_order order);

C atomic_load_explicit(
    const volatile A *obj, memory_order order);
void atomic_store_explicit(
    volatile A *obj, C desired, memory_order order);

bool atomic_compare_exchange_weak_explicit(
    A *obj, C *expected, C desired,
    memory_order succ, memory_order fail);

- Atomic functions all have _explicit variants
- Lets you request weaker consistency than S.C.
  - …for which compiler may be able to generate faster code
Memory ordering

• Six possible `memory_order` values:
  1. `memory_order_relaxed`: no memory ordering
  2. `memory_order_consume`: super tricky, see [Preshing] for discussion
  3. `memory_order_acquire`: for start of critical section
  4. `memory_order_release`: for end of critical section
  5. `memory_order_acq_rel`: combines previous two
  6. `memory_order_seq_cst`: full sequential consistency

• Also have fence operation not tied to particular atomic:
  ```
  void atomic_thread_fence(memory_order order);
  ```

• Suppose thread 1 **releases** and thread 2 **acquires**
  - Thread 1’s preceding accesses can’t move past the `release` store
  - Thread 2’s subsequent accesses can’t move before the `acquire` load
  - Warning: other threads might see a completely different order
Types of memory fence

- Load-Load
- Load-Store
- Store-Load
- Store-Store

- Acquire fence
- Release fence
- Seq_cst fence
- Acq_rel fence

- $X$-$Y$ fence = operations of type $X$ sequenced before the fence happen before operations of type $Y$ sequenced after the fence

---

2 Credit to [Preshing](#) for explaining it this way
```
_Atomic(int) packet_count;

void recv_packet(...)
{
    :
    atomic_fetch_add_explicit(&packet_count, 1,
                             memory_order_relaxed);
    :
}
```

- Need to count packets accurately
- Don’t need to other memory accesses across threads
- Relaxed memory order can avoid unnecessary overhead
  - Depending on hardware, of course (not x86)
Example: Producer, consumer 1

```c
struct message msg_buf;
_Atomic(_Bool) msg_ready;

void send(struct message *m) {
    msg_buf = *m;
    atomic_thread_fence(memory_order_release);
    /* Prior loads+stores happen before subsequent stores */
    atomic_store_explicit(&msg_ready, 1,
                          memory_order_relaxed);
}

struct message *recv(void) {
    _Bool ready = atomic_load_explicit(&msg_ready,
                                        memory_order_relaxed);
    if (!ready)
        return NULL;
    atomic_thread_fence(memory_order_acquire);
    /* Prior loads happen before subsequent loads+stores */
    return &msg_buf;
}
```
struct message msg_buf;
_Atomic(_Bool) msg_ready;

void send(struct message *m) {
  msg_buf = *m;
  atomic_store_explicit(&msg_ready, 1,
       memory_order_release);
}

struct message *recv(void) {
  _Bool ready = atomic_load_explicit(&msg_ready,
       memory_order_acquire);
  if (!ready)
    return NULL;
  return &msg_buf;
}

- This is potentially faster than previous example
  - E.g., other stores after send can be moved before msg_buf
void spin_lock(atomic_flag *lock) {
    while (atomic_flag_test_and_set_explicit(lock, memory_order_acquire))
    {
    }
}

void spin_unlock(atomic_flag *lock) {
    atomic_flag_clear_explicit(lock, memory_order_release);
}
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/* PRODUCER */
for (;;) {
    item *nextProduced = produce_item ();

    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);
    consume_item (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 that each variable only has a single writer

- Producer/consumer example revisited
  - Assume you have sequential consistency (or need fences)
  - 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
void producer (void *ignored) {
    for (;;) {
        item *nextProduced = produce_item ();
        while ( ((in + 1) % BUF_SIZE) == out )
            thread_yield ();
        buffer [in] = nextProduced;
        atomic_thread_fence(memory_order_release);
        in = (in + 1) % BUF_SIZE;
    }
}

void consumer (void *ignored) {
    for (;;) {
        while ( in == out )
            thread_yield ();
        atomic_thread_fence(memory_order_acquire);
        nextConsumed = buffer[out];
        out = (out + 1) % BUF_SIZE;
        consume_item (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 that hardware provide the right kind of atomics
  - Simple test-and-set is insufficient
  - Atomic compare and swap is good: $\text{CAS}(\text{mem, old, new})$
    
    If $\*\text{mem} == \text{old}$, then swap $\*\text{mem} \leftrightarrow \text{new}$ 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])
  - Entire kernels have been written w/o locks [Greenwald]
Example: non-blocking stack

```c
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

```
i = *stack;
reg ← i->next
```

```
stack  A  B  C
stack  B  C  NULL
stack  C  NULL
stack  A' C  NULL
```

Meanwhile, memory of object A gets recycled for A' of same type

```
CAS (stack, i, i->next)
```

```
stack  B  garbage
```

- “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

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

- Know you can get away with race

```c
if (!initialized) {
    lock (m);
    if (!initialized) {
        initialize ();
        atomic_thread_fence (memory_order_release); /* why? */
        initialized = 1;
    }
    unlock (m);
}
```
Read-copy update [McKenney]

- Some data is read way more often than written
  - Routing tables consulted for each forwarded packet
  - Data maps in system with 100+ disks (updated on disk failure)

- Optimize for the common case of reading without lock
  - E.g., global variable: routing_table *rt;
  - Call lookup (rt, route); with no lock

- Update by making copy, swapping pointer
  
  ```c
  routing_table *newrt = copy_routing_table (rt);
  update_routing_table (newrt);
  atomic_thread_fence (memory_order_release);
  rt = newrt;
  ```
Is RCU really safe?

- Consider the use of global `rt` with no fences:
  
  ```
  lookup (rt, route);
  ```

- Could a CPU read new pointer then get old contents of `*rt`?

  Yes on alpha, No on all other existing architectures

  We are saved by dependency ordering in hardware
  - Instruction `B` depends on `A` if `B` uses result of `A`

  Non-alpha CPUs won’t re-order dependent instructions
  - If writer uses release fence, safe to load pointer then just use it

  This is the point of `memory_order_consume`
  - Should be equivalent to acquire barrier on alpha
  - But should compile to nothing (be free) on other machines

  Active area of discussion for C++ committee [WG21]
Is RCU really safe?

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  - Should be equivalent to acquire barrier on alpha
  - But should compile to nothing (be free) on other machines
  - Active area of discussion for C++ committee [WG21]
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)
• Building a better spinlock
• What interface should kernel provide for sleeping locks?
• Deadlock
• Scalable interface design