Synchronization I

COMS W4118
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References: Operating Systems Concepts (9e), Linux Kernel Development, previous W4118s

Banking example

```
int balance = 0;
int main()
{
        pthread_t t1, t2;
        pthread_create(&t1, NULL, deposit, (void*)1);
        pthread_create(&t2, NULL, withdraw, (void*)2);
        pthread_join(t1, NULL);
        pthread_join(t2, NULL);
        printf(“all done: balance = %d\n”, balance);
        return 0;
}
```

```
void* deposit(void *arg)
{
        int i;
        for(i=0; i<1e7; ++i)
                ++ balance;
}
```

```
void* withdraw(void *arg)
{
        int i;
        for(i=0; i<1e7; ++i)
                -- balance;
}
```

Results of the banking example

```
$ gcc –Wall –lpthread –o bank bank.c
$ bank
all done: balance = 0
$ bank
all done: balance = 140020
$ bank
all done: balance = -94304
$ bank
all done: balance = -191009
```

Why?

A closer look at the banking example

```
$ objdump –d bank
…
08048464 <deposit>:
…                                   // ++ balance
8048473:  a1 80 97 04 08          mov    0x8049780,%eax
8048478:  83 c0 01                add    $0x1,%eax
804847b:  a3 80 97 04 08          mov    %eax,0x8049780
…

0804849b <withdraw>:
…                                   // -- balance
80484aa:  a1 80 97 04 08          mov    0x8049780,%eax
80484af:  83 e8 01                sub    $0x1,%eax
80484b2: a3 80 97 04 08           mov    %eax,0x8049780
…
```

One possible schedule

CPU 0

CPU 1

time

balance: 0

mov 0x8049780,%eax

eax: 0

add $0x1,%eax

eax: 1

mov %eax,0x8049780

balance: 1

mov 0x8049780,%eax

eax: 1

sub $0x1,%eax

eax: 0

mov %eax,0x8049780

balance: 0

One deposit and one withdraw,
balance unchanged. Correct

Another possible schedule

CPU 0

CPU 1

balance: 0

mov 0x8049780,%eax

eax: 0

add $0x1,%eax

eax: 1

mov 0x8049780,%eax

eax: 0

mov %eax,0x8049780

time

balance: 1

sub $0x1,%eax

eax: -1

mov %eax,0x8049780

balance: -1

One deposit and one withdraw,
balance becomes less. Wrong!

Race condition

- Definition: a timing dependent error involving shared state

- Can be very bad
  - "non-deterministic:" don't know what the output will be, and it is likely to be different across runs
  - Hard to detect: too many possible schedules
  - Hard to debug: "heisenbug," debugging changes timing so hides bugs (vs "bohr bug")

How to avoid race conditions?

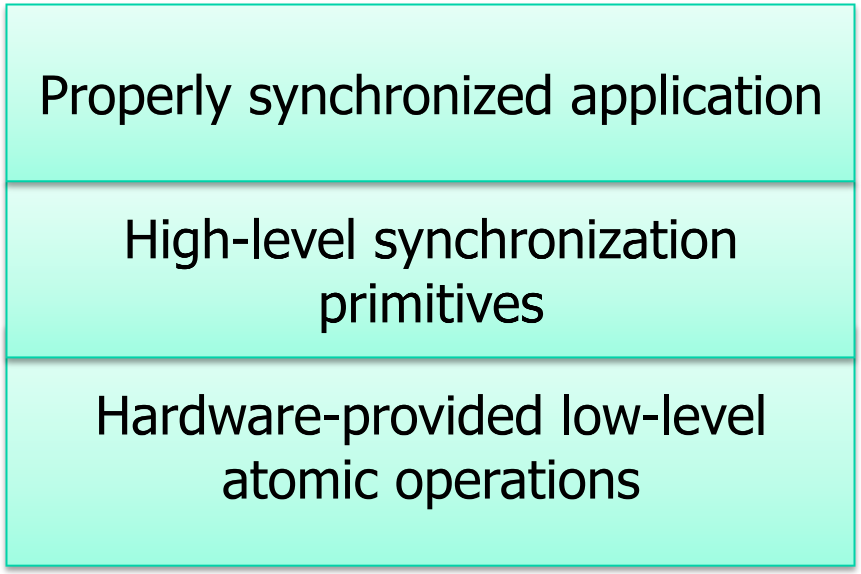
- Atomic operations: no other instructions can be interleaved, executed "as a unit" "all or none", guaranteed by hardware
- A possible solution: create a super instruction that does what we want atomically
  - inc 0x8049780
- Problem
  - Can't anticipate every possible way we want atomicity
  - Increases hardware complexity, slows down other instructions

```
// ++ balance
mov    0x8049780,%eax
add    $0x1,%eax
mov    %eax,0x8049780
...
```

```
// -- balance
mov    0x8049780,%eax
sub    $0x1,%eax
mov    %eax,0x8049780
...
```

Layered approach to synchronization

- Hardware provides simple low-level atomic operations, upon which we can build high-level, synchronization primitives, upon which we can implement critical sections and build correct multi-threaded/multi-process programs



Properly synchronized application

High-level synchronization primitives

Hardware-provided low-level atomic operations

Example synchronization primitives

- Low-level atomic operations
  - On uniprocessor, disable/enable interrupt
  - On x86, aligned load and store of words
  - Special instructions

- High-level synchronization primitives
  - Lock
  - Semaphore
  - Monitor

Outline

- Critical section requirements
- Implementing locks
- Readers-writer lock
- RCUs

Avoid race conditions

- Critical section: a segment of code that accesses a shared variable (or resource)

- No more than one thread in critical section at a time.

```
// ++ balance
mov    0x8049780,%eax
add    $0x1,%eax
mov    %eax,0x8049780
…
```

```
// -- balance
mov    0x8049780,%eax
sub    $0x1,%eax
mov    %eax,0x8049780
…
```

Critical section requirements

- Safety (aka mutual exclusion): no more than one thread in critical section at a time.
- Liveness (aka progress):
  - If multiple threads simultaneously request to enter critical section, must allow one to proceed
  - Must not depend on threads outside critical section
- Bounded waiting (aka starvation-free)
  - Must eventually allow waiting thread to proceed
- Makes no assumptions about the speed and number of CPU
  - However, assumes each thread makes progress

Critical section desirable properties

- Efficient: don’t consume too much resource while waiting
  - Don’t busy wait (spin wait) for a long time. Better to relinquish CPU and let other thread run

- Fair: don’t make one thread wait longer than others. Hard to do efficiently

- Simple: should be easy to use

Implementing critical section using locks

- lock(l): acquire lock exclusively; wait if not available
- unlock(l): release exclusive access to lock

```
pthread_mutex_t   l = PTHREAD_MUTEX_INITIALIZER
```

```
void* deposit(void *arg)
{
        int i;
        for(i=0; i<1e7; ++i) {
          pthread_mutex_lock(&l);
                ++ balance;
          pthread_mutex_unlock(&l);
        }
}
```

```
void* withdraw(void *arg)
{
        int i;
        for(i=0; i<1e7; ++i) {
                pthread_mutex_lock(&l);
                -- balance;
                pthread_mutex_unlock(&l);
        }
}
```

Outline

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Version 1: Disable interrupts

- Can cheat on uniprocessor: implement locks by disabling and enabling interrupts

```
lock()                                unlock()
{                                     {
        disable_interrupt();                  enable_interrupt();
}                                     }
```

- Good: simple!
- Bad:
  - Both operations are privileged, can't let user program use
  - Doesn't work on multiprocessors
  - Cant use for long critical sections

Version 2: Software Locks

- Peterson's algorithm: software-based lock implementation (2 page paper with proof)

- Good: doesn't require much from hardware
- Only assumptions:
  - Loads and stores are atomic
  - They execute in order
  - Does not require special hardware instructions

Reference: G. L. Peterson: "Myths About the Mutual Exclusion Problem", *Information Processing Letters* 12(3) 1981, 115–116

Software-based lock: 1st attempt

```
// 0: lock is available, 1: lock is held by a thread
int flag = 0;

lock()
{
        while (flag == 1)
      ; // spin wait
        flag = 1;
}
```

```
unlock()
{
        flag = 0;
}
```

- Idea: use one flag, test then set; if unavailable, spin-wait
- Problem?
  - Not safe: both threads can be in critical section
  - Not efficient: busy wait, particularly bad on uniprocessor (will solve this later)

Unsafe software lock, 1st attempt

```
lock()
{
        1: while (flag == 1)
      ; // spin wait
        2: flag = 1;
}
```

```
unlock()
{
        3: flag = 0;
}
```

flag=0;

Thread 0:	Thread 1:
call lock()	
1: while (flag ==1) // it is 0, so continue	
	call lock()
	1: while(flag == 1) // it is 0, so continue
2: flag = 1;	
	2: flag = 1; // ! Thread 0 is already in critical section

In general, adversarial scheduler model useful to think about concurrency problems

Software-based locks: 2nd attempt

```
// 1: a thread wants to enter critical section, 0: it doesn't
int flag[2] = {0, 0};
```

```
lock()
{
        flag[self] = 1; // I need lock
        while (flag[1- self] == 1)
      ; // spin wait
}
```

```
unlock()
{
        // not any more
        flag[self] = 0;
}
```

- Idea: use per thread flags, set then test, to achieve mutual exclusion
- Why doesn't work?
  - Not live: can deadlock

Deadlock: 2nd attempt

```
// 1: a thread wants to enter critical section, 0: it doesn't
int flag[2] = {0, 0};
lock()                                      unlock()
{                                           {
      flag[self] = 1; // I need lock              // not any more
      while (flag[1- self] == 1)                  flag[self] = 0;
    ; // spin wait                          }
}
```

```
      Thread 0                          Thread1
      call lock()
      flag[0] = 1;
                                   flag[1] = 1;
                                   while (flag[0] == 1) ;
                                   //spins forever!
                                   ...
      while (flag[1] == 1) ;
      // spins forever too!
```

Software-based locks: 3rd attempt

```
// whose turn is it?
int turn = 0;

lock()
{
        // wait for my turn
        while (turn == 1 – self)
      ; // spin wait
}
```

```
unlock()
{
        // I’m done. your turn
        turn = 1 – self;
}
```

- Idea: strict alternation to achieve mutual exclusion
- Why doesn’t work?
  - Not live: depends on threads outside critical section
  - Can’t handle repeated calls to lock by same thread

Software-based locks: final attempt (Peterson’s algorithm)

```
// whose turn is it?
int turn = 0;
// 1: a thread wants to enter critical section, 0: it doesn’t
int flag[2] = {0, 0};
```

```
lock()
{
       flag[self] = 1; // I need lock
       turn = 1 – self;
       // wait for my turn
       while (flag[1-self] == 1
     && turn == 1 – self)
     ;  // spin wait while the
             // other thread has intent
             // AND it is the other
             // thread’s turn
}
```

```
unlock()
{
       // not any more
       flag[self] = 0;
}
```

- Why works?
  - Safe?
  - Live?
  - Bounded wait?

Software-based lock

- Problem
  - It’s hard!
  - N>2 threads? (Lamport’s Bakery algorithm)
  - Modern out of order processors?

Multiprocessor Challenges

- Modern processors are out-of-order/speculative
  - Reorder instructions to keep execution units full
  - Try very hard to avoid inconsistency
  - Guarantees valid only within single execution stream
- Memory access guarantees on x86
  - x86 is relatively conservative with reordering
  - Loads not reordered with other loads
  - Stores not reordered with other stores
  - Stores not reordered with older loads
  - All loads and stores to same location are not reordered
  - Load can reorder with older store to different addr
- Breaks Peterson's algorithm!

Reference: http://www.linuxjournal.com/article/8211

http://www.intel.com/content/dam/www/public/us/en/documents/manuals/64-ia-32-architectures-software-developer-manual-325462.pdf

Instruction Reordering affects Locking

Thread 0

```
Lock: flag[0] = 1; // I need lock
  turn = 1;
  while (flag[1]==1 && turn==1)
}
```

Thread 1

```
Lock: flag[1] = 1; // I need lock
  turn = 0;
  while (flag[0]==1 && turn==0)
}
```

- Possible for mutual exclusion to be violated?
  - Yes!

```
Lock: r1 = Load(flag[1])

Reorder

  turn = 1;
  flag[0] = 1; // I need lock
  while (r1==1 && turn==1);
  // flag[1]==0
}
```

```
Lock: flag[1] = 1; // I need lock
  turn = 0;
  while (flag[0]==1 && turn==0);
  // flag[0]==0
}
```

Memory Barriers

- A memory barrier or fence
  - Ensures that all memory operations up to the barrier are executed before proceeding
- x86 provides several memory fence instructions
  - Relatively expensive (100s of cycles)
  - mfence: all prior memory accesses completed
  - lfence: all prior loads completed
  - sfence: all prior stores flushed

```
lock() {
        flag[self] = 1; // I need lock
        turn = 1 – self;
        sfence; // Store barrier
        while (flag[1-self] == 1 && turn == 1 – self);
}
```

Lamport’s Bakery Algorithm

- Support more than 2 processes
  - Integer tokens (increasing numbers)
  - Each customer gets next largest token
  - Same token? Smaller thread_id gets priority
  - Smallest token enters critical region

```
bool flag[1..NUM_THREADS] = {0};    // Want to enter
int token[1..NUM_THREADS] = {0};    // My token
lock(i) {   // Lock by thread i
   flag [i] = 1;
   token[i] = 1 + max(token[0..NUM_THREADS-1]);
   flag[i] = 0;
   for (j = 1; j <= NUM_THREADS; j++) {
      while (flag[j]); // Is j getting token?
      while ((token[j] && ((token[j], j) < (token[i], i))); // j has smaller token?
}
```

```
unlock(integer i) {
   token[i] = 0;
}
```

Reference: A New Solution of Dijkstra's Concurrent Programming Problem. L. Lamport. Communications of the ACM, 1974. http://research.microsoft.com/en-us/um/people/lamport/pubs/bakery.pdf

Version 3: Hardware Instructions

```
// 0: lock is available, 1: lock is held by a thread
int flag = 0;
lock()
{
        while(test_and_set(&flag))
            ;
}
```

```
unlock()
{
        flag = 0;
}
```

- Problem with the test-then-set approach: test and set are not atomic
- Fix: special atomic operation
  -
    ```
    int test_and_set (int *lock) {
      int old = *lock;
      *lock = 1;
      return old;
    }
    ```
  - Atomically returns *lock and sets *lock to 1

Implementing test_and_set on x86

```
long test_and_set(volatile long* lock)
{
        int old;
        asm("xchgl %0, %1"
            : "=r"(old), "+m"(*lock)  // output
            : "0"(1)                 // input
            : "memory“                // can clobber anything in memory
            );
        return old;
}
```

- xchg reg, addr: atomically swaps *addr and reg
- Spin locks on x86 are implemented using this instruction
- x86 also provides a lock prefix that allows bus to be locked for inst
- In Linux:
  - Arch independent: kernel/spinlock.c
  - Arch dependent: arch/x86/include/asm/spinlock.h

Spin-wait or block?

- Problem of spin-wait: waste CPU cycles
  - Worst case: thread holding a busy-wait lock gets preempted, other threads try to acquire the same lock

- On uniprocessor: should not use spin-lock
  - Yield CPU when lock not available (need OS support)

- On multi-processor
  - Thread holding lock gets preempted ➔ ???
  - Correct action depends on how long before lock release
    - Lock released "quickly" ➔ ?
    - Lock released "slowly" ➔ ?

Problem with simple yield

```
lock()
{
        while(test_and_set(&flag))
            yield();
}
```

- Problem:
  - Still a lot of context switches: thundering herd
  - Starvation possible

- Why? No control over who gets the lock next
- Need explicit control over who gets the lock

Version 4: Sleep Locks

```
lock() {
  while
(test_and_set(&flag)))
     add myself to wait queue
     yield
  …
}
```

```
unlock() {
    flag = 0
    if(any thread in wait queue)
       wake up one wait thread
  …
}
```

Lock from another thread?

- The idea: add thread to queue when lock unavailable; in unlock(), wake up one thread in queue

- Problem I: lost wakeup

- Problem II: wrong thread gets lock

Lost wakeup

```
lock() {
  1: while (test_and_set(&flag)))
      2: add myself to wait queue
      3: yield
  …
}
```

```
unlock() {
    4: flag = 0
    5: if(any thread in wait queue)
       6: wake up one wait thread
  …
}
```

```
Thread 0:                                  Thread 1
call lock()
while (test_and_set(&flag)) {
                                           call unlock()
                                           flag = 0
                                           if (any thread in wait queue) // No!
                                                wake_up_one_wait_thread
    add myself to wait queue
    yield
} // wait forever (or until next unlock)!
```

i

- Fix: use a spin_lock or lock w/ simple yield!
- Doesn't avoid spin-wait, but make wait time short

Wrong thread gets lock

```
lock() {
  1: while (test_and_set(&flag)))
      2: add myself to wait queue
      3: yield
  …
}
```

```
unlock() {
    4: flag = 0
    5: if(any thread in wait queue)
       6: wake up one wait thread
  …
}
```

```
Thread 0:                       Thread 1                     Thread 2
call lock()
while (test_set(&flag))
    add myself to wait queue
    yield                       call unlock()
                                    flag = 0
                                    if (thread in wait queue)
                                        wake_up_thread       call lock()
                                                                 while (test_set(&flag))
```

- Fix: unlock() directly transfers lock to waiting thread

Implementing locks: version 4, the code

```
typedef struct __mutex_t {
    int flag;       // 0: mutex is available,  1: mutex is not available
    int guard;      // guard lock to avoid losing wakeups
    queue_t *q;  // queue of waiting threads
} mutex_t;
```

```
void lock(mutex_t *m) {
    while (test_and_set(m->guard))
        ; //acquire guard lock by spinning
    if (m->flag == 0) {
        m->flag = 1; // acquire mutex
        m->guard = 0;
    } else {
        enqueue(m->q, self);
        m->guard = 0;
        yield();
    }
}
```

```
void unlock(mutex_t *m) {
   while (test_and_set(m->guard))
        ;
   if (queue_empty(m->q))
       // release mutex; no one wants mutex
        m->flag = 0;
   else
       // direct transfer mutex to next thread
        wakeup(dequeue(m->q));
   m->guard = 0;
}
```

Adaptive Mutexes

- Cons of Spinlocks
  - Inefficient if lock is held for long duration
  - Inefficient on uniprocessors
- Cons of Sleeplocks
  - Higher overhead, state maintenance
- Solaris, OS X, FreeBSD
  - Idea: use spinlock if holder is currently running, sleeplock otherwise
  - Best of both worlds

Outline

- Critical section requirements
- Implementing locks
- Readers-writer lock
- RCUs

Readers-Writers problem

- A reader is a thread that needs to look at the shared data but won't change it
- A writer is a thread that modifies the shared data
- Example: making an airline reservation
- Courtois et al 1971

Solving Readers-Writers w/ regular lock

```
lock_t lock;
```

Writer

```
    lock (&lock);
    . . .
    // write shared data
    . . .
    unlock (&lock);
```

Reader

```
    lock (&lock);
    . . .
    // read shared data
    . . .
    unlock (&lock);
```

- Problem: unnecessary synchronization
  - Only one writer can be active at a time
  - However, any number of readers can be active simultaneously!
- Solution: acquire lock for read mode and write mode

Readers-writer lock

```
rwlock_t lock;
```

Writer

```
write_lock (&lock);
. . .
// write shared data
. . .
write_unlock (&lock);
```

Reader

```
read_lock (&lock);
. . .
// read shared data
. . .
read_unlock (&lock);
```

- read_lock: acquires lock in read (shared) mode
  - Lock is not acquired or is acquired in read mode → success
  - Otherwise (lock is in write mode) → wait
- write_lock: acquires lock in write (exclusive) mode
  - Lock is not acquired → success
  - Otherwise → wait

Implementing readers-writer lock

```
struct rwlock_t {
    int nreader;       // init to 0
    lock_t guard;      //  init to unlocked
    lock_t lock;        // init to unlocked
};

write_lock(rwlock_t *l)
{
    lock(&l->lock);
}

write_unlock(rwlock_t *l)
{
    unlock(&l->lock);
}
```

Problem: may starve writer!

```
read_lock(rwlock_t *l)
{
    lock(&l->guard);
    ++ nreader;
    if(nreader == 1) // first reader
        lock(&l->lock);
    unlock(&l->guard);
}

read_unlock(rwlock_t *l)
{
    lock(&l->guard);
    -- nreader;
    if(nreader == 0) // last reader
       unlock(&l->lock);
    unlock(&l->guard);
}
```

Driving out readers in a RW-Lock

```
struct rwlock_t {
    int nreader;       // init to 0
    lock_t guard;      //  init to unlocked
    lock_t lock;       // init to unlocked
    lock_t writer;     // init to unlocked
};

write_lock(rwlock_t *l)
{
     lock(&l->writer);
     lock(&l->lock);
     unlock(&l->writer);
}

write_unlock(rwlock_t *l)
{
    unlock(&l->lock);
}
```

```
read_lock(rwlock_t *l)
{
    lock(&l->writer);
    lock(&l->guard);
    ++ nreader;
    if(nreader == 1) // first reader
        lock(&l->lock);
    unlock(&l->guard);
    unlock(&l->writer);
}

read_unlock(rwlock_t *l)
{
    lock(&l->guard);
    -- nreader;
    if(nreader == 0) // last reader
       unlock(&l->lock);
    unlock(&l->guard);
}
```

Q: In write_lock, can we just use guard instead of writer lock?

Outline

- Critical section requirements
- Implementing locks
- Readers-writer lock
- RCUs

Drawbacks of Locks

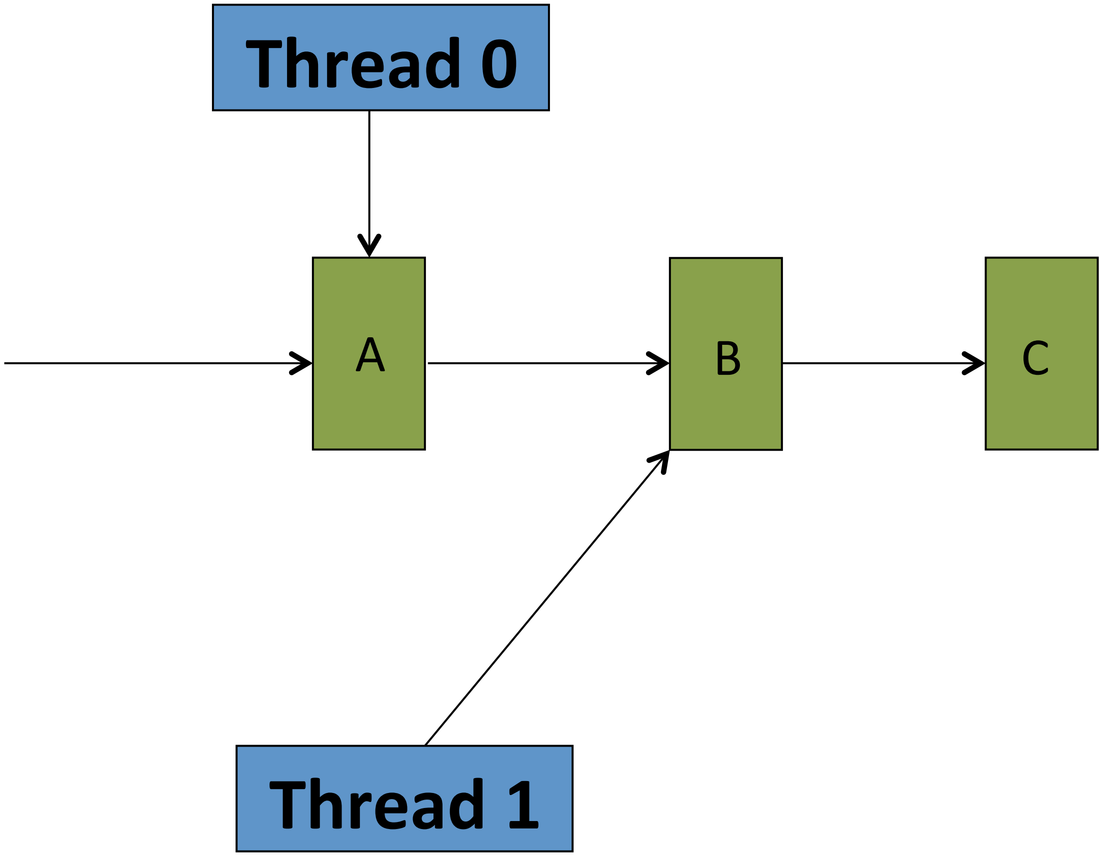
- Reader-writers lock is faster than plain lock
- But acquiring read lock is still expensive
  - Can still lead to blocking
  - If update time is long, all readers must wait
  - Can't do when time critical operations involved
  - Poor scalability – serializes concurrent access
- Can lead to deadlocks
  - Bug in single reader breaks other code
  - Hard to get right
- Lock free data structures
  - Basic Idea: use versions instead of locks
  - Borrowed from database community
  - Eliminate locking altogether

RCU (Read-Copy Update)

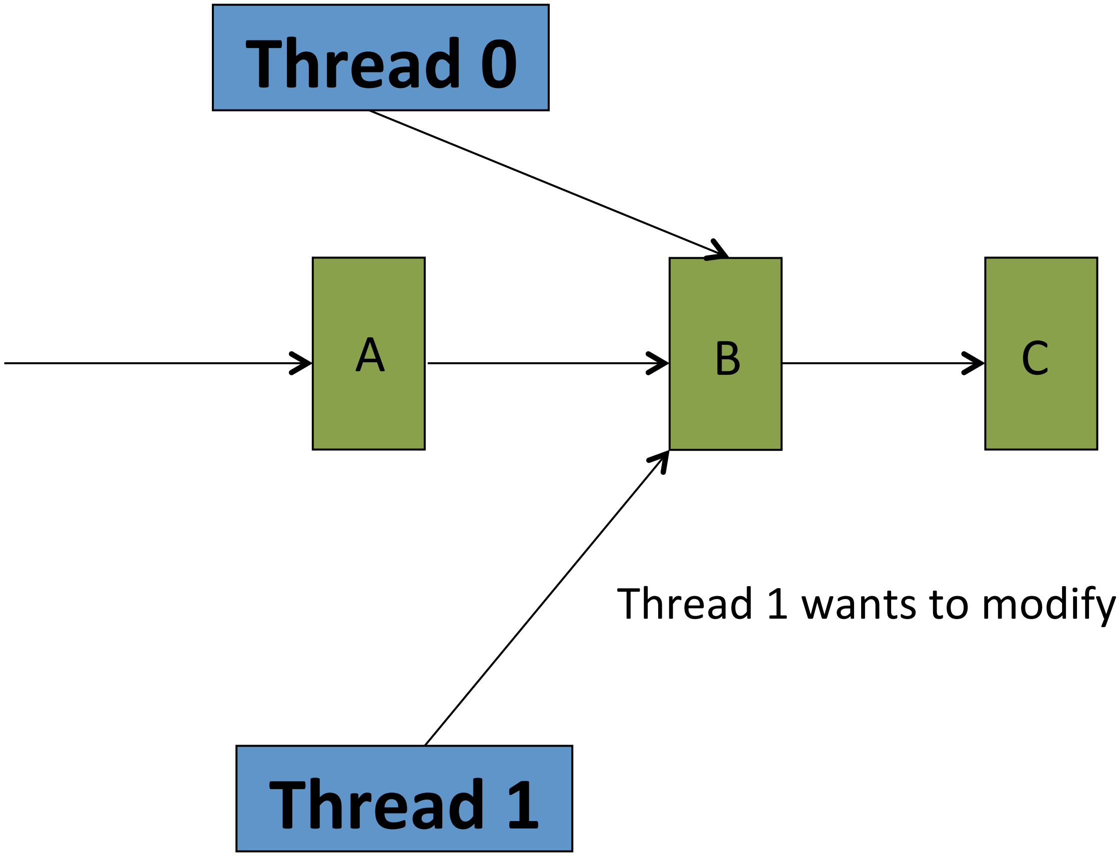
- Useful for read-mostly data structures
- Replace locking in time vs. locking in space
  - Writer creates a new version of data structure offline
  - Swaps in the new version atomically
  - Existing readers continue with older version
  - New readers use newer version
  - Old version garbage collected
  - Used in UNIX filesystem
- No locks, no deadlocks
  - Readers read block-free
  - Writers can update without blocking
  - Need to wait to garbage collect

Reference: http://www.rdrop.com/users/paulmck/paper/rclockpdcsproof.pdf

How RCUs Work

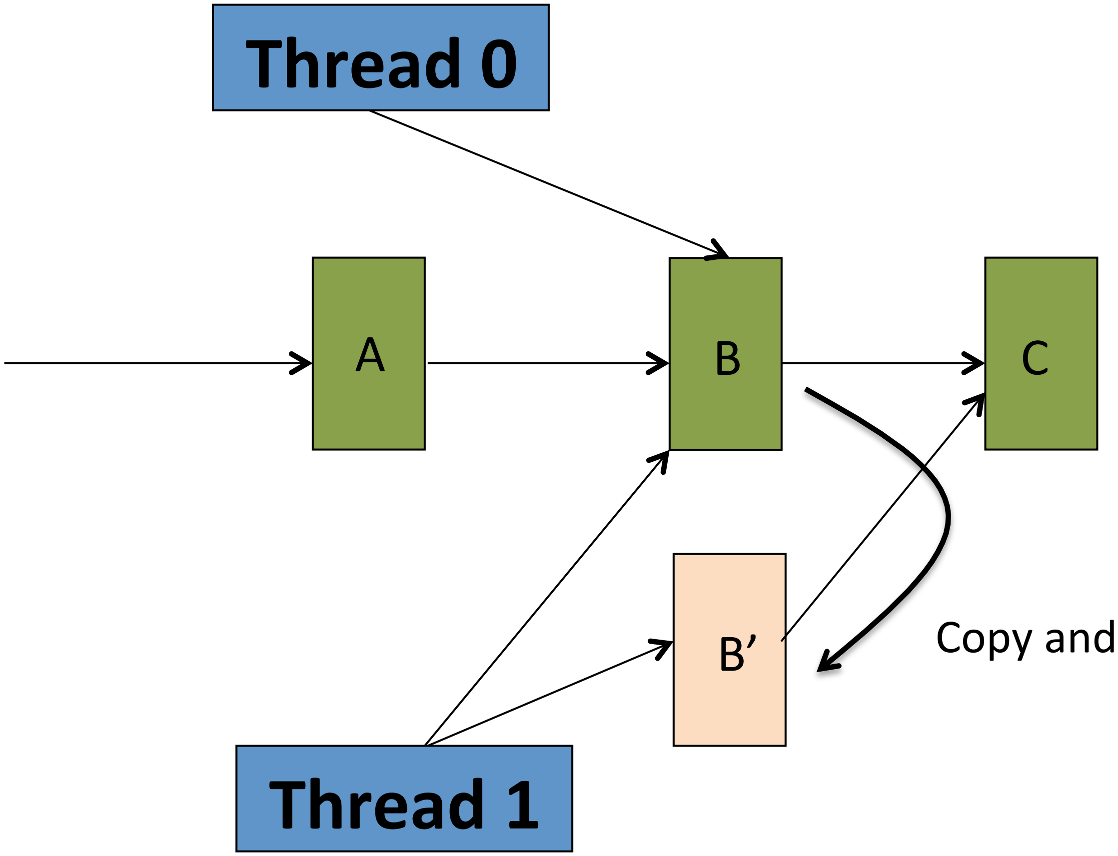


How RCUs Work



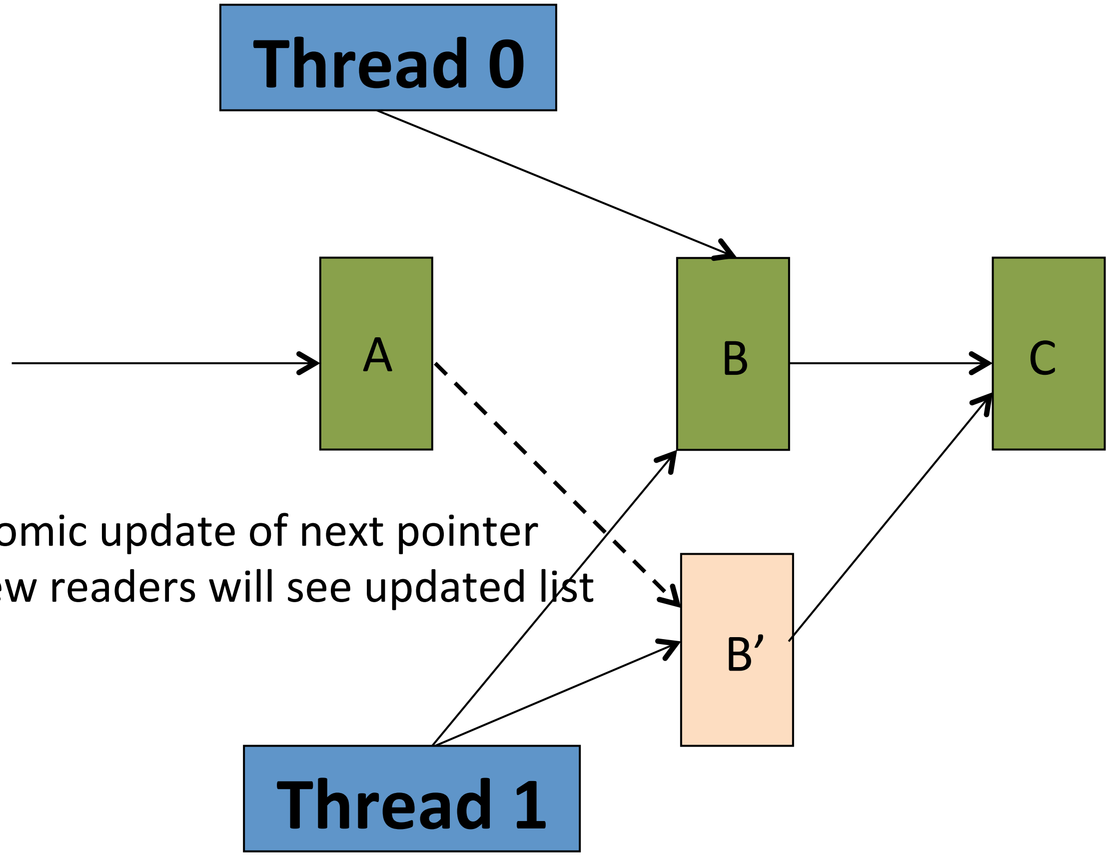
Thread 1 wants to modify B

How RCUs Work



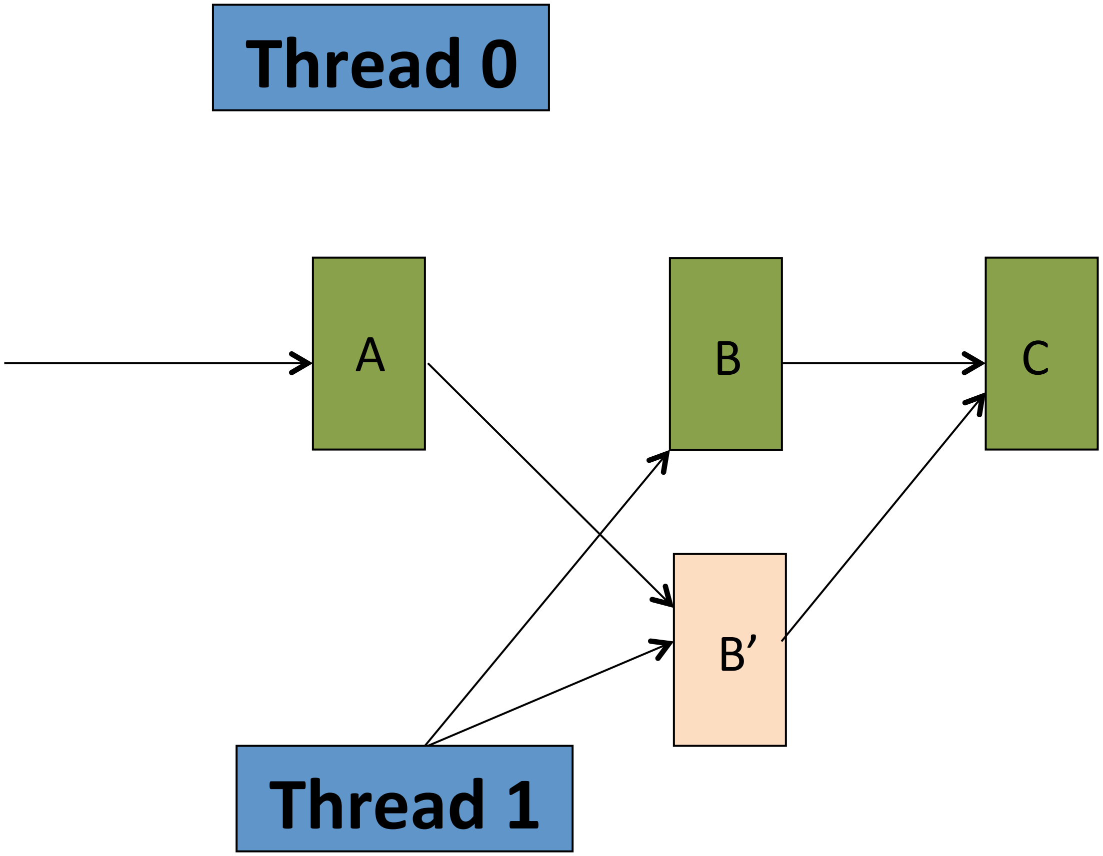
Copy and update the copy

How RCUs Work



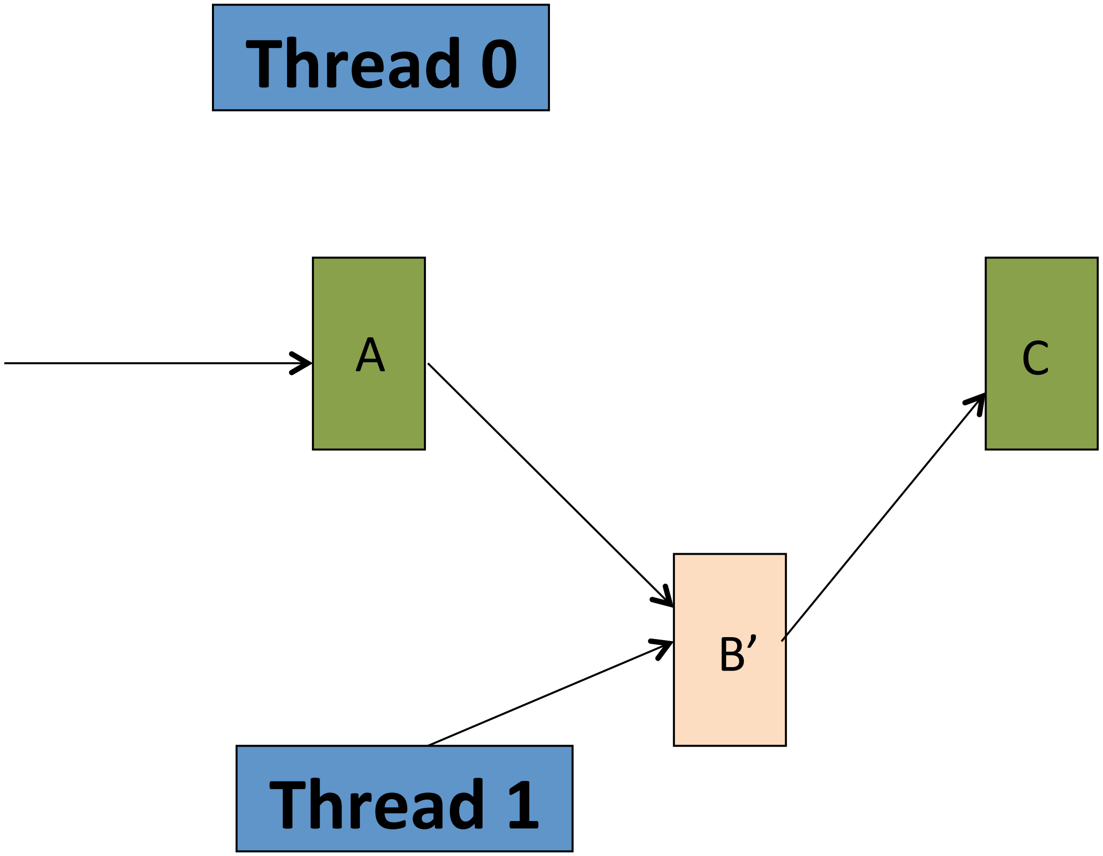
Atomic update of next pointer
New readers will see updated list

How RCUs Work



- Thread 0 looses reference to B. Can GC.

How RCUs Work



How/When to Garbage Collect?

- Need to know when no outstanding references to a data structure (quiescence state)
  - Updater can wait for quiescence or register callback
- On non-preemptive kernels, can do cheaply
  - Impose spinlock semantics, no sleeping while holding RCU pointers
  - Then, a context switch ensures quiescence!
  - Zero overhead for readers, GC forces context switch
- On preemptive kernels
  - Need some form of reference counting
  - Global reference counting using a lock like API
  - lock, unlock increments/decrements global RCU ref counter
  - When reference count is 1, can garbage collect

RCU Pros and Cons

- Pros
  - Readers never block
  - Updates never block
  - Extremely scalable for large number of cores
  - No deadlocks
- Cons
  - Still need to synchronize multiple concurrent writers
  - Need to maintain multiple versions – can get complex
  - Not a universal mechanism
  - Better to wrap in higher level API (e.g., list API, tree API)
- Widely used in Linux kernel
  - From 35 uses in 2002 to > 10000 in 2012
  - http://www.rdrop.com/users/paulmck/RCU/linuxusage/rculocktab.html

Linux RCU API

- Low Level
  - Readers: rcu_read_lock(), rcu_read_unlock()
  - Atomic update: rcu_dereference(), rcu_assign_pointer()
  - Wait for garbage collection:
    - synchronize_rcu(): wait for all readers to finish
    - call_rcu(f, d): call f(d) when all readers finish
- RCU Lists (works on Linux list_head lists)
  - Traversal: list_for_each_entry_rcu()
  - Update: list_add_rcu(), list_del_rcu(), list_replace_rcu()
- RCU red-black trees

RCU Reading Materials

- A nice tutorial on RCUs is found here:
  - Part 1: http://lwn.net/Articles/262464/
  - Part 2: http://lwn.net/Articles/263130/
  - Part 3: http://lwn.net/Articles/264090/
- Linux documentation in: documentation/RCU in kernel source tree
- Exhaustive description can be found in: Exploiting Deferred Destruction: *An Analysis of Read-Copy-Update Techniques in Operating System Kernels.* Paul McKenney. Ph.D. dissertation, Oregon State U., 2007. http://www.rdrop.com/users/paulmck/RCU/RCUdissertation.2004.07.14e1.pdf