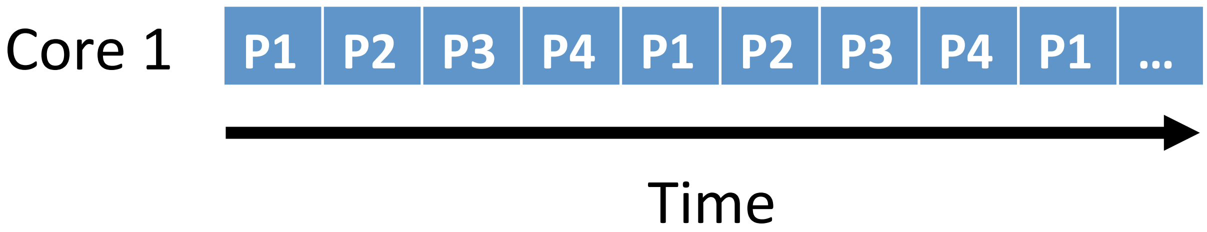
CS 5600
Computer Systems

Lecture 5: Synchronization, Deadlock

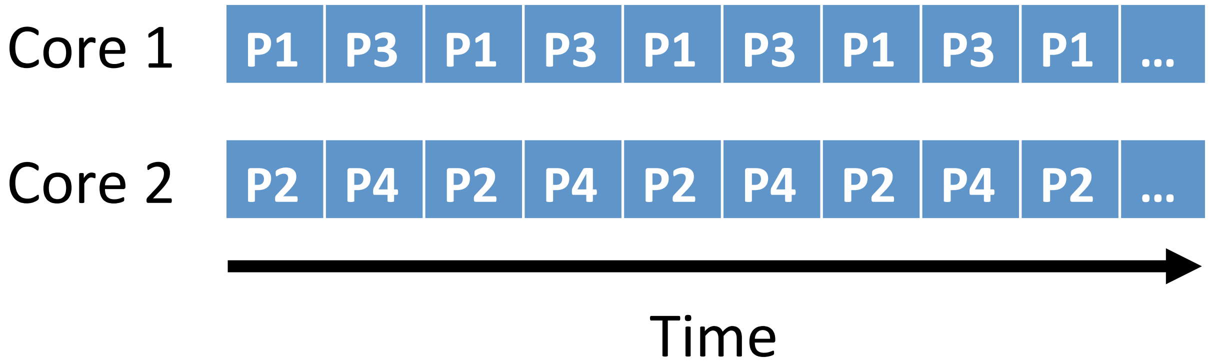
- Motivating Parallelism
- Synchronization Basics
- Types of Locks and Deadlock

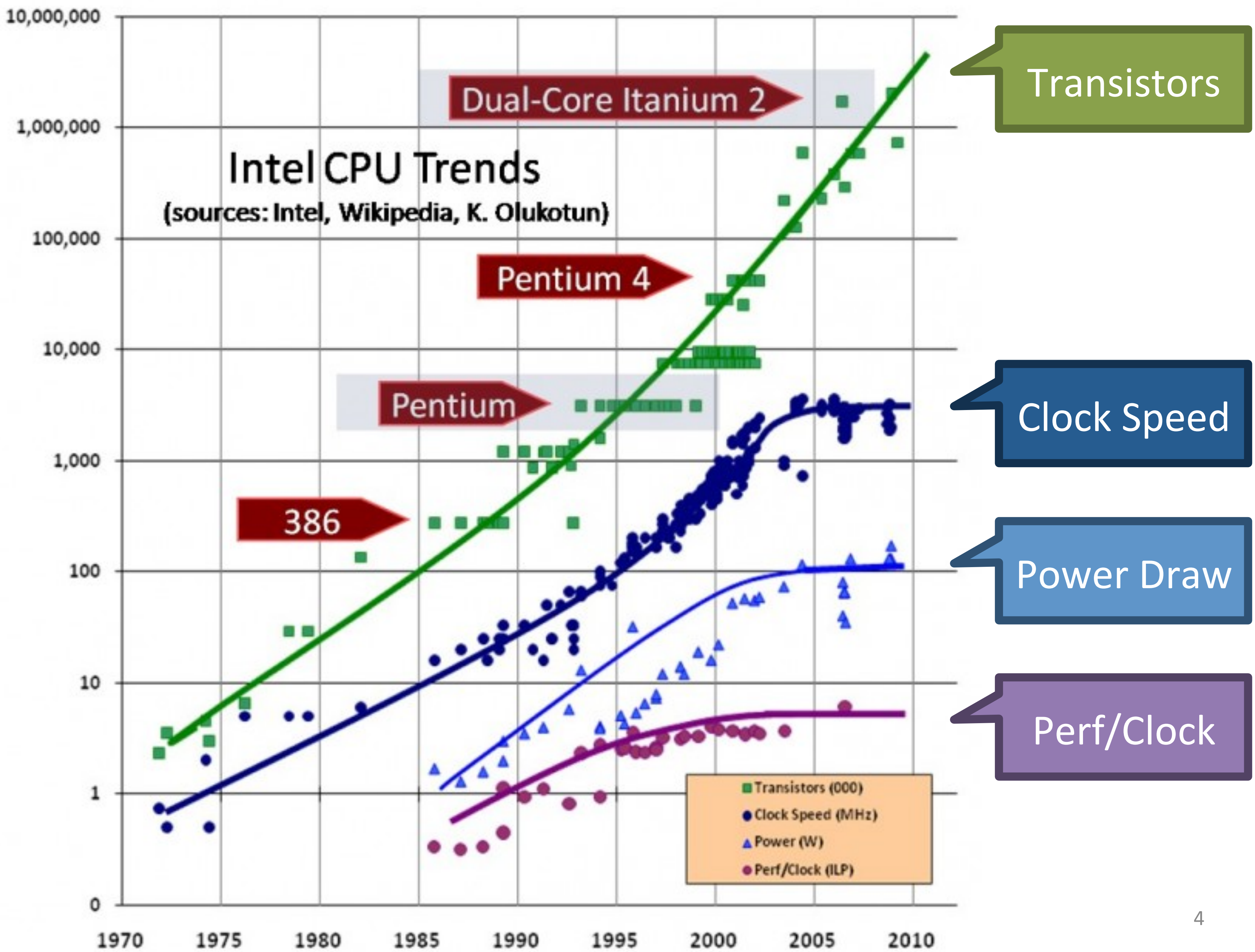
Concurrency vs. Parallelism

- Concurrent execution on a single-core system:



- Parallel execution on a dual-core system:




Intel CPU Trends
(sources: Intel, Wikipedia, K. Olukotun)
Dual-Core Itanium 2
Pentium 4
Pentium
386
10,000,000
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1970
1975
1980
1985
1990
1995
2000
2005
2010
Transistors (000)
Clock Speed (MHz)
Power (W)
Perf/Clock (ILP)
Transistors
Clock Speed
Power Draw
Perf/Clock

Implications of CPU Evolution

- Increasing transistor count/clock speed
  - Greater number of tasks can be executed concurrently
- However, clock speed increases have essentially stopped in the past few years
  - Instead, more transistors = more CPU cores
  - More cores = increased opportunity for parallelism

Two Types of Parallelism

- Data parallelism
  - **Same task** executes on many cores
  - **Different data** given to each task
  - Example: MapReduce
- Task parallelism
  - **Different tasks** execute on each core
  - Example: any high-end videogame
    - 1 thread handles game AI
    - 1 thread handles physics
    - 1 thread handles sound effects
    - 1+ threads handle rendering

Amdahl's Law

- Upper bound on performance gains from parallelism
  - If I take a single-threaded task and parallelize it over *N* CPUs, how much more quickly will my task complete?
- Definition:
  - *S* is the fraction of processing time that is serial (sequential)
  - *N* is the number of CPU cores

$$\text{Speedup} \leq 1/S+(1-S)/N$$

Example of Amdahl's Law

- Suppose we have an application that is 75% parallel and 25% serial
  - 1 core: 1/(.25+(1-.25)/1) = 1 (no speedup, obviously)
  - 2 core: 1/(.25+(1-.25)/2) = 1.6
  - 4 core: 1/(.25+(1-.25)/4) = 2.29
- What happens as N→∞?
  - Speedup ≤ $1/S+(1-S)/N$
  - Speedup approaches 1/S
  - *The serial portion of the process has a disproportionate effect on performance improvement*

Limits of Parallelism

- Amdahl's Law is a simplification of reality
  - Assumes code can be cleanly divided into serial and parallel portions
  - In other words, trivial parallelism
- Real-world code is typically more complex
  - Multiple threads depend on the same data
  - In these cases, parallelism may introduce errors
- Real-world speedups are typically < what is predicted by Amdahl's Law

- Motivating Parallelism
- Synchronization Basics
- Types of Locks and Deadlock

The Bank of Lost Funds

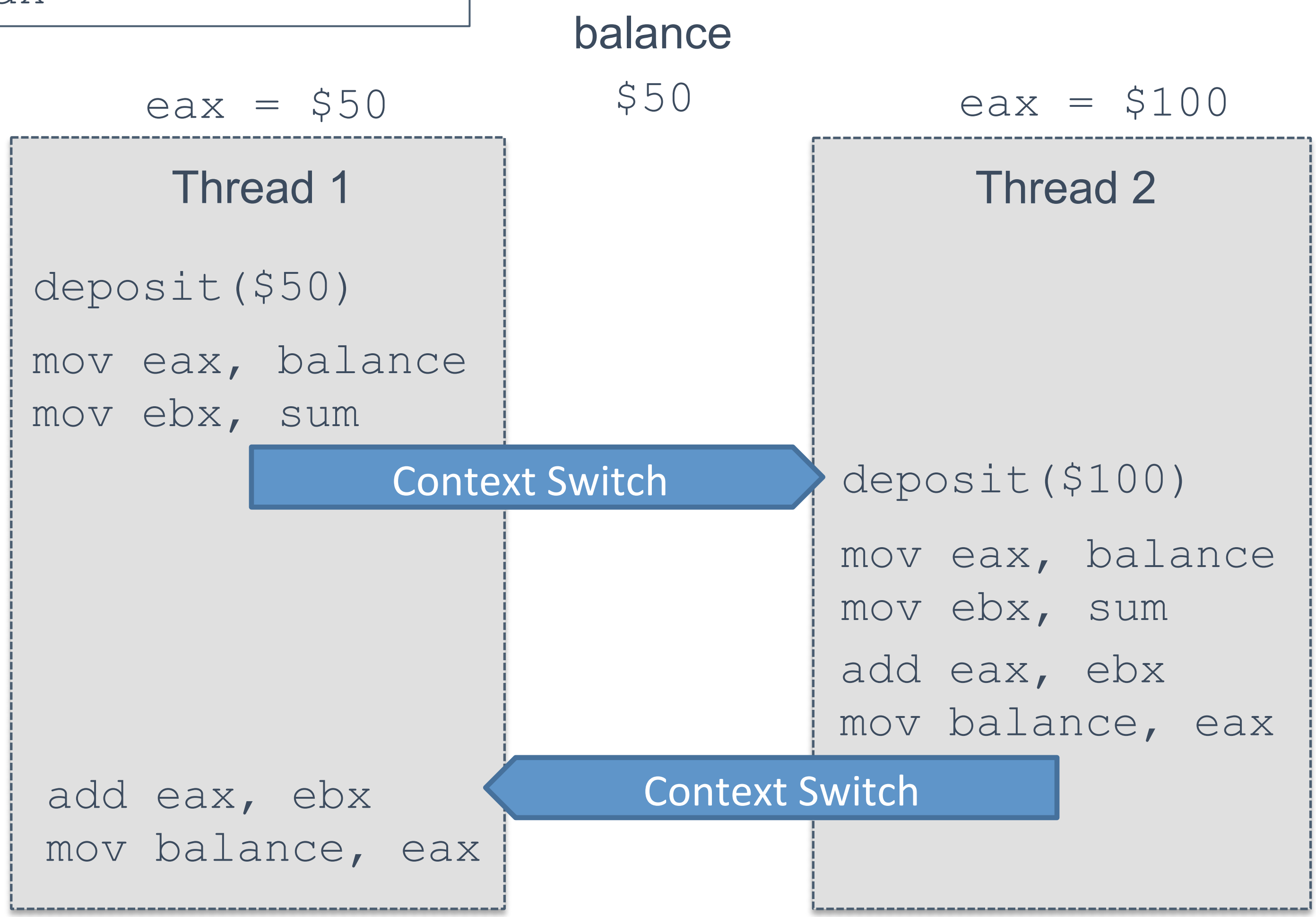
- Consider a simple banking application
  - Multi-threaded, centralized architecture
  - All deposits and withdrawals sent to the central server

```
class account {
    private money_t balance;
    public deposit(money_t sum) {
     balance = balance + sum;
    }
}
```

- What happens if two people try to deposit money into the same account at the same time?

```
balance = balance + sum;

mov eax, balance
mov ebx, sum
add eax, ebx
mov balance, eax
```



Race Conditions

- The previous example shows a race condition
  - Two threads “race” to execute code and update shared (dependent) data
  - Errors emerge based on the ordering of operations, and the scheduling of threads
  - Thus, errors are nondeterministic

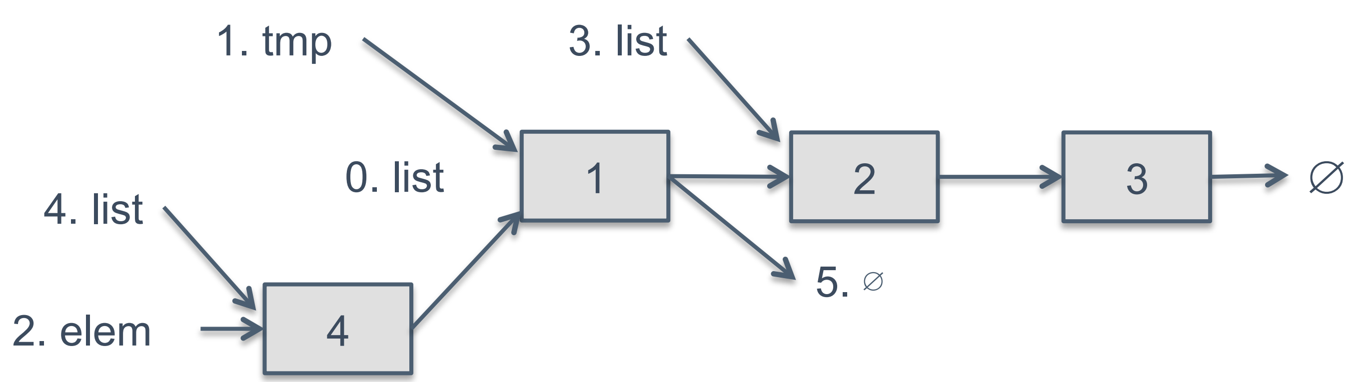
Example: Linked List

```
elem = pop(&list):
        tmp = list
        list = list->next
        tmp->next = NULL
        return tmp
```

```
push(&list, elem):
    elem->next = list
    list = elem
```

- What happens if one thread calls pop(), and another calls push() at the same time?

Thread 1	Thread 2
`1. tmp = list`	
	`2. elem->next = list`
`3. list = list->next`	
	`4. list = elem`
`5. tmp->next = NULL`	



Critical Sections

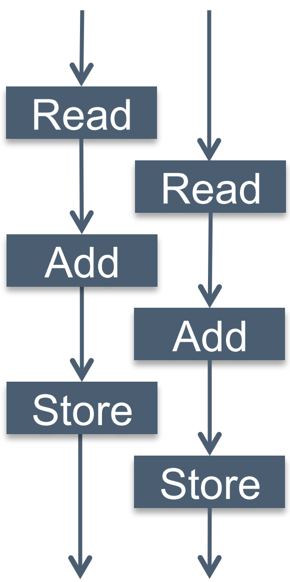
- These examples highlight the critical section problem
- Classical definition of a critical section:

"A piece of code that accesses a shared resource that must not be concurrently accessed by more than one thread of execution."

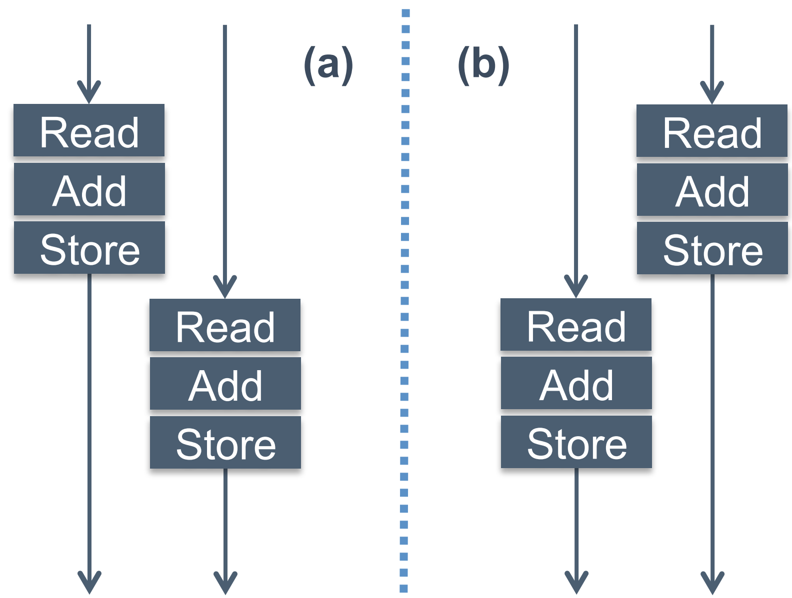
- Two problems
  - Code was not designed for concurrency
  - Shared resource (data) does not support concurrent access

Atomicity

- Race conditions lead to errors when sections of code are interleaved
- These errors can be prevented by ensuring code executes atomically



Interleaved Execution

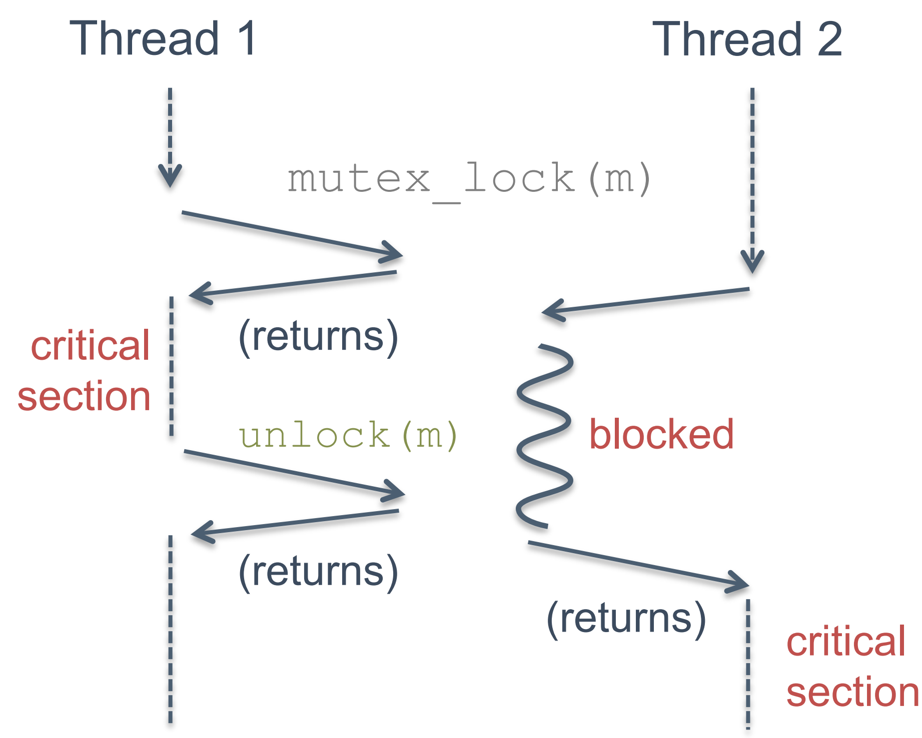


Non-Interleaved (Atomic) Execution

Mutexes for Atomicity

- Mutual exclusion lock (mutex) is a construct that can enforce atomicity in code

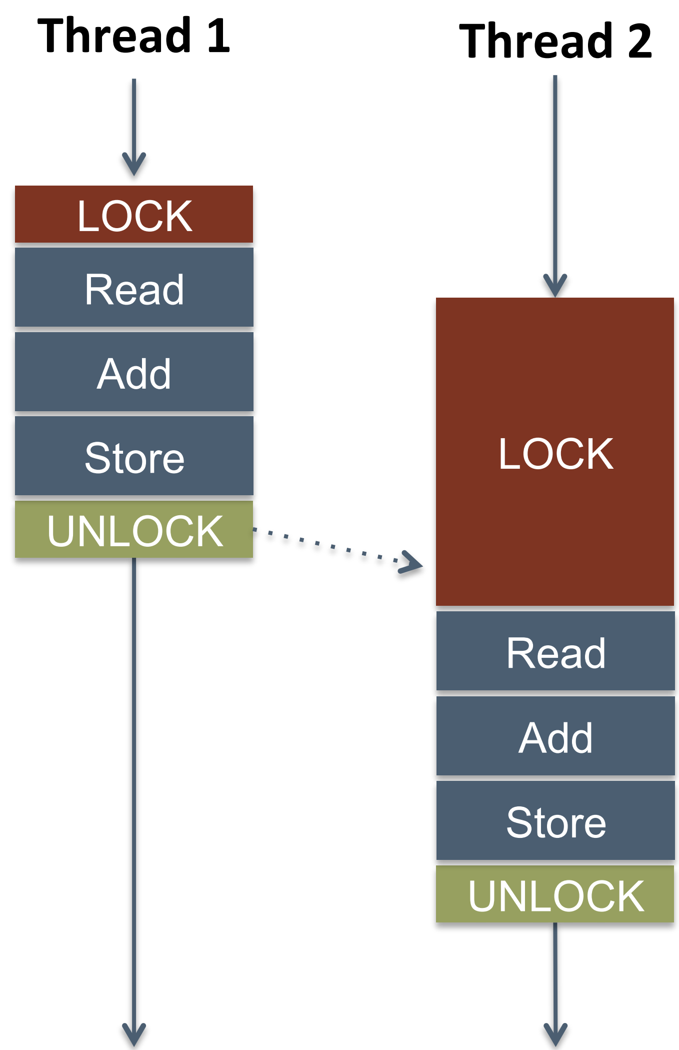
```
m = mutex_create();
…
mutex_lock(m);
// do some stuff
mutex_unlock(m);
```



Fixing the Bank Example

```
class account {
    mutex   m;
    money_t balance

    public deposit(money_t sum) {
        m.lock();
        balance = balance + sum;
        m.unlock();
    }
}
```



Implementing Mutual Exclusion

- Typically, developers don't write their own locking-primitives
  - You use an API from the OS or a library
- Why don't people write their own locks?
  - Much more complicated than they at-first appear
  - Very, very difficult to get correct
  - May require access to privileged instructions
  - May require specific assembly instructions
    - Instruction architecture dependent

Mutex on a Single-CPU System

```
void lock_acquire(struct lock * lock) {
    sema_down(&lock->semaphore);
    lock->holder = thread_current();
}
```

```
void sema_down(struct semaphore * sema) {
    enum intr_level old_level;
    old_level = intr_disable();
    while (sema->value == 0) { /* wait */ }
    sema->value--;
    intr_level(old_level);
}
```

- On a single-CPU system, the only preemption mechanism is interrupts
  - If interrupts are disabled, the currently executing code is guaranteed to be atomic
- This system is *concurrent*, but not *parallel*

The Problem With Multiple CPUs

- In a multi-CPU (SMP) system, two or more threads may execute in *parallel*
  - Data can be read or written by parallel threads, even if interrupts are disabled

sema->value = 1

CPU 1 - Thread 1

```
sema_down() {
    while (sema->value == 0) { … }
    sema->value--;
}
```

CPU 2 - Thread 2

```
sema_down() {
    while (sema->value == 0) { … }
    sema->value--;
}
```

sema->value = ?

Instruction-level Atomicity

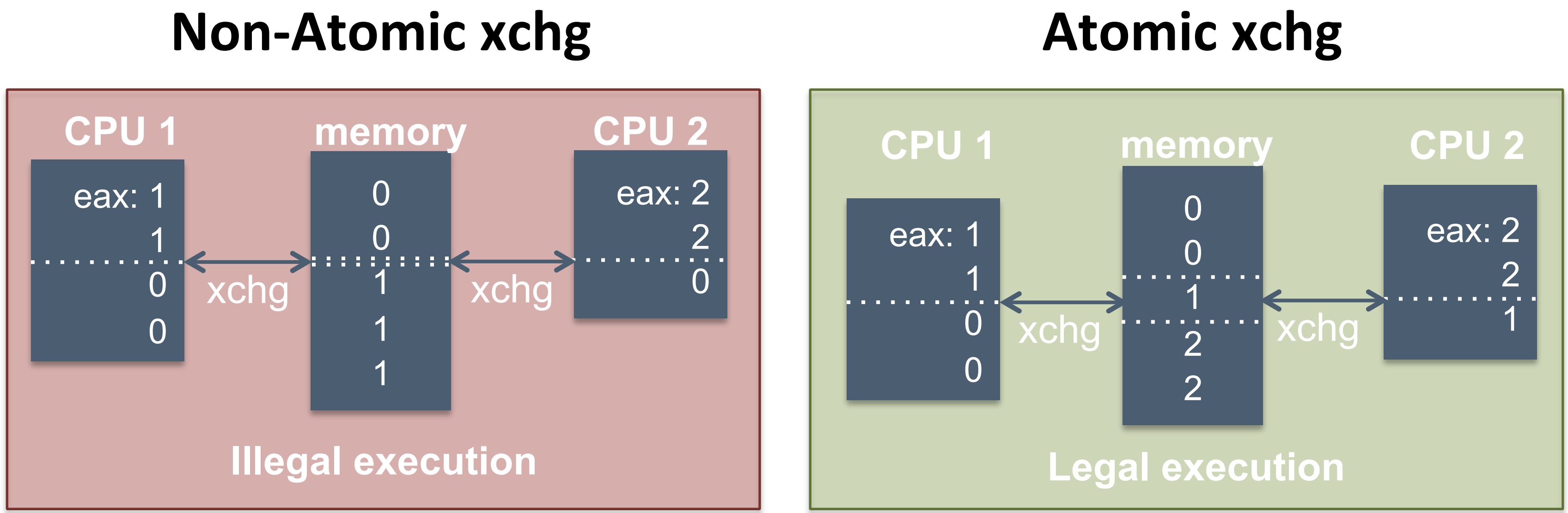
- Modern CPUs have atomic instruction(s)
  - Enable you to build high-level synchronized objects
- On x86:
  - The lock prefix makes an instruction atomic

    ```
    lock inc eax ; atomic increment
    lock dec eax ; atomic decrement
    ```

    - Only legal with some instructions
  - The xchg instruction is guaranteed to be atomic

    ```
    xchg eax, [addr] ; swap eax and the value in memory
    ```

Behavior of xchg



- Atomicity ensures that each xchg occurs before or after xchgs from other CPUs

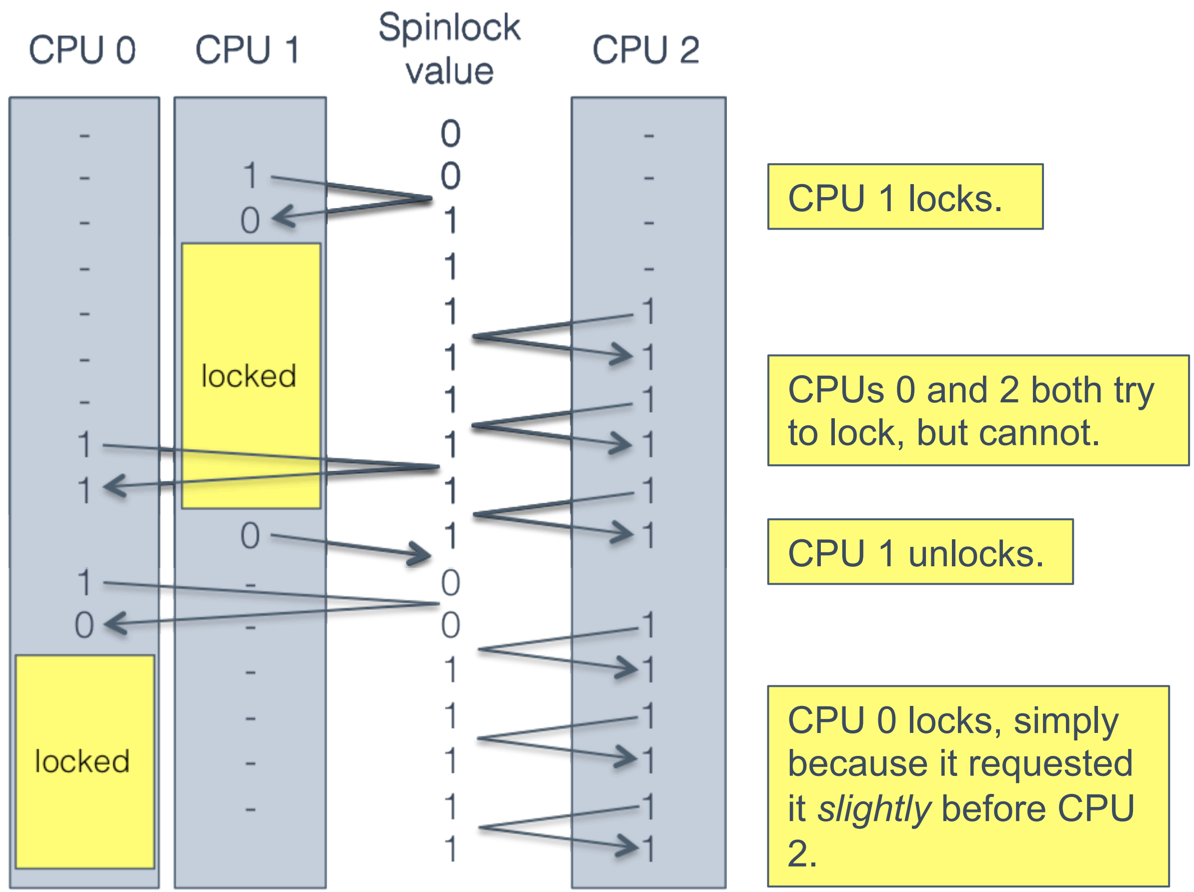
Building a Spin Lock with xchg

spin_lock:

```
mov eax, 1
xchg eax, [lock_addr]
test eax, eax
jnz spin_lock
```

spin_unlock:

```
mov [lock_addr], 0
```



Building a Multi-CPU Mutex

```
typedef struct mutex_struct {
    int spinlock = 0; // spinlock variable
    int locked = 0;   // is the mutex locked? guarded by spinlock
    queue waitlist;   // waiting threads, guarded by spinlock
} mutex;

void mutex_lock(mutex * m) {
    spin_lock(&m->spinlock);
    if (!m->locked){
        m->locked = 1;
        spin_unlock(&m->spinlock);
    } else {
        m->waitlist.add(current_process);
        spin_unlock(&m->spinlock);
        yield();
        // wake up here when the mutex is acquired
    }
}
```

Building a Multi-CPU Mutex

```
typedef struct mutex_struct {
    int spinlock = 0; // spinlock variable
    int locked = 0;   // is the mutex locked? guarded by spinlock
    queue waitlist;   // waiting threads, guarded by spinlock
} mutex;

void mutex_unlock(mutex * m) {
    spin_lock(&m->spinlock);
    if (m->waitlist.empty()) {
        m->locked = 0;
        spin_unlock(&m->spinlock);
    } else {
        next_thread = m->waitlist.pop_from_head();
        spin_unlock(&m->spinlock);
        wake(next_thread);
    }
}
```

Compare and Swap

- Sometimes, literature on locks refers to *compare and swap* (CAS) instructions
  - CAS instructions combine an xchg and a test
- On x86, known as *compare and exchange*

```
spin_lock:
    mov ecx, 1
    mov eax, 0
    lock cmpxchg ecx, [lock_addr]
    jnz spinlock
```

  - cmpxchg compares eax and the value of lock_addr
  - If eax == [lock_addr], swap ecx and [lock_addr]

The Price of Atomicity

- Atomic operations are very expensive on a multi-core system
  - Caches must be flushed
    - CPU cores may see different values for the same variable if they have out-of-date caches
    - Cache flush can be forced using a memory fence (sometimes called a memory barrier)
  - Memory bus must be locked
    - No concurrent reading or writing
  - Other CPUs may stall
    - May block on the memory bus or atomic instructions

- Motivating Parallelism
- Synchronization Basics
- Types of Locks and Deadlock
- Lock-Free Data Structures

Other Types of Locks

- Mutex is perhaps the most common type of lock
- But there are several other common types
  - Semaphore
  - Read/write lock
  - Condition variable
    - Used to build monitors

Semaphores

- Generalization of a mutex
  - Invented by Edsger Dijkstra
  - Associated with a positive integer *N*
  - May be locked by up to *N* concurrent threads
- Semaphore methods
  - wait() – if $N > 0$, *N*--; else sleep
  - signal() – if waiting threads > 0, wake one up; else *N*++

The Bounded Buffer Problem

- Canonical example of semaphore usage
  - Some threads produce items, add items to a list
  - Some threads consume items, remove items from the list
  - **Size of the list is bounded**

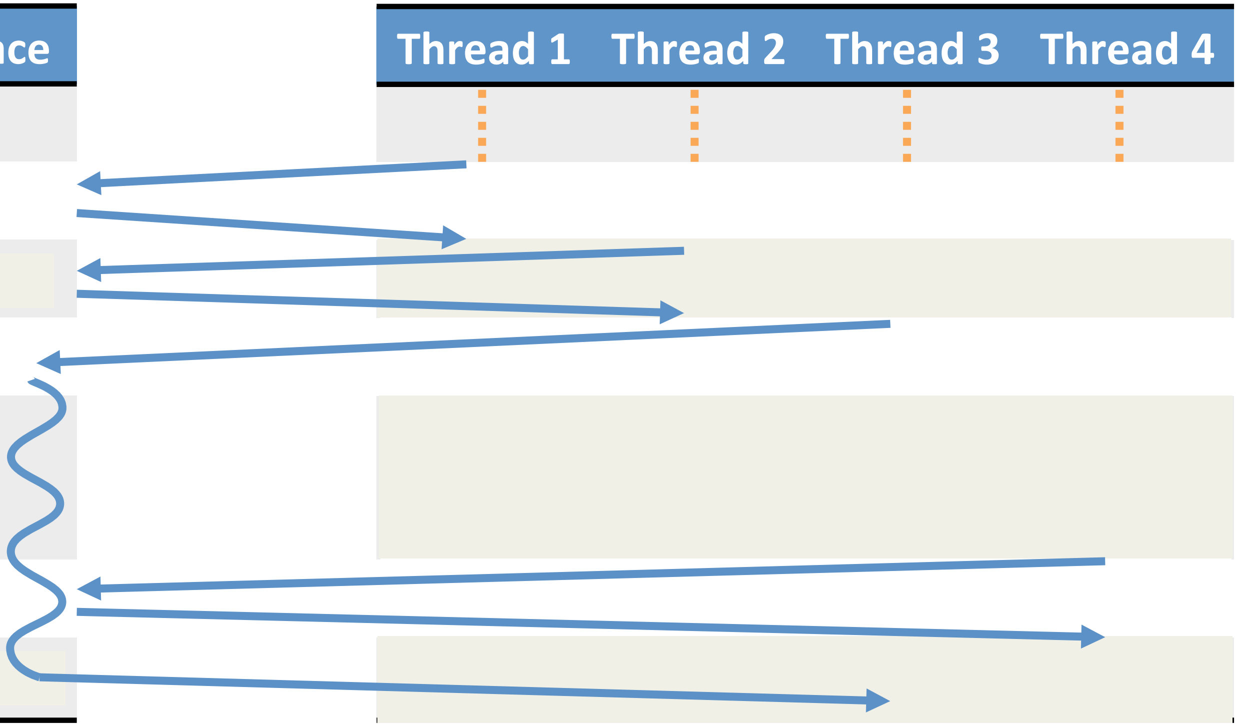
```
class semaphore_bounded_buffer:
  mutex     m
  list      buffer
  semaphore S_space = semaphore(N)
  semaphore S_items = semaphore(0)

  put(item):
      S_space.wait()
      m.lock()
      buffer.add_tail(item)
      m.unlock()
      S_items.signal()

  get():
      S_items.wait()
      m.lock()
      result = buffer.remove_head()
      m.unlock()
      S_space.signal()
      return result
```

Example Bounded Buffer

buffer	S_items	S_space
[]	0	2

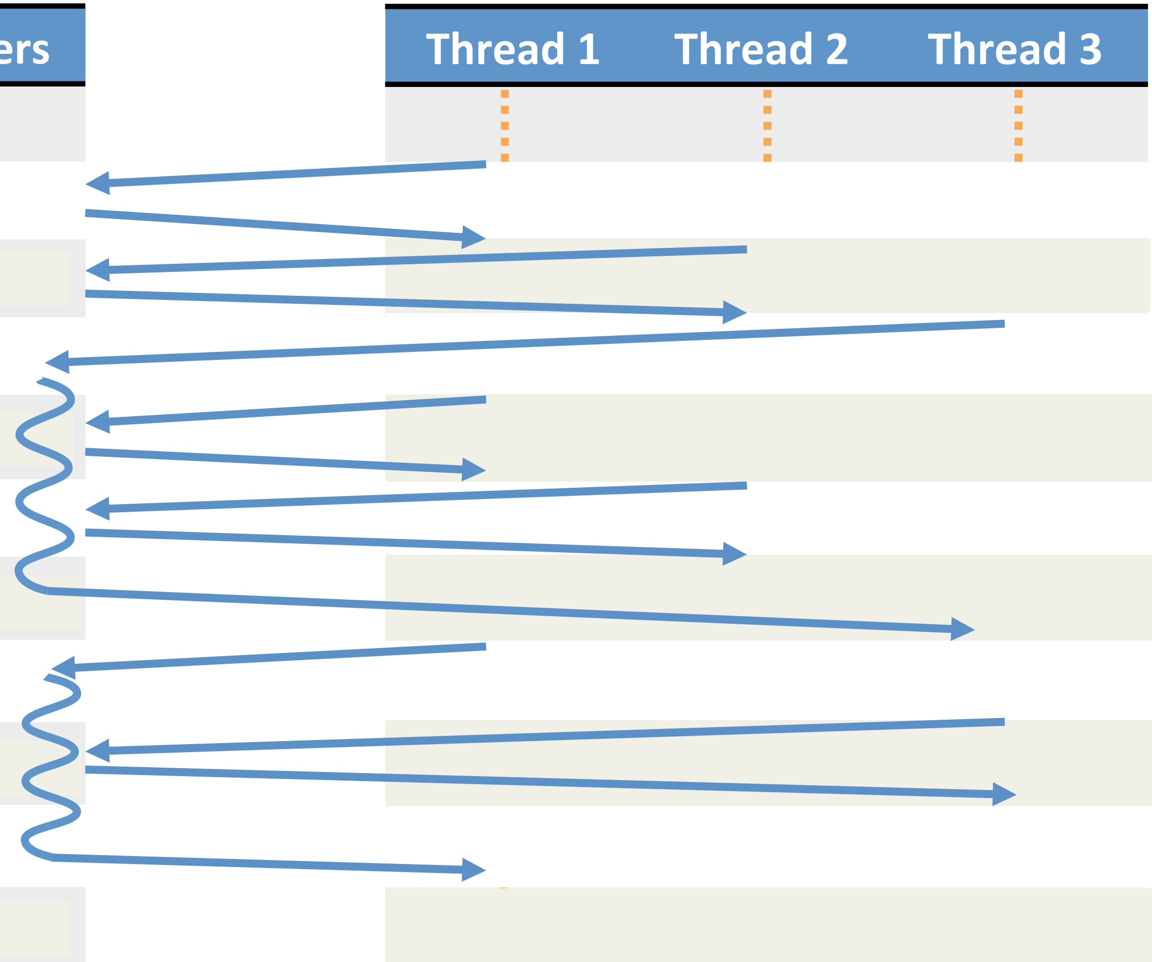


Read/Write Lock

- Sometimes known as a shared mutex
  - **Many threads** may hold the read lock in parallel
  - Only **one thread** may hold the write lock at a time
    - Write lock cannot be acquired until all read locks are released
    - New read locks cannot be acquired if a writer is waiting
- Ideal for cases were updates to shared data are rare
  - Permits maximum read parallelization

Example Read/Write Lock

list	readers	writers
[a, b]	0	0



When is a Semaphore Not Enough?

```
class weighted_bounded_buffer:
  mutex    m
  list     buffer
  int      totalweight

get(weight):
  while (1):
    m.lock()
    if totalweight >= weight:
      result = buffer.remove_head()
      totalweight -= result.weight
      m.unlock()
      return result
    else:
      m.unlock()
      yield()
```

```
put(item):
  m.lock()
  buffer.add_tail(item)
  totalweight += item.weight
  m.unlock()
```

- No guarantee the condition will be satisfied when this thread wakes up
- Lots of useless looping :(

- In this case, semaphores are not sufficient
  - weight is an unknown parameter
  - After each put(), totalweight must be checked

Condition Variables

- Construct for managing control flow amongst competing threads
  - Each condition variable is associated with a mutex
  - Threads that cannot run yet wait() for some condition to become satisfied
  - When the condition is satisfied, some other thread can signal() to the waiting thread(s)
- **Condition variables are not locks**
  - They are control-flow managers
  - Some APIs combine the mutex and the condition variable, which makes things slightly easier

Condition Variable Example

```
class weighted_bounded_buffer:
  mutex     m
  condition c
  list      buffer
  int       totalweight = 0
  int       neededweight = 0

get(weight):
  m.lock()
  if totalweight < weight:
    neededweight += weight
    c.wait(m)

  neededweight -= weigh
  result = buffer.remove_hea
  totalweight -= result.weight
  m.unlock()
  return result
```

```
put(item):
  m.lock()
  buffer.add_tail(item)
  totalweight += item.weight
  if totalweight >= neededweight
          and neededweight > 0:
    c.signal(m)
  else:
    m.unlock()
```

- signal() hands the locked mutex to a waiting thread

- wait() unlocks the mutex and blocks the thread
- When wait() returns, the mutex is locked

- In essence, we have built a construct of the form:

  wait_until(totalweight >= weight)

Monitors

- Many textbooks refer to monitors when they discuss synchronization
  - A monitor is just a combination of a mutex and a condition variable
- There is no API that gives you a monitor
  - You ***use*** mutexes and condition variables
  - You have to ***write*** your own monitors
    - In OO design, you typically make some user-defined object a monitor if it is shared between threads
- Monitors enforce mutual exclusion
  - Only one thread may access an instance of a monitor at any given time
  - synchronized keyword in Java is a simple monitor

Be Careful When Writing Monitors

Original Code

```
get(weight):
  m.lock()
  if totalweight < weight:
    neededweight += weight
    c.wait(m)

  neededweight -= weight
  result = buffer.remove_head()
  totalweight -= result.weight
  m.unlock()
  return result

put(item):
  m.lock()
  buffer.add_tail(item)
  totalweight += item.weight
  if totalweight >= neededweight
          and neededweight > 0:
    c.signal(m)
  else:
    m.unlock()
```

Modified Code

```
get(weight):
  m.lock()
  if totalweight < weight:
    neededweight += weight
    c.wait(m)

  result = buffer.remove_head()
  totalweight -= result.weight
  m.unlock()
  return result

  if totalweight >=          eight
          and needed         ht > 0:
    c.signal(m)
    neededweight -= item.weight
  else:
    m.unlock()
```

Incorrect! The mutex is not locked at this point in the code

Pthread Synchronization API

Mutex

```
pthread_mutex_t m;
pthread_mutex_init(&m, NULL);
pthread_mutex_lock(&m);
pthread_mutex_trylock(&m);
pthread_mutex_unlock(&m);
pthread_mutex_destroy(&m);
```

Condition Variable

```
pthread_cond_t c;
pthread_cond_init(&c, NULL);
pthread_cond_wait(&c &m);
pthread_cond_signal(&c);
pthread_cond_broadcast(&c);
pthread_cond_destroy(&c);
```

Read/Write Lock

```
pthread_rwlock_t rwl;
pthread_rwlock_init(&rwl, NULL);
pthread_rwlock_rdlock(&rwl);
pthread_rwlock_wrlock(&rwl);
pthread_rwlock_tryrdlock(&rwl);
pthread_rwlock_trywrlock(&rwl);
pthread_rwlock_unlock(&rwl);
pthread_rwlock_destroy(&rwl);
```

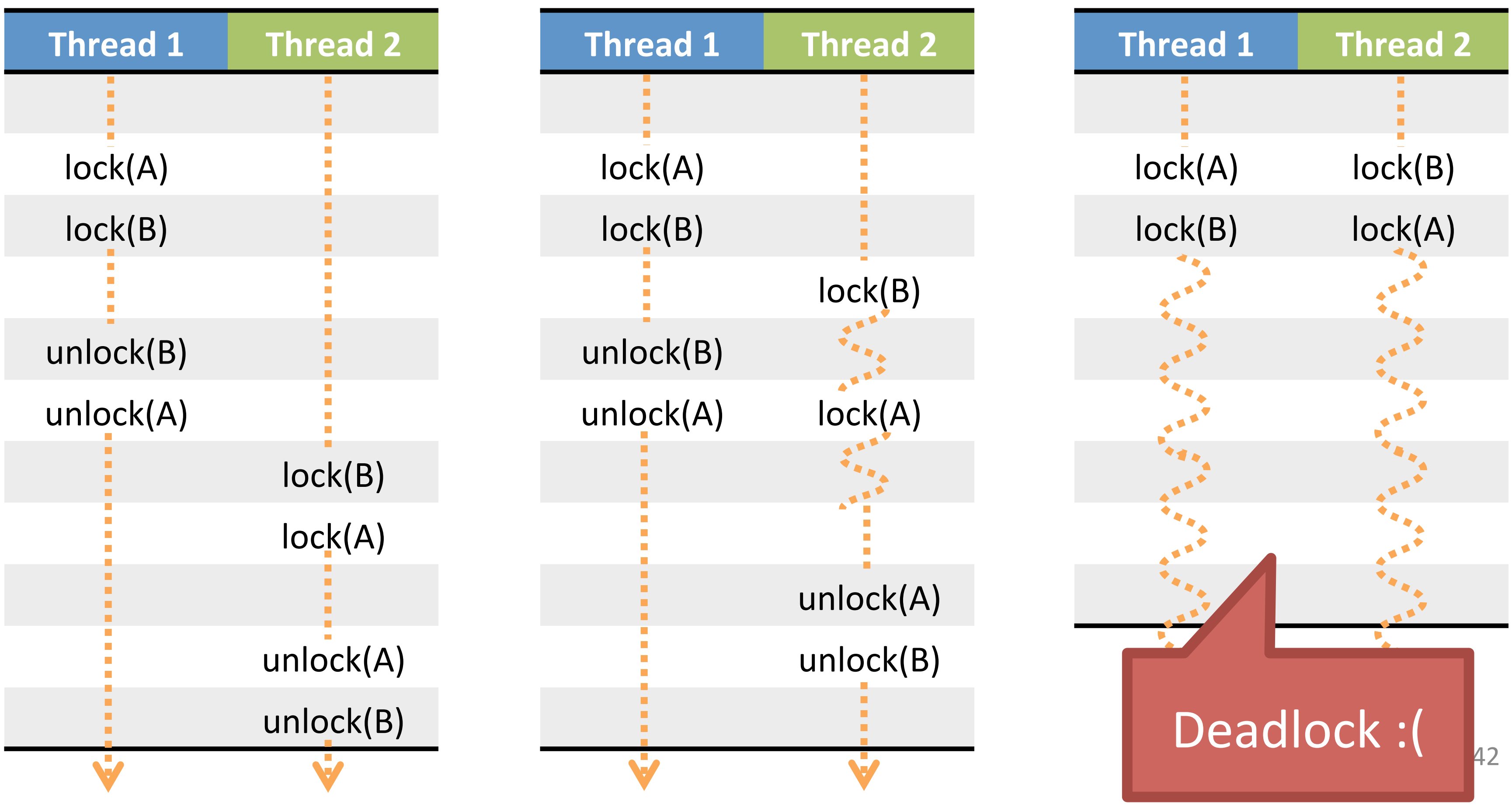
POSIX Semaphore

```
sem_t s;
sem_init(&s, NULL, <value>);
sem_wait(&s);
sem_post(&s);
sem_getvalue(&s, &value);
sem_destroy(&s);
```

Layers of Locks

	Thread 1	Thread 2

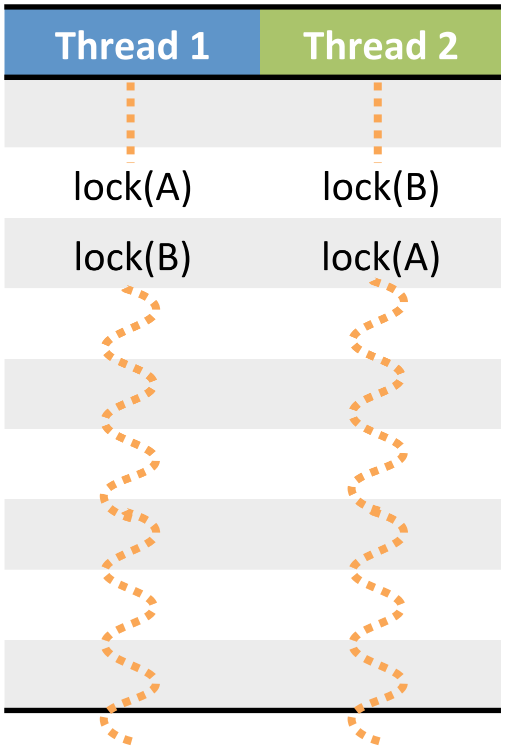
`mutex A`
`mutex B`
	`lock A`
	`lock B`
	`// do something`
	`unlock B`
	`unlock A`
		`lock B`
		`lock A`
		`// do something`
		`unlock A`
		`unlock B`



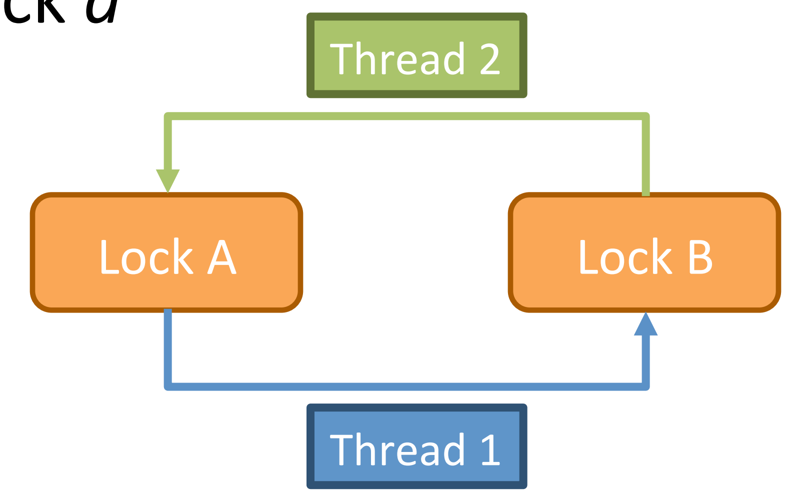
When Can Deadlocks Occur?

- Four classic conditions for deadlock
  1. Mutual exclusion: resources can be exclusively held by one process
  2. Hold and wait: A process holding a resource can block, waiting for another resource
  3. No preemption: one process cannot force another to give up a resource
  4. Circular wait: given conditions 1-3, if there is a circular wait then there is potential for deadlock
- One more issue:
  5. Buggy programming: programmer forgets to release one or more resources

Circular Waiting



- Simple example of circular waiting
  - Thread 1 holds lock *a*, waits on lock *b*
  - Thread 2 holds lock *b*, waits on lock *a*



Avoiding Deadlock

- If circular waiting can be prevented, no deadlocks can occur
- Technique to prevent circles: lock ranking
  1. Locate all locks in the program
  2. Number the locks in the order (rank) they should be acquired
  3. Add assertions that trigger if a lock is acquired out-of-order
- No automated way of doing this analysis
  - Requires careful programming by the developer(s)

Lock Ranking Example

	Thread 1	Thread 2

`#1: mutex A`
`#2: mutex B`
	`lock A`
	`assert(islocked(A))`
	`lock B`
	`// do something`
	`unlock B`
	`unlock A`
		`assert(islocked(A))`
		`lock B`
		`lock A`
		`// do something`
		`unlock A`
		`unlock B`

- Rank the locks
- Add assertions to enforce rank ordering
- In this case, Thread 2 assertion will fail at runtime

When Ranking Doesn't Work

- In some cases, it may be impossible to rank order locks, or prevent circular waiting
- In these cases, eliminate the hold and wait condition using trylock()

Example: Thread Safe List

```
class SafeList {
method append(SafeList more_items){
    lock(self)
    lock(more_items)
```

Problem:

Safelist A, B

Thread 1: A.append(B)

Thread 2: B.append(A)

Solution: Replace lock() with trylock()

```
method append(SafeList more_items){
  while (true) {
    lock(self)
    if (trylock(more_items) == locked_OK)
      break
    unlock(self)
  }
  // now both lists are safely locked
```

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Beyond Locks

- Mutual exclusion (locking) solves many issues in concurrent/parallel applications
  - Simple, widely available in APIs
  - (Relatively) straightforward to reason about
- However, locks have drawbacks
  - Priority inversion and deadlock only exist because of locks
  - Locks reduce parallelism, thus hinder performance

Lock-Free Data Structures

- Is it possible to build data structures that are thread-safe without locks?
  - YES
- Lock-free data structures
  - Include no locks, but are thread safe
  - However, may introduce starvation
    - Due to retry loops (example in a few slides)

Wait-Free Data Structures

- Wait-free data structures
  - Include no locks, are thread safe, and avoid starvation
  - Wait-free implies lock-free
    - Wait-free is much stronger than lock-free
- Wait-free structures are **very** hard to implement
  - Impossible to implement for many data structures
  - Often restricted to a fixed number of threads

Advantages of Going Lock-Free

- Potentially much more performant than locking
  - Locks necessitate waits, context switching, CPU stalls, etc…
- Immune to thread killing
  - If a thread dies while holding a lock, you are screwed
- Immune to deadlock and priority inversion
  - You can't deadlock/invert when you have no locks :)

Caveats to Going Lock-Free

- Very few standard libraries/APIs implement these data structures
  - Implementations are often platform-dependent
  - Rely on low-level assembly instructions
  - Many structures are very new, not widely known
- Not all data structures can be made lock-free
  - For many years, nobody could figure out how to make a lock-free doubly linked list
- Buyer beware if implementing yourself
  - Very difficult to get right

Lock-free Queue Example: Enqueue

- Usage: one reader, one writer

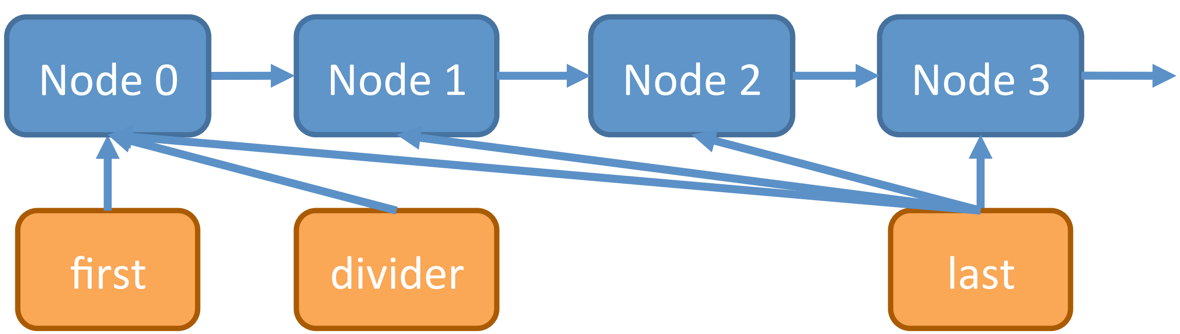
```
void enqueue(int& t) {
  last->next = new Node(t);
  last = last->next;

  // garbage collect dequeued nodes
  while (first != divider) {
    Node * tmp = first;
    first = first->next;
    delete tmp;
  }
}
```

```
class Node {
  Node * next;
  int data;
};

// Queue pointers
volatile Node * first;
volatile Node * last;
volatile Node * divider;

lock_free_queue() {
  // add the dummy node
  first = last = divider
    = new Node(0);
}
```



Lock-free Queue Example: Dequeue

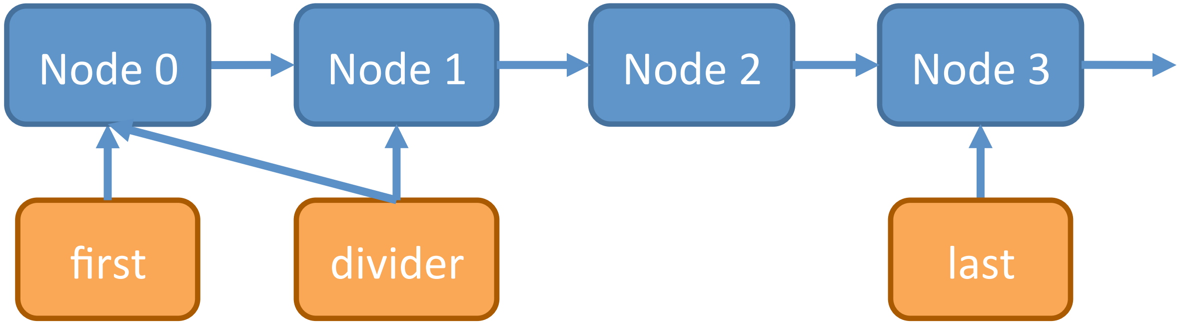
- Usage: one reader, one writer

```
bool dequeue(int& t) {
  if (divider != last) {
    t = divider->next->value;
    divider = divider->next;
    return true;
  }
  return false;
}
```

```
class Node {
  Node * next;
  int data;
};

// Queue pointers
volatile Node * first;
volatile Node * last;
volatile Node * divider;

lock_free_queue() {
  // add the dummy node
  first = last = divider
    = new Node(0);
}
```



Lock-free Queue Example: Enqueue

- Usage: one reader, one writer

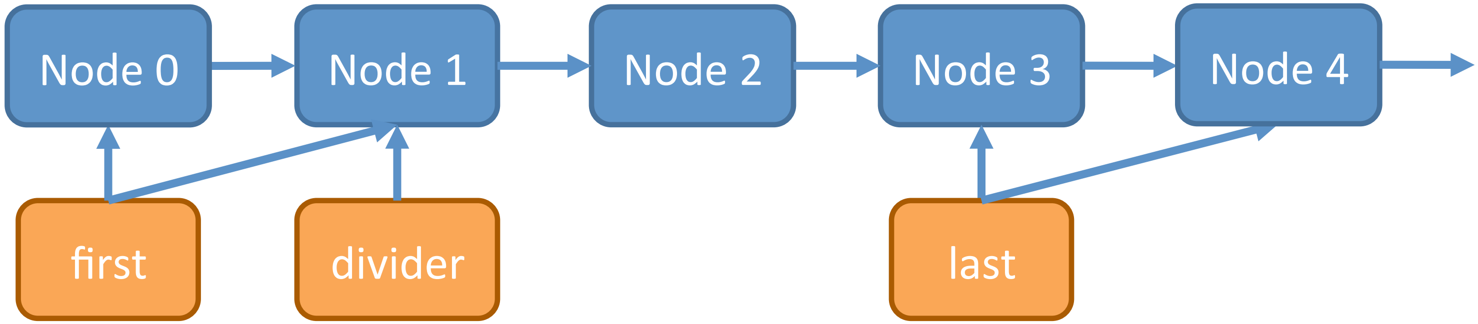
```
void enqueue(int& t) {
  last->next = new Node(t);
  last = last->next;

  // garbage collect dequeued nodes
  while (first != divider) {
    Node * tmp = first;
    first = first->next;
    delete tmp;
  }
}
```

```
class Node {
  Node * next;
  int data;
};

// Queue pointers
volatile Node * first;
volatile Node * last;
volatile Node * divider;

lock_free_queue() {
  // add the dummy node
  first = last = divider
    = new Node(0);
}
```



Why Does This Work?

- The enqueue thread and dequeue thread write different pointers
  - Enqueue: last, last->next, first, first->next
  - Dequeue: divider, divider->next
  - Enqueue operations are independent of dequeue operations
  - If these pointers overlap, then no work needs to be done
- The queue always has >1 nodes (starting with the dummy node)

More Advanced Lock-Free Tricks

- Many lock-free data structures can be built using compare and swap (CAS)

```
bool cas(int * addr, int oldval, int newval) {
    if (*addr == oldval) { *addr = newval; return true; }
    return false;
}
```

- This can be done atomically on x86 using the cmpxchg instruction
- Many compilers have built in atomic swap functions
  - GCC: **__sync_bool_compare_and_swap(ptr, oldval, newval)**
  - MSVC: **InterlockedCompareExchange(ptr,oldval,newval)**

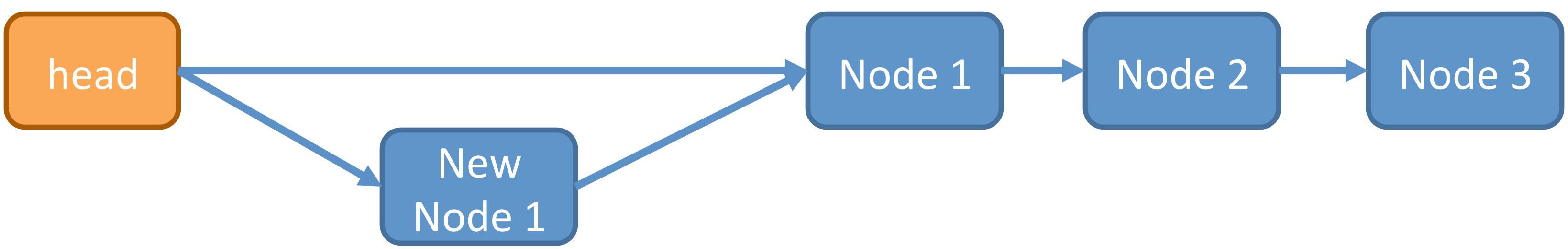
Lock-free Stack Example: Push

- Usage: any number of readers and writers

```
class Node {
  Node * next;
  int data;
};

// Root of the stack
volatile Node * head;
```

```
void push(int t) {
  Node* node = new Node(t);
  do {
    node->next = head;
  } while (!cas(&head, node->next, node));
}
```



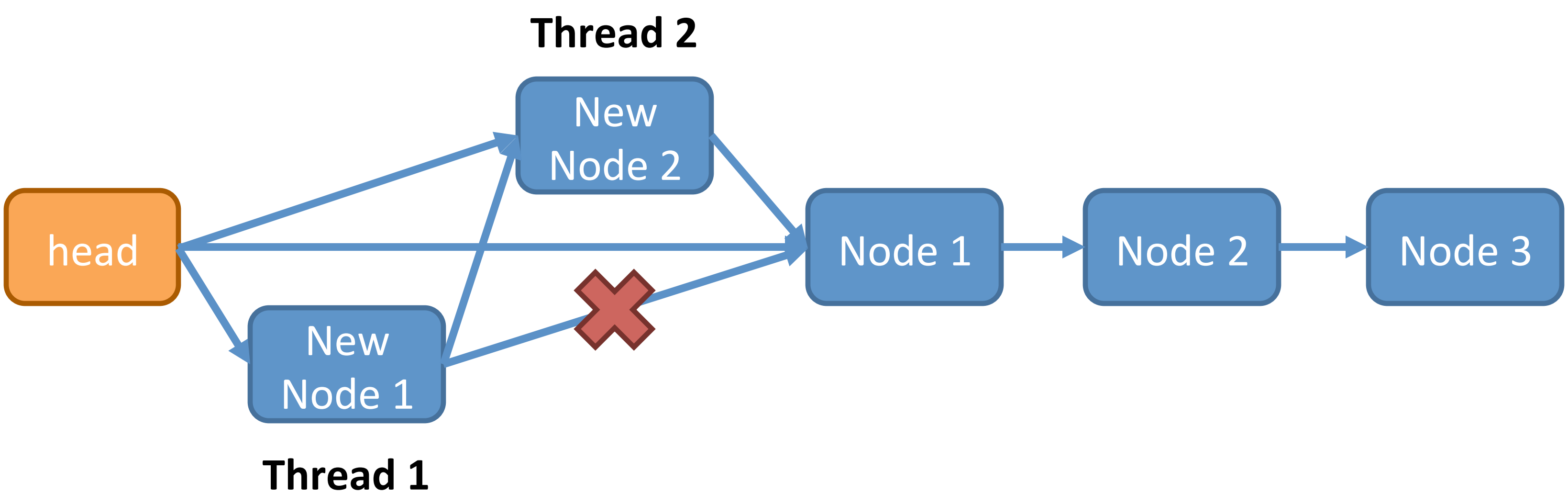
Lock-free Stack Example: Push

- Usage: any number of readers and writers

```
class Node {
  Node * next;
  int data;
};

// Root of the stack
volatile Node * head;
```

```
void push(int t) {
  Node* node = new Node(t);
  do {
    node->next = head;
  } while (!cas(&head, node->next, node));
}
```

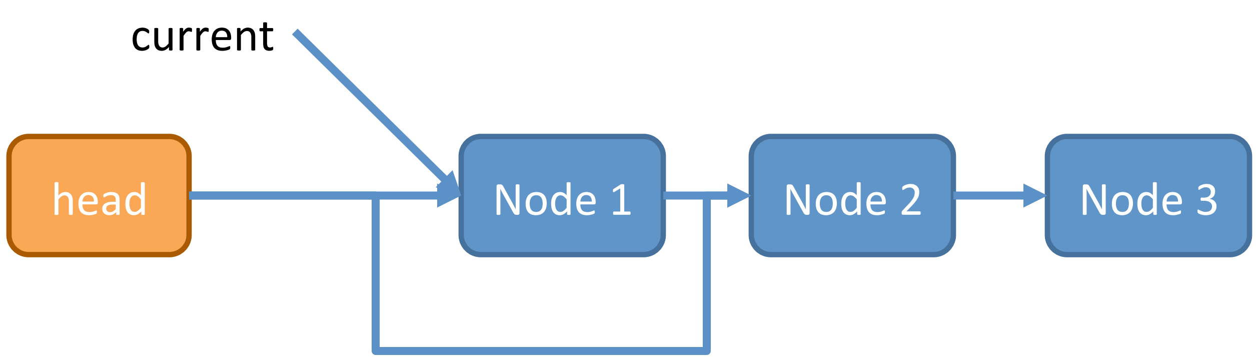


Lock-free Stack Example: Pop

```
bool pop(int& t) {
  Node* current = head;
  while(current) {
    if(cas(&head, current, current->next)) {
      t = current->data;
      delete current;
      return true;
    }
    current = head;
  }
  return false;
}
```

```
class Node {
  Node * next;
  int data;
};

// Root of the stack
volatile Node * head;
```



Retry Looping is the Key

- Lock free data structures often make use of the retry loop pattern
  1. Read some state
  2. Do a useful operation
  3. Attempt to modify global state if it hasn't changed (using CAS)
- This is similar to a spinlock
  - But, the assumption is that wait times will be small
  - However, retry loops may introduce starvation
- Wait-free data structures remove retry loops
  - But are much more complicated to implement

Many Reads, Few Writes

- Suppose we have a map (hashtable) that is:
  - Constantly read by many threads
  - Rarely, but occasionally written
- How can we make this structure lock free?

```
class readmap {
  mutex mtx;
  map<string, string> map;

  string lookup(const string& k) {
    lock l(mtx);
    return map[k];
  }

  void update(const string& k,
              const string& v) {
    lock lock(mtx);
    map[k] = v;
  }
};
```

Duplicate and Swap

```
class readmap {
  map<string, string> * map;

  readmap() { map = new map<string, string>(); }

  string lookup(const string& k) {
    return (*map)[k];
  }

  void update(const string& k, const string& v) {
    map<string, string> * new_map = 0;
    do {
      map<string, string> * old_map = map;
      if (new_map) delete new_map;
      // clone the existing map data
      new_map = new map<string, string>(*old_map);
      (*new_map)[k] = v;
      // swap the old map for the new, updated map!
    } while (cas(&map, old_map, new_map));
  }
};
```

Memory Problems

- What is the problem with the previous code?

```
} while (cas(&map, old_map, new_map));
```

- The old map is not deleted (memory leak)
- Does this fix things?

```
} while (cas(&map, old_map, new_map));
delete old_map;
```

- Readers may still be accessing the old map!
  - Deleting it will cause nondeterministic behavior
- Possible solution: store the old_map pointer, delete it after some time has gone by

Hazard Pointers

- Construct for managing memory in lock-free data structures
- Straightforward concept:
  - Read threads publish hazard pointers that point to any data they are currently reading
  - When a write thread wants to delete data:
    - If it is not associated with any hazard pointers, delete it
    - If it is associated with a hazard pointer, add it to a list
    - Periodically go through the list and reevaluate the data
- Of course, this is tricky in practice
  - You need lock-free structures to:
    - Enable publishing/updating hazard pointers
    - Store the list of data blocked by hazards

The ABA Problem

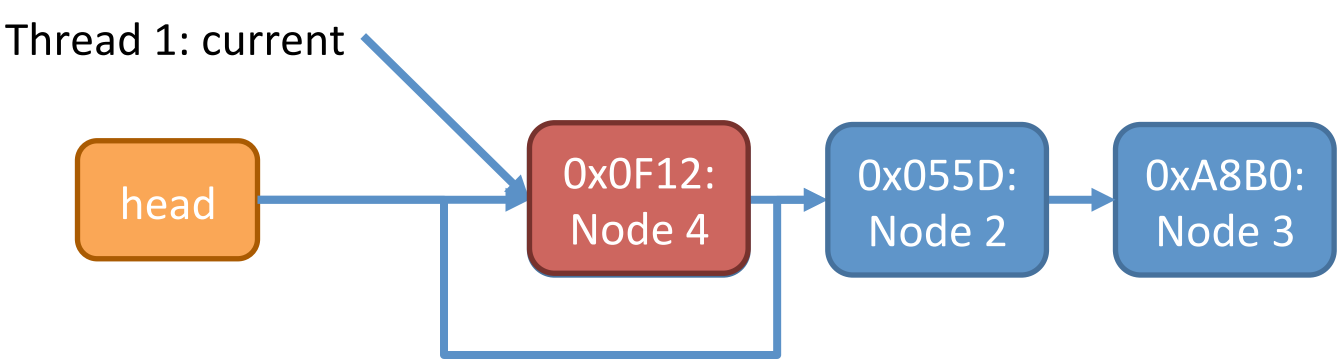
- Subtle problem that impacts many lock-free algorithms
- Compare and swap relies on the uniqueness of pointers
  - Example: cas(&head, current, current->next)
- However, sometimes the memory manager will reuse pointers

```
item * a = stack.pop();
free a;
item * b = new item();
stack.push(b);
assert(a != b); // this assertion may fail!
```

ABA Example

```
bool pop(int& t) {
  Node* current = head;
  while(current) {
    if(cas(&head, current, current->next)) {
      t = current->data;
      delete current;
      return true;
    }
    current = head;
  }
  return false;
}
```

Order of Events	
Thread 1: pop() { current = head;	



Applications of Lock-Free Structures

- Stack
- Queue
- Deque
- Linked list
- Doubly linked list
- Hash table
- Many variations on each
  - Lock free vs. wait free
- Memory managers
  - Lock free malloc() and free()
- The Linux kernel
  - Many key structures are lock-free

References

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  - http://www.drdobbs.com/parallel/writing-lock-free-code-a-corrected-queue/210604448