Lecture 18:

Fine-grained synchronization & lock-free programming

Parallel Computer Architecture and Programming
CMU 15-418/15-618, Spring 2020

Today’s Topics

- Atomic operations
- Fine-grained Locking
- Lock-free Programming

Locking Problem

- Locks can be big and expensive
  - How many atomic operations does one lock require?
  - How much data requires one lock?
  - How much does it force threads to serialize?

CUDA 7 atomic operations

```
int   atomicAdd(int* address, int val);
float atomicAdd(float* address, float val);
int   atomicSub(int* address, int val);
int   atomicExch(int* address, int val);
float atomicExch(float* address, float val);
int   atomicMin(int* address, int val);
int   atomicMax(int* address, int val);
unsigned int atomicInc(unsigned int* address, unsigned int val);
unsigned int atomicDec(unsigned int* address, unsigned int val);
int   atomicCAS(int* address, int compare, int val);
int   atomicAnd(int* address, int val);  // bitwise
int   atomicOr(int* address, int val);   // bitwise
int   atomicXor(int* address, int val);  // bitwise
```

(omitting additional 64 bit and unsigned int versions)

GCC atomic built-in functions

```
type __sync_fetch_and_add (type *ptr, type value, ...)
type __sync_fetch_and_sub (type *ptr, type value, ...)
type __sync_fetch_and_or (type *ptr, type value, ...)
type __sync_fetch_and_and (type *ptr, type value, ...)
type __sync_fetch_and_xor (type *ptr, type value, ...)
type __sync_fetch_and_nand (type *ptr, type value, ...)
type __sync_add_and_fetch (type *ptr, type value, ...)
type __sync_sub_and_fetch (type *ptr, type value, ...)
type __sync_or_and_fetch (type *ptr, type value, ...)
type __sync_and_and_fetch (type *ptr, type value, ...)
type __sync_xor_and_fetch (type *ptr, type value, ...)
type __sync_nand_and_fetch (type *ptr, type value, ...)

type can be (unsigned) char, short, int, or long
```

Recall: Atomic Increment in GCC / x86

```
type __sync_fetch_and_add (type *ptr, type value)
type __sync_add_and_fetch (type *ptr, type value)
```

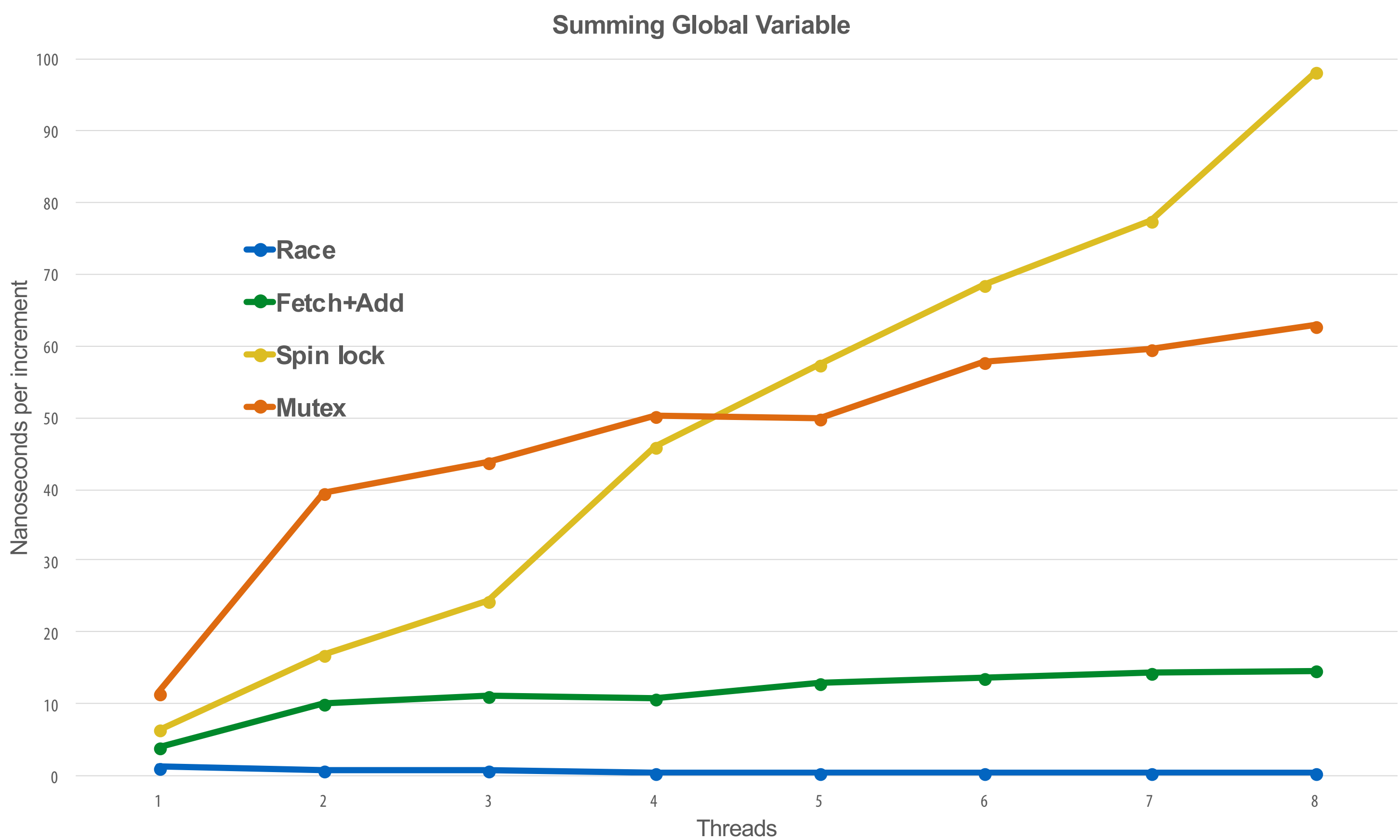
```
int fadd(int *addr, int x) {
    return __sync_fetch_and_add(addr, x);
}
```

```
0000000000000000 <fadd>:
   0:   89 f0                       mov    %esi,%eax        # x
   2:   f0 0f c1 07                 lock xadd %eax,(%rdi)  # t = *addr; *addr += x
   6:   c3                          retq                   # return t
```

- **Direct hardware implementation**
- **No need for a loop**
- **Fetch-and-subtract also implemented with xadd**

Fetch & Add Performance

- **Task**
  - *K* threads each incrementing single global variable *N* times
  - Measure $NPI = \frac{T \cdot 10^9}{N \cdot K}$



Atomic Compare-And-Swap (CAS)

```
// atomicCAS:
// atomic compare and swap performs this logic atomically
int atomicCAS(int* addr, int compare, int val) {
   int old = *addr;
   if (old == compare)
       *addr = val;
   return old;
}
```

- **Exercise: how can you build an atomic fetch+op out of atomicCAS()?**
  - **try: atomic_fetch_and_min()**

```
int atomic_fetch_and_min(int* addr, int x) {
   int old, new;
   do {
       old = *addr;
       new = min(old, x);
   } while (atomicCAS(addr, old, new) != old);
   return old;
}
```

x86 cmpxchg

- **Compare and exchange (atomic when used with lock prefix)**

```
lock cmpxchg src, dst
```

often a memory address (dst)

lock prefix (makes operation atomic) (lock)

```
if (dst == %eax)
    ZF = 1
    dst = src
else
    ZF = 0
    %eax = dst
```

x86 accumulator register (%eax)

flag register (ZF)

Self-check: Can you implement ASM for atomic compare-and-swap using `cmpxchg`?

```
bool compare_and_swap(int* x, a, b) {
   if (*x == a) {
     *x = b;
     return true;
   }

   return false;
}
```

Other Atomic Ops in GCC / x86

```
type __sync_fetch_and_xor (type *ptr, type value)
type __sync_xor_and_fetch (type *ptr, type value)
```

```
int fxor(int *addr, int x) {
    return __sync_fetch_and_xor(addr, x);
}
```

```
0000000000000020 <fxor>:
  20:   8b 07                   mov    (%rdi),%eax          # old = *addr
  22:   41 89 c0                mov    %eax,%r8d            # loop: t = old
  25:   89 c1                   mov    %eax,%ecx            # r = old
  27:   41 31 f0                xor    %esi,%r8d            # new = old^x
  # if *addr==t then *addr = new else old = *addr
  2a:   f0 44 0f b1 07          lock cmpxchg %r8d,(%rdi)
  2f:   75 f1                   jne    22 <fxor+0x2>        # Goto loop if failed
  31:   89 c8                   mov    %ecx,%eax            # Return r
  33:   c3                      retq
```

- Uses cmpxchg
- Requires loop
- Other bit-level ops are similar

C++ 11 atomic<T>

- **Provides atomic read, write, read-modify-write of entire objects**
  - Atomicity may be implemented by mutex or efficiently by processor-supported atomic instructions (if T is a basic type)
- **Provides memory ordering semantics for operations before and after atomic operations**
  - By default: sequential consistency
  - See std::memory_order or more detail

```
atomic<int> i;
i++; // atomically increment i

int a = i;
// do stuff
i.compare_exchange_strong(a, 10);   // if i has same value as a, set i to 10
bool b = i.is_lock_free();          // true if implementation of atomicity
                                    // is lock free
```

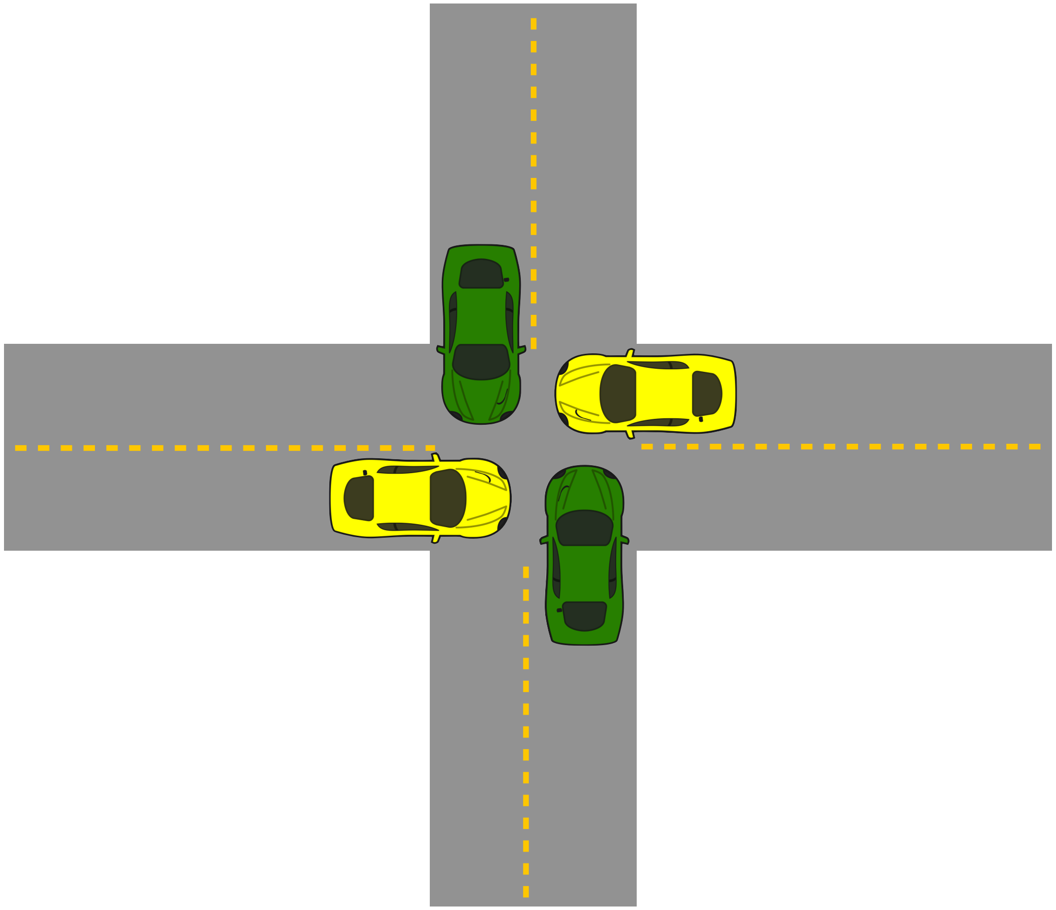
- **Will be useful if implementing the lock-free programming ideas in C++**

How are the operations atomic?

- x86 Lock prefix
  - If the memory location is cached, then the cache retains that location until the operation completes
  - If not:
    - With bus: the processor uses the lock signal and holds the bus until the operation completes
    - With directories: the processor (probably) NACKs any request for the cache line until the operation completes

N.B. Operations must be made on non-overlapping addresses

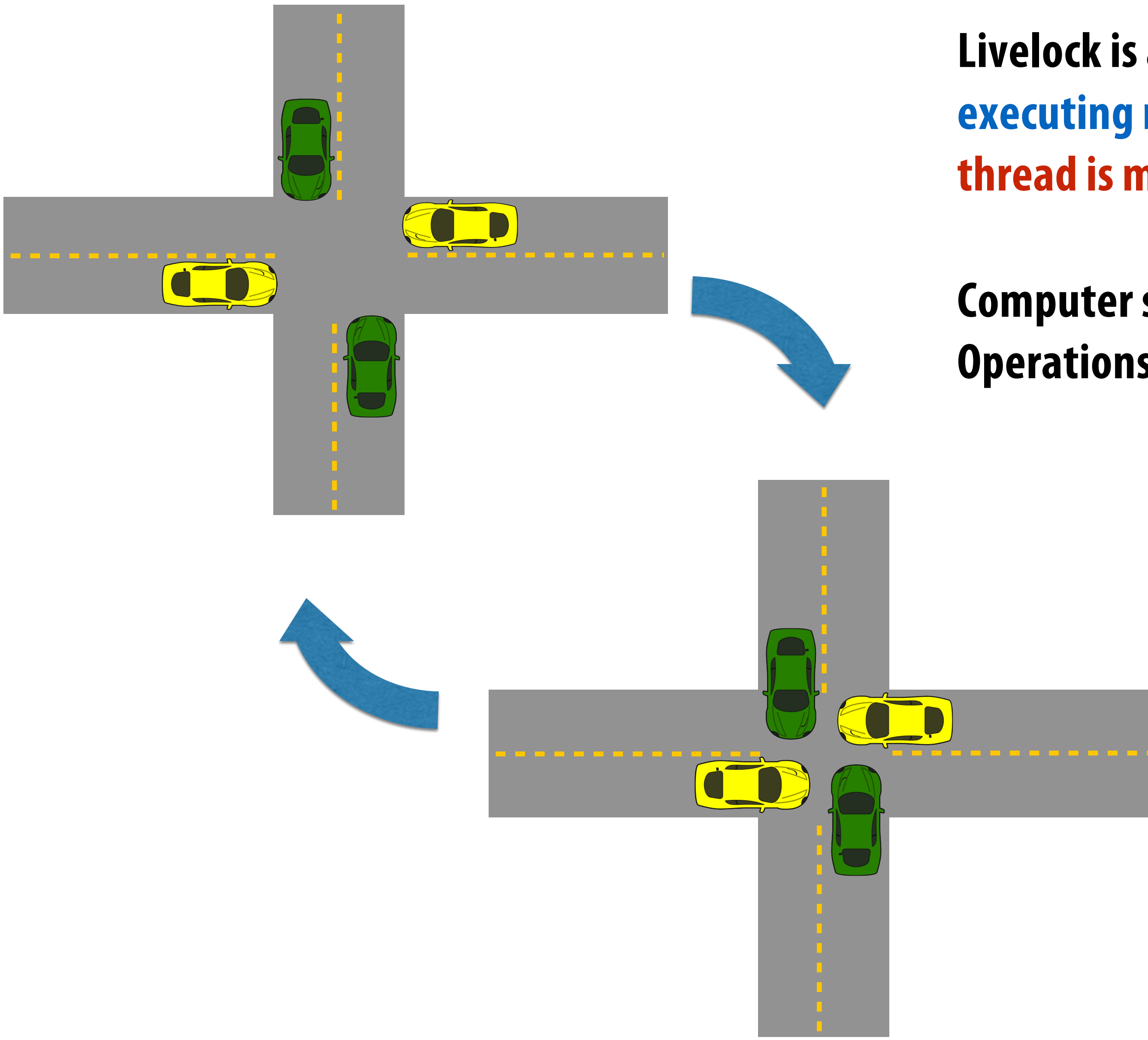
Atomic Operations: Deadlock?



Deadlock is a state where a system has outstanding operations to complete, but no operation can make progress.

Can arise when each operation has acquired a shared resource that another operation needs.

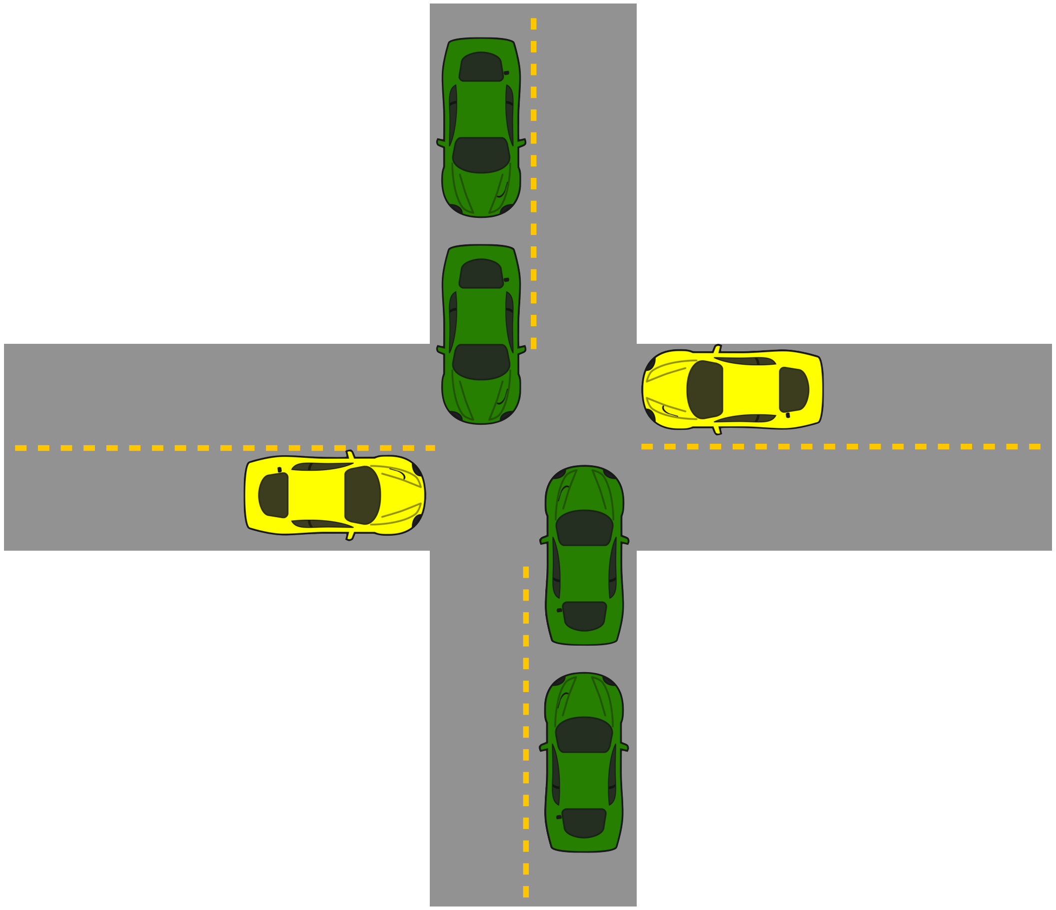
Atomic Operations: Livelock?



Livelock is a state where a system is executing many operations, but no thread is making meaningful progress.

Computer system examples:
Operations continually abort and retry

Atomic Operations: Starvation/Unfairness



State where a system is making overall progress, but some processes make no progress.

(green cars make progress, but yellow cars are stopped)

In this example: assume traffic moving left/right (yellow cars) must yield to traffic moving up/down (green cars)

Locking more than one location

- Data structures are often larger than a single memory location
  - How can an entire data structure be protected?

    E.g. 15213 Proxylab cache

Example: a sorted linked list

```
struct Node {
   int value;
   Node* next;
};
```

```
struct List {
  Node* head;
};
```

What can go wrong if multiple threads operate on the linked list simultaneously?

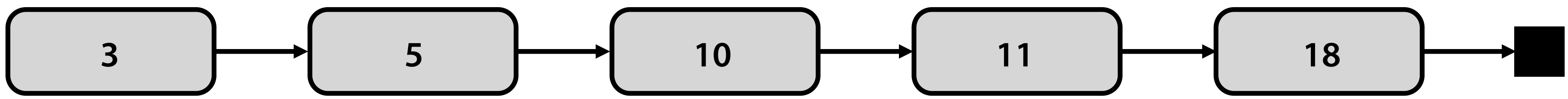
```
void insert(List* list, int value) {

   Node* n = new Node;
   n->value = value;

   // assume case of inserting before head of
   // of list is handled here (to keep slide simple)

   Node* prev = list->head;
   Node* cur = list->head->next;

   while (cur) {
     if (cur->value > value)
       break;

     prev = cur;
     cur = cur->next;
   }

   n->next = cur;
   prev->next = n;  // Insertion
}
```

```
void delete(List* list, int value) {

   // assume case of deleting first element is
   // handled here (to keep slide simple)

   Node* prev = list->head;
   Node* cur = list->head->next;

   while (cur) {
     if (cur->value == value) {
       prev->next = cur->next; // Deletion
       delete cur;
       return;
     }

     prev = cur;
     cur = cur->next;
   }
}
```

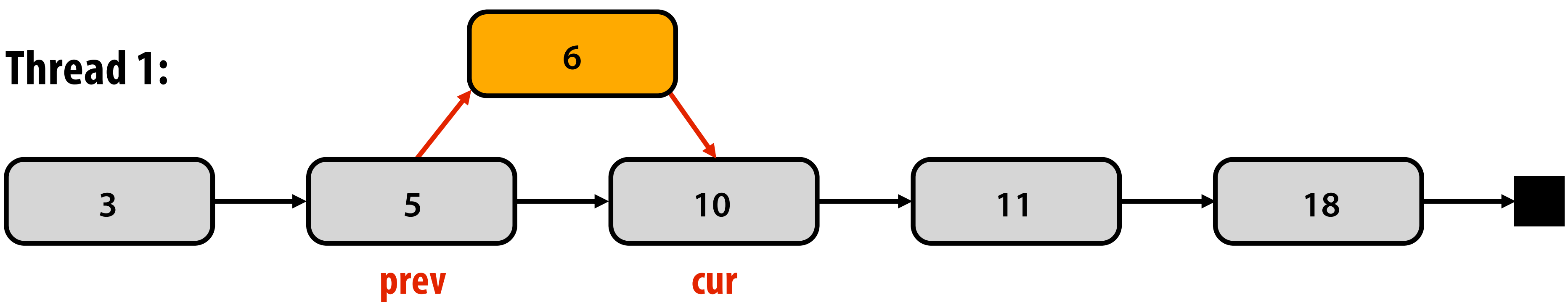
Example: simultaneous insertion

Thread 1 attempts to insert 6

Thread 2 attempts to insert 7



Thread 1:



Example: simultaneous insertion

Thread 1 attempts to insert 6

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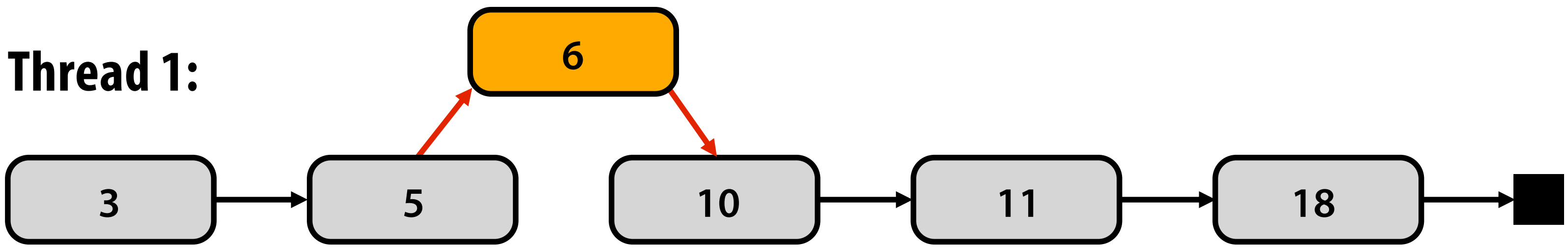
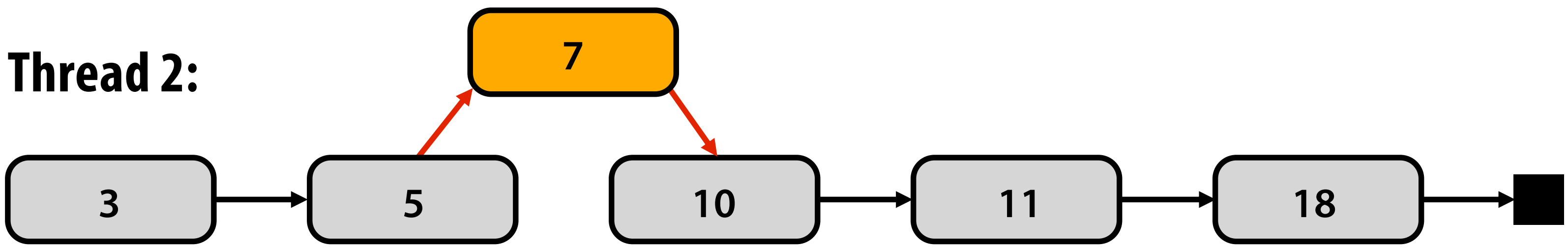
Thread 1:

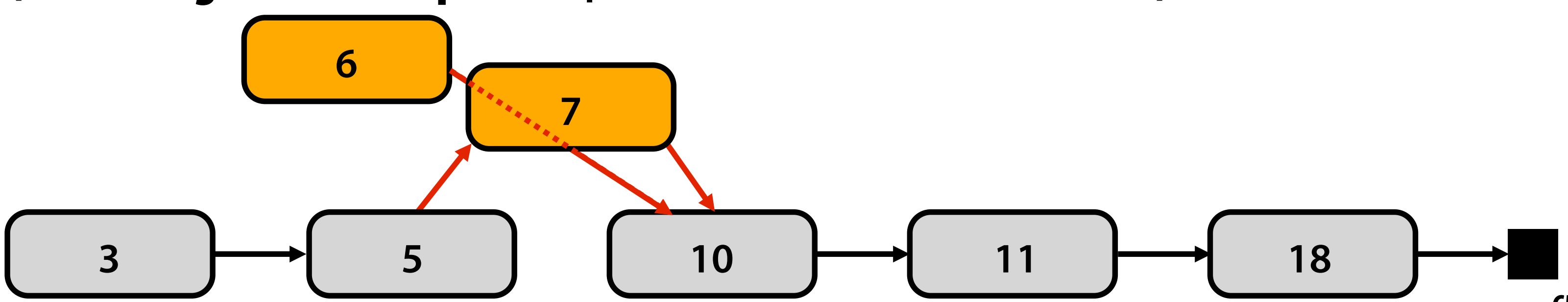


Thread 2:



Thread 1 and thread 2 both compute same prev and cur.
Result: one of the insertions gets lost!

Result: (assuming thread 1 updates `prev->next` before thread 2)



Solution 1: protect the list with a single lock

```
struct Node {
   int value;
   Node* next;
};
```

```
struct List {
  Node* head;
  Lock  lock;      <------ Per-list lock
};
```

```
void insert(List* list, int value) {

   Node* n = new Node;
   n->value = value;

   lock(list->lock);

   // assume case of inserting before head of
   // of list is handled here (to keep slide simple)

   Node* prev = list->head;
   Node* cur = list->head->next;

   while (cur) {
     if (cur->value > value)
       break;

     prev = cur;
     cur = cur->next;
   }
   n->next = cur;
   prev->next = n;
   unlock(list->lock);
}
```

```
void delete(List* list, int value) {

   lock(list->lock);

   // assume case of deleting first element is
   // handled here (to keep slide simple)

   Node* prev = list->head;
   Node* cur = list->head->next;

   while (cur) {
     if (cur->value == value) {
       prev->next = cur->next;
       delete cur;
       unlock(list->lock);
       return;
     }

     prev = cur;
     cur = cur->next;
   }
   unlock(list->lock);
}
```

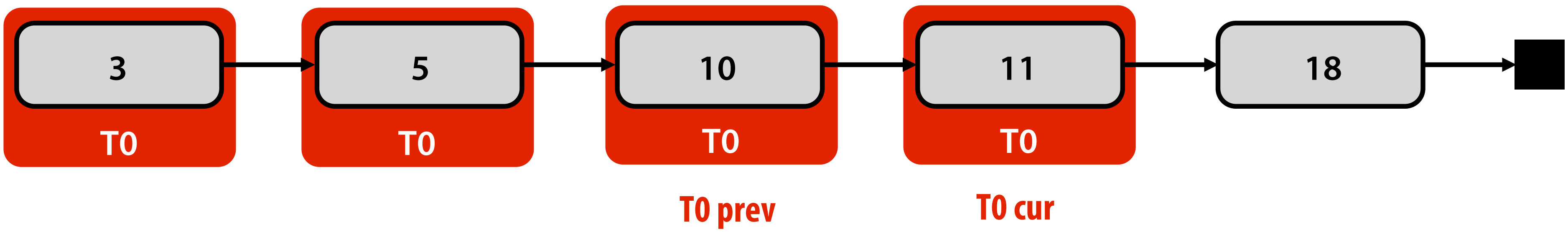
Single global lock per data structure

- **Good:**
  - It is relatively simple to implement correct mutual exclusion for data structure operations (we just did it!)

- **Bad:**
  - Operations on the data structure are serialized
  - <u>May</u> limit parallel application performance

Solution 2: "hand-over-hand" locking

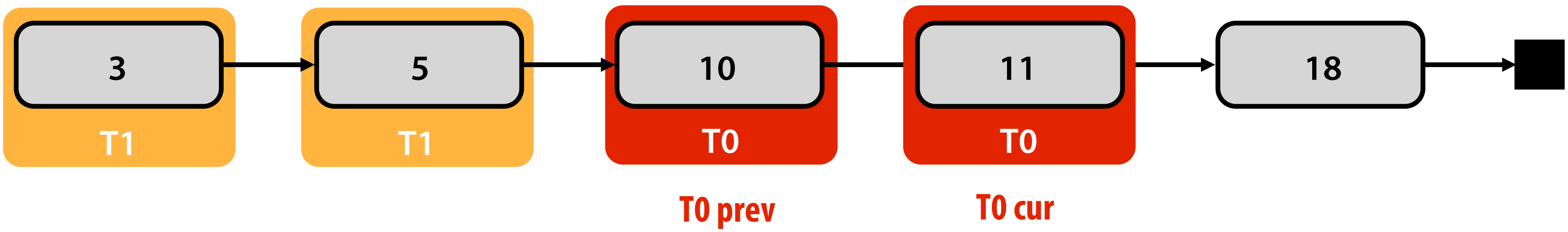
Thread 0: delete(11)



- At any time, hold lock on at least one element
  - Move along list "hand-over-hand"
  - Prevents later operations from catch up
  - Guarantees that don't interfere with earlier operations

Solution 2: "hand-over-hand" locking

Thread 0: delete(11)
Thread 1: delete(10)



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Thread 0: delete(11)
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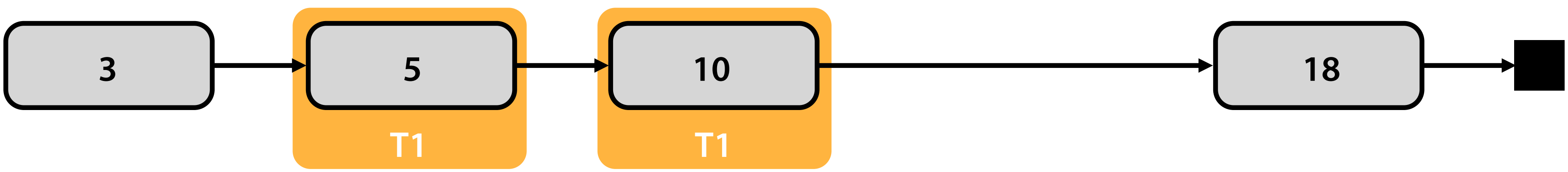
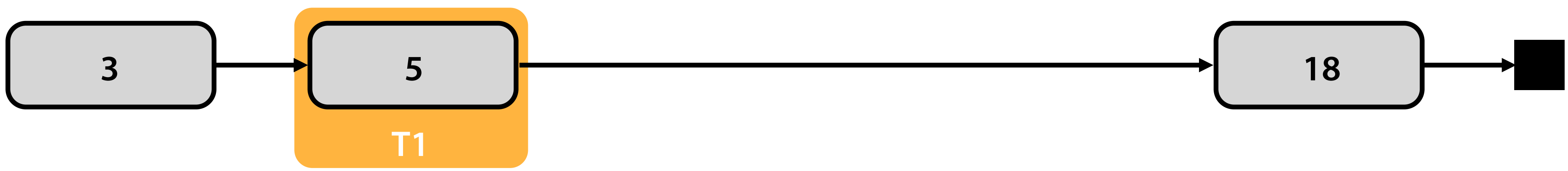
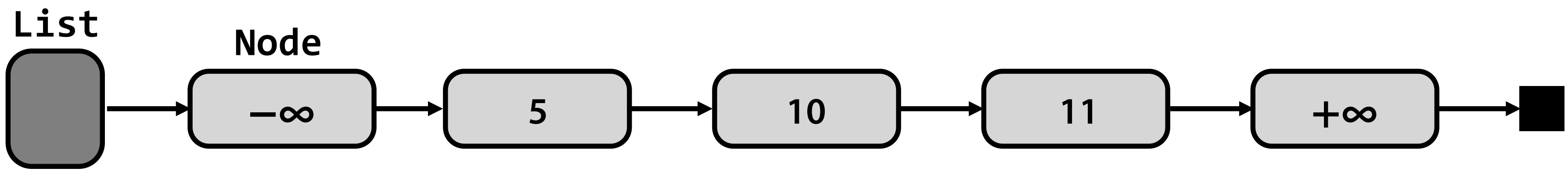


Solution 2: "hand-over-hand" locking

Thread 0: delete(11)
Thread 1: delete(10)



Version 2a: Padded List



- Assume
  - Only insert/delete finite values
  - List starts with −∞
  - List ends with +∞
  - Guaranteed to find insertion/deletion point within list

Solution 2a: Padded List HOH Locking

```
struct Node {                    struct List {
   int value;                      Node* head;
   Node* next;                   };
   Lock* lock;
};
```

```
void insert(List* list, int value) {

   Node* n = new Node;
   n->value = value;

   Node *prev, *cur, *old_prev;

   prev = list->head;
   lock(prev->lock);
   cur = prev->next;
   lock(cur->lock);

   while (value < cur->value) {
     // Holding locks on prev & cur
     old_prev = prev;
     prev = cur;
     cur = cur->next;
     unlock(old_prev->lock);
     lock(cur->lock);
   }

   n->next = cur;
   prev->next = n;

   unlock(prev->lock);
   unlock(cur->lock);
}
```

```
void delete(List* list, int value) {

   Node *prev, *cur, *old_prev;
   Node *del = NULL;

   prev = list->head;
   lock(prev->lock);
   cur = prev->next;
   lock(cur->lock);

   while (value < cur->value) {
     // Holding locks on prev & cur
     old_prev = prev;
     prev = cur;
     cur = cur->next;
     unlock(old_prev->lock);
     lock(cur->lock);
   }

   if (value == cur->value) {
     // Found
     prev->next = cur->next;
     del = cur;
   }

   unlock(prev->lock);
   unlock(cur->lock);

   if (del) delete del;
}
```

Fine-grained (HOH) Locking

- **Goal: enable parallelism in data structure operations**
  - Reduces contention for global data structure lock
  - In previous linked-list example: a single monolithic lock is overly conservative (operations on different parts of the linked list can proceed in parallel)

- **Challenge: tricky to ensure correctness**
  - Determining when mutual exclusion is required
  - Deadlock? (how do you immediately know the earlier linked-list code is deadlock free?)
  - Livelock?

- **Costs?**
  - Overhead of taking a lock each traversal step (extra instructions + traversal now involves memory writes)
  - Be sure to use spin locks!
  - Extra storage cost (a lock per node)

Where Can HOH Locking (Possibly) Be Used?

- Acyclic data structures
  - Must be able to order lock acquistion/release
  - Singly linked list
    - E.g., hash table bucket chain
  - Binary search tree (very tricky)
  - Skip list
- Not for cyclic structures
  - E.g., doubly-linked list

Lock-free data structures

Blocking algorithms/data structures

- A blocking algorithm allows one thread to prevent other threads from completing operations on a shared data structure indefinitely
- Example:
  - Thread 0 takes a lock on a node in our linked list
  - Thread 0 is swapped out by the OS, or crashes, or is just really slow (takes a page fault), etc.
  - Now, no other threads can complete operations on the data structure (although thread 0 is not actively making progress modifying it)

- An algorithm that uses locks is blocking regardless of whether the lock <u>implementation</u> uses spinning or pre-emption

Lock-free algorithms

- Non-blocking algorithms are lock-free if <u>some</u> thread is guaranteed to make progress ("systemwide progress")
  - In lock-free case, it is not possible to preempt one of the threads at an inopportune time and prevent progress by rest of system
  - Note: this definition does not prevent starvation of any one thread

Single Reader/Single Writer Bounded Queue

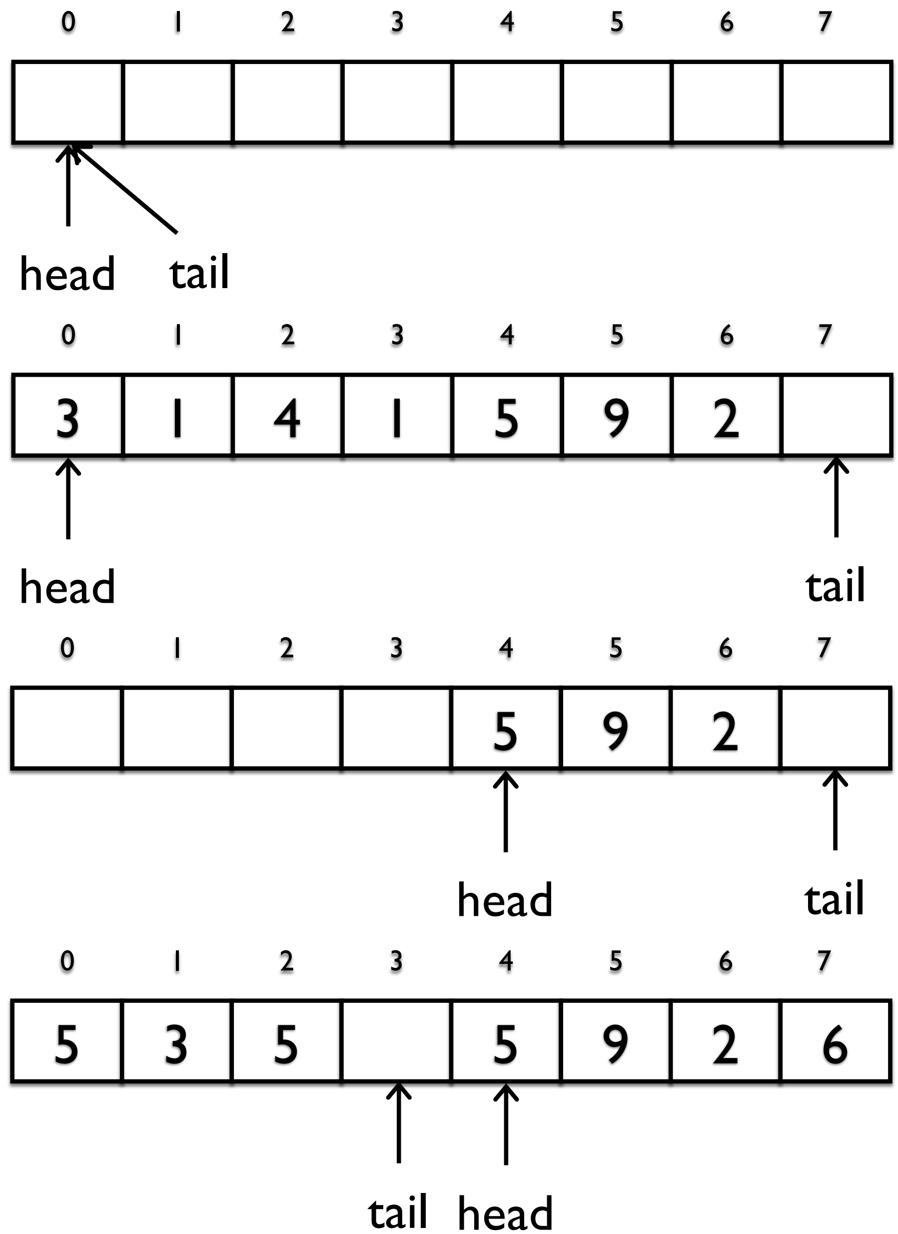
Empty

Push 3, 1, 4, 1, 5, 9, 2

Pop 4X

Returns 3, 1, 4, 1

Push 6, 5, 3, 5



Single reader, single writer <u>bounded</u> queue *

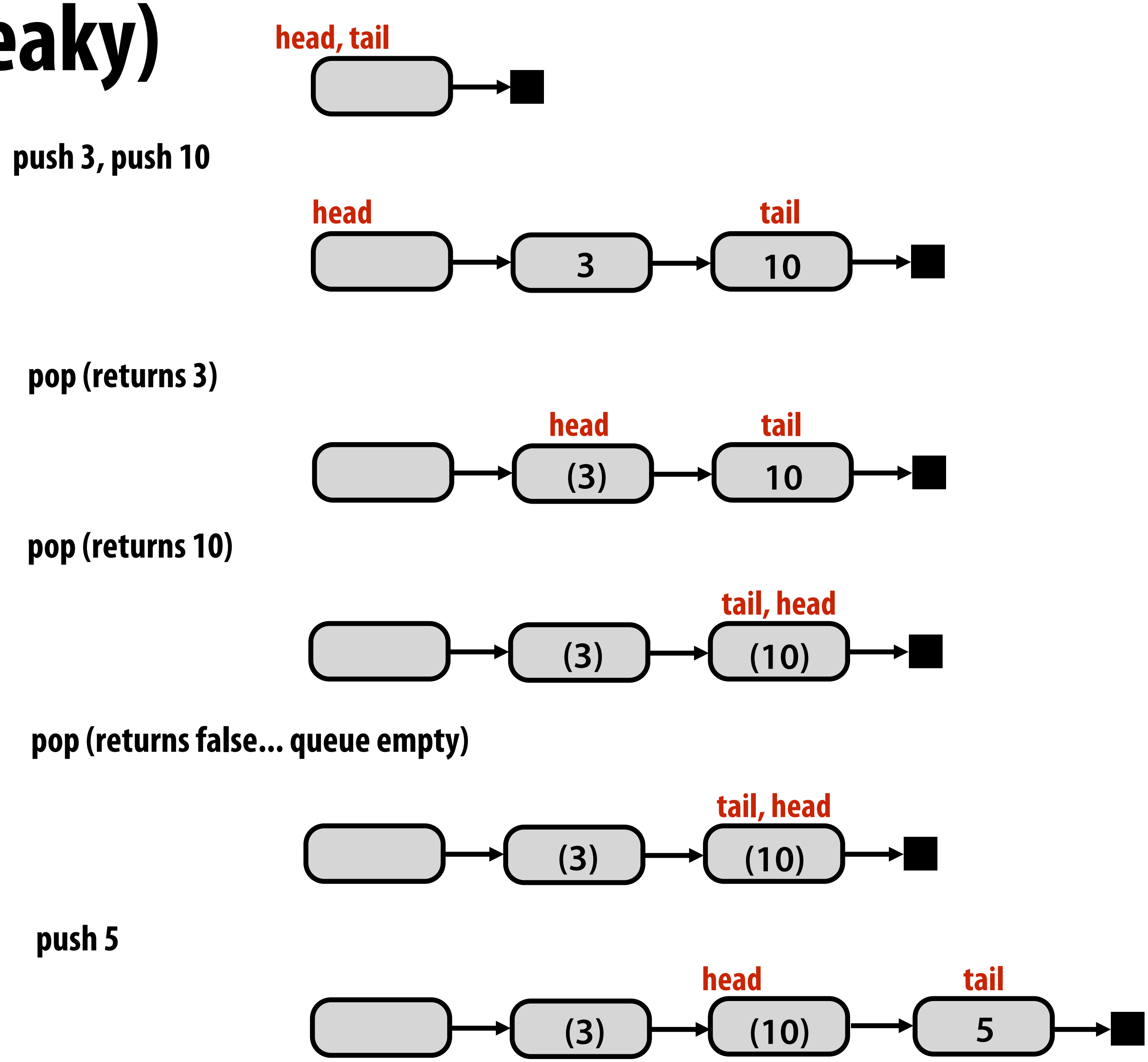
```
struct Queue {
  int data[N];
  unsigned head; // head of queue
  unsigned tail; // next free element
};

void init(Queue* q) {
   q->head = q->tail = 0;
}
```

```
// return false if queue is full
bool push(Queue* q, int value) {

   // queue is full if tail is element before head
   if (q->head == MOD_N(q->tail + 1))
     return false;

   q.data[q->tail] = value;
   q->tail = MOD_N(q->tail + 1);
   return true;
}

// returns false if queue is empty
bool pop(Queue* q, int* value) {

   // if not empty
   if (q->head != q->tail) {
     *value = q->data[q->head];
     q->head = MOD_N(q->head + 1);
     return true;
  }
  return false;
}
```

- Only two threads (one producer, one consumer) accessing queue at the same time
- Threads never synchronize or wait on each other
  - When queue is empty (pop fails), when it is full (push fails)
  - *What is special about operations on head & tail that avoids need for synchronization?*

* Assume a sequentially consistent memory system

Single reader, single writer unbounded queue (Leaky)



Single reader, single writer unbounded queue * (Leaky)

Source: Dr. Dobbs Journal

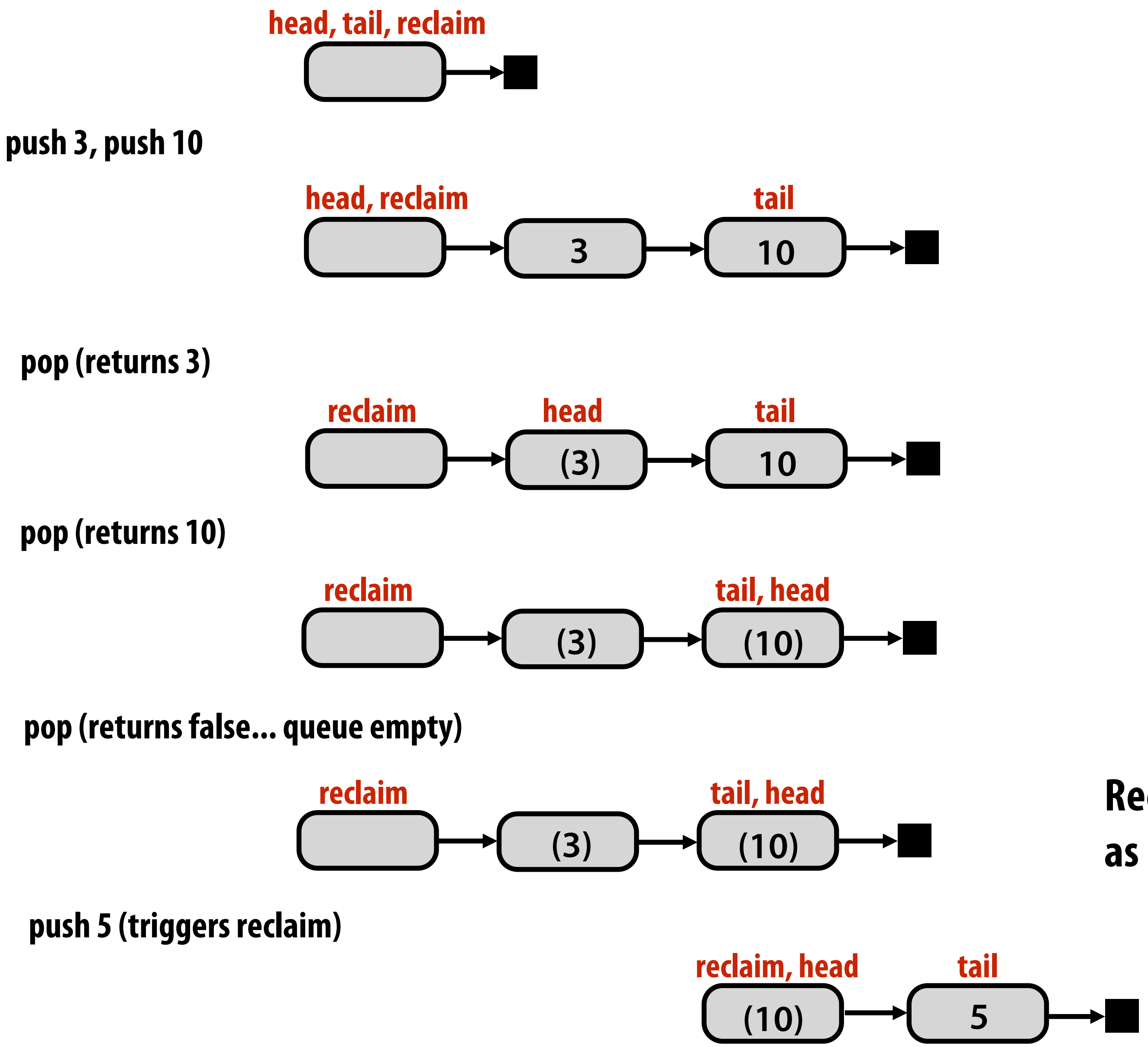
```
struct Node {
  Node* next;
  int value;
};

struct Queue {
  Node* head;
  Node* tail;
};

void init(Queue* q) {
  q->head = q->tail = new Node;
}
```

```
void push(Queue* q, int value) {

   Node* n = new Node;
   n->next = NULL;
   n->value = value;

   q->tail->next = n;
   q->tail = q->tail->next;

}

// returns false if queue is empty
bool pop(Queue* q, int* value) {

   if (q->head != q->tail) {
     *value = q->head->next->value;
     q->head = q->head->next;
     return true;
   }
   return false;
}
```

- Tail points to last element added
- Head points to element BEFORE head of queue
- Construction of list performed by single thread
  - Only push modifies tail; only pop modifies head

* Assume a sequentially consistent memory system

Single reader, single writer unbounded queue



Reclaiming performed as part of push

Single reader, single writer unbounded queue *

Source: Dr. Dobbs Journal

```
struct Node {
  Node* next;
  int value;
};

struct Queue {
  Node* head;
  Node* tail;
  Node* reclaim;
};

void init(Queue* q) {
  q->head = q->tail = q->reclaim = new Node;
}
```

```
void push(Queue* q, int value) {

   Node* n = new Node;
   n->next = NULL;
   n->value = value;

   q->tail->next = n;
   q->tail = q->tail->next;

   while (q->reclaim != q->head) {
      Node* tmp = q->reclaim;
      q->reclaim = q->reclaim->next;
      delete tmp;
   }
}

// returns false if queue is empty
bool pop(Queue* q, int* value) {

   if (q->head != q->tail) {
     *value = q->head->next->value;
     q->head = q->head->next;
     return true;
   }
   return false;
}
```

- Tail points to last element added
- Head points to element BEFORE head of queue
- Allocation and deletion performed by the same thread (producer)
  - Only push modifies tail & reclaim; only pop modifies head

* Assume a sequentially consistent memory system

Lock-free stack (first try)

```
struct Node {
  Node* next;
  int value;
};

struct Stack {
  Node* top;
};
```

```
void init(Stack* s) {
  s->top = NULL;
}

void push(Stack* s, Node* n) {
  while (1) {
    Node* old_top = s->top;
    n->next = old_top;
    if (compare_and_swap(&s->top, old_top, n) == old_top)
      return;
  }
}

Node* pop(Stack* s) {
  while (1) {
    Node* old_top = s->top;
    if (old_top == NULL)
      return NULL;
    Node* new_top = old_top->next;
    if (compare_and_swap(&s->top, old_top, new_top) == old_top)
      return old_top;  // Assume that consumer then recycles old_top
  }
}
```

Main idea: as long as no other thread has modified the stack, a thread's modification can proceed.

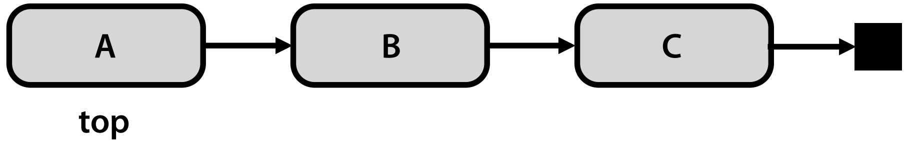
Note difference from fine-grained locks example earlier: before, implementation locked a part of a data-structure for fine-grained access. Here, threads do not hold lock on data-structure at all.

* Assume a sequentially consistent memory system

The ABA problem

A, B, C, and D are stack node addresses.

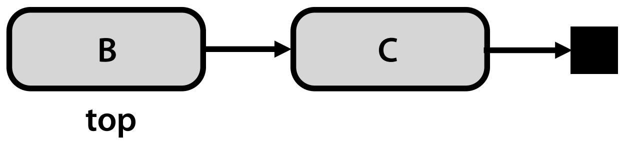
Thread 0 | **Thread 1**



begin pop() (local variable: old_top = A, new_top = B)

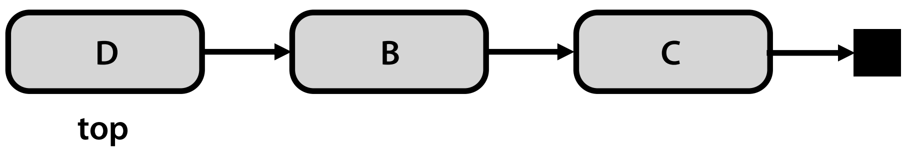
begin pop() (local variable old_top == A)

complete pop() (returns A)



begin push(D)

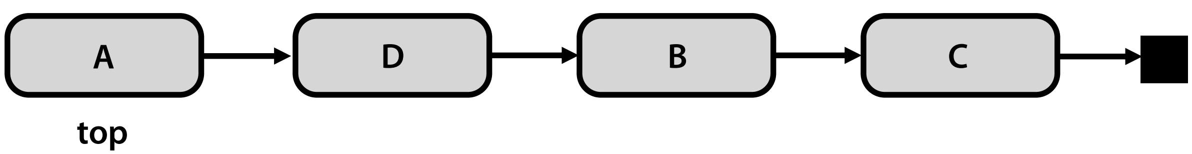
complete push(D)



modify node A: e.g., set value = 42

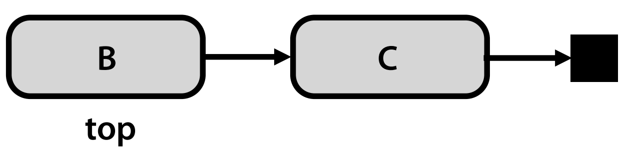
begin push(A)

complete push(A)



CAS succeeds (sets top to B!)

complete pop() (returns A)



time

Stack structure is corrupted! (lost D)

Why Does ABA Problem Arise?

- Use node address as identifier
  - Assume that if atomic CAS gets matching address, list has not been modified
- But, what if node has been deleted and recycled?
  - Atomic CAS can get matching address, even though has been modified

Lock-free stack using counter for ABA soln

```
struct Node {
  Node* next;
  int value;
};

struct Stack {
  Node* top;
  int pop_count;
};
```

```
void init(Stack* s) {
  s->top = NULL;
}

void push(Stack* s, Node* n) {
  while (1) {
    Node* old_top = s->top;
    n->next = old_top;
    if (compare_and_swap(&s->top, old_top, n) == old_top)
      return;
  }
}

Node* pop(Stack* s) {
  while (1) {
    int pop_count = s->pop_count;
    Node* top = s->top;
    if (top == NULL)
      return NULL;
    Node* new_top = top->next;
    if (double_compare_and_swap(&s->top,       top,       new_top,
                                &s->pop_count, pop_count, pop_count+1))
      return top;
  }
}
```

test to see if either have changed (in this example: return true if no changes)

- Maintain counter of pop operations
- Requires machine to support "double compare and swap" (DCAS) or doubleword CAS
- Could also solve ABA problem with node allocation and/or element reuse policies

Compare and swap on x86

- x86 supports a “wide” compare-and-swap instruction
  - Not quite the “double compare-and-swap” used in the code on the previous slide
  - But could simply ensure the stack’s count and top fields are contiguous in memory to use the 64-bit wide single compare-and-swap instruction below.
- cmpxchg8b
  - “compare and exchange eight bytes”
  - Can be used for compare-and-swap of two 32-bit values
- cmpxchg16b
  - “compare and exchange 16 bytes”
  - Can be used for compare-and-swap of two 64-bit values

Another Concern: Referencing Freed Memory

```
struct Node {
  Node* next;
  int value;
};

struct Stack {
  Node* top;
  int pop_count;
};
```

```
void init(Stack* s) {
  s->top = NULL;
}

void push(Stack* s, Node* n) {
  while (1) {
    Node* old_top = s->top;
    n->next = old_top;
    if (compare_and_swap(&s->top, old_top, n) == old_top)
      return;
  }
}

Node* pop(Stack* s) {
  while (1) {
    int pop_count = s->pop_count;
    Node* top = s->top;
    if (top == NULL)
      return NULL;
    Node* new_top = top->next;
    if (double_compare_and_swap(&s->top,       top,       new_top,
                                &s->pop_count, pop_count, pop_count+1))
      return top;
  }
}
```

What if top has been freed at this point by another thread that popped it?

T1 & T2 both popping

Case 1:

1. **T1 completes pop and gets copy of top**
2. **T2 starts pop**
- **But will get different value for top**

Case 2:

1. **T1 has not yet done CAS**
2. **T2 starts pop**
- **Both have same copy of top**
- **Both have same value for pop_count**
3. **T1 does CAS**
- **Then CAS by T2 will fail**
- **So, doesn't matter that T2 had stale data**

Possible for T1 to recycle top and therefore T2 to get bogus value for new_top, but CAS will fail. So, this all looks OK.

Another ABA Solution: Hazard Pointers

```
struct Node {
  Node* next;
  int value;
};

struct Stack {
  Node* top;
};

Node *hazard[NUM_THREADS];
```

```
void init(Stack* s) {
  s->top = NULL;
}

void push(Stack* s, Node* n) {
  while (1) {
    Node* old_top = s->top;
    n->next = old_top;
    if (compare_and_swap(&s->top, old_top, n) == old_top)
      return;
  }
}

Node* pop(Stack* s) {
  while (1) {
    hazard[t] = s->top;
    Node* top = hazard[t];
    if (top == NULL)
      return NULL;
    Node* new_top = top->next;
    if (compare_and_swap(&s->top, top, new_top))
      return top;  // Caller must clear hazard[t] when it's done with top
  }
}
```

- Node cannot be recycled or reused if matches any hazard pointer

Lock-free linked list insertion *

```
struct Node {                struct List {
   int value;                  Node* head;
   Node* next;               };
};

// insert new node after specified node
void insert_after(List* list, Node* after, int value) {

   Node* n = new Node;
   n->value = value;

   // assume case of insert into empty list handled
   // here (keep code on slide simple for class discussion)

   Node* prev = list->head;

   while (prev->next) {
     if (prev == after) {
       while (1) {
         Node* old_next = prev->next;
         n->next = old_next;
         if (compare_and_swap(&prev->next, old_next, n) == old_next)
            return;
       }
     }

     prev = prev->next;
   }
}
```

Compared to fine-grained locking implementation:

No overhead of taking locks
No per-node storage overhead

* For simplicity, this slide assumes the *only* operation on the list is insert

Lock-free linked list deletion

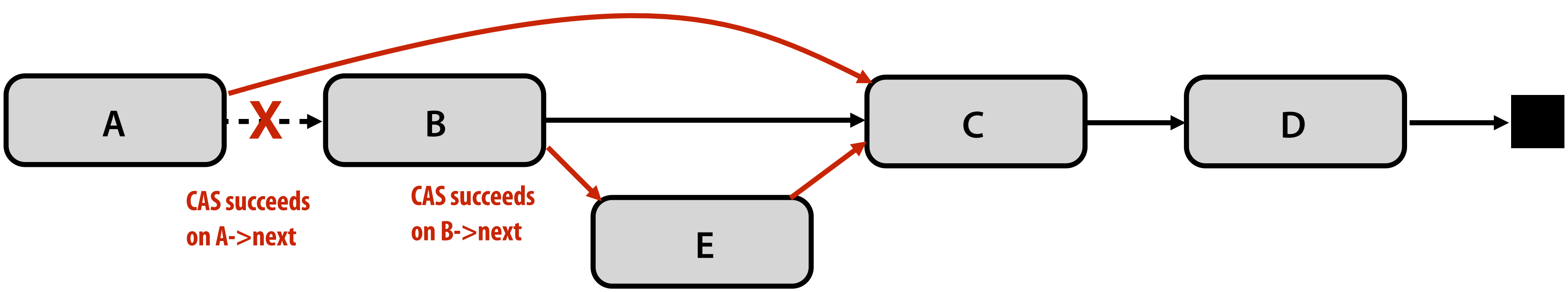
Supporting lock-free deletion significantly complicates data-structure

Consider case where B is deleted simultaneously with successful insertion of E after B.

B now points to E, but B is not in the list!

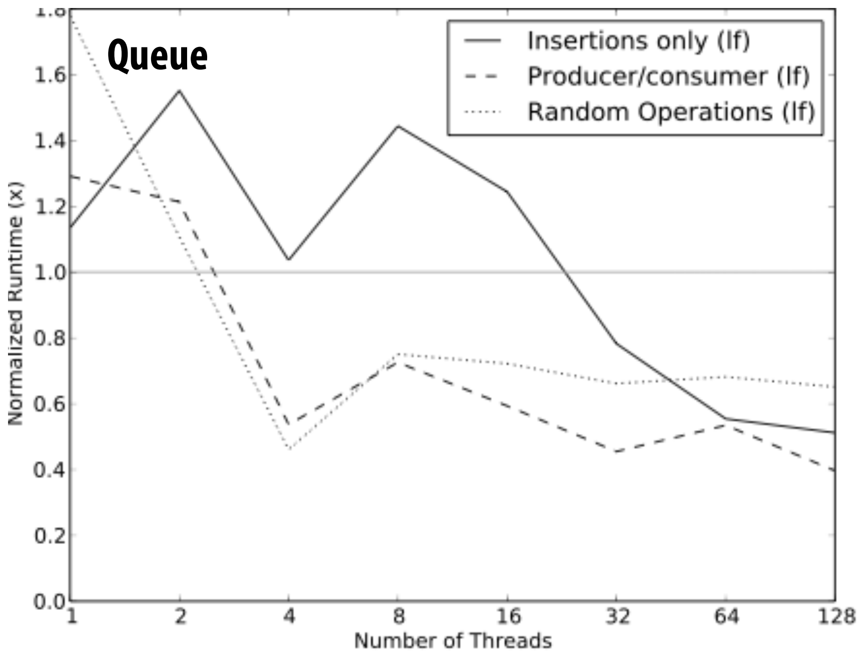
For the curious:

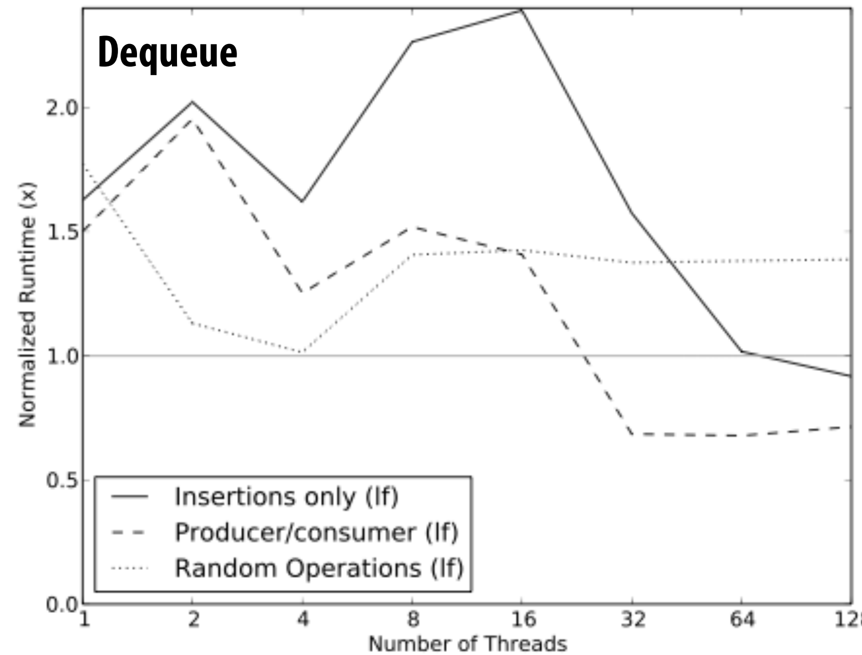
- Harris 2001. A Pragmatic Implementation of Non-blocking Linked-Lists
- Fomitchev 2004. Lock-free linked lists and skip lists

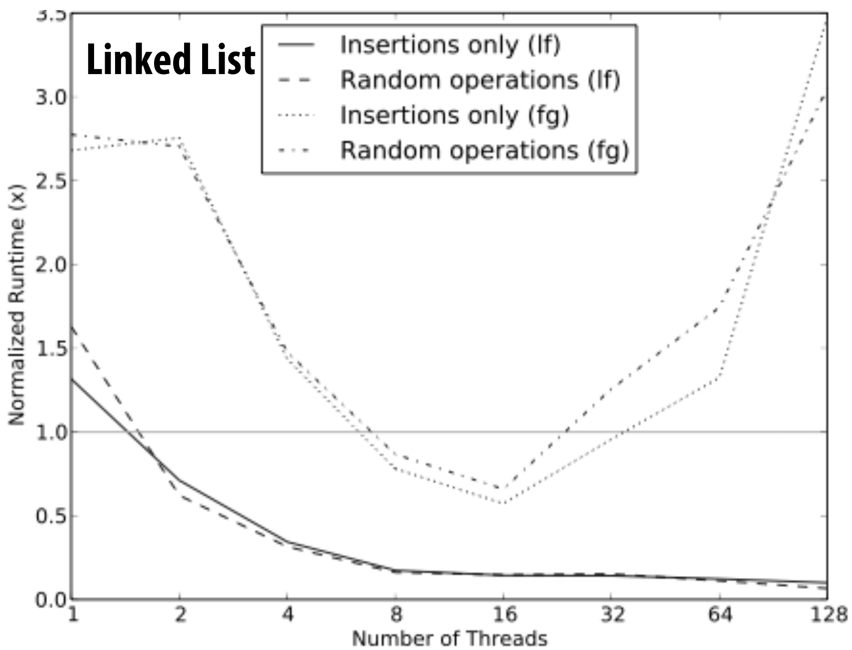


Lock-free vs. locks performance comparison

Lock-free algorithm run time normalized to run time of using pthread mutex locks







lf = "lock free"
fg = "fine grained lock"

Source: Hunt 2011. Characterizing the Performance and Energy Efficiency of Lock-Free Data Structures

In practice: why lock free data-structures?

- When optimizing parallel programs in this class you often assume that only your program is using the machine
  - Because you care about performance
  - Typical assumption in scientific computing, graphics, data analytics, etc.
- In these cases, well written code with locks can be as fast (or faster) than lock-free code
- But there are situations where code with locks can suffer from tricky performance problems
  - Multi-programmed situations where page faults, pre-emption, etc. can occur while thread is in a critical section
  - Creates problems like priority inversion, convoying, crashing in critical section, etc. that are often discussed in OS classes
- Lock free also does well with large data structures with sparse updates
  - Chances of two updates at same place are very low

Summary

- **Use fine-grained locking to reduce contention (maximize parallelism) in operations on shared data structures**
  - But fine-granularity can increase code complexity (errors) and increase execution overhead

- **Lock-free data structures: non-blocking solution to avoid overheads due to locks**
  - But can be tricky to implement (ensuring correctness in a lock-free setting has its own overheads)
  - Still requires appropriate memory fences on modern relaxed consistency hardware

- **Note: a lock-free design does not eliminate contention**
  - Compare-and-swap can fail under heavy contention, requiring spins

More reading

- Michael and Scott 1996. Simple, Fast and Practical Non-Blocking and Blocking Concurrent Queue Algorithms
  - Multiple reader/writer lock-free queue

- Harris 2001. A Pragmatic Implementation of Non-Blocking Linked-Lists
- Many good blog posts and articles on the web:
  - http://www.drdobbs.com/cpp/lock-free-code-a-false-sense-of-security/210600279
  - http://developers.memsql.com/blog/common-pitfalls-in-writing-lock-free-algorithms/

- Often students like to implement lock-free data structures for projects
  - Linked list, skip-list based maps (Java's ConcurrentSkipListMap), list-based sets, etc.
  - Recommend using CMU Ph.D. student Michael Sullivan's RMC system to implement these projects.