Lecture 17:

Fine-grained synchronization & lock-free programming

Parallel Computer Architecture and Programming
CMU 15-418/15-618, Fall 2025

Today's Topics

- Fine-grained Synchronization
- 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?**

Recall 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 Builtins

```
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

Implementing atomic fetch-and-op

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

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

```
void atomic_max(int* addr, int x) {
   int old = *addr;
   int new = max(old, x);
   while (atomicCAS(addr, old, new) != old) {
     old = *addr;
     new = max(old, x);
   }
}
```

- **What about these operations?**

```
int atomic_increment(int* addr, int x);   // for signed values of x
void lock(int* addr);
```

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 for more details

```
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:
    - On a bus, the processor uses the lock signal and holds the bus until the operation completes
    - On other designs, the processor (probably) NACKs any request for the cache line until the operation completes

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

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?

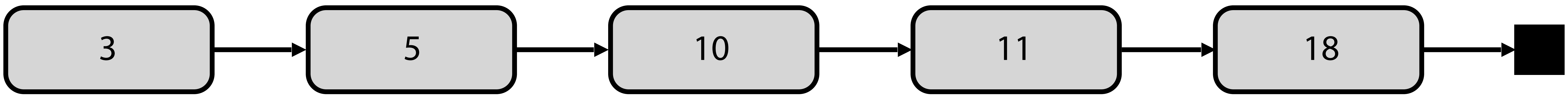
```
void insert(List* list, int value) {

   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;
}
```

```
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;
       delete cur;
       return;
     }

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

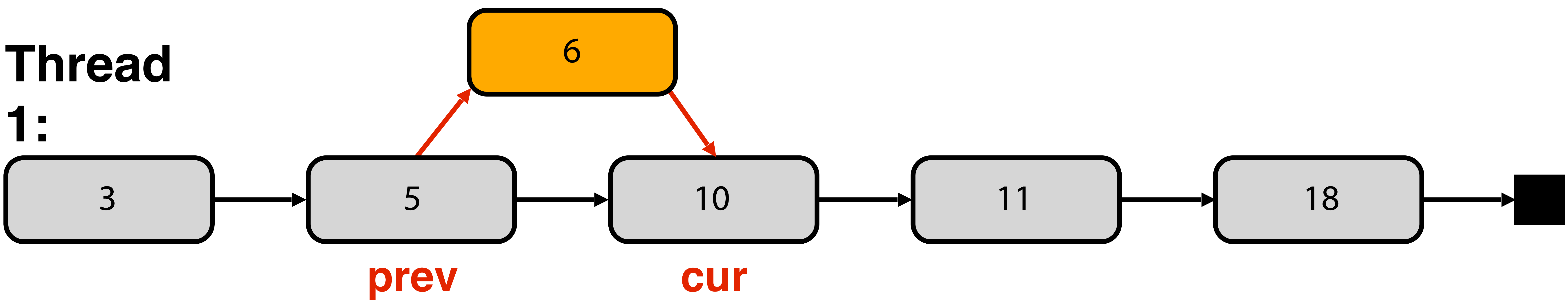
Example: simultaneous insertion

Thread 1 attempts to insert 6

Thread 2 attempts to insert 7



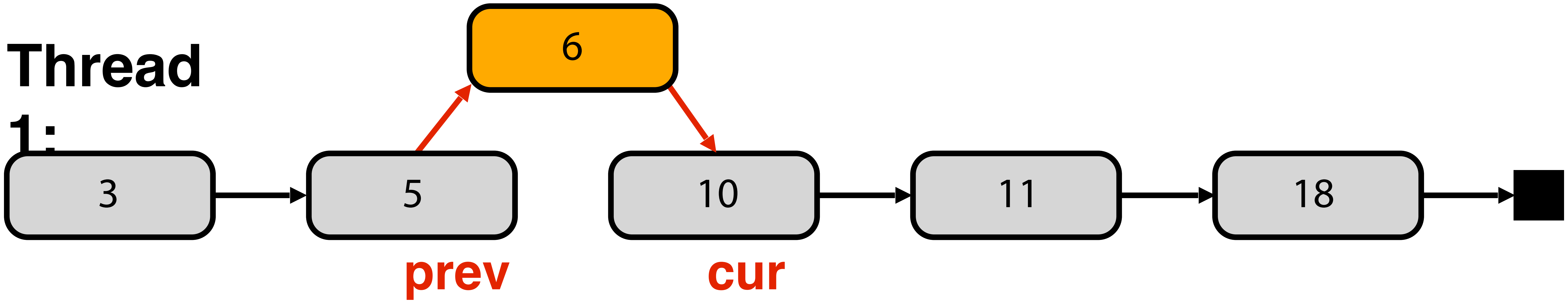
Thread 1:



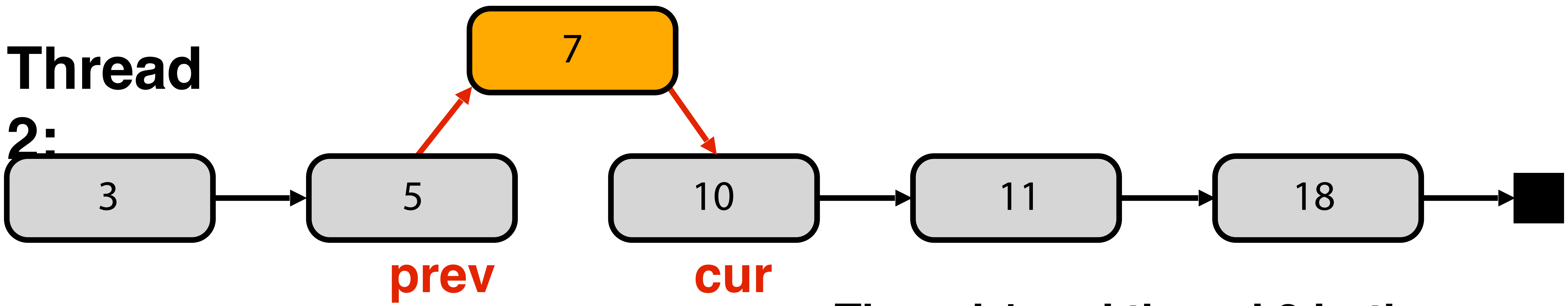
Example: simultaneous insertion

Thread 1 attempts to insert 6
Thread 2 attempts to insert 7

Thread 1:

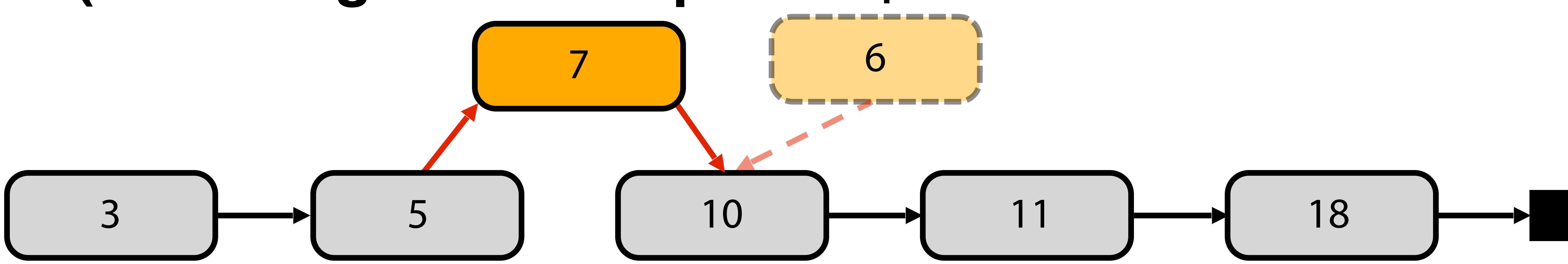


Thread 2:



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

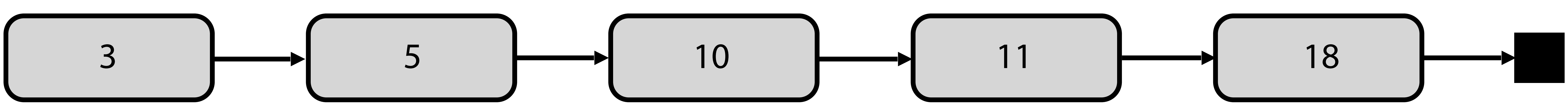
Challenge: who can do better?

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

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

```
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;
   }

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

```
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;
       delete cur;
       return;
     }

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

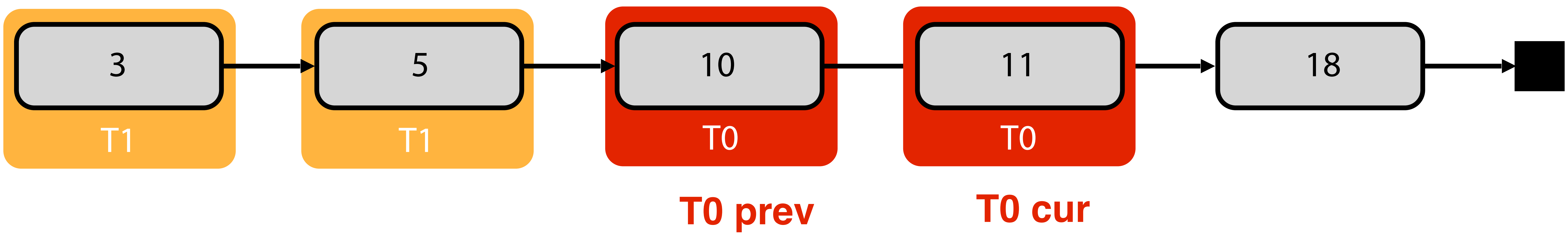


Solution 2: “hand-over-hand” locking

Thread 0: delete(11)

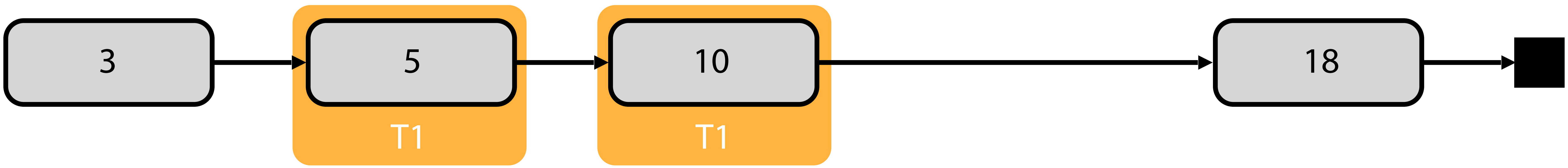
Solution 2: "hand-over-hand" locking

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



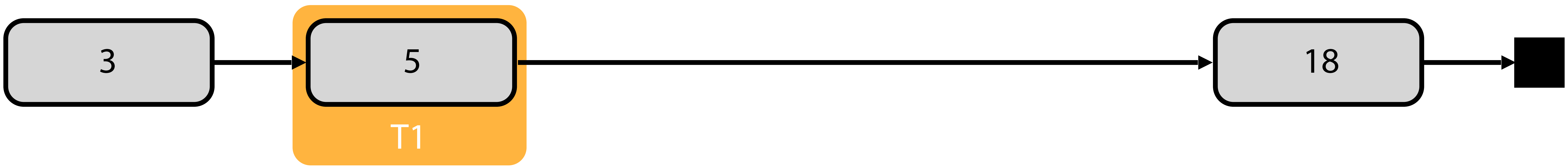
Solution 2: "hand-over-hand" locking

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



Solution 2: "hand-over-hand" locking

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



Solution 2: fine-grained locking

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

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

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

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

   // assume case of insert before head handled
   // here (to keep slide simple)

   Node* prev, *cur;

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

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

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

     Node* old_prev = prev;
     prev = cur;
     cur = cur->next;
     unlock(old_prev->lock);
     if (cur) lock(cur->lock);
   }

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

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

Challenge to students: there is way to further improve the implementation of insert(). What is it?

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

   // assume case of delete head handled here
   // (to keep slide simple)

   Node* prev, *cur;

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

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

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

     Node* old_prev = prev;
     prev = cur;
     cur = cur->next;
     unlock(old_prev->lock);
     if (cur) lock(cur->lock);
   }
   unlock(prev->lock);
}
```

Fine-grained 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)
  - Extra storage cost (a lock per node)
  - What is a middle-ground solution that trades off some parallelism for reduced overhead? (hint: similar issue to selection of task granularity)

Practice exercise

- **Implement a fine-grained locking implementation of a binary search tree supporting insert and delete**

```
struct Tree {
  Node* root;
};

struct Node {
   int value;
   Node* left;
   Node* right;
};

void insert(Tree* tree, int value);
void delete(Tree* tree, int value);
```

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 <u>bounded</u> queue *

```
struct Queue {
  int data[N];
  int head;   // head of queue
  int 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->tail == MOD_N(q->head - 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)**

*** Assume a sequentially consistent memory system for now (or the presence of appropriate memory fences, or C++ 11 atomic<>)**

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

Source: Dr. Dobbs Journa

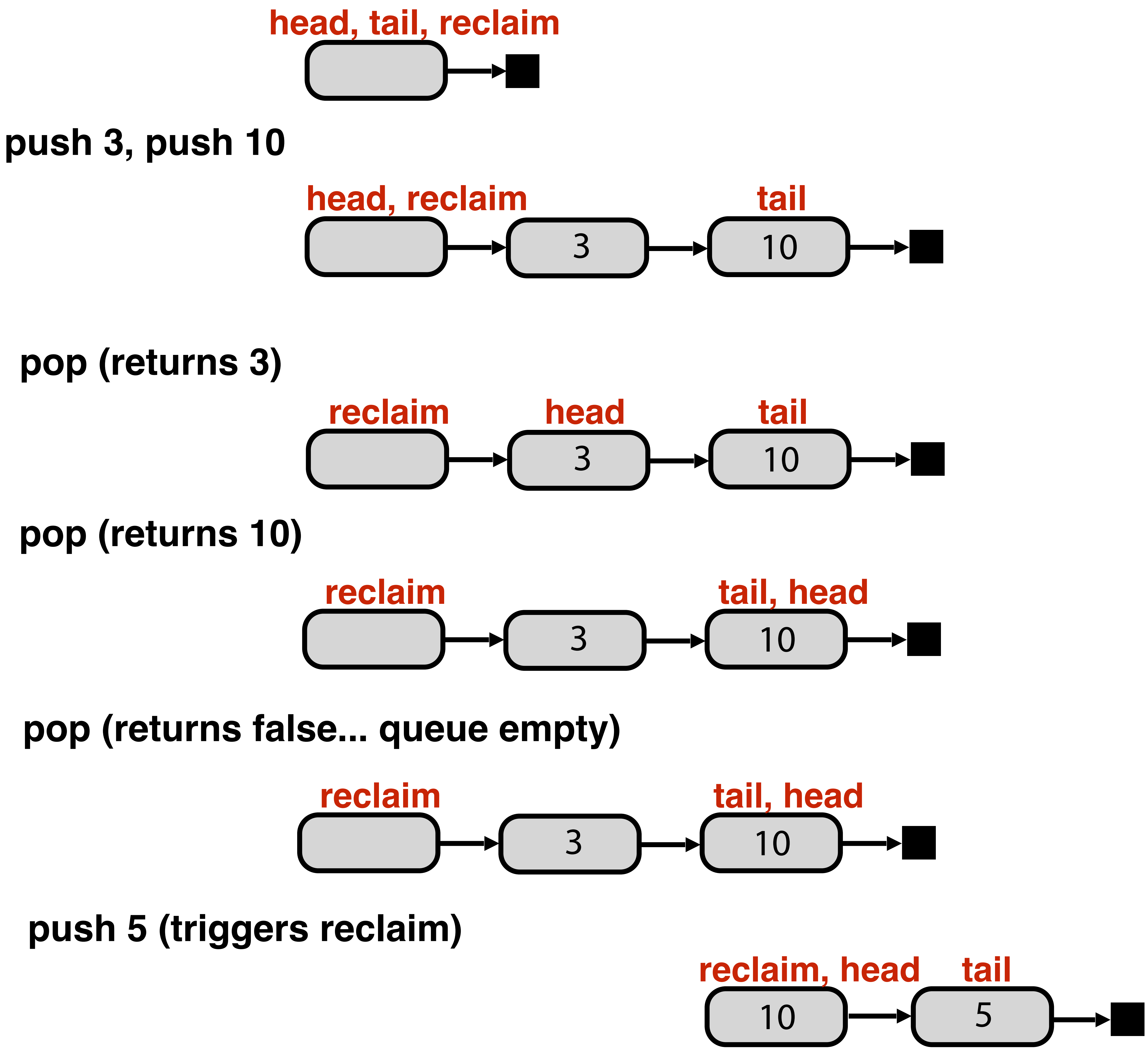
```
struct Node {
  Node* next;
  int value;
};

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)

* Assume a sequentially consistent memory system for now
(or the presence of appropriate memory fences, or C++ 11 atomic<>)

Single reader, single writer unbounded queue



Lock-free stack (first try)

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

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

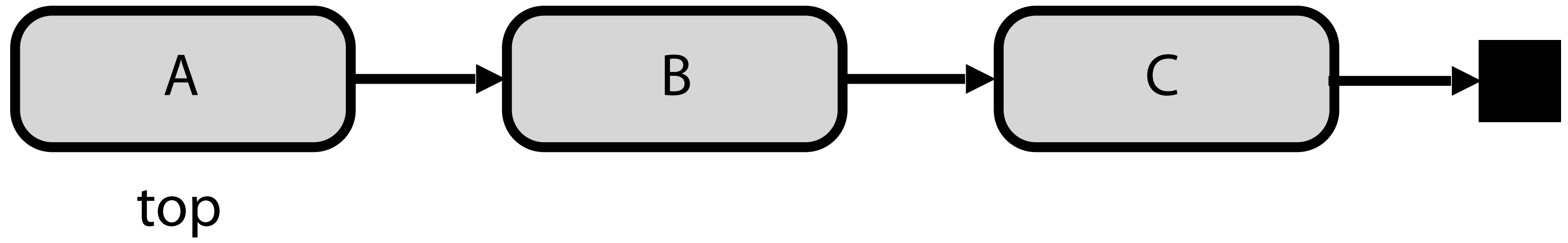
```
void init(Stack* s) {
  s->top = NULL;
}

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;
  }
}
```

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.

The ABA problem

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

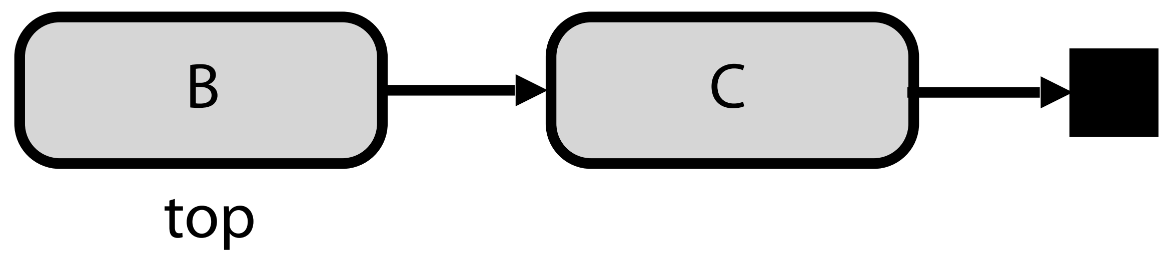
Thread 0	Thread 1



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

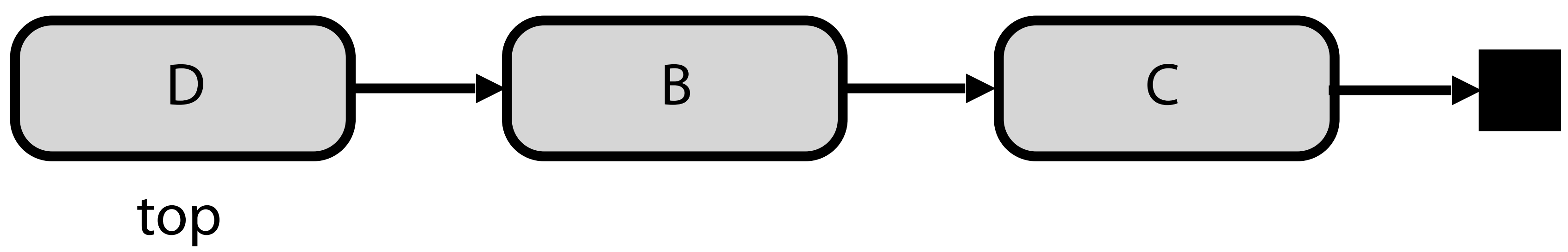
begin pop() (local variable old_top == A)

complete pop() (returns A)

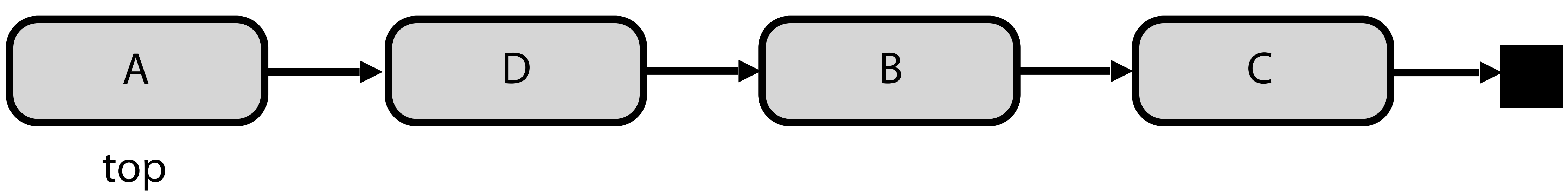


begin push(D)

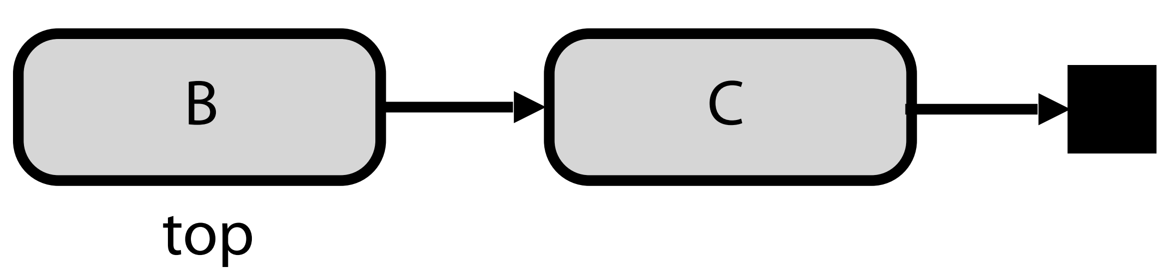
complete push(D)



modify node A: e.g., set value = 42
begin push(A)
complete push(A)



CAS succeeds (sets top to B!)
complete pop() (returns A)



Stack structure is corrupted! (lost D)

time

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 problem: 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, int value) {
  Node* n = new Node;
  n->value = value;
  while (1) {
    Node* old_top = s->top;
    n->next = old_top;
    if (compare_and_swap(&s->top, old_top, n) == old_top)
      return;
  }
}

int pop(Stack* s) {
  while (1) {
    Stack old;
    old.pop_count = s->pop_count;
    old.top = s->top;

    if (old.top == NULL)
      return NULL;

    Stack new_stack;
    new_stack.top = old.top->next;
    new_stack.pop_count = old.pop_count+1;

    if (doubleword_compare_and_swap(&s, &old, new_stack))
      int value = top->value;
      delete top;
      return value;
    }
  }
}
```

top might have been freed at this point by the thread that popped it.

Hazard pointer: avoid freeing nodes until its determined all other threads do not hold reference to node

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

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

// per thread ptr (node that cannot
// be deleted since the thread is
// accessing it)
Node* hazard;

// per-thread list of nodes thread
// must delete
Node* retireList;
int   retireListSize;

// delete nodes if possible
void retire(Node* ptr) {
  push(retireList, ptr);
  retireListSize++;

  if (retireListSize > THRESHOLD)
     for (each node n in retireList) {
        if (n not pointed to by any
            thread's hazard pointer) {
           remove n from list
           delete n;
        }
     }
}
```

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

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

int pop(Stack* s) {
  while (1) {
    Stack old;
    old.pop_count = s->pop_count;
    old.top = s->top;

    if (old.top == NULL) return NULL;

    hazard = old.top;
    Stack new_stack;
    new_stack.top = old.top->next;
    new_stack.pop_count = old.pop_count+1;

    if (doubleword_compare_and_swap(&s, &old, new_stack))
    {
      int value = old.top->value;
      retire(old.top);
      return value;
    }
    hazard = NULL;
  }
}
```

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**

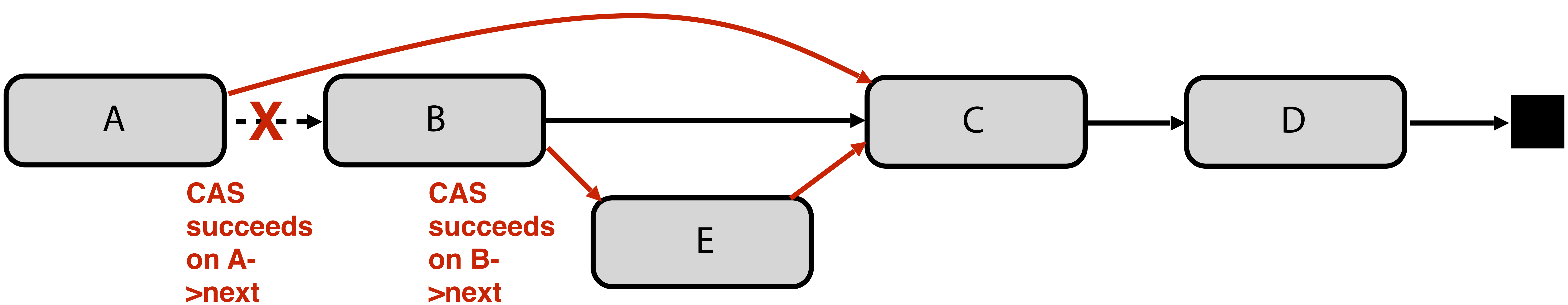
Lock-free linked list deletion

Supporting lock-free deletion significantly complicates data-structure

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

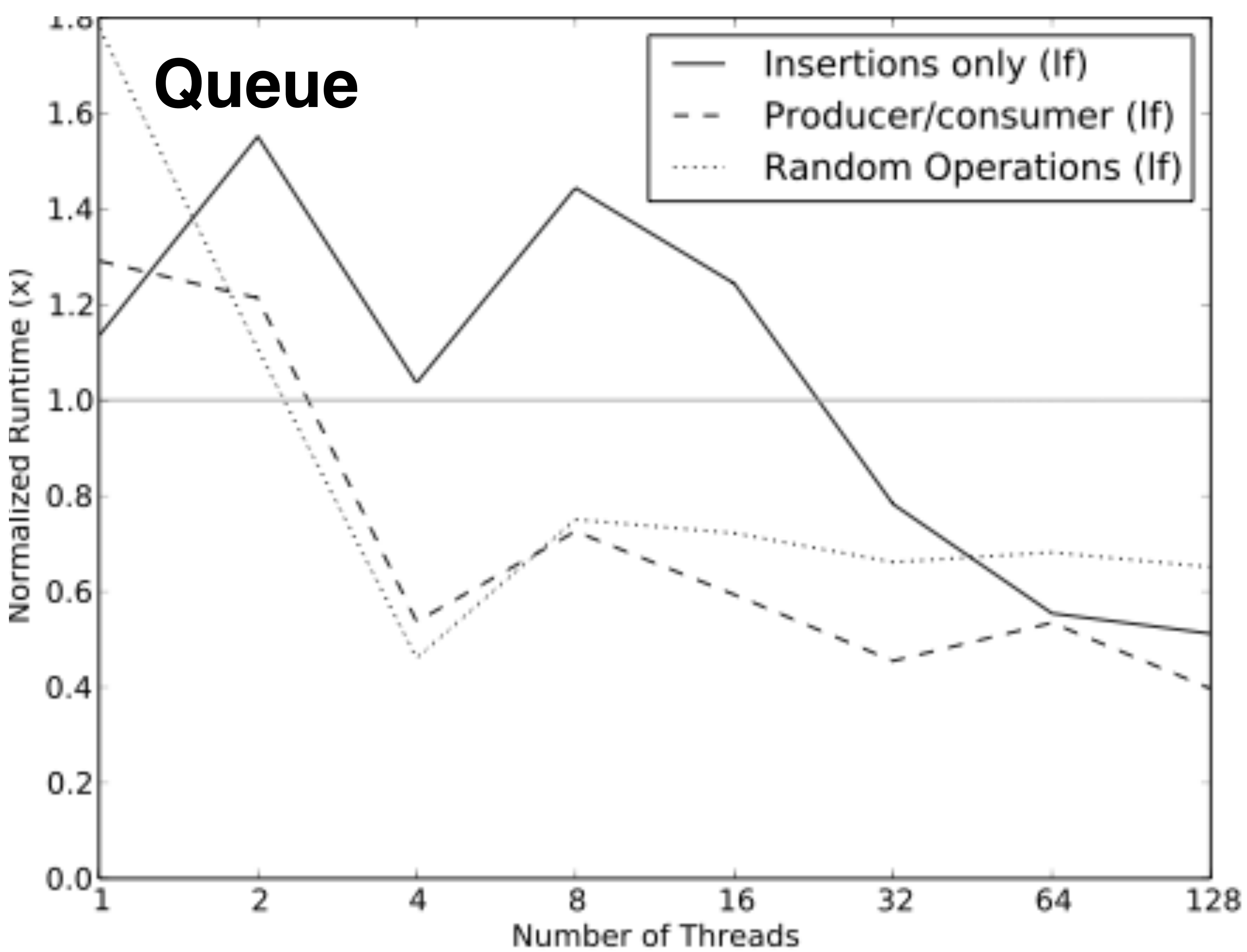
B now points to E, but B is not in the list!

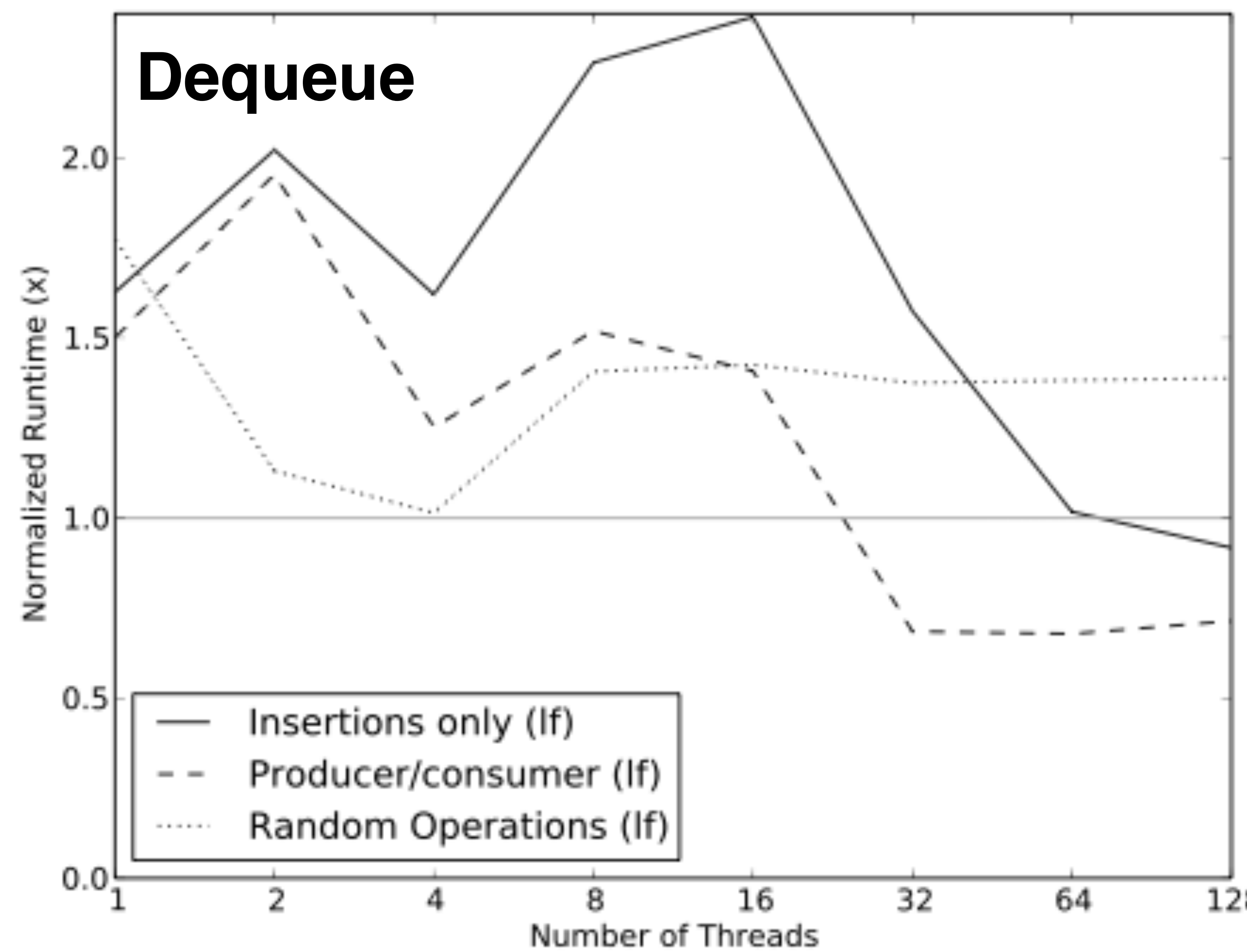
For the curious:
- Harris 2001. A Pragmatic Implementation of Non-blocking Linked-Lists
- Fomitchev 2004. Lock-free linked lists and skip lists

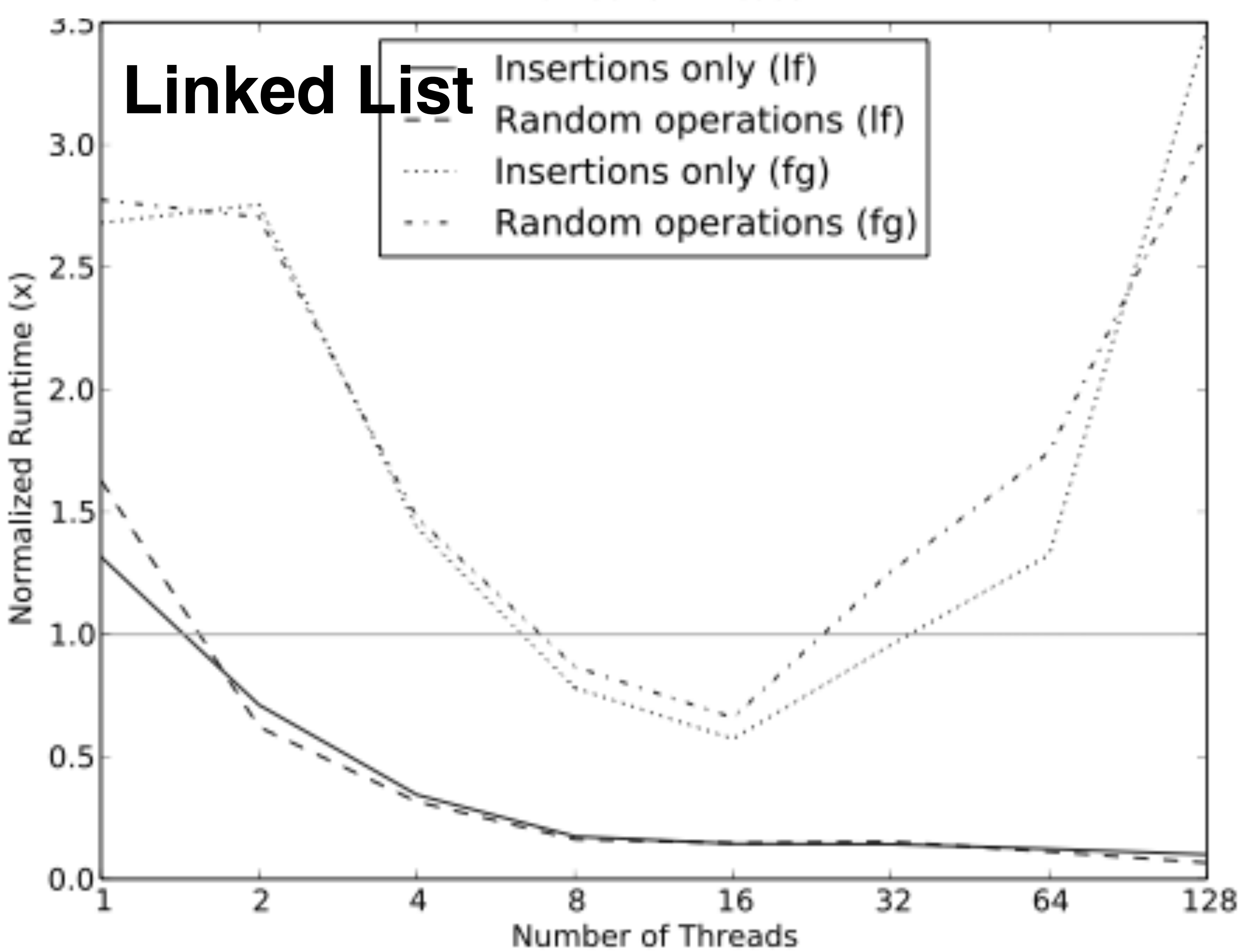


Lock-free vs. locks performance comparison

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

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.