Lecture 17:

Fine-grained synchronization & lock-free programming

Parallel Computer Architecture and Programming
CMU 15-418/15-618, Fall 2023

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

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;
    }
}
```
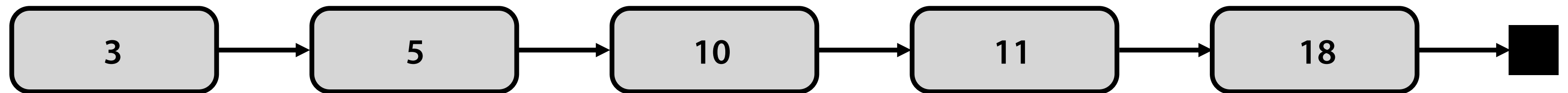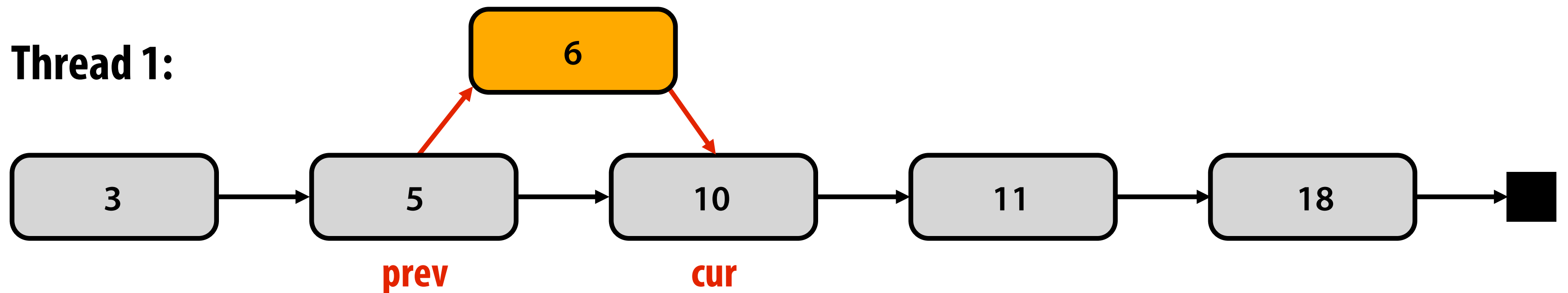
Example: simultaneous insertion

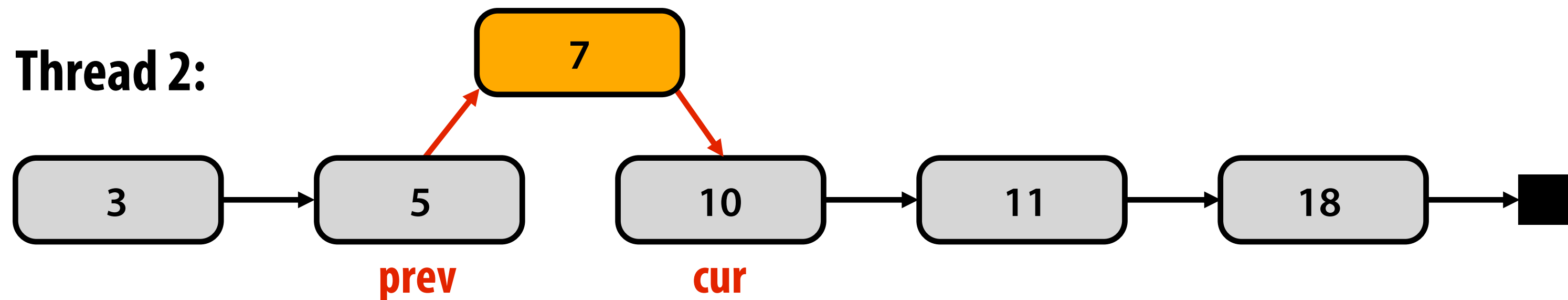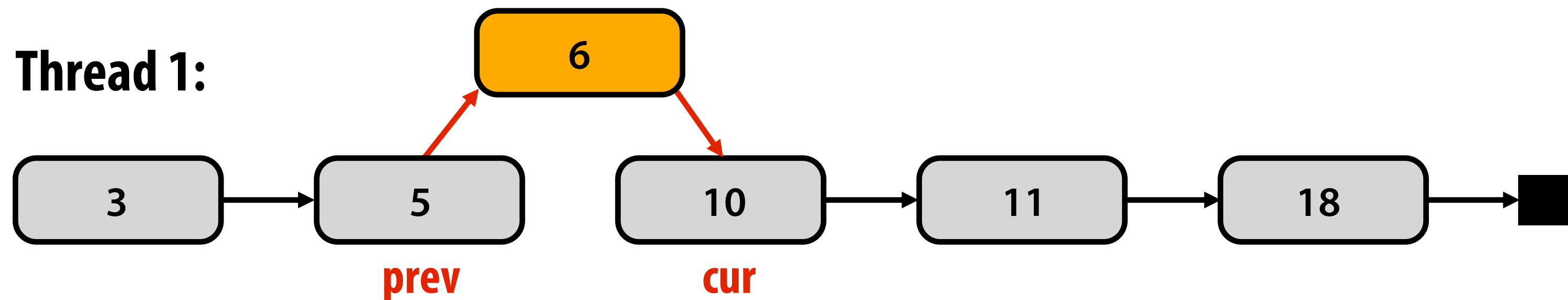**Thread 1 attempts to insert 6**

Thread 2 attempts to insert 7

| 3 | → | 5 | → | 10 | → | 11 | → | 18 | → ■ |

Thread 1:

| 6 |

| 3 | → | 5 | → | 10 | → | 11 | → | 18 | → ■ |

prev   **cur**

Example: simultaneous insertion

Thread 1 attempts to insert 6

Thread 2 attempts to insert 7

Thread 1:

6

3 → 5 → 10 → 11 → 18 → ■

prev **cur**

Thread 2:

7

3 → 5 → 10 → 11 → 18 → ■

prev **cur**

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)

7   6

3 → 5 → 10 → 11 → 18 → ■
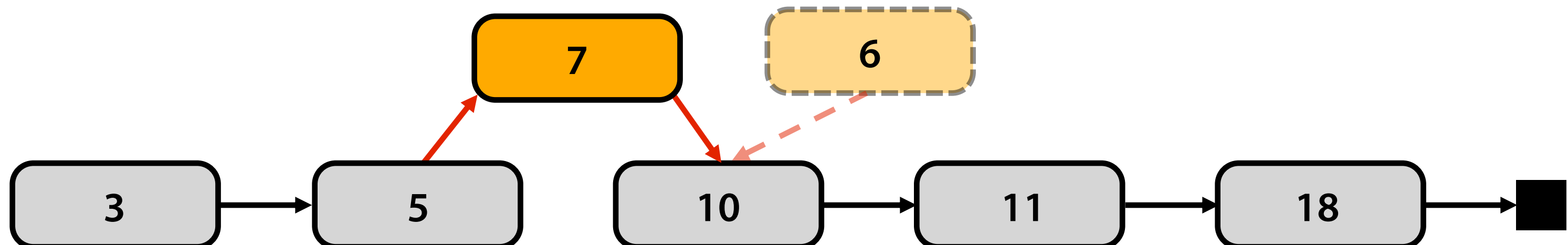
Solution 1: protect the list with a single lock

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

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

    Node* n = new Node;                            // assume case of deleting first element is
    n->value = value;                              // handled here (to keep slide simple)

    // assume case of inserting before head of     Node* prev = list->head;
    // of list is handled here (to keep slide simple)  Node* cur = list->head->next;

    Node* prev = list->head;                       while (cur) {
    Node* cur = list->head->next;                    if (cur->value == value) {
                                                       prev->next = cur->next;
    while (cur) {                                      delete cur;
      if (cur->value > value)                          return;
        break;                                       }

      prev = cur;                                    prev = cur;
      cur = cur->next;                               cur = cur->next;
    }                                              }
                                                 }
    prev->next = n;
    n->next = cur;
}
```
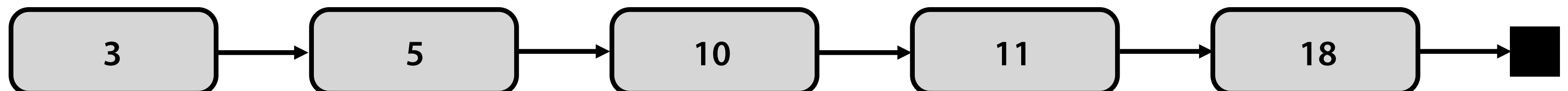
```
+-----+     +-----+     +-----+     +-----+     +-----+
|  3  | --> |  5  | --> | 10  | --> | 11  | --> | 18  | --> ■
+-----+     +-----+     +-----+     +-----+     +-----+
```
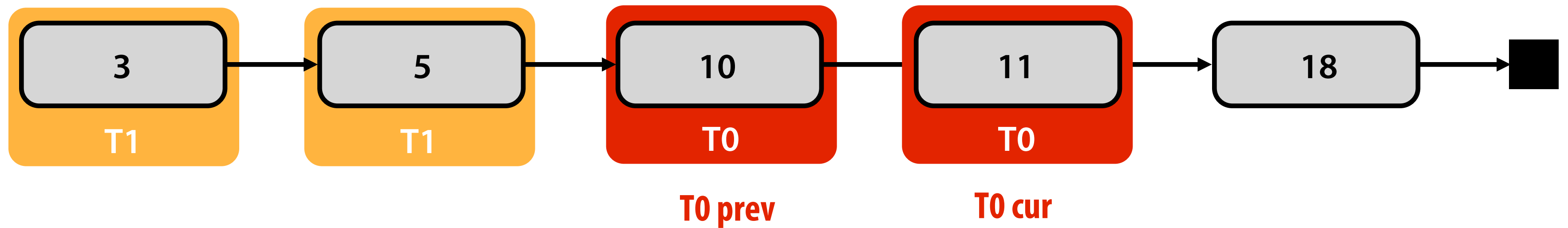
Solution 2: "hand-over-hand" locking

Thread 0: delete(11)

Solution 2: "hand-over-hand" locking
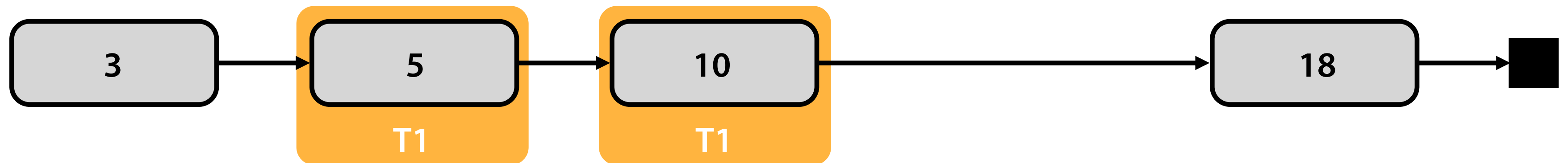
Thread 0: delete(11)
Thread 1: delete(10)

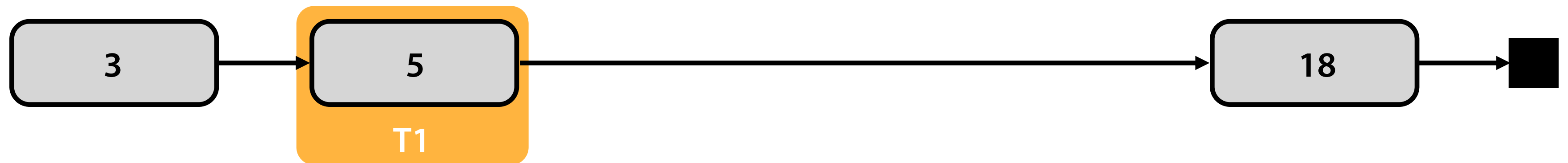# Solution 2: "hand-over-hand" locking

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

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

```
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);
}
```

```
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 __bounded__ 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 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)**

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

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Single reader, single writer unbounded queue

head, tail, reclaim

push 3, push 10

head, reclaim   **tail**

3   10

pop (returns 3)

reclaim   **head**   **tail**

3   10

pop (returns 10)

reclaim   **tail, head**

3   10

pop (returns false... queue empty)

reclaim   **tail, head**

3   10

push 5 (triggers reclaim)

reclaim, head   **tail**

10   5

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
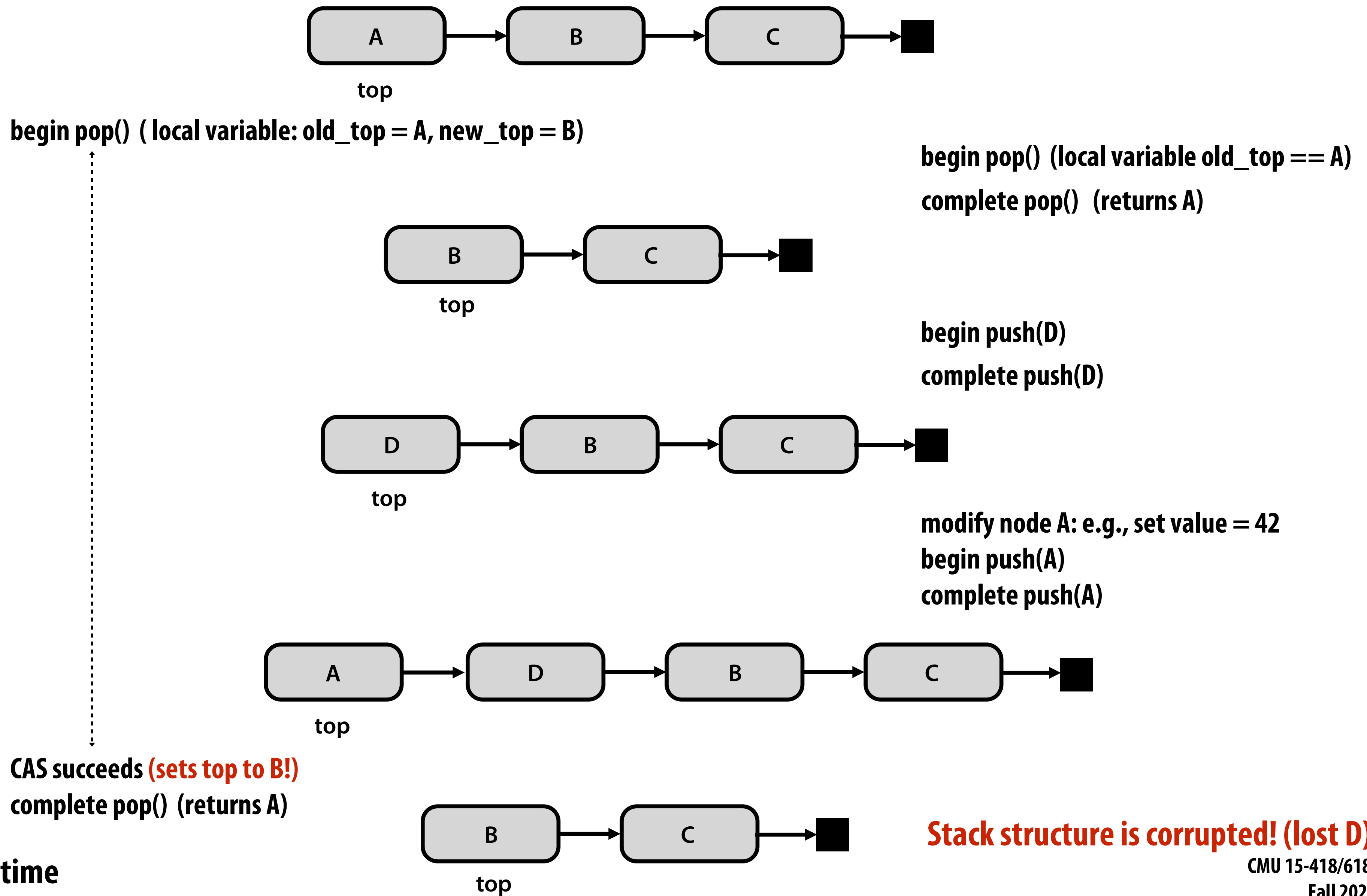data-structure for fine-grained access.   Here, threads do not hold lock on data-structure at all.**

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

The ABA problem

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

Thread 0   **Thread 1**

A → B → C → ■

top

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

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

complete pop() (returns A)

B → C → ■

top

begin push(D)

complete push(D)

D → B → C → ■

top

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

A → D → B → C → ■

top

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

B → C → ■

top

Stack structure is corrupted! (lost D)

time

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Lock-free stack using counter for ABA soln

```
struct Node {                    void init(Stack* s) {
  Node* next;                      s->top = NULL;
  int value;                     }
};
                                 void push(Stack* s, Node* n) {
struct Stack {                     while (1) {
  Node* top;                         Node* old_top = s->top;
  int pop_count;                     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.

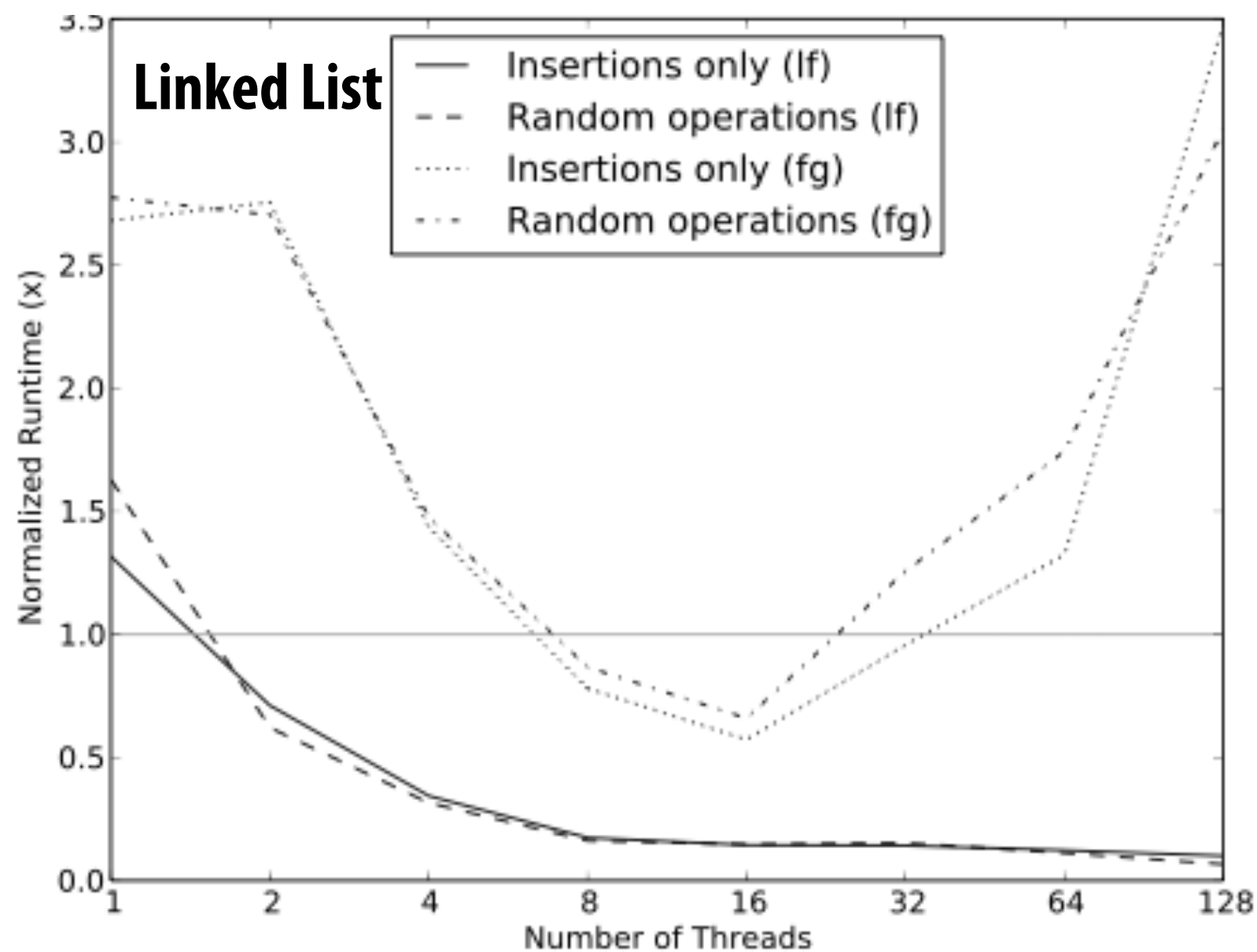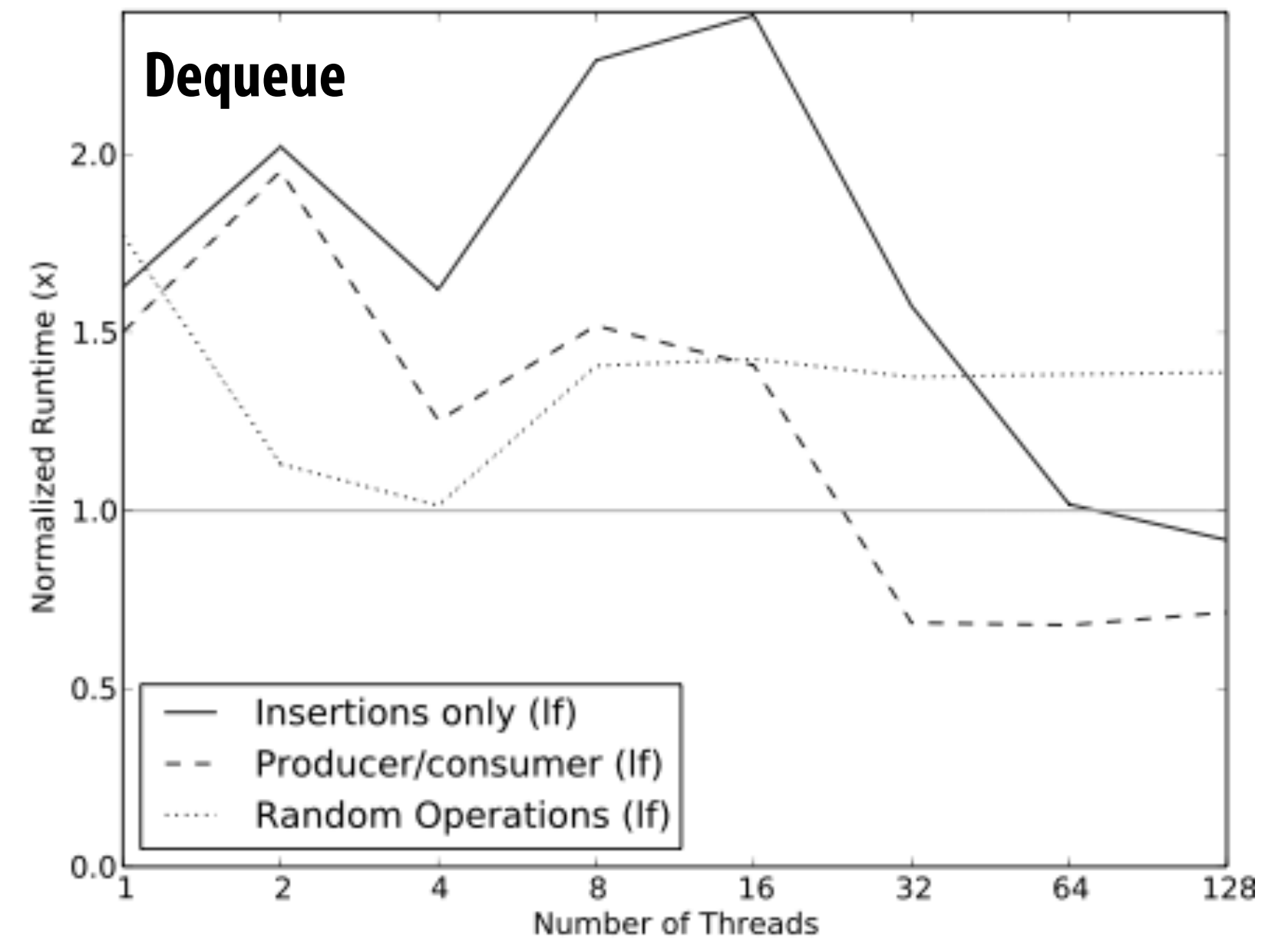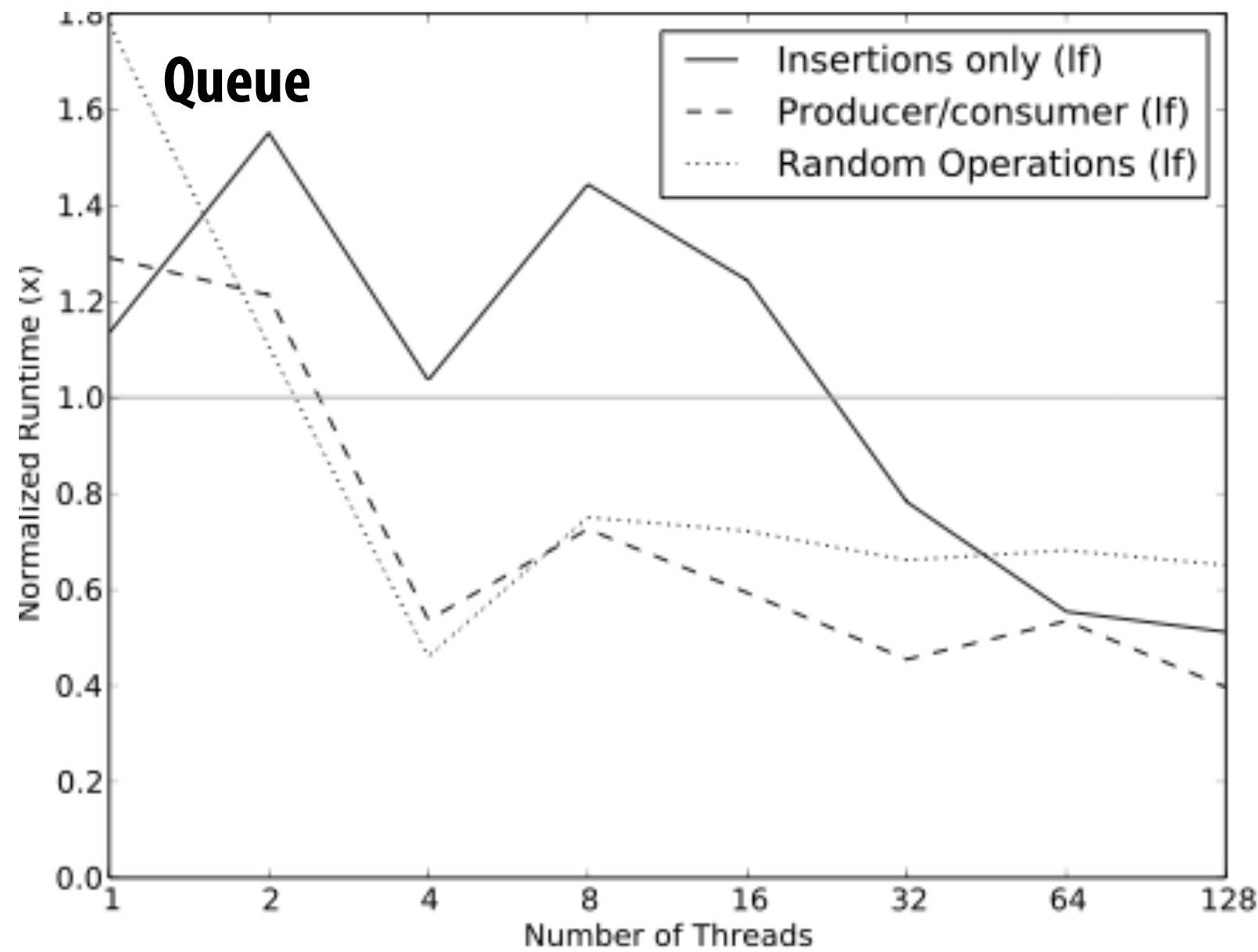B now points to E, but B is not in the list!

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

CAS succeeds on A->next

CAS succeeds on B->next
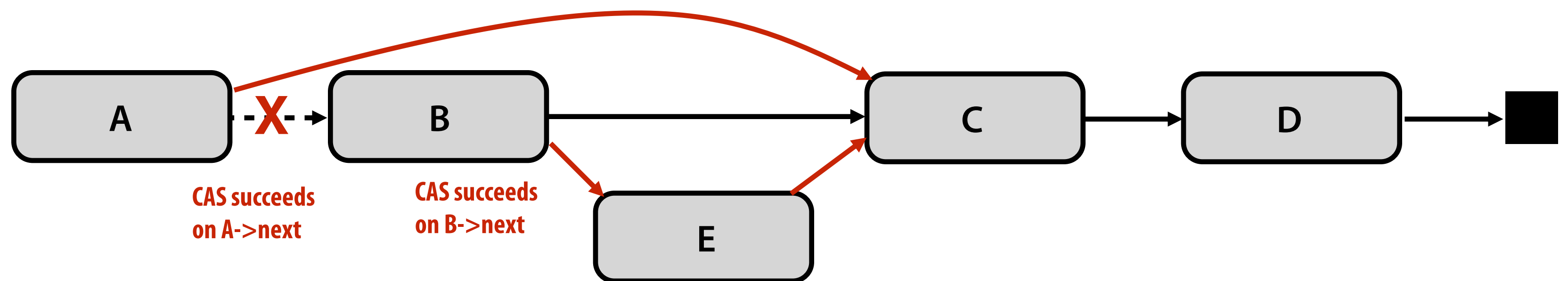
Lock-free vs. locks performance comparison
Lock-free algorithm run time normalized to run time of using pthread mutex locks

If = "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.**