Lecture 13:

Fine-grained Synchronization & Lock-free Programming

Parallel Computing
Stanford CS149, Fall 2019

Tunes

Yeah Yeah Yeahs
“Heads Will Roll”

“Have you seen implementations of lock-free data structures in non- garbage collected languages? ”
- Karen O

Some terminology

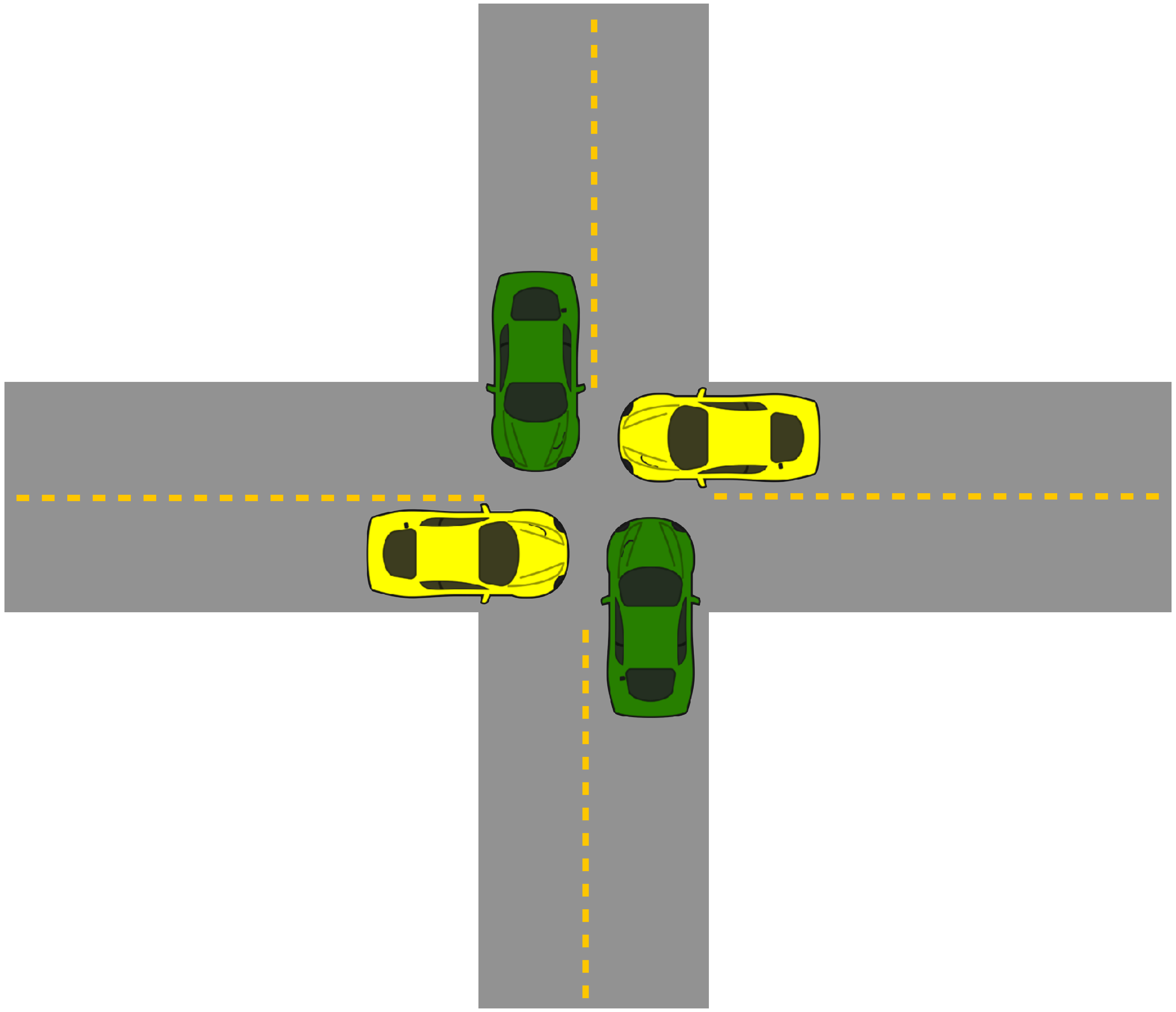
Deadlock

Livelock

Starvation

(Deadlock and livelock concern program correctness. Starvation is really an issue of fairness.)

Deadlock



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

Deadlock can arise when each operation has acquired a <u>shared resource</u> that another operation needs.

In a deadlock situations, there is no way for any thread (or, in this illustration, a car) to make progress unless some thread relinquishes a resource ("backs up")

Traffic deadlock

Non-technical side note for car-owning students: Deadlock happens all the %$* time in SF.**

(However, deadlock can be amusing when a bus driver decides to let another driver know they have caused deadlock... "go take cs149 you fool!")

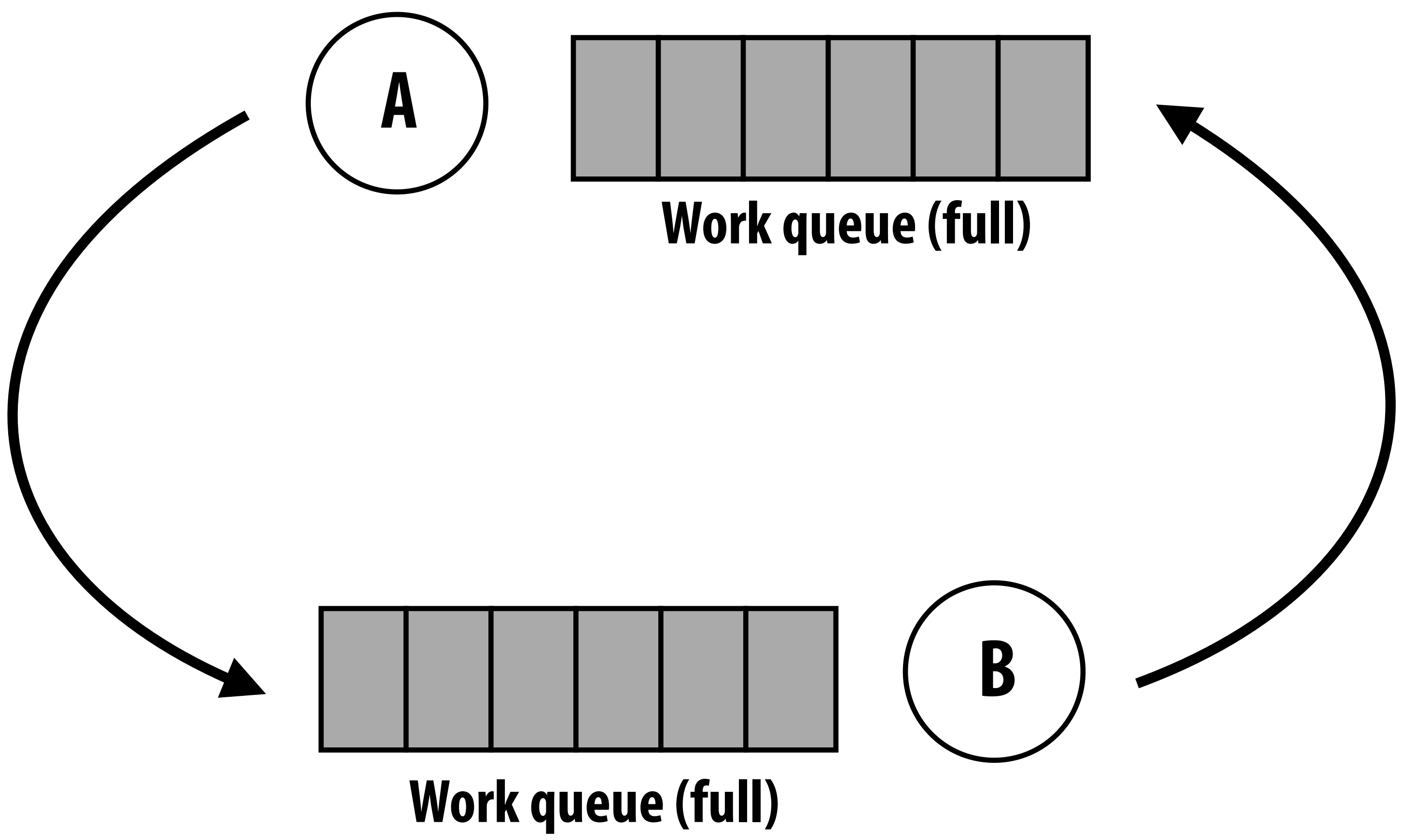
More illustrations of deadlock

Credit: David Maitland, National Geographic

Why are these examples of deadlock?

Deadlock in computer systems

Example 1:



Thread A produces work for B's work queue

Thread B produces work for A's work queue

Queues are finite and workers wait if no output space is available

Example 2:

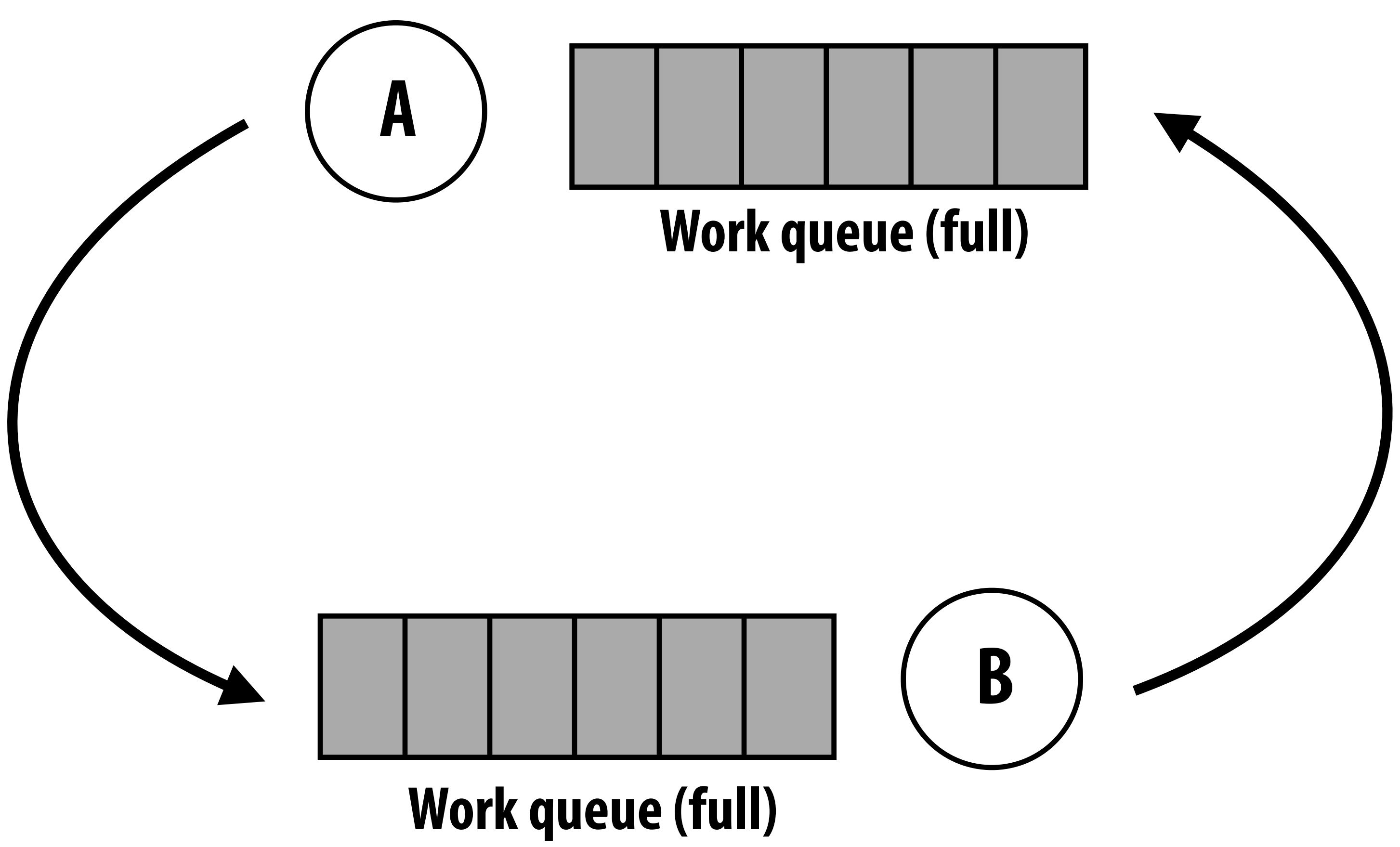
```
const int numEl = 1024;
float msgBuf1[numEl];
float msgBuf2[numEl];

int threadId getThreadId();

... do work ...


MsgSend(msgBuf1, numEl * sizeof(int), threadId+1, ...
MsgRecv(msgBuf2, numEl * sizeof(int), threadId-1, ...
```

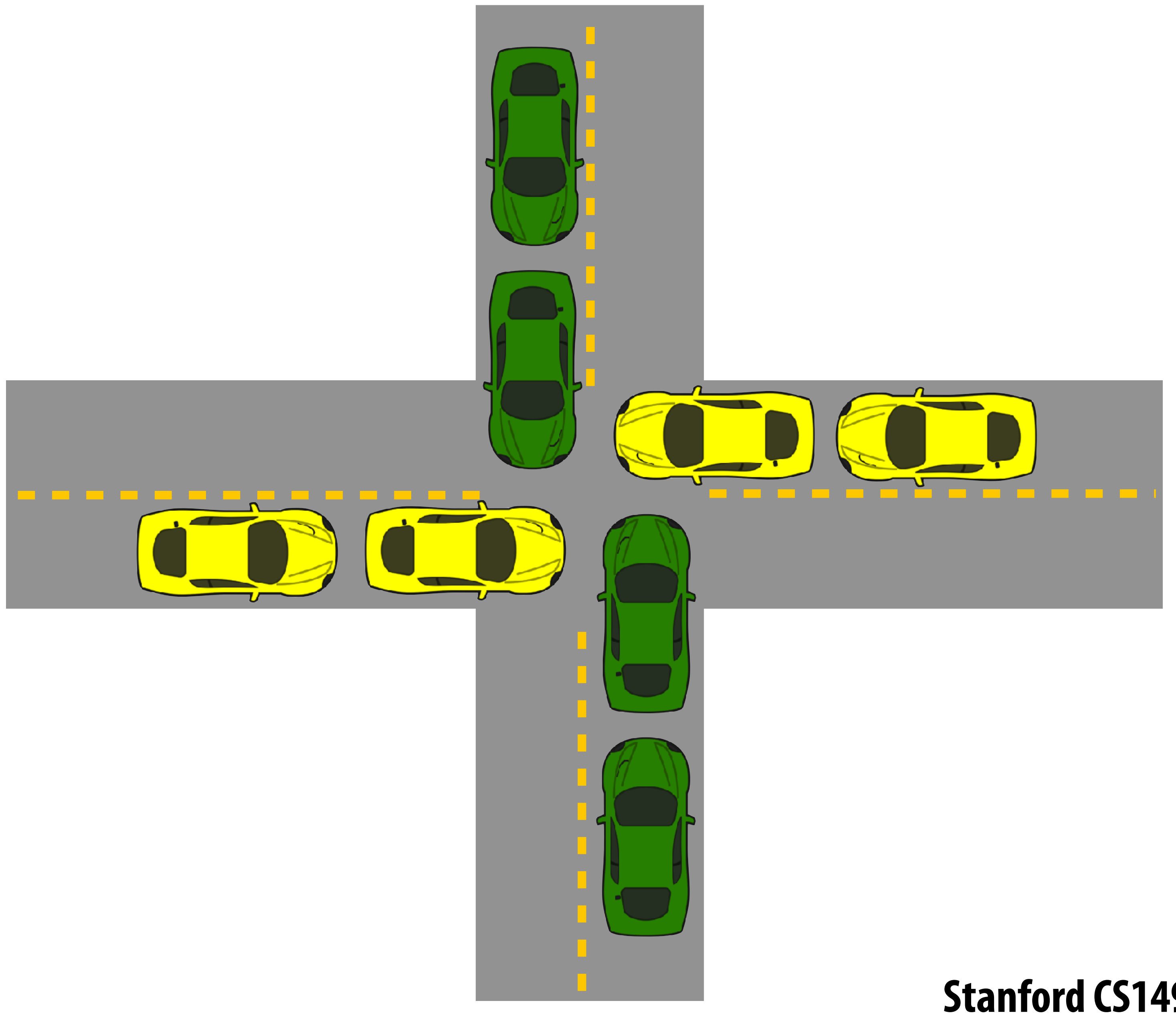
Every thread sends a message (blocking send) to the thread with the next higher id

Then thread receives message from thread with next lower id.

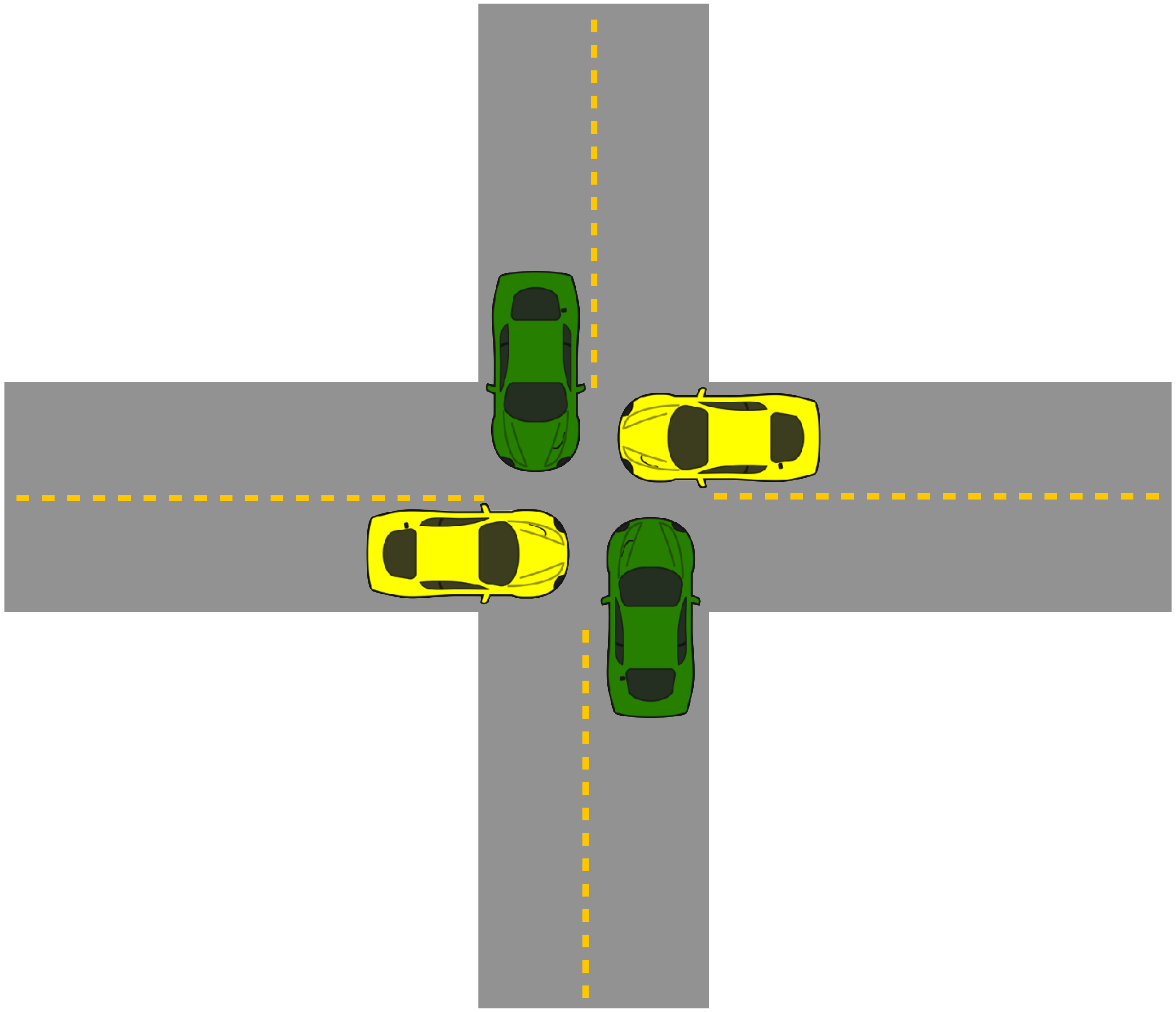
Required conditions for deadlock

1. Mutual exclusion: only one processor can hold a given resource at once
2. Hold and wait: processor must <u>hold</u> the resource while <u>waiting</u> for other resources it needs to complete an operation
3. No preemption: processors don't give up resources until operation they wish to perform is complete
4. Circular wait: waiting processors have mutual dependencies (a cycle exists in the resource dependency graph)

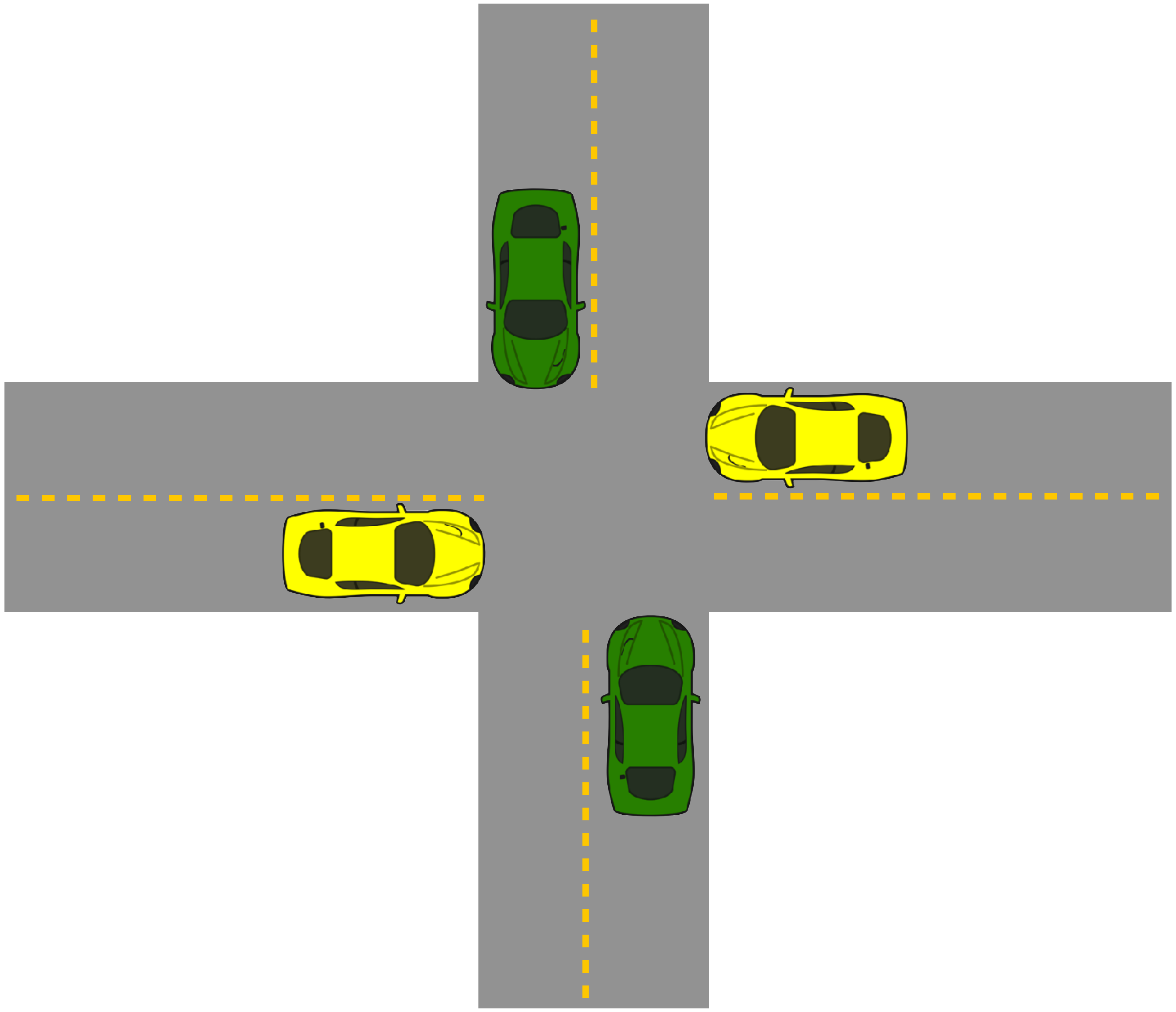




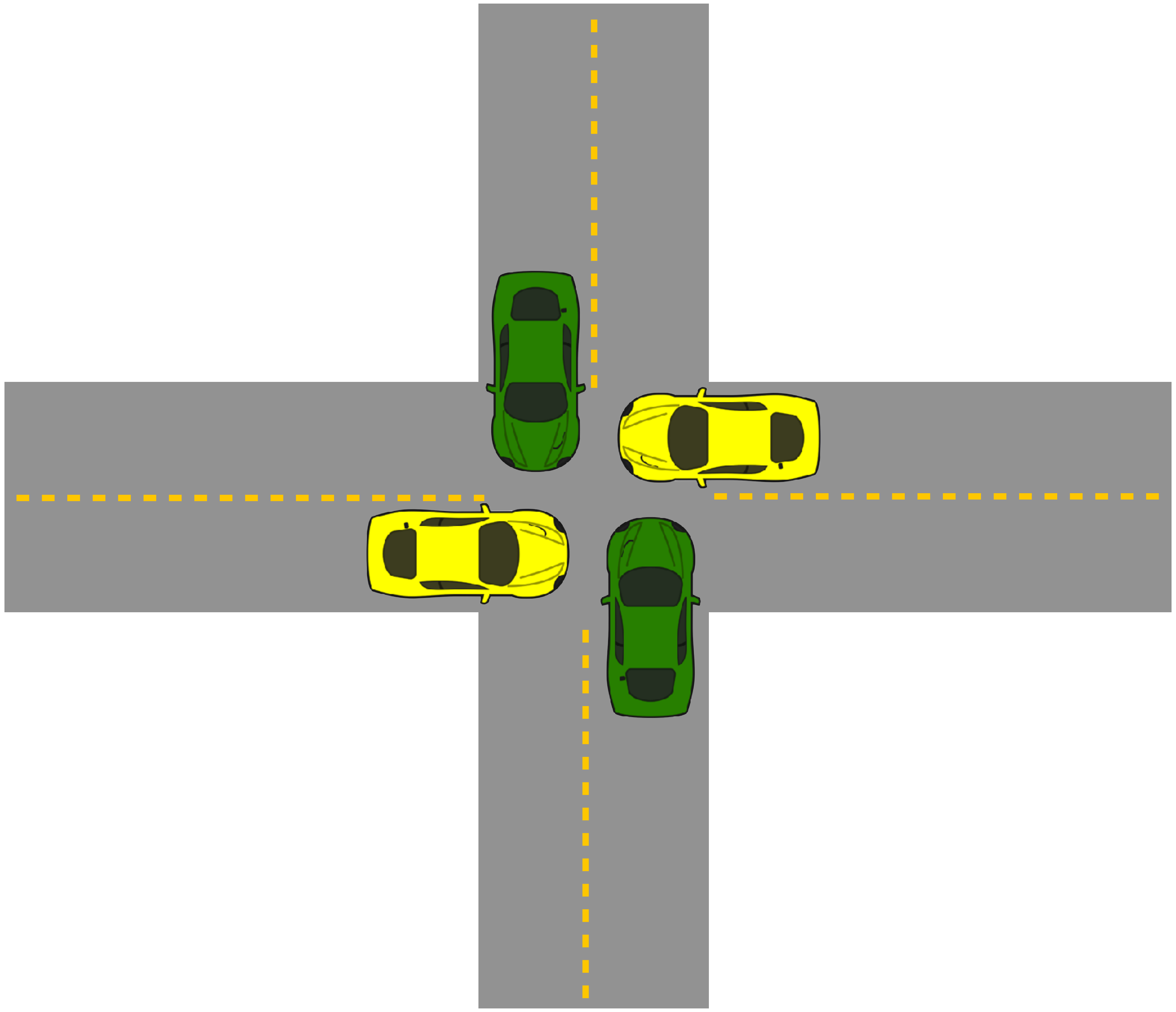
Livelock



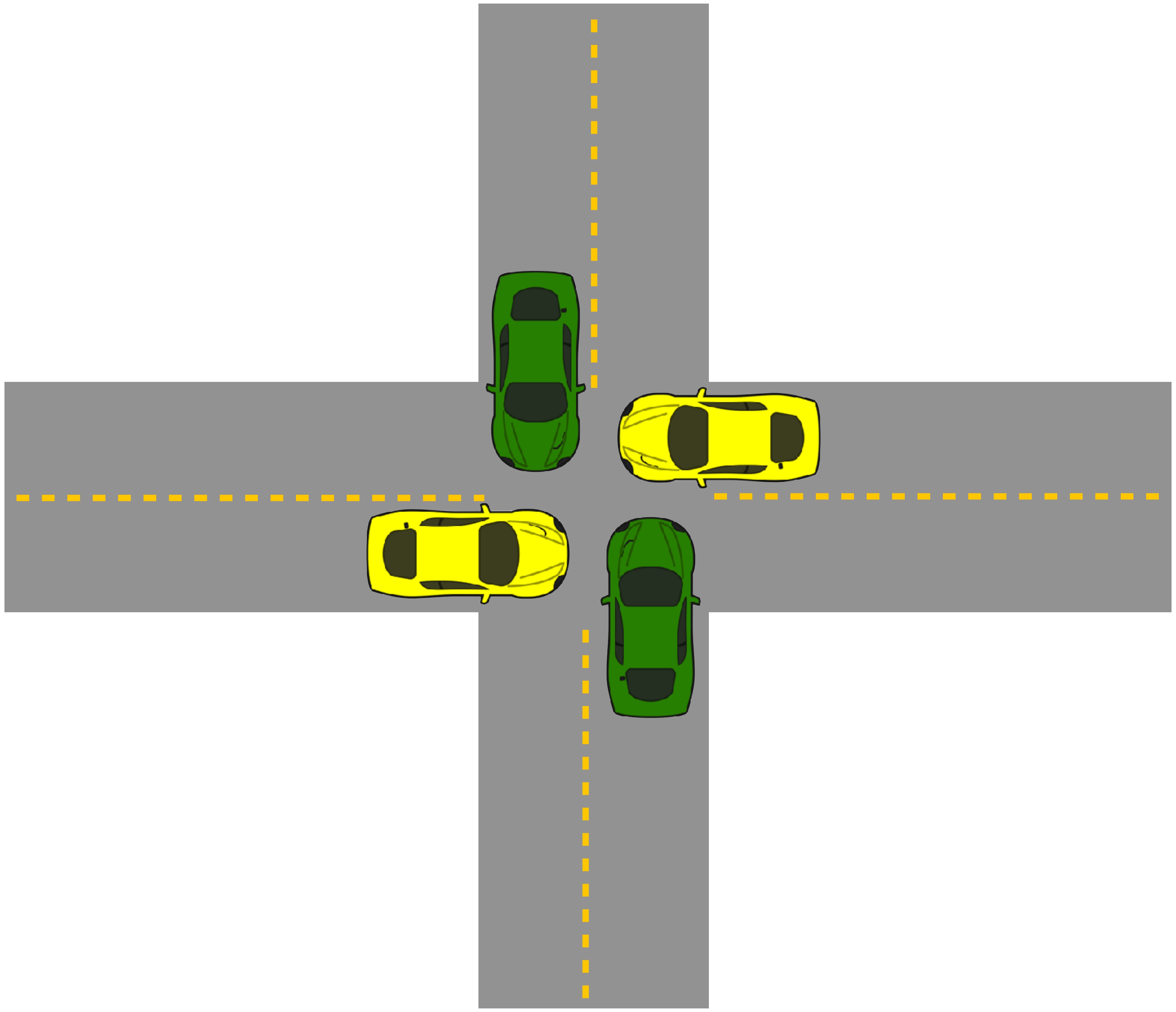
Livelock



Livelock



Livelock



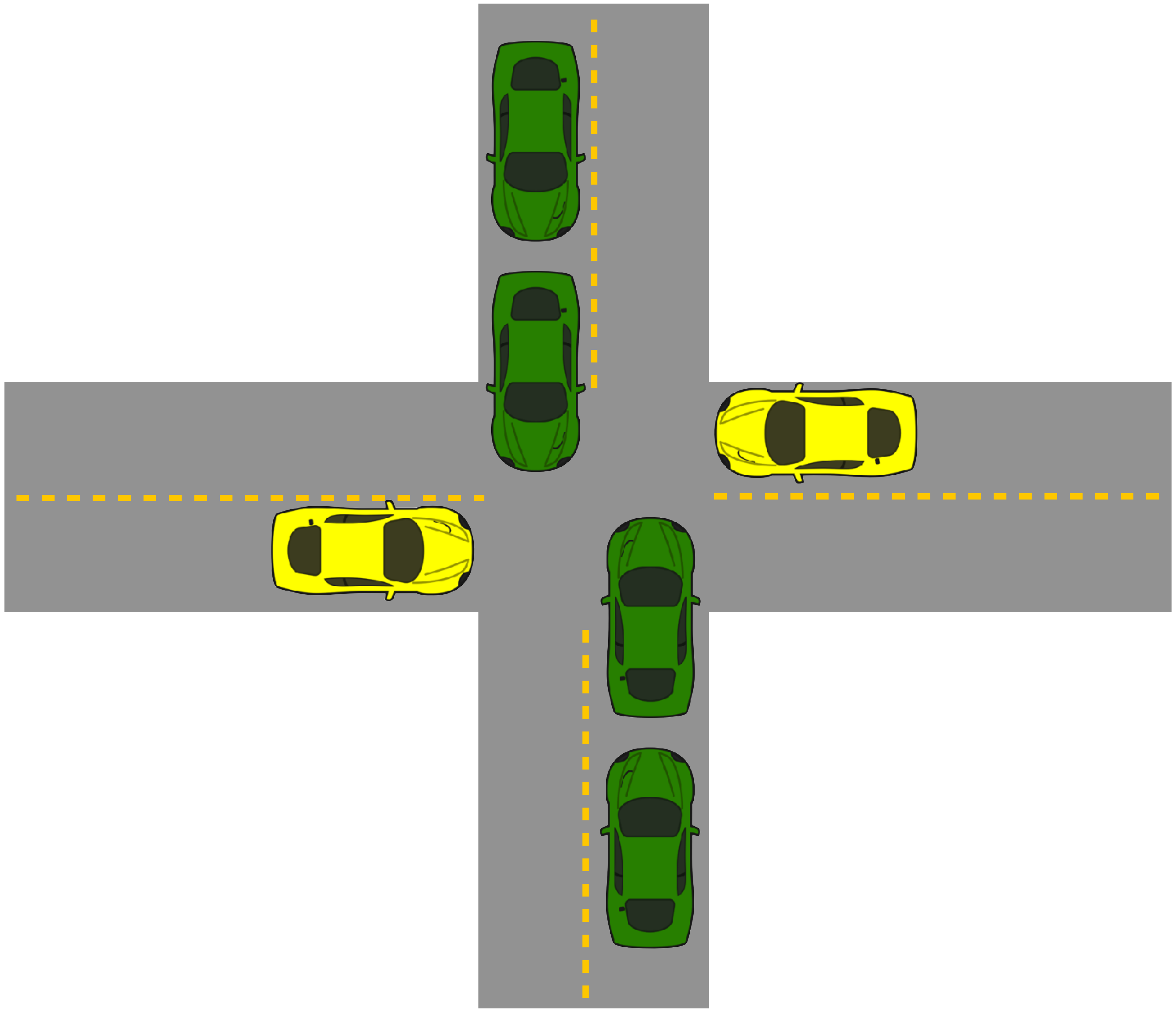
Livelock is a state where a system is executing many operations, but no thread is making meaningful progress.

Can you think of a good daily life example of livelock?

Computer system examples:

Operations continually abort and retry

Starvation



State where a system is making overall progress, but some processes make no progress.
(green cars make progress, but yellow cars are stopped)

Starvation is usually not a permanent state
(as soon as green cars pass, yellow cars can go)

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

Ok, let's get started…

Warm up (and review)

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

Let's build a lock using compare and swap:

```
typedef int lock;

void lock(Lock* l) {
  while (atomicCAS(l, 0, 1) == 1);
}

void unlock(Lock* l) {
  *l = 0;
}
```

The following is potentially more efficient under contention: Why?

```
void lock(Lock* l) {
  while (1) {
     while(*l == 1);
     if (atomicCAS(l, 0, 1) == 0)
        return;
  }
}
```

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?

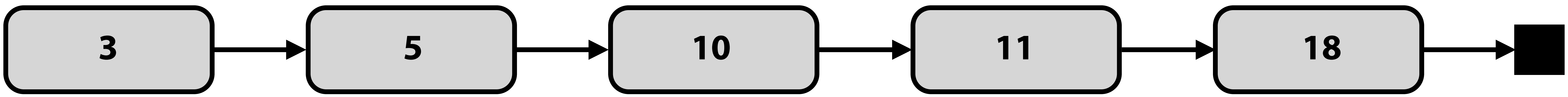
```
void insert(List* list, int value) {

   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 node in list
   // 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;
   }
}
```

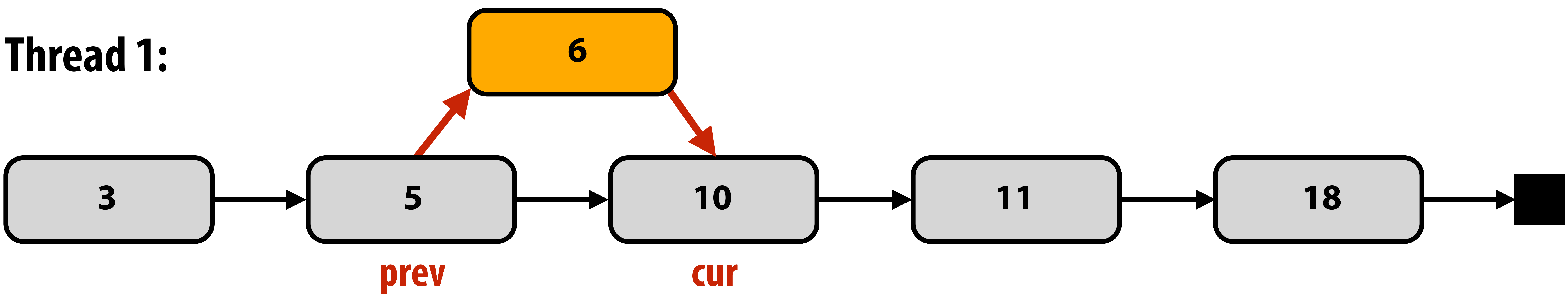
Example: simultaneous insertion

Thread 1 attempts to insert 6

Thread 2 attempts to insert 7



Thread 1:

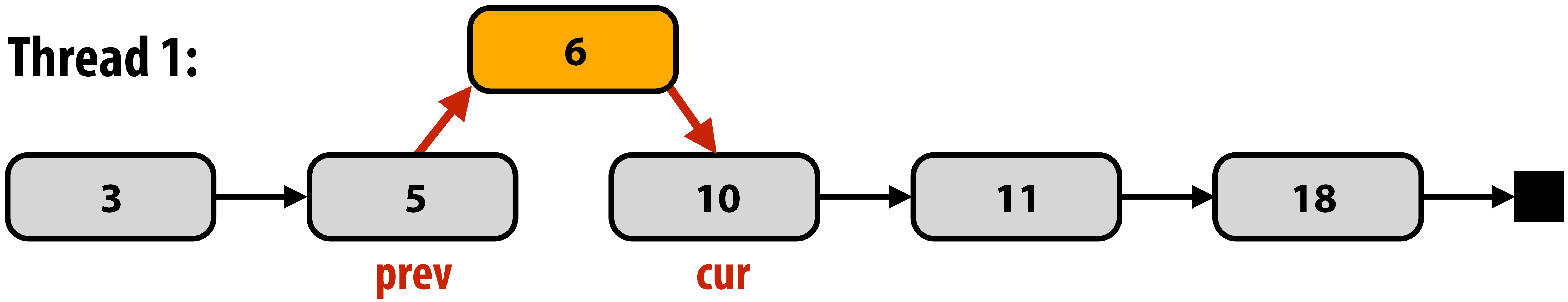


Example: simultaneous insertion

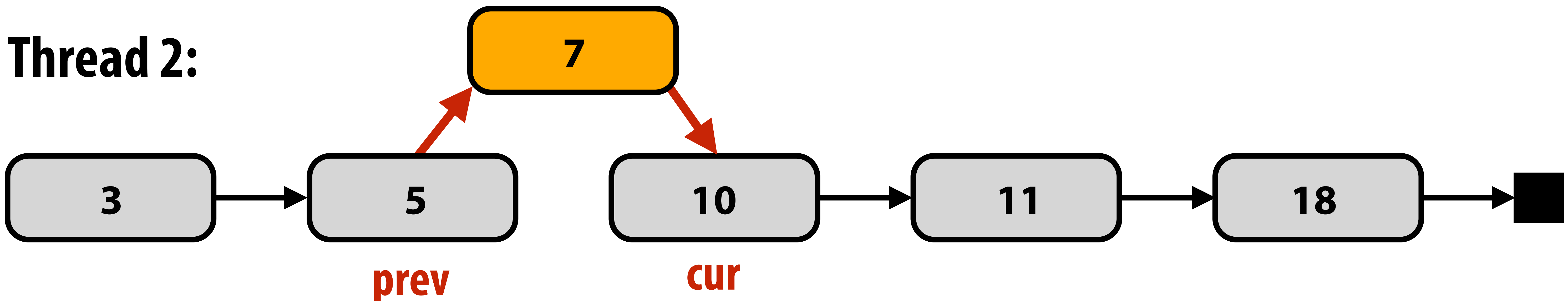
Thread 1 attempts to insert 6

Thread 2 attempts to insert 7

Thread 1:

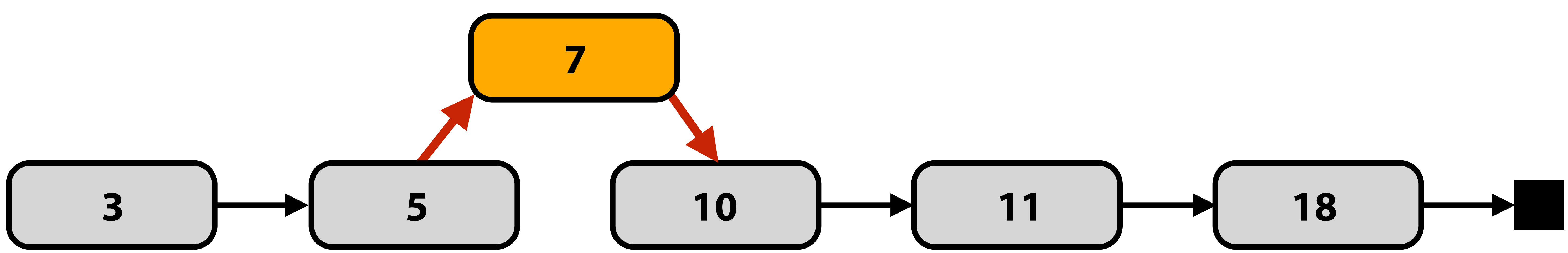


Thread 2:



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)

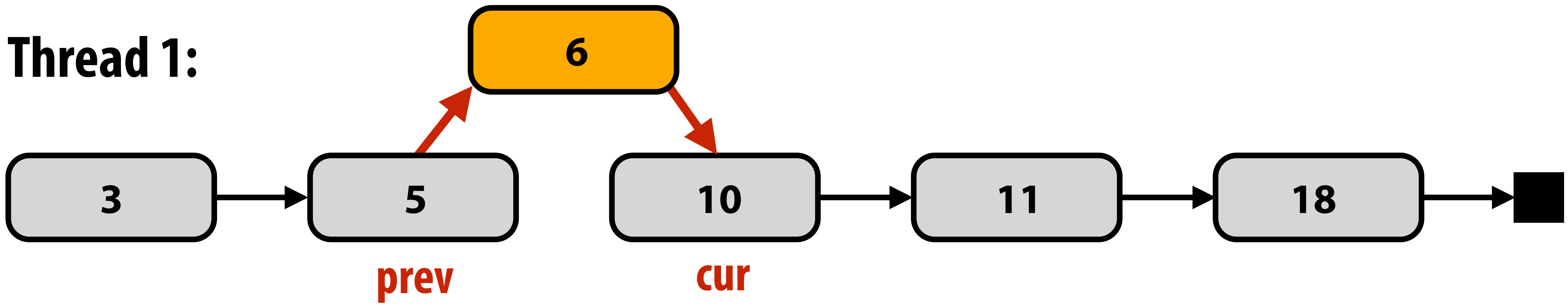


Example: simultaneous insertion/deletion

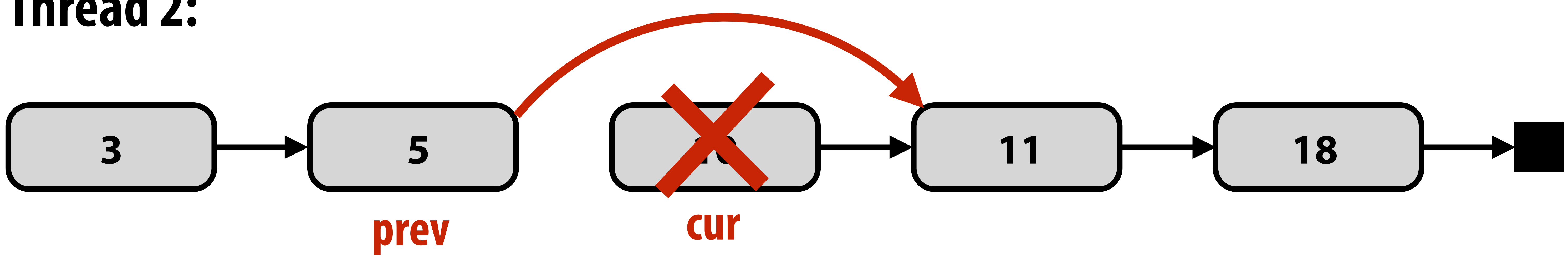
Thread 1 attempts to insert 6

Thread 2 attempts to delete 10

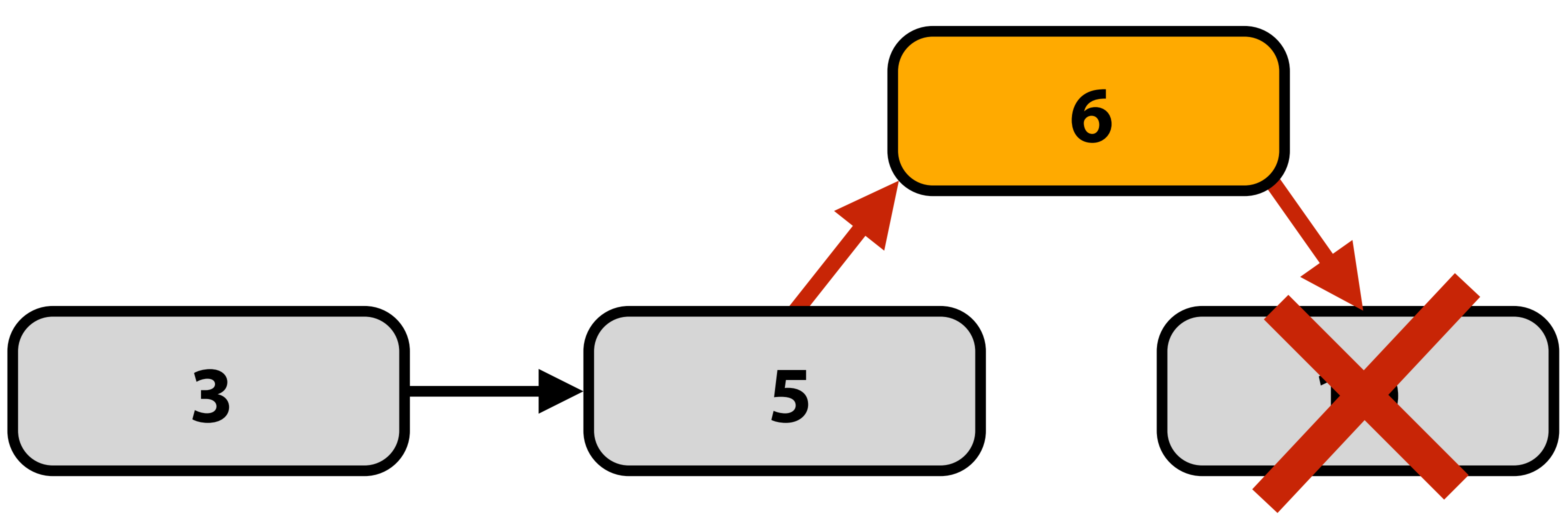
Thread 1:



Thread 2:



Possible result: (thread 2 finishes delete first)



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!)**

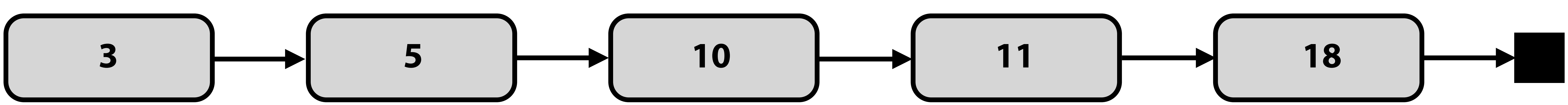
- **Bad:**
  - **Operations on the data structure are serialized**
  - **May limit parallel application performance**

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;
   }
}
```

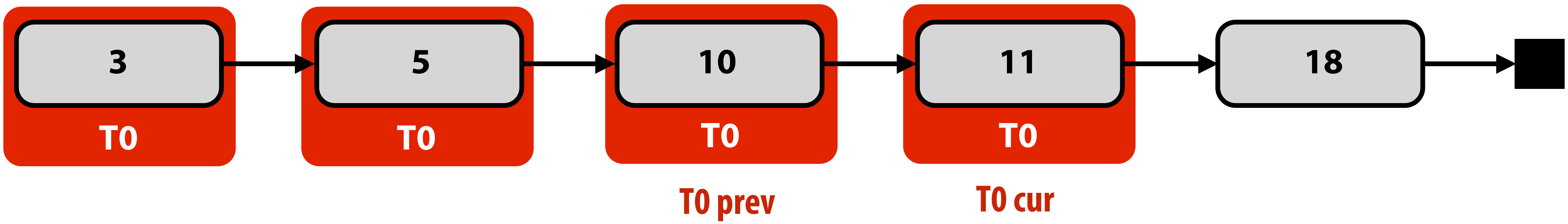


Hand-over-hand traversal

Credit: (Hal Boedeker, Orlanda Sentinel) American Ninja Warrior

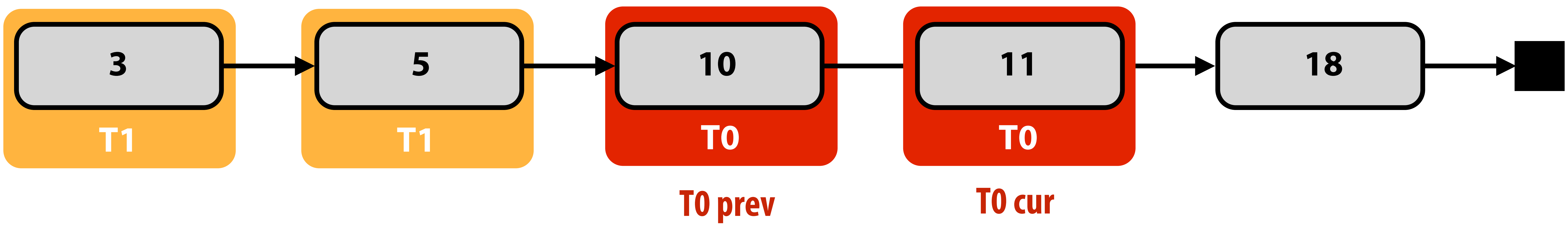
Solution 2: "hand-over-hand" locking

Thread 0: delete(11)



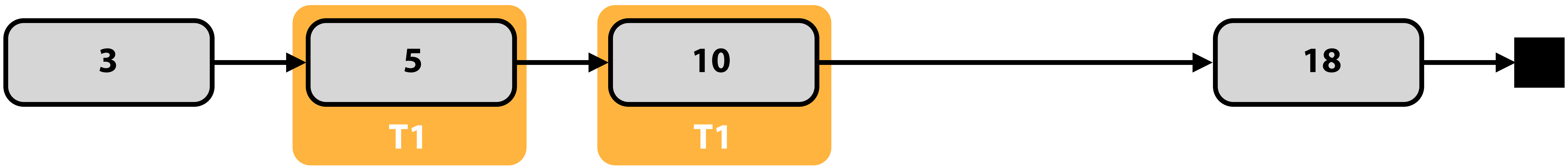
Solution 2: "hand-over-hand" locking

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



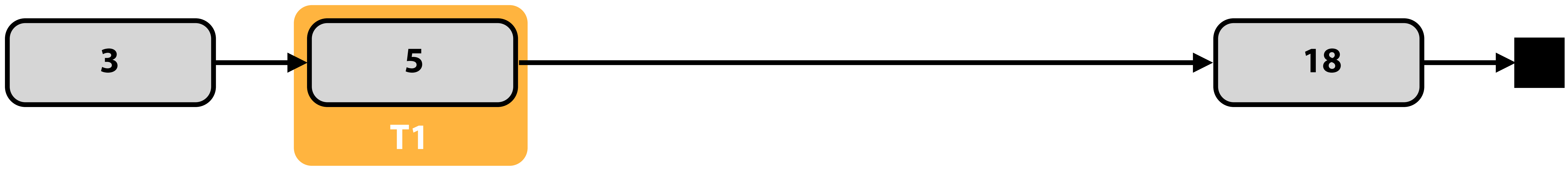
Solution 2: “hand-over-hand” locking

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;
};
```

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;

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

   cur = prev->next;
   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;

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

   cur = prev->next;
   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? (Self-check: in the linked-list example from the prior slides, why do you immediately that the 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 (on your own time)

- **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 **unbounded** queue *

Source: Dr. Dobbs Journal

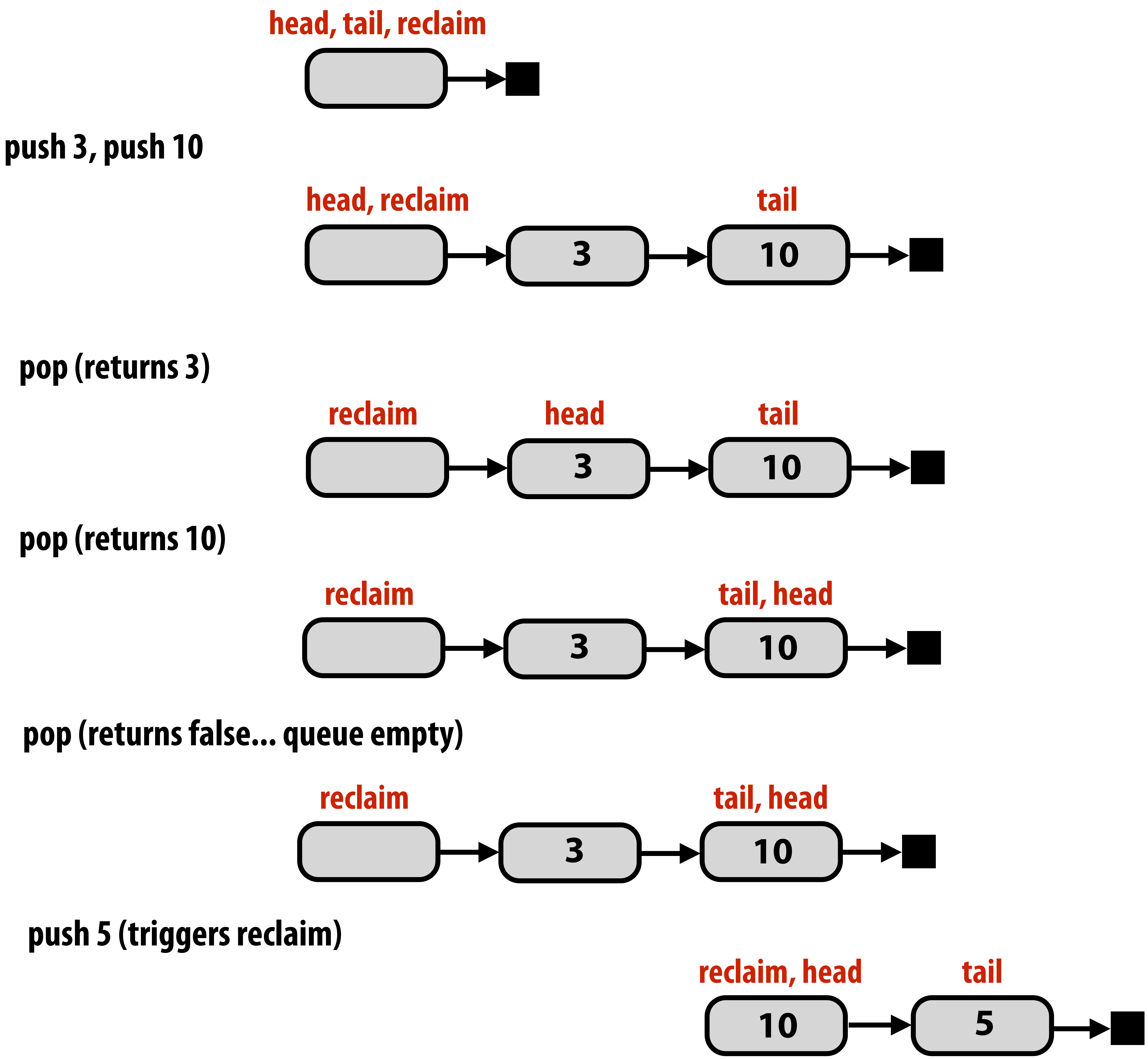
```
struct Node {
  Node* next;
  int   value;
};

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 (if non-empty)
- Head points to element BEFORE head of queue
- Node allocation and deletion performed by the same thread (producer thread)

* 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.

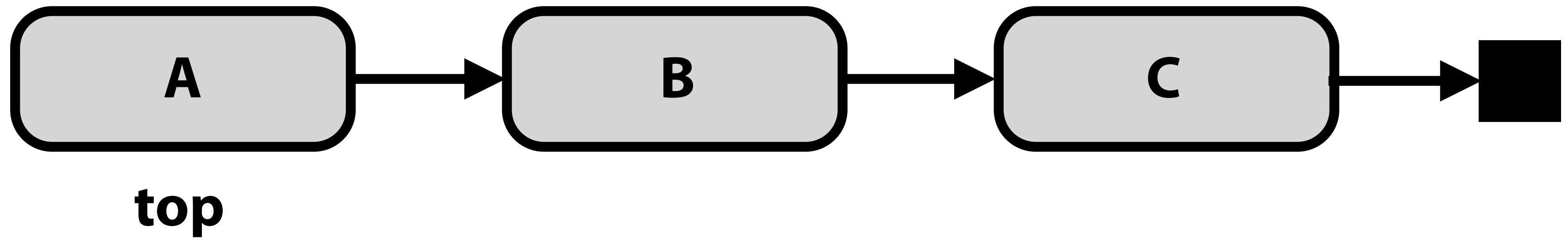
Note difference from fine-grained locking: In fine-grained locking, the implementation locked a part of a data structure. Here, threads do not hold lock on data structure at all.

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

The ABA problem

Careful: On this slide A, B, C, and D are addresses of nodes, not value stored by the nodes!

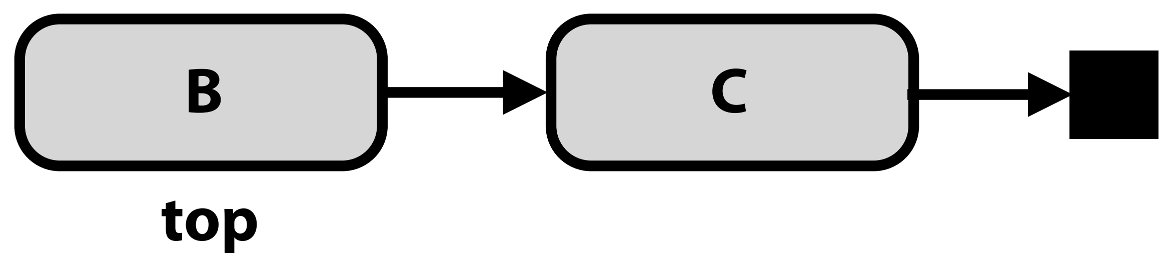
Thread 0 | **Thread 1**



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

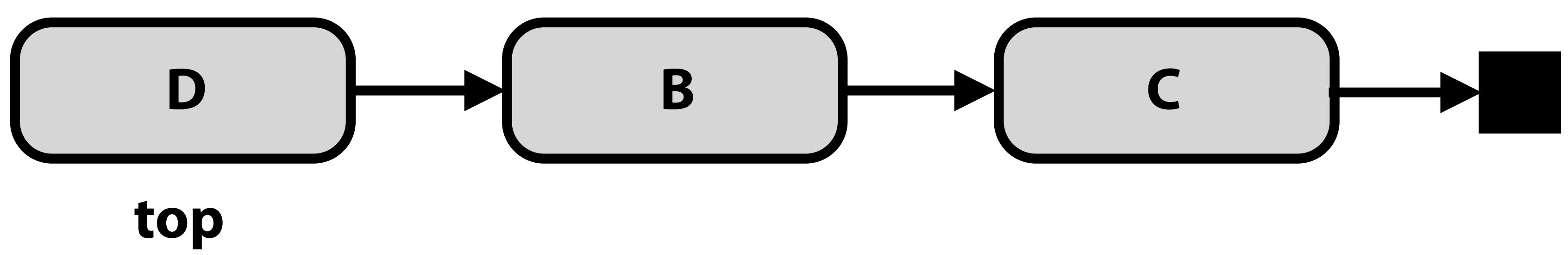
begin pop() (local variable old_top == A)

complete pop() (returns A)



begin push(D)

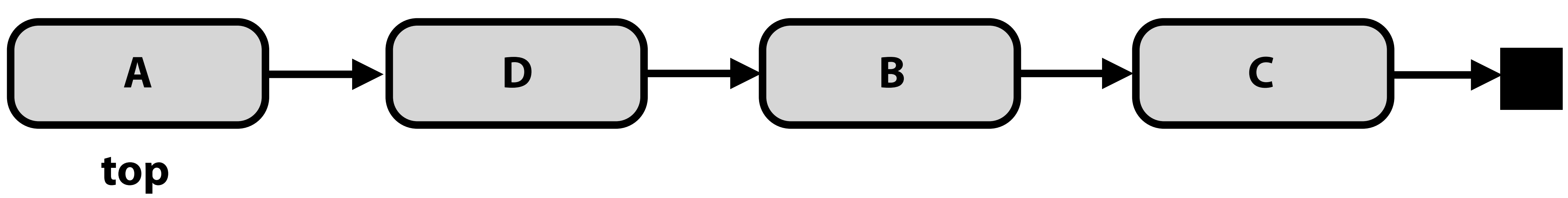
complete push(D)



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

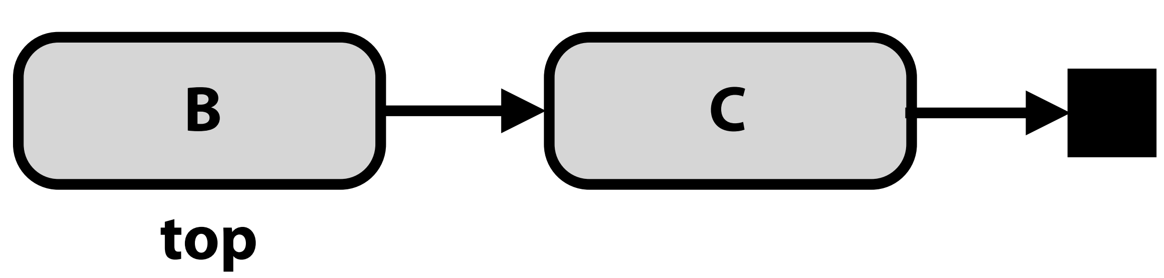
begin push(A)

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 (assume function returns 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 careful node allocation and/or element reuse policies

Compare and swap on x86

- **x86 supports a "double-wide" compare-and-swap instruction**
  - Not quite the "double compare-and-swap" used 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 = old.top->value;
      delete old.top;
      return value;
    }
  }
}
```

old top might have been freed at this point (by some other thread that popped it)

Hazard pointer: avoid freeing a node until it's known that all other threads do not hold reference to it

```
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;

// list of nodes this thread must
// delete (this is a per thread list)
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 = hazard = 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 = 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. Delete is more complex.

Lock-free linked list deletion

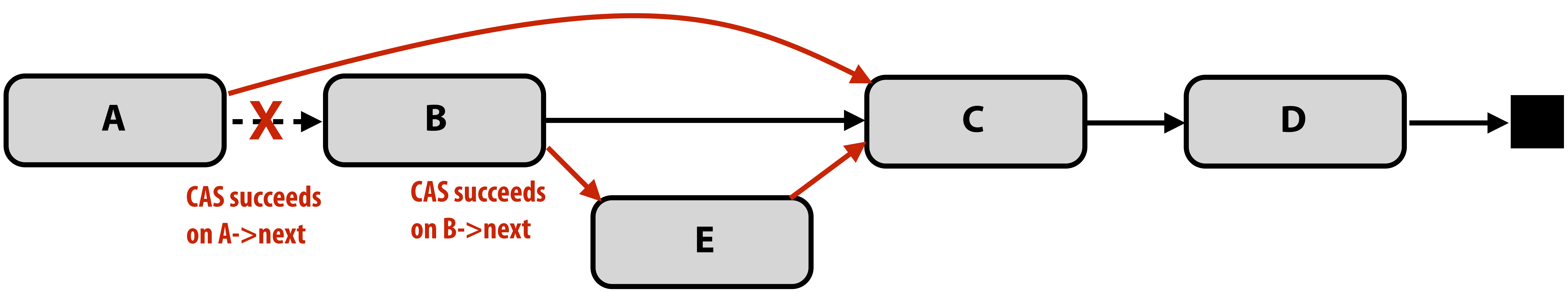
Supporting lock-free deletion significantly complicates data-structure

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

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

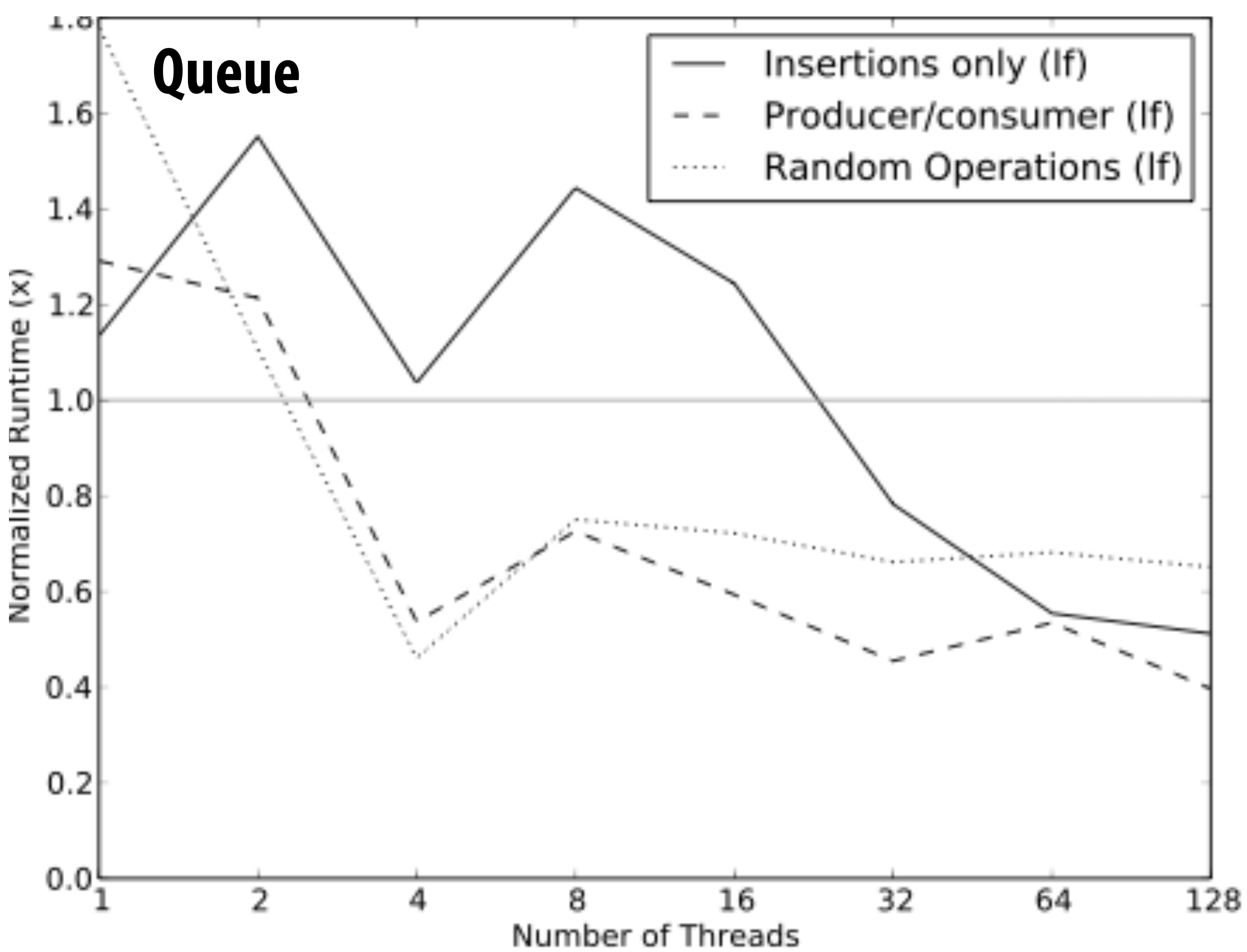
For the curious:

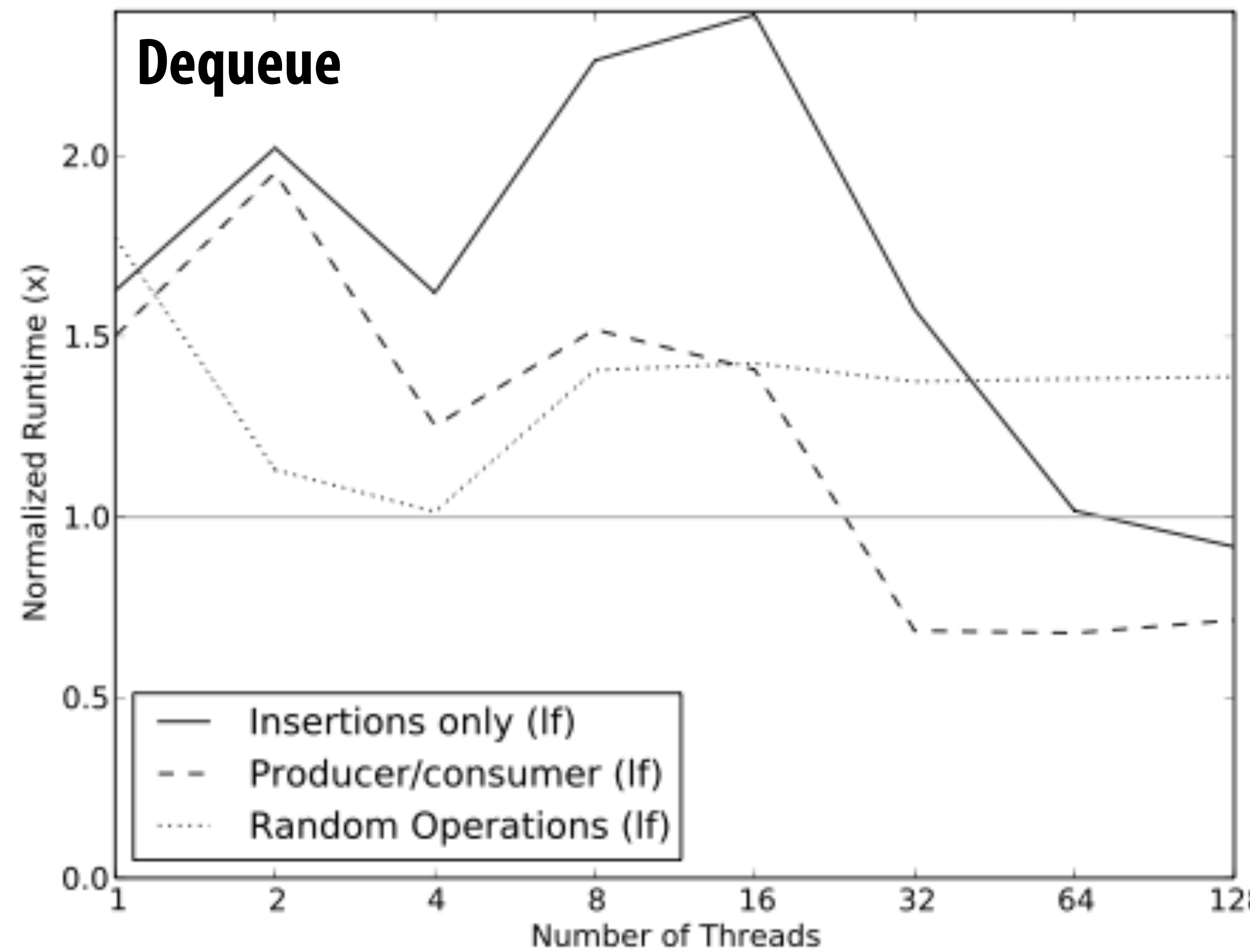
- Harris 2001. "A Pragmatic Implementation of Non-blocking Linked-Lists"
- Fomitchev 2004. "Lock-free linked lists and skip lists"

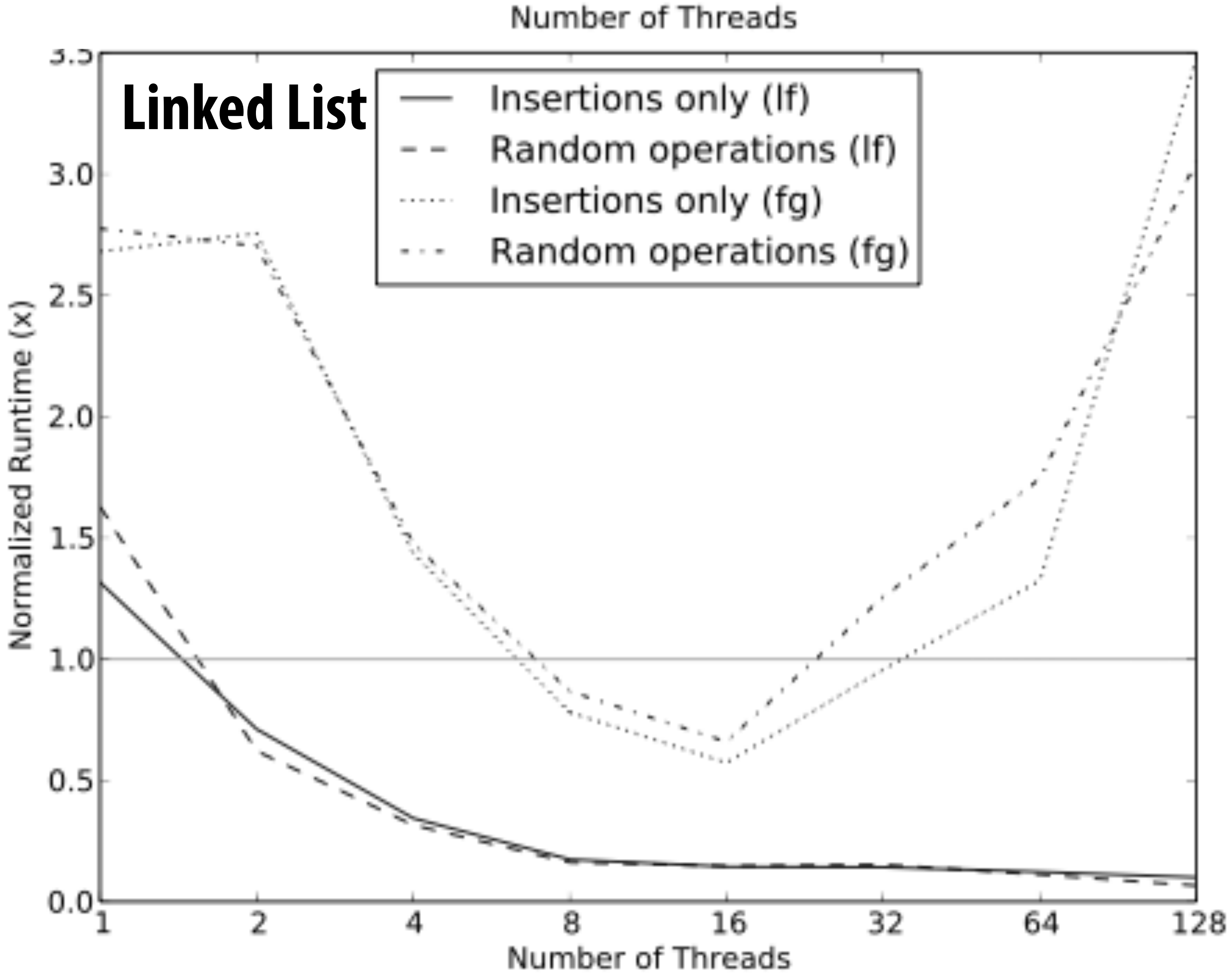


Lock-free vs. locks performance comparison

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, machine learning, data analytics, etc.

- In these cases, well-written code with locks can sometimes be as fast (or faster) than lock-free code

- But there are situations where code with locks can suffer from tricky performance problems
  - Situations where a program features many threads (e.g., database, webserver) and page faults, pre-emption, etc. can occur while a thread is in a critical section
  - Locks create 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 (and 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

Preview: transactional memory

- Q. What was the role of the compare and swap in our lock-free implementations?

- A. Determining if another thread had modified the data structure while the calling thread was in the middle of an operation.

- Next time… transactional memory
  - A more general mechanism to allow a system to speculate that an operation will be successfully completed before another thread attempts to modify the structure
  - With mechanisms to "abort" an operation in the event another thread does.

Preview: transactional memory

```
atomic
{   // begin transaction

   perform atomic computation here ...

}   // end transaction
```

Instead of ensuring mutual exclusion via locks, system will proceed as if no synchronization was necessary. (it speculates!)

System provides hardware/software support for "rolling back" all loads and stores in the critical region if it detects (at run-time) that another thread has entered same region at the same time.

More reading on lock-free structures

- 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
- Michael Sullivan's Relaxed Memory Calculus (RMC) compiler
  - https://github.com/msullivan/rmc-compiler
- 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/