PURDUE UNIVERSITY

Principles of Concurrency

Lecture 6

Concurrent Data Structures (cont)

Material adapted from Herlihy and Shavit, Art of Multiprocessor Programming, Chapters 10 and 11

The Problem

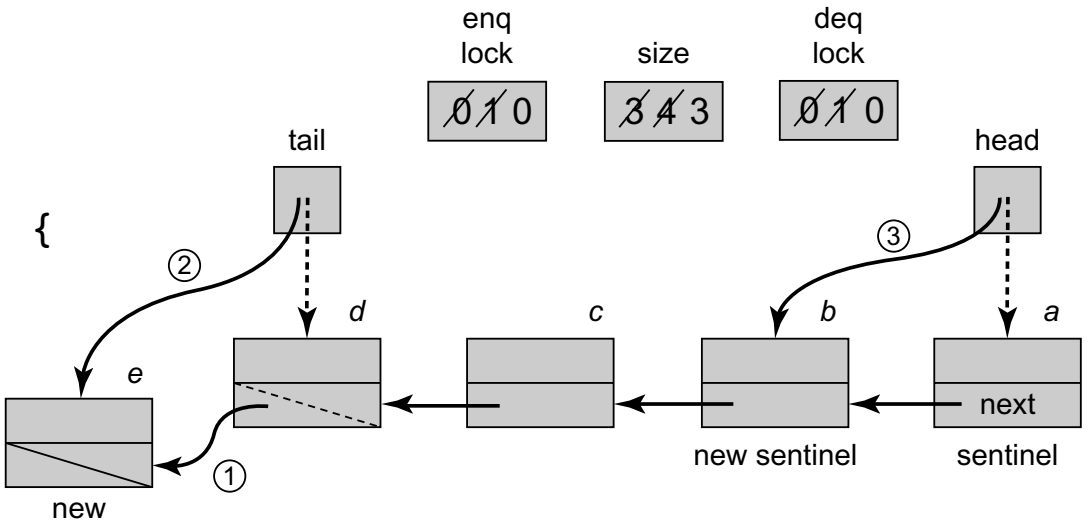
- Data structures like queues and stacks differ from sets:
  - no contains() method
  - an item can appear more than once
- These structures can be:
  - bounded or unbounded
  - total, partial, or synchronous:
    - total: every operation is non-blocking e.g., attempting to retrieve an element from an empty stack simply returns failure
    - partial: certain conditions may need to hold before an operation is allowed to complete, e.g., adding an element to a full bounded queue must wait until an element is removed
    - synchronous: one method waits for another to overlap its call/return interval, e.g., a method that adds an element to a queue blocks until a request to remove an element is received. These implementations implement a form of rendevous protocol.

Queues

A bounded partial queue

- enq() and deq() operations operate over different parts of the queue
- As long as the queue is neither full nor empty, these operations can proceed without interference
- Use locks for enq() and deq() to regulate concurrent enq() and deq() operations

```
fun <T> enq(x : T) = {
    var mustWakeDequeuers = false
    enq.acquire()
    while (size.get() == capacity {
       wait(notFullCondition)
     }
    var node = new Node(x)
    tail.next = tail =  node
    if (size.getAndIncrement() == 0) {
       mustWakeDequeuers = true
    enq.release()
    if (mustWakeDequeuers) {
      deq.acquire()
      signal(notEmptyCondition)
      deq.release()
    }
```



Abstract queue's head and tail not necessarily the same as implementations. Why is this ok?

Unbounded Lock-Free Queue

- An unbounded total queue always successfully enqueues and item, with deq() throwing an exception if the queue is empty.
- This implementation does not requiring checking any conditions before proceeding with an operation.

```
fun <T>enq(item : T) = {
   var node = new Node(value)
   while (true) {
      val last = tail.get()
      val next = last.next.get()
      if (last == tail.get()) {
        if (next == null) {
           if (last.next.CAS(next, node))
              tail.CAS(last, node)
              return
          } else {
              tail.CAS(last, next)
           }
     }
}
```

create the node

locate presumed last element

get this last element's next pointer (when can it be non-null?)

if no new element concurrently added, append node

set the tail to point to the new node, return successfully even if the CAS fails

tail node already has a successor (half-finished prior enq(), help that prior node to complete

Appending a node to the list, and setting the tail to point to that node are not atomic. Use a "helping" mechanism to allow other nodes to finish the `enq()` of an operation that was preempted between these two actions.

Unbounded Lock-free Queue

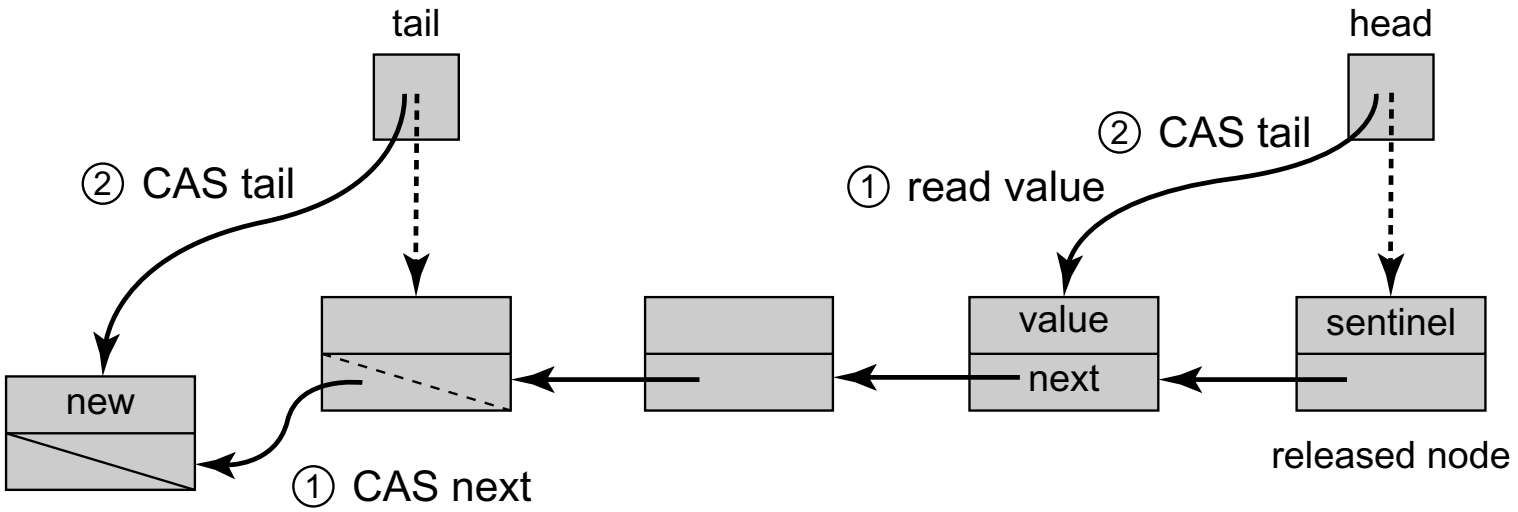

```
fun <T>deq() {
   while (true) {
      val first = head.get()
      val last = tail.get()
      val next = first.next.get()
      if (first == head.get()) {
        if (first == last) {
          if (next == null) {
            throw EmptyExn()
          }
          tail.CAS(last, next)
      } else {
          val value = next.value
          if (head.CAS(first, next) {
           return value
        }
      }
  }
}
```

Queue is empty: head and tail pointing to the same node, head's next is null

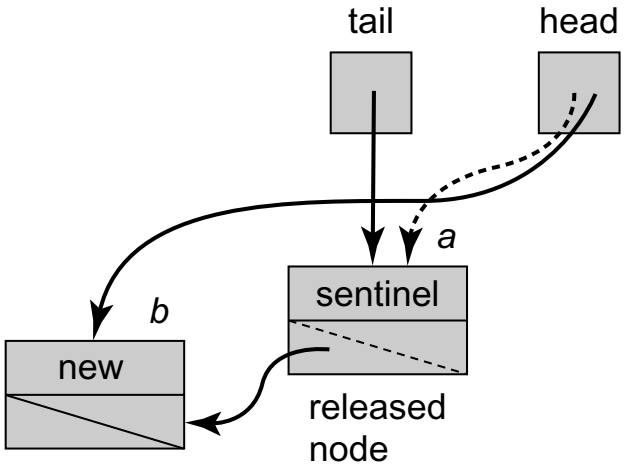
Tail is out-of-sync, help to move it to the next element

point head to the next element

Unbounded Lock-free Queue



Basic operation



Dequeuer's help fix-up lagging tail from concurrent enqueue operations

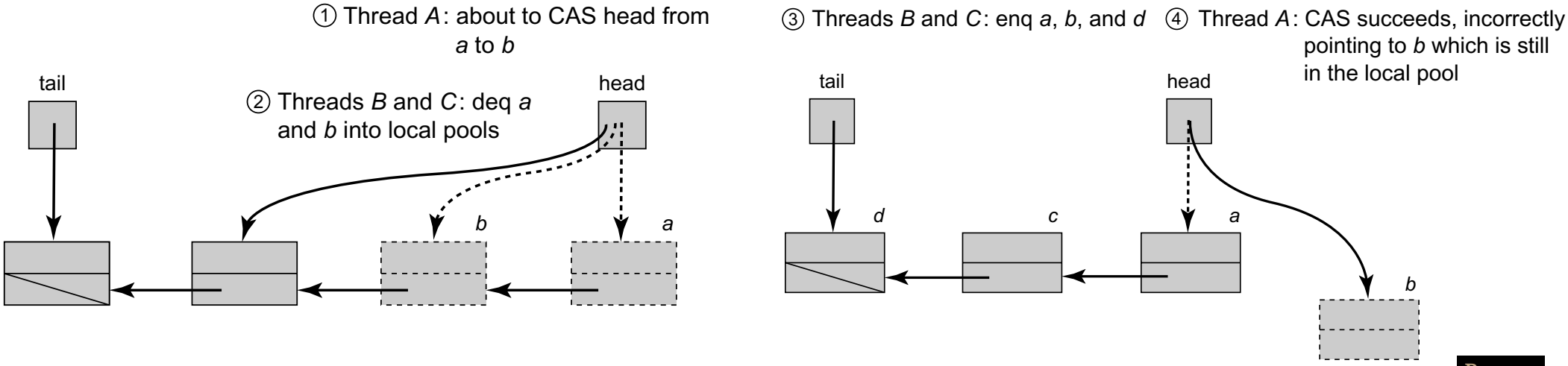
The ABA Problem

How do we deal with dequeued nodes? In a language without garbage collection, we need to provide our own memory management mechanism.

Idea: every thread maintains its own local node freelist. An enqueuing operation removes a node from the freelist (or allocates a new node if the list is empty). A dequeueing thread adds the node back to the freelist.

Subtle problem:

- A `deq()` operation observes a node `a` followed by `b`
- It attempts to update head to point to `b` using CAS and is preempted
- Concurrently, other `deq()` operations remove both `a` and `b`
- Node `a` is recycled
- The preempted node resumes and (incorrectly) observes that head still points to `a` and completes the CAS operation so that head now points to `b` (a recycled node)



Lock-free Stack


```
fun tryPush(n : Node) =  {
   val oldTop = top.get()
   n.next = oldTop
   top.CAS(oldTop, node)
}

fun <T>push(value : T) = {
   var node = new Node(value)
   while (true)  {
      if (tryPush(node)) {
        return
     }
}
```

When can the CAS operations in tryPush() and tryPop() fail?

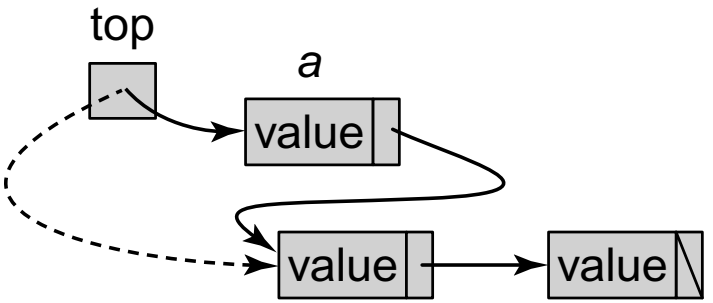
```
fun tryPop()  = {
   val oldTop = top.get()
   if (oldTop == null) {
      throw EmptyExn();
   }
   val newTop = oldTop.next()
   if (top.CAS(oldTop, newTop) {
      return oldTop
   } else {
        return null
    }
}

fun <T>pop() = {
   while (true) {
      val returnNode = tryPop()
      if (returnNode != null) {
         return returnNode.value
     }
  }
}
```

Lock-free Stack

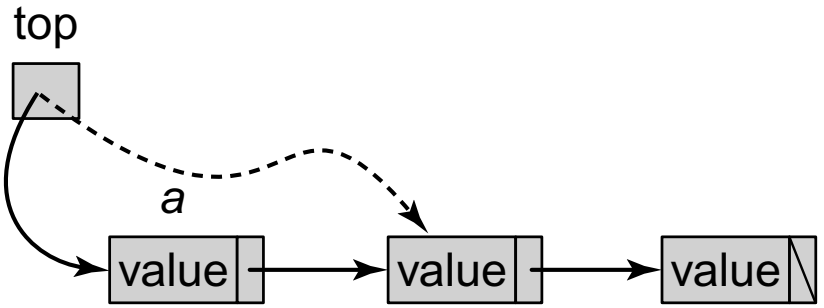
(a)

A:push()



(b)

A:pop()



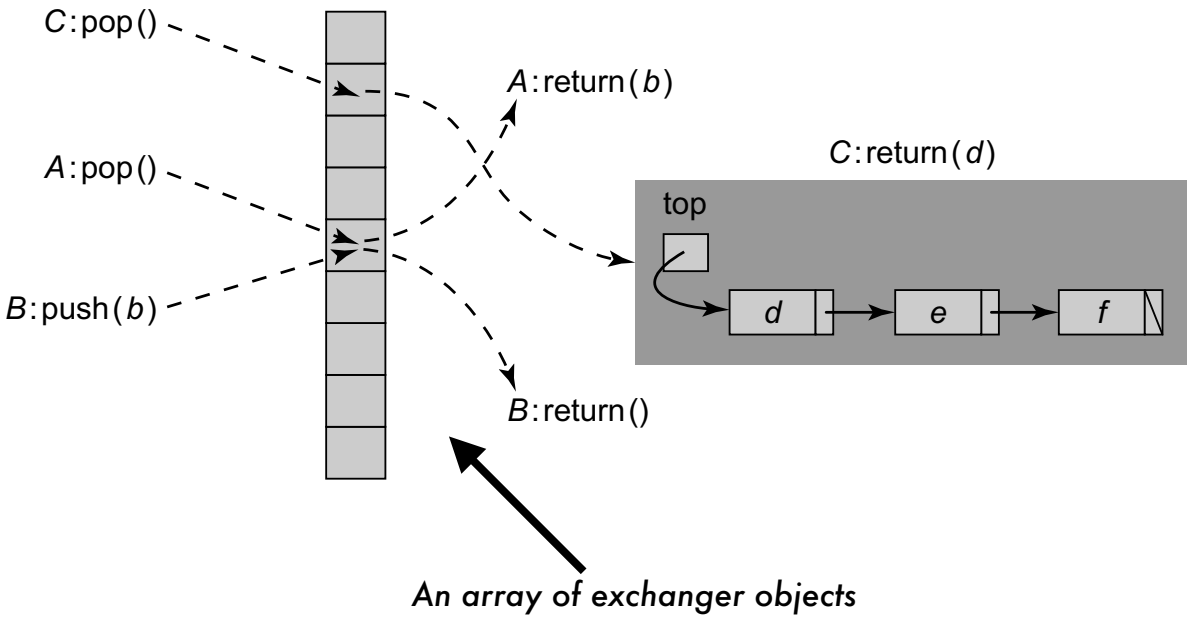
Elimination Stack

The lockfree stack has poor scalability:

- CAS operations sequentialize access to the stack's top field

Alternative approach:

- Pair concurrent pushes and pops - threads calling `push()` exchange values with threads calling `pop()`
- This exchange happens without modifying the stack



LockFreeExchanger:

- permits two threads to atomically exchange values
- First thread spins waiting for the second until a timeout

Three state automaton:

- EMPTY
- BUSY
- WAITING

1. Slot initially EMPTY
2. First thread sets it to WAITING using CAS
   - if not successful, retries
   - if successful, spins
3. Another thread that accesses this slot sets the state to BUSY
4. Item can be consumed and the state reset to EMPTY