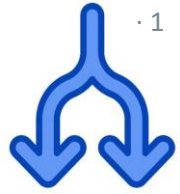


Practical Concurrent and Parallel Programming VII

Lock-Free Data Structures

Raúl Pardo

Based on slides of PCPP 2019

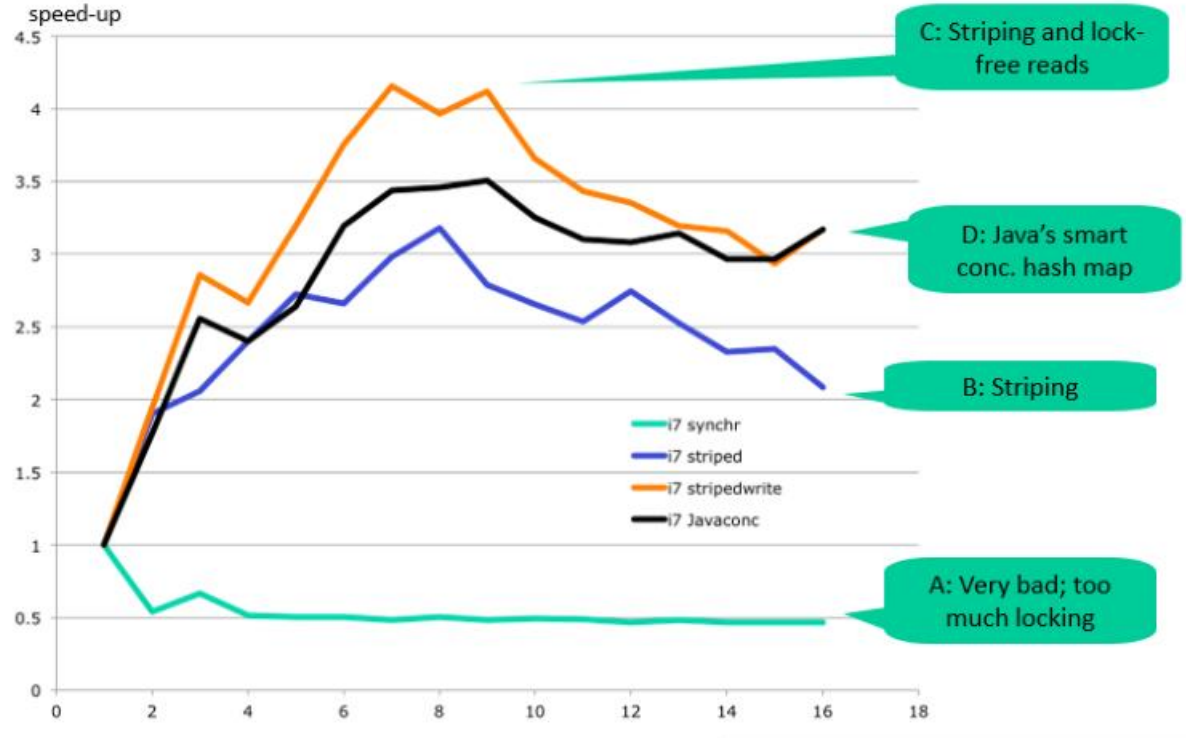
Office hours

- What of these time slots suit you better

https://www.menti.com/kmu63g4wdb

Previously on PCPP…

Reducing locking



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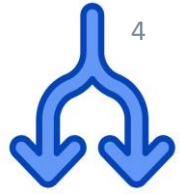
Agenda



- Compare-And-Swap (CAS)
  - Lock-free Counter
  - Atomic libraries
  - CAS based lock implementation
- Lock-free stack
- Lock-free queue
- ABA problem

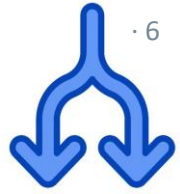
HW support for atomic compound operations

- Early processors had atomic compound operations to implement mutexes
  - *test-and-set*
  - Not suitable for implementing advanced lock-free data structures

See Herlihy Sections 5.1 – 5.8
(outside the scope of the course)

- Modern processors provide special instructions to for managing concurrent access to shared variables
  - *store-conditional,* ***compare-and-swap* (CAS)**

Compare-And-Swap (CAS)



- **`v.compareAndSwap(a,b)`**
  - Compares the value of `v` and `a`, and, if they are equal `v` is set to `b`, otherwise it does nothing. In either case, it returns the current value in `v`, i.e., the value when CAS was executed
  - This instruction is executed atomically by the hardware

CAS pseudo-code

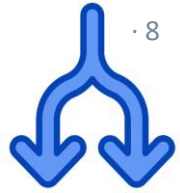
```
class MyAtomicInteger {
    private int value;    // Visibility ensured by locking

    public synchronized int compareAndSwap(int oldValue, int newValue) {
        int valueInRegister = this.value;
        if (this.value == oldValue)
            this.value = newValue;
        return valueInRegister;
    }

    public synchronized boolean compareAndSet(int oldValue, int newValue) {
        return oldValue == this.compareAndSwap(oldValue,newValue);
    }

    public synchronized int get() { return this.value; }
…
}
```

Illustrative implementation of CAS

Common alternative.
Also abbreviated as CAS
(optional exercise: implement natively compareAndSet)

- Only to *illustrate* CAS semantics
  - Internally, locks are implemented using CAS
  - Not the other way around

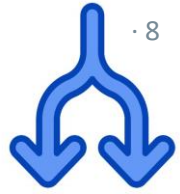
AtomicInteger operations via CAS



- Standard AtomicInteger operations can now be implemented using the CAS operations *without blocking*
- This is an example of *optimistic* concurrency
  - In a nutshell, trying several times until the operation succeeds

```
class MyAtomicInteger {
…
  public int addAndGet(int delta) {
     int oldValue, newValue;
     do {
         oldValue = get();
         newValue = oldValue + delta;
     } while (!compareAndSet(oldValue, newValue));
     return newValue;
  }

  public int getAndAdd(int delta) {
     int oldValue, newValue;
     do {
         oldValue = get();
         newValue = oldValue + delta;
     } while (!compareAndSet(oldValue, newValue));
     return oldValue;
  }
…
}
```

AtomicInteger operations via CAS



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  }

  public int getAndAdd(int delta) {
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     do {
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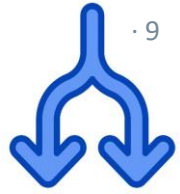
          newValue = oldValue + delta;
     } while (!compareAndSet(oldValue, newValue));
     return oldValue;
  }
…
}
```

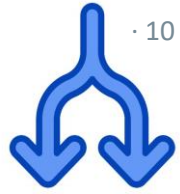
Is this the same as busy-wait?

Visibility of CAS



- In Java, **`AtomicXX`** CAS operations have the same memory semantics of volatile read/write
  - https://github.com/AdoptOpenJDK/openjdk-jdk16u/blob/8ddb1d8453017eccd153b7bc4bc6e23de3ba4959/src/java.base/share/classes/jdk/internal/misc/Unsafe.java#L1434

Implementing Locks using CAS



1. Simple TryLock
   - Non-blocking tryLock, the lock may be acquired only once
   - Regular unlock
2. Reentrant TryLock
   - Non-blockin tryLock, the lock may be acquired repeatedly by the same thread
   - Regular (reentrant) unlock
3. Simple Lock
   - Blocking lock, the lock may be acquired only once
   - Regular unlock
4. Reentrant Lock
   - Block lock, the lock may be acquired repeatedly by the same thread
   - Regular (reentrant) unlock

See **`TestCasLocks.java`**

1. SimpleTryLock, non-blocking

```
class SimpleTryLock {

    // Refers to holding thread, null iff unheld
    private final AtomicReference<Thread> holder = new AtomicReference<Thread>();

    public boolean tryLock() {
      final Thread current = Thread.currentThread();
      return holder.compareAndSet(null, current);
    }


    public void unlock() {
      final Thread current = Thread.currentThread();
      if (!holder.compareAndSet(current, null))
          throw new RuntimeException("Not lock holder");
    }


}
```

If the lock is free (holder == null), takes it and return true. Otherwise, holder is unmodified and returns false.

Sets holder to null. If CAS returns false throws an exception indicating that this thread is not holding the lock.

1. SimpleTryLock, non-blocking

```
class SimpleTryLock {

    // Refers to holding thread, null iff unheld
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    public boolean tryLock() {
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       final Thread current = Thread.currentThread();
       if (!holder.compareAndSet(current, null))
            throw new RuntimeException("Not lock holder");
    }

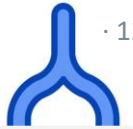

}
```

If the lock is free (holder == null), takes it and return true. Otherwise, holder is unmodified and returns false.

How is CAS used here to determine that the lock is not held by the thread executing unlock?

Sets holder to null. If CAS returns false throws an exception indicating that this thread is not holding the lock.

2. ReentrantTryLock, non-blocking



```
class ReentrantTryLock {
    private final AtomicReference<Thread> holder = new AtomicReference<Thread>();
    private volatile int holdCount = 0;

    public boolean tryLock() {
      final Thread current = Thread.currentThread();
      if (holder.get() == current) {
          holdCount++;
          return true;
      } else if (holder.compareAndSet(null, current)) {
          holdCount = 1;
          return true;
      }
      return false;
    }

    public void unlock() {
      final Thread current = Thread.currentThread();
      if (holder.get() == current) {
          holdCount--;
          if (holdCount == 0)
            holder.compareAndSet(current, null);
          return;
      }
      throw new RuntimeException("Not lock holder");
    }
}
```

If the calling thread already holds the lock, we increase the counter

If not, we try to acquire the lock and set the count to 1

2. ReentrantTryLock, non-blocking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      }
      return false;
    }

    public void unlock() {
      final Thread current = Thread.currentThread();
      if (holder.get() == current) {
          holdCount--;
          if (holdCount == 0)
            holder.compareAndSet(current, null);
          return;
      }
      throw new RuntimeException("Not lock holder");
    }
}
```
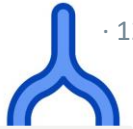

Don't we have a possible data race here

If the calling thread already holds the lock, we increase the counter

If not, we try to acquire the lock and set the count to 1

2. ReentrantTryLock, non-blocking



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          return true;
      }
      return false;
    }

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      final Thread current = Thread.currentThread();
      if (holder.get() == current) {
          holdCount--;
          if (holdCount == 0)
            holder.compareAndSet(current, null);
          return;
      }
      throw new RuntimeException("Not lock holder");
    }
}
```

If the calling thread already holds the lock, we increase the counter

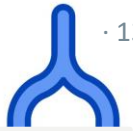
If not, we try to acquire the lock and set the count to 1

If the calling thread holds the hold we decrement the counter

If the counter is 0 then we release the lock

If the calling thread does not hold the lock we throw an exception

3. SimpleLock, blocking



```
class SimpleLock {
    private final AtomicReference<Thread> holder = new AtomicReference<Thread>();
    // The FIFO queue of threads waiting for this lock
    private final Queue<Thread> waiters = new ConcurrentLinkedQueue<Thread>();

    public void lock() {
      final Thread current = Thread.currentThread();
      waiters.add(current);
      while (waiters.peek() != current || !holder.compareAndSet(null, current)) {
          LockSupport.park(this);
      }
      waiters.remove();
    }




    public void unlock() {
      final Thread current = Thread.currentThread();
      if (holder.compareAndSet(current, null))
          LockSupport.unpark(waiters.peek());
      else
          throw new RuntimeException("Not lock holder");
    }
}
```

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}
```

First we add the thread to a waiting queue

We check whether the current thread is at the head of the queue and try to take the lock

If not successful, we put the thread to wait (see Javadoc LockSupport)

Finally, we remove the thread from the waiting list

3. SimpleLock, blocking


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      while (waiters.peek() != current || !holder.compareAndSet(null, current)) {
          LockSupport.park(this);
      }
      waiters.remove();
    }

    public void unlock() {
      final Thread current = Thread.currentThread();
      if (holder.compareAndSet(current, null))
          LockSupport.unpark(waiters.peek());
      else
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    }
}
```

First we add the thread to a waiting queue

We check whether the current thread is at the head of the queue and try to take the lock

If not successful, we put the thread to wait (see Javadoc LockSupport)

Finally, we remove the thread from the waiting list

We simply try to release the lock

If successful, we wake up one of the waiting threads, if any

As before, we throw an exception if the calling thread is not the thread holding the lock

3. SimpleLock, blocking (interruptions)


```
class SimpleLock {
    private final AtomicReference<Thread> holder = new AtomicReference<Thread>();
    // The FIFO queue of threads waiting for this lock
    private final Queue<Thread> waiters = new ConcurrentLinkedQueue<Thread>();

    public void lock() {
      final Thread current = Thread.currentThread();
      boolean wasInterrupted = false;
      waiters.add(current);
      while (waiters.peek() != current || !holder.compareAndSet(null, current)) {
         LockSupport.park(this);
         if (Thread.interrupted())
          wasInterrupted = true;
      }
      waiters.remove();
      if (wasInterrupted)
         current.interrupt();
    }
…
}
```

We use a flag to record whether the thread has been interrupted during execution

Immediately After taking the lock we check if the thread was interrupted

If the thread was interrupted we call interrupt to propagate the interruption.

4. SimpleReentrantLock, blocking

```
class MyReentrantLock {
    private final AtomicReference<Thread> holder = new AtomicReference<Thread>();
    private final Queue<Thread> waiters = new ConcurrentLinkedQueue<Thread>();
    private volatile int holdCount = 0;

    public void lock() {
      final Thread current = Thread.currentThread();
      if (holder.get() == current)
          holdCount++;
      else {
          boolean wasInterrupted = false;
          waiters.add(current);
          while (waiters.peek() != current || !holder.compareAndSet(null, current)) {
            LockSupport.park(this);
            if (Thread.interrupted())
                wasInterrupted = true;
          }
          holdCount = 1;
          waiters.remove();
          if (wasInterrupted)
            current.interrupt();
      }
    }
…
}
```

Here we simply combine what we have seen in threads 2 and 3

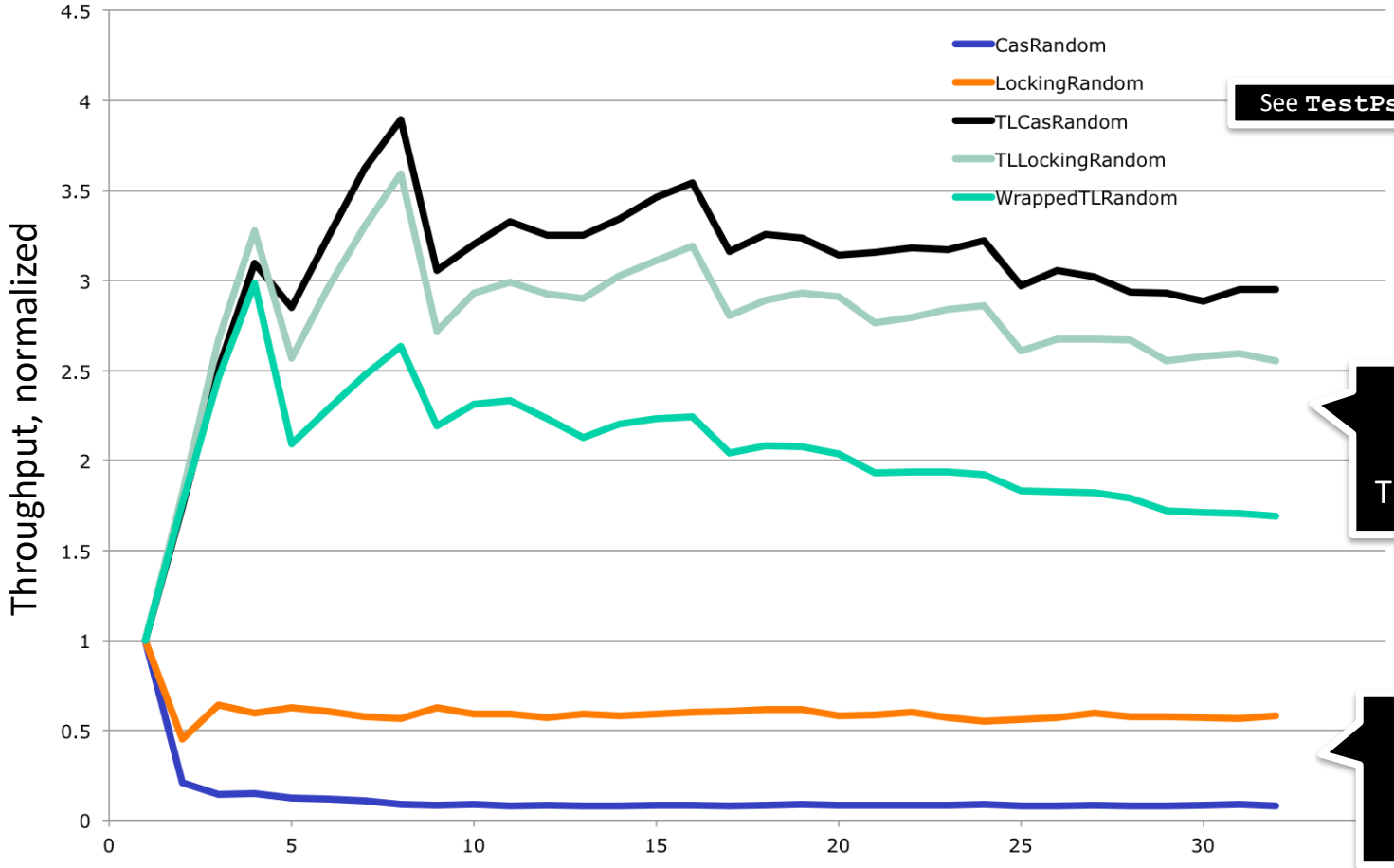
Scalability of CAS

- Pros
  - A CAS operation is faster than acquiring a lock
  - An unsuccessful CAS operation does not cause thread de-scheduling (blocking)

- Cons
  - CAS operations result in high memory overhead

Will CAS based implementations always scale well?
(that is, better that lock based)

Scalability of PRNGs (unrealistic contention)

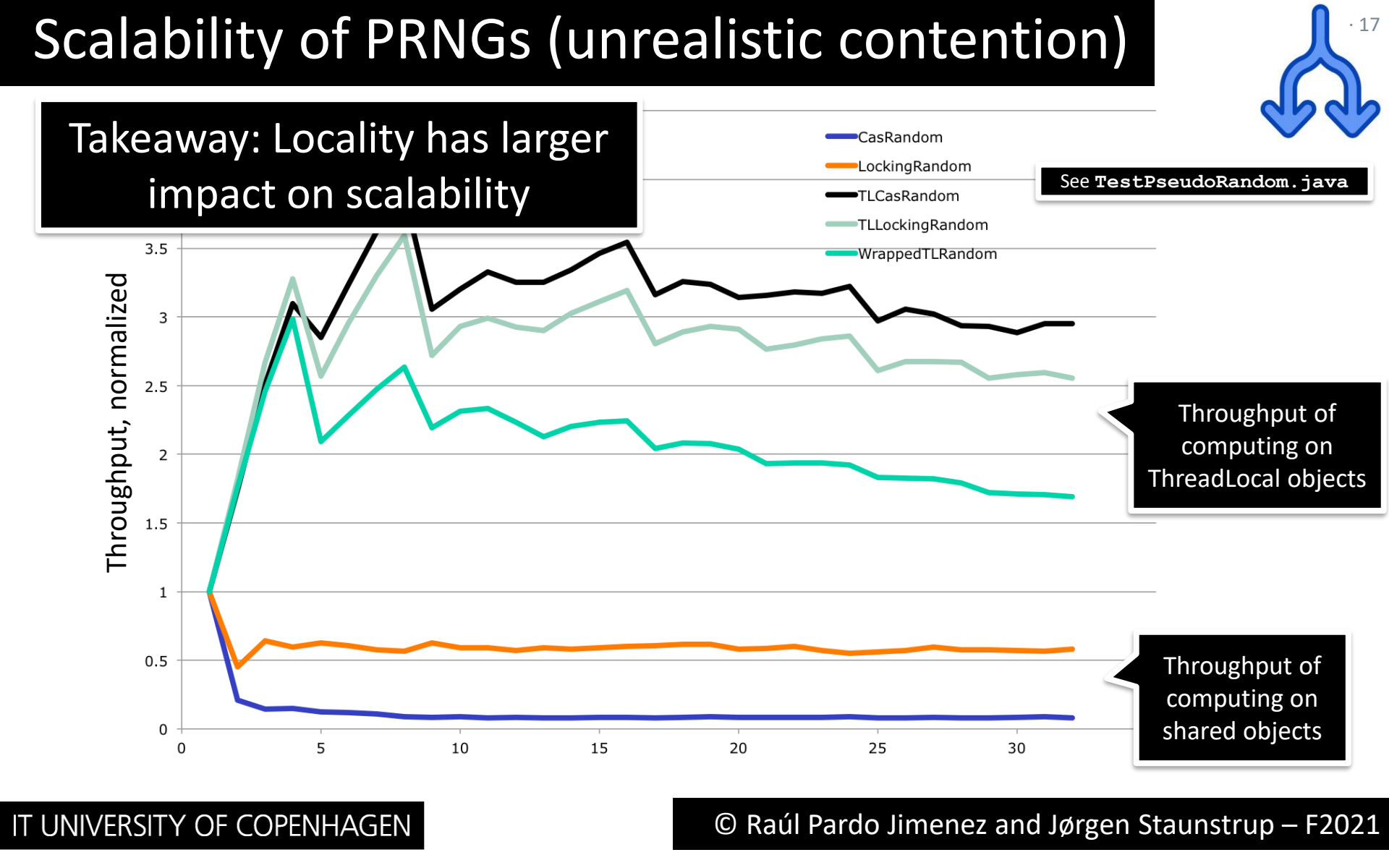


See `TestPseudoRandom.java`

Throughput of computing on ThreadLocal objects

Throughput of computing on shared objects

Scalability of PRNGs (unrealistic contention)



Takeaway: Locality has larger impact on scalability

See `TestPseudoRandom.java`

Throughput of computing on ThreadLocal objects

Throughput of computing on shared objects

Lock-free data structures

What is a lock-free data structure/algorithm?

- There exist 3 main notions of progress in non-blocking computation

1. *wait-free*: My operations are guaranteed to complete in a bounded number of steps (no matter what other threads do)

2. *lock-free*: Somebody's operations are guaranteed to complete in a bounded number of my steps
   - Most non-blocking data structures are lock-free, e.g., Treabor's stack (see next slides)

3. *obstruction-free*: My operations are guaranteed to complete in a bounded of steps (if I get to execute them)

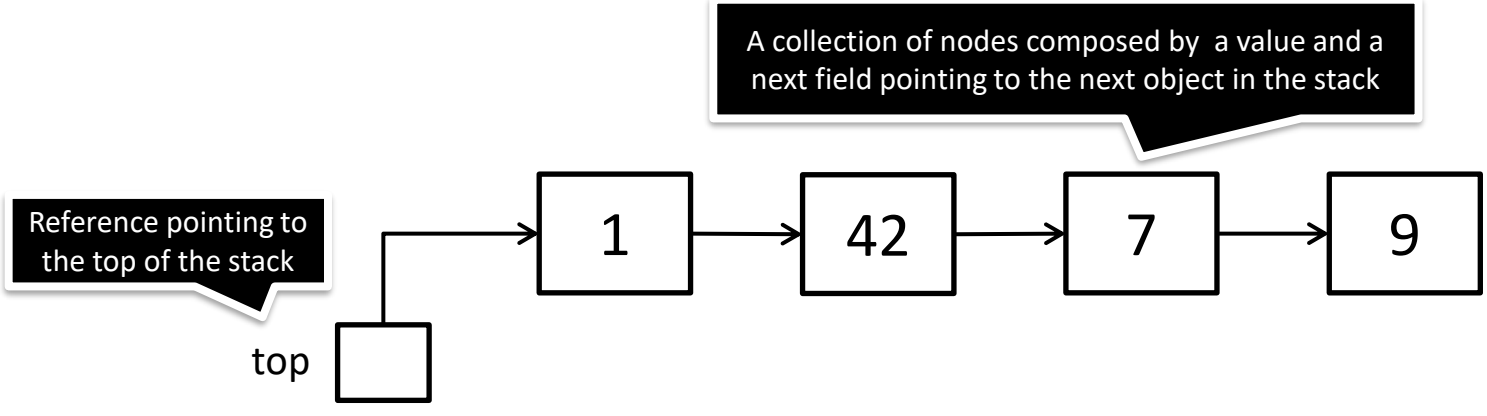
$$wait\text{-}free \Rightarrow lock\text{-}free \Rightarrow obstruction\text{-}free$$

Slide from Michael Scott's presentation: https://www.youtube.com/watch?v=9XAx279s7gs

How do we model an empty stack?

- A stack is a data structure following a LIFO *(last-in-first-out)* policy
  - push() – adds an element to the top of the stack
  - pop() – removes the top of the stack
- It is typically implemented as a linked list

Introduced by Treiber in 1986



Lock-free Stack

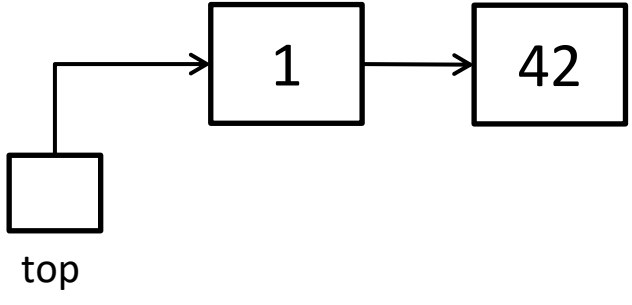
Introduced by Treiber in 1986

```
class LockFreeStack<T> {
    AtomicReference<Node<T>> top =
          new AtomicReference<Node<T>>();

    public void push(T value) {
        Node<T> newHead = new Node<T>(value);
        Node<T> oldHead;
        do {
         oldHead      = top.get();
         newHead.next = oldHead;
        } while (!top.compareAndSet(oldHead,newHead));
    }

    public T pop() {
        Node<T> newHead;
        Node<T> oldHead;
        do {
         oldHead = top.get();
         if(oldHead == null) { return null; }
         newHead = oldHead.next;
        } while (!top.compareAndSet(oldHead,newHead));
        return oldHead.value;
    }
}
```

See **TestLockFreeStack.java**



Lock-free Heap | push()

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    }
  …
}
```

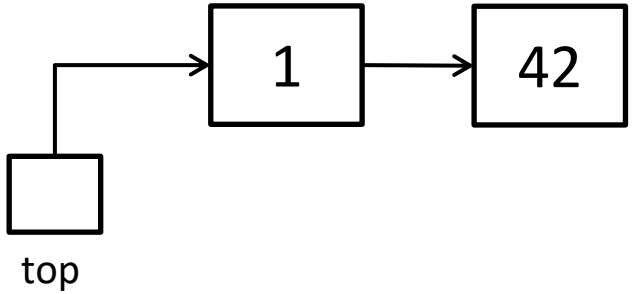

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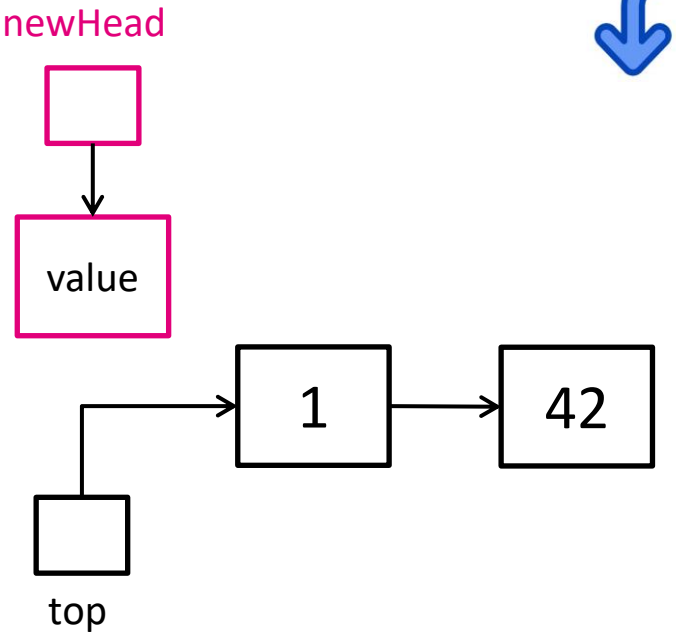

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  …
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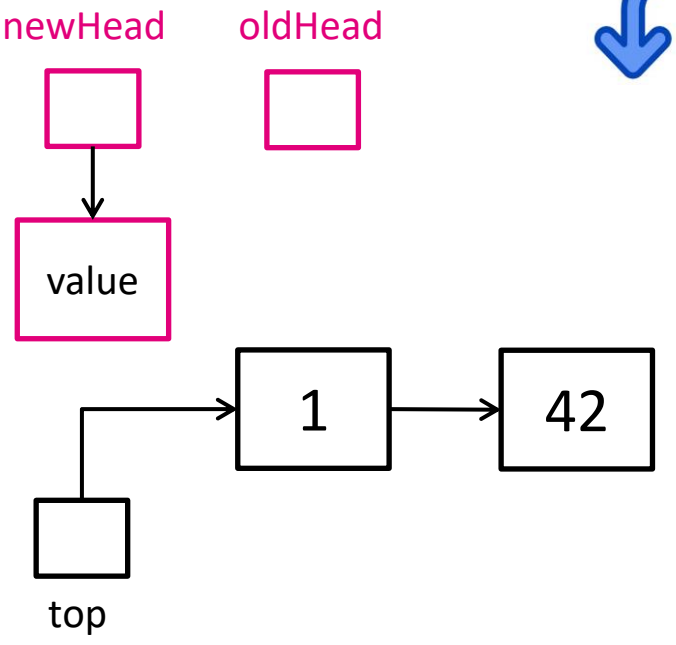
```



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  …
}
```

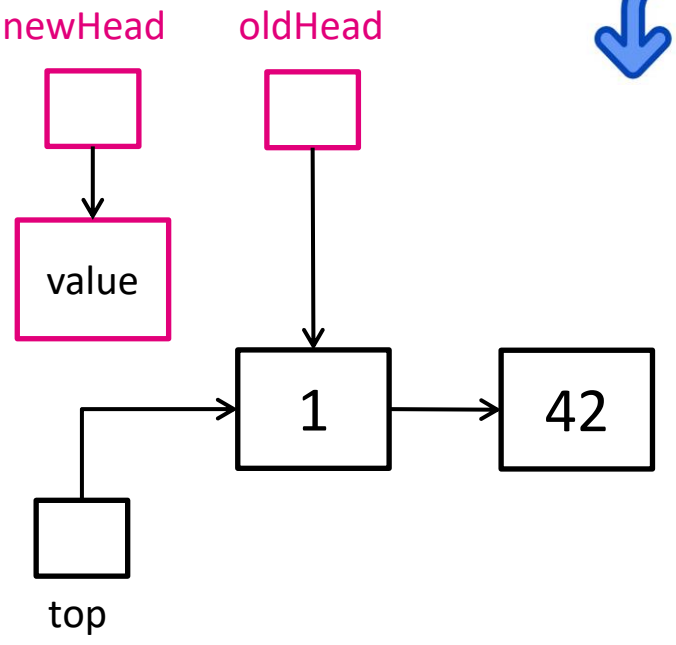

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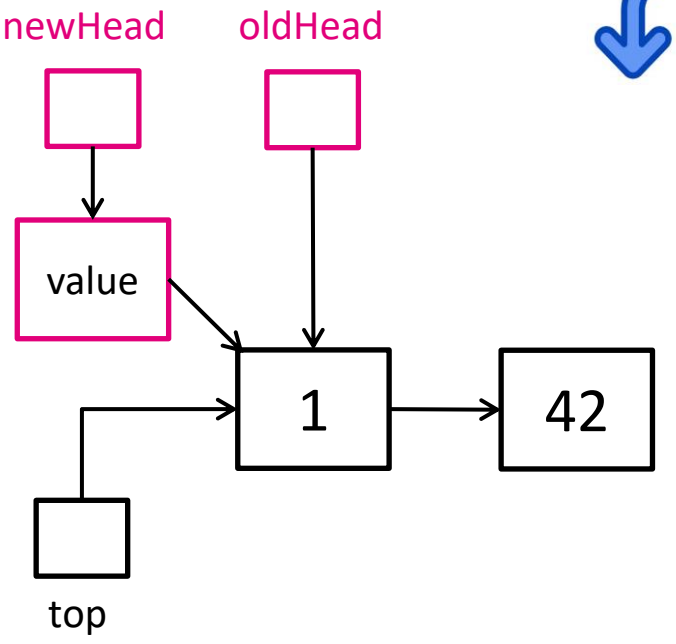

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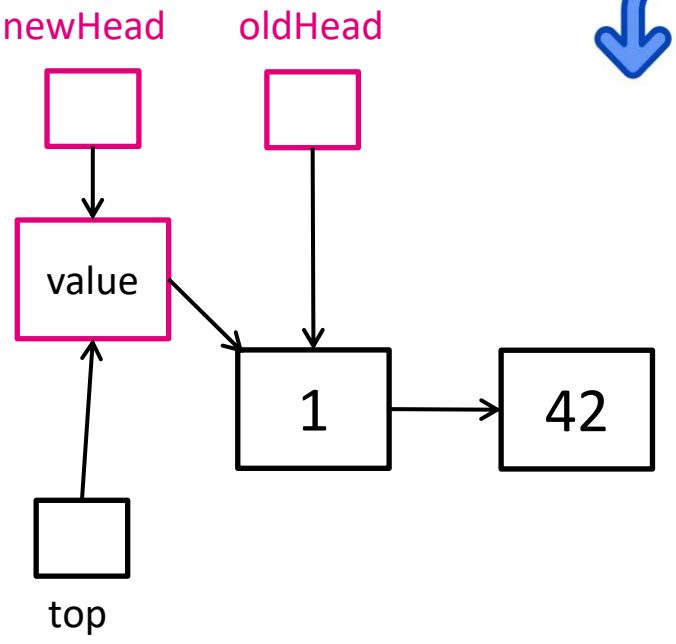
}
```

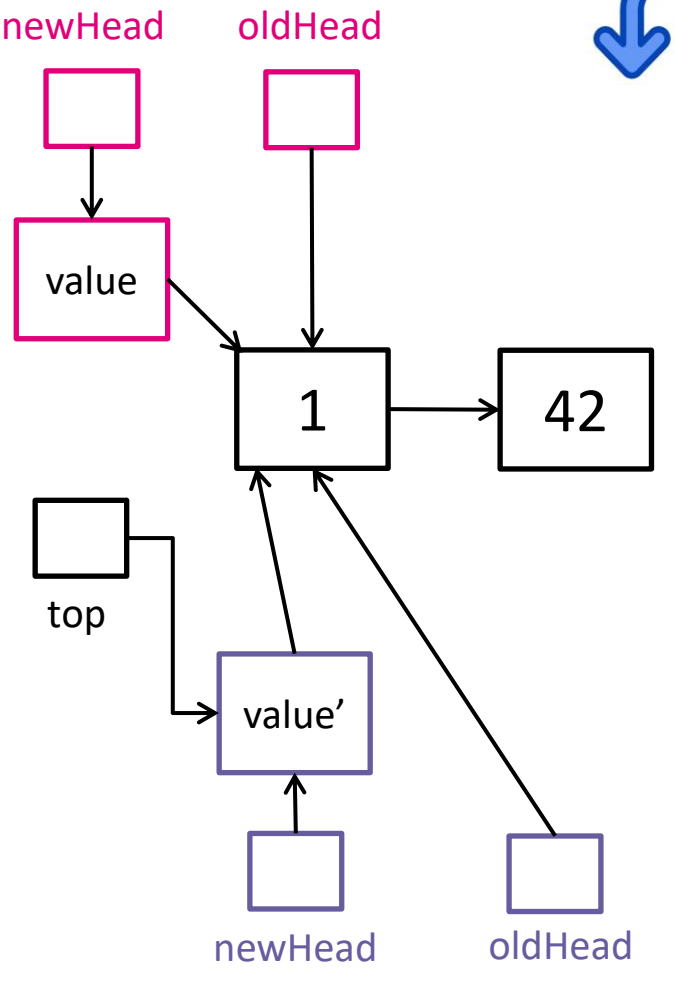


Lock-free Heap | push()

```
class LockFreeStack<T> {
    AtomicReference<Node<T>> top =
         new AtomicReference<Node<T>>();

    public void push(T value) {
        Node<T> newHead = new Node<T>(value);
        Node<T> oldHead;
        do {
         oldHead      = top.get();
         newHead.next = oldHead;
        } while (!top.compareAndSet(oldHead,newHead));
    }
  …
}
```

If before the pink thread executes CAS another thread had pushed concurrently, then CAS fails and push restarts



Lock-free Heap | push()

```
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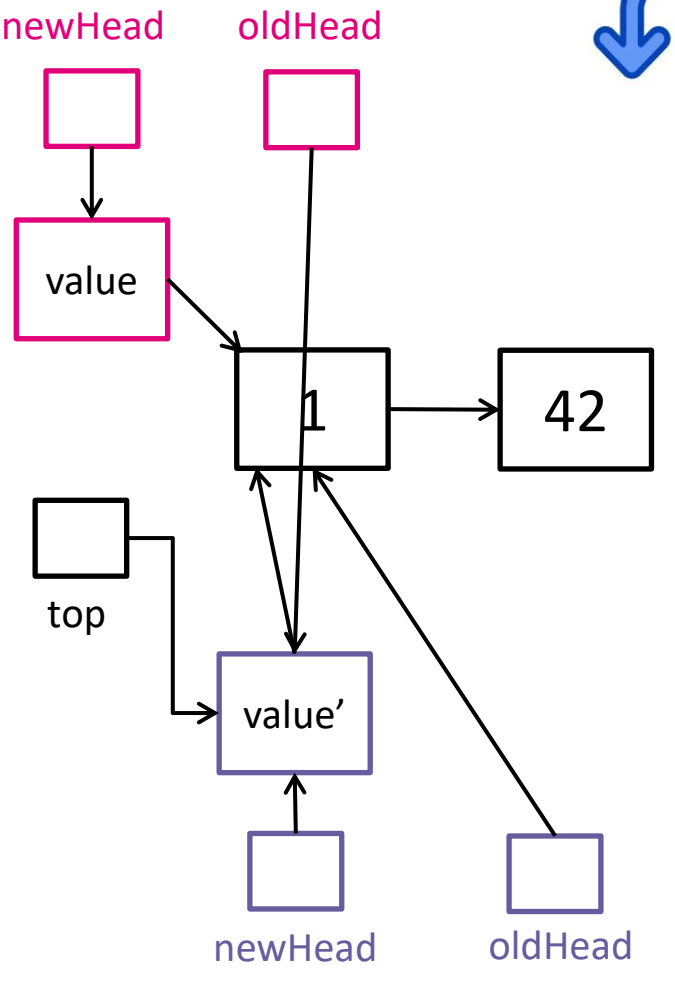
        Node<T> oldHead;
        do {
         oldHead      = top.get();
         newHead.next = oldHead;
        } while (!top.compareAndSet(oldHead,newHead));
    }
  …
}
```

If before the pink thread executes CAS another thread had pushed concurrently, then CAS fails and push restarts



Lock-free Heap | push()

```
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        Node<T> oldHead;
        do {
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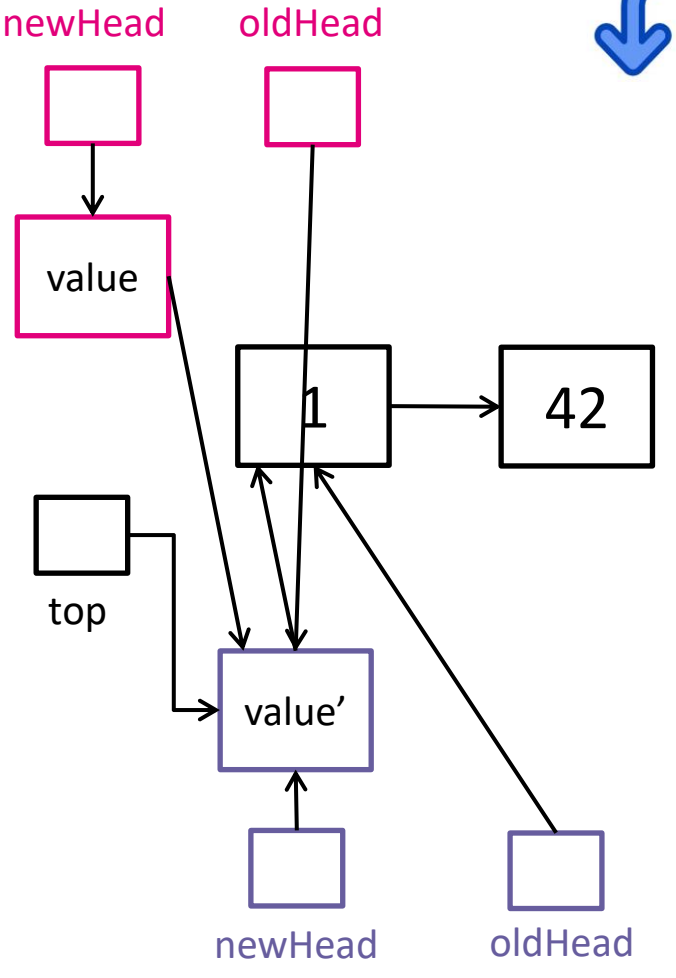
         newHead.next = oldHead;
        } while (!top.compareAndSet(oldHead,newHead));
    }
  …
}
```

If before the pink thread executes CAS another thread had pushed concurrently, then CAS fails and push restarts



Lock-free Heap | push()

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        Node<T> oldHead;
        do {
         oldHead      = top.get();
         newHead.next = oldHead;
        } while (!top.compareAndSet(oldHead,newHead));
    }
  …
}
```
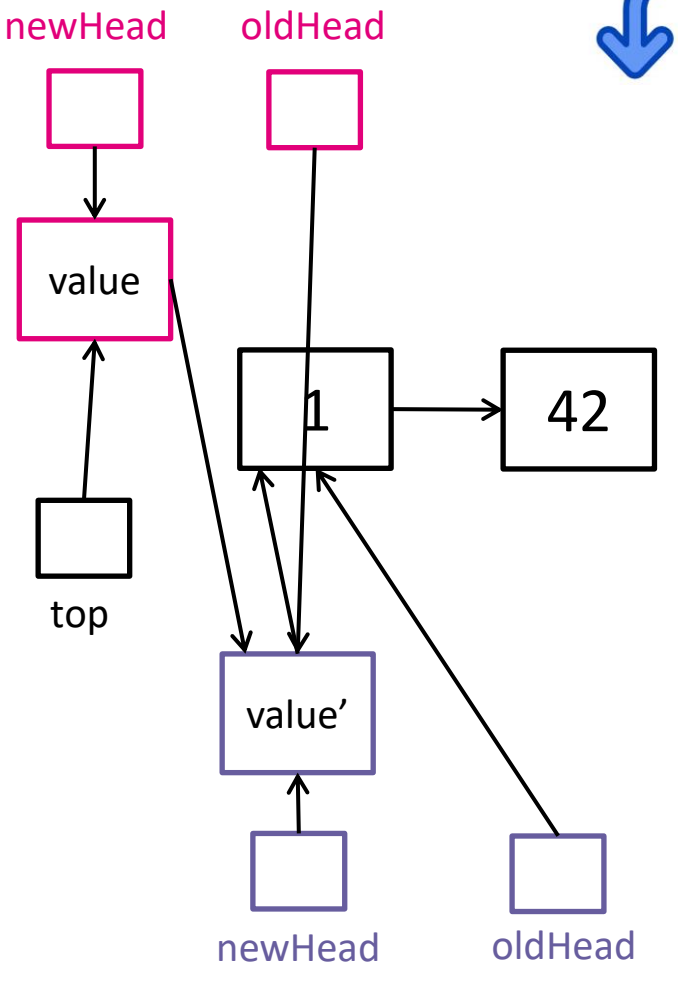
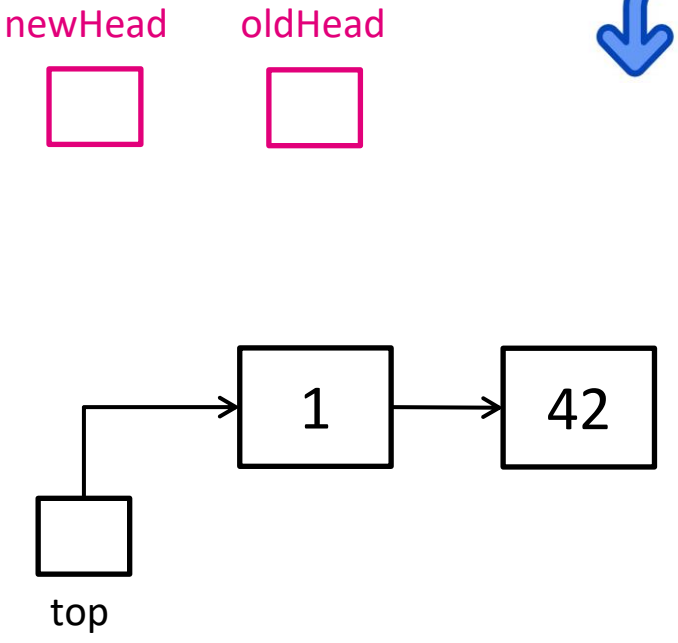

If before the pink thread executes CAS another thread had pushed concurrently, then CAS fails and push restarts



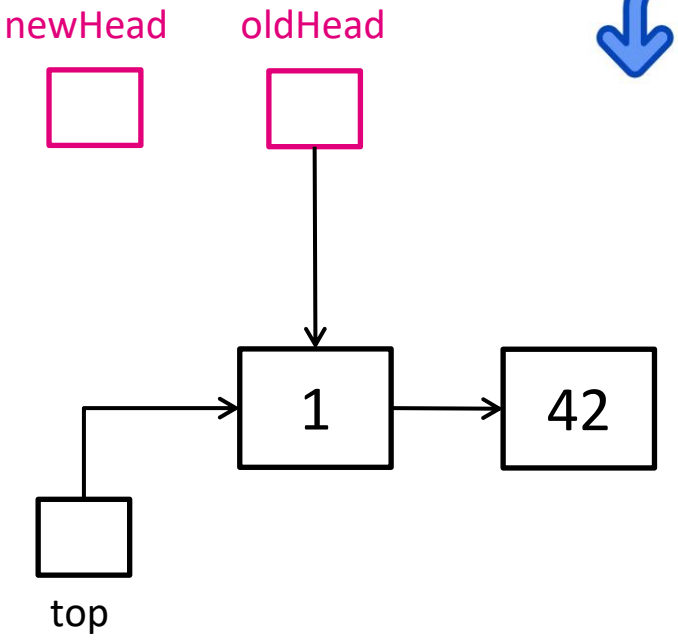
Lock-free Heap | pop()


```
class LockFreeStack<T> {
…
     public T pop() {
         Node<T> newHead;
         Node<T> oldHead;
         do {
          oldHead = top.get();
          if(oldHead == null) { return null; }
          newHead = oldHead.next;
         } while (!top.compareAndSet(oldHead,newHead));
         return oldHead.value;
     }
 }
```



Lock-free Heap | pop()


```
class LockFreeStack<T> {
…
     public T pop() {
         Node<T> newHead;
         Node<T> oldHead;
         do {
          oldHead = top.get();
          if(oldHead == null) { return null; }
          newHead = oldHead.next;
         } while (!top.compareAndSet(oldHead,newHead));
         return oldHead.value;
     }
 }
```



Lock-free Heap | pop()


```
class LockFreeStack<T> {
…
     public T pop() {
         Node<T> newHead;
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         do {
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          if(oldHead == null) { return null; }
          newHead = oldHead.next;
         } while (!top.compareAndSet(oldHead,newHead));
         return oldHead.value;
     }
 }
```
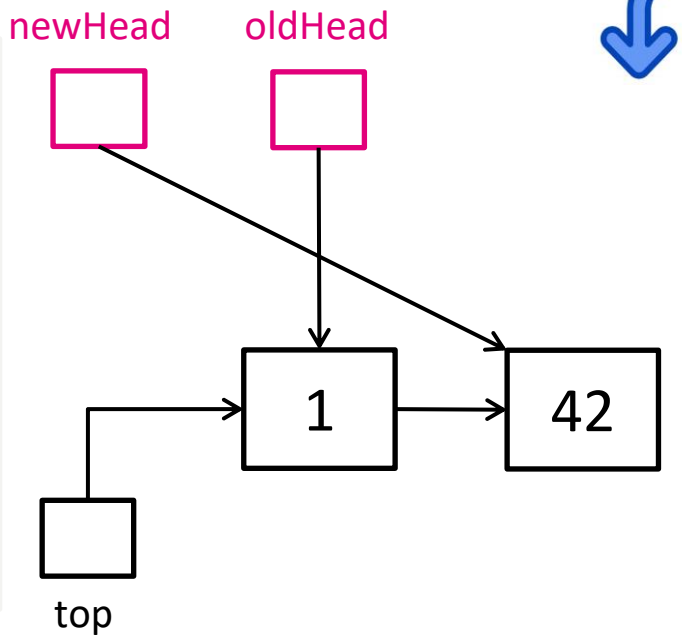
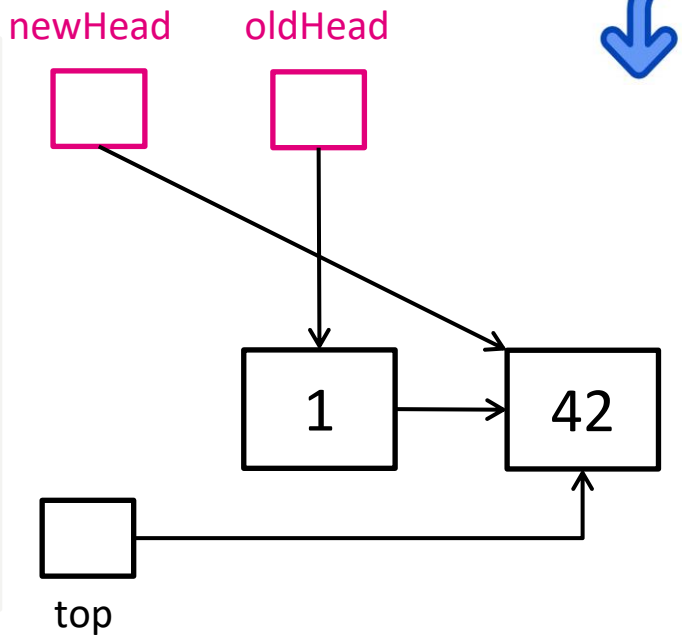



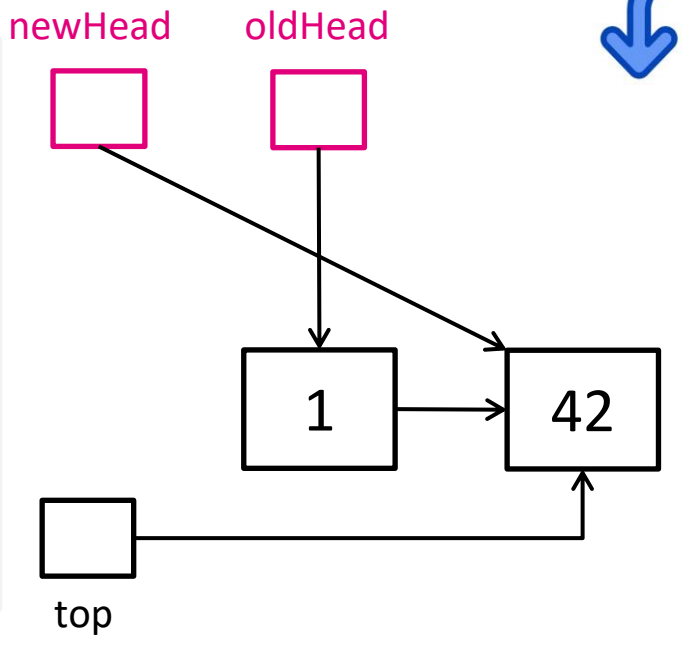
Lock-free Heap | pop()


```
class LockFreeStack<T> {
…
     public T pop() {
         Node<T> newHead;
         Node<T> oldHead;
         do {
          oldHead = top.get();
          if(oldHead == null) { return null; }
          newHead = oldHead.next;
         } while (!top.compareAndSet(oldHead,newHead));
         return oldHead.value;
     }
 }
```



Lock-free Heap | pop()


```
class LockFreeStack<T> {
…
     public T pop() {
         Node<T> newHead;
         Node<T> oldHead;
         do {
          oldHead = top.get();
          if(oldHead == null) { return null; }
          newHead = oldHead.next;
         } while (!top.compareAndSet(oldHead,newHead));
         return oldHead.value;
     }
 }
```

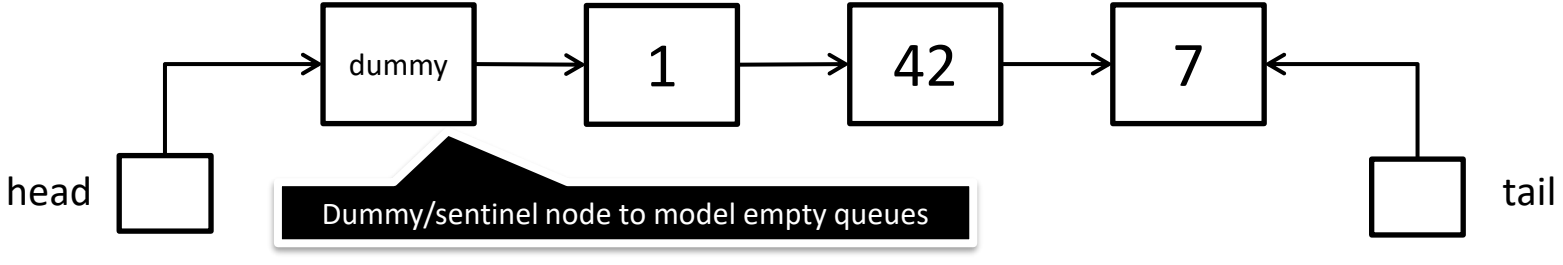


Would there be any problem if another thread is executing pop() concurrently?

Queues

- A queue is a data structure following a FIFO *(first-in-first-out)* policy
  - enqueue() – adds an element to the tail of the queue
  - dequeue() – removes an element from the head of the queue

- It is typically implemented as a linked list



Lock-free queue

- Michael-Scott lock free queue, introduced in 1996 (see optional readings)

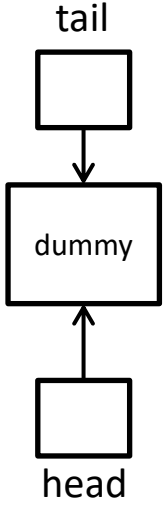
- Implemented in ConcurrentLinkedQueue in java.concurrent.* by Doug Lea et. al. (see here)
  - The version on the right is not the JDK implementation

```
class MSQueue<T> implements UnboundedQueue<T> {
    private final AtomicReference<Node<T>> head, tail;

    public MSQueue() {
        Node<T> dummy = new Node<T>(null, null);
        head = new AtomicReference<Node<T>>(dummy);
        tail = new AtomicReference<Node<T>>(dummy);
    }

    public void enqueue(T item) {
        Node<T> node = new Node<T>(item, null);
        while (true) {
            Node<T> last = tail.get(), next = last.next.get();
            if (last == tail.get()) {
                if (next == null)  {
                    // In quiescent state, try inserting new node
                    if (last.next.compareAndSet(next, node)) {
                        // Insertion succeeded, try advancing tail
                        tail.compareAndSet(last, node);
                        return;
                    }
                } else
                    // Queue in intermediate state, advance tail
                    tail.compareAndSet(last, next);
            }
        }
    }

    public T dequeue() {
        while (true) {
            Node<T> first = head.get(), last = tail.get(), next = first.next.get();
            if (first == head.get()) {        // D5
                if (first == last) {
                    if (next == null)
                        return null;
                    else
                        tail.compareAndSet(last, next);
                } else {
                    T result = next.item;
                    if (head.compareAndSet(first, next)) // D13
                        return result;
                }
            }
        }
    }
…
```

See **`TestMSQueue.java`**

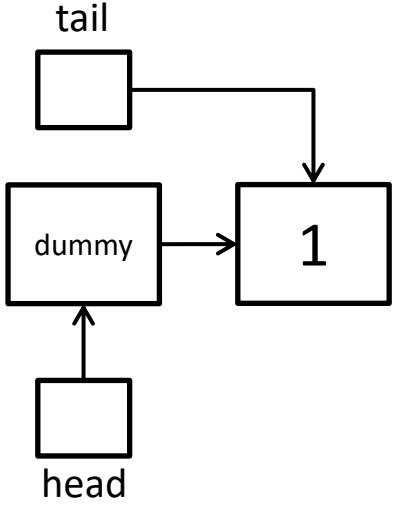
Lock-free queue | initialization


```
class MSQueue<T> implements UnboundedQueue<T> {
    private final AtomicReference<Node<T>> head, tail;

    public MSQueue() {
      Node<T> dummy = new Node<T>(null, null);
      head = new AtomicReference<Node<T>>(dummy);
      tail = new AtomicReference<Node<T>>(dummy);
    }
…
}
```



Lock-free queue | enqueue


```
class MSQueue<T> implements UnboundedQueue<T> {
…
 public void enqueue(T item) {
      Node<T> node = new Node<T>(item, null);
      while (true) {
          Node<T> last = tail.get();
          Node<T> next = last.next.get();
          if (last == tail.get()) {
            if (next == null)  {
                // In quiescent state, try inserting new node
                if (last.next.compareAndSet(next, node)) {
                  // Insertion succeeded, try advancing tail
                  tail.compareAndSet(last, node);
                  return;
                }
            } else
                // Queue in intermediate state, advance tail
                tail.compareAndSet(last, next);
          }
      }
    }
…
}
```



Lock-free queue | enqueue


```
class MSQueue<T> implements UnboundedQueue<T> {
…
 public void enqueue(T item) {
      Node<T> node = new Node<T>(item, null);
      while (true) {
          Node<T> last = tail.get();
          Node<T> next = last.next.get();
          if (last == tail.get()) {
            if (next == null)  {
                // In quiescent state, try inserting new node
                if (last.next.compareAndSet(next, node)) {
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                  tail.compareAndSet(last, node);
                  return;
                }
            } else
                // Queue in intermediate state, advance tail
                tail.compareAndSet(last, next);
          }
      }
    }
…
}
```

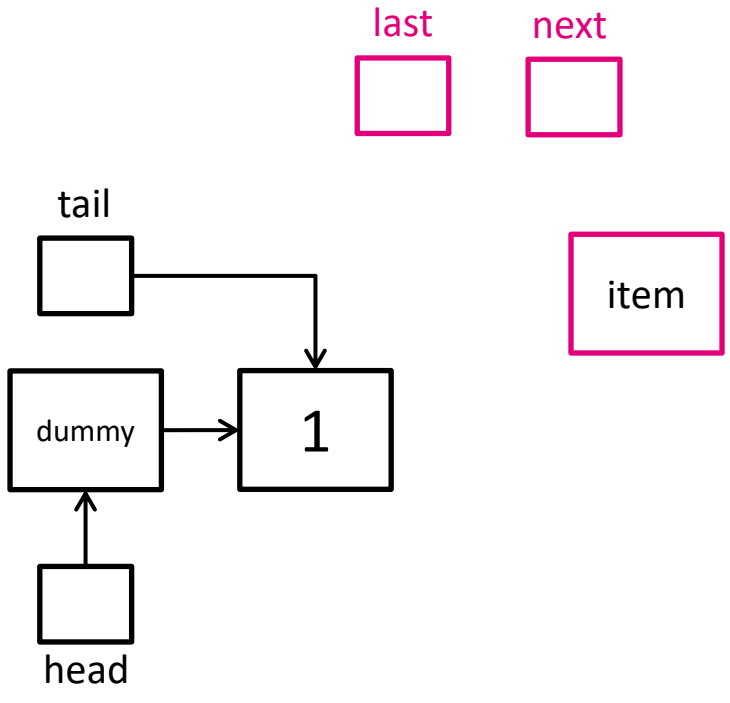

Lock-free queue | enqueue


```
class MSQueue<T> implements UnboundedQueue<T> {
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                  return;
                }
            } else
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                tail.compareAndSet(last, next);
          }
      }
    }
…
}
```

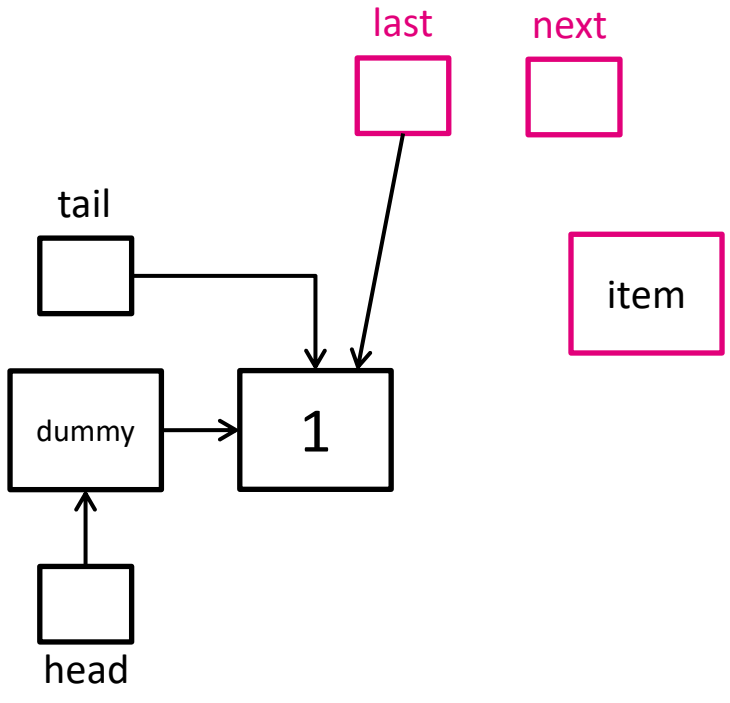

Lock-free queue | enqueue


```
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                  tail.compareAndSet(last, node);
                  return;
                }
            } else
                // Queue in intermediate state, advance tail
                tail.compareAndSet(last, next);
          }
      }
    }
…
}
```

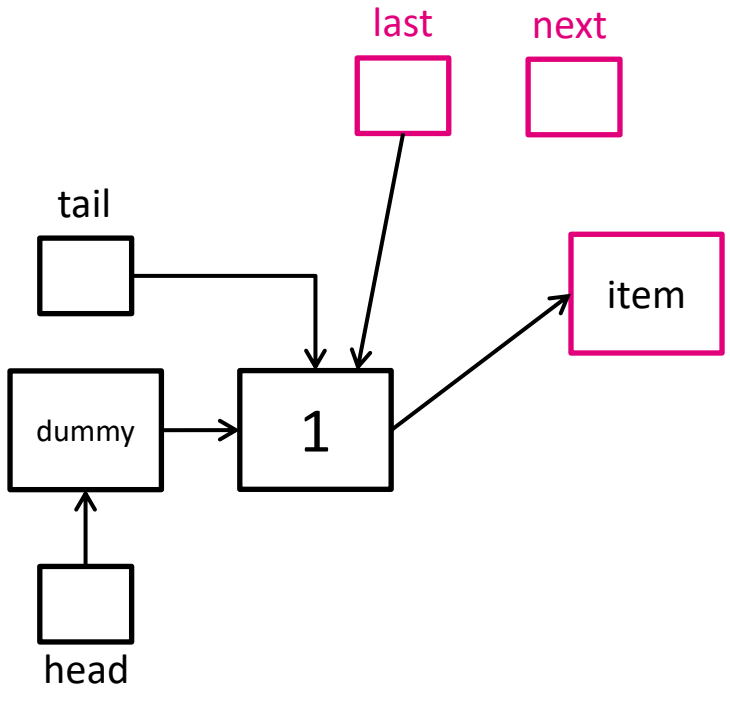

Lock-free queue | enqueue


```
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                  tail.compareAndSet(last, node);
                  return;
                }
            } else
                // Queue in intermediate state, advance tail
                tail.compareAndSet(last, next);
          }
      }
    }
…
}
```

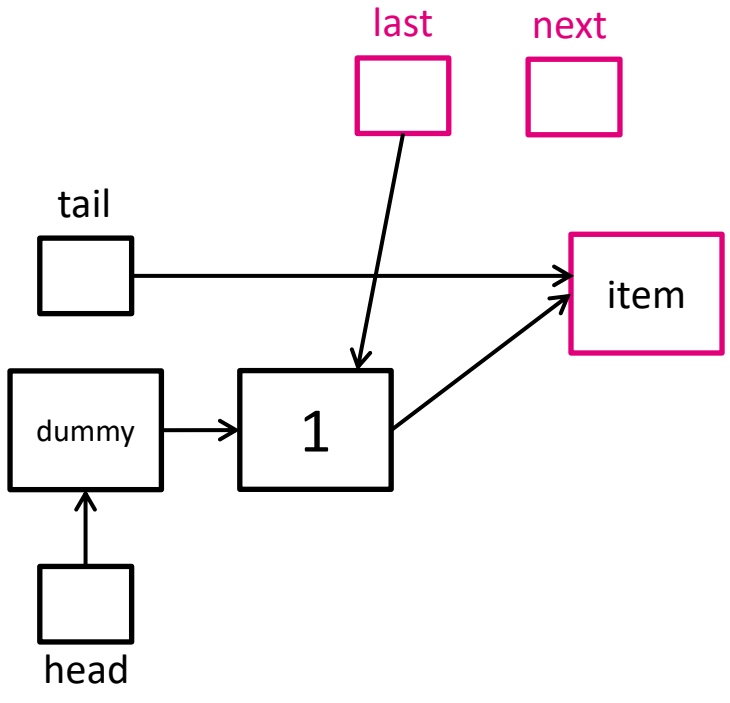

Lock-free queue | enqueue


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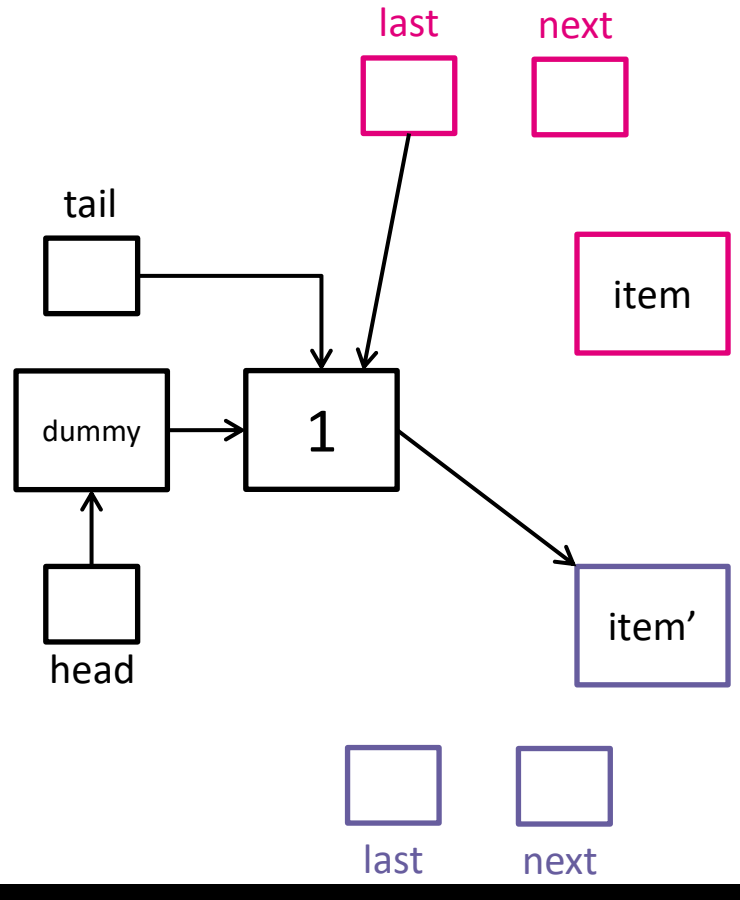
          if (last == tail.get()) {
            if (next == null)  {
                // In quiescent state, try inserting new node
                if (last.next.compareAndSet(next, node)) {
                  // Insertion succeeded, try advancing tail
                  tail.compareAndSet(last, node);
                  return;
                }
            } else
                // Queue in intermediate state, advance tail
                tail.compareAndSet(last, next);
          }
      }
    }
…
}
```



Lock-free queue | enqueue


```
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…
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            if (next == null)  {
                // In quiescent state, try inserting new node
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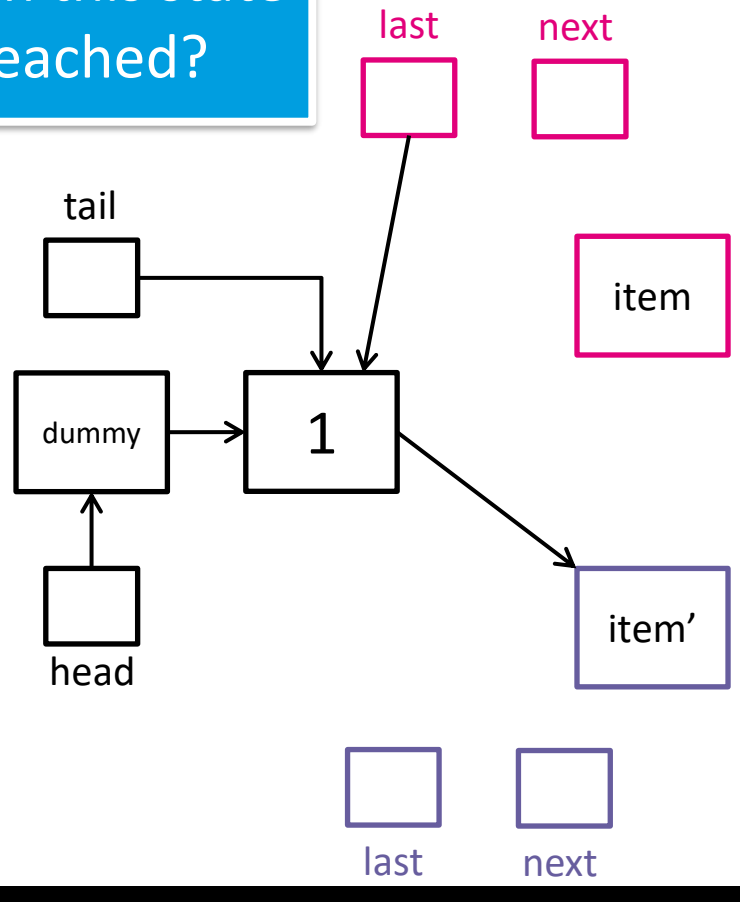
                  tail.compareAndSet(last, node);
                  return;
                }
            } else
                // Queue in intermediate state, advance tail
                tail.compareAndSet(last, next);
          }
      }
    }
…
}
```

How can this state be reached?



Lock-free queue | enqueue


```
class MSQueue<T> implements UnboundedQueue<T> {
…
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          if (last == tail.get()) {
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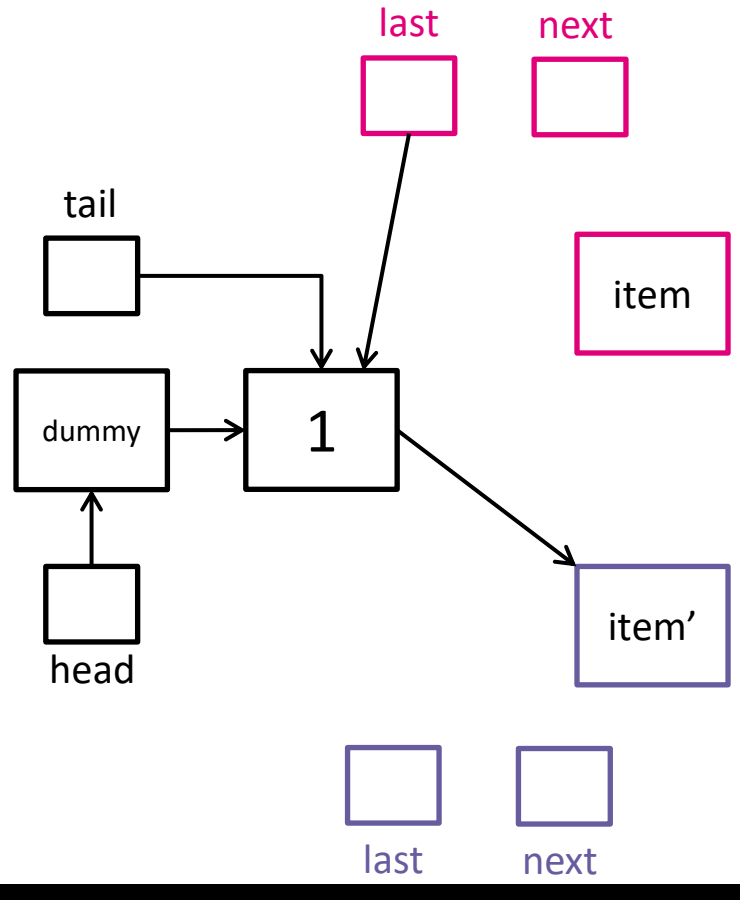
                  return;
                }
            } else
                // Queue in intermediate state, advance tail
                tail.compareAndSet(last, next);
          }
      }
    }
…
}
```



Lock-free queue | enqueue


```
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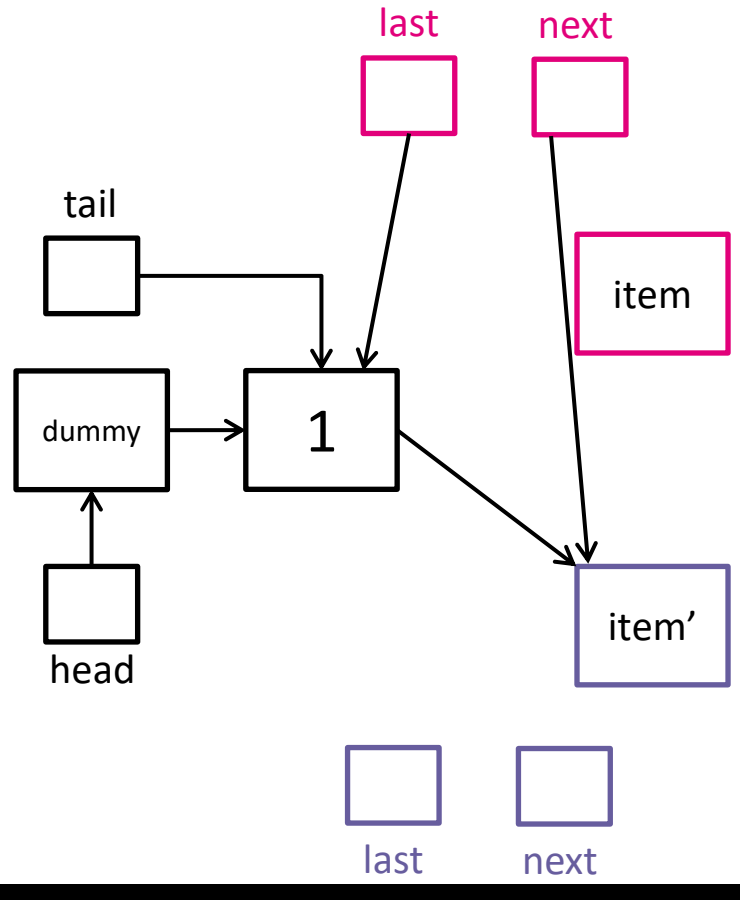
                }
            } else
                // Queue in intermediate state, advance tail
                tail.compareAndSet(last, next);
          }
      }
    }
…
}
```



Lock-free queue | enqueue


```
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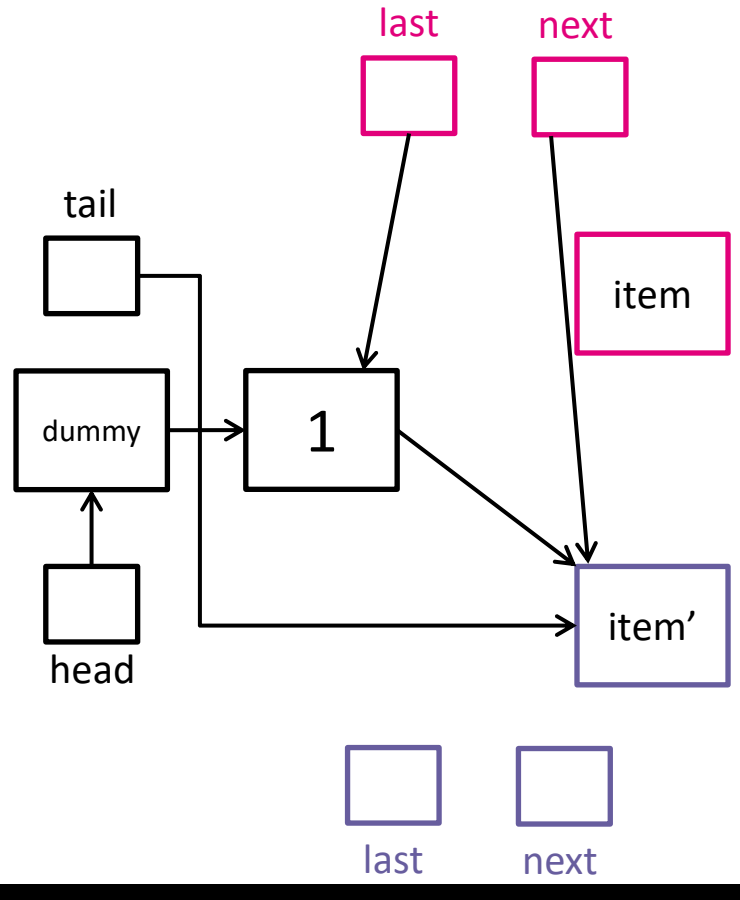
                }
            } else
                // Queue in intermediate state, advance tail
                tail.compareAndSet(last, next);
          }
      }
    }
…
}
```



Lock-free queue | enqueue


```
class MSQueue<T> implements UnboundedQueue<T> {
…
 public void enqueue(T item) {
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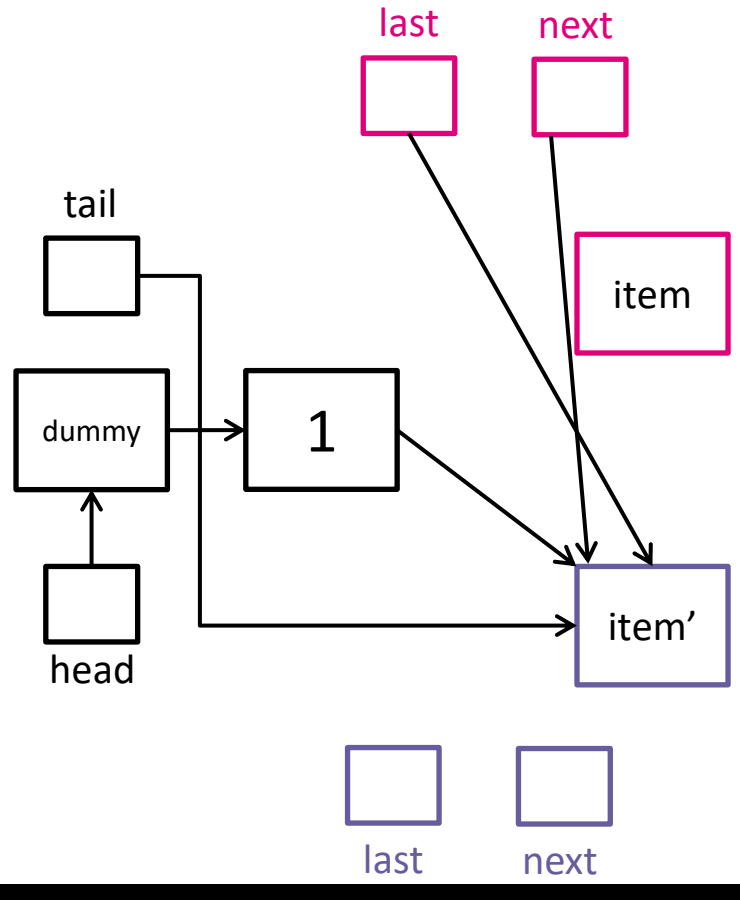
          }
      }
    }
…
}
```



Lock-free queue | enqueue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                  tail.compareAndSet(last, node);
                  return;
                }
            } else
                // Queue in intermediate state, advance tail
                tail.compareAndSet(last, next);
          }
      }
    }
…
}
```
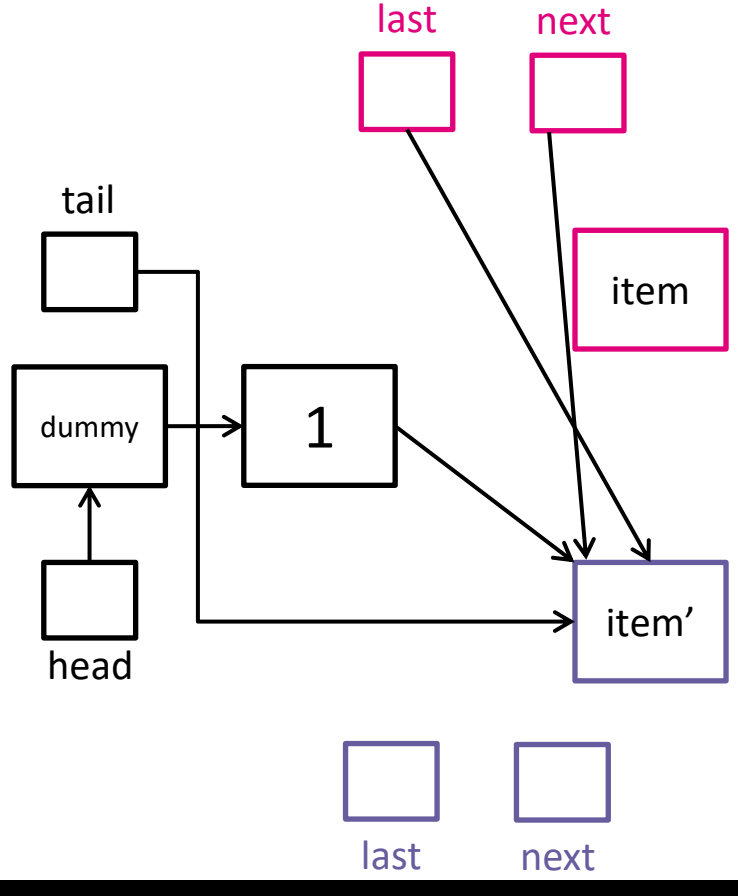

In case another thread is enqueuing, and didn't update the tail, the current thread helps by advancing the tail



Lock-free queue | enqueue


```
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                }
            } else
                // Queue in intermediate state, advance tail
                tail.compareAndSet(last, next);
          }
      }
    }
…
}
```
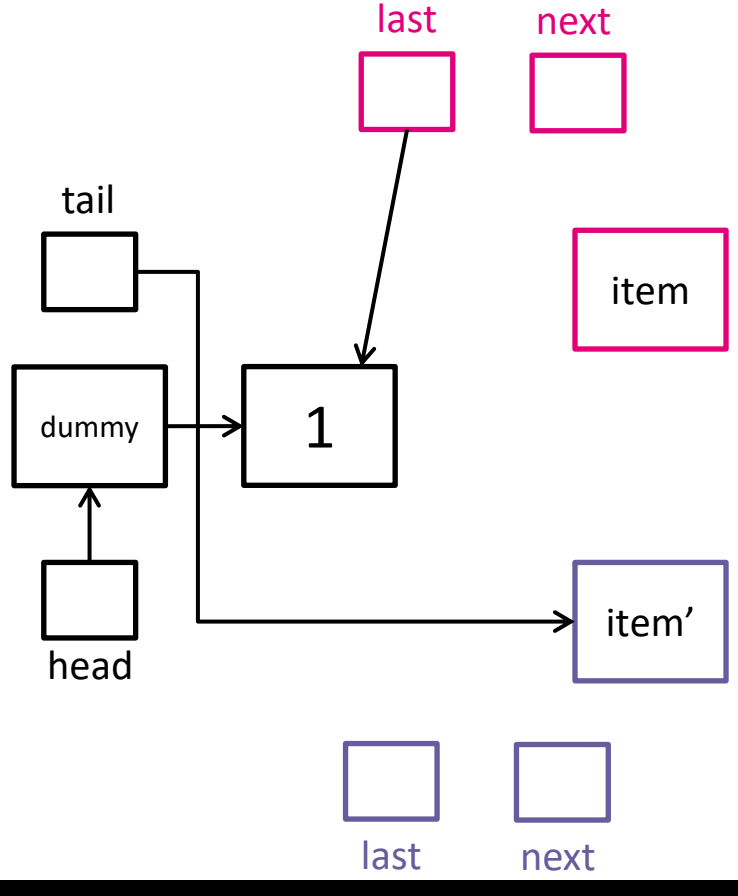

If the tail has been changed, then the thread restarts right away



Lock-free queue | dequeue


```
class MSQueue<T> implements UnboundedQueue<T> {
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    public T dequeue() {
      while (true) {
          Node<T> first = head.get();
          Node<T> last = tail.get();
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            if (first == last) {
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                  return null;
                else
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                T result = next.item;
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                  return result;
            }
          }
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}
```

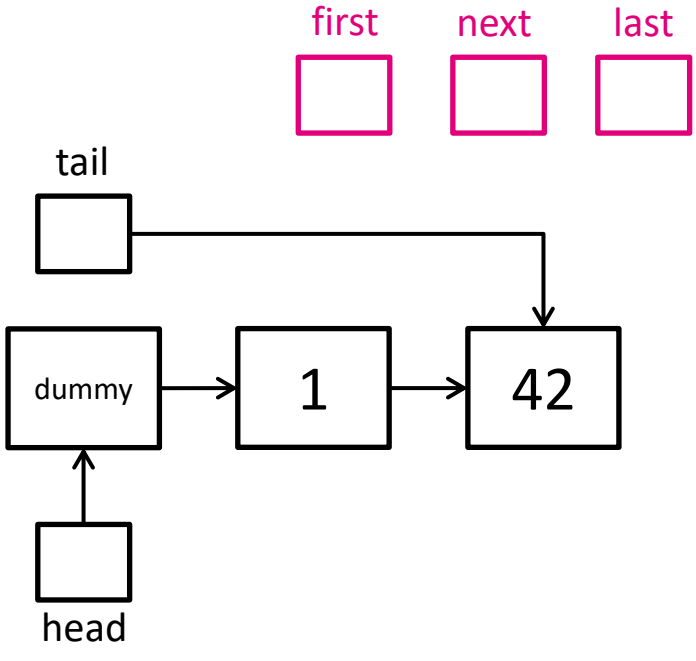

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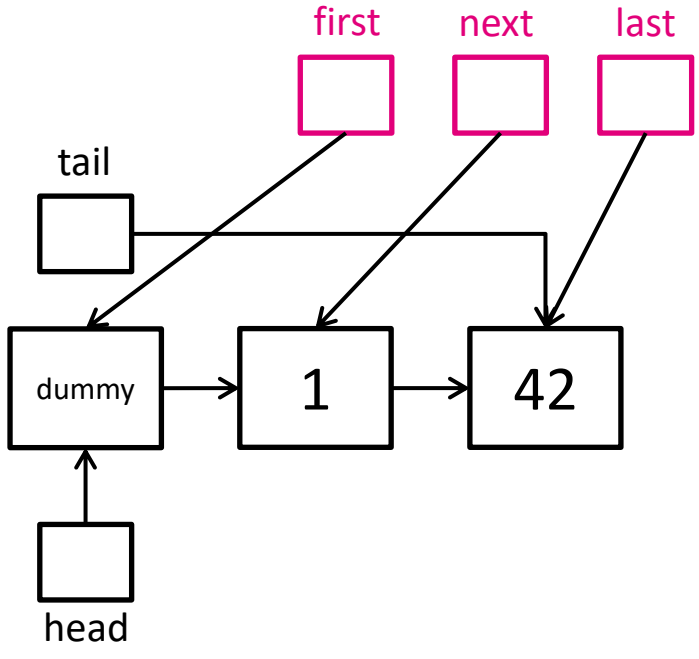

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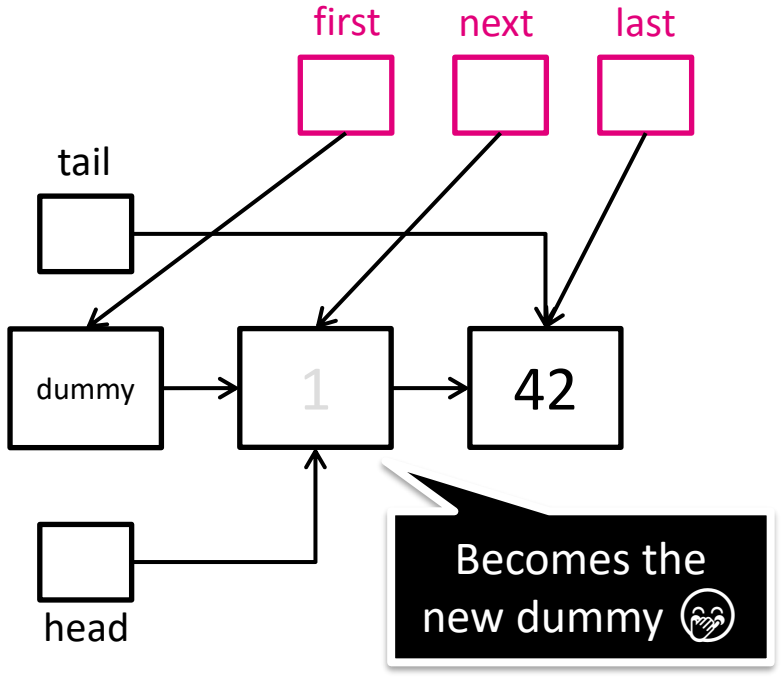

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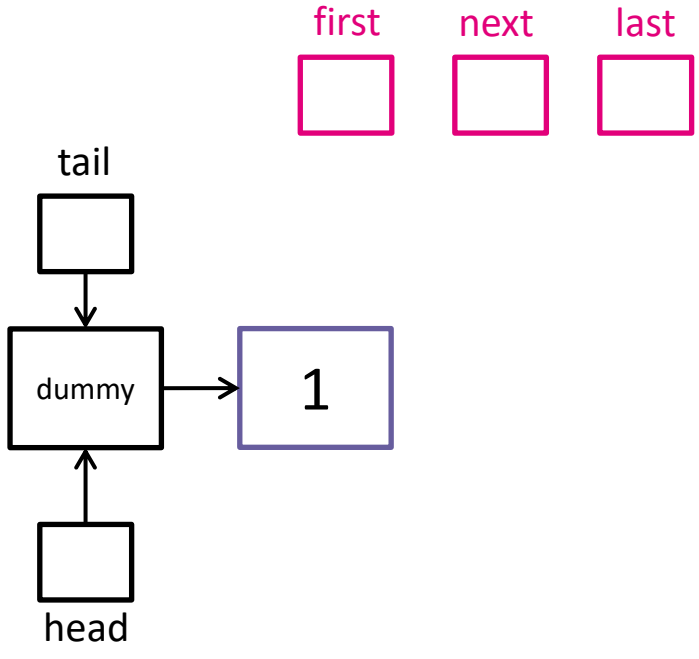

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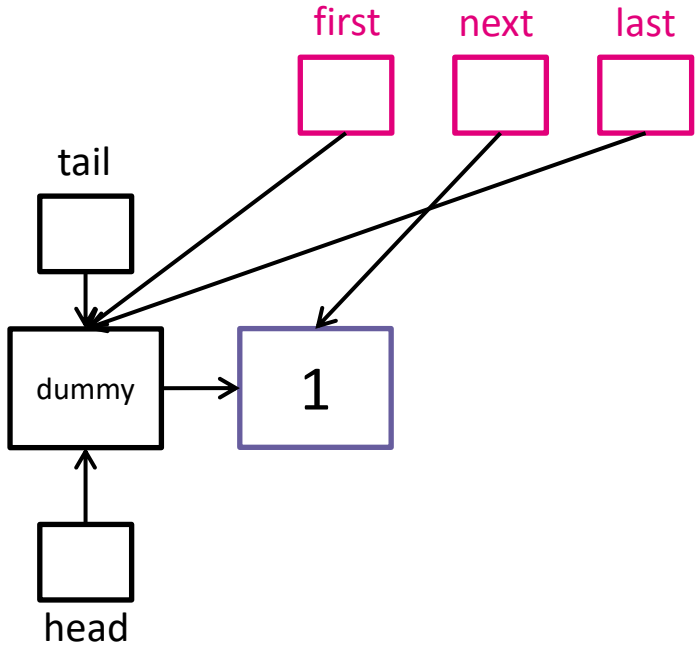

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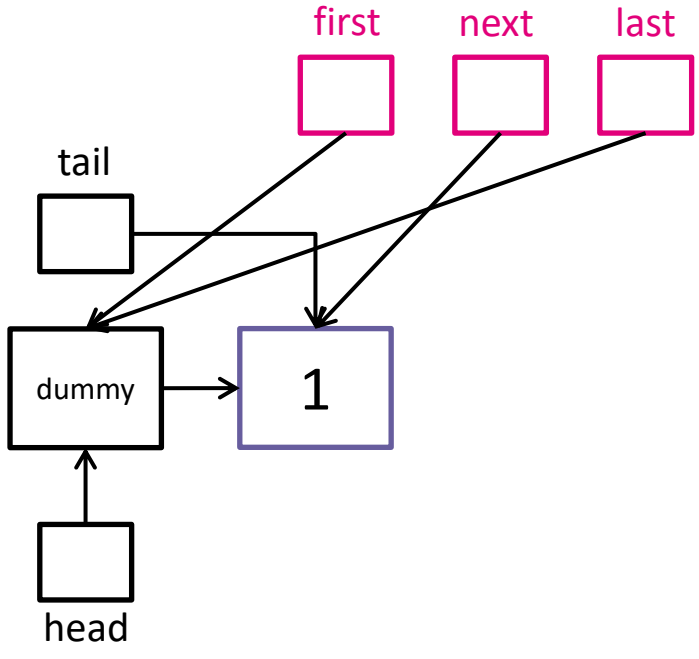
            }
          }
      }
…
}
```

If the next field of the head is not null (because another thread push in the meantime), then the calling thread helps advancing the tail and tries to pop again.



Lock-free queue | dequeue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            }
          }
      }
    }
…
}
```

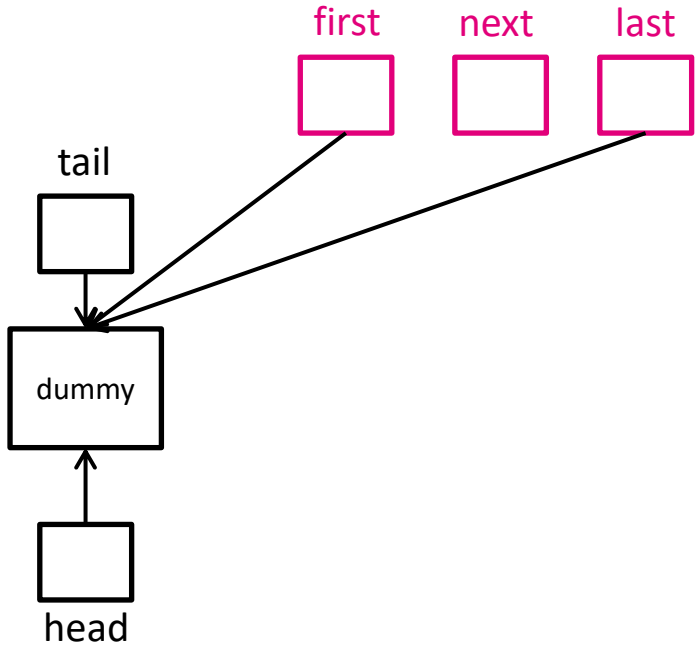

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                  tail.compareAndSet(last, next);
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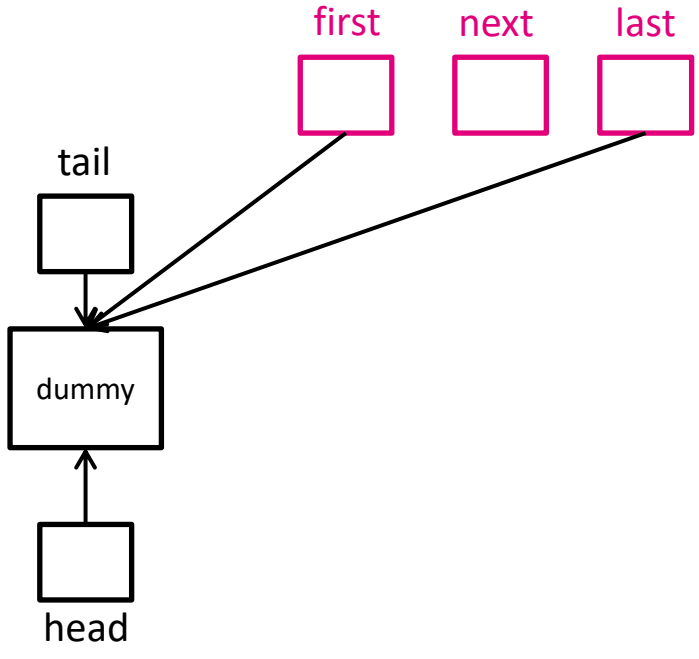
            }
          }
      }
…
}
```



If the next field of the head is pointing to null, then we return null. Why is this correct?

Lock-free queue | dequeue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                T result = next.item;
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                  return result;
            }
…
}
```
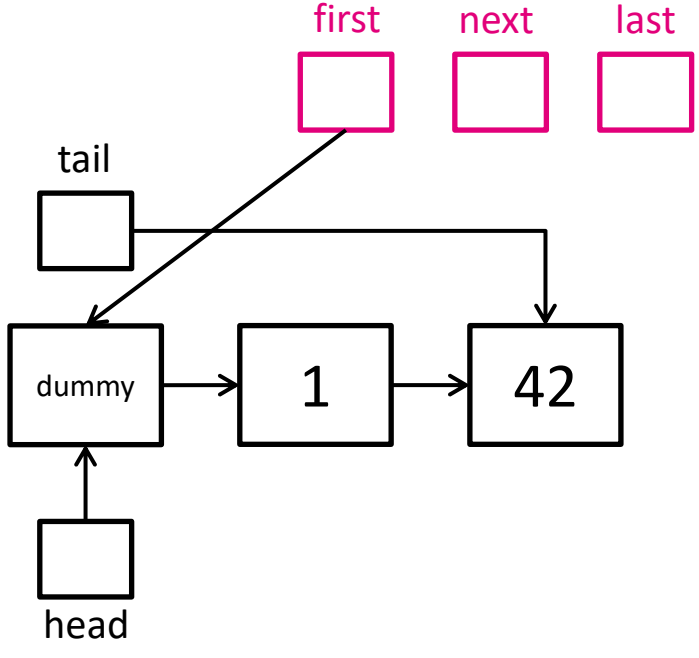
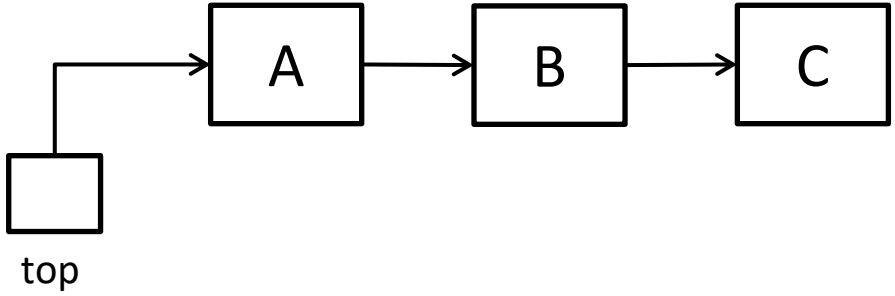

How can a state where first != head.get() be reached?



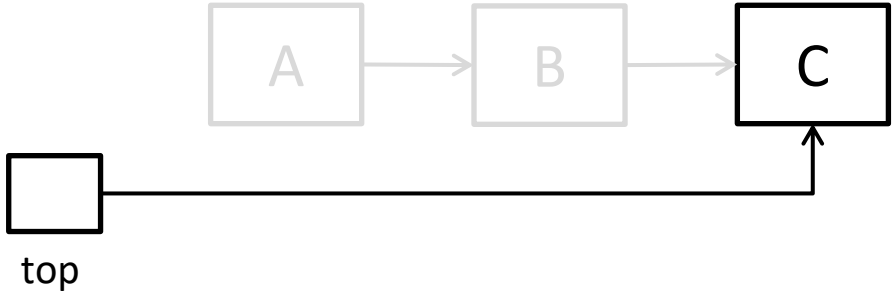
ABA Problem

1. Thread 1 *starts* popping A



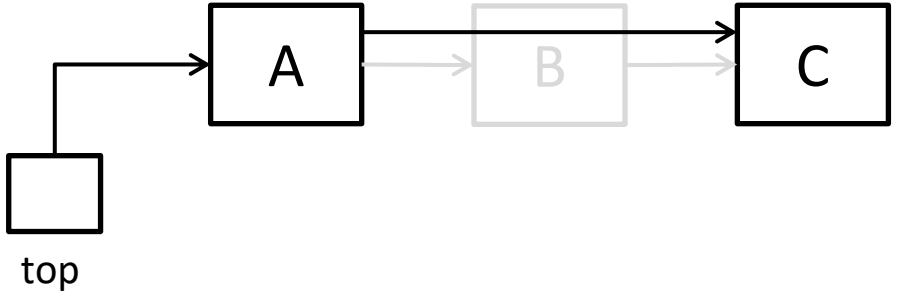
ABA Problem

1. Thread 1 *starts* popping A
2. Before thread 1 finishes, thread 2 pops A and B



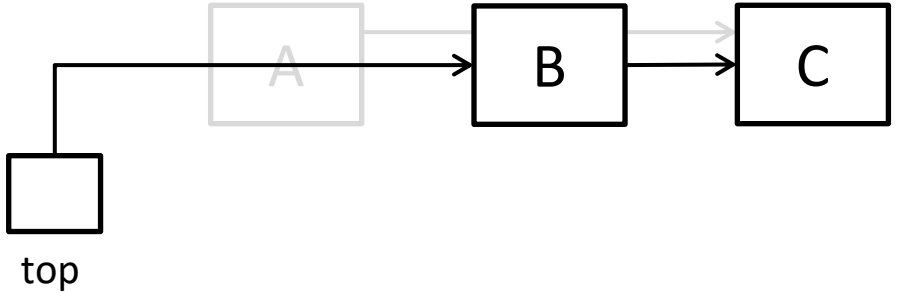
ABA Problem

1. Thread 1 *starts* popping A
2. Before thread 1 finishes, thread 2 pops A and B
3. Thread 2 pushes A back *// recovered from memory (same as thread 1 was popping)*



ABA Problem

1. Thread 1 *starts* popping A
2. Before thread 1 finishes, thread 2 pops A and B
3. Thread 2 pushes A back *// recovered from memory (same as thread 1 was popping)*
4. Thread 1 finishes popping A
    1. Incorrectly, as it thinks that A is the same as before thread 2 operations



ABA Problem

- It is a memory allocation issue which affects mainly languages without garbage collection (e.g., C and C++)

- Languages such as Java do not have this problem because garbage collection ensures that newly created objects are fresh
  - Step 3 in the previous slides would have created a new A object

Agenda

- Compare-And-Swap (CAS)
  - Lock-free Counter
  - Atomic libraries
  - CAS based lock implementation
- Lock-free stack
- Lock-free queue
- ABA problem

Guest lecturer in two weeks!

- After the fall break we will a guest lecture by Viet Yen Nguyen
- He will talk about how they use concurrent and parallel programming in the data processing pipeline for data analytics

The PCPP teaching team wishes you
a nice and well-deserved fall break

See you in two weeks!