CMSC 433 – Programming Language Technologies and Paradigms

Atomic Variables

Nonblocking Synchronization

java.util.concurrent Performance

- Many java.util.concurrent classes perform better then synchronized alternatives. Why?
  - Atomic variables & nonblocking algorithms
- Atomic variables – lock-free atomic operations
- Nonblocking algorithms are concurrent algorithms that derive their thread safety from low-level atomic hardware primitives (not locks)

Disadvantages of Locking

- When a thread fails to acquire a lock, it can be suspended
  - Context switching & resumption can be expensive
- When waiting for a lock, thread can't do anything
- If thread holding lock is delayed, no thread that needs that lock can progress
  - Can result in priority inversion: low priority thread has lock needed by a high priority thread
- Caveat: contention, rather than locking, is the real issue. YMMV

Hardware Support

- Locking is pessimistic
  - If contention is infrequent, most locking was unneeded
- In earlier lecture we discussed optimistic trying
  - Proceed with the update
  - Check for collision
  - If update fails, retry
- Processor can use atomic operations to support optimistic trying

Atomic Variables

- Holder classes for scalars, references and fields
- Supports atomic operations
  - Compare-and-set (CAS) (discussed later)
  - Get, set and arithmetic (where applicable)
- Some main classes: {int, long, ref} X {value, field, array}
  - E.g. AtomicInteger useful for counters, sequences, statistics
- Essential for writing efficient code on MPs
  - Nonblocking data structures & optimistic algorithms
  - Reduce overhead/contention updating “hot” fields
- JVM uses best construct available on platform
  - CAS, load-linked/store-conditional, locks

AtomicInteger

- Some methods include:
- int get() – returns the current value
- void set(int newValue) – sets to the given value
- int getAndSet(int newValue) - Atomically sets to the given value and returns the old value
- boolean compareAndSet(int expect, int update) - Atomically sets the value to the given updated value if the current value == the expected value

Summary of Atomic Variables

- Generalization of volatile variables
- Allows atomic read-modify-write operations without intrinsic locking
- Scope of contention limited to a single variable
- Faster than locking -- no scheduling impact
- Like volatiles, can’t synchronize two atomic vars
- In general, doesn’t support atomic check-then-act sequences

A Synchronized Counter

```
public final class SynchronizedCounter {
  private int c= 0;
  public synchronized int increment() {
    return ++c;
  }
  public synchronized int decrement() {
    return --c;
  }
 public synchronized int value() {
     return c;
  }
}
```

AtomicCounter

```
class AtomicCounter implements Counter {
   private AtomicInteger c = new AtomicInteger(0);
   public void increment() {
      c.incrementAndGet();
   }
   public void decrement() {
      c.decrementAndGet();
   }
   public int value() {
      return c.get();
  }
}
```

Atomic Variables

- See: CounterTest.java

Compare and Swap (CAS)

- CAS has 3 operands
  - Memory location V, expected value A, new value B
- Atomically updates V to value B, only if current value is A
- Multiple threads try to update V, only one succeeds
  - But the losers don't get punished with suspension
  - They can just try again

Simulated CAS

```
public class SimulatedCAS { // not implemented this way!
 private int value;
 public synchronized int get() {return currValue;}
 public synchronized int compareAndSwap ( int expectedValue, int newValue) {
    int oldValue = value;
    if (oldValue == expectedValue)
      value= newValue;
    return oldValue ;
 }
 public synchronized boolean compareAndSet(int expectedValue, int newValue) {
   return (expectedValue == compareAndSwap(expectedValue, newValue));
 }
}
```

A Nonblocking Counter

```
// demonstrates the use of CAS
public class NonblockingCounter {
  private AtomicInteger value;

  public int getValue() {
     return value.get();
  }

  public int increment() {
    int v;
    do {
      v = value.get();
    }while (!value.compareAndSet(v, v + 1));
    return v + 1;
   }
}
```

Updating Complex Objects

- Suppose we have an invariant over two variables
  - Can't maintain this invariant using volatile fields
- General strategy
  - Turn compound update into single update

CasNumberRange

```
// INVARIANT: lower <= upper
// How do you make this thread-safe?
private static class IntPair {
    final int lower, upper;
    public IntPair(int lower, int upper) {….}
    public void setLower(int i) {….}
    public void setUpper(int i)  {….}
}
```

CasNumberRange

```
public class CasNumberRange {
// IntPair is a pair of Integers
 private final AtomicReference<IntPair> values =
              new AtomicReference<IntPair>(new IntPair(0, 0));

public void setLower(int i) {
      while (true) {
          IntPair oldv = values.get(); // gets the current value atomically
          if (i > oldv.upper) throw new IllegalArgumentException();
          IntPair newv = new IntPair(i, oldv.upper);
          if (values.compareAndSet(oldv, newv)) return;
      }
  }
 // setUpper() similar to setLower()
}
```

Performance Comparison

- Two implementations of a psuedo-random number generator (PRNG)
  - One uses locks: ReentrantLockPseudoRandom.java
  - One is nonblocking: AtomicPseudoRandom.java
- PRNG issues
  - Next value based on last value, so you need to remember last value
- How do lock-based and non-lock-based implementations compare?

ReentrantLockPseudoRandom

```
public class ReentrantLockPseudoRandom extends PseudoRandom {
  private final Lock lock = new ReentrantLock(false);
  private int seed;

  ReentrantLockPseudoRandom(int seed) {this.seed = seed;}

  public int nextInt(int n) {
    lock.lock();
    try {
      int s = seed;  seed = calculateNext(s);  int remainder = s % n;
      return remainder > 0 ? remainder : remainder + n;
    } finally {
       lock.unlock();
    }
  }
}
```

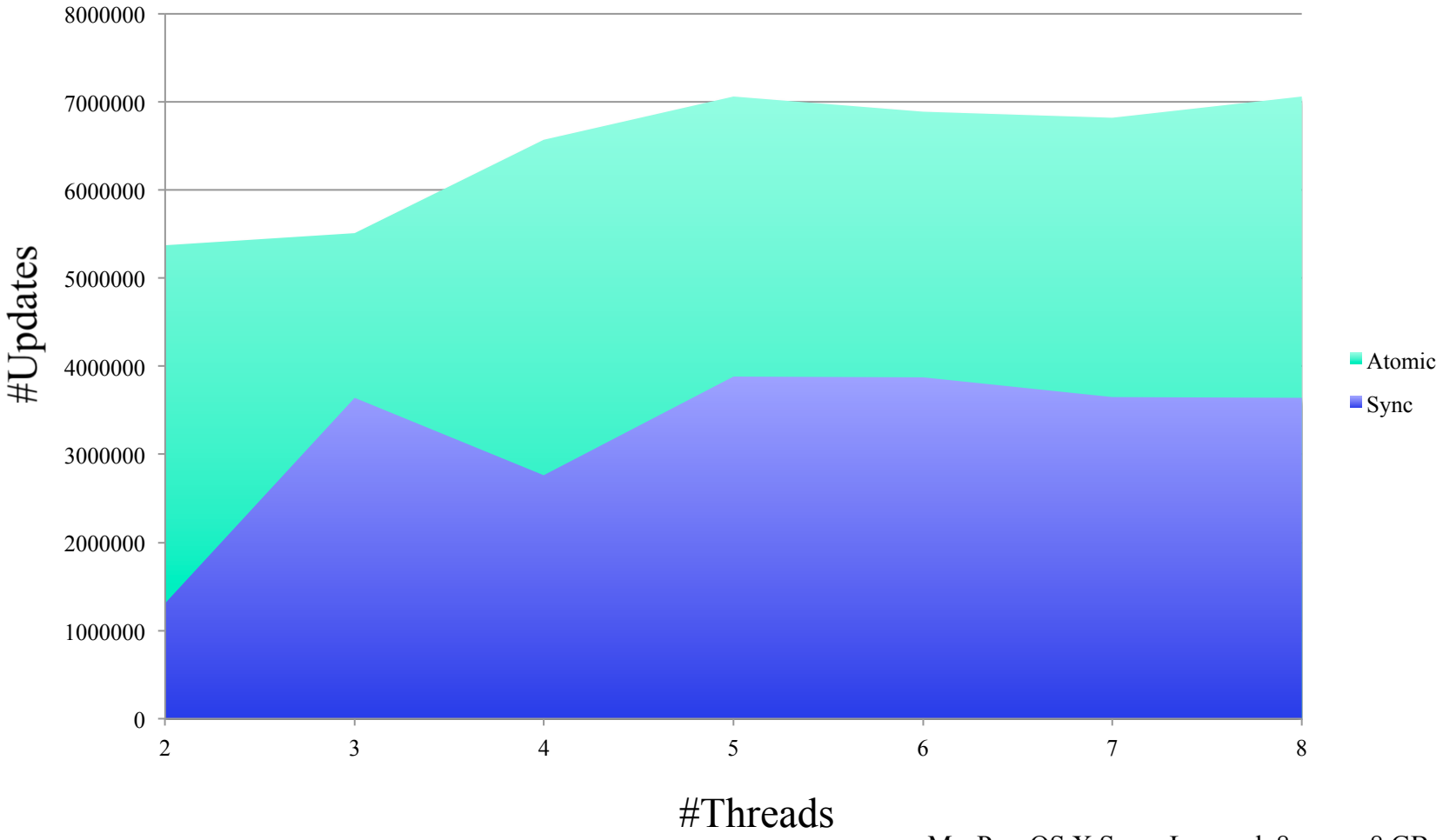
AtomicPseudoRandom

```
public class AtomicPseudoRandom extends PseudoRandom {
  private AtomicInteger seed;

  AtomicPseudoRandom(int seed) {this.seed = new AtomicInteger(seed);}

  public int nextInt(int n) {
    while (true) {
      int s = seed.get();
      int nextSeed = calculateNext(s);
      if (seed.compareAndSet(s, nextSeed)) {
        int remainder = s % n;
        return remainder > 0 ? remainder : remainder + n;
      }
    }
  }
}
```

Comparing Performance



MacPro, OS X Snow Leopard, 8 cores, 8 GB of RAM

Nonblocking Algorithms

- No software locks
- Stopping one thread will not prevent global progress
  - Immune to deadlock
  - Starvation is possible
- Writing correct nonblocking algorithms is very hard!

Nonblocking Stack

```
public class ConcurrentStack <E> {

   private static class Node <E> {
        public final E item;
        public Node<E> next;

   public Node(E item) {
            this.item = item;
        }
   }
  AtomicReference<Node<E>> top =
                              new AtomicReference<Node<E>>();
```

Nonblocking Stack

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

Nonblocking Stack

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

push() & pop()

```
public void push(E item) {
    Node<E> nh= new Node<E>(item);
    Node<E> oh;
    do {
        oh = top.get();
        nh.next = oh;
    } while (!top.compareAndSet(oh, nh));
}
```

```
public E pop() {
    Node<E> oh;  Node<E> nh;
    do {
        oh = top.get();
        if (oh == null)
            return null;
        nh = oh.next;
    } while (!top.compareAndSet(oh, nh));
    return oh.item;
}
```

Nonblocking Stack

- See: ConcurrentStack.java & SynchStack.java

A Nonblocking Queue

- Remember general strategy
  - Limit change to one variable
- Harder for a Queue because we need to update both head and tail
- See: SynchQueue.java & ConcurrentQueue.java

Overview of Michael & Scott Approach

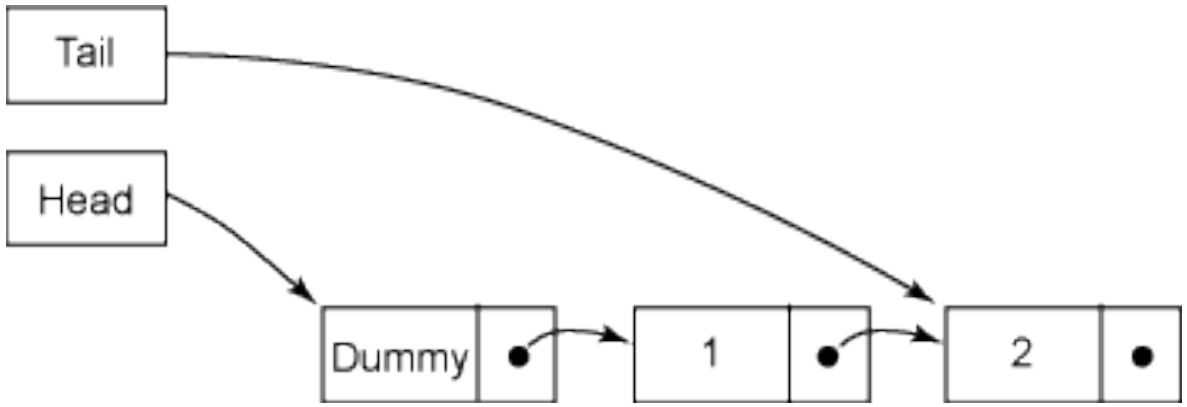
- Make sure queue is always in consistent state
- Threads must be able to detect whether another operation is is already in progress
  - Thread B can wait for thread A to finish before starting
- Prevents corruption, but late thread can fail if early thread fails

Overview of Michael & Scott Approach

- If thread B arrives while operation in progress for thread A, let B finish update for A
  - Then B can progress without waiting for A
  - If A finds some of its work done, it doesn't repeat. It just skips doing it itself

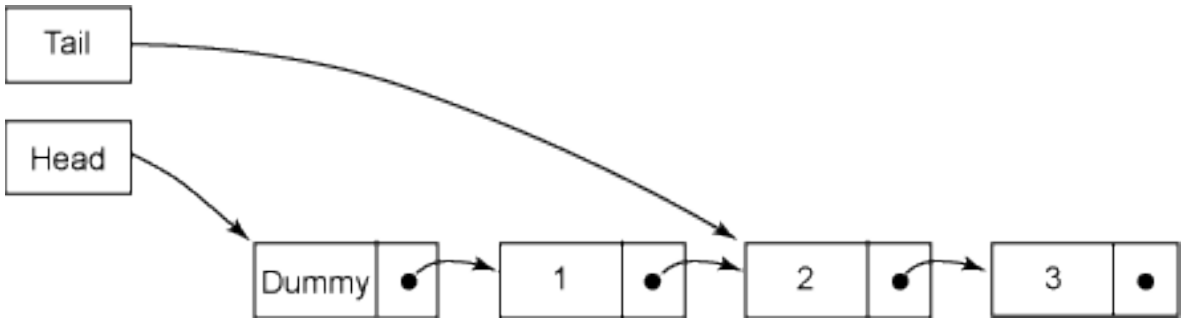
Michael & Scott Nonblocking Queue

- Queue with two elements in quiescent state



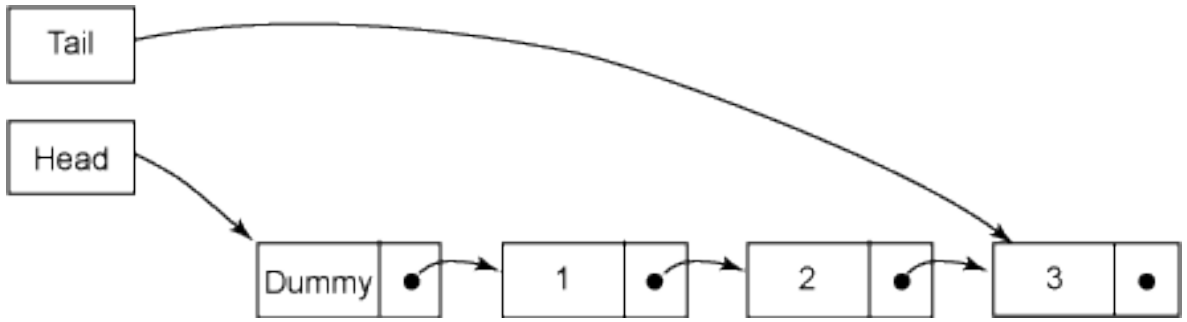
Michael & Scott Nonblocking Queue

- Queue in intermediate state during insertion
  - After the new element is added but before the tail pointer is updated



Michael & Scott Nonblocking Queue

- Queue in quiescent state again after the tail pointer is updated



Michael & Scott Nonblocking Queue

- Observation:
  - If tail.next is non-null, then a put() operation is in progress
- If a thread finds an put() operation in progress, it will try to advance tail to return queue to stable state
  - Then it will reload tail and repeat process

ConcurrentQueue

```
public class ConcurrentQueue  <E> {
    private static class Node <E> {
        final E item;
        final AtomicReference<Node<E>> next;
        public Node(E item, Node<E> next) {
            this.item = item;
            this.next = new AtomicReference<Node<E>>(next);
        }
    }
    private final Node<E> dummy = new Node<E>(null, null);
    private final AtomicReference<Node<E>> head
            = new AtomicReference<Node<E>>(dummy);
    private final AtomicReference<Node<E>> tail
            = new AtomicReference<Node<E>>(dummy);
```

ConcurrentQueue

```
public boolean put(E item) {
    Node<E> newNode = new Node<E>(item, null);
    while (true) {
        Node<E> curTail = tail.get();
        Node<E> tailNext = curTail.next.get();
        if (curTail == tail.get()) { // did tail change?
            if (tailNext != null) { // Queue in intermediate state, advance tail
                tail.compareAndSet(curTail, tailNext);
            } else { // In quiescent state, try inserting new node
                if (curTail.next.compareAndSet(null, newNode)) {
                    // Insertion succeeded, try advancing tail
                    tail.compareAndSet(curTail, newNode); // will fail if tail already moved
                    return true;
                }
            }
        }
    }
}
```

ConcurrentQueue

```
public E take() {
    for (;;) {
      Node<E> oldHead = head.get();                    // get current head
      Node<E> oldTail = tail.get();                    // get current tail
      Node<E> oldHeadNext = oldHead.next.get();        // get current head.next
      if (oldHead == head.get()) {                     // has another take happened?
        if (oldHead == oldTail) {                      // Queue empty or tail being updated
          if (oldHeadNext == null)                     // Is queue empty? If yes,
            return null;
          tail.compareAndSet(oldTail, oldHeadNext);    // tail needs update. Try to advance it
        } else {                                       // No need to deal with tail
          if (head.compareAndSet(oldHead, oldHeadNext))
                    return oldHeadNext.item;
        }
      }
    }
}
```

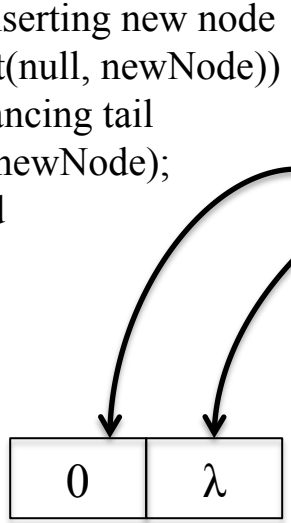
Execution Traces

- 2 threads attempt to put()

Trace 1

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```

Var	T1	T2
tailNext		
curTail		
newNode		
	head	
	tail	



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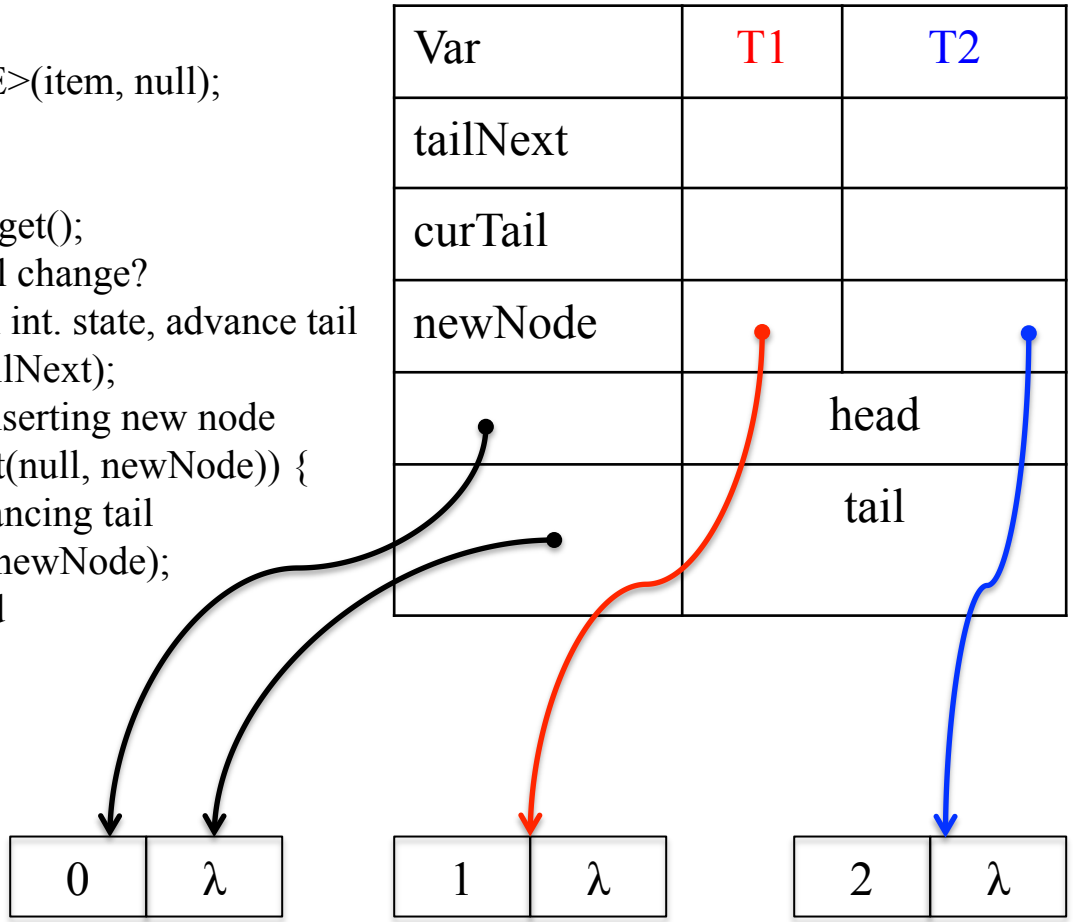
           // Insertion succeeded, try advancing tail
10           tail.compareAndSet(curTail, newNode);
           // will fail if tail already moved
11         return true;
           }
         }
       }
     }
   }
```



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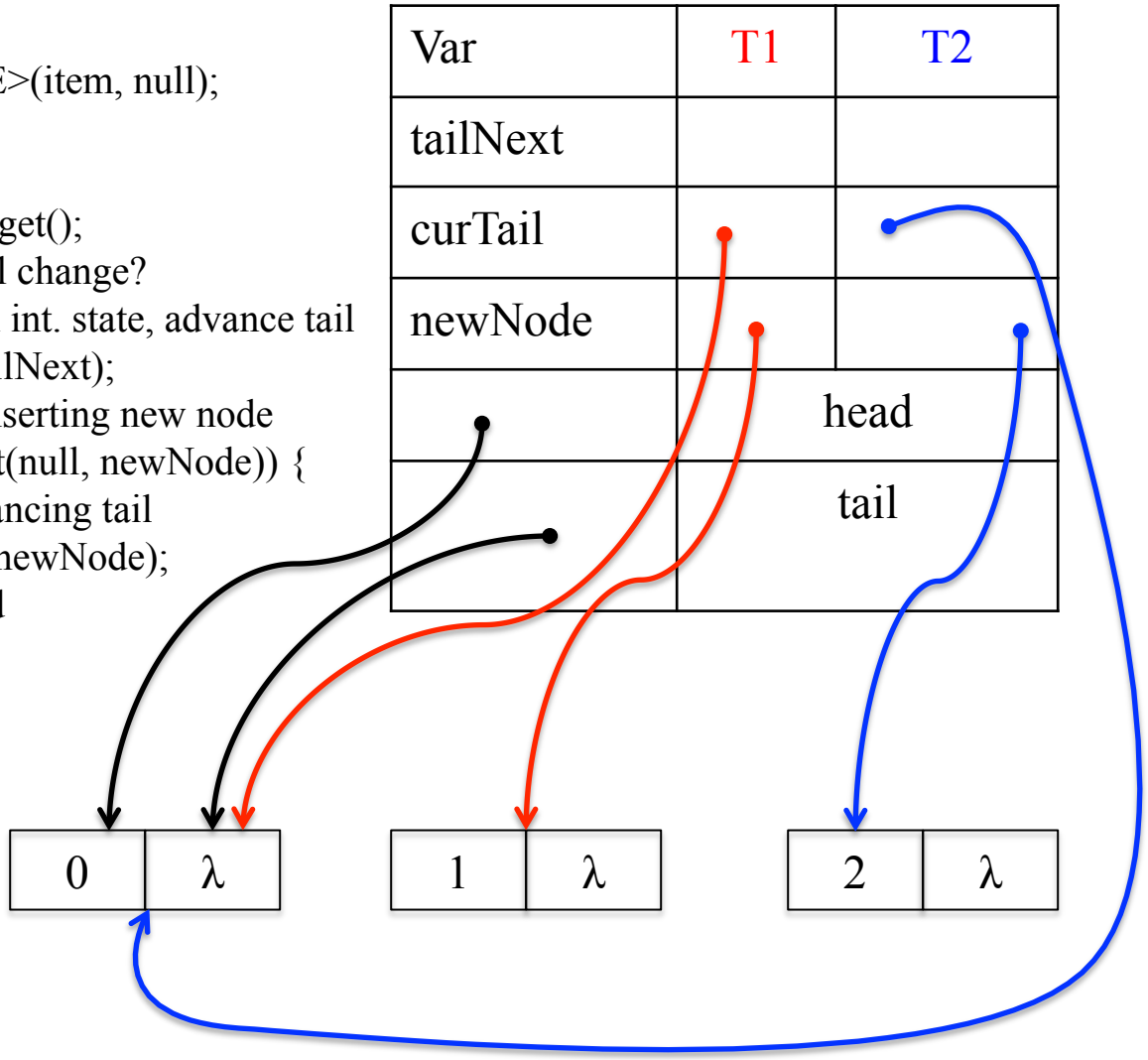
          }
        }
      }
    }
```



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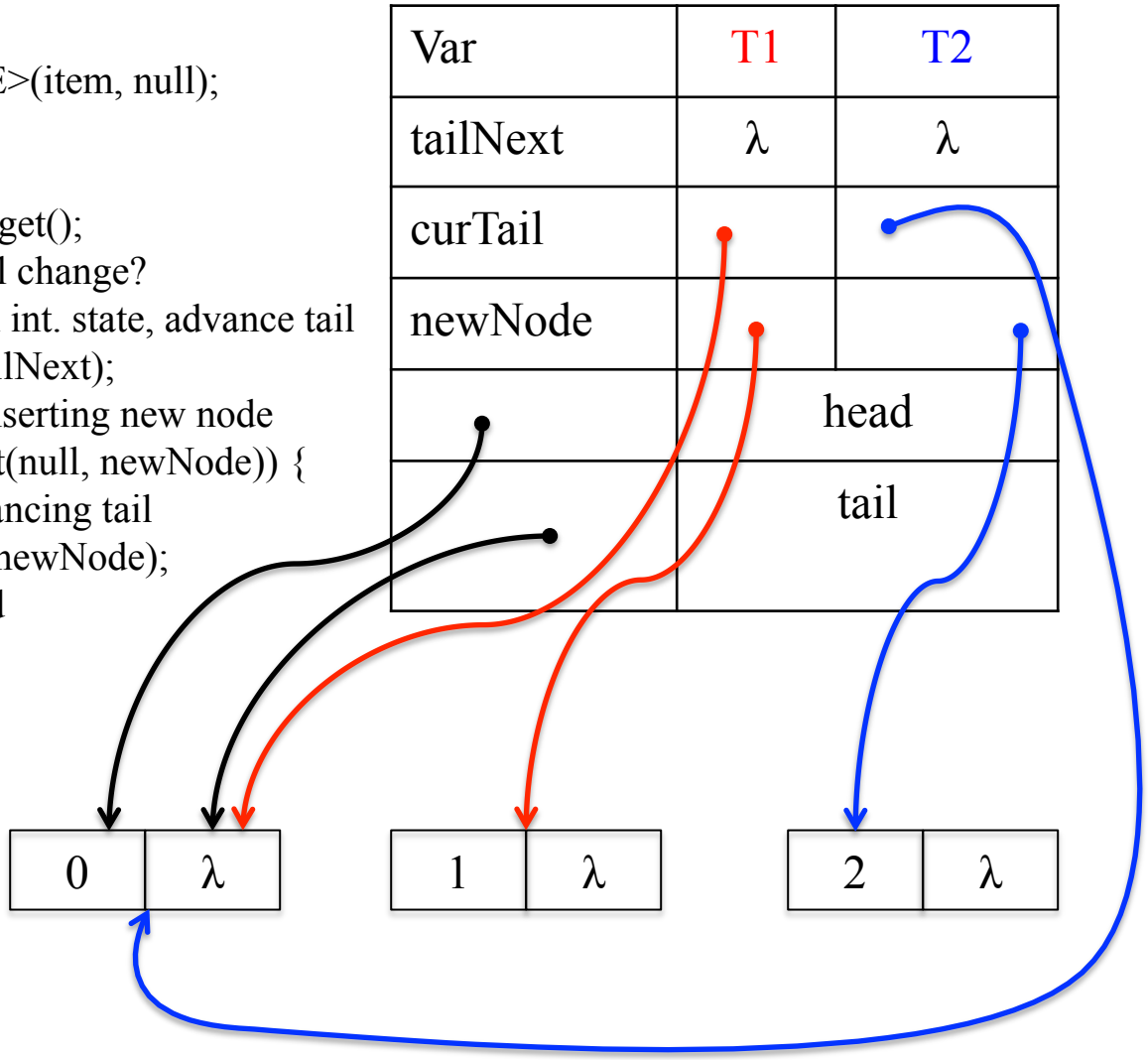

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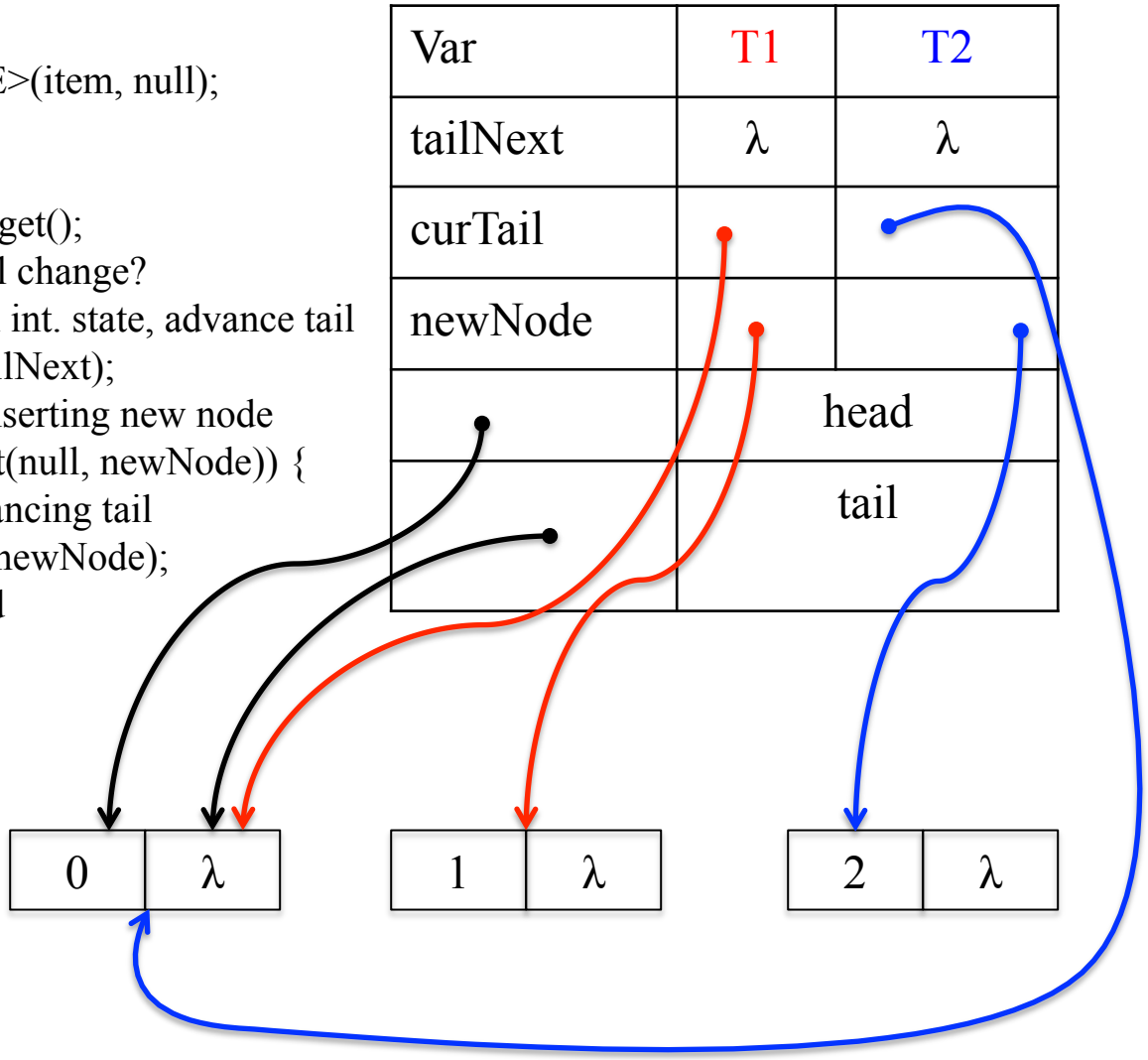
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



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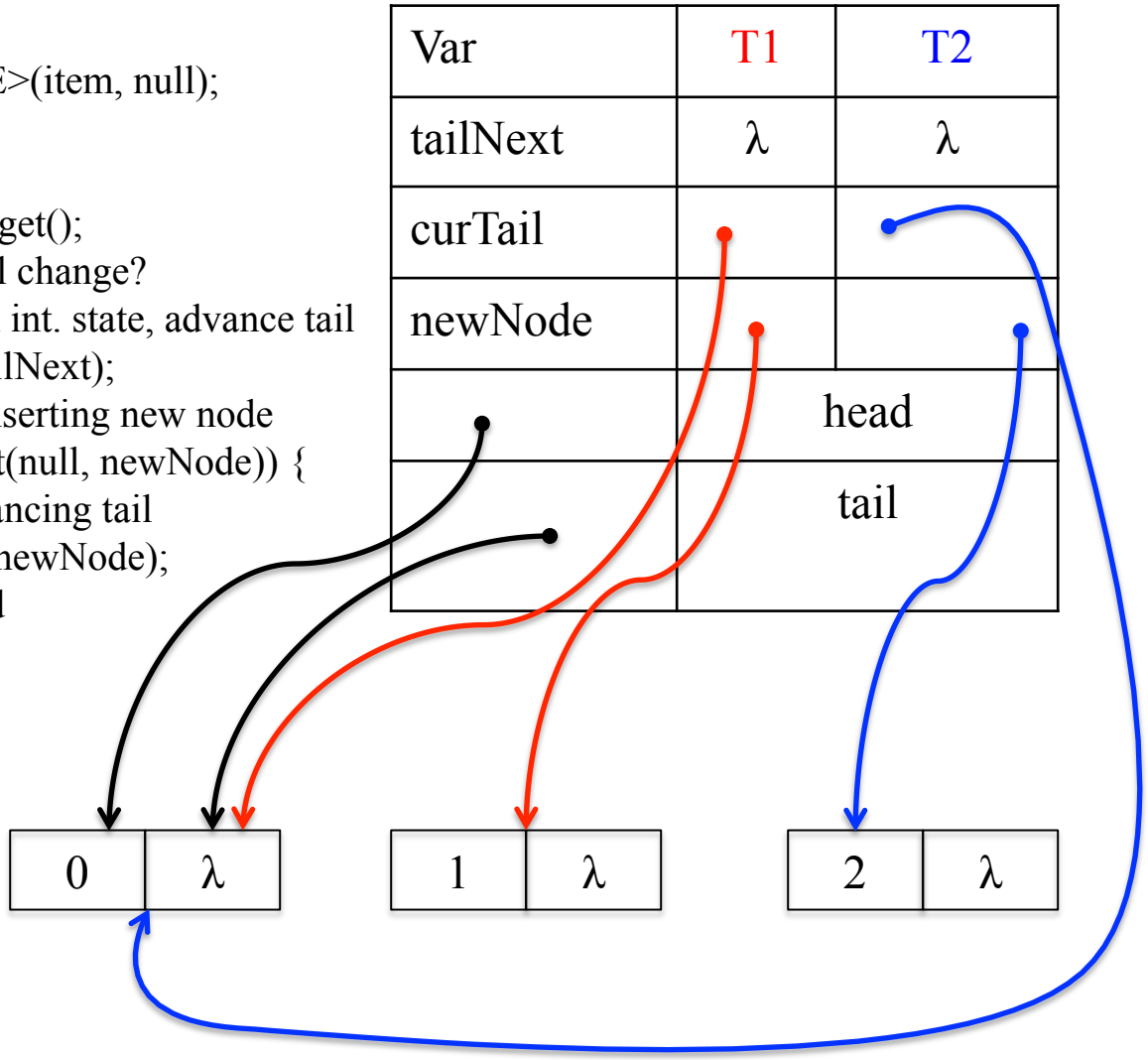
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



Trace 1: T1 wins

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
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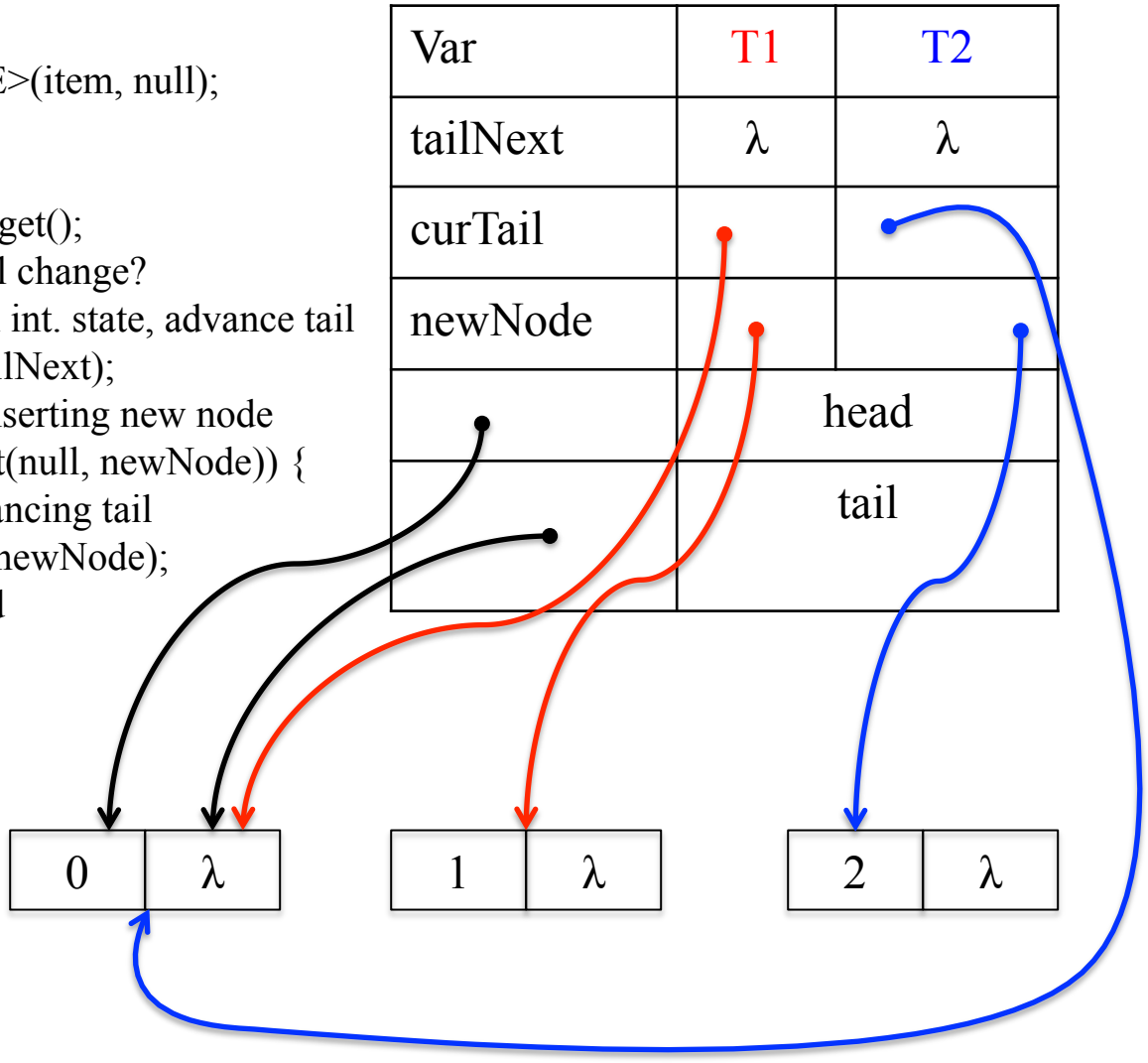
            }
          }
        }
      }
    }
```



Trace 1: After CAS

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
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            // Insertion succeeded, try advancing tail
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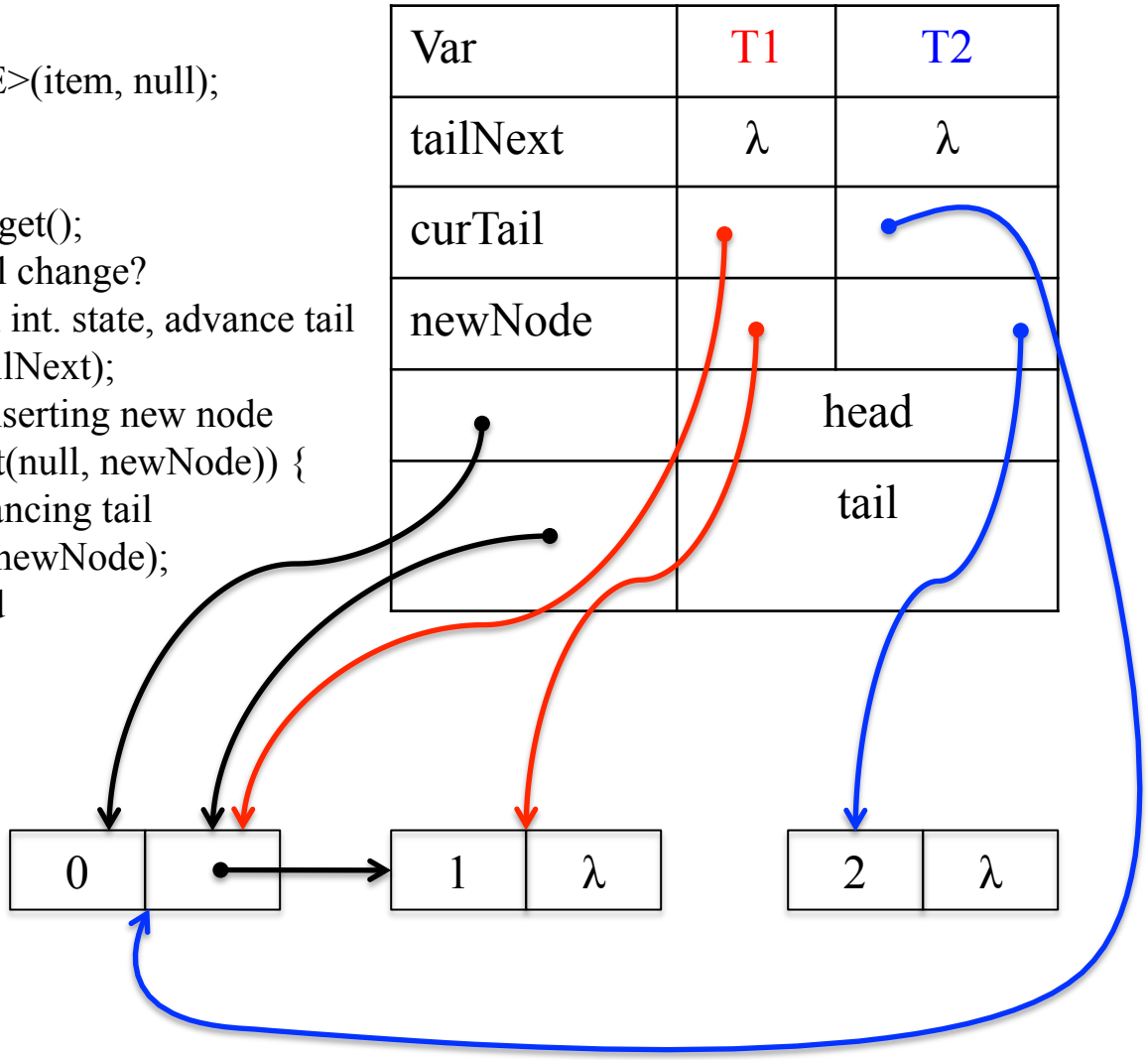
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



Trace 1: T2 Continues & CAS Fails

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
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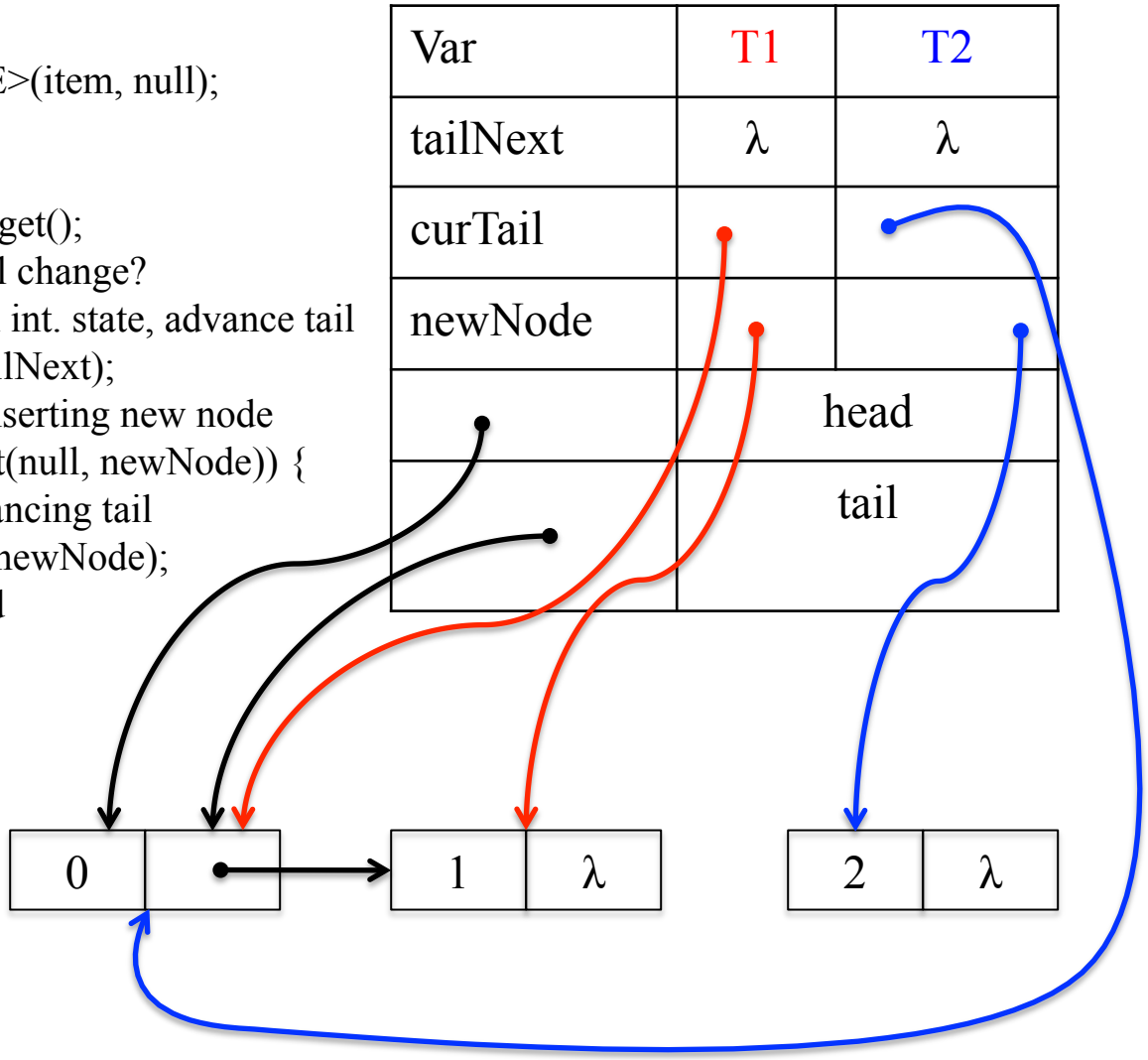
          }
        }
      }
    }
```



Trace 1: T1 Continues

```
public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
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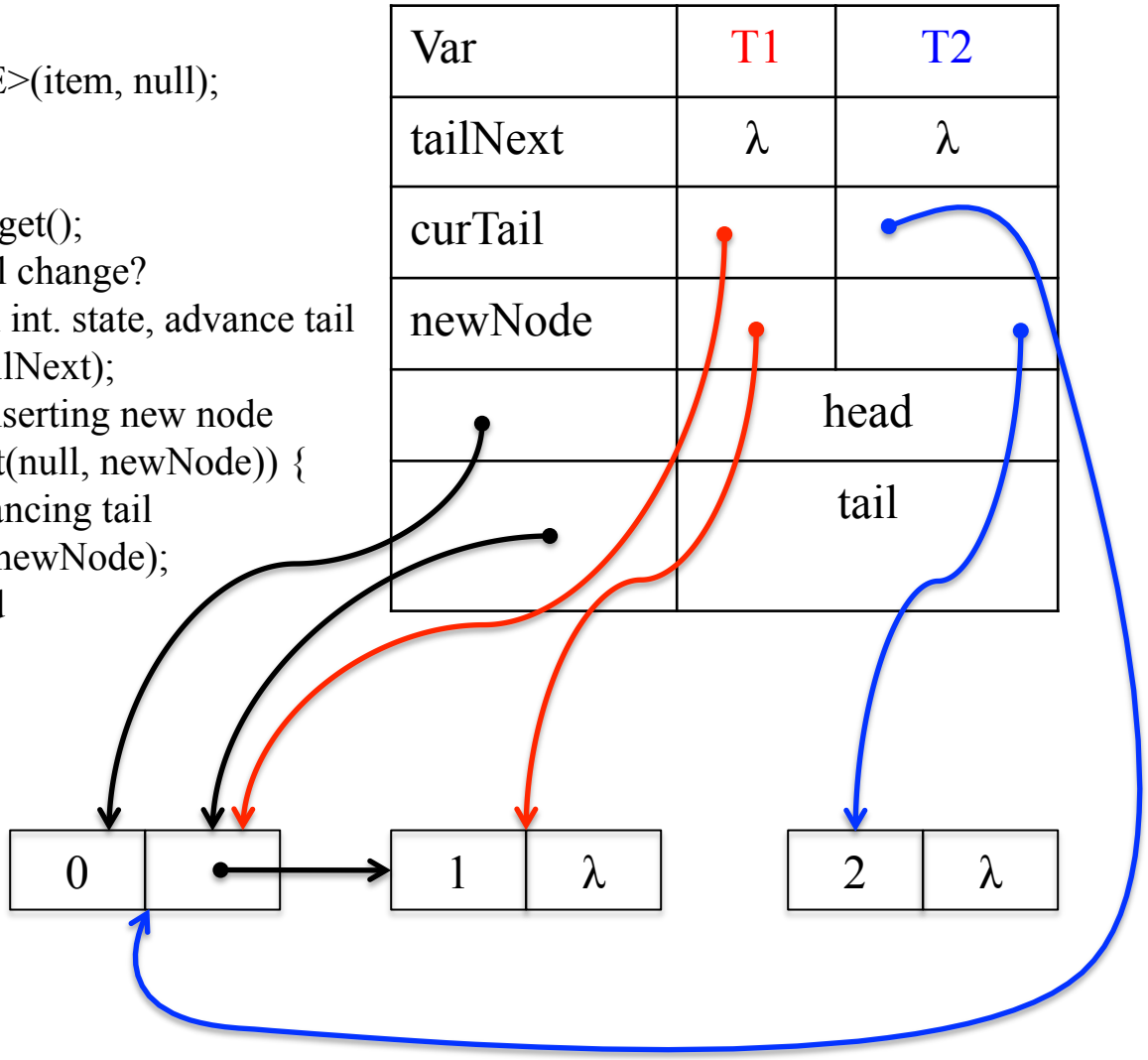
```



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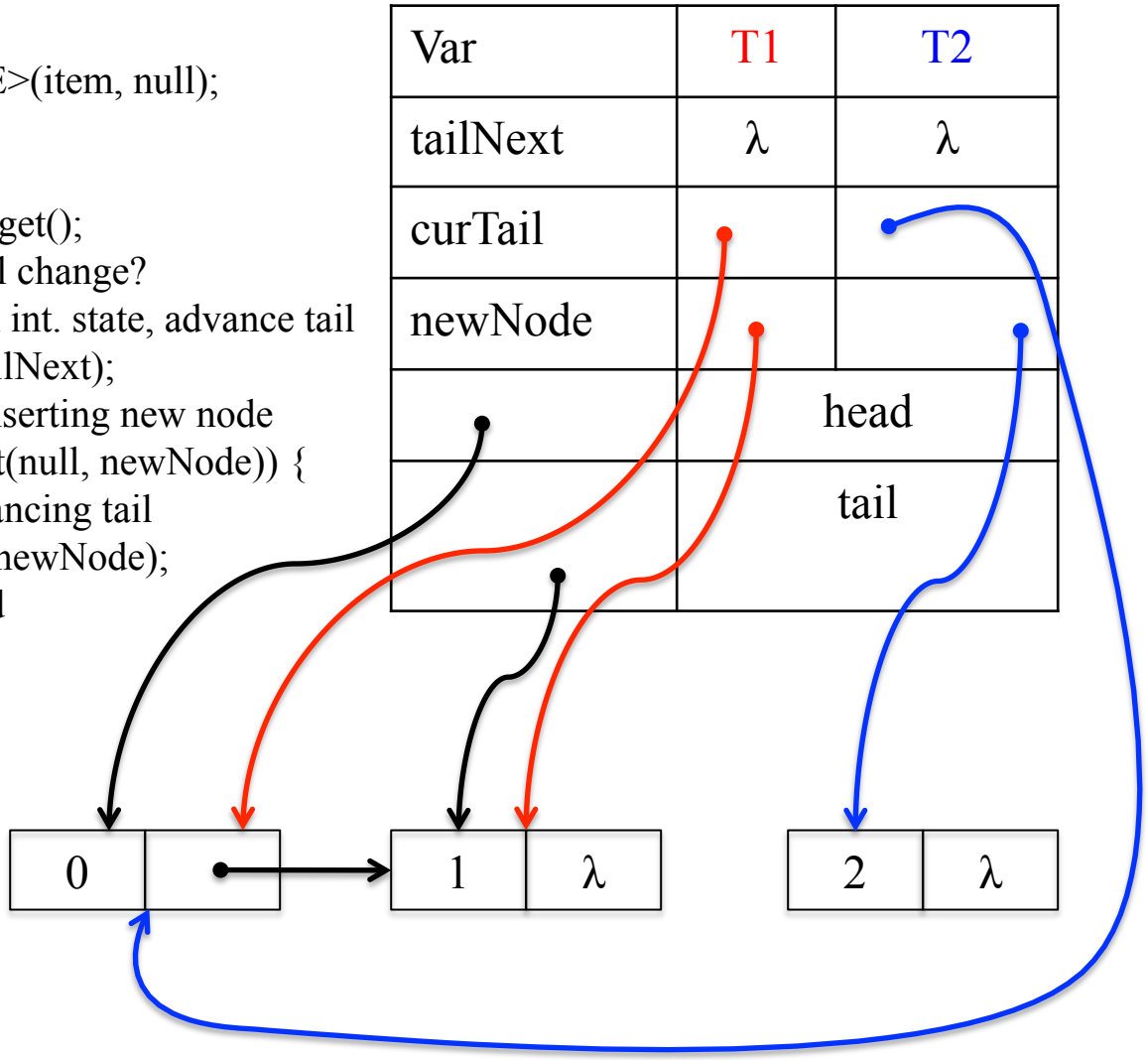
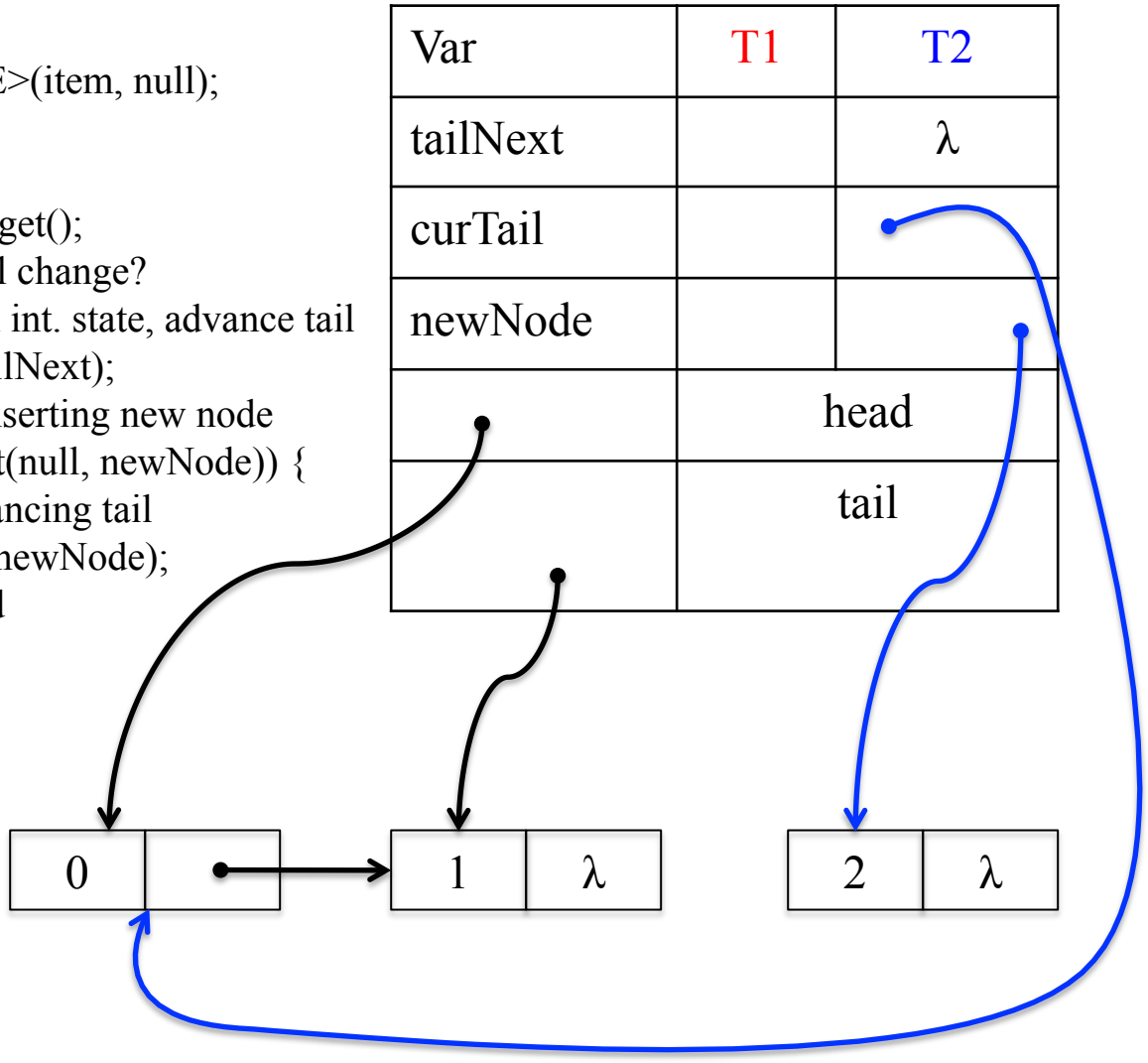
    }
```



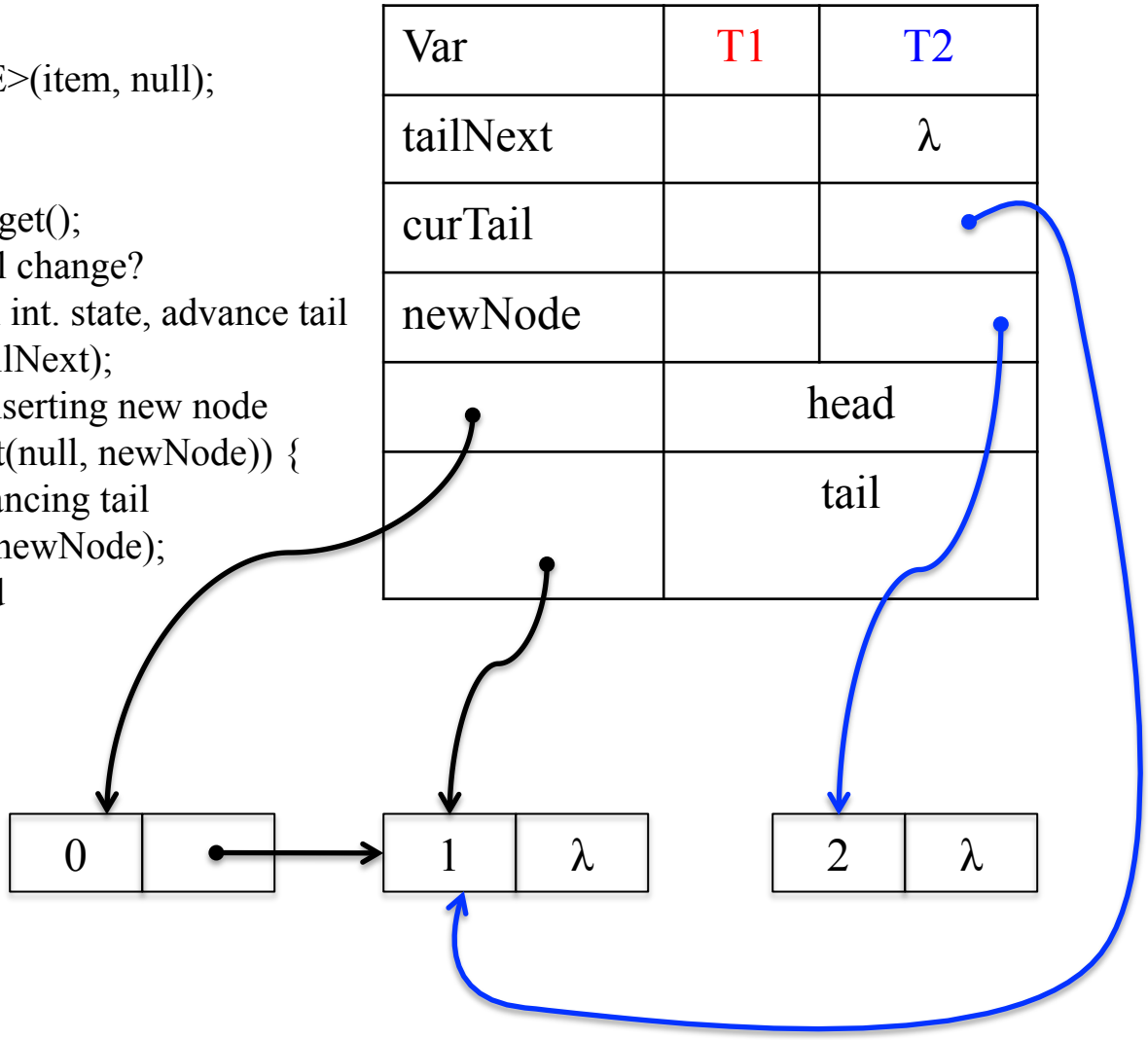
Trace 1: T1 exits

```
public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



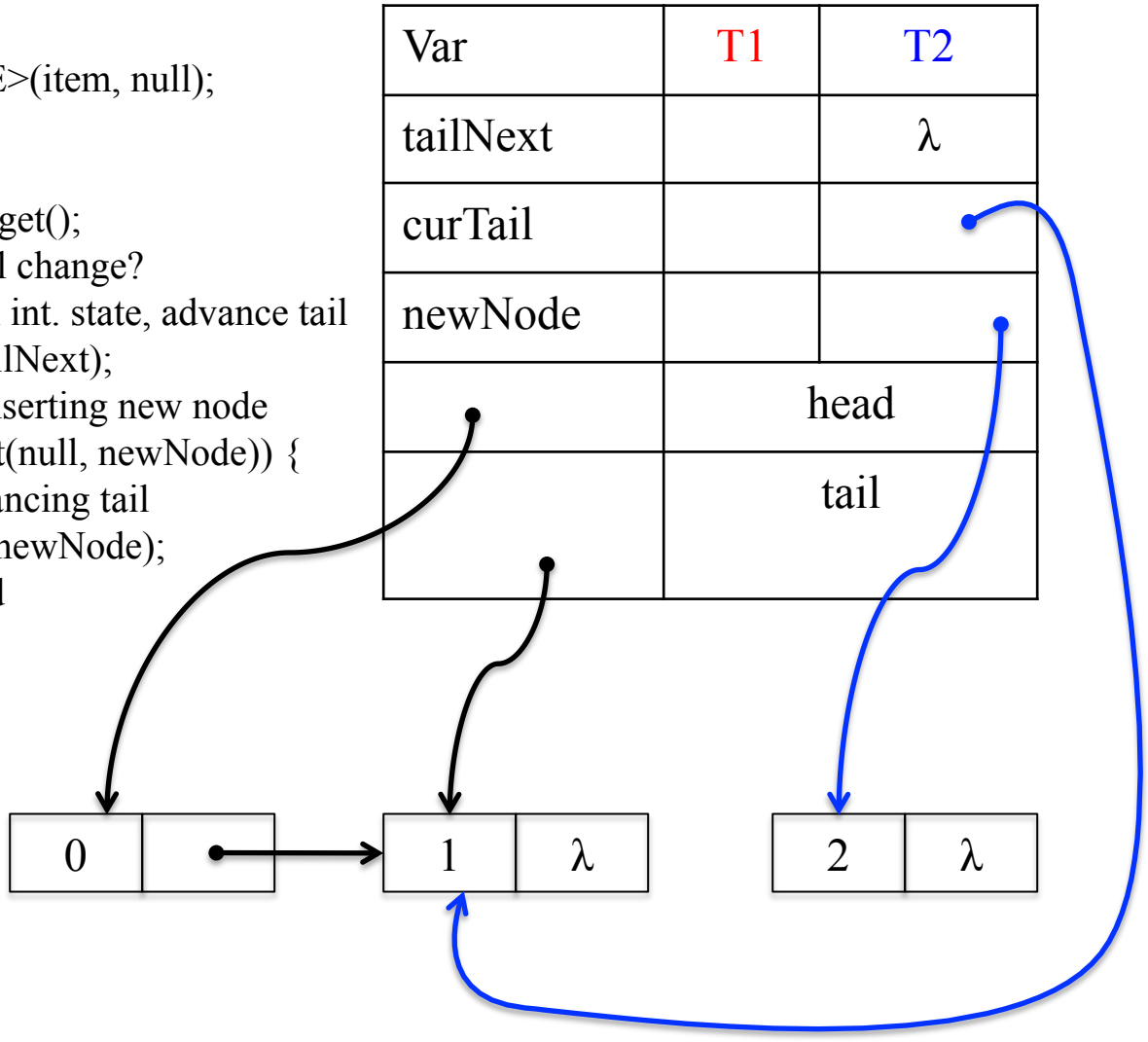
Trace 1: T2 Continues

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



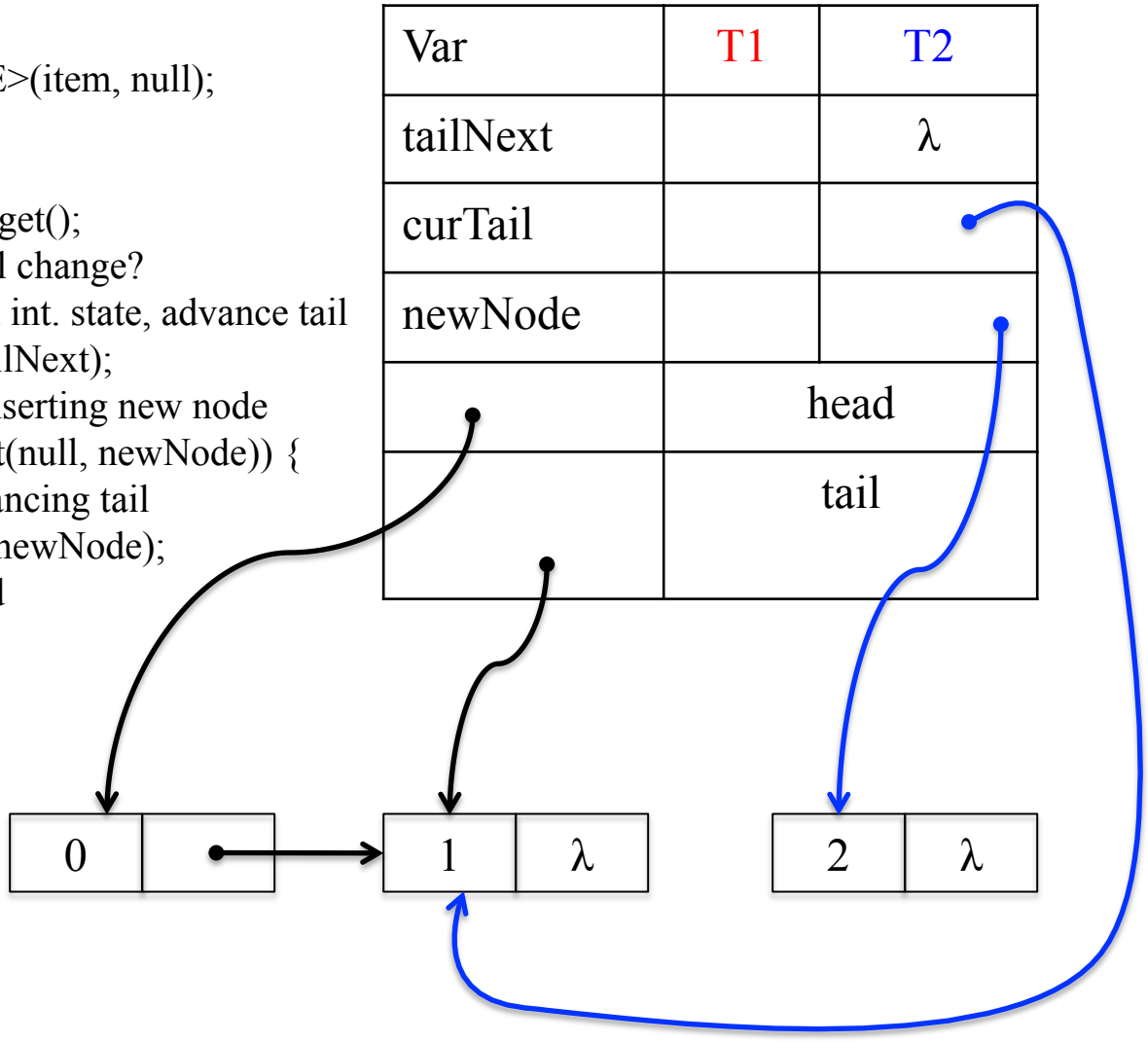
Trace 1: T2 Continues

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



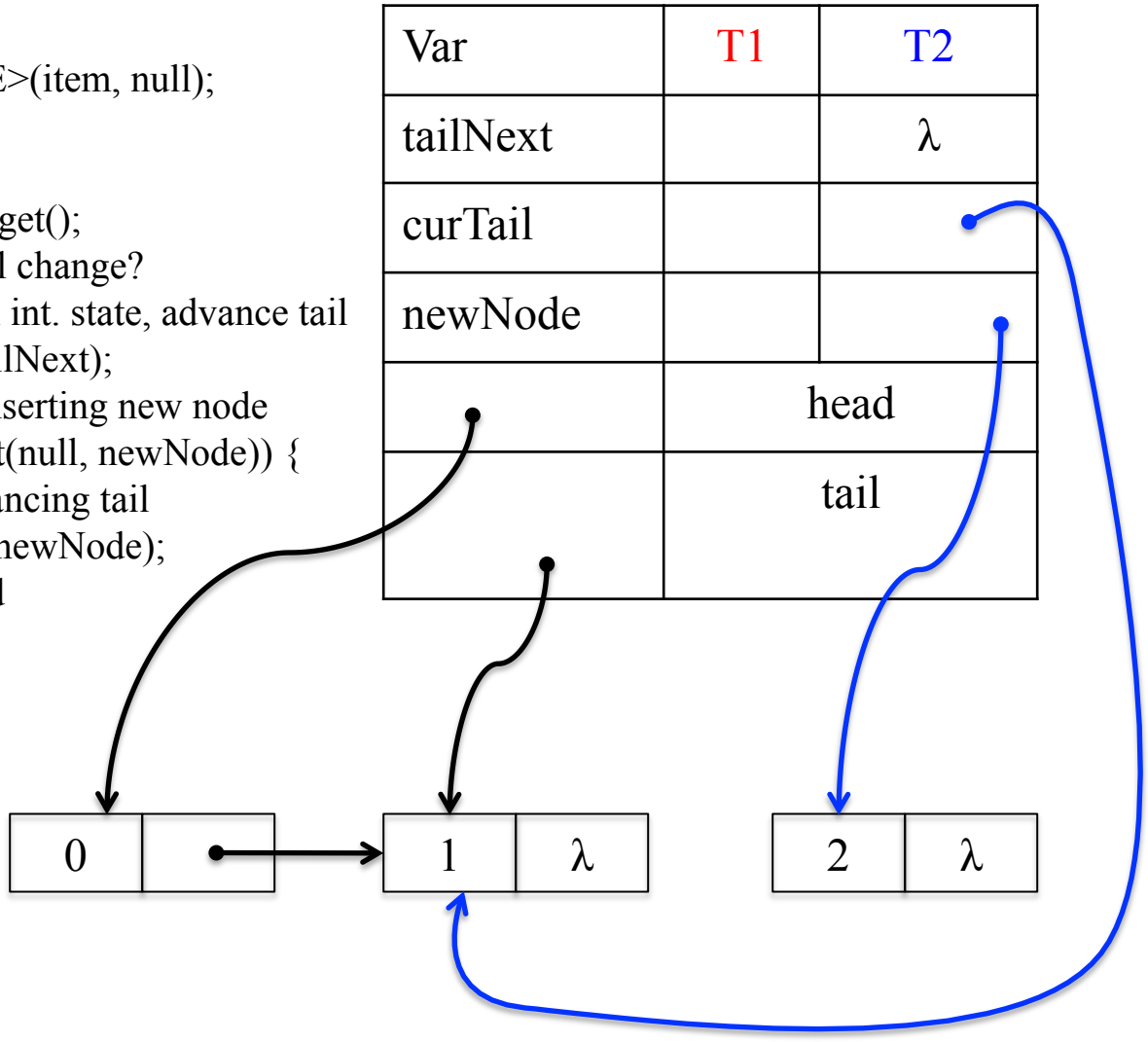
Trace 1: T2 Continues

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



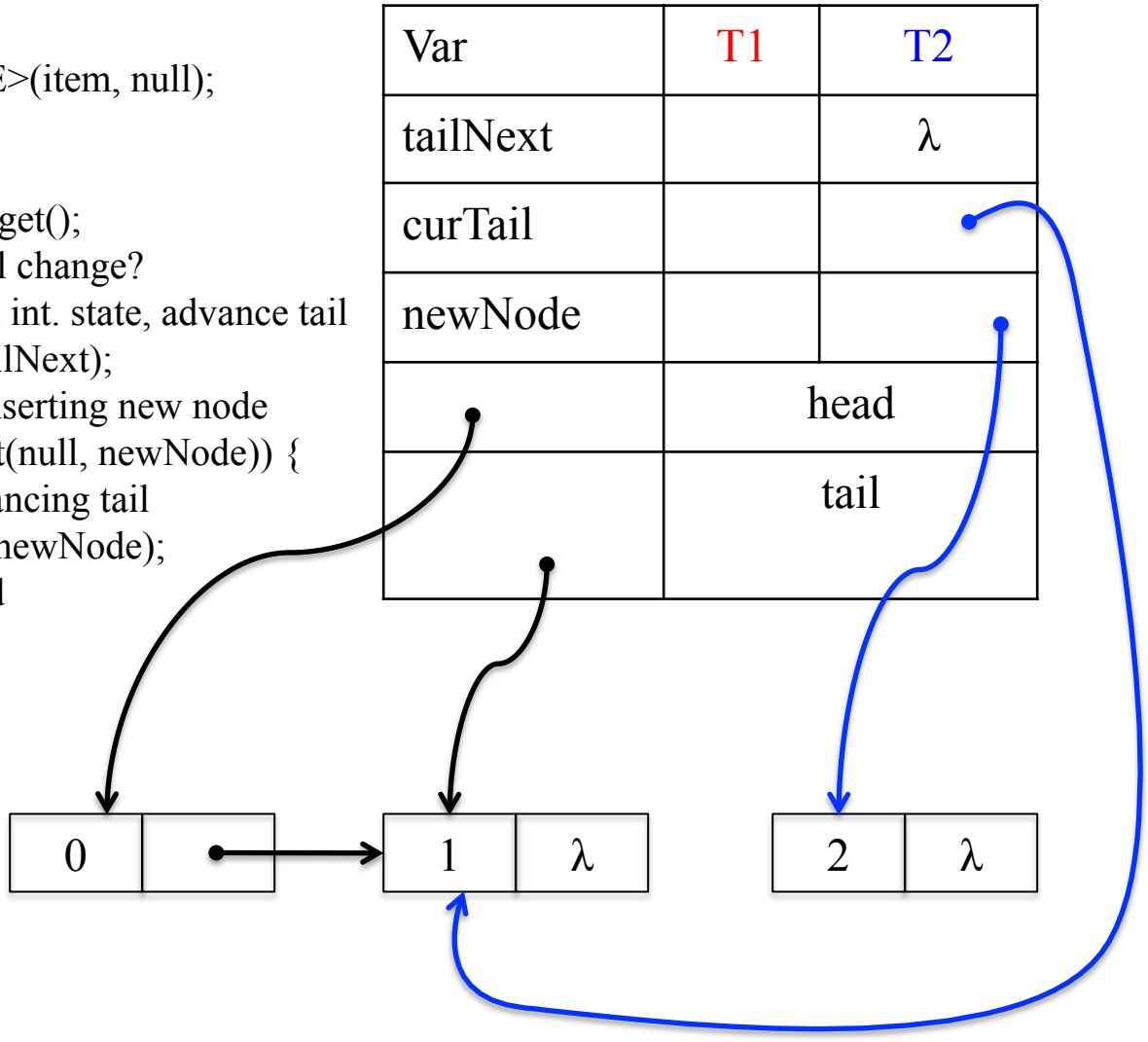
Trace 1: T2 Continues

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



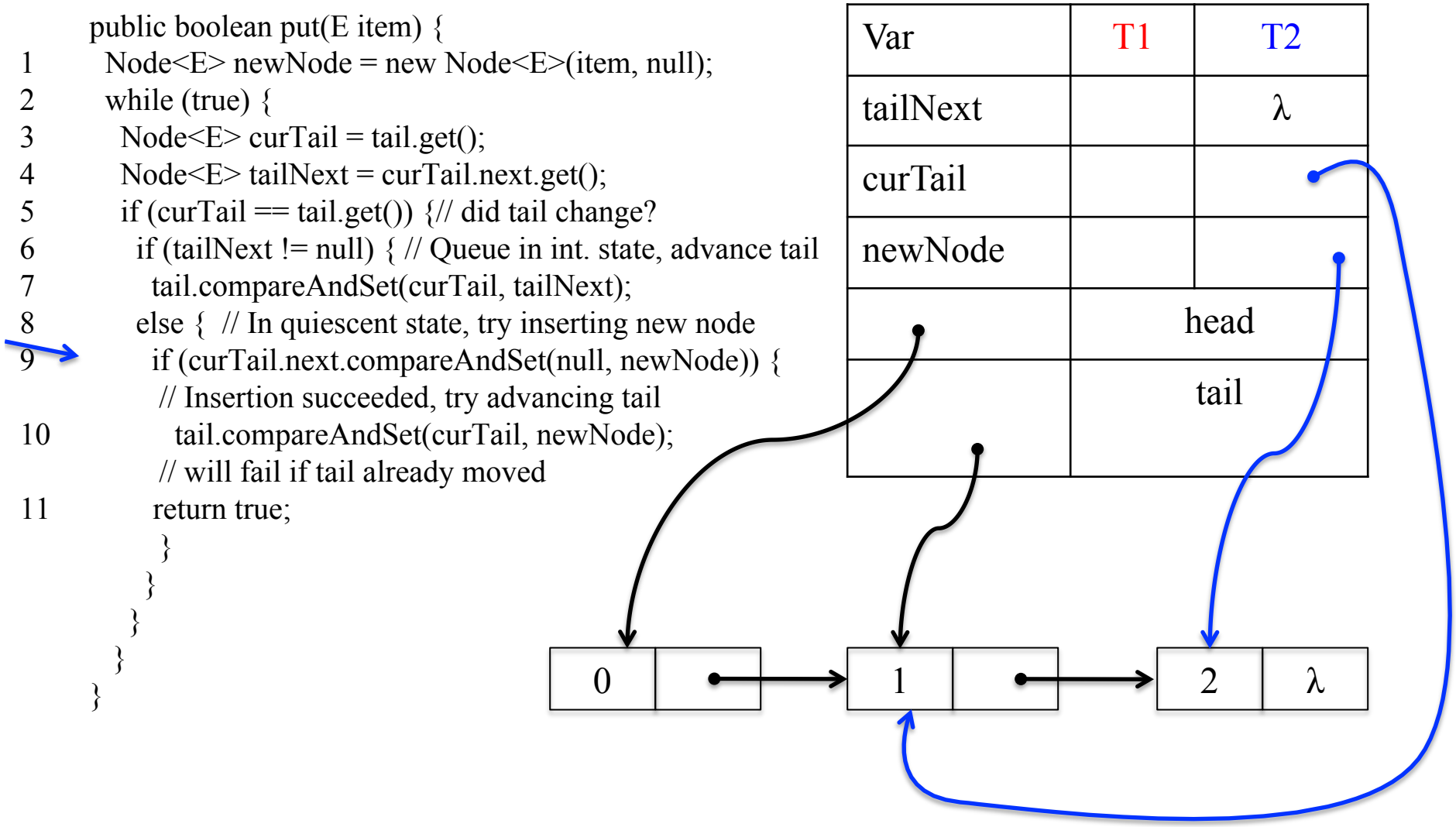
Trace 1: T2 Continues

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



Trace 1: After CAS

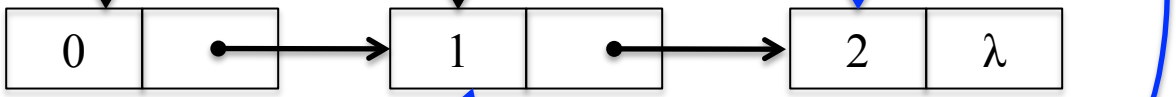
```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



Trace 1: T2 Continues

```
public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```

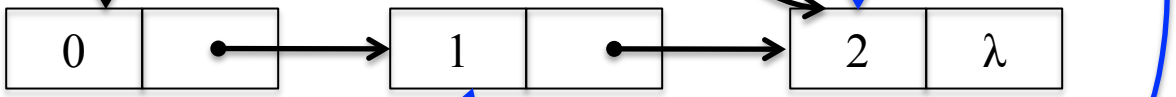
Var	T1	T2
tailNext		λ
curTail		
newNode		
	head	
	tail	



Trace 1: T2 Continues

```
public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```

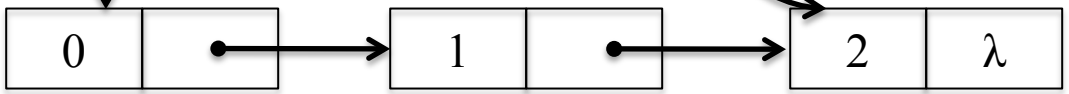
Var	T1	T2
tailNext		λ
curTail		
newNode		
	head	
	tail	



Trace 1: T2 Exits

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```

Var	T1	T2
tailNext		
curTail		
newNode		
	head	
	tail	



Trace 2

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
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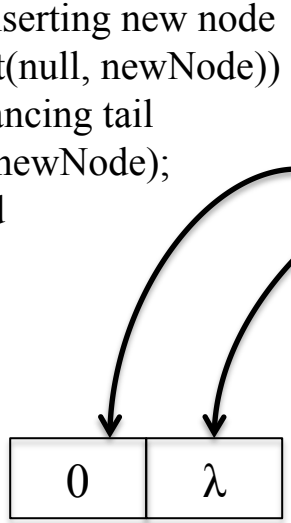
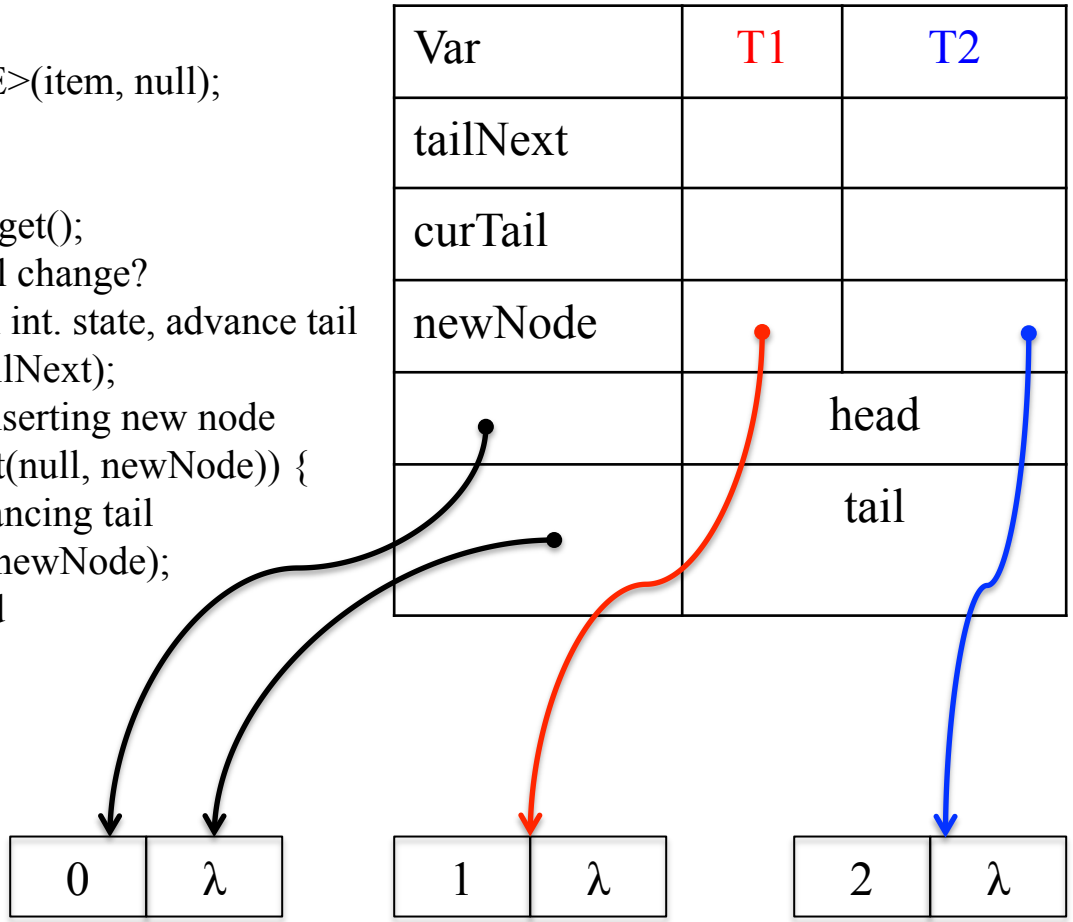
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```

Var	T1	T2
tailNext		
curTail		
newNode		
	head	
	tail	



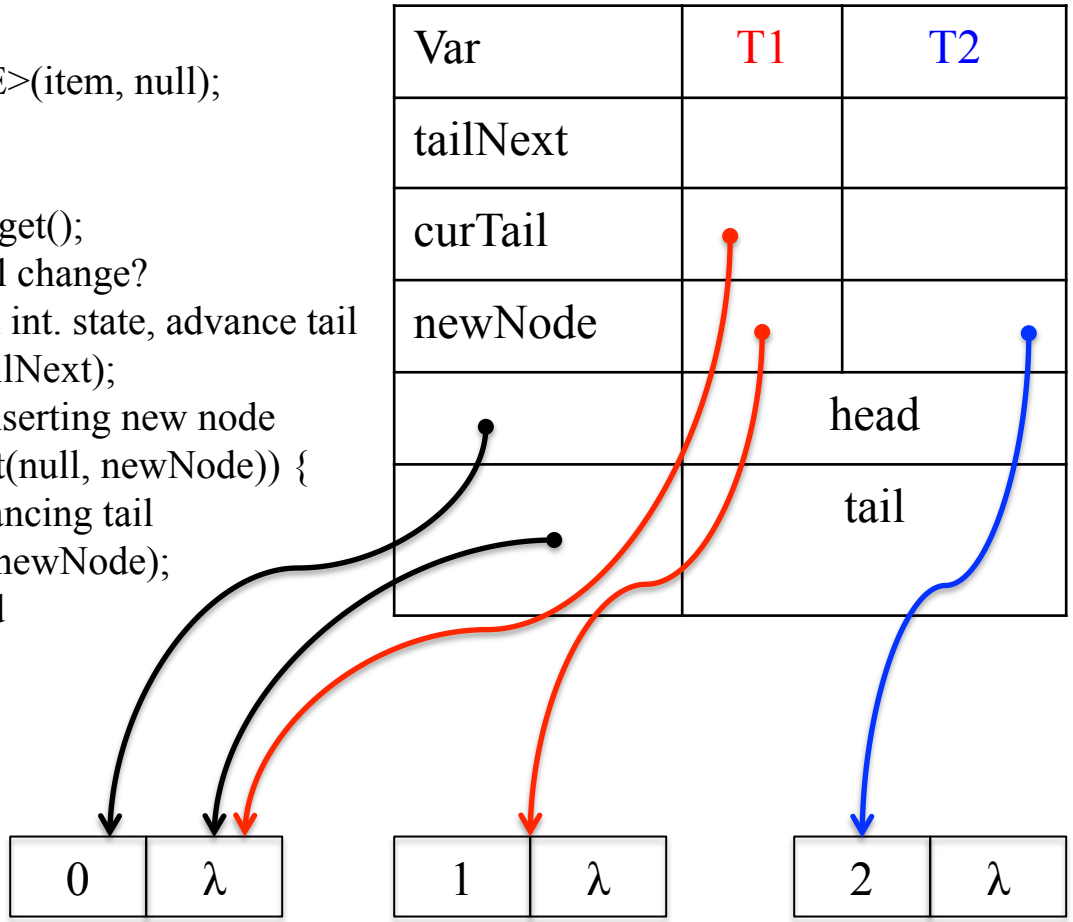
Trace 2

```
   public boolean put(E item) {
1    Node<E> newNode = new Node<E>(item, null);
2    while (true) {
3      Node<E> curTail = tail.get();
4      Node<E> tailNext = curTail.next.get();
5      if (curTail == tail.get()) {// did tail change?
6        if (tailNext != null) { // Queue in int. state, advance tail
7          tail.compareAndSet(curTail, tailNext);
8        else {  // In quiescent state, try inserting new node
9          if (curTail.next.compareAndSet(null, newNode)) {
           // Insertion succeeded, try advancing tail
10           tail.compareAndSet(curTail, newNode);
           // will fail if tail already moved
11         return true;
           }
         }
       }
     }
   }
```



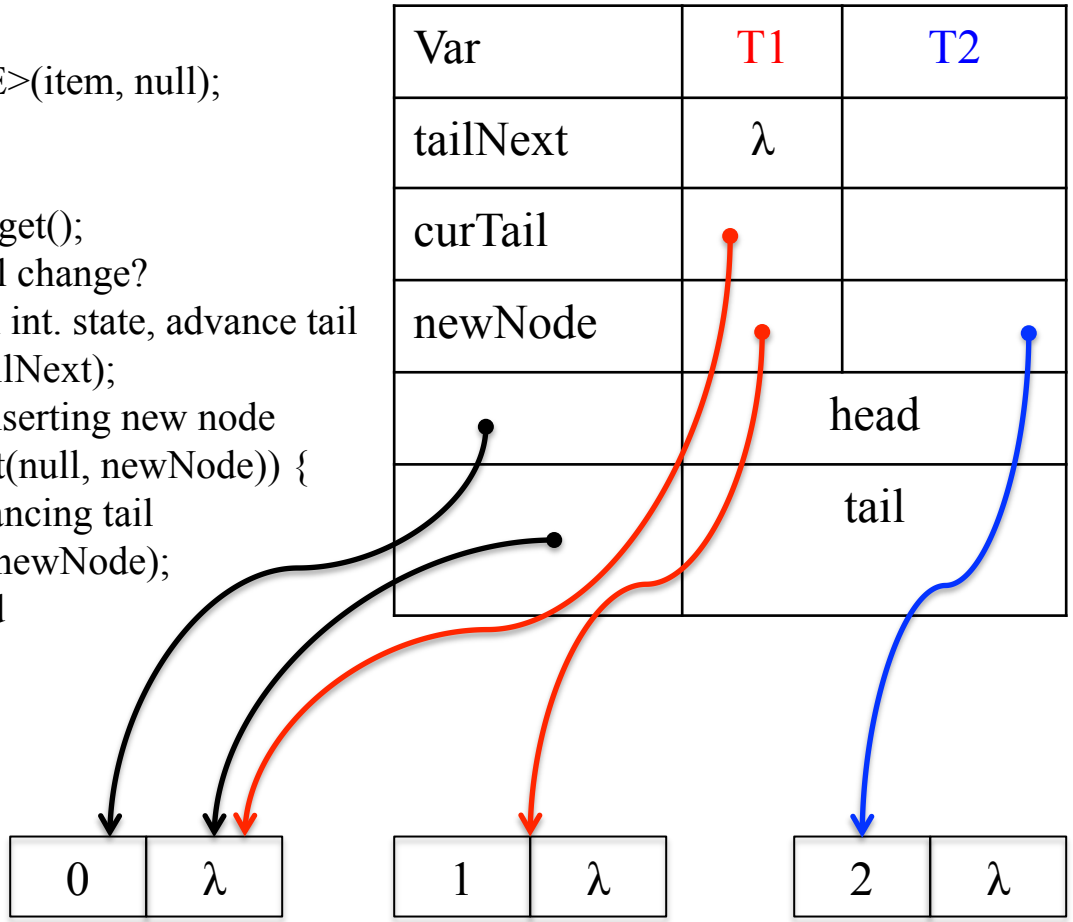
Trace 2

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



Trace 2

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



Trace 2

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
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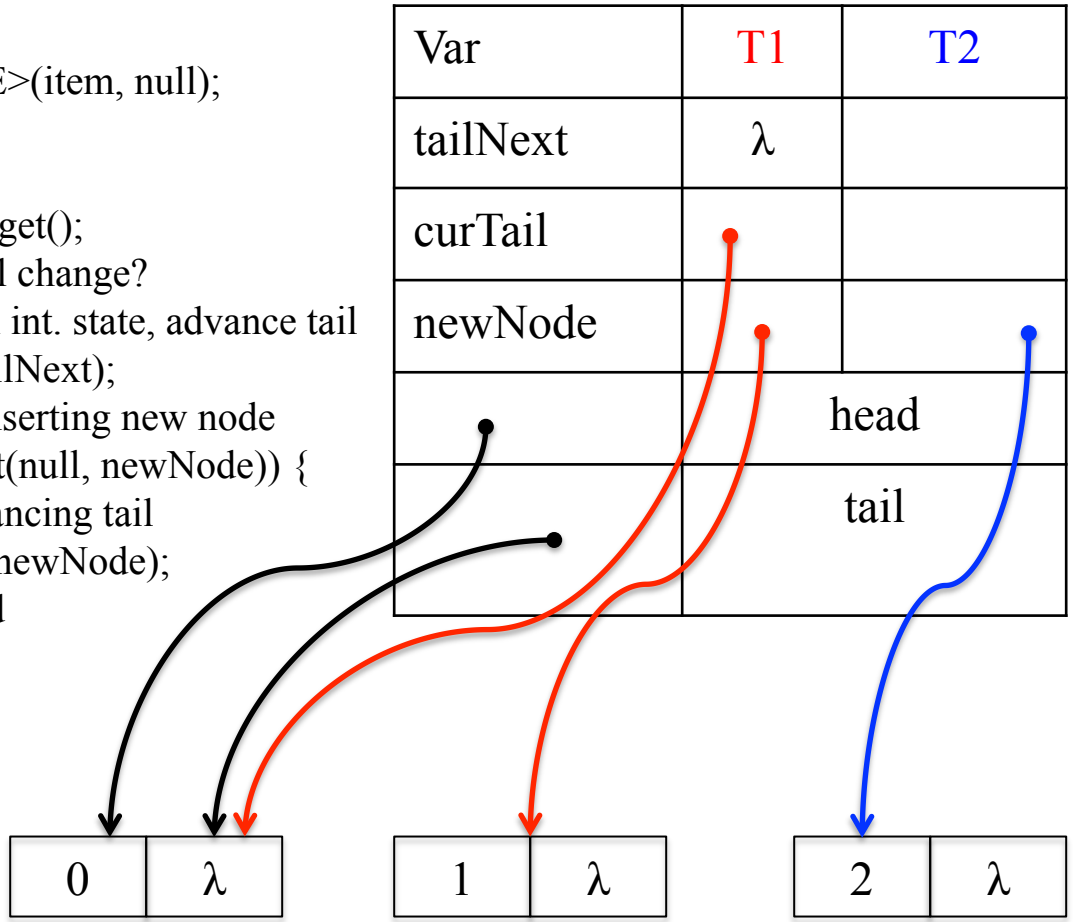
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



Trace 2

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
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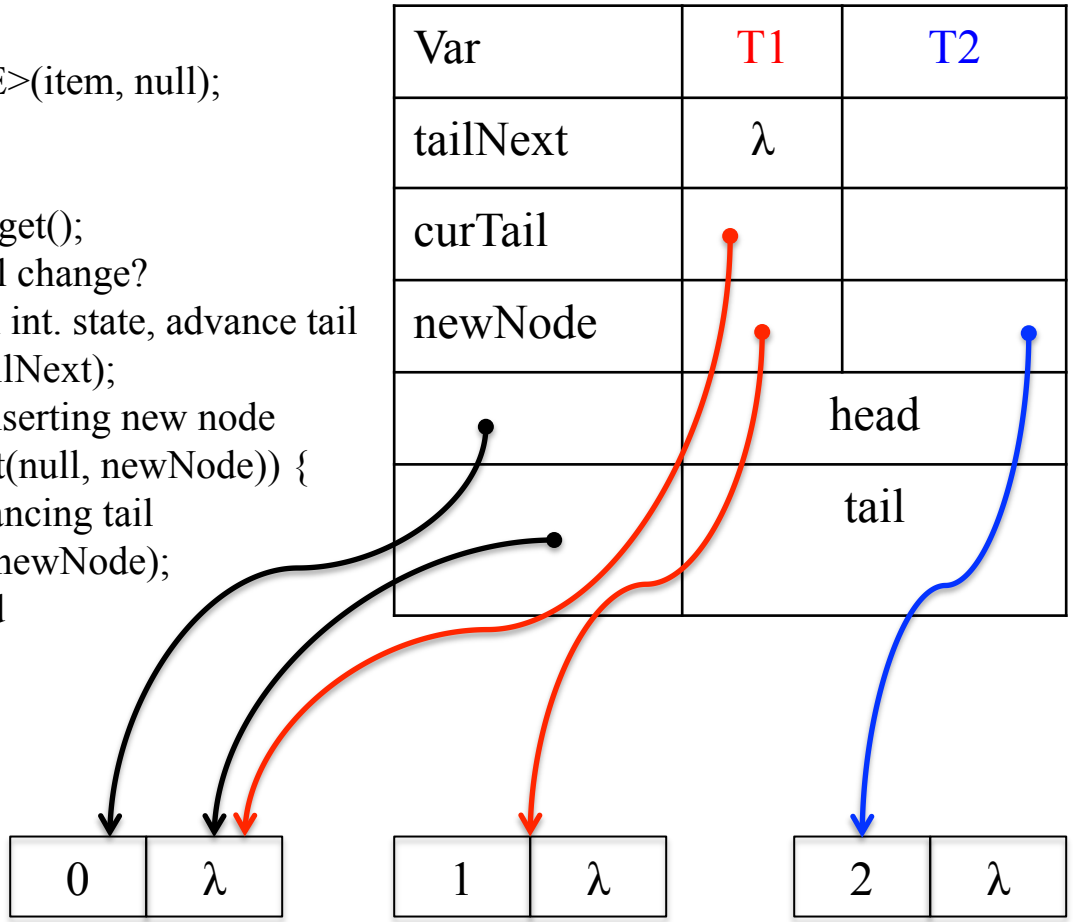
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



Trace 2

```
public boolean put(E item) {
1   Node<E> newNode = new Node<E>(item, null);
2   while (true) {
3     Node<E> curTail = tail.get();
4     Node<E> tailNext = curTail.next.get();
5     if (curTail == tail.get()) {// did tail change?
6       if (tailNext != null) { // Queue in int. state, advance tail
7         tail.compareAndSet(curTail, tailNext);
8       else {  // In quiescent state, try inserting new node
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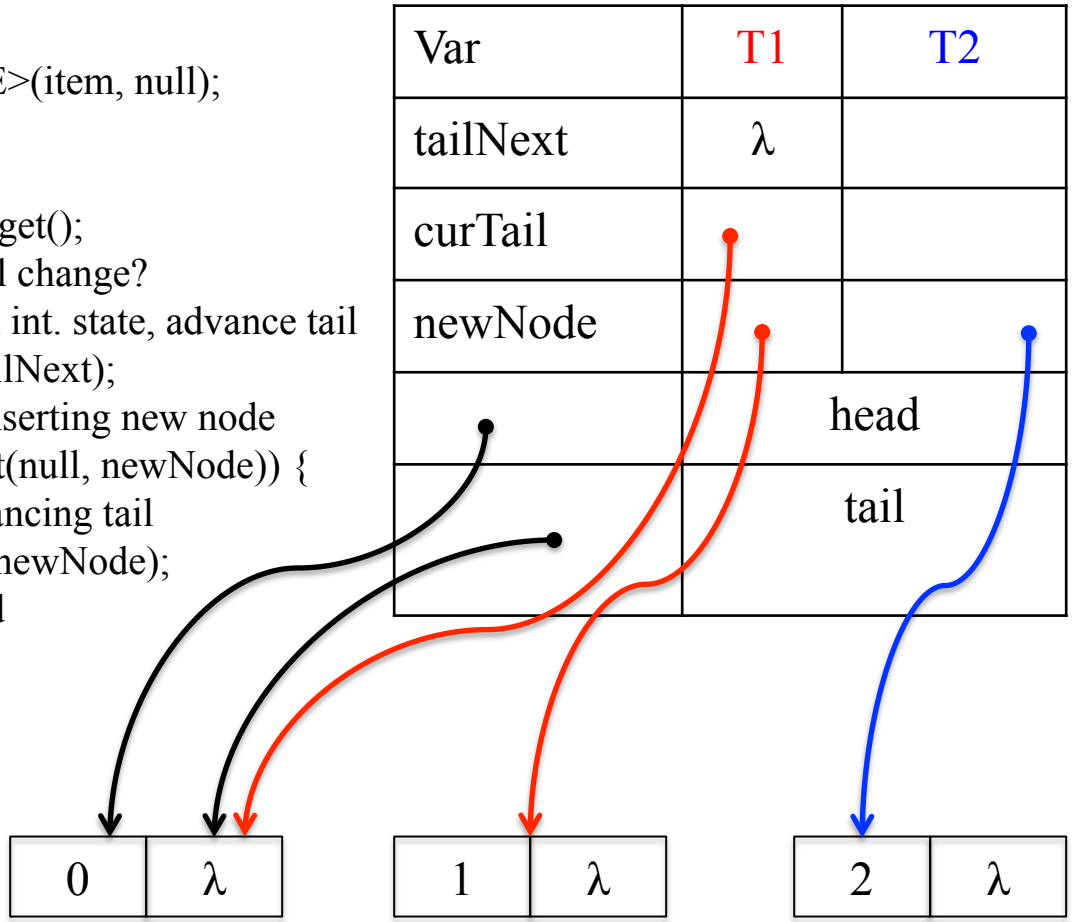
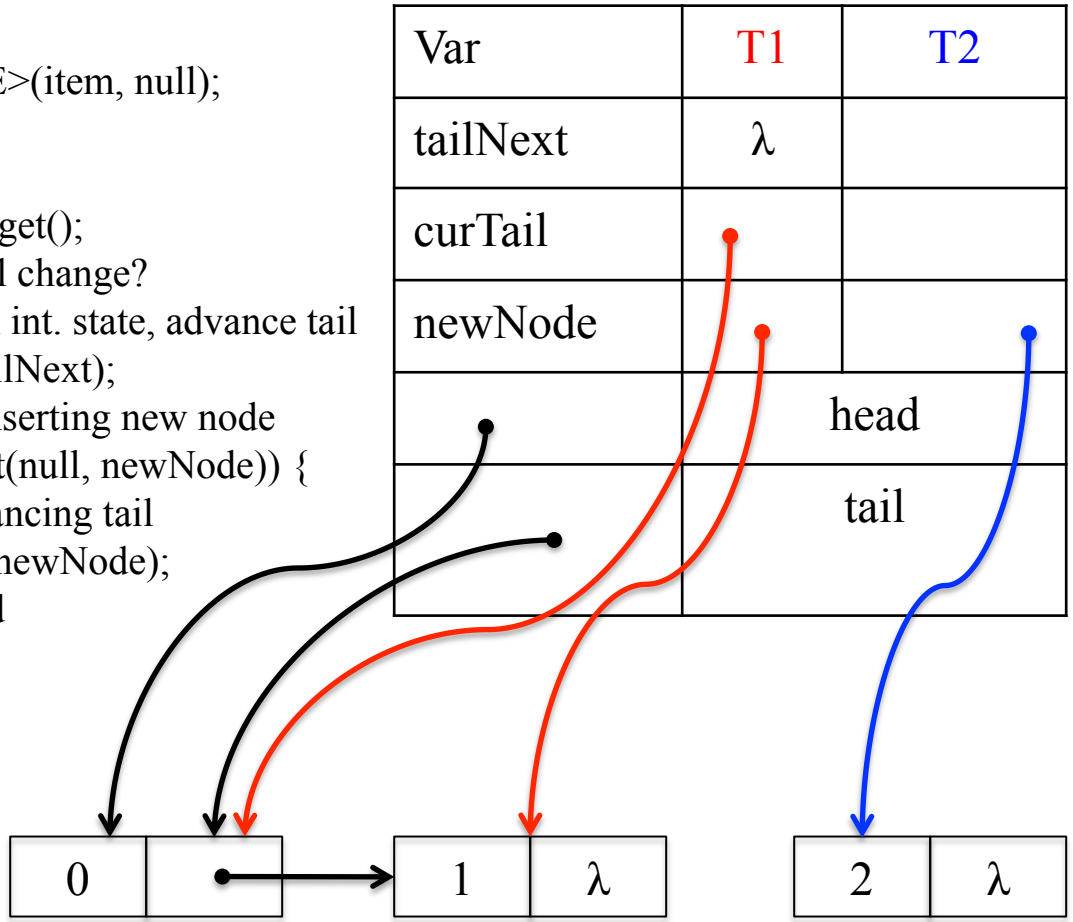
          // Insertion succeeded, try advancing tail
10          tail.compareAndSet(curTail, newNode);
          // will fail if tail already moved
11        return true;
          }
        }
      }
    }
  }
```



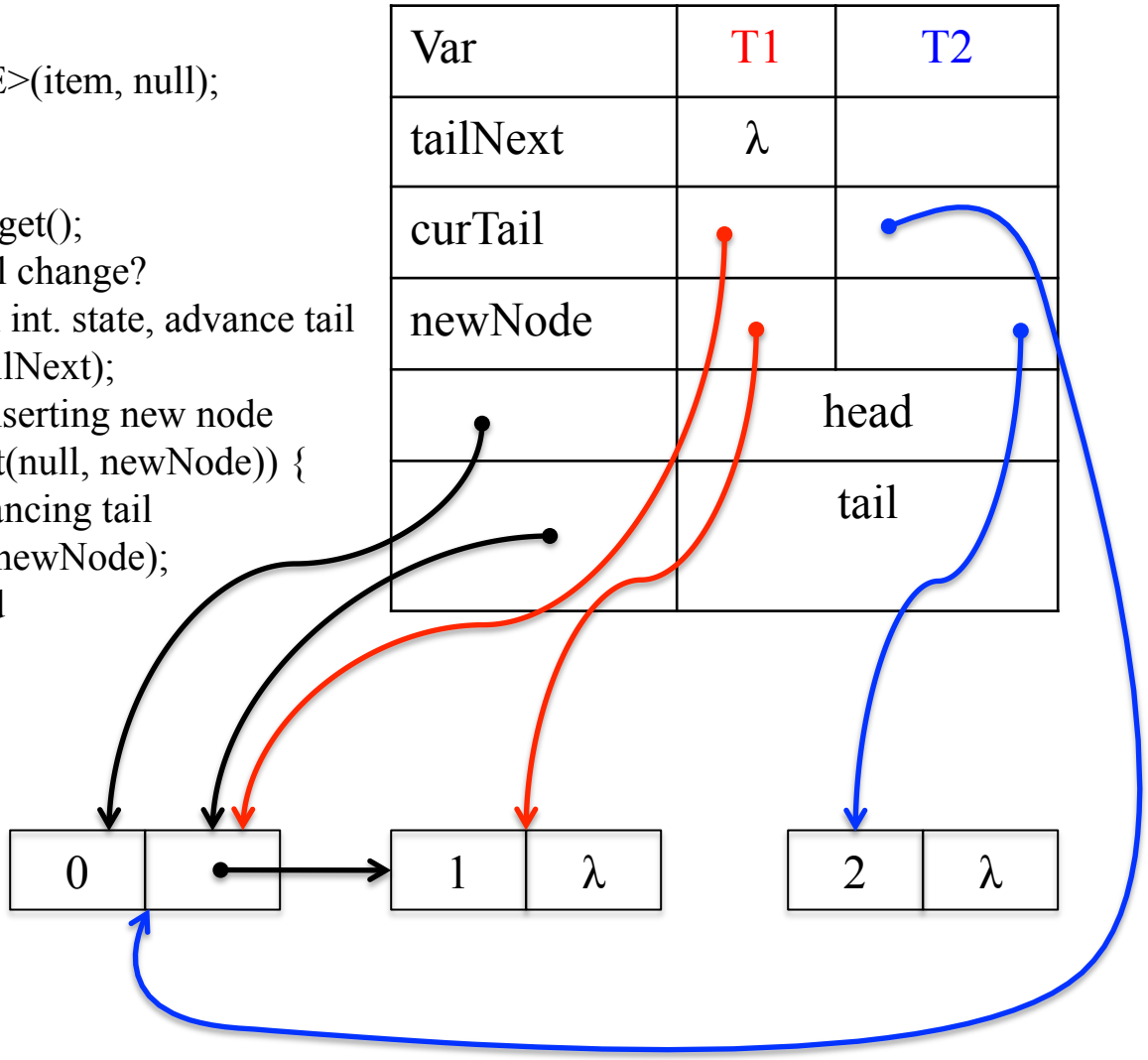
Trace 2: After CAS

```
public boolean put(E item) {
1   Node<E> newNode = new Node<E>(item, null);
2   while (true) {
3     Node<E> curTail = tail.get();
4     Node<E> tailNext = curTail.next.get();
5     if (curTail == tail.get()) {// did tail change?
6       if (tailNext != null) { // Queue in int. state, advance tail
7         tail.compareAndSet(curTail, tailNext);
8       else {  // In quiescent state, try inserting new node
9         if (curTail.next.compareAndSet(null, newNode)) {
          // Insertion succeeded, try advancing tail
10          tail.compareAndSet(curTail, newNode);
          // will fail if tail already moved
11        return true;
          }
        }
      }
    }
  }
```



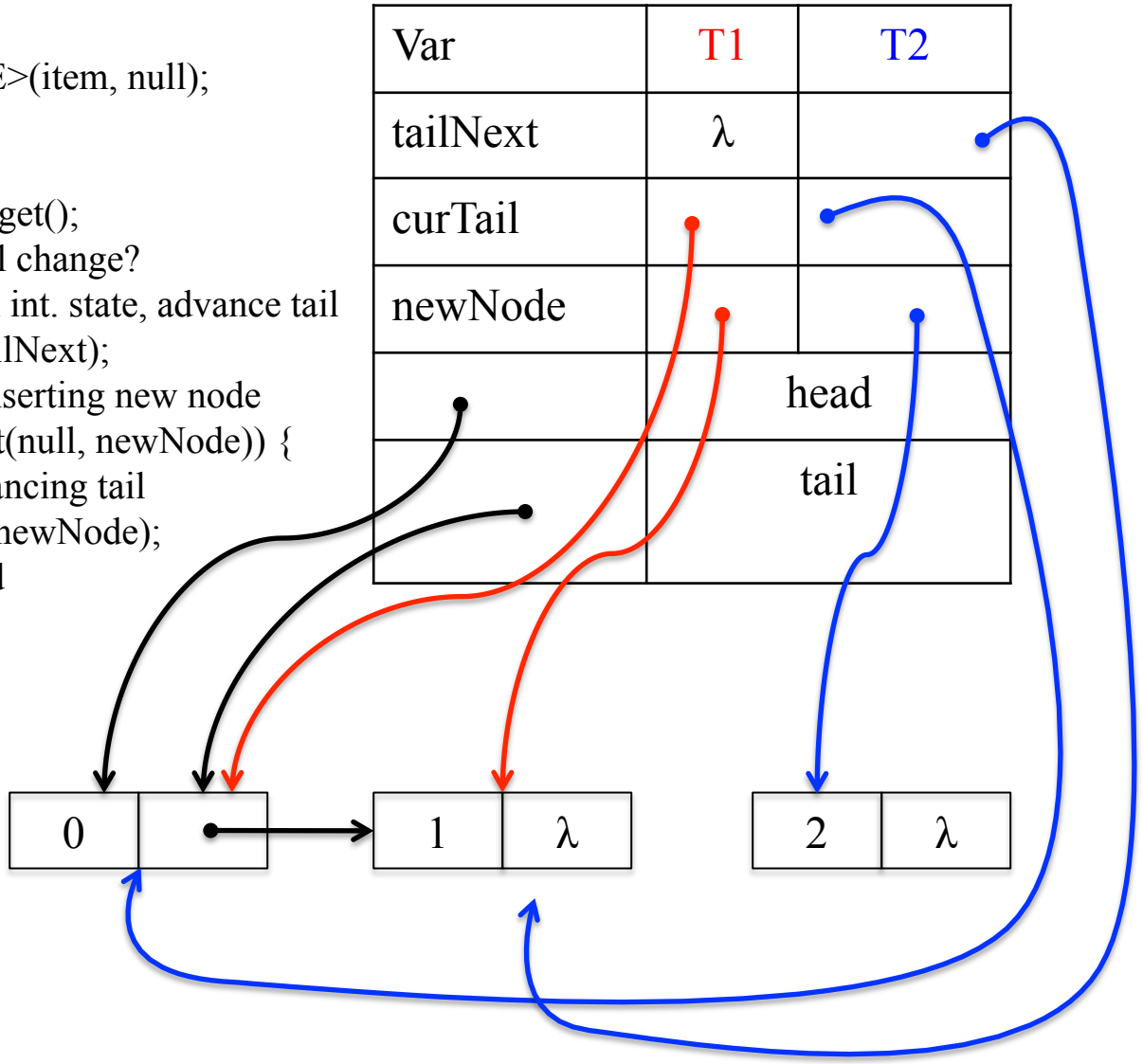
Trace 2: T2 continues

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



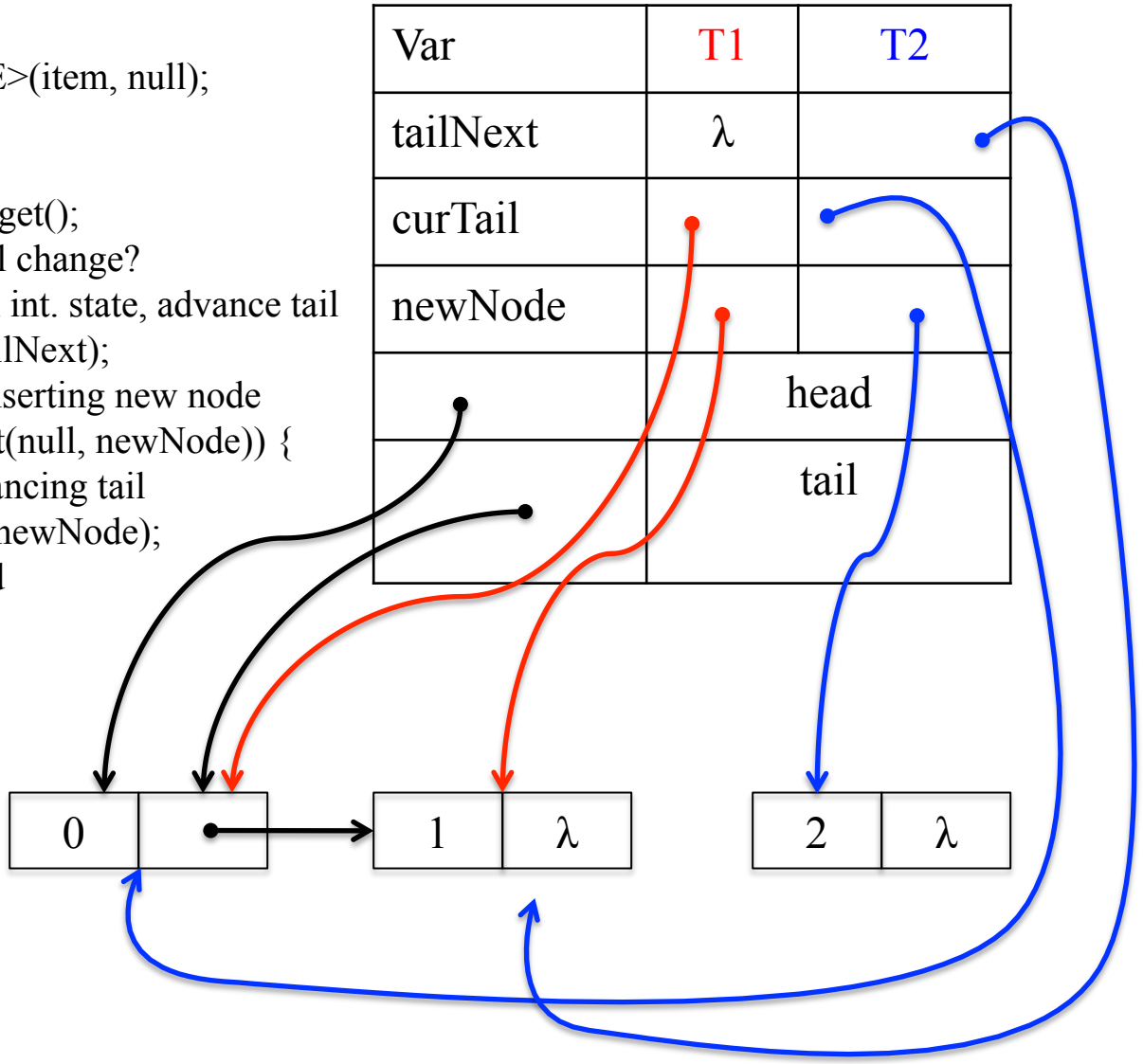
Trace 2

```
public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



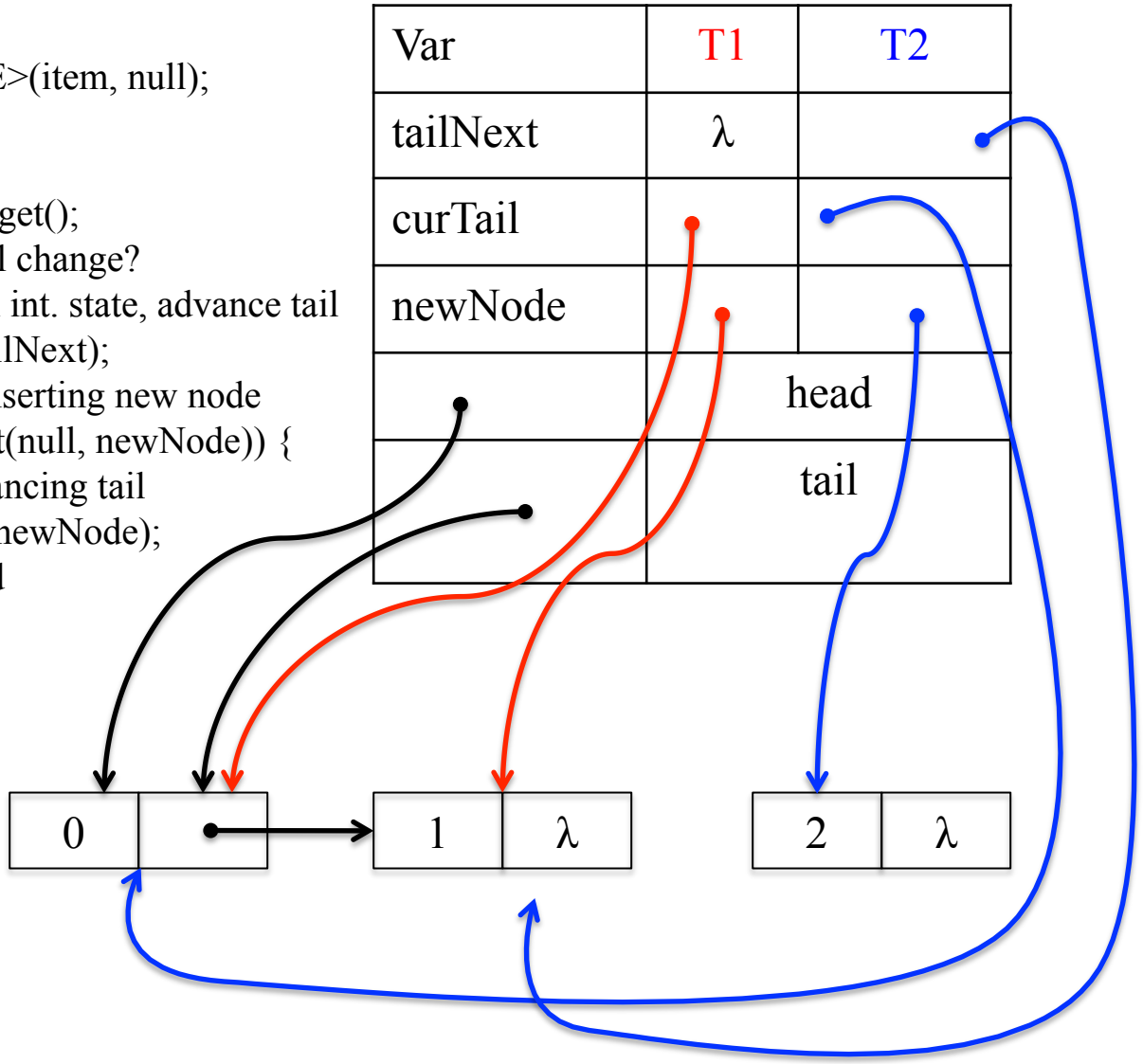
Trace 2

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



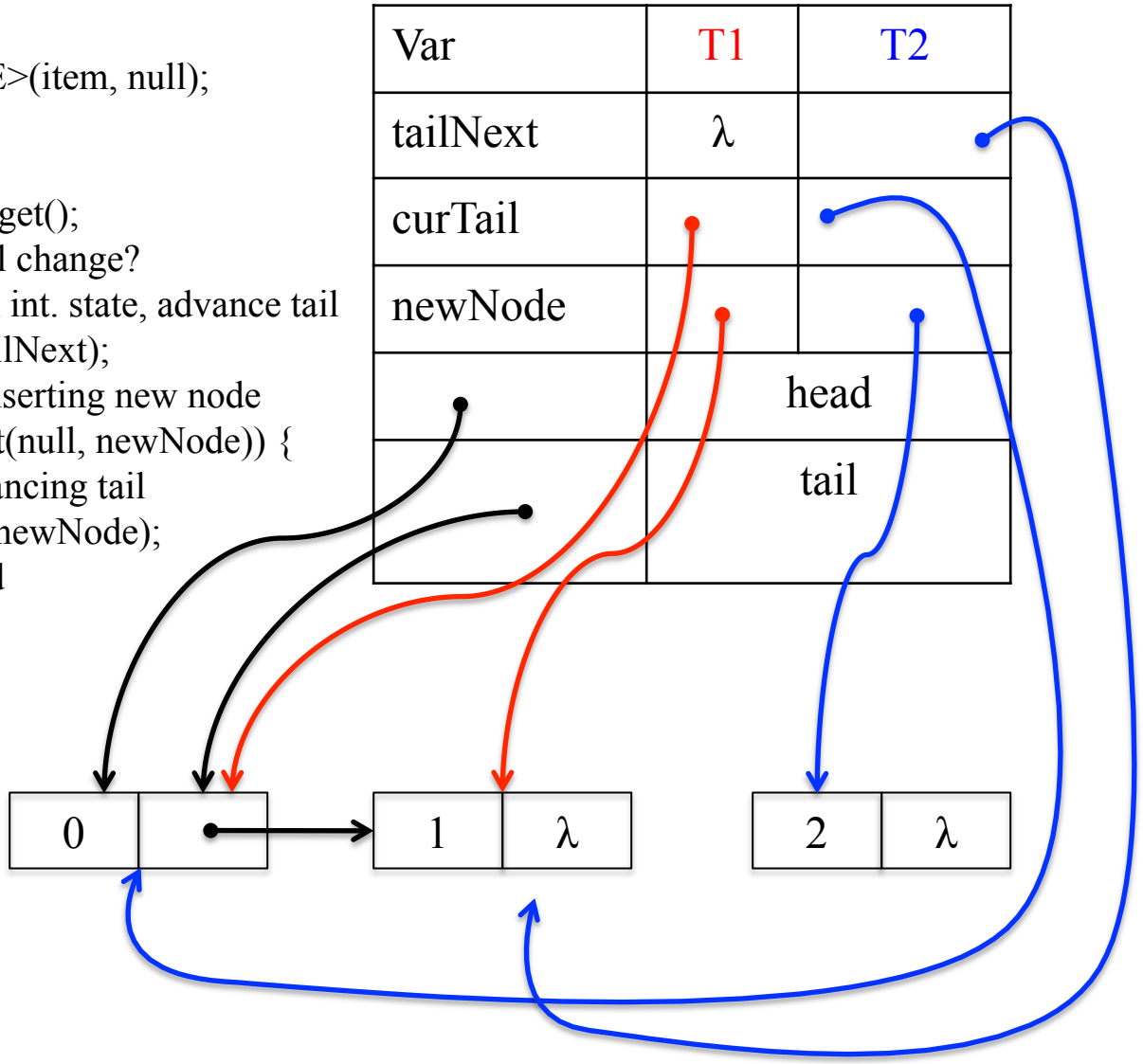
Trace 2

```
public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



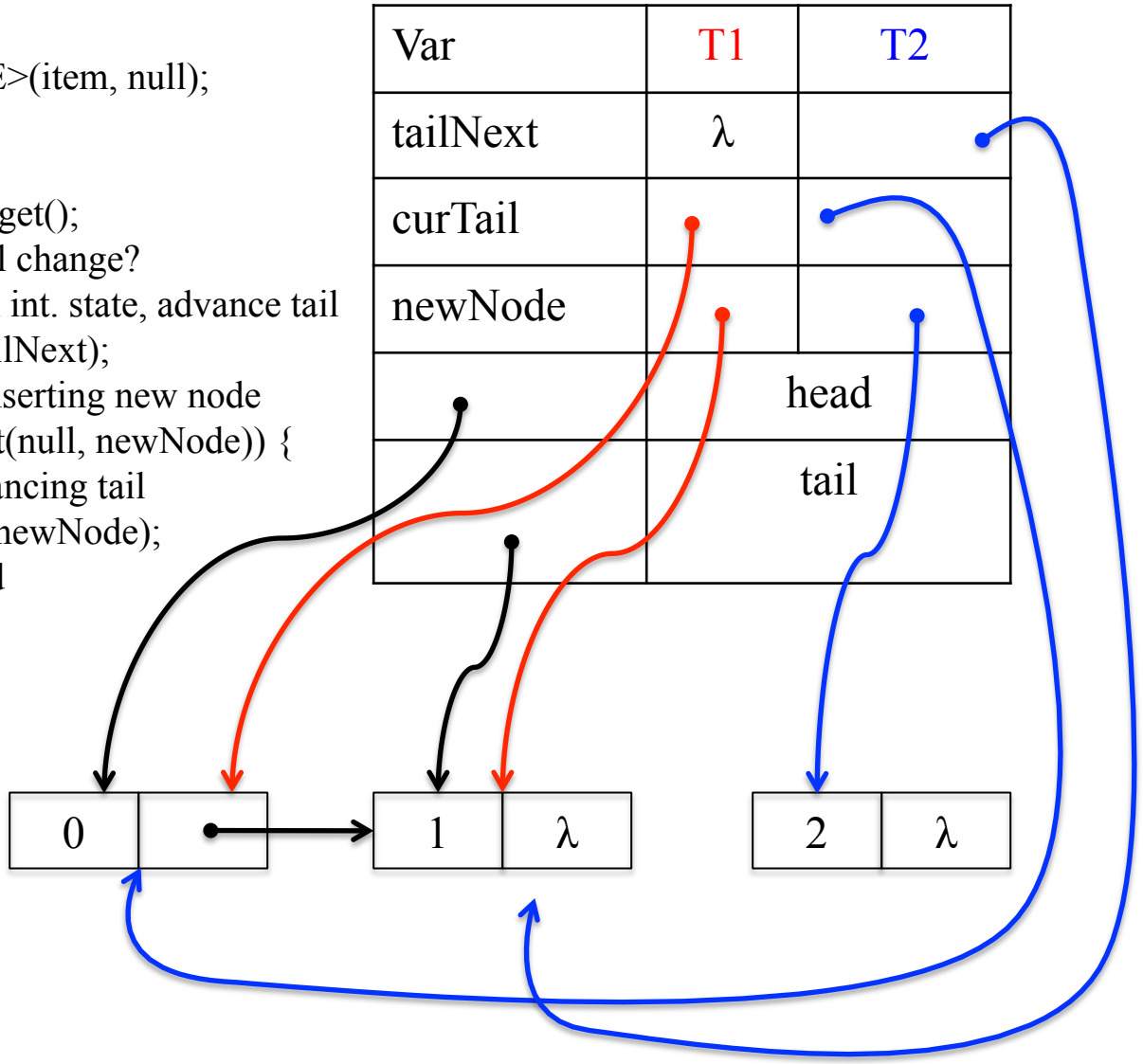
Trace 2:T2 wins

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



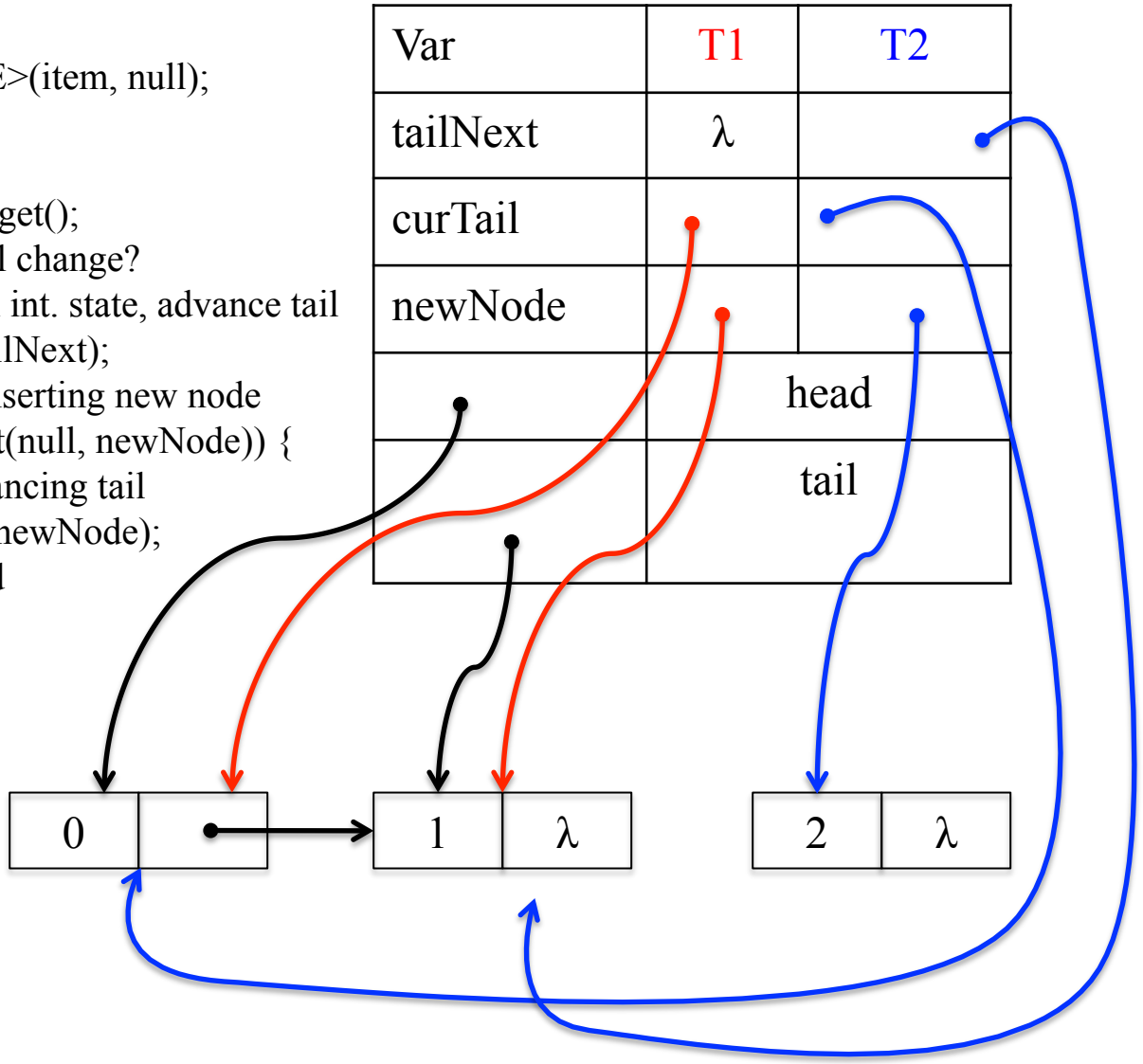
Trace 2: After CAS

```
public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



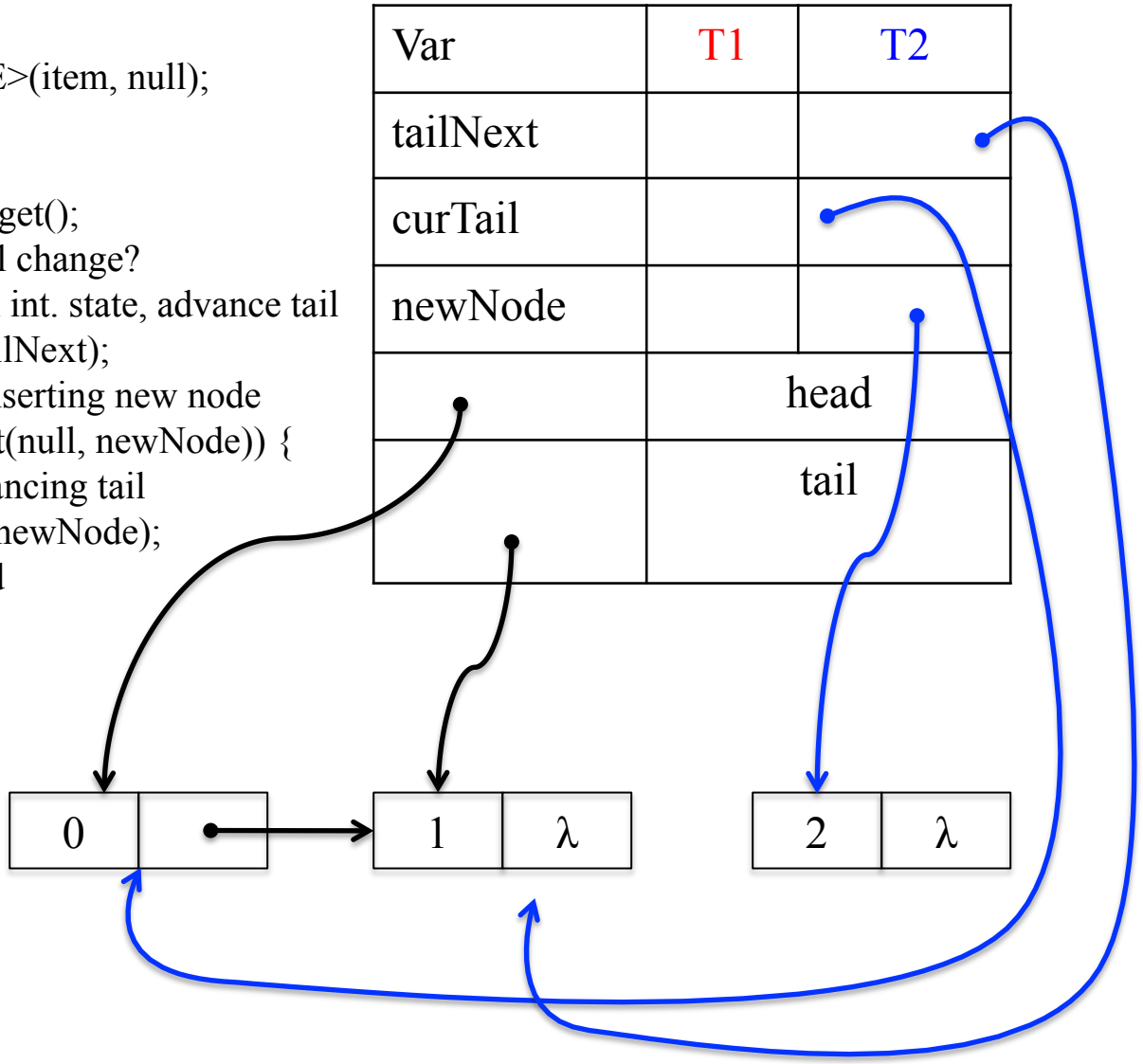
Trace 2: T1 continues: CAS fails

```
public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



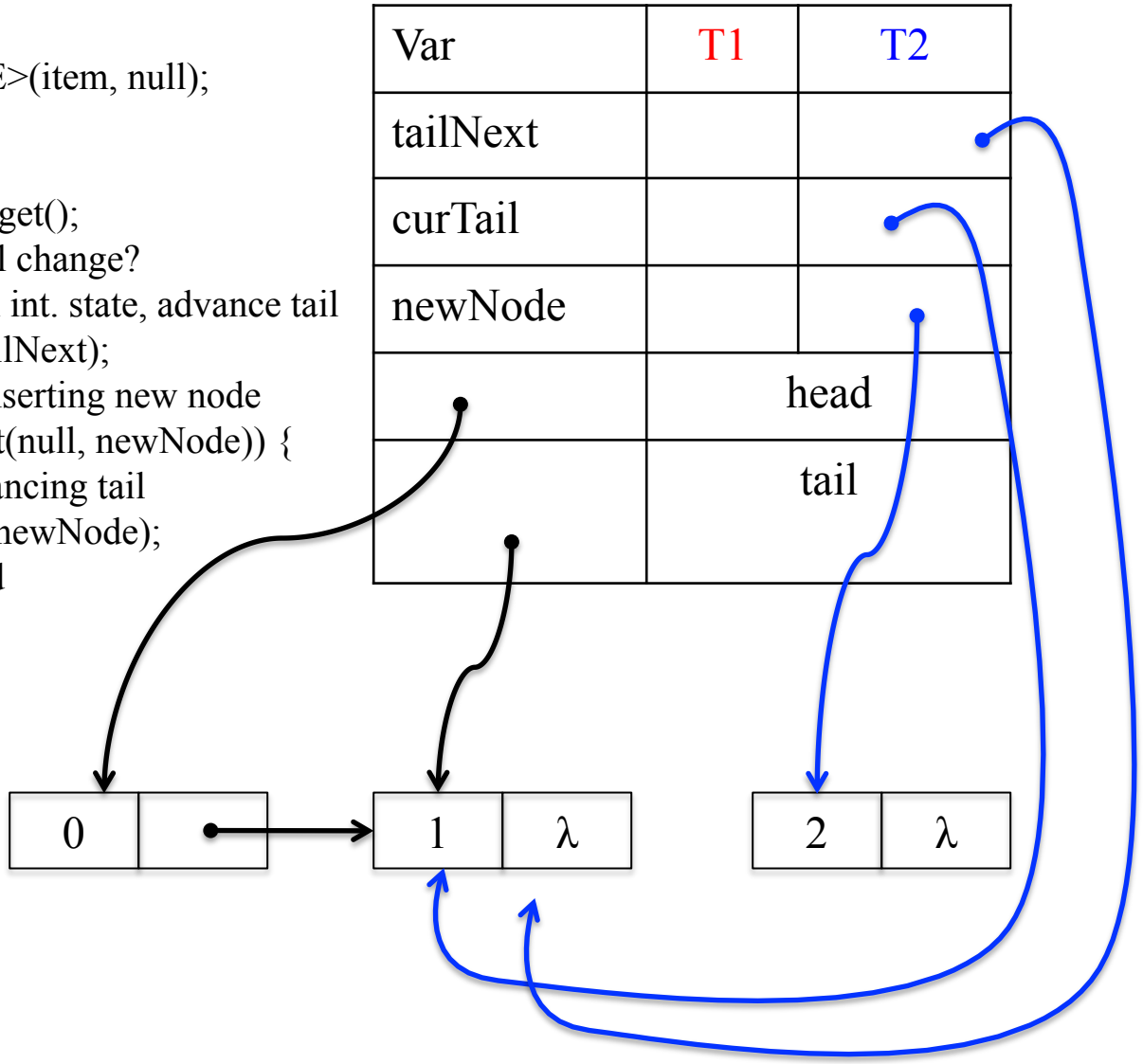
Trace 2: T1 exits

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



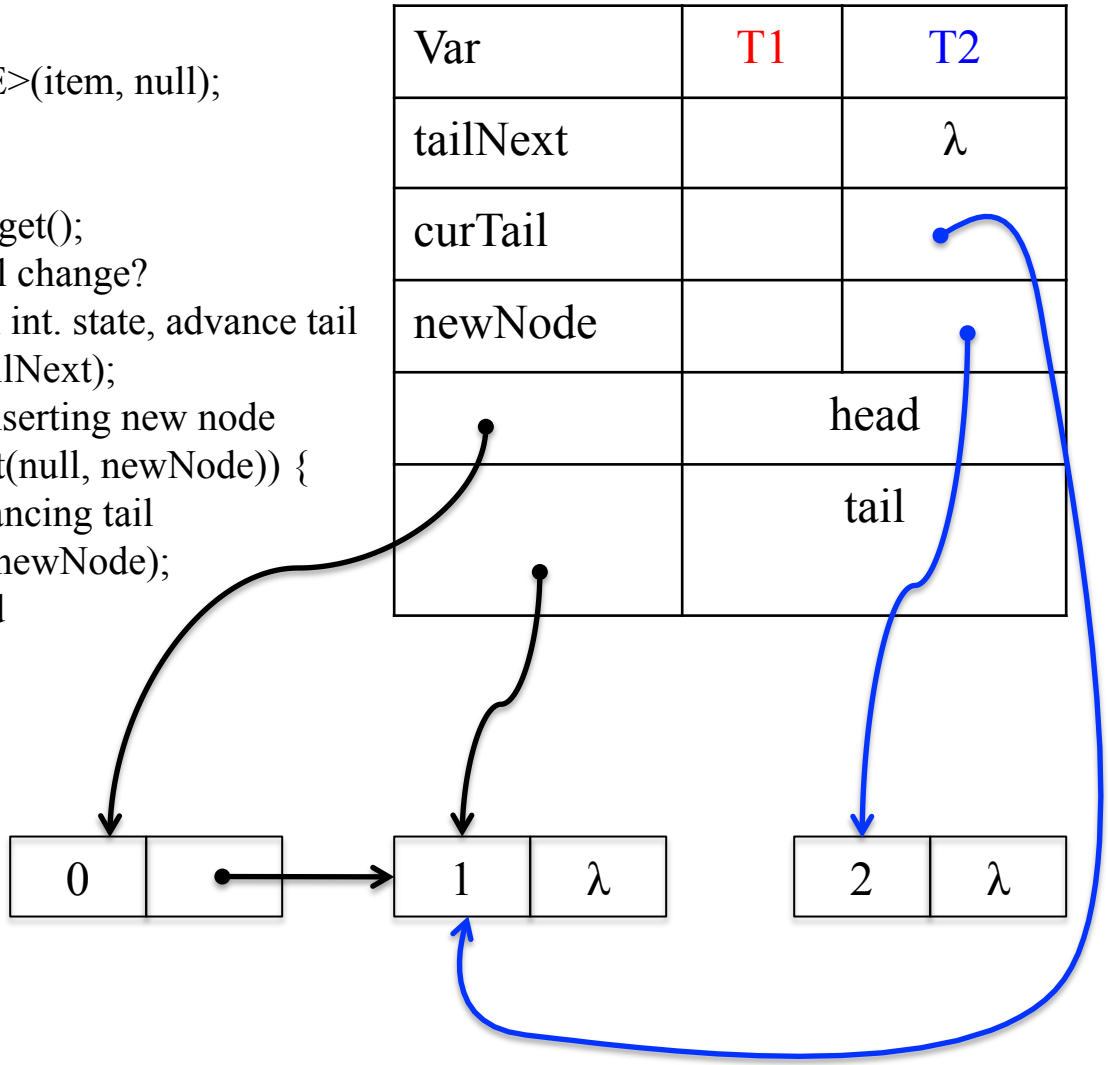
Trace 2: T2 continues

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



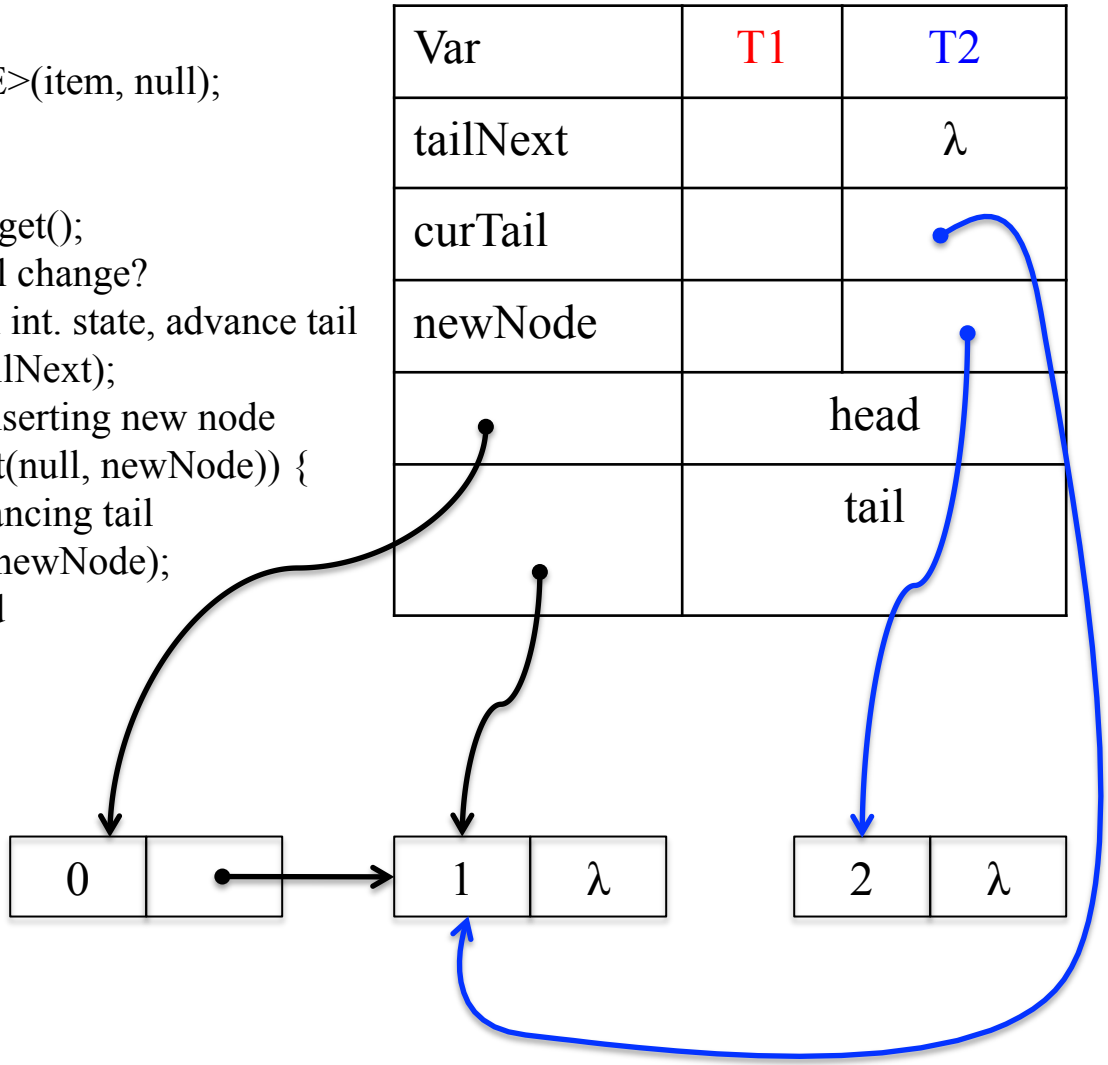
Trace 2: T2 continues

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



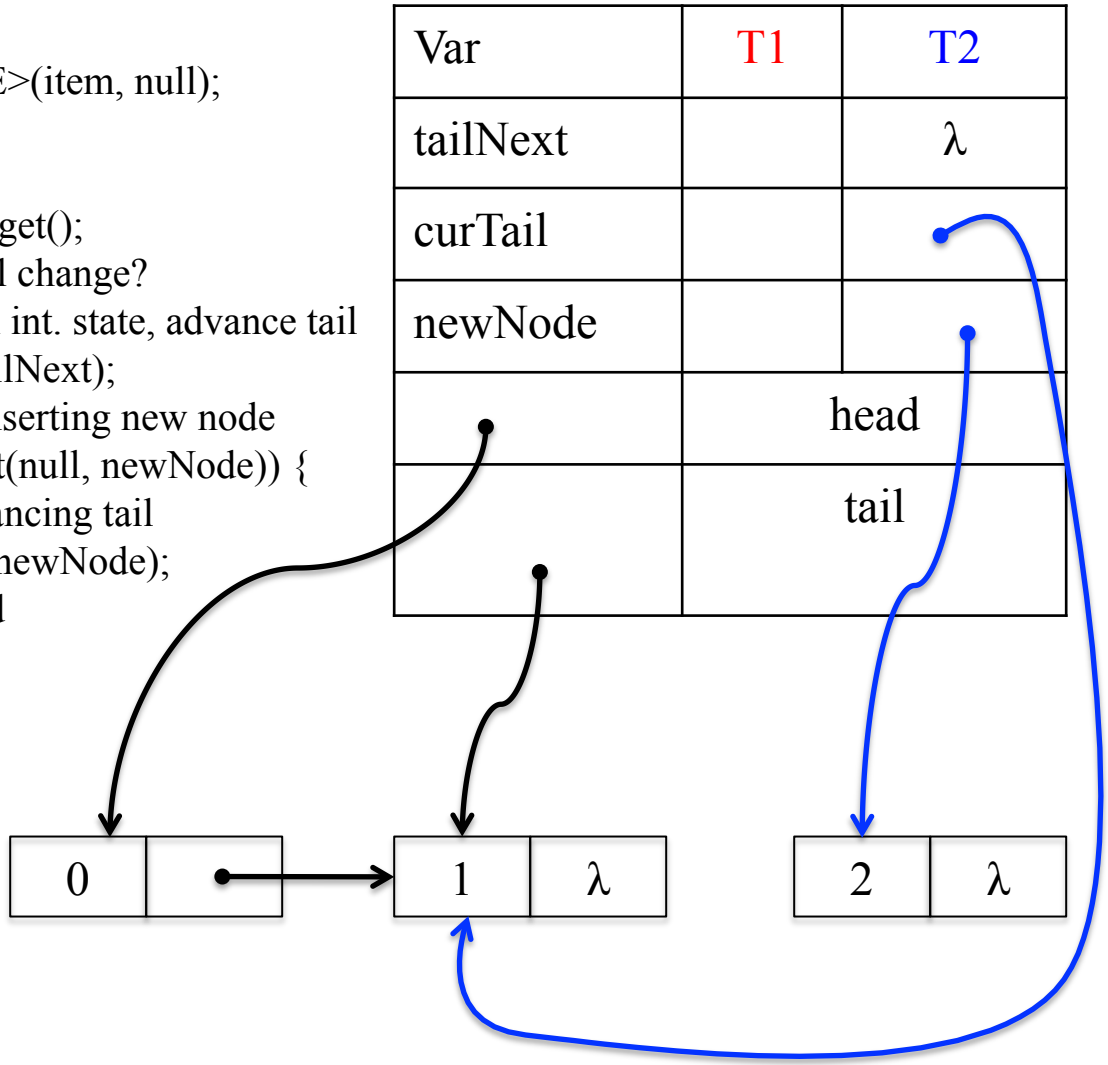
Trace 2: T2 continues

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



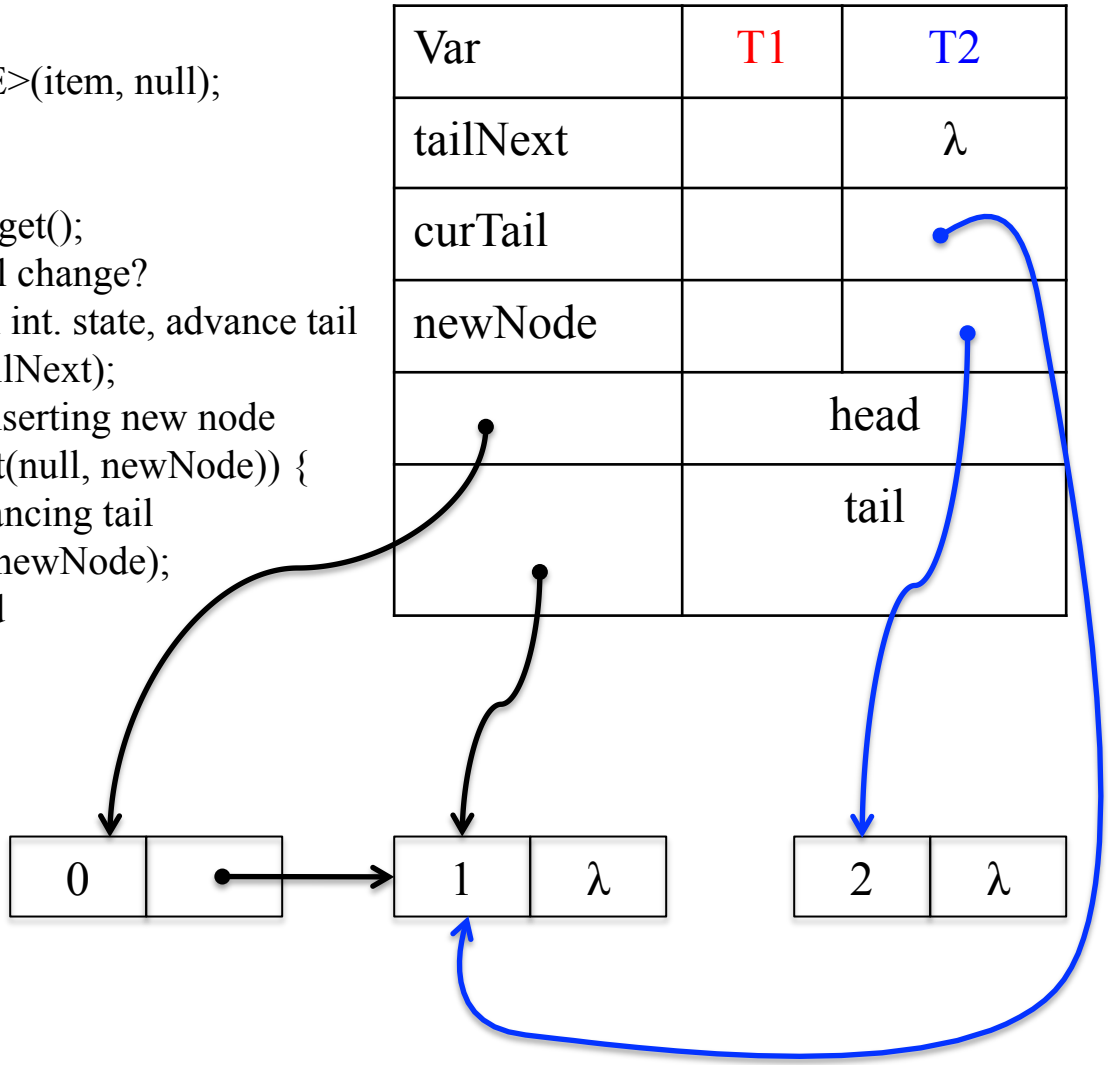
Trace 2: T2 continues

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



Trace 2: T2 continues

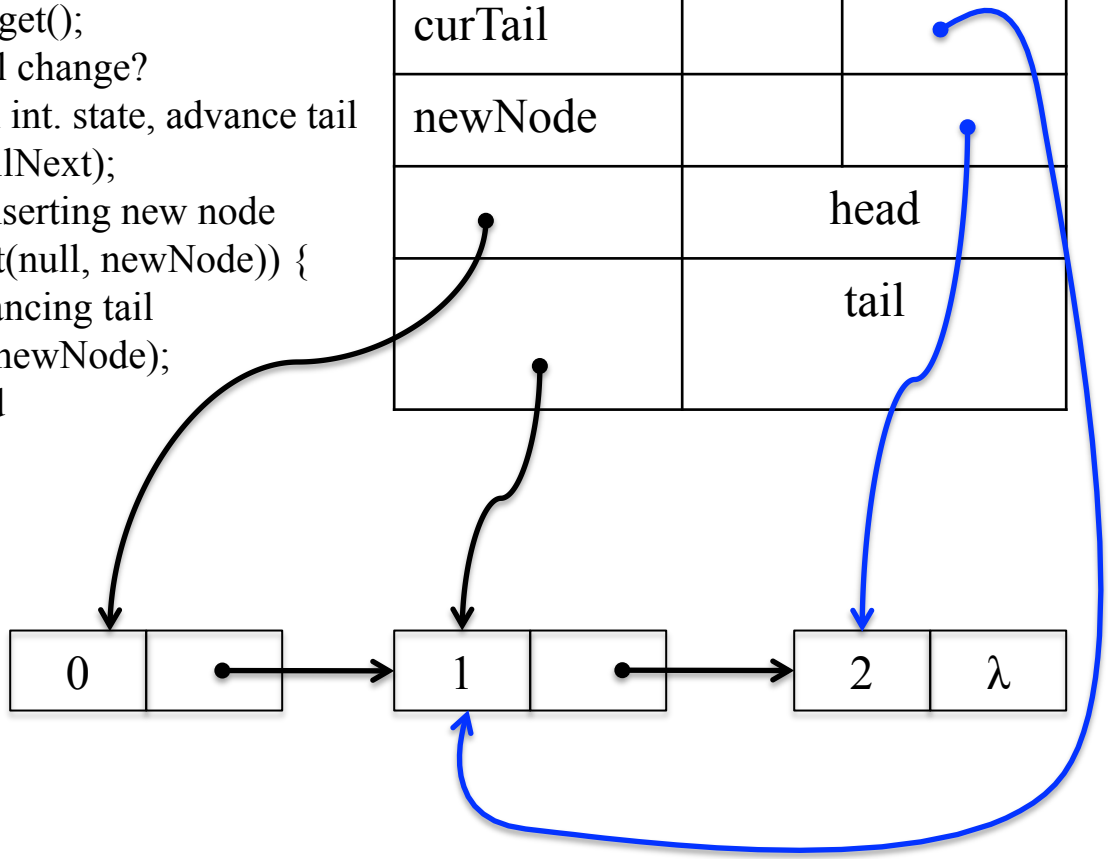
```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



Trace 2: After CAS

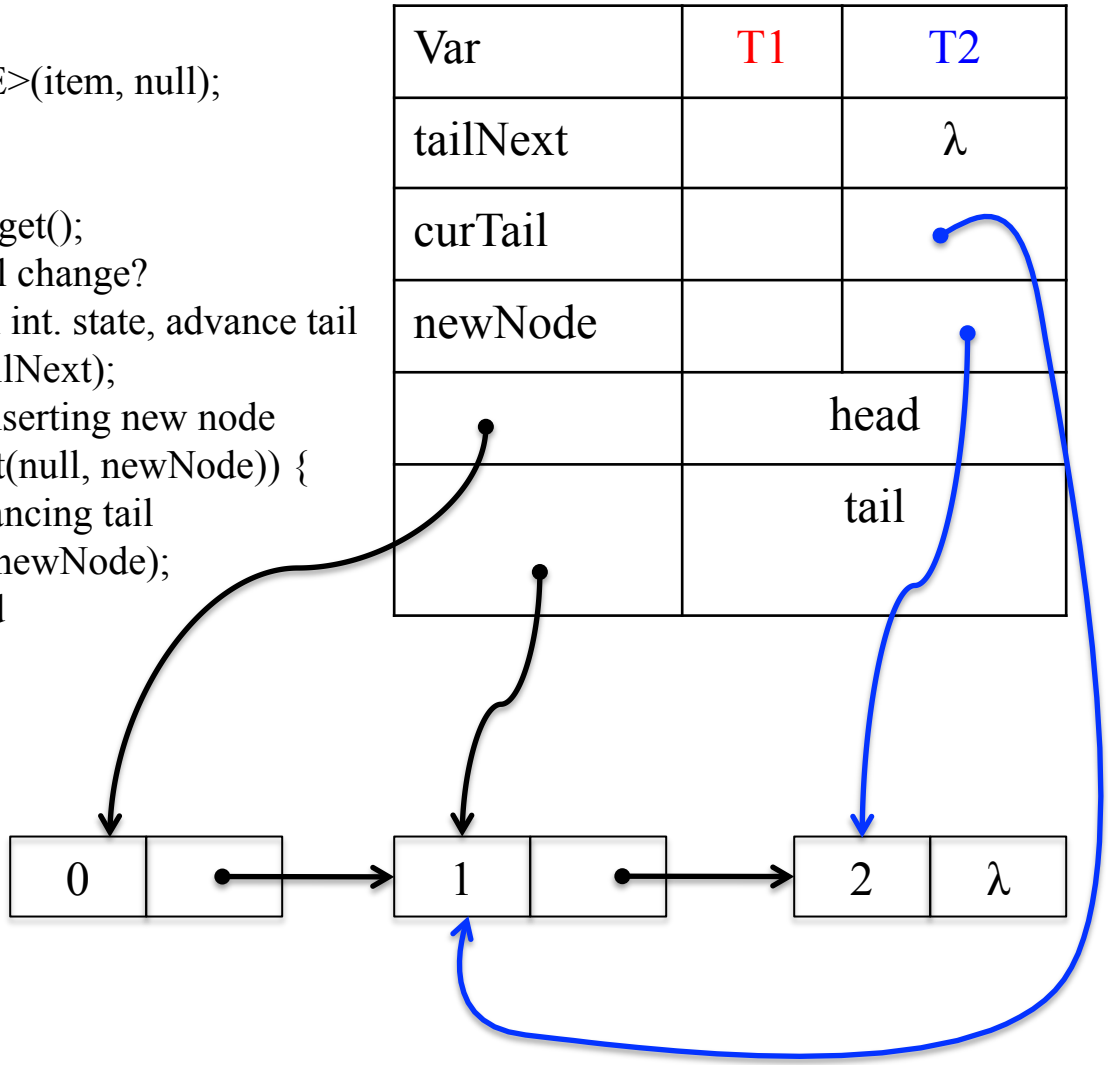
```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```

Var	T1	T2
tailNext		λ
curTail		
newNode		
	head	
	tail	



Trace 2: T2 continues

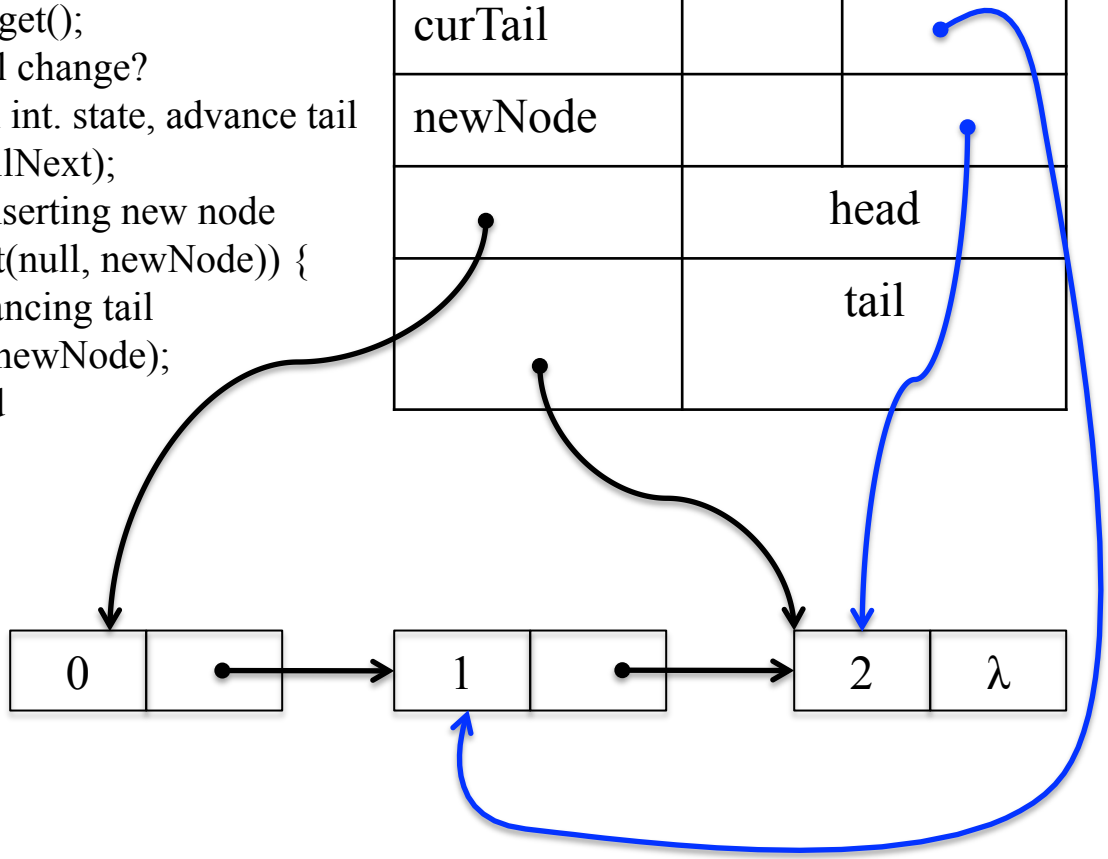
```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



Trace 2: After CAS

```
public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```

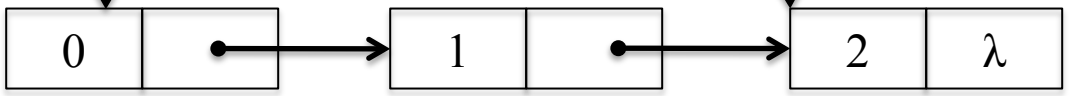
Var	T1	T2
tailNext		λ
curTail		
newNode		
	head	
	tail	



Trace 2: T2 Exits

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```

Var	T1	T2
tailNext		
curTail		
newNode		
	head	
	tail	



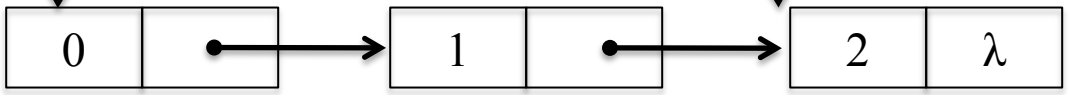
Execution Traces

- 2 threads attempt to take()

Trace 1

```
    public E take() {
    for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5          if (oldHead == oldTail) {      //Queue empty or tail updated?
6            if (oldHeadNext == null) { // Is queue empty?
7               return null;                //Queue is empty, can't take
             }
8            tail.compareAndSet(oldTail, oldHeadNext); // tail updating
           } else {                                  // No need to deal with tail
9            if (head.compareAndSet(oldHead, oldHeadNext)) {
10              return oldHeadNext.item;
             }
           }
        }
      }
    }
```

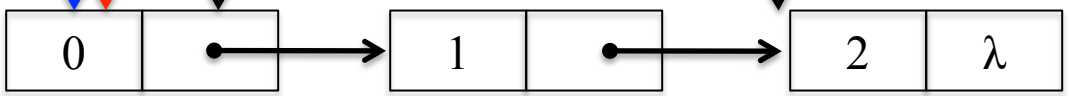
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



Trace 1

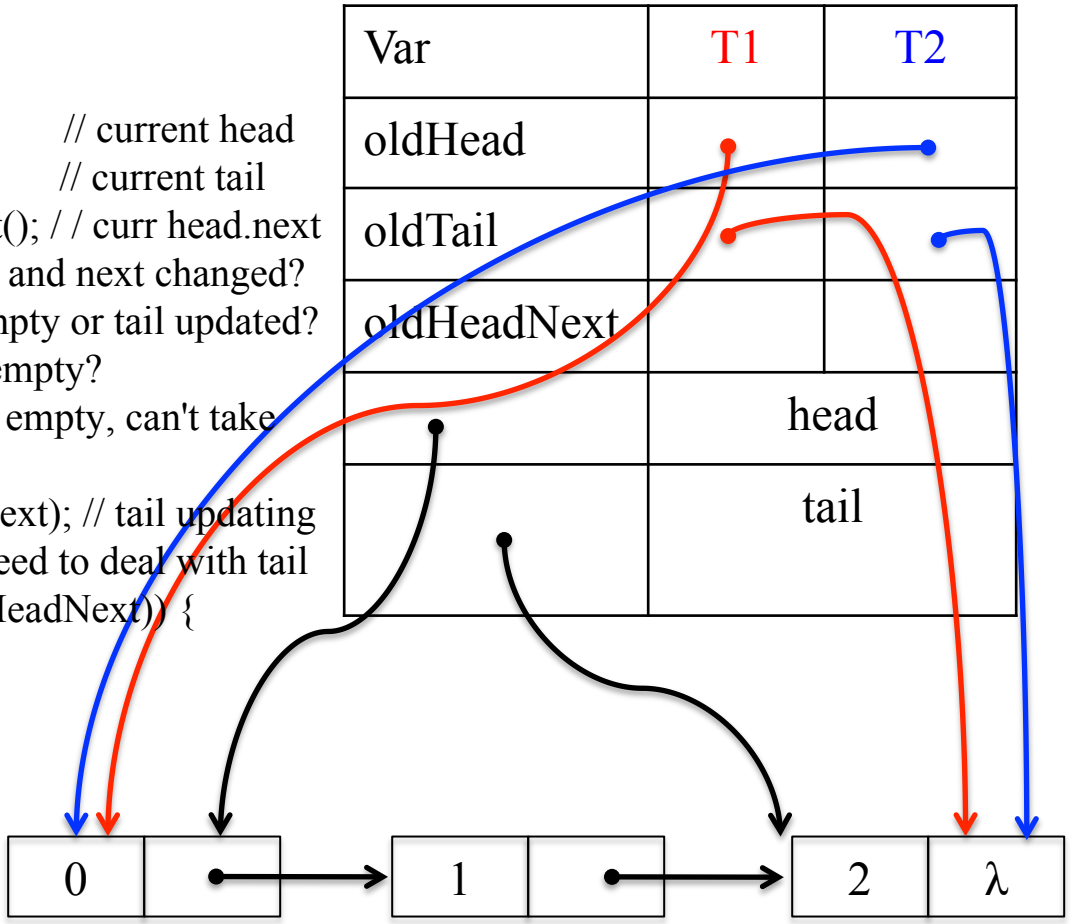
```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                    //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



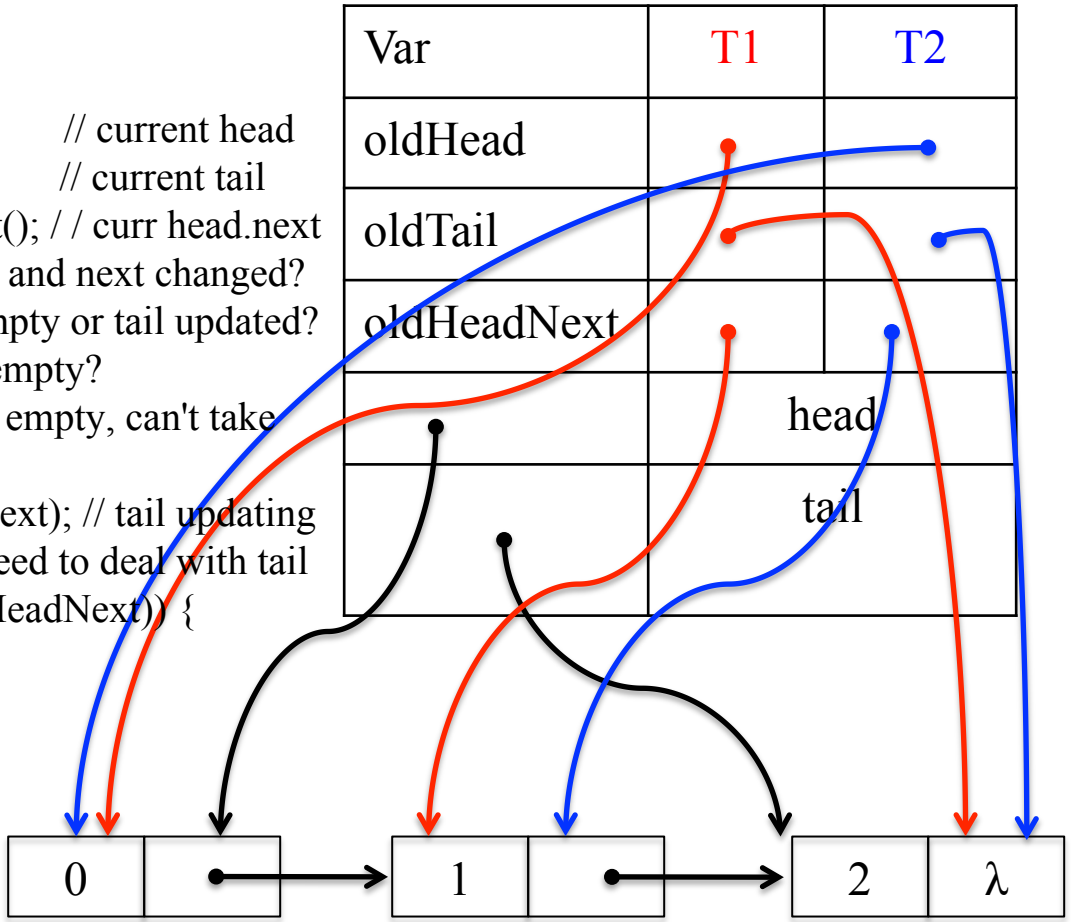
Trace 1

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



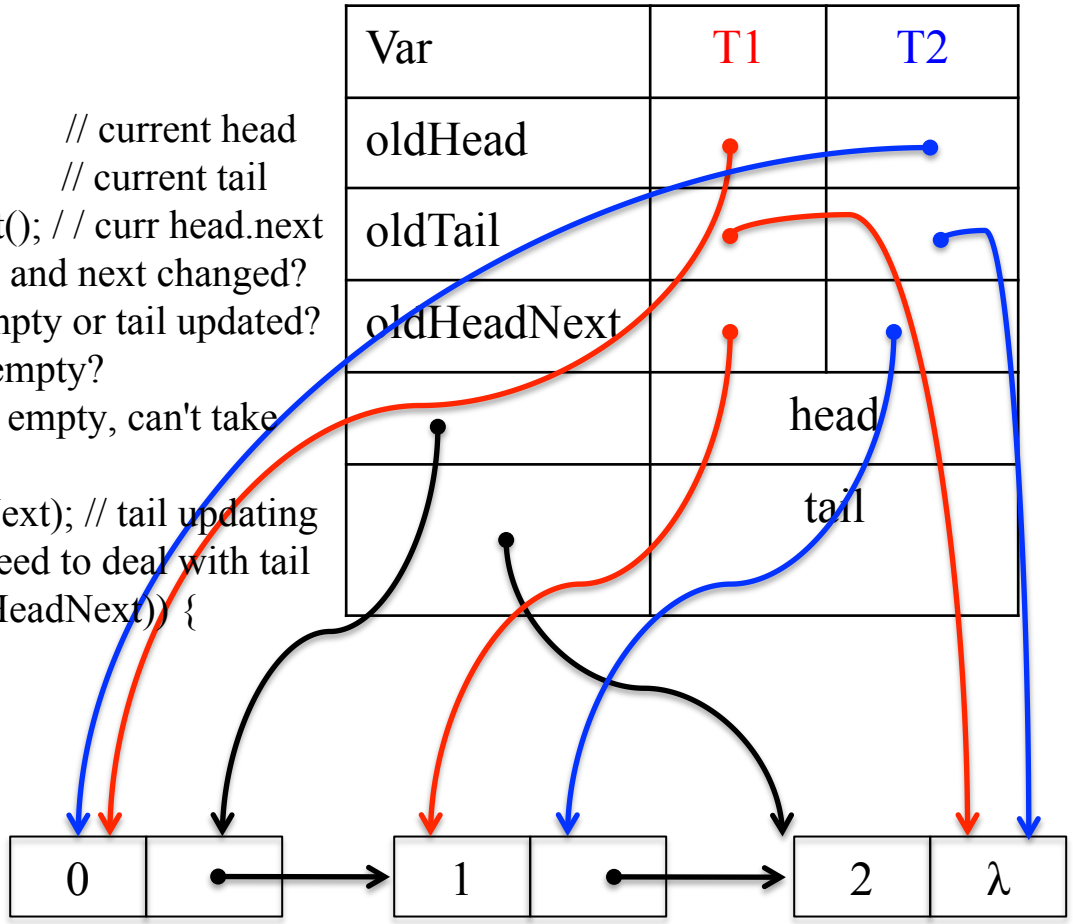
Trace 1

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



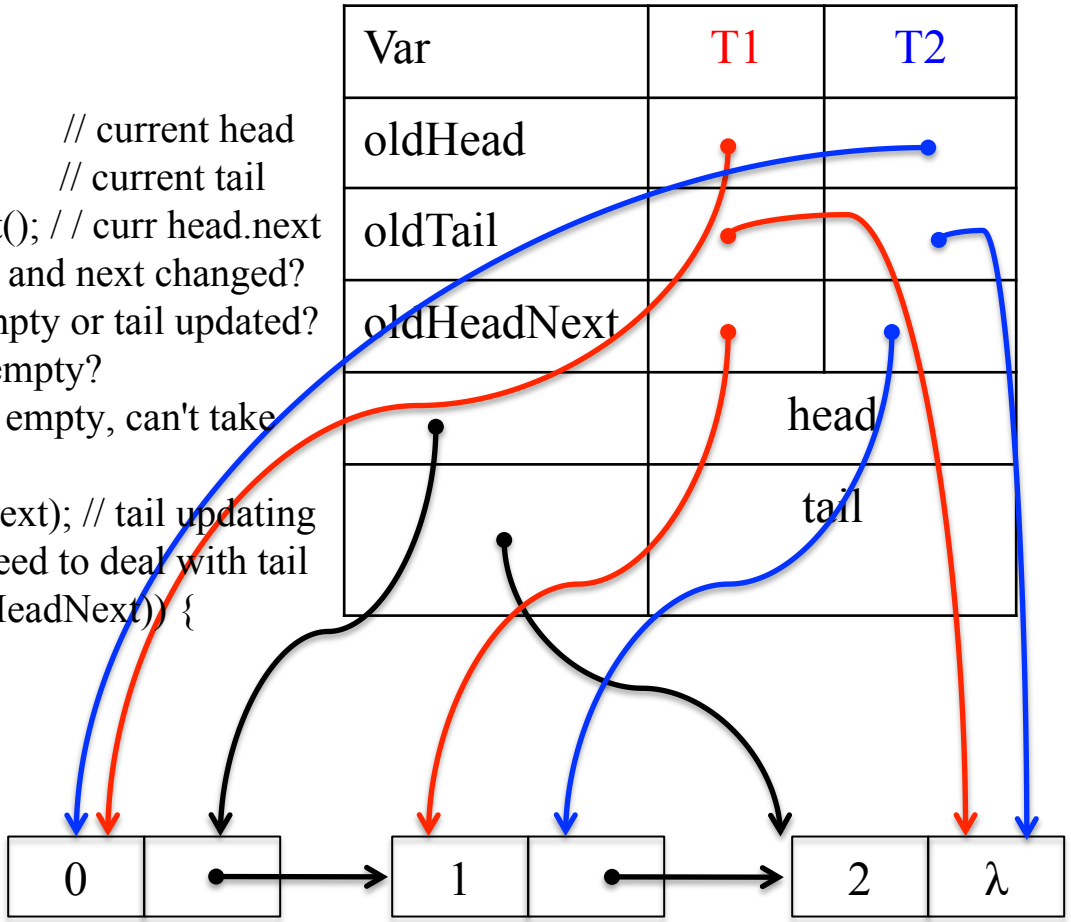
Trace 1

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



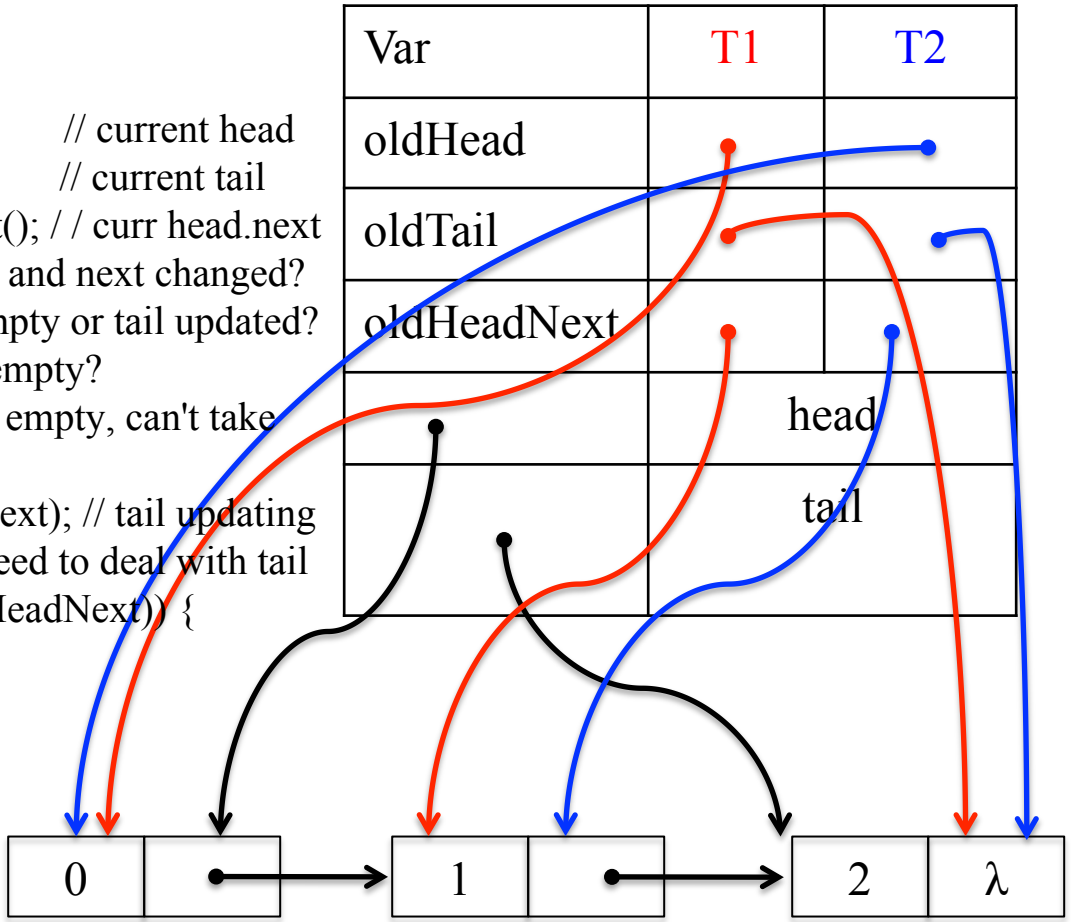
Trace 1

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



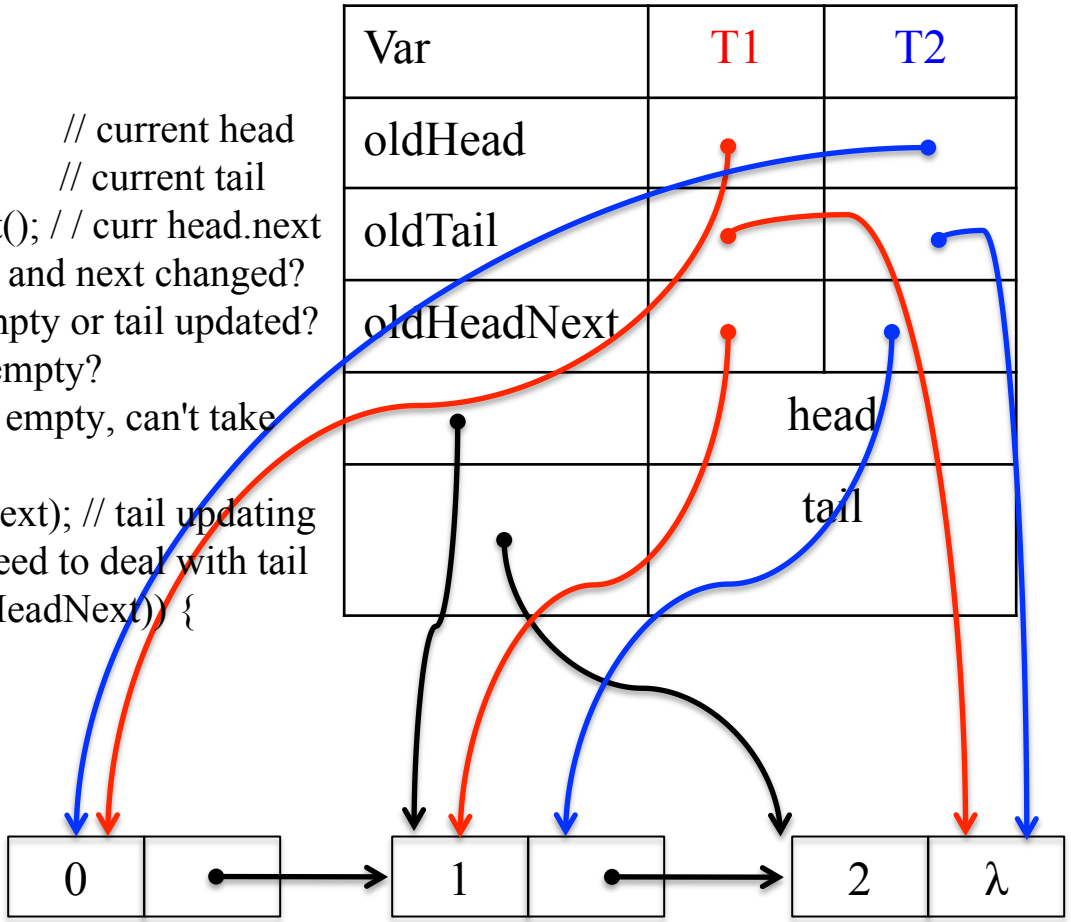
Trace 1: T1 wins, CAS succeeds

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



Trace 1: T1 wins - after CAS

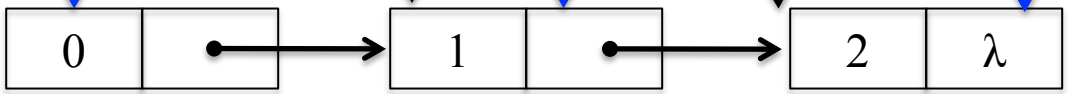
```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



Trace 1: T1 Exits

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

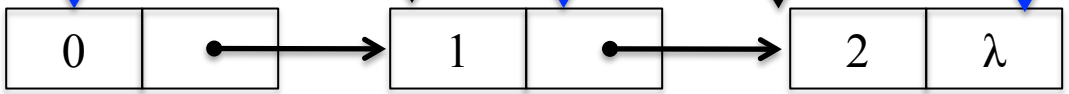
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



Trace 1: T2 continues, CAS fails

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

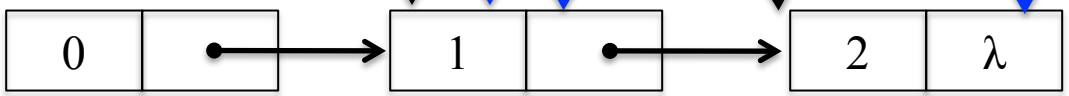
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



Trace 1: T2 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

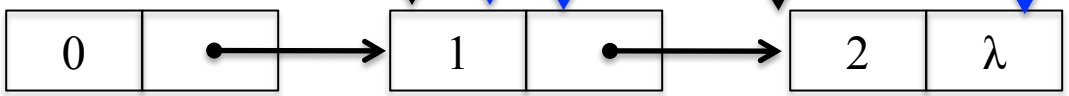
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



Trace 1: T2 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

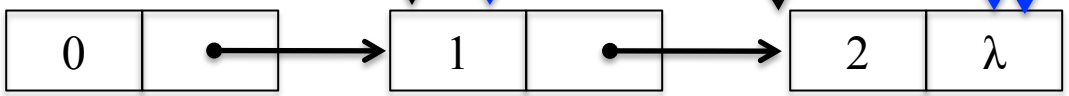
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



Trace 1: T2 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

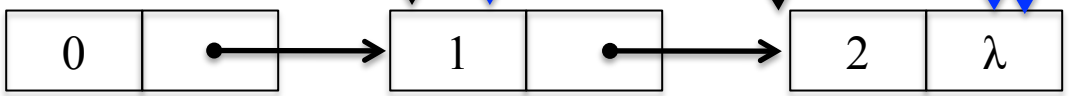
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



Trace 1: T2 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

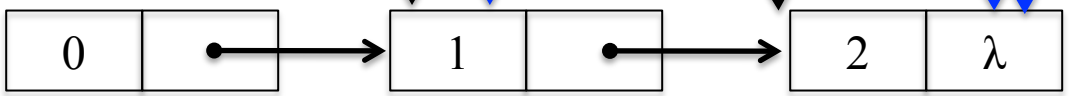
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



Trace 1: T2 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

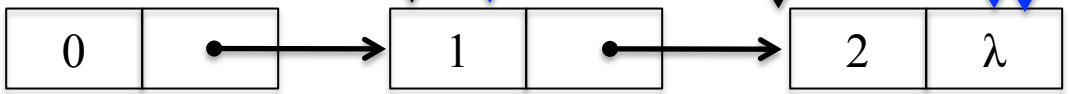
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



Trace 1: T2 continues, CAS succeeds

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

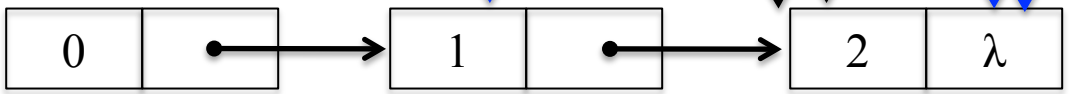
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



Trace 1: T2 continues, after CAS

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

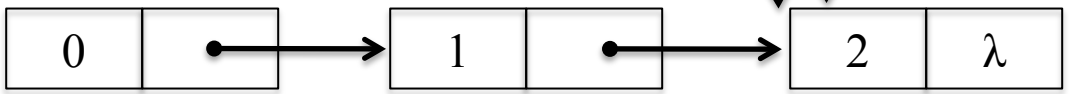
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



Trace 1: T2 exits

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5          if (oldHead == oldTail) {      //Queue empty or tail updated?
6            if (oldHeadNext == null) { // Is queue empty?
7               return null;                //Queue is empty, can't take
             }
8            tail.compareAndSet(oldTail, oldHeadNext); // tail updating
           } else {                                  // No need to deal with tail
9            if (head.compareAndSet(oldHead, oldHeadNext)) {
10              return oldHeadNext.item;
             }
           }
        }
      }
    }
```

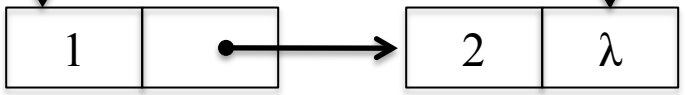
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



Trace 2

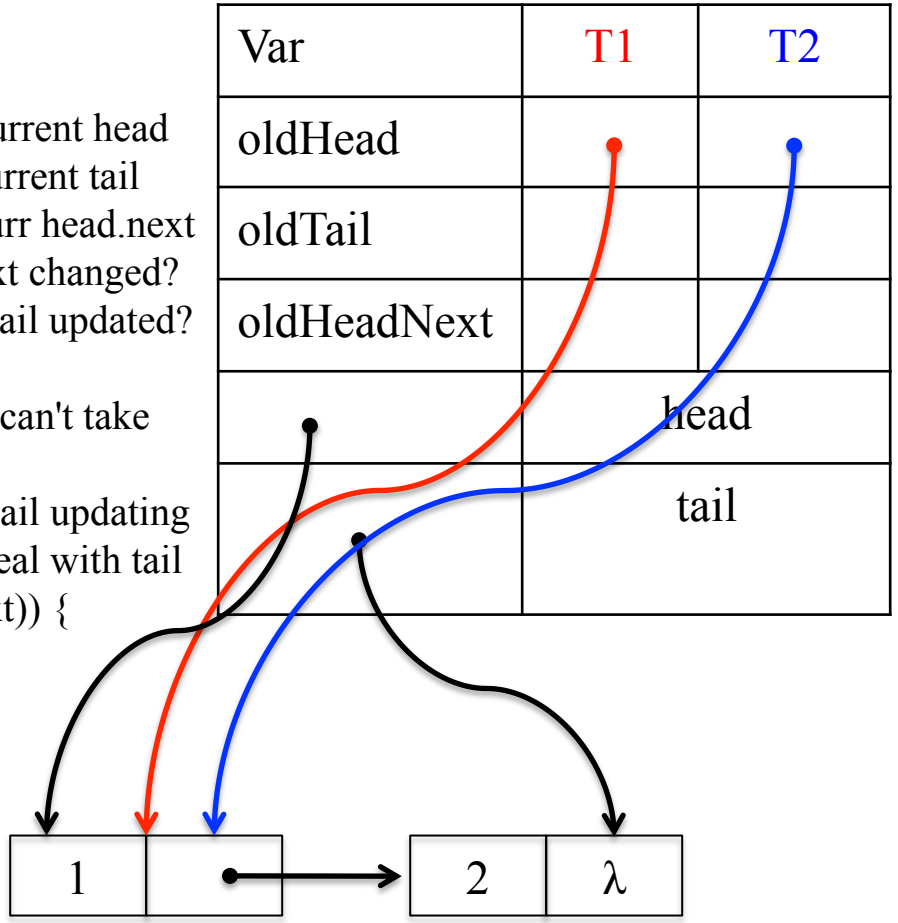
```
    public E take() {
    for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5          if (oldHead == oldTail) {      //Queue empty or tail updated?
6            if (oldHeadNext == null) { // Is queue empty?
7               return null;                //Queue is empty, can't take
             }
8            tail.compareAndSet(oldTail, oldHeadNext); // tail updating
           } else {                                  // No need to deal with tail
9            if (head.compareAndSet(oldHead, oldHeadNext)) {
10              return oldHeadNext.item;
             }
           }
        }
      }
    }
```

Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



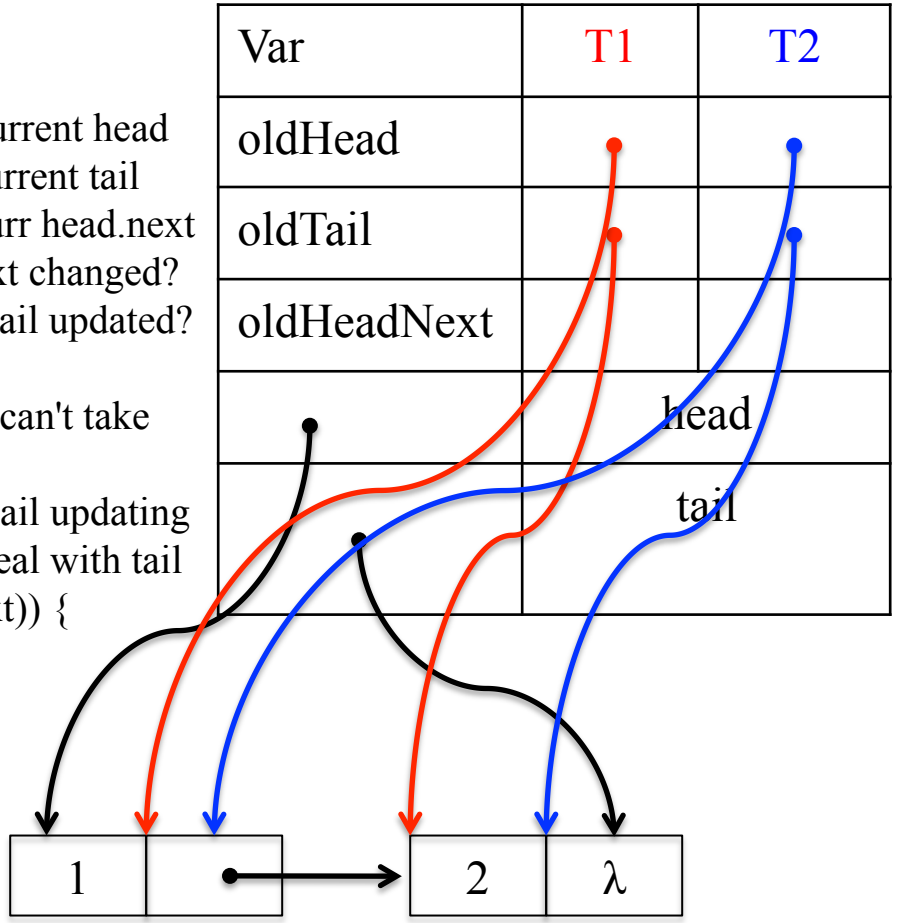
Trace 2

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



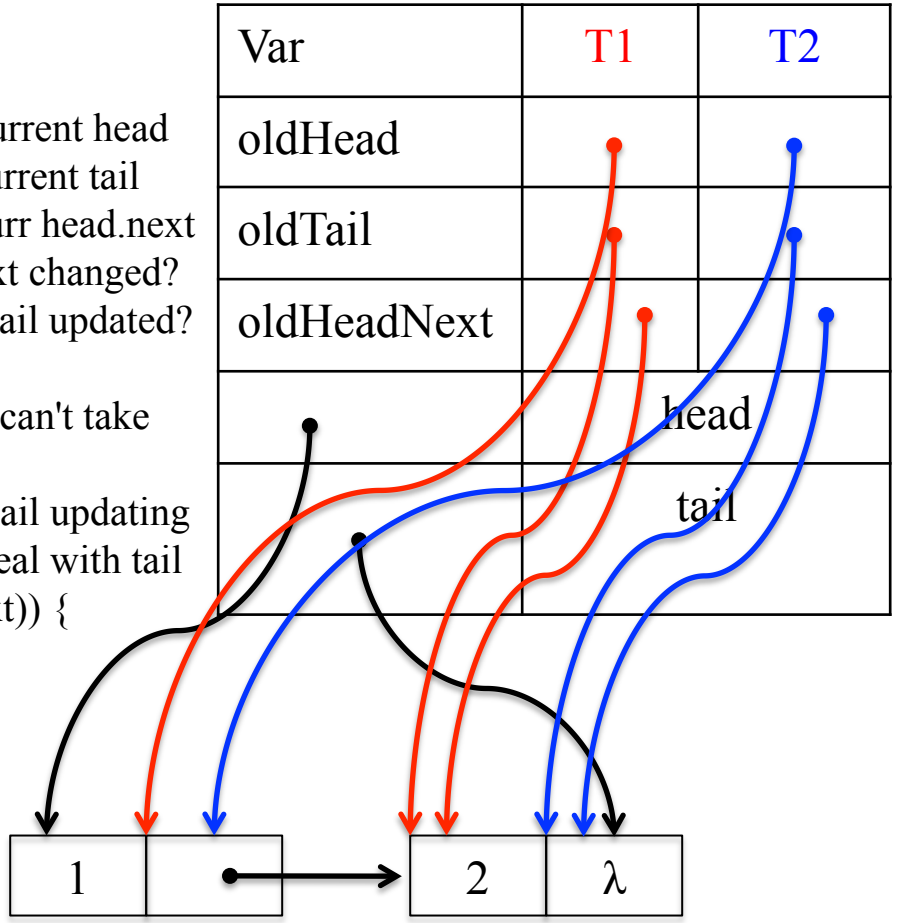
Trace 2

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



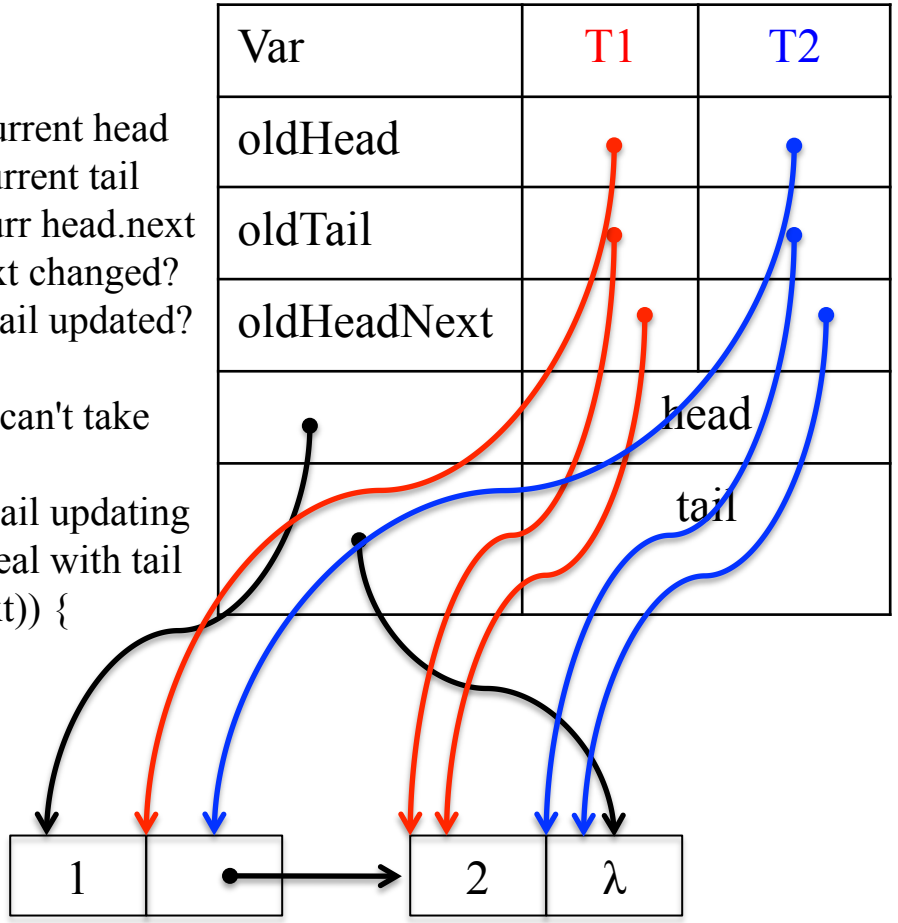
Trace 2

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



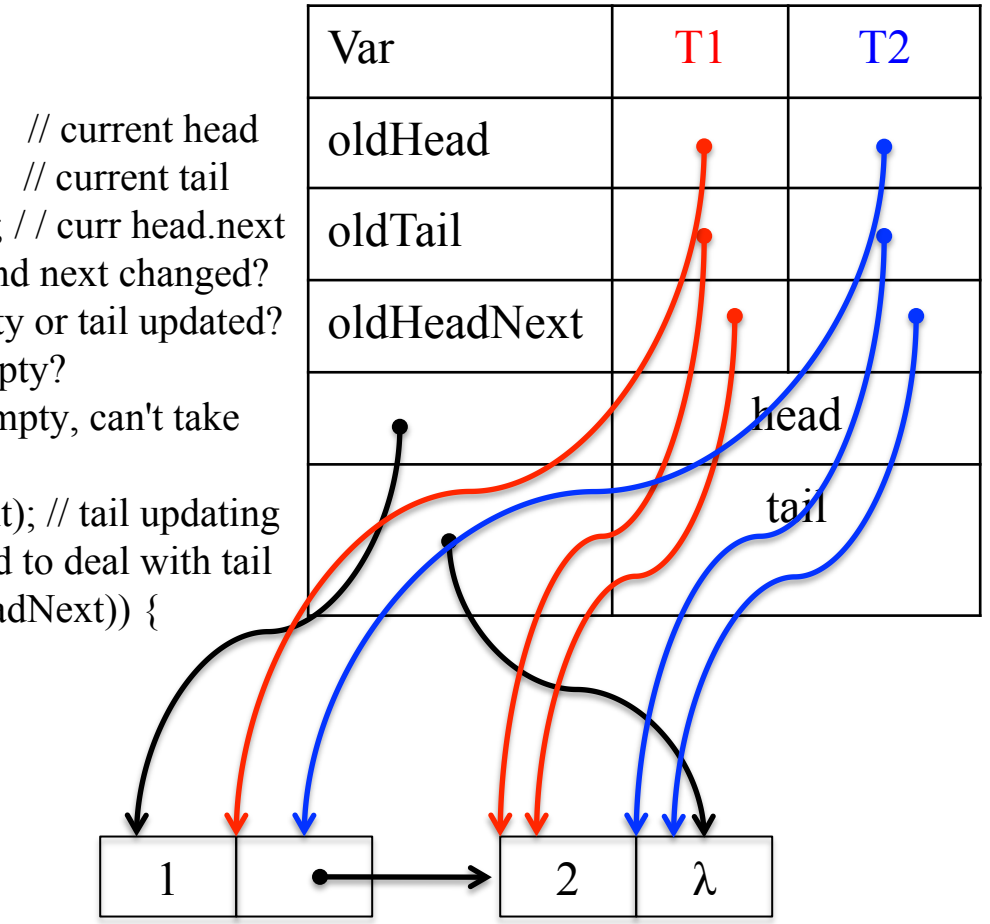
Trace 2

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



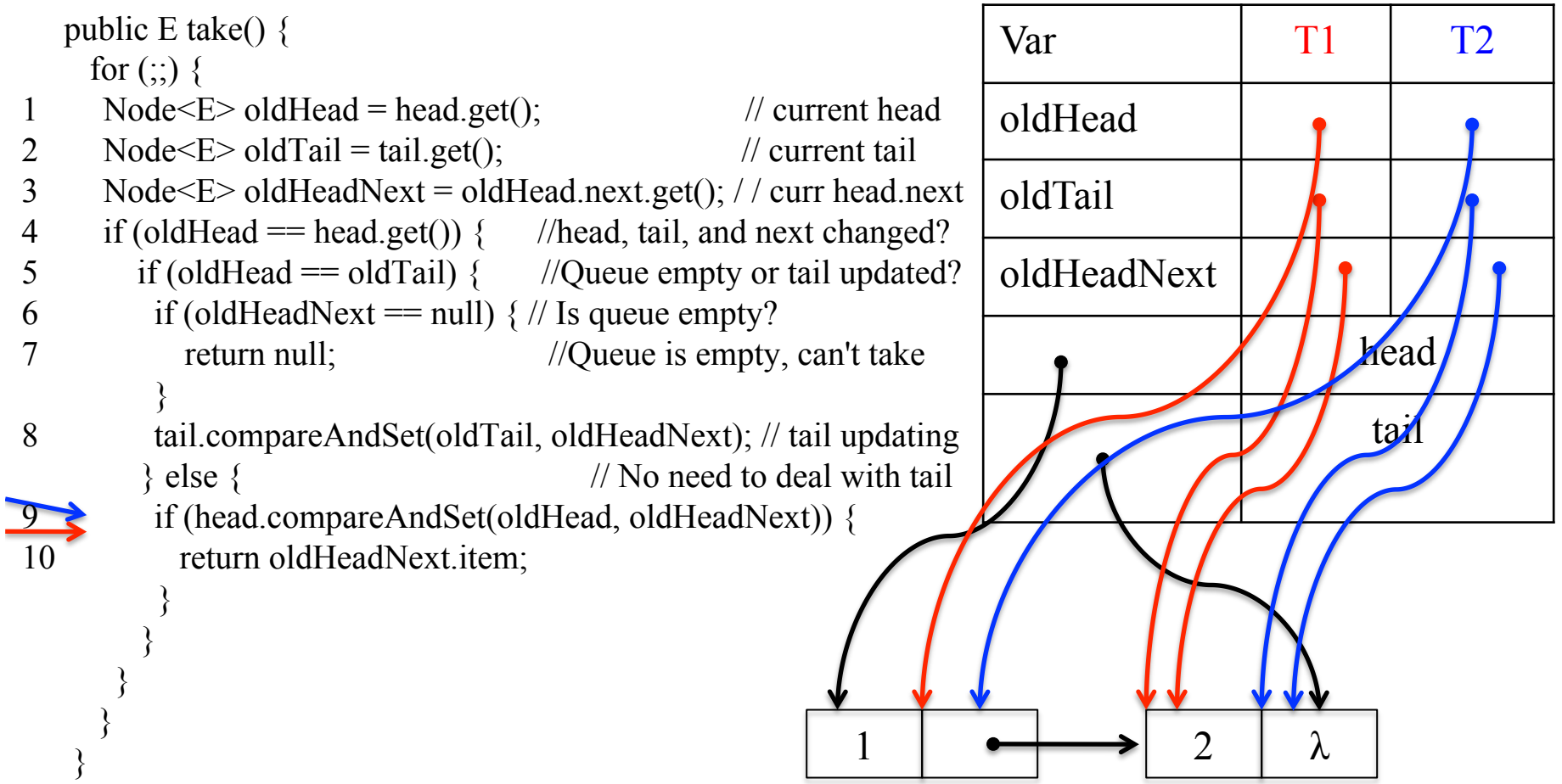
Trace 2

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



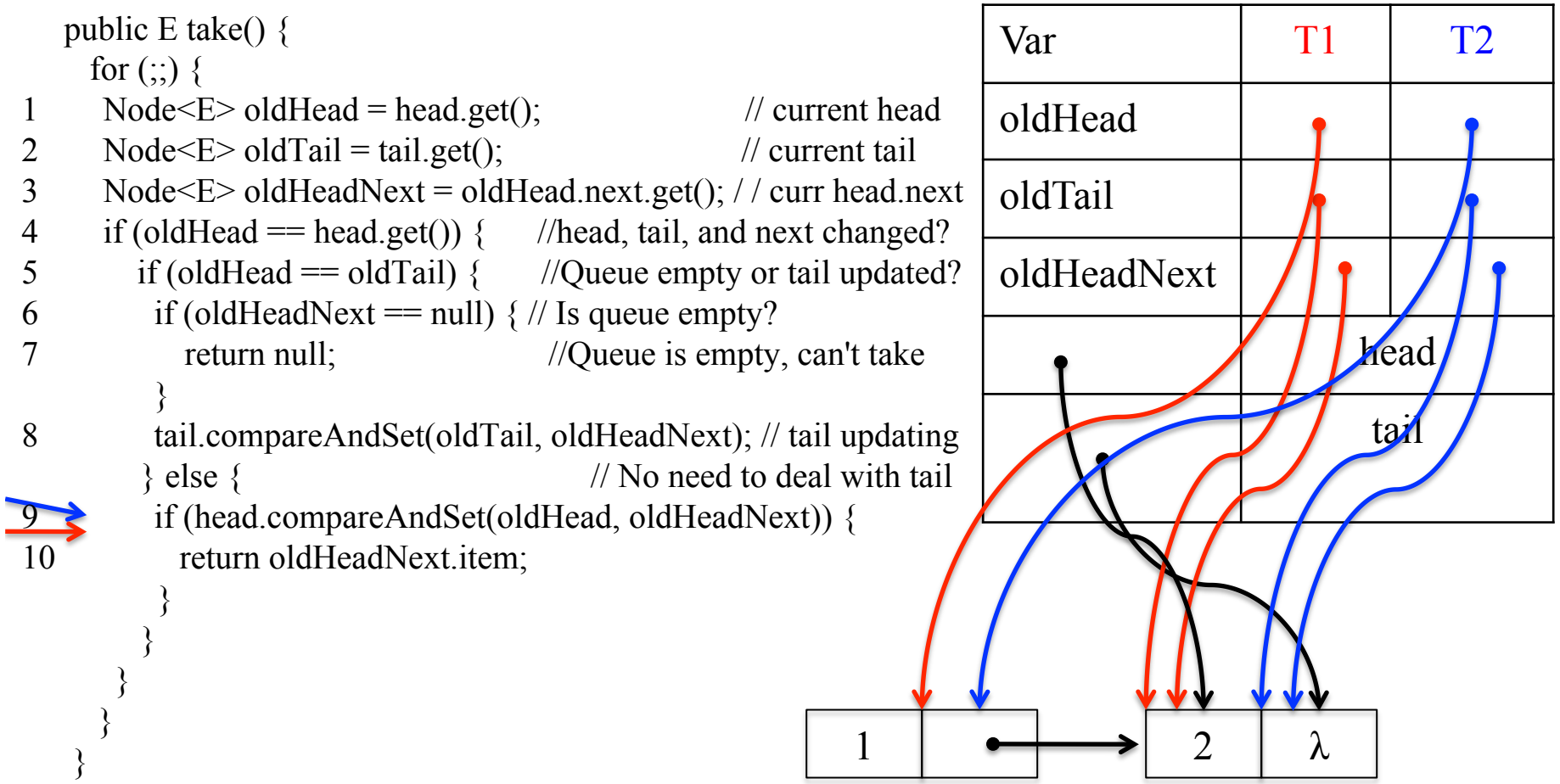
Trace 2: T1 wins, CAS succeeds

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



Trace 2: after CAS

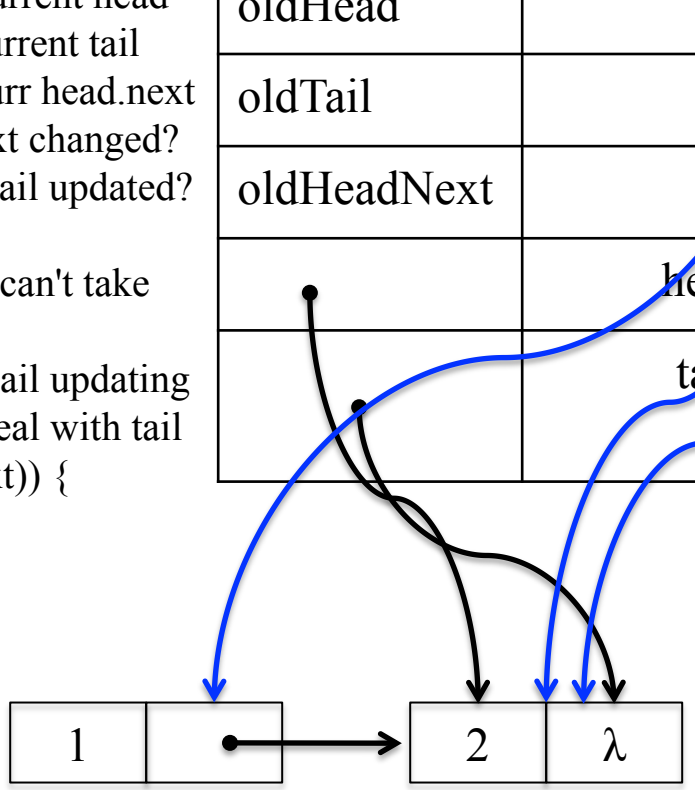
```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



Trace 2: T1 exits

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

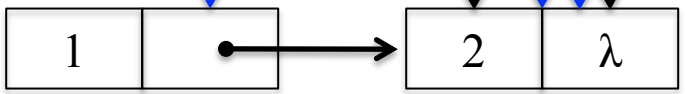
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



Trace 2: T2 continues, CAS fails

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

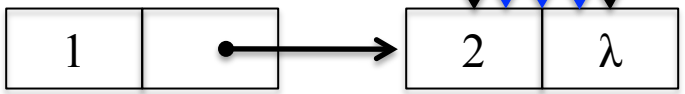
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



Trace 2: T2 continues, retry

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

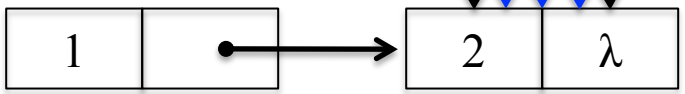
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



Trace 2: T2 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

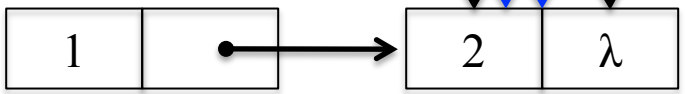
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



Trace 2: T2 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

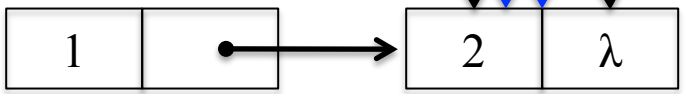
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		λ
	head	
	tail	



Trace 2: T2 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

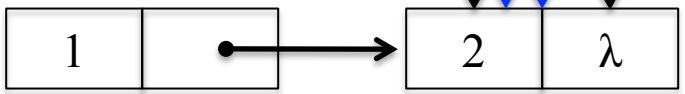
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		λ
	head	
	tail	



Trace 2: T2 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

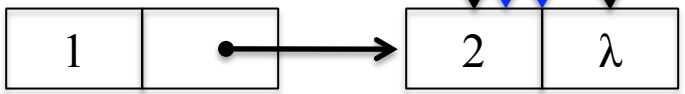
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		λ
	head	
	tail	



Trace 2: T2 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

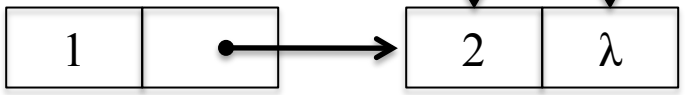
Var	T1	T2
oldHead		
oldTail		
oldHeadNext		λ
	head	
	tail	



Trace 2: T2 exits

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5          if (oldHead == oldTail) {      //Queue empty or tail updated?
6            if (oldHeadNext == null) { // Is queue empty?
7               return null;                //Queue is empty, can't take
             }
8            tail.compareAndSet(oldTail, oldHeadNext); // tail updating
           } else {                                  // No need to deal with tail
9            if (head.compareAndSet(oldHead, oldHeadNext)) {
10              return oldHeadNext.item;
             }
           }
        }
      }
    }
```

Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



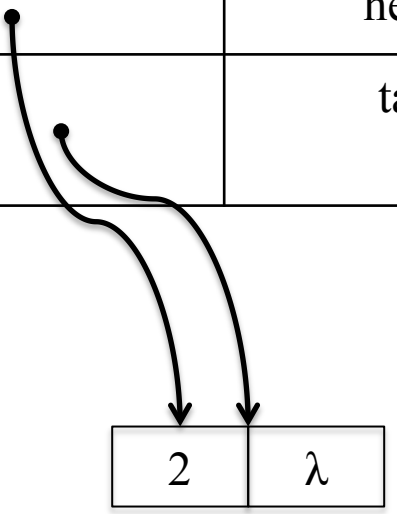
Execution Traces

- 1thread calls take()
- 1 thread calls put()

Trace 1

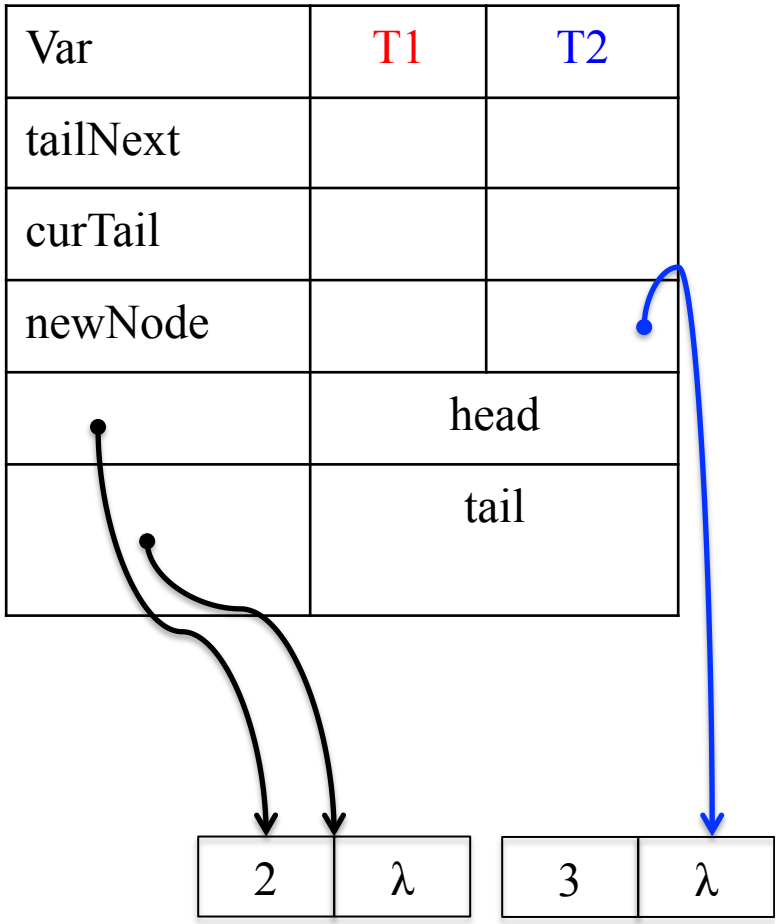
```
    public E take() {
    for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5          if (oldHead == oldTail) {       //Queue empty or tail updated?
6            if (oldHeadNext == null) { // Is queue empty?
7               return null;                  //Queue is empty, can't take
             }
8            tail.compareAndSet(oldTail, oldHeadNext); // tail updating
           } else {                                  // No need to deal with tail
9            if (head.compareAndSet(oldHead, oldHeadNext)) {
10              return oldHeadNext.item;
             }
           }
        }
      }
    }
```

Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



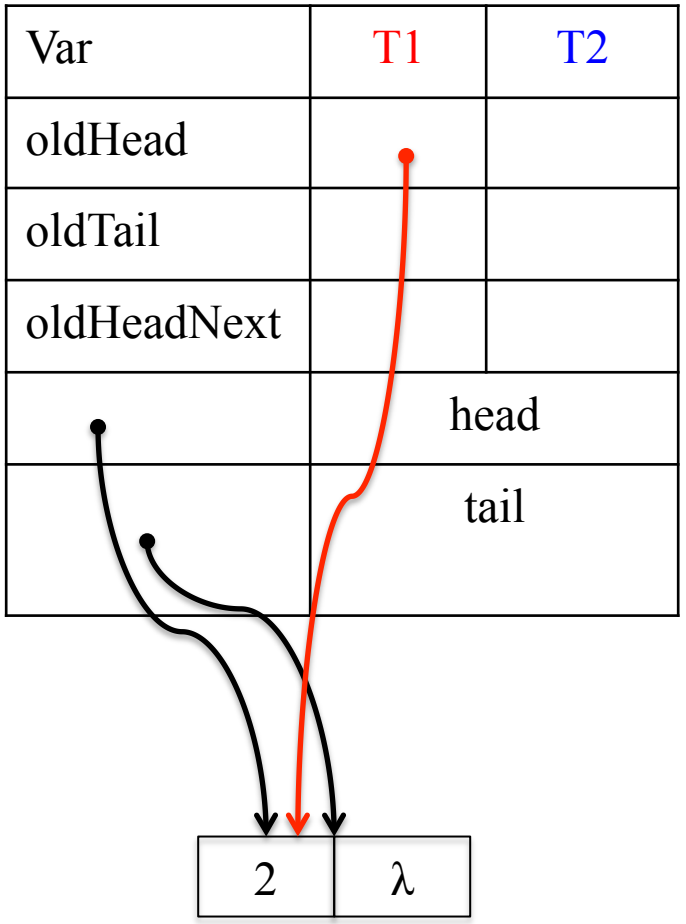
Trace 1

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



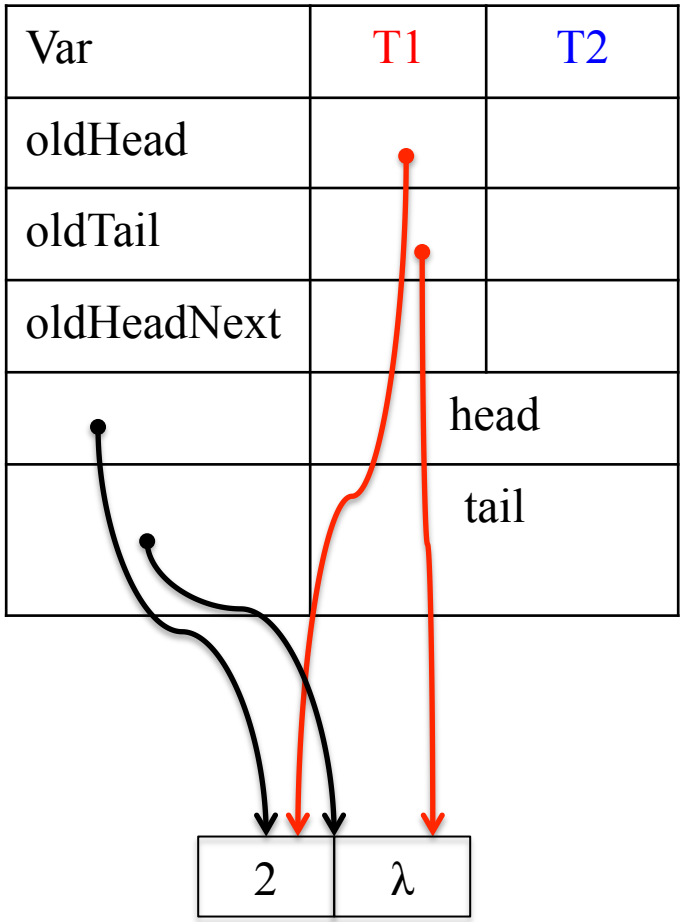
Trace 1: T1 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



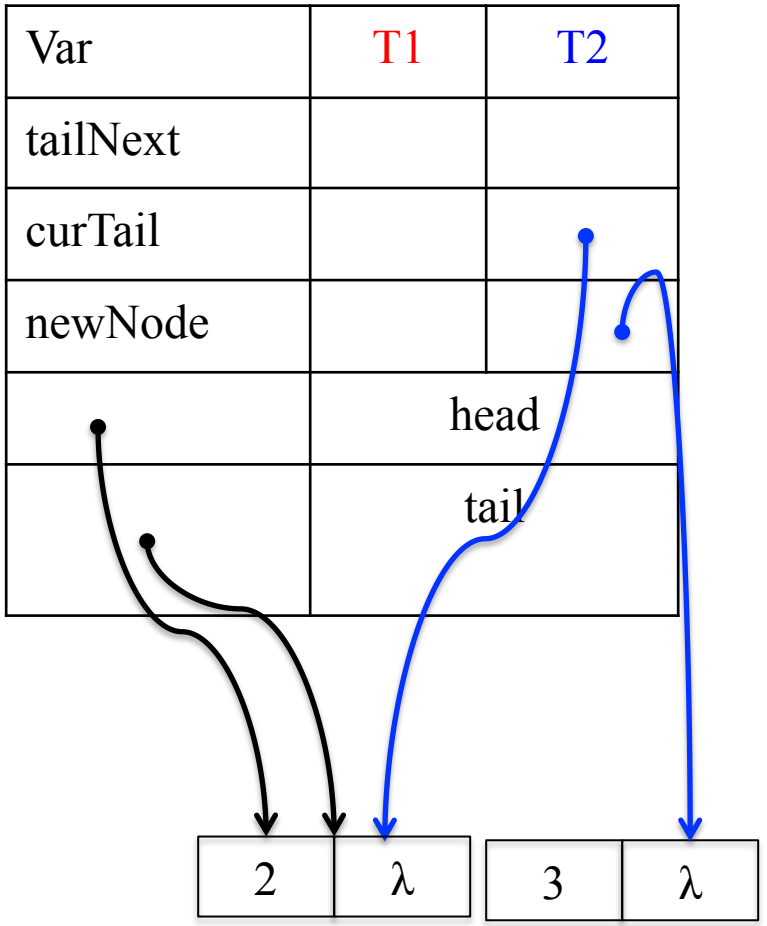
Trace 1: T1 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



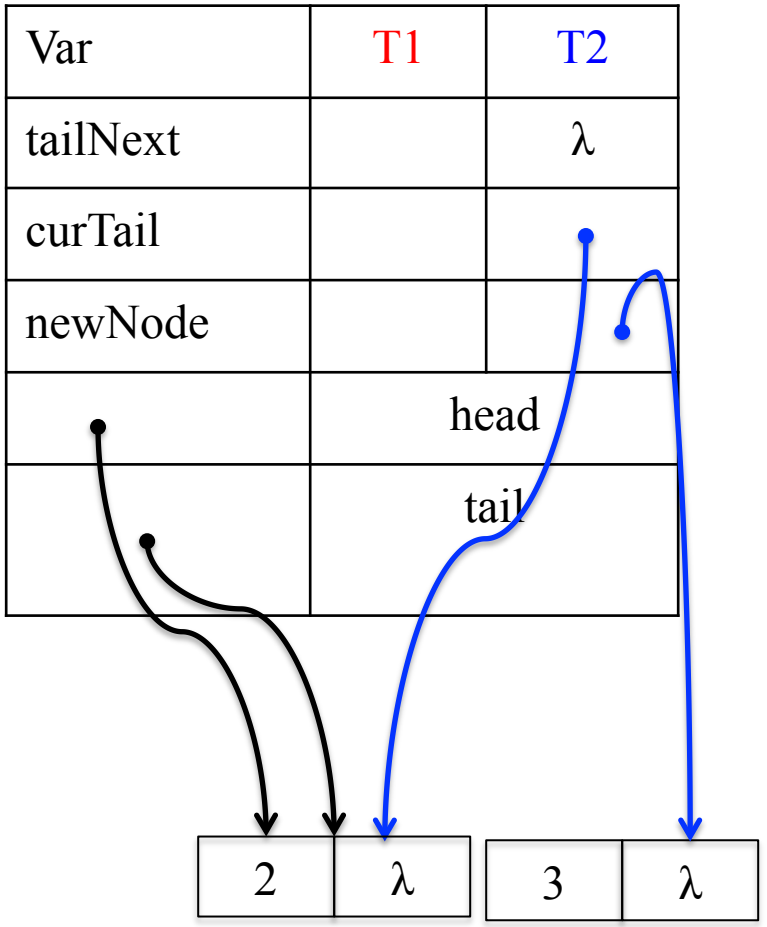
Trace 1: T2 continues

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



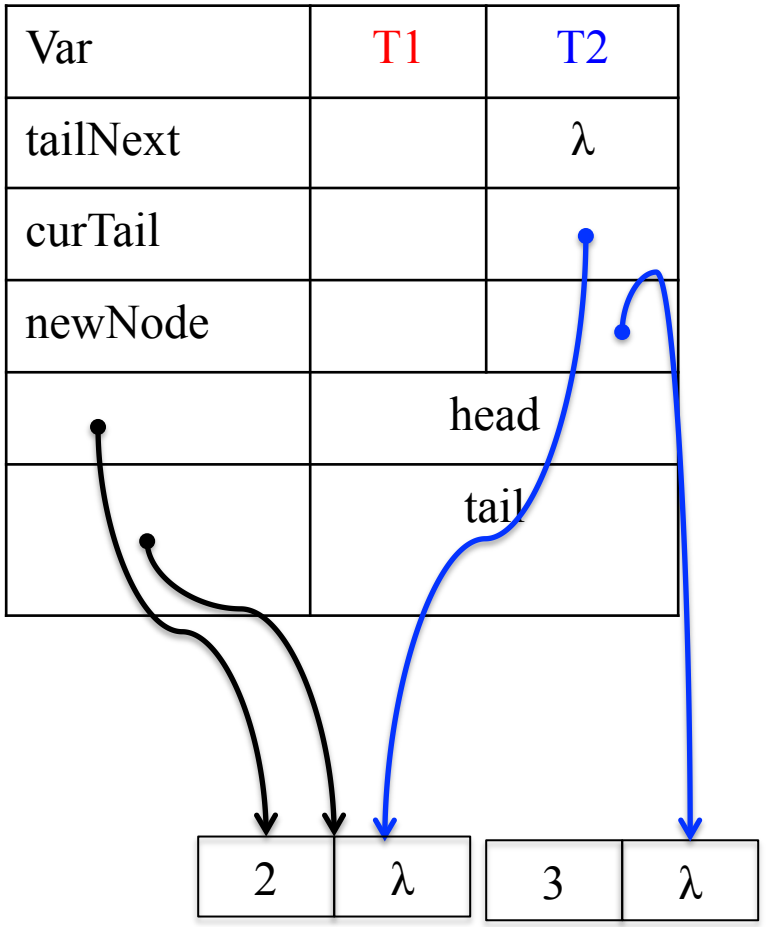
Trace 1: T2 continues

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



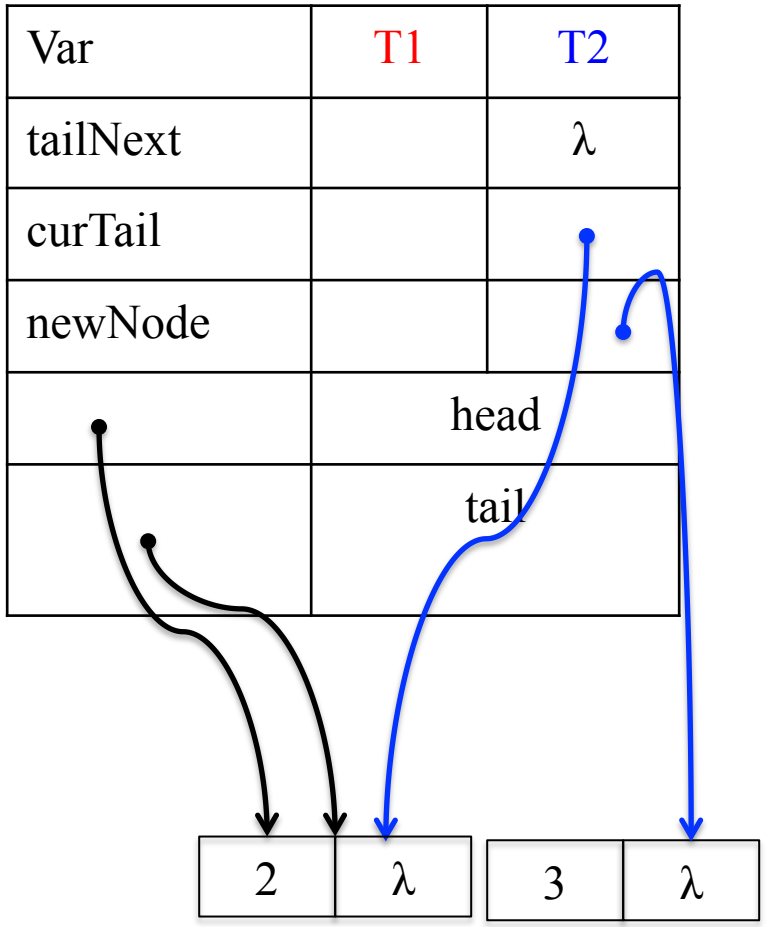
Trace 1: T2 continues

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



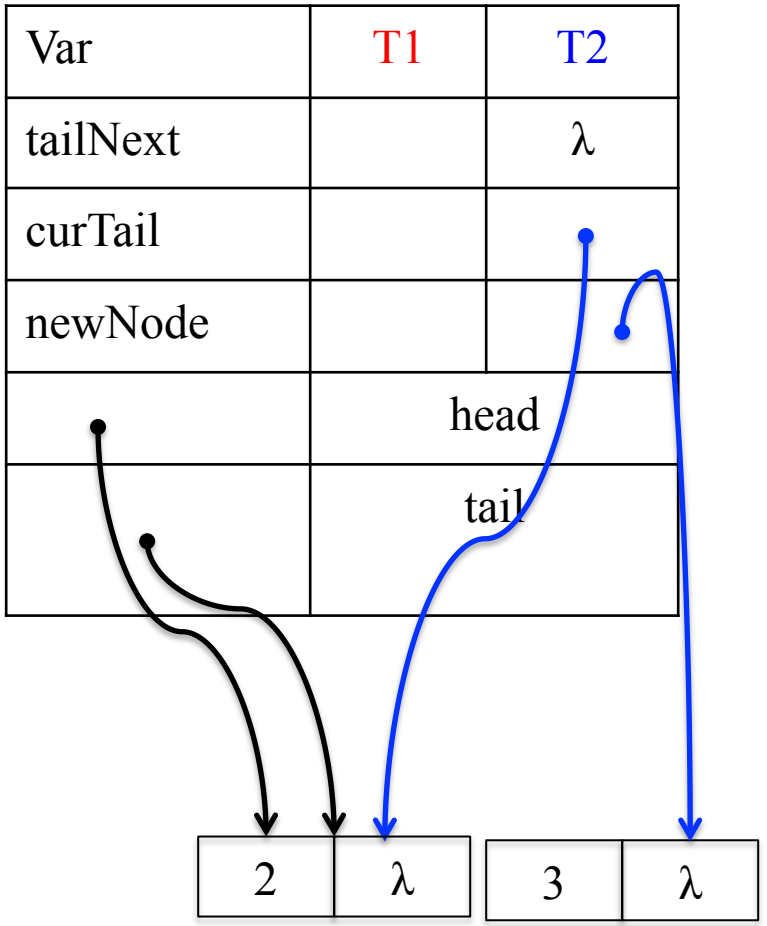
Trace 1: T2 continues

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



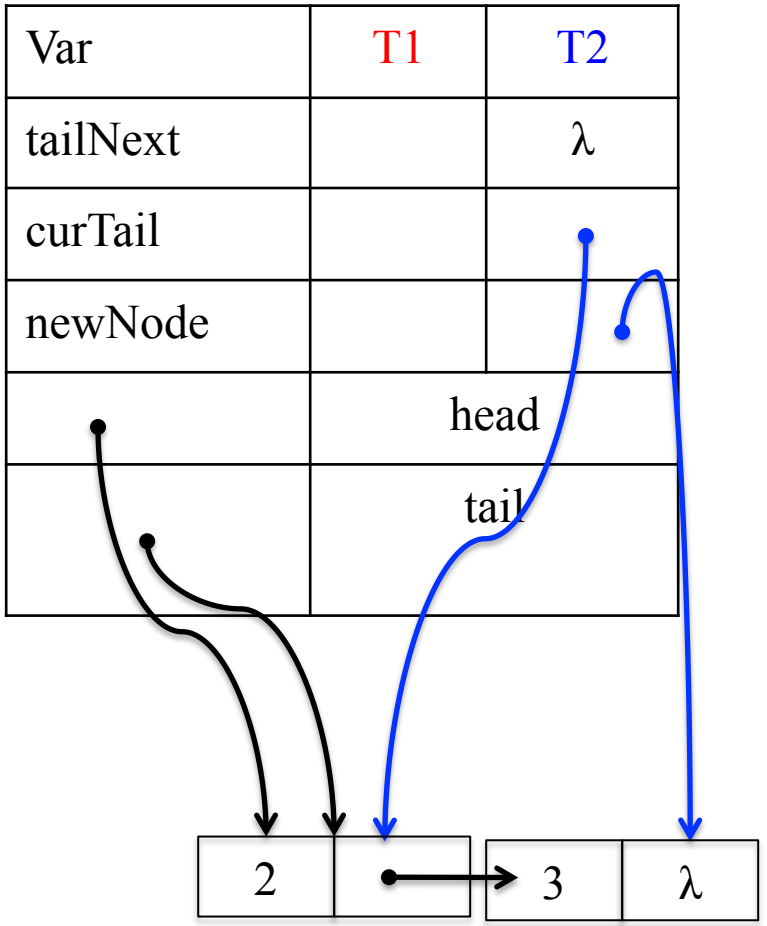
Trace 1: CAS succeeds

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



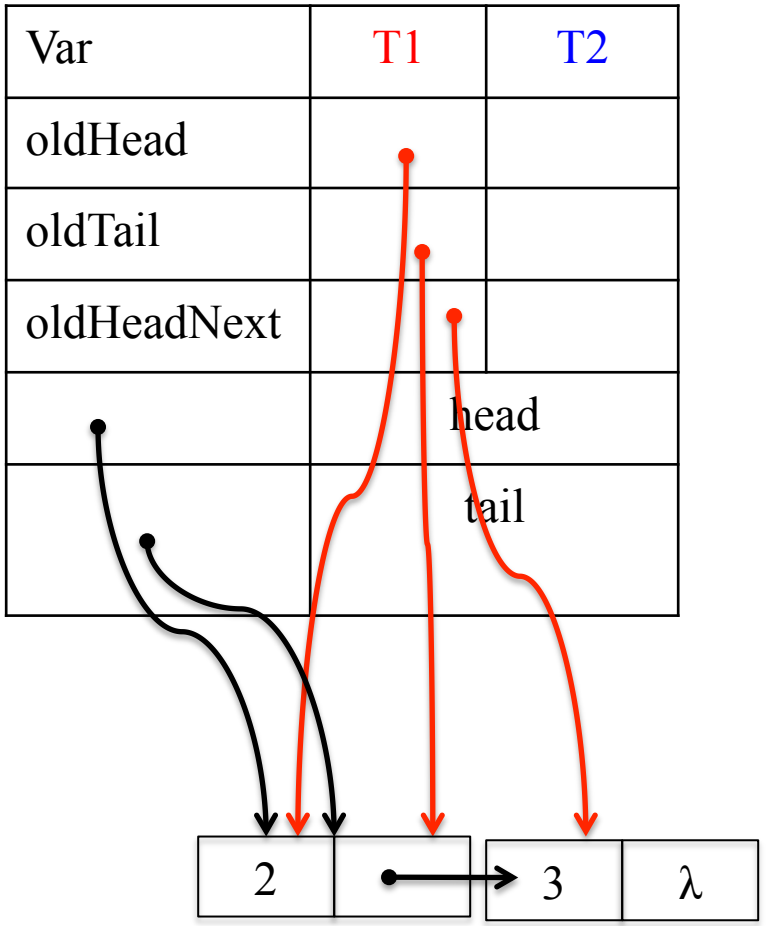
Trace 1: after CAS

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```



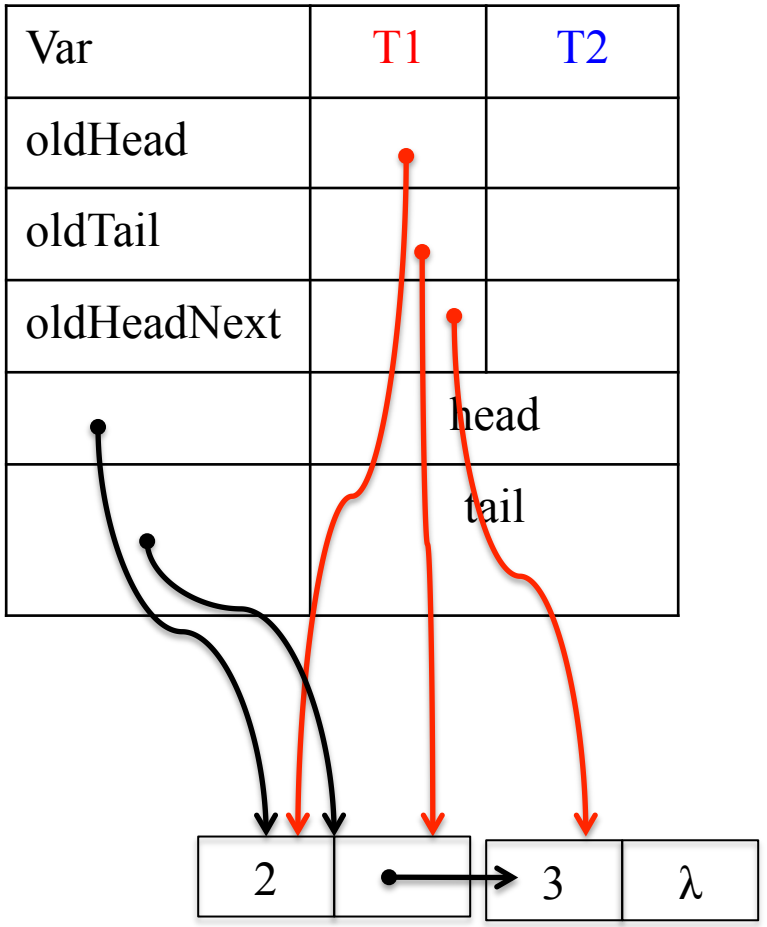
Trace 1: T1 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



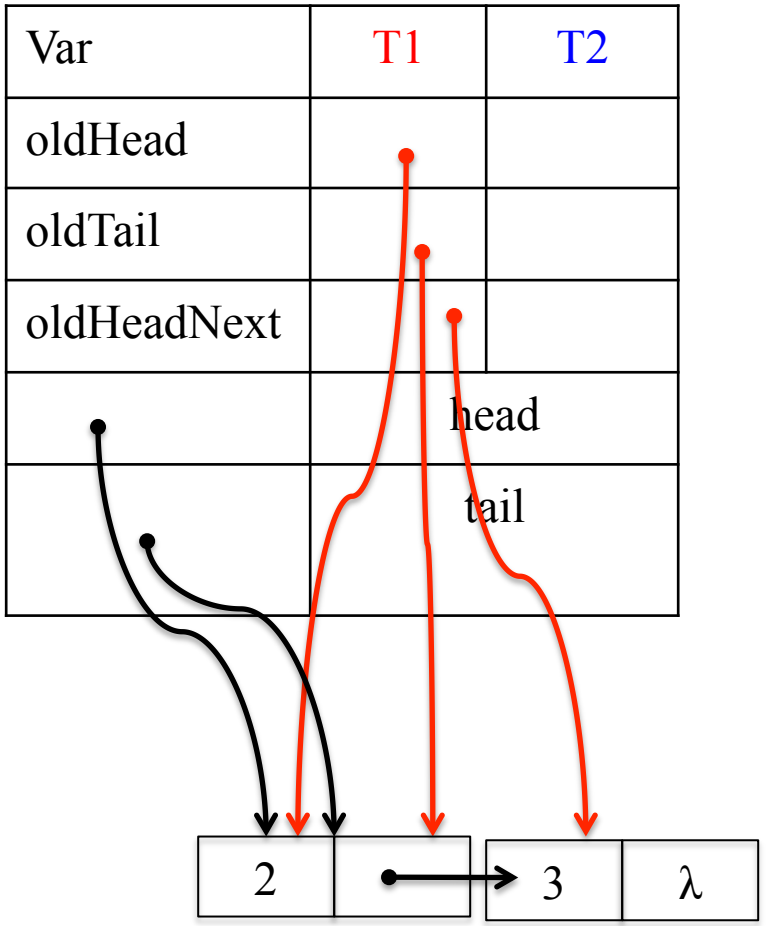
Trace 1: T1 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



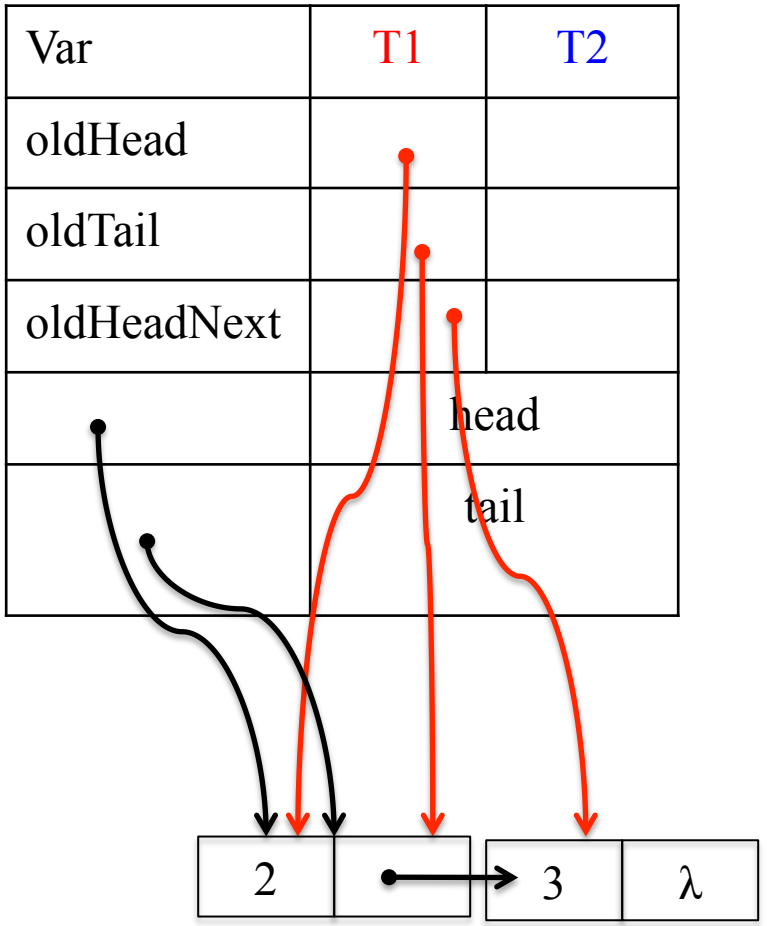
Trace 1: T1 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



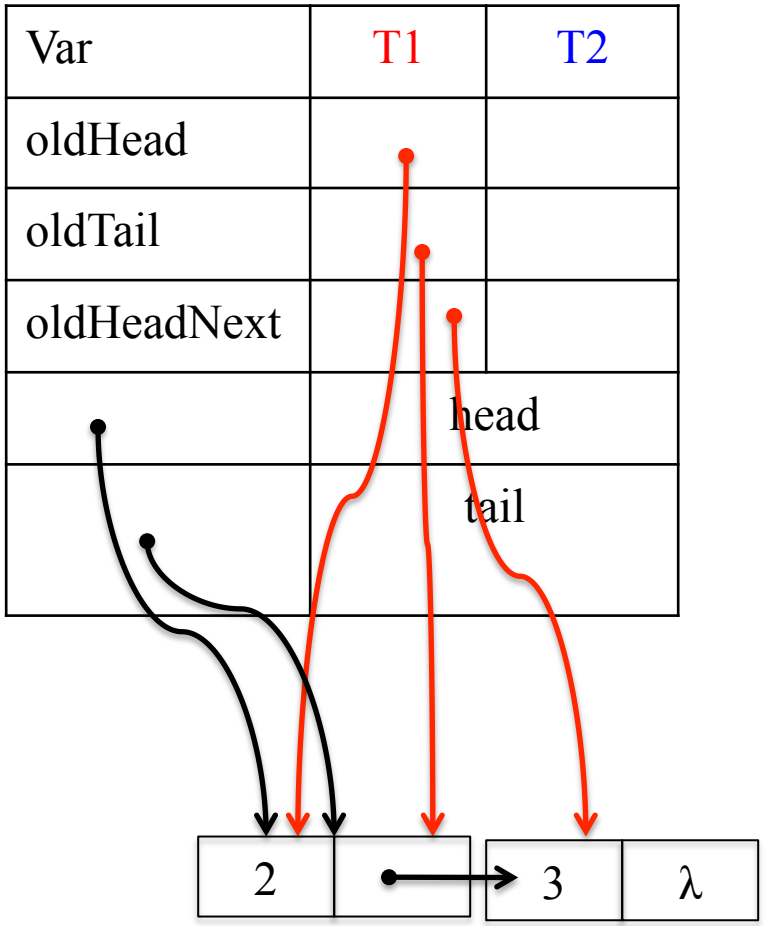
Trace 1: T1 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



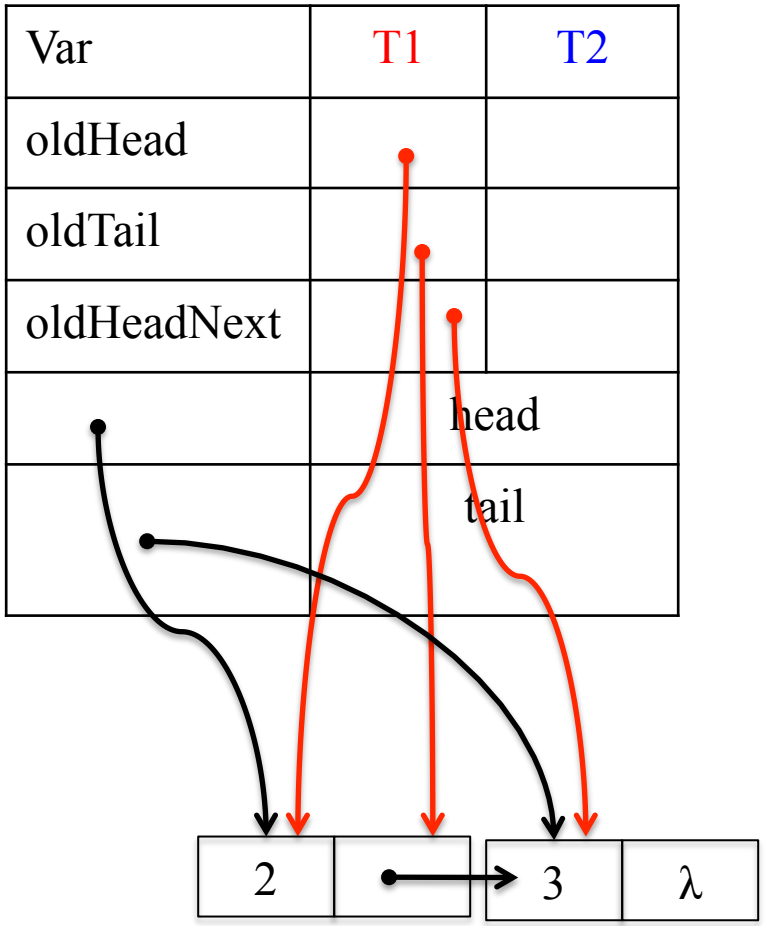
Trace 1: CAS succeeds

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



Trace 1: after CAS

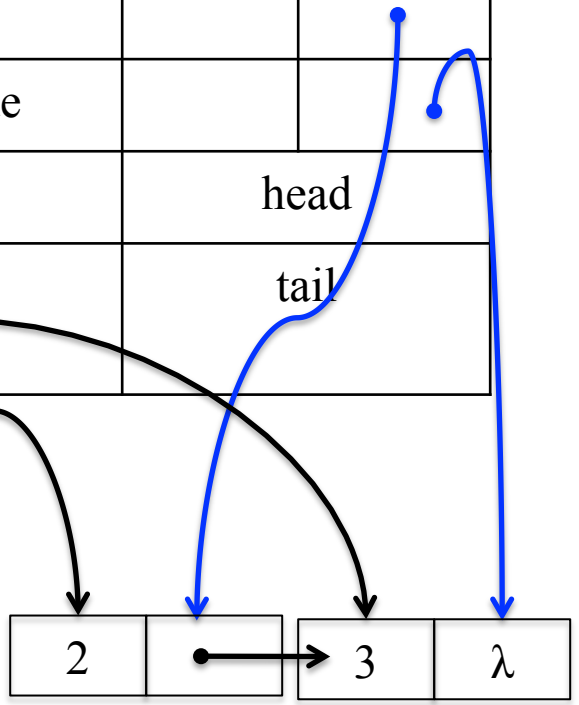
```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



Trace 1: T2 continues & CAS fails

```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```

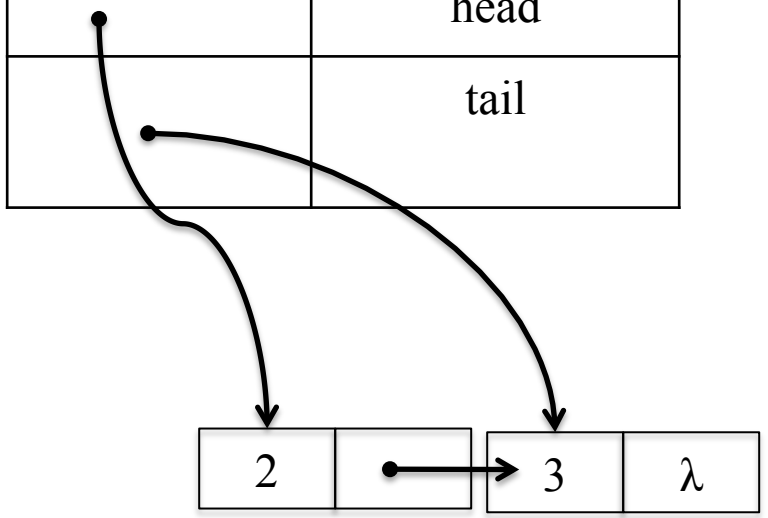
Var	T1	T2
tailNext		λ
curTail		
newNode		
	head	
	tail	



Trace 1: T2 exits

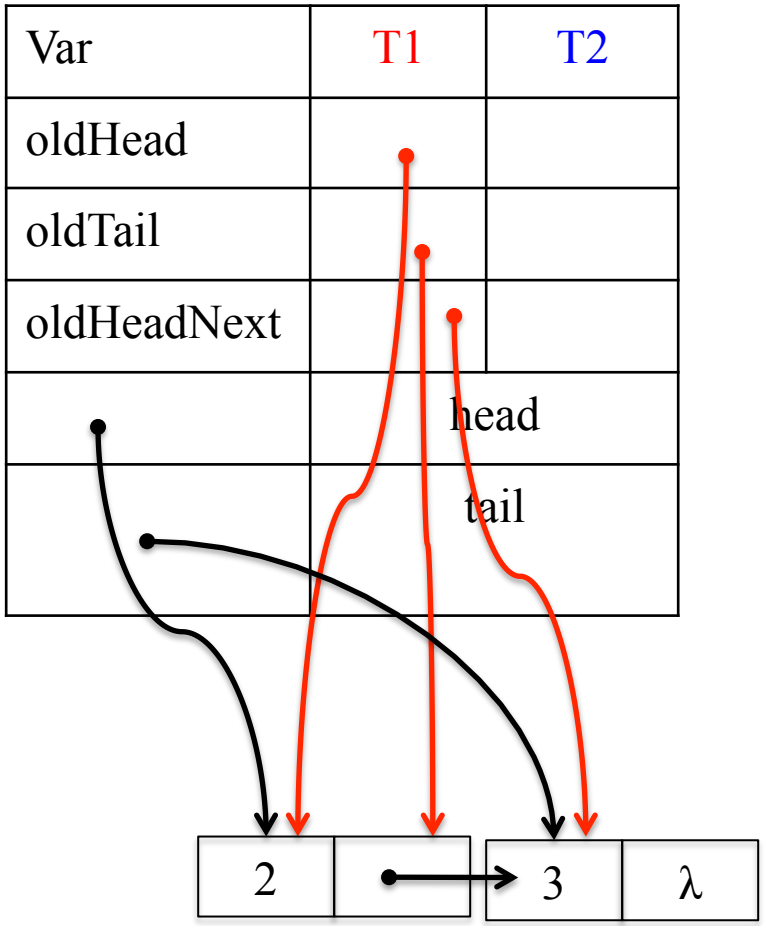
```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
7           tail.compareAndSet(curTail, tailNext);
8         else {  // In quiescent state, try inserting new node
9           if (curTail.next.compareAndSet(null, newNode)) {
            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```

Var	T1	T2
tailNext		
curTail		
newNode		
	head	
	tail	



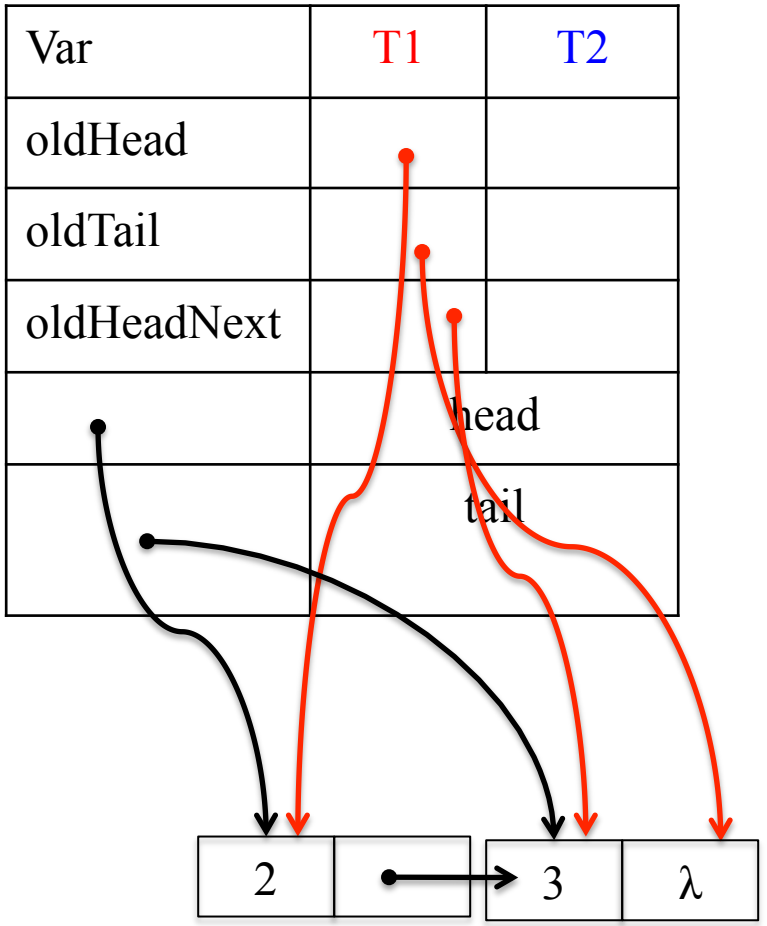
Trace 1: T1 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



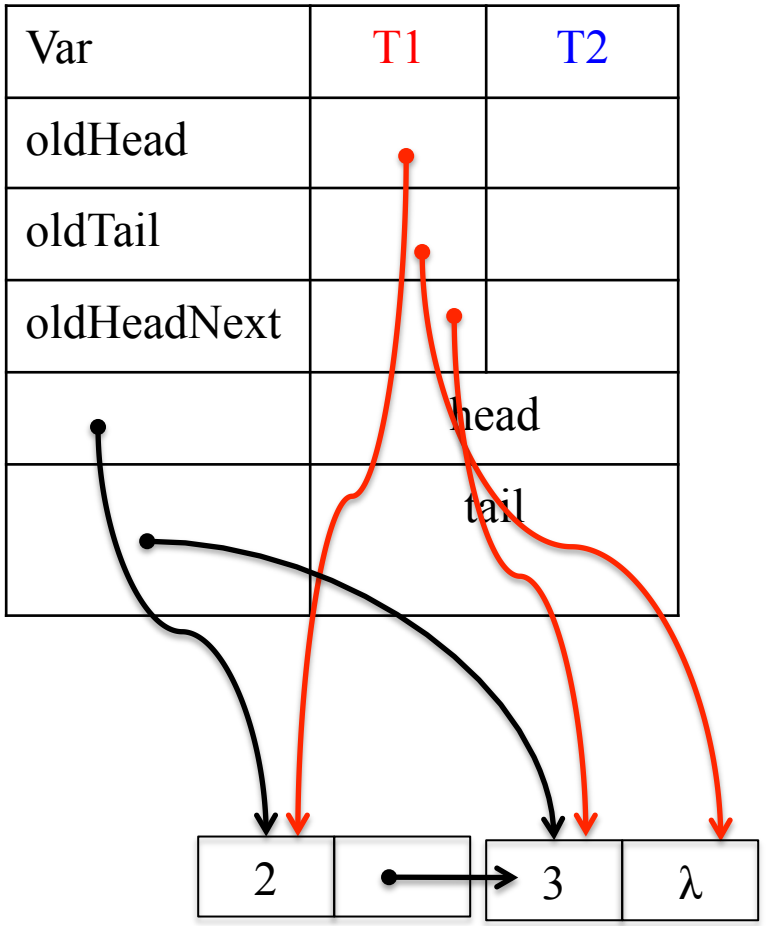
Trace 1: T1 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



Trace 1: T1 continues

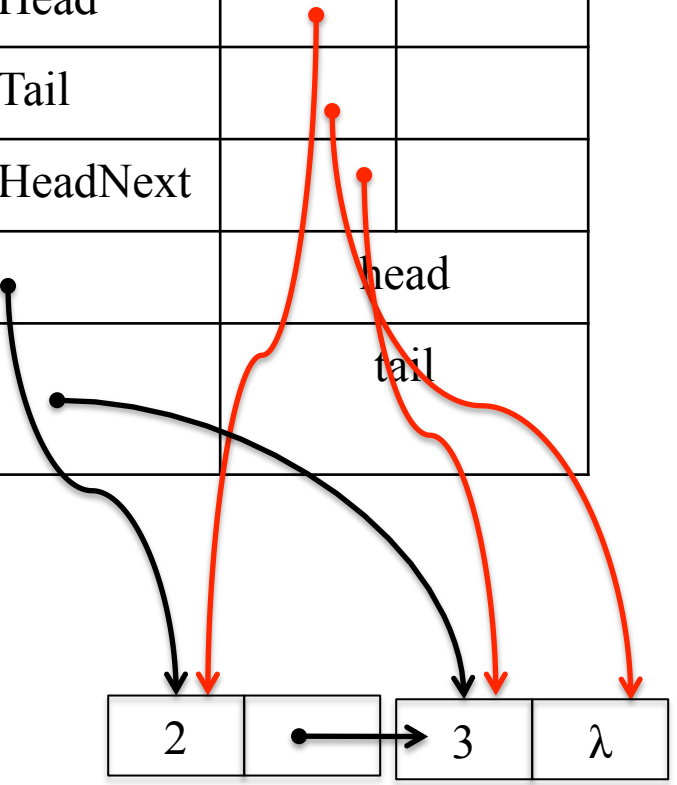
```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



Trace 1: T1 continues

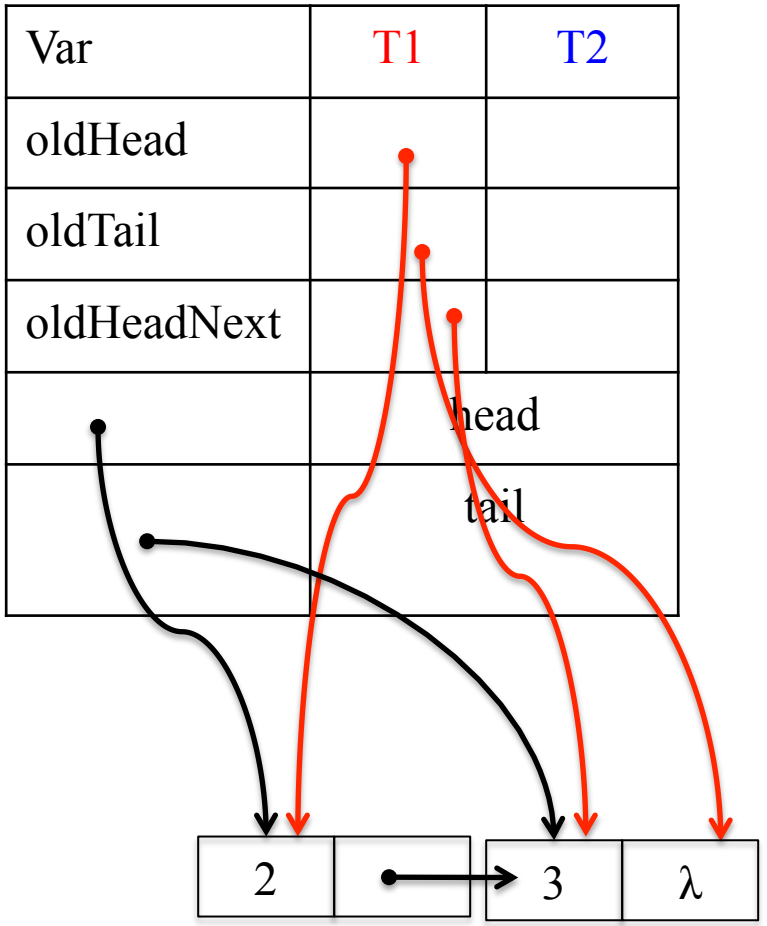
```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



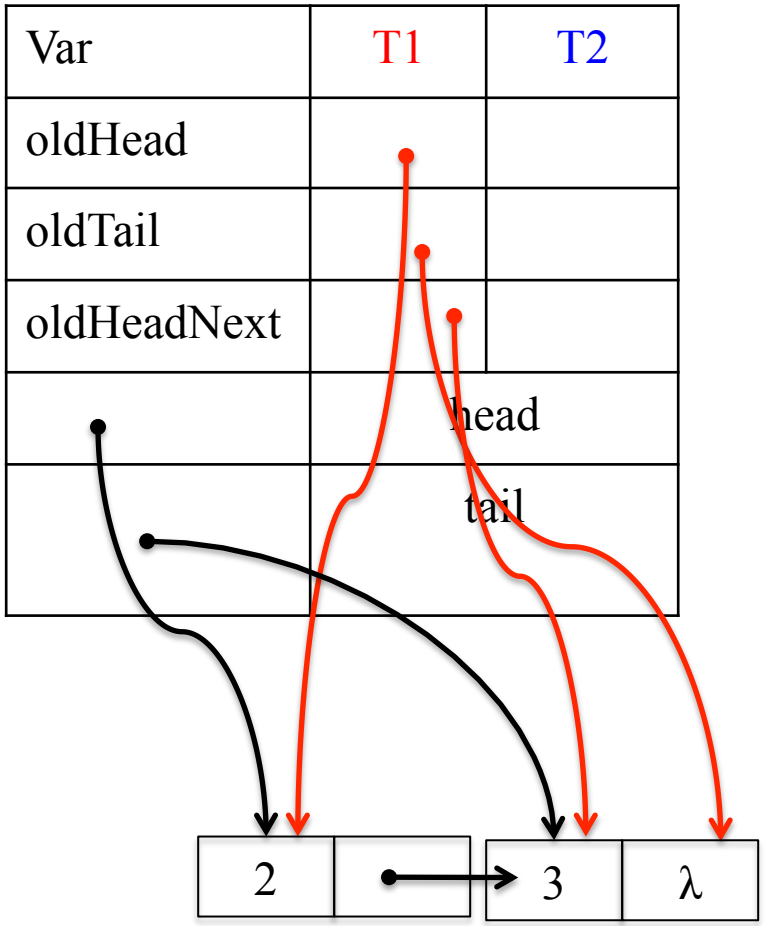
Trace 1: T1 continues

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



Trace 1: T1 CAS succeeds

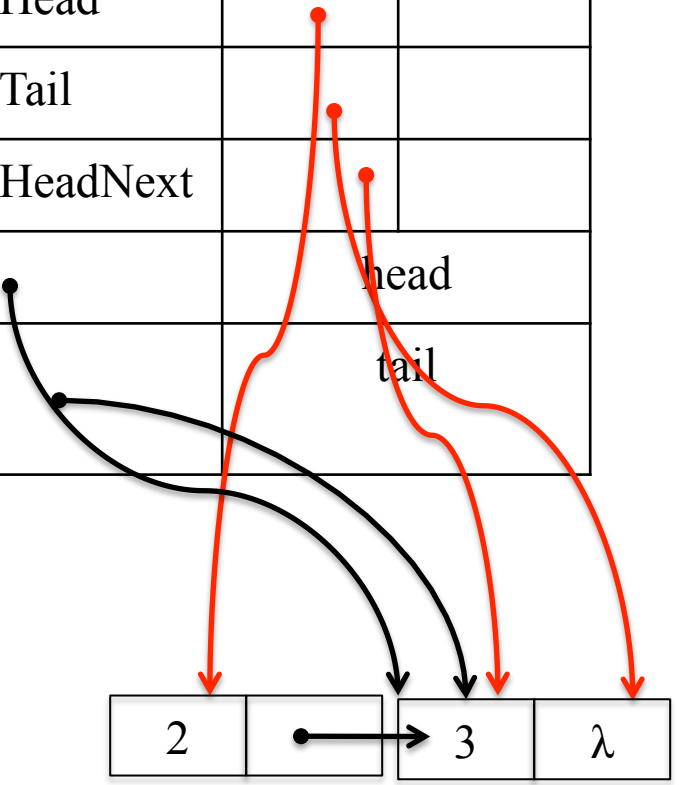
```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```



Trace 1: T1 after CAS

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5         if (oldHead == oldTail) {       //Queue empty or tail updated?
6           if (oldHeadNext == null) { // Is queue empty?
7             return null;                  //Queue is empty, can't take
            }
8           tail.compareAndSet(oldTail, oldHeadNext); // tail updating
          } else {                                  // No need to deal with tail
9           if (head.compareAndSet(oldHead, oldHeadNext)) {
10            return oldHeadNext.item;
            }
          }
        }
      }
    }
```

Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail	



Trace 1: T1 exits

```
    public E take() {
      for (;;) {
1       Node<E> oldHead = head.get();                    // current head
2       Node<E> oldTail = tail.get();                    // current tail
3       Node<E> oldHeadNext = oldHead.next.get(); / / curr head.next
4       if (oldHead == head.get()) {      //head, tail, and next changed?
5          if (oldHead == oldTail) {      //Queue empty or tail updated?
6            if (oldHeadNext == null) { // Is queue empty?
7               return null;                //Queue is empty, can't take
             }
8            tail.compareAndSet(oldTail, oldHeadNext); // tail updating
           } else {                                  // No need to deal with tail
9            if (head.compareAndSet(oldHead, oldHeadNext)) {
10              return oldHeadNext.item;
             }
           }
        }
      }
    }
```

Var	T1	T2
oldHead		
oldTail		
oldHeadNext		
	head	
	tail