Atomic Variables & Nonblocking Synchronization

CMSC 433

Fall 2013

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(with some slides due to Rance Cleaveland)

A Locking Counter

```
public final class Counter {
   private long value = 0;
   public synchronized long getValue() {
      return value;
  }

  public synchronized long increment() {
     return ++value;
  }
}
```

Java.util.concurrent Performance

- Many java.util.concurrent classes perform better then synchronized alternatives. Why?
  - Atomic variables & nonblocking synchronization
- We've already talked about atomic variables
- 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 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

Compare and Swap (CAS)

- CAS has 3 operands
  - Memory location V, expected value A, new value B
- Atomically updates V to value B, but only if current value is A
- If 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));
 }
}
```

Critical observation: uses == here to compare old and new values; not .equals() method call!

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;
   }
}
```

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

Atomic Variable Classes

- AtomicInteger
- AtomicLong
- AtomicBoolean
- AtomicReference<T>
  - set(), get() operations
  - getAndSet() atomicallys sets to new value, returns old value
  - Boolean compareAndSet(int expect, int new)
  - Arithmetic (increment, decrement) as appropriate
    - getAndAdd – return old value
    - addAndGet – return new value
    - getAndIncrement
    - incrementAndGet
- Also AtomicIntegerArray, AtomicLongArray, AtomicReferenceArray
  - Each element in array supports atomic operations

Updating Complex Objects

- Example: Want to manage two related variables
  - Can't do this with volatiles
- Idiom: 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

- Will show 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();}
  }
}
```

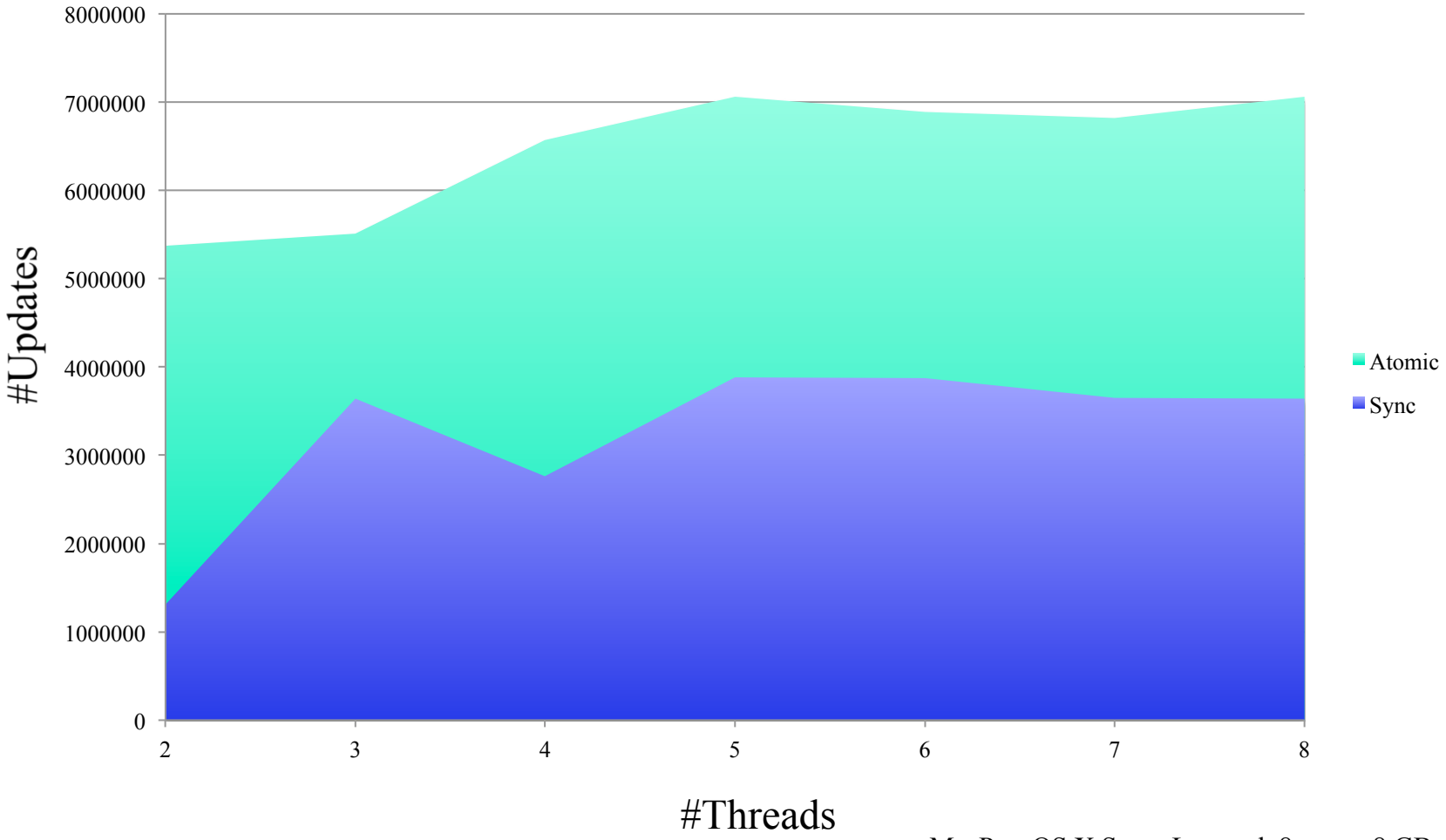
AtomicPseudoRandom

```
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;
      }
    }
  }
}
```

Nonblocking Algorithm Flavors

- Wait-Free
  - All threads complete in finite count of steps
  - Low priority threads cannot block high priority threads
- Lock-Free
  - Every successful step makes global progress
  - Individual threads may starve; priority inversion possible
  - No live-lock
- Obstruction-Free
  - A single thread in isolation completes in finite count of steps
  - Threads may block each other; live-lock possible
  - Example: optimistic retry

Comparing Performance



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

Nonblocking Algorithms

- No 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>>();

  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;
    }
}
```

Nonblocking Stack

- See: ConcurrentStack.java & SynchStack.java

A Nonblocking Queue

- Rule of thumb– 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

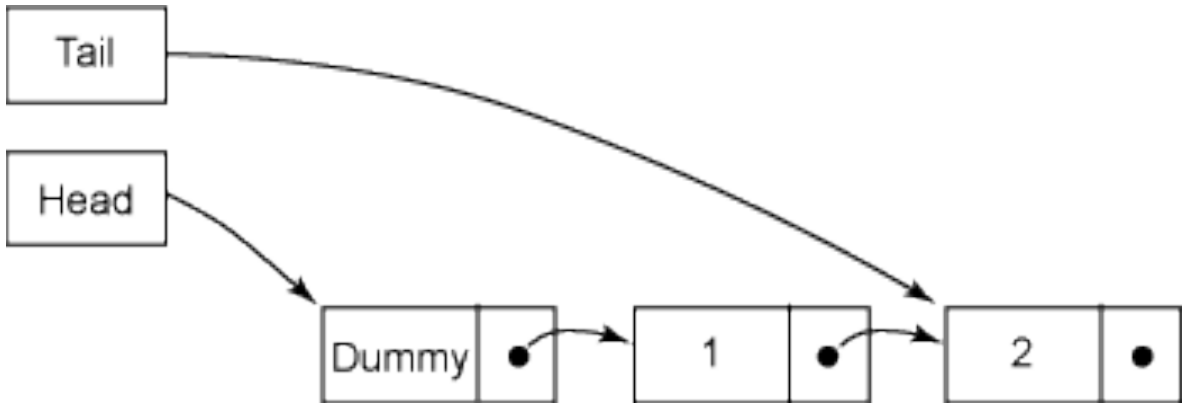
- Make sure queue is always in consistent state
- Threads should know whether another operation is is already in progress
  - Thread B can wait for thread A to finish before starting
- Prevents corruption, but late thread can fail if early thread fails

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

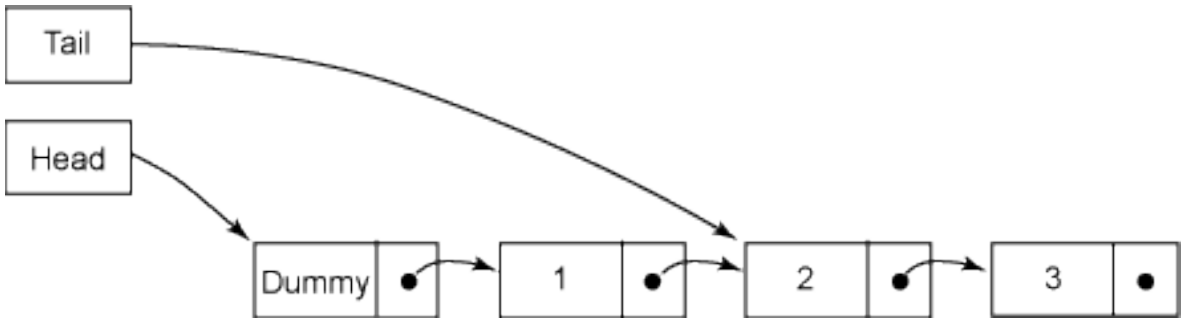
Michael & Scott Nonblocking Queue

- Queue with two elements in quiescent state



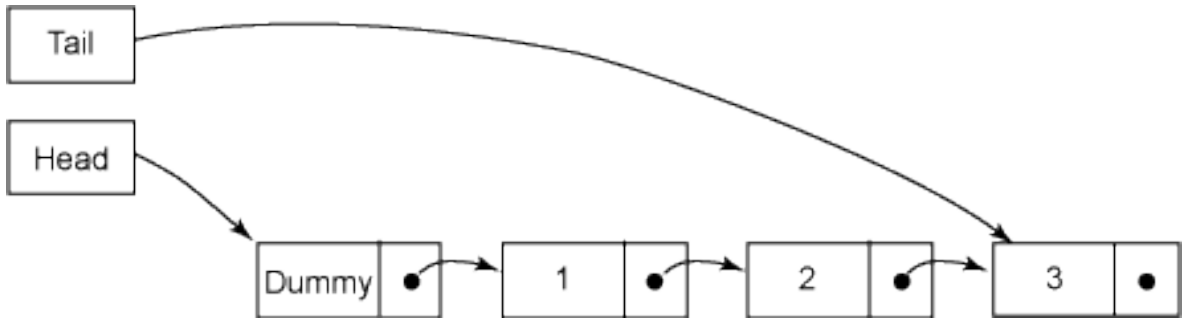
Michael & Scott Nonblocking Queue

- 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 operation is in progress
- If a thread finds an 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;
                }
            }
        }
    }
}
```

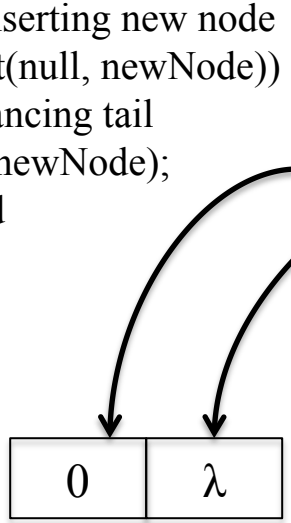
ConcurrentQueue

```
public E take() {
    for (;;) {                                              // # Keep trying until take is done
      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()) {                          // Are head, tail, and next consistent?
         if (oldHead == oldTail) {                          // Queue empty or tail being updated?
            if (oldHeadNext == null)                        // Is queue empty?
               return null; // Queue is empty, can't take
            tail.compareAndSet(oldTail, oldHeadNext);  // tail updated. try to advance it
       } else {                                             // No need to deal with tail
            if (head.compareAndSet(oldHead, oldHeadNext))
                        return oldHeadNext.item;
       }
     }
  }
```

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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         }
       }
     }
   }
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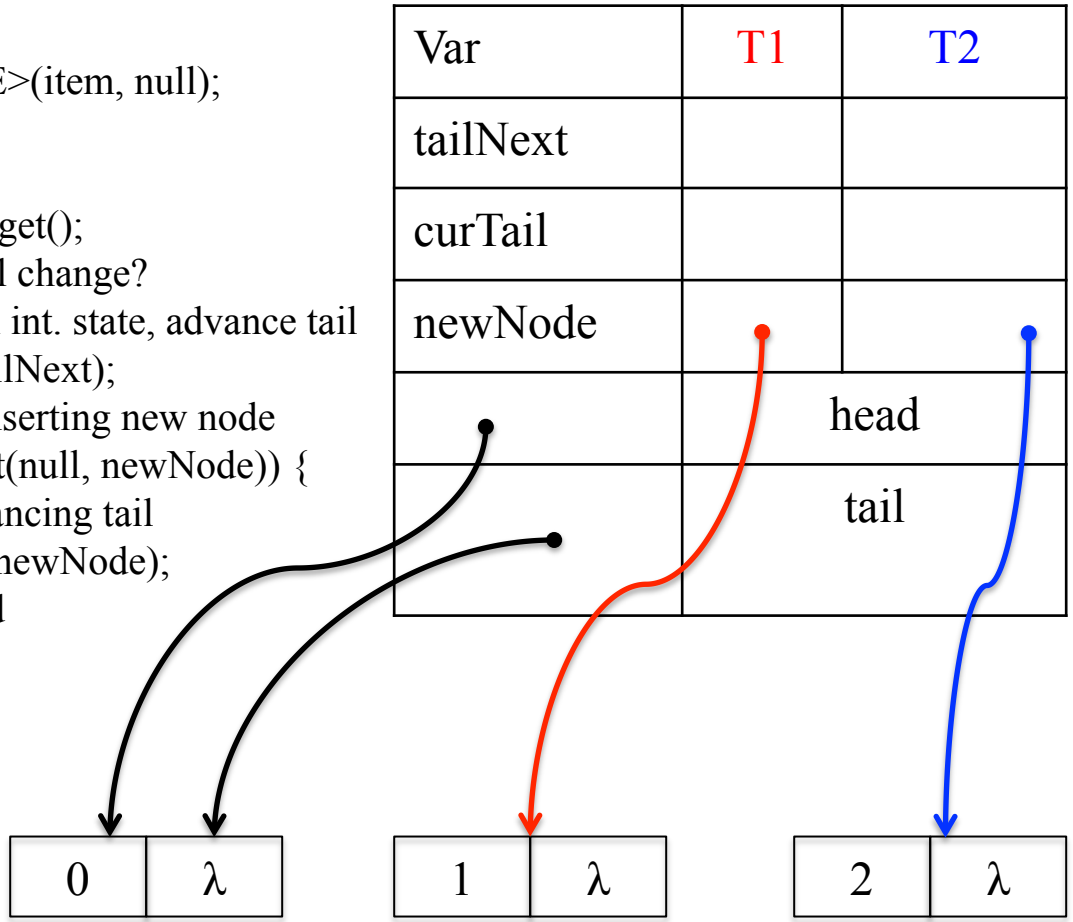

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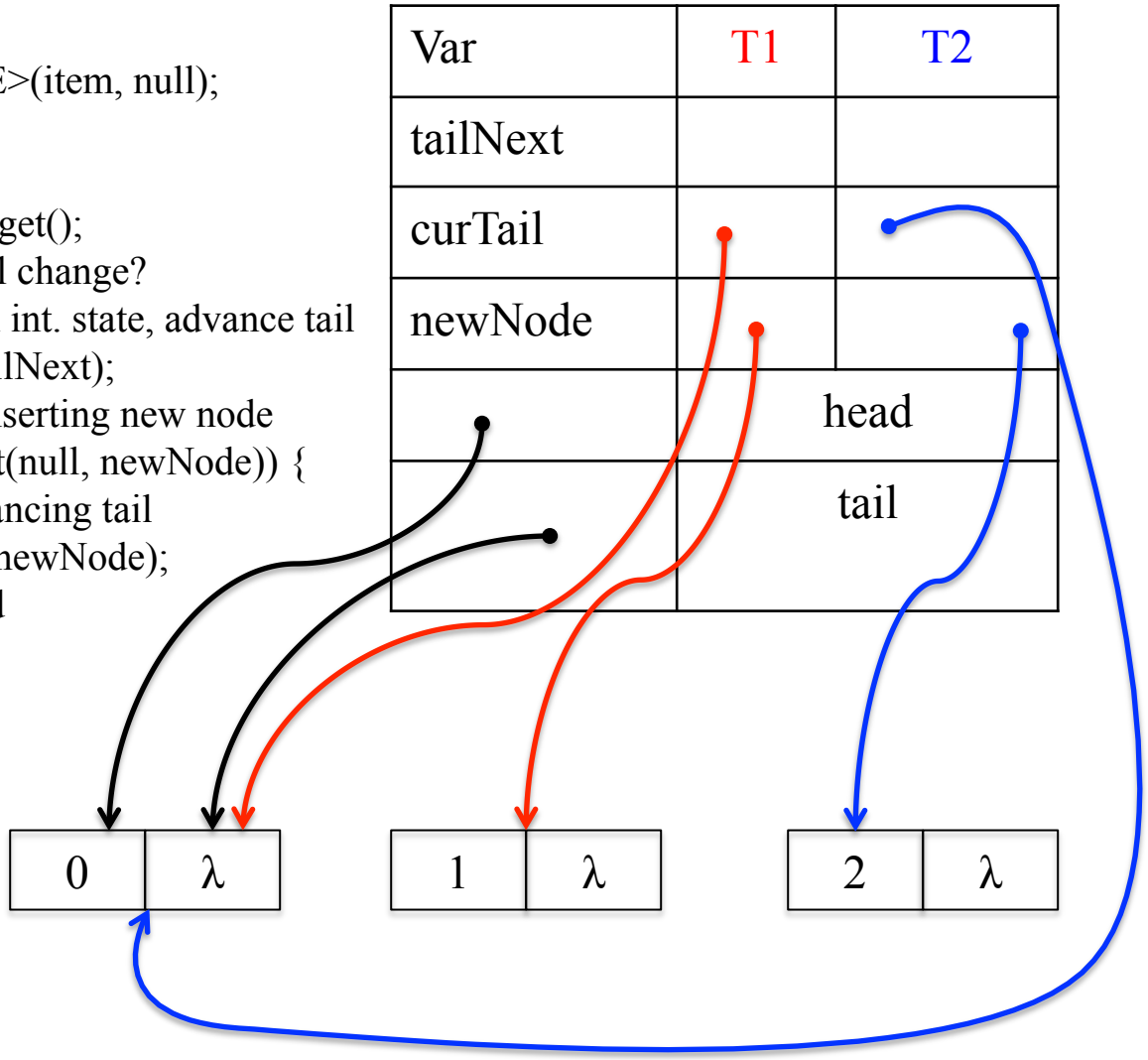

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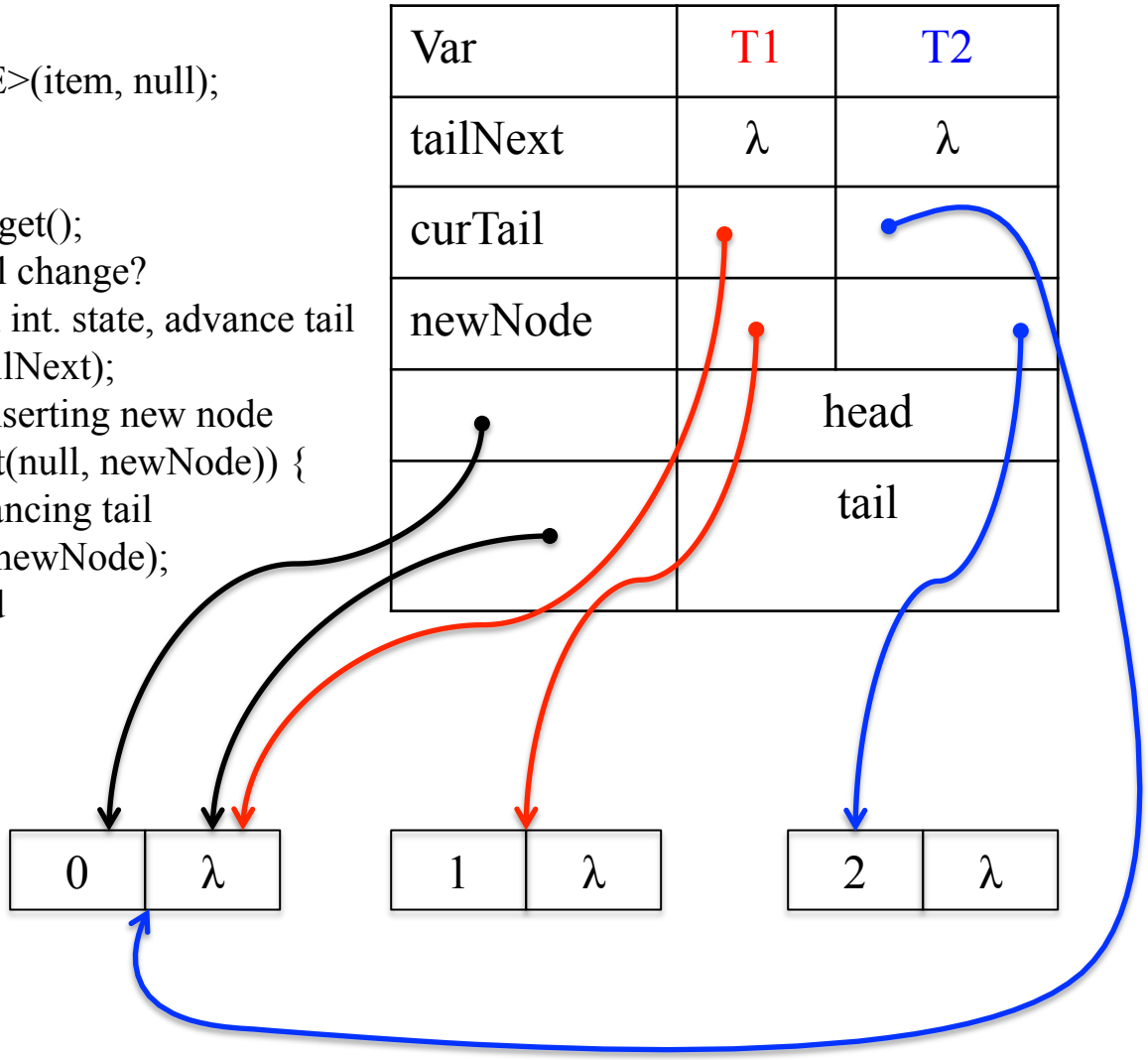

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11          return true;
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        }
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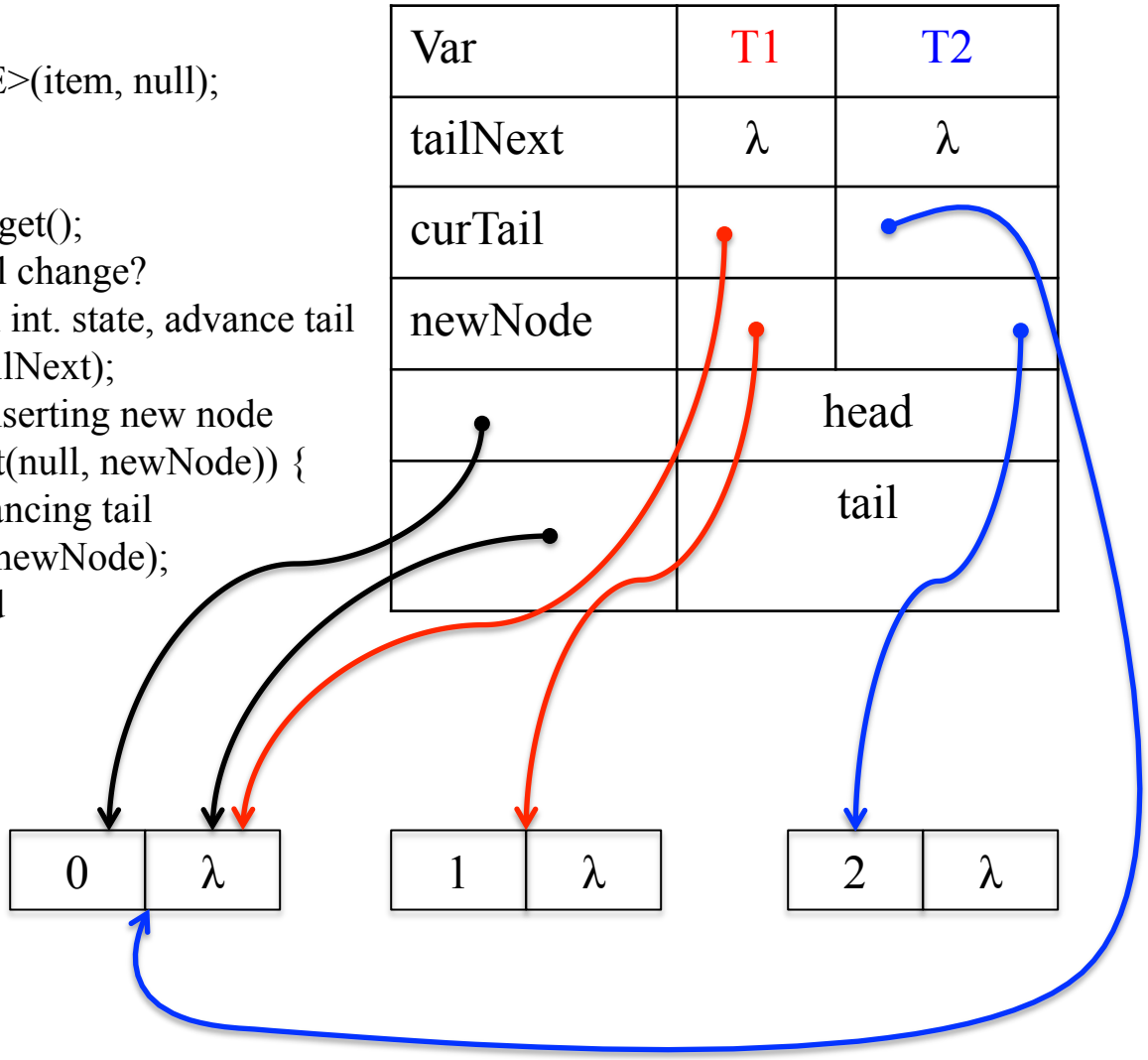
```



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5       if (curTail == tail.get()) {// did tail change?
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            // Insertion succeeded, try advancing tail
10            tail.compareAndSet(curTail, newNode);
            // will fail if tail already moved
11          return true;
            }
          }
        }
      }
    }
```

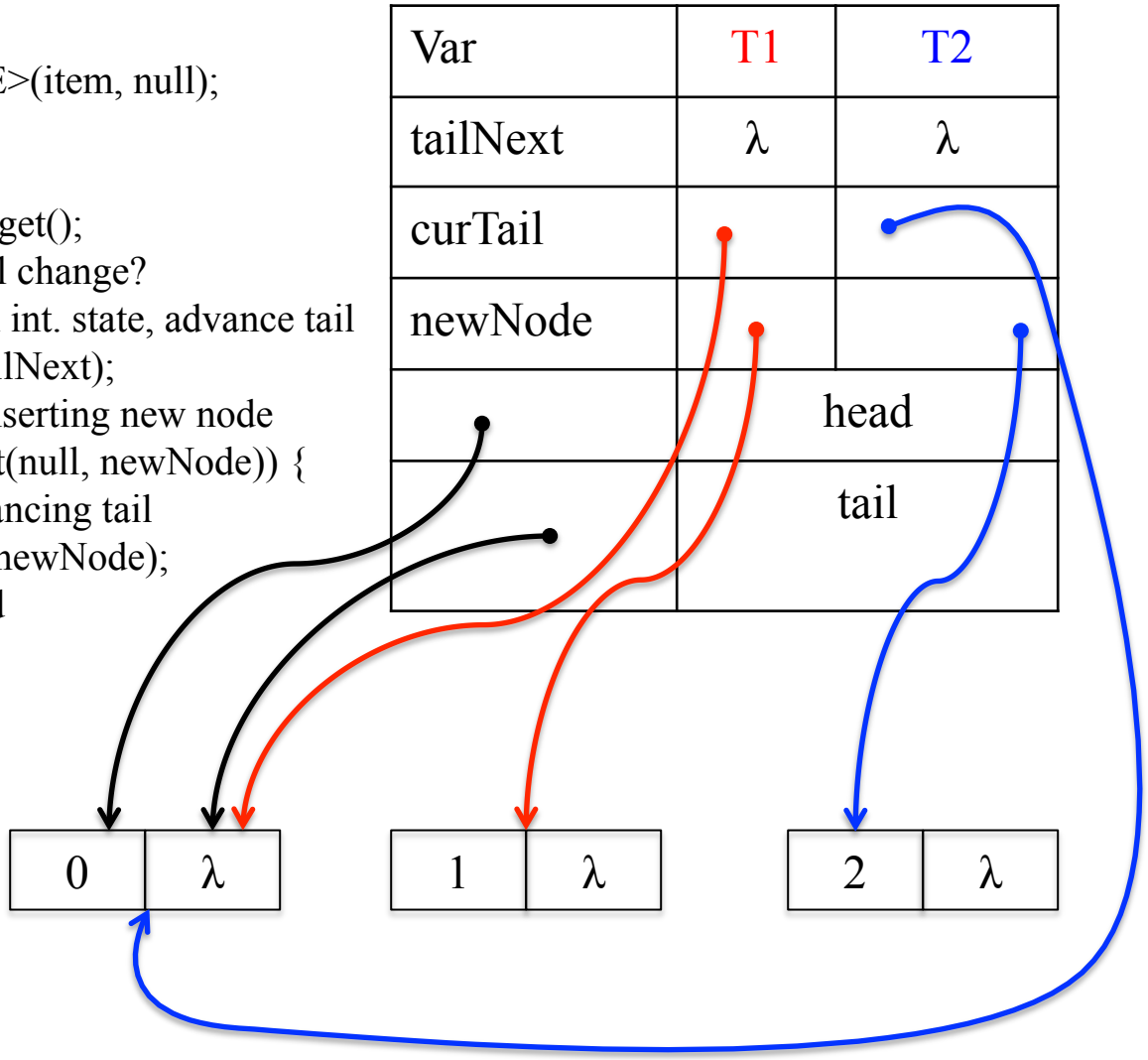

Trace 1: T1 wins

```
    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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            }
          }
        }
      }
    }
```

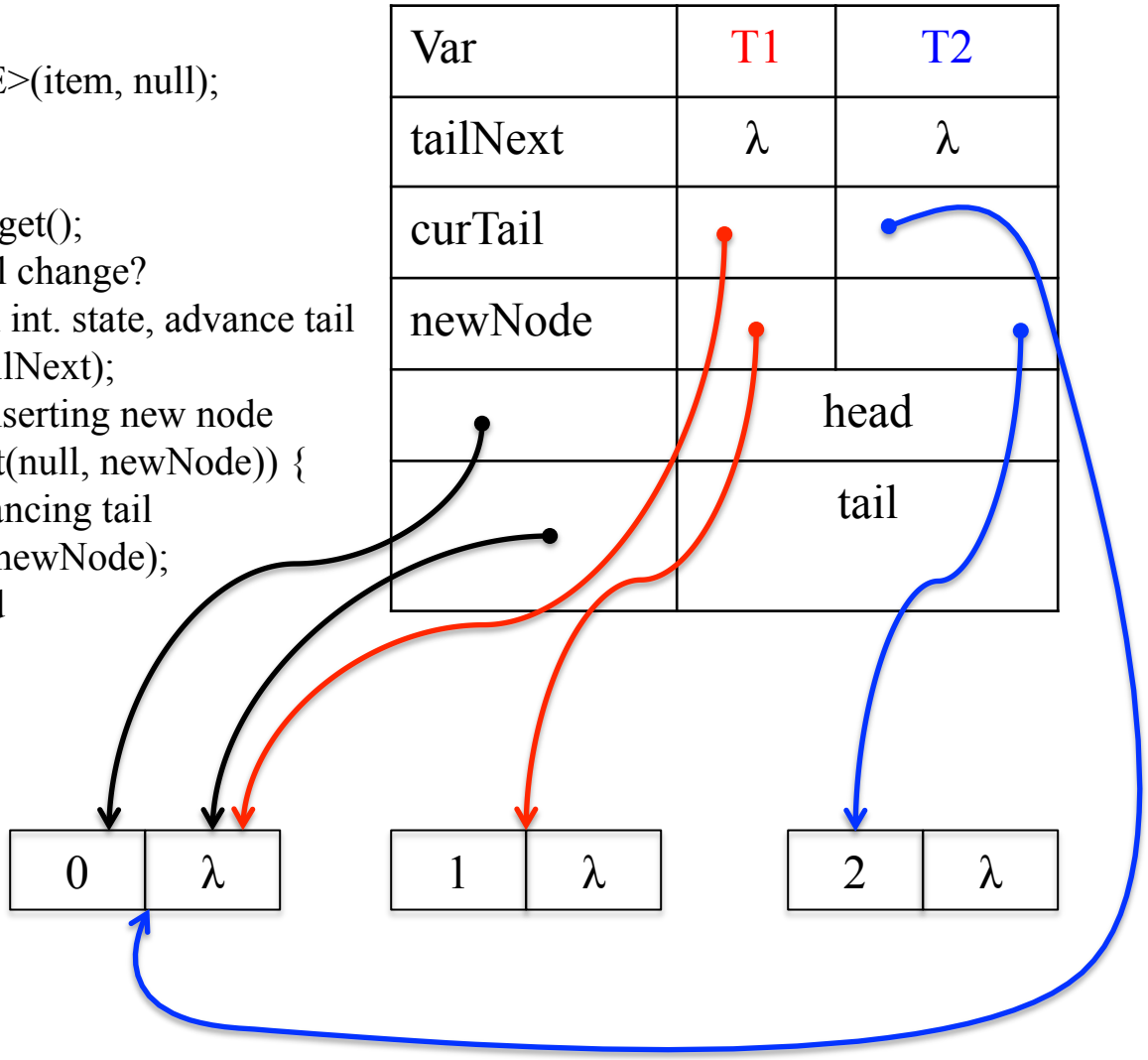

Trace 1: After CAS

```
    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;
            }
          }
        }
      }
    }
```

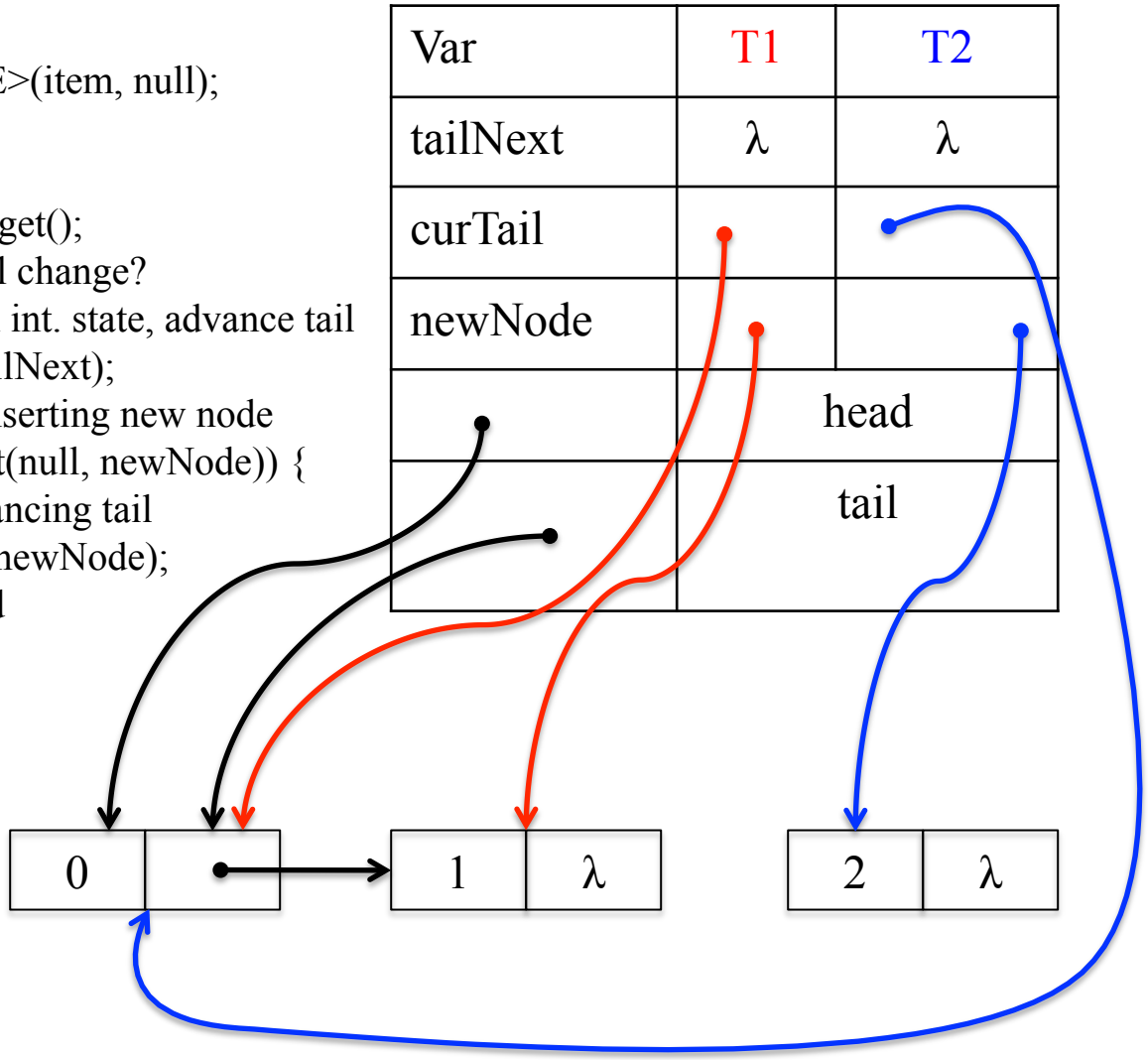

Trace 1: T2 Continues & CAS Fails

```
    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();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state, advance tail
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11          return true;
            }
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    }
```
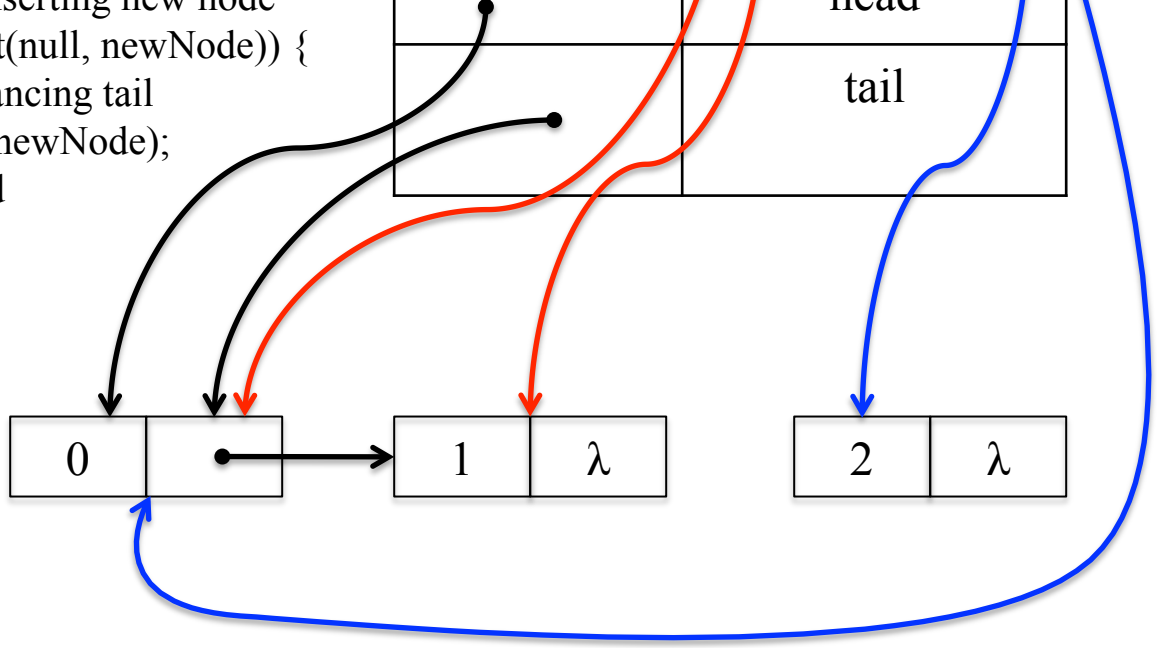

Var	T1	T2
tailNext	λ	λ
curTail		
newNode		
	head	
	tail	



Trace 1: T1 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?
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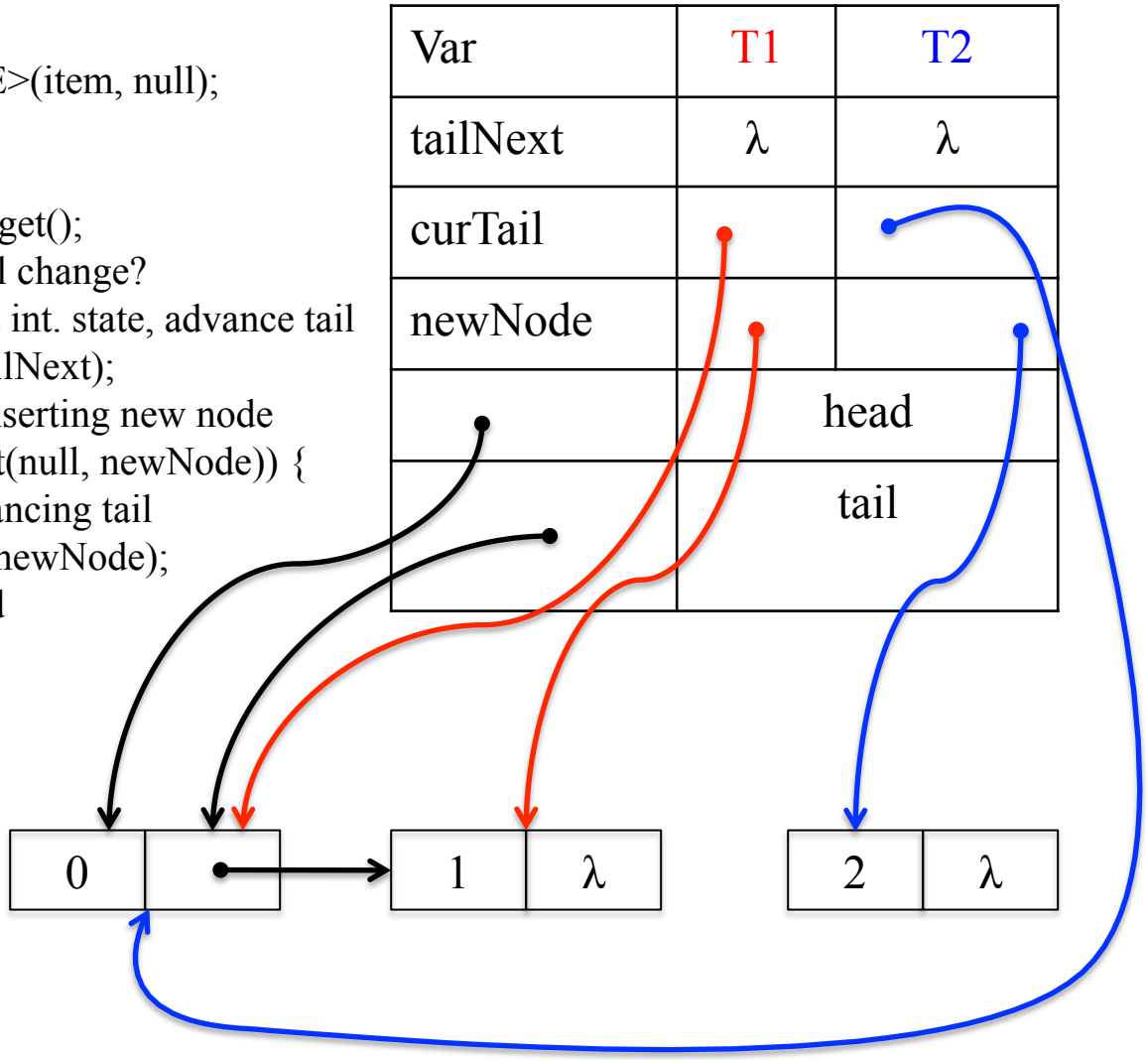

Trace 1: After CAS

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```

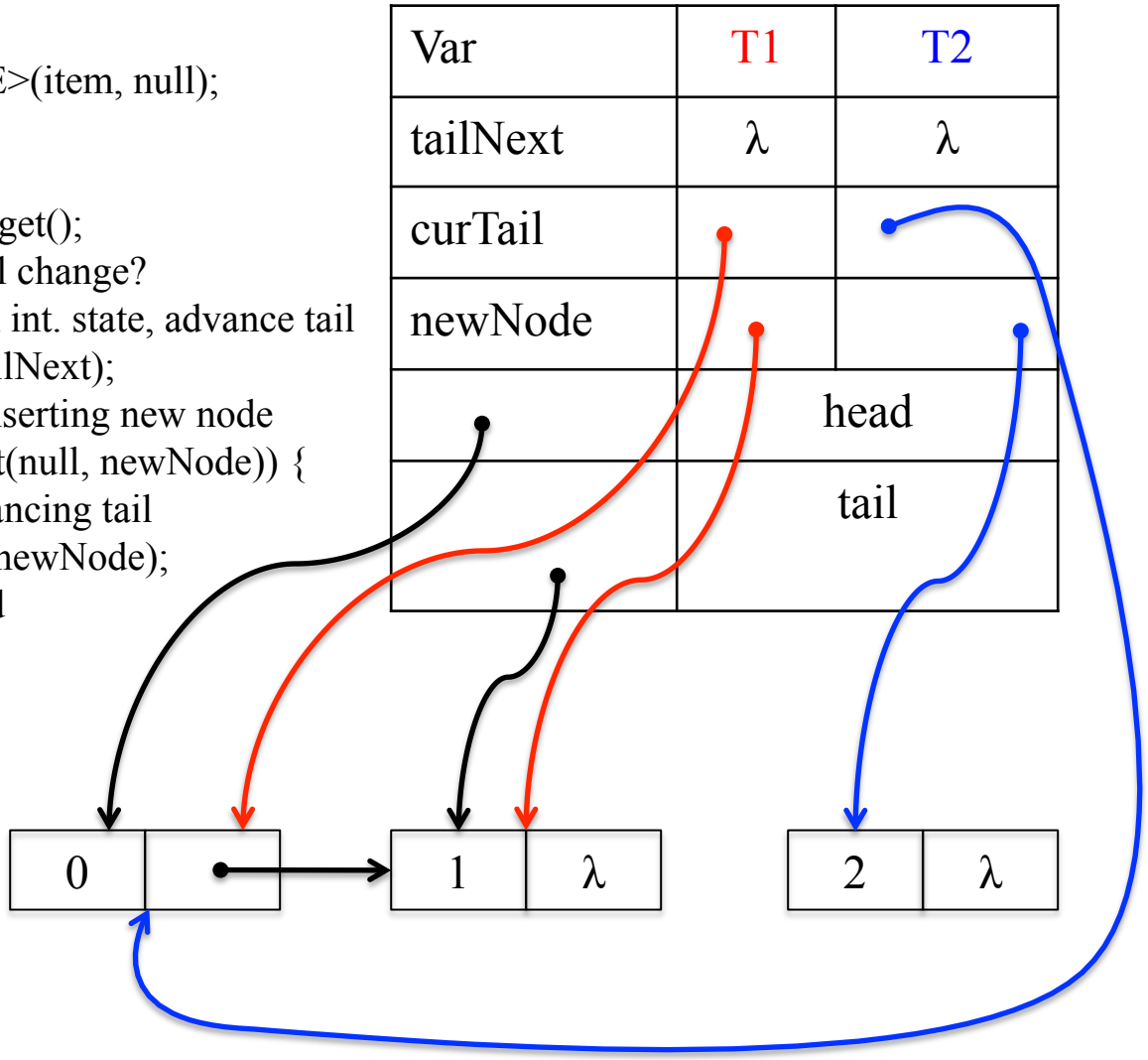

Trace 1: T1 exits

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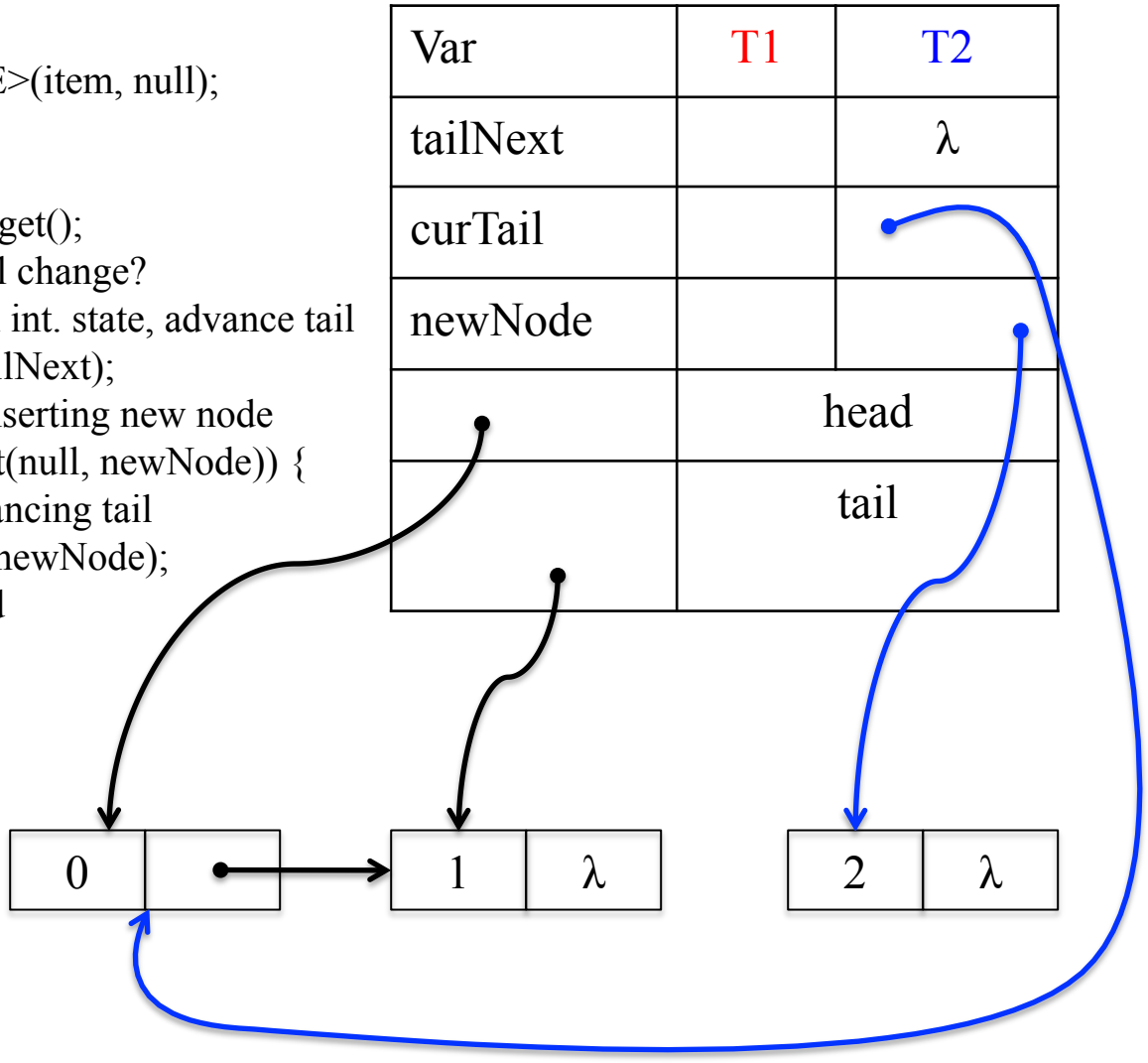
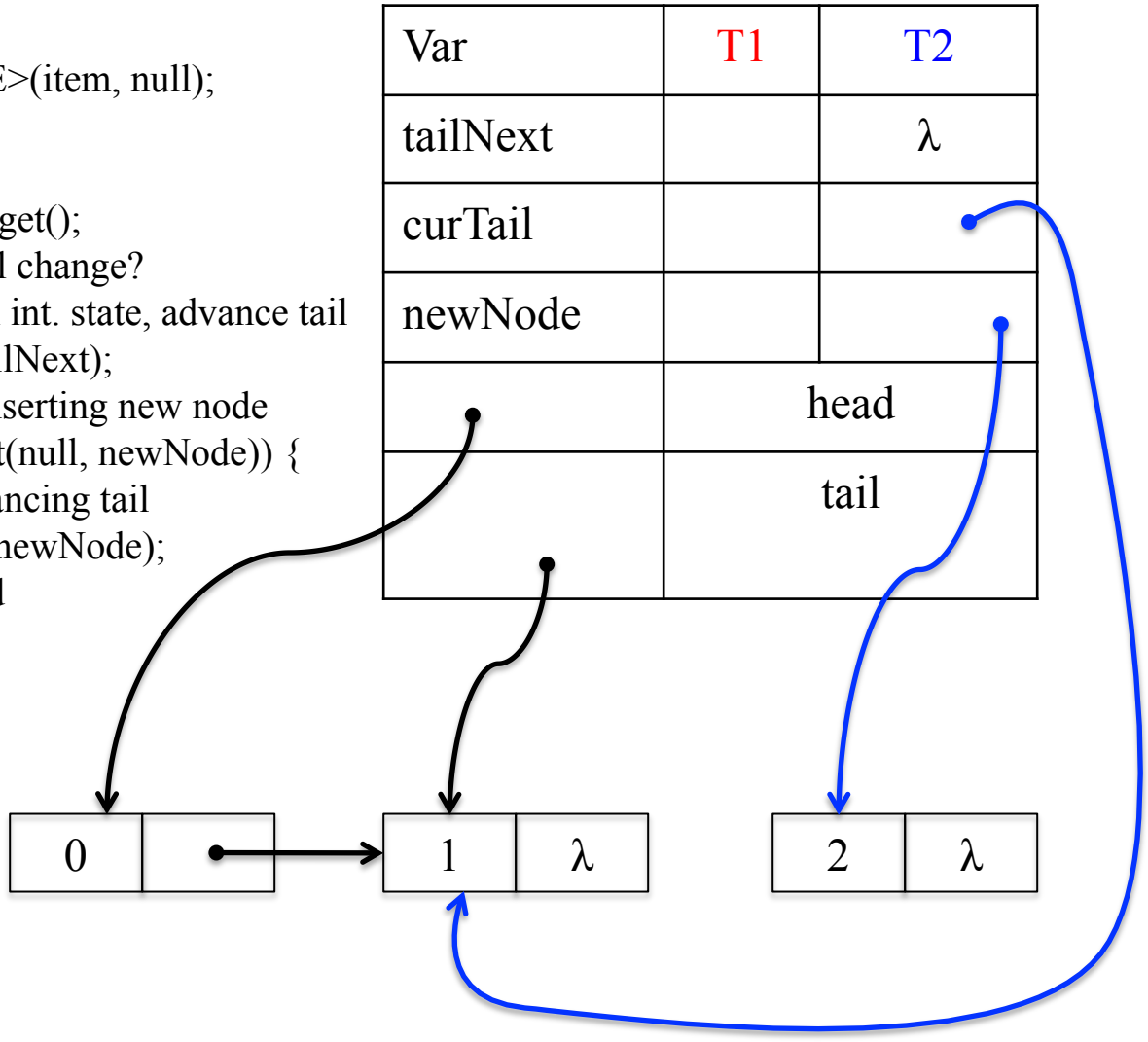



Trace 1: T2 Continues

```
    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?
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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;
            }
          }
        }
      }
    }
```
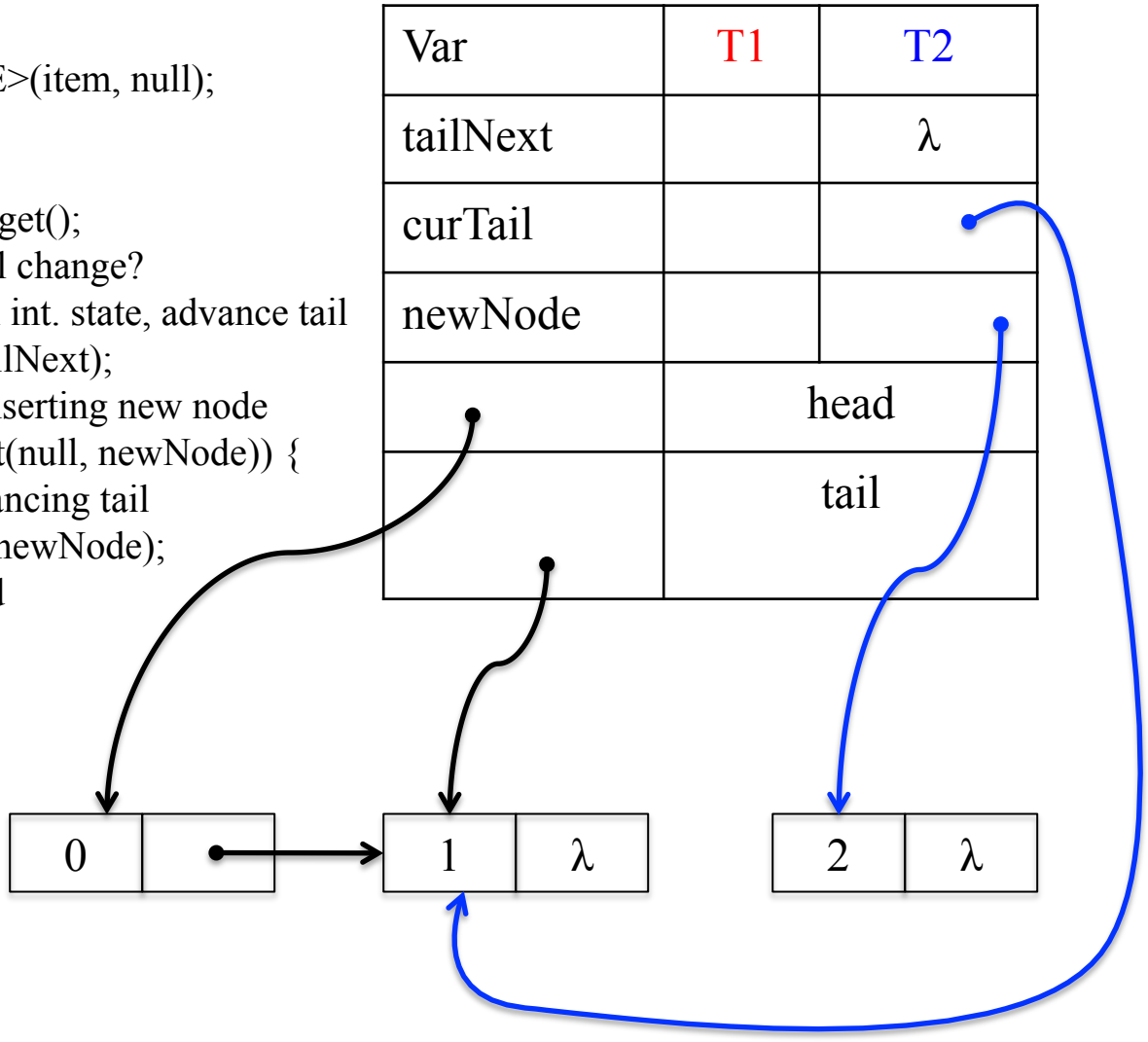
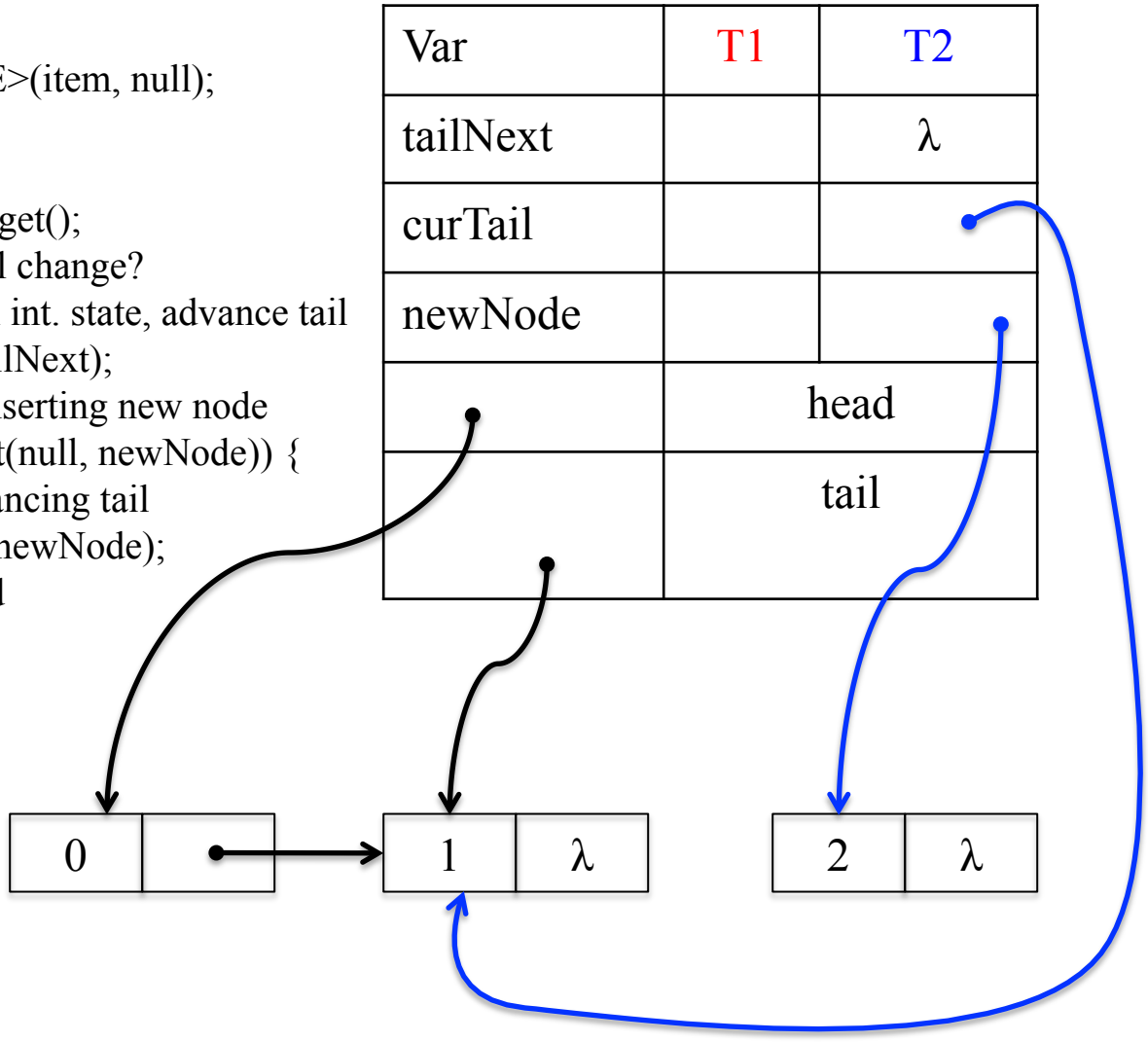



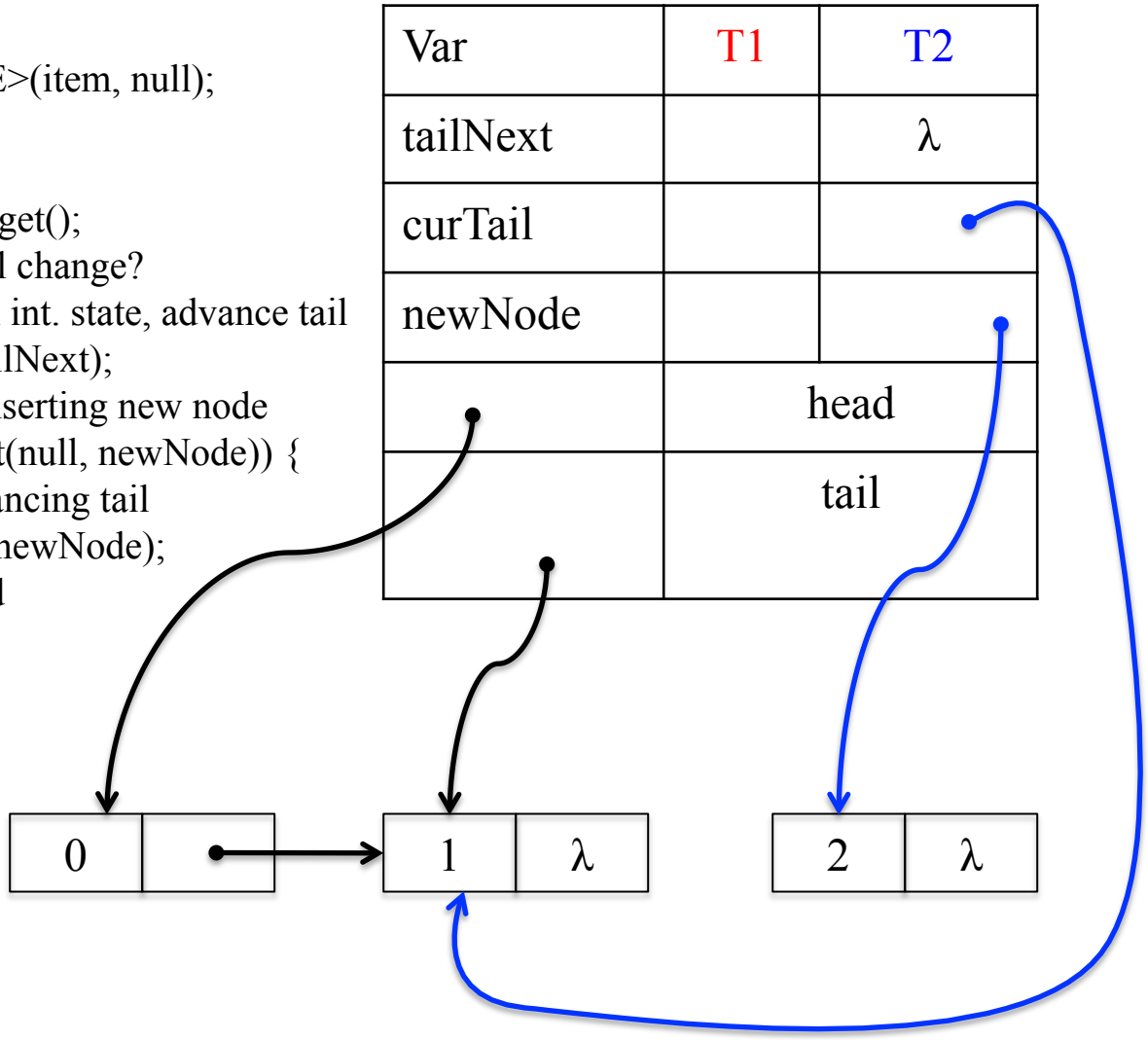
Trace 1: T2 Continues

```
    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;
            }
          }
        }
      }
    }
```



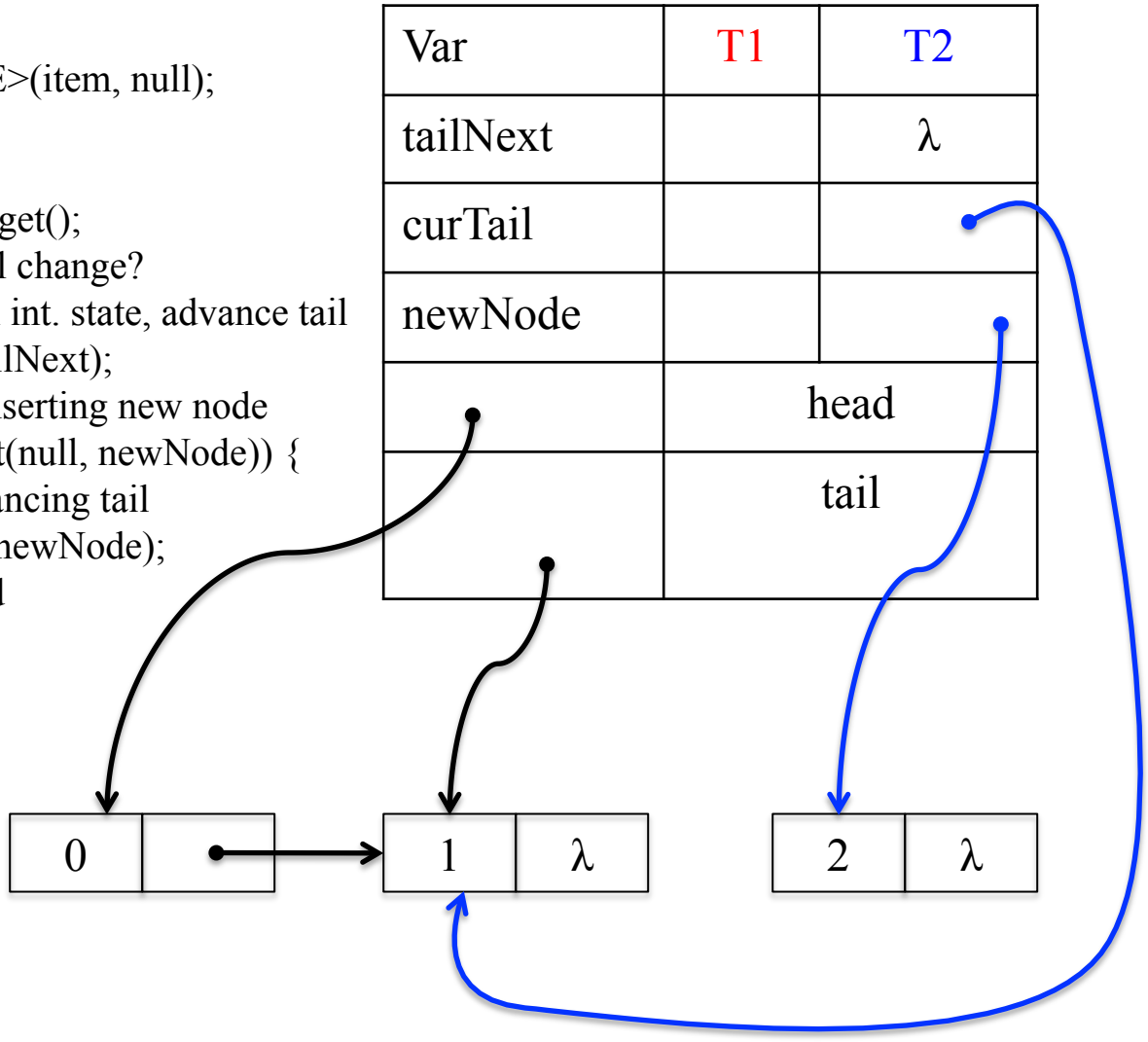
Trace 1: T2 Continues

```
    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;
            }
          }
        }
      }
    }
```



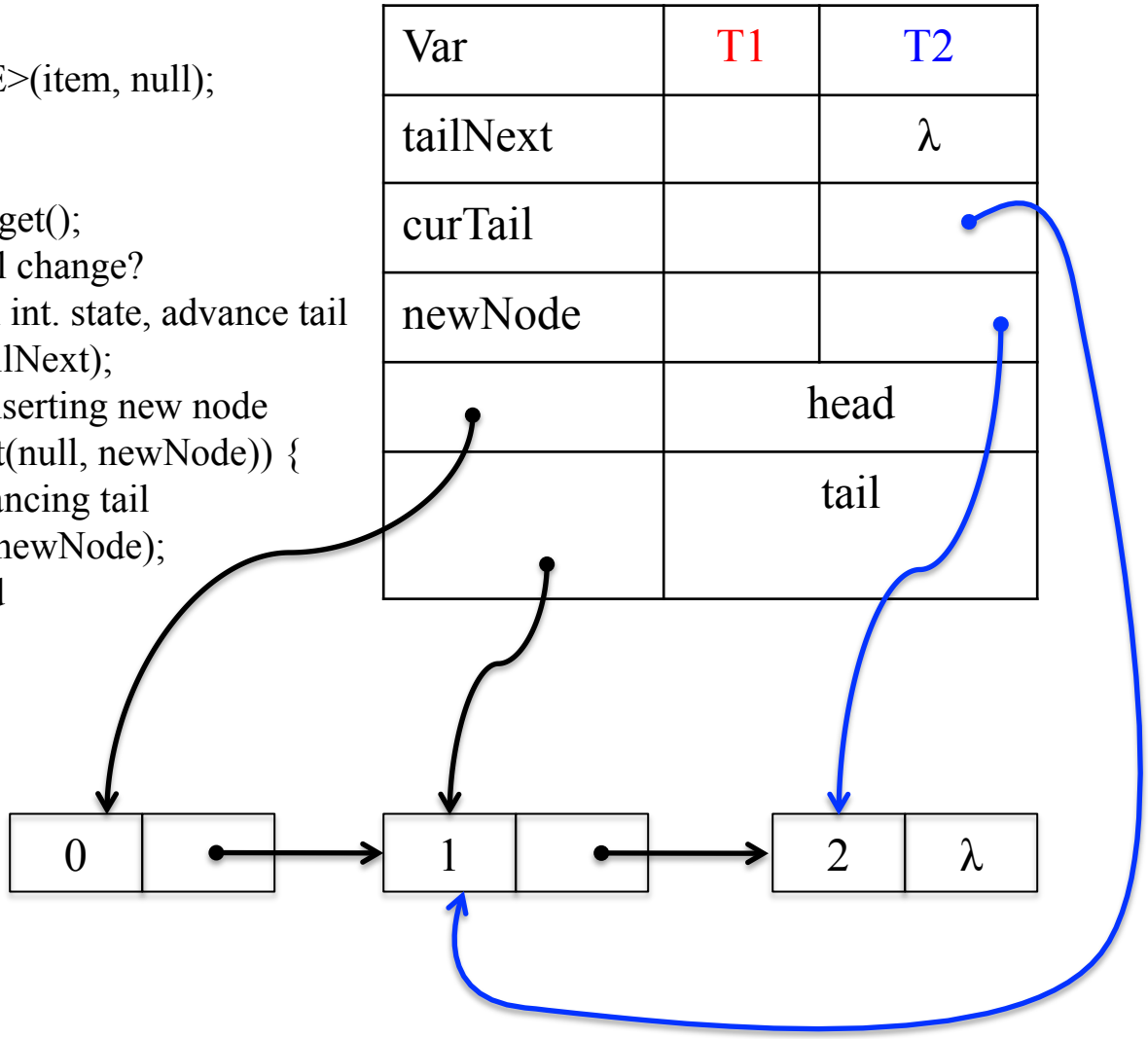
Trace 1: T2 Continues

```
    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;
            }
          }
        }
      }
    }
```



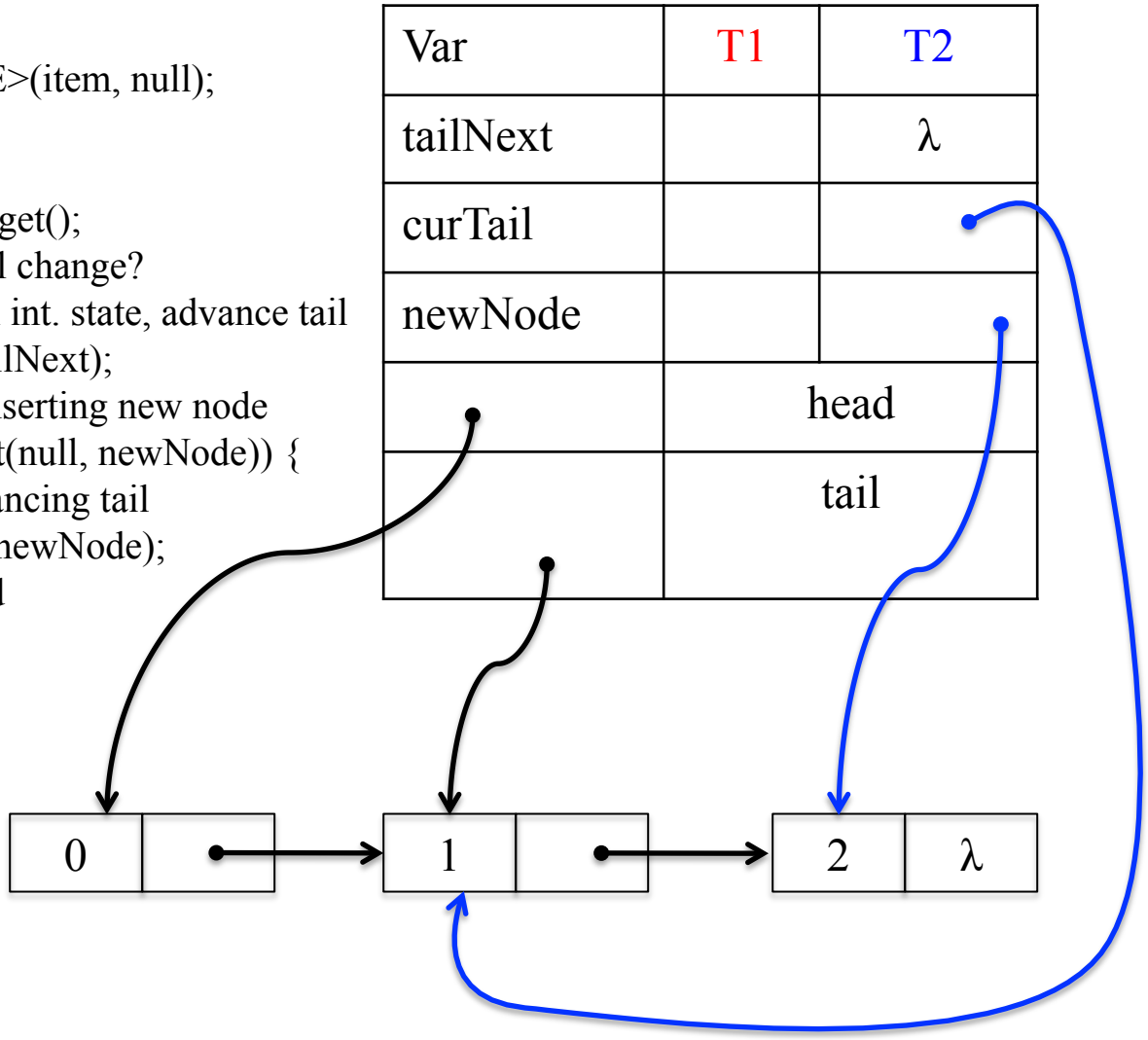
Trace 1: After CAS

```
    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

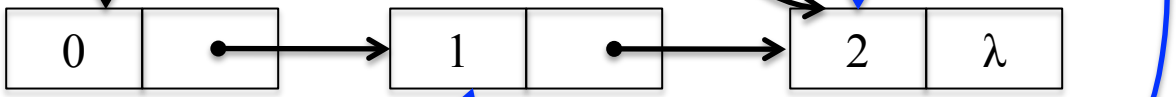
```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state,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



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;
            }
          }
        }
      }
    }
}
```

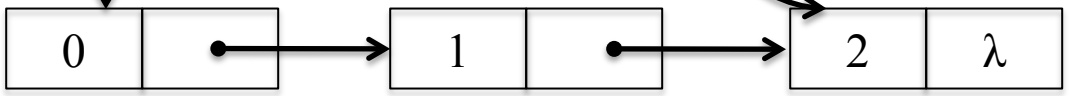
Var	T1	T2
tailNext		λ
curTail		
newNode		
	head	
	tail	



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);
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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;
            }
          }
        }
      }
    }
```
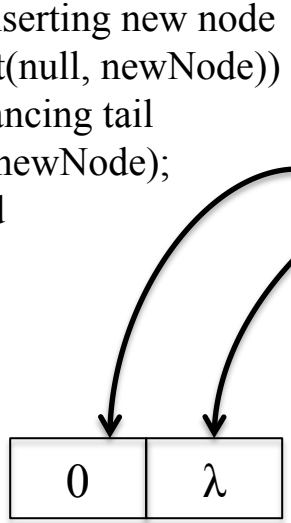
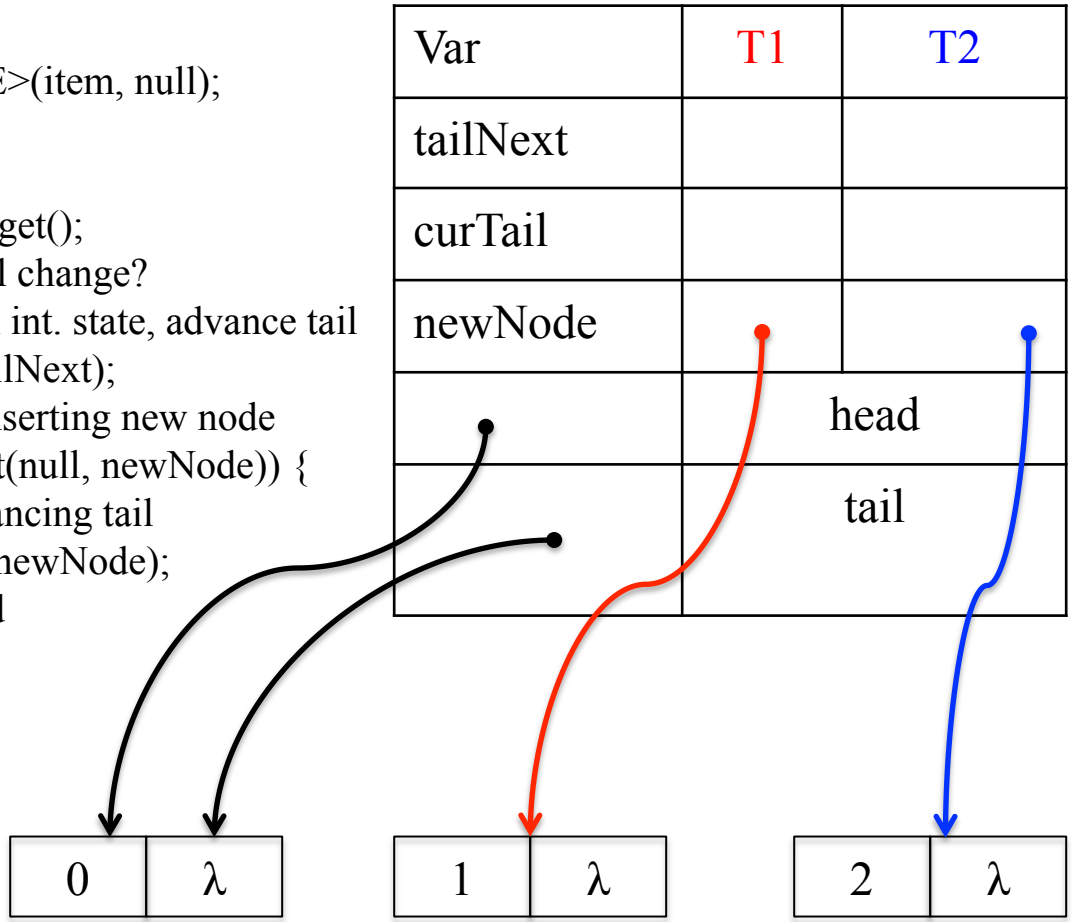

Var	T1	T2
tailNext		
curTail		
newNode		
	head	
	tail	



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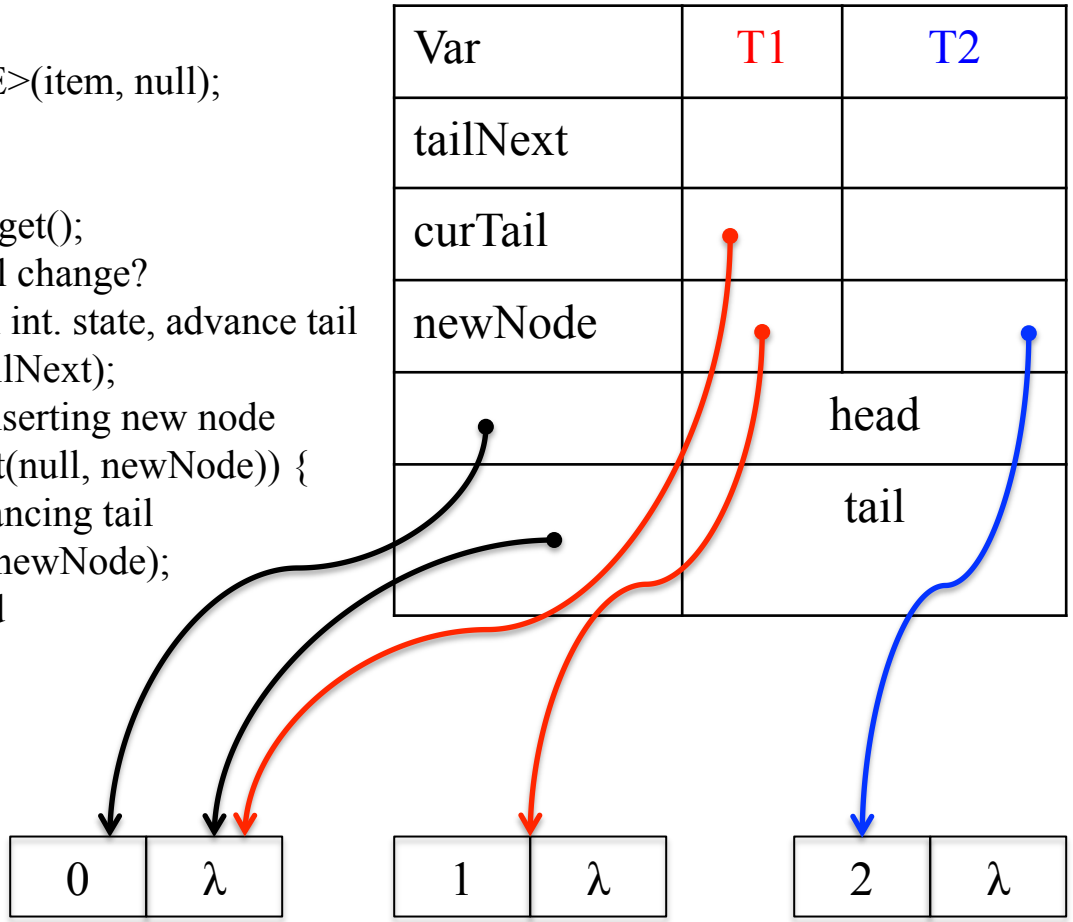
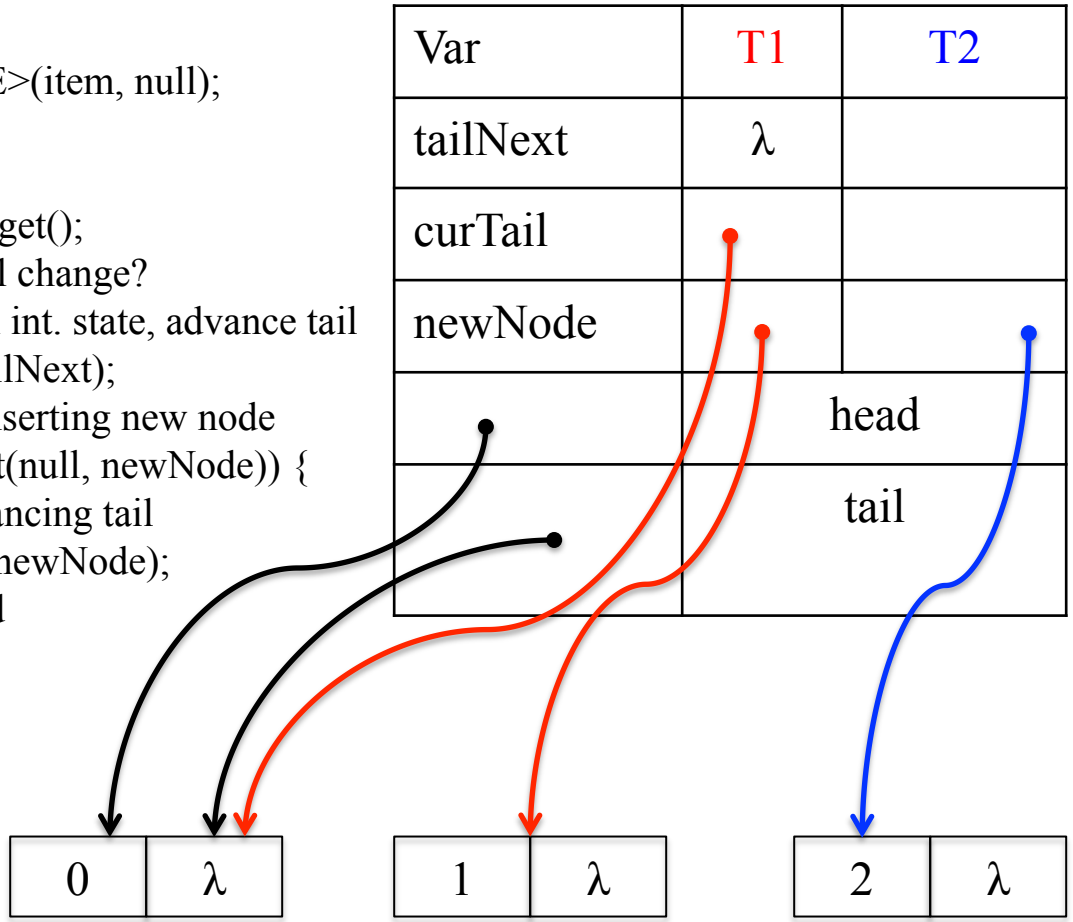



Trace 2

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

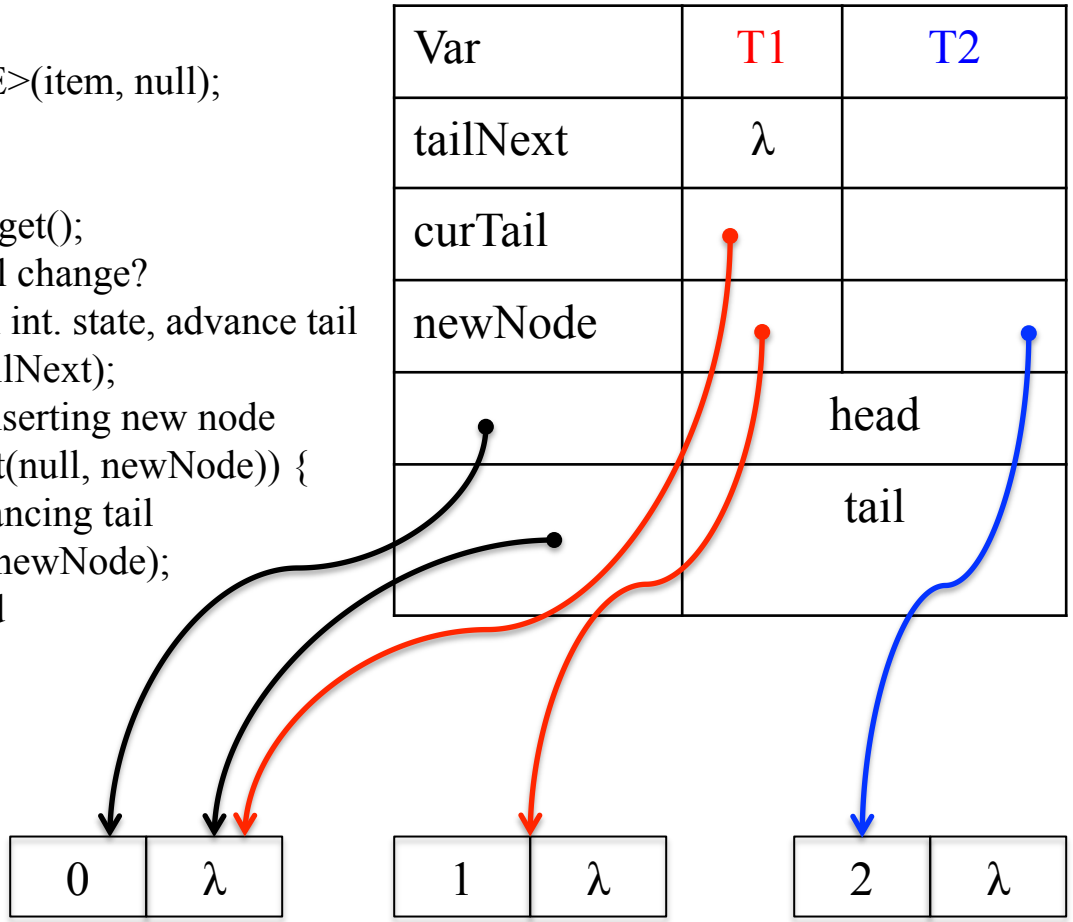

Trace 2

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    public boolean put(E item) {
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5       if (curTail == tail.get()) {// did tail change?
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            // Insertion succeeded, try advancing tail
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            // will fail if tail already moved
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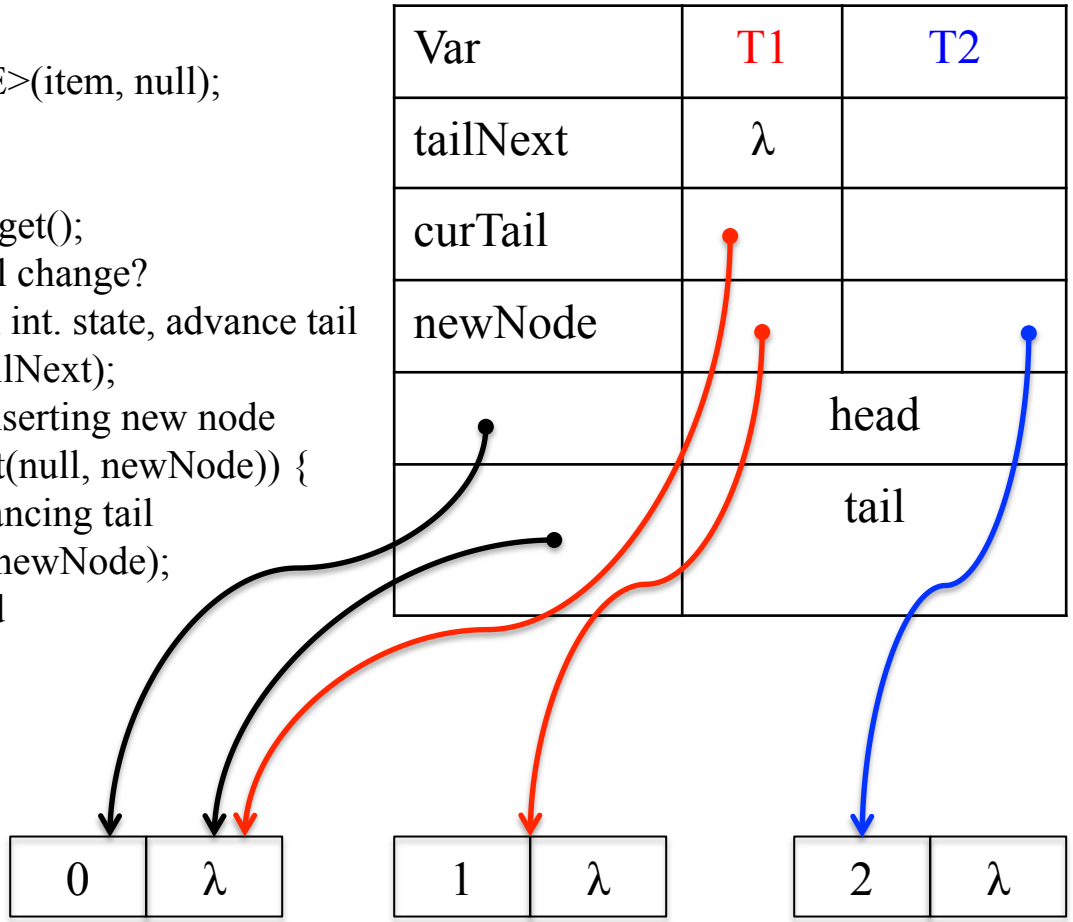
            }
          }
        }
      }
    }
```



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            // Insertion succeeded, try advancing tail
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            // will fail if tail already moved
11          return true;
          }
        }
      }
    }
  }
```
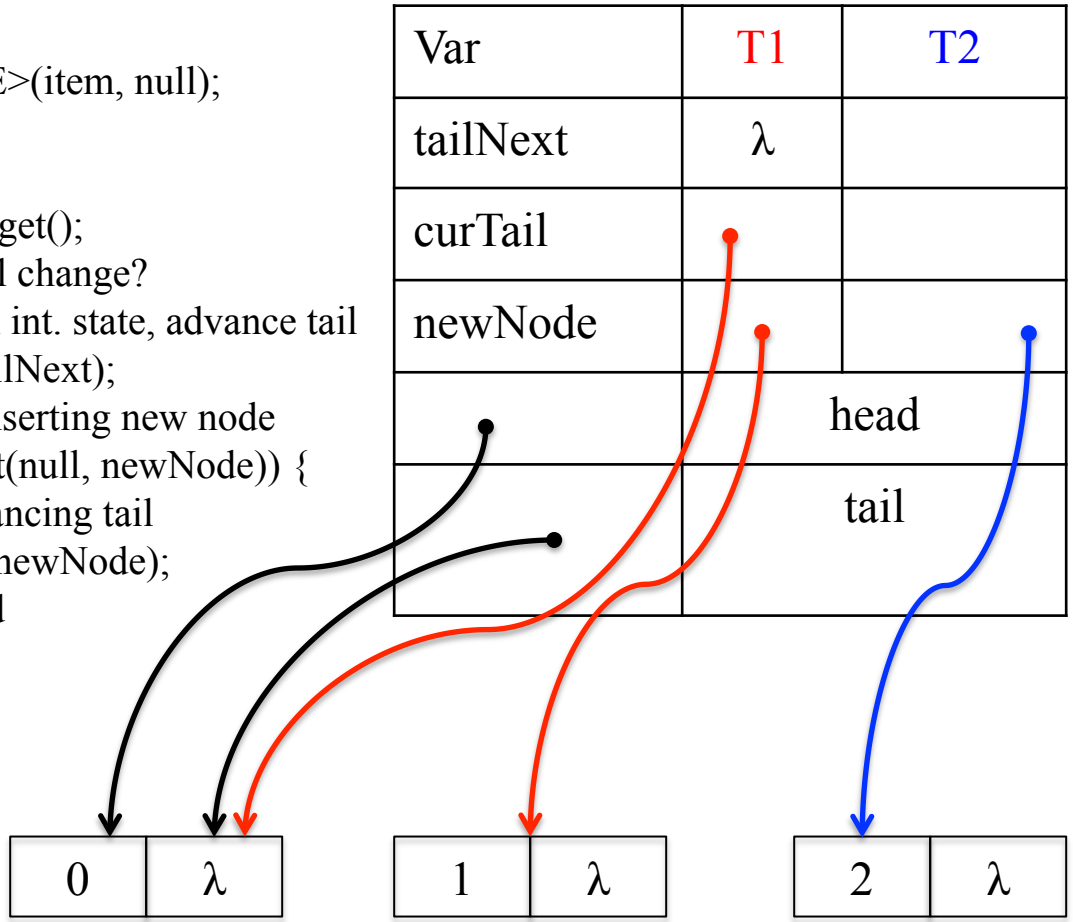
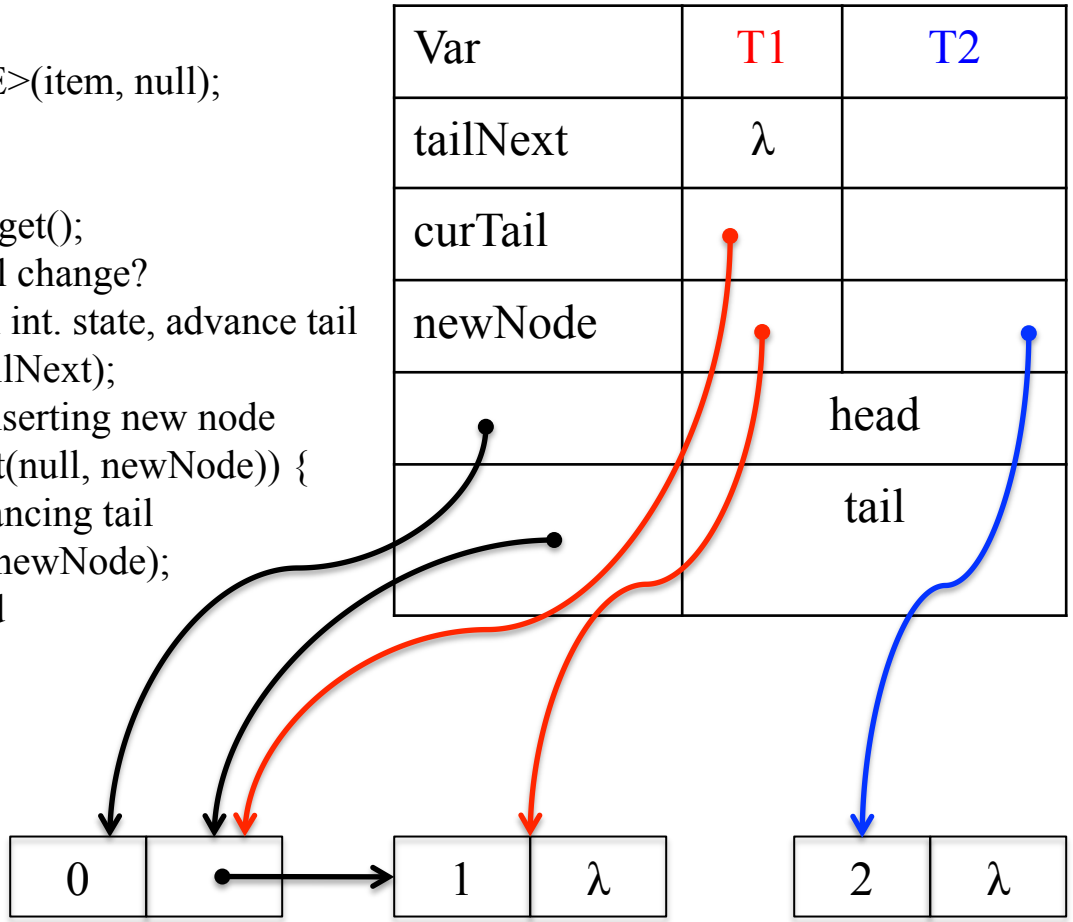



Trace 2: After CAS

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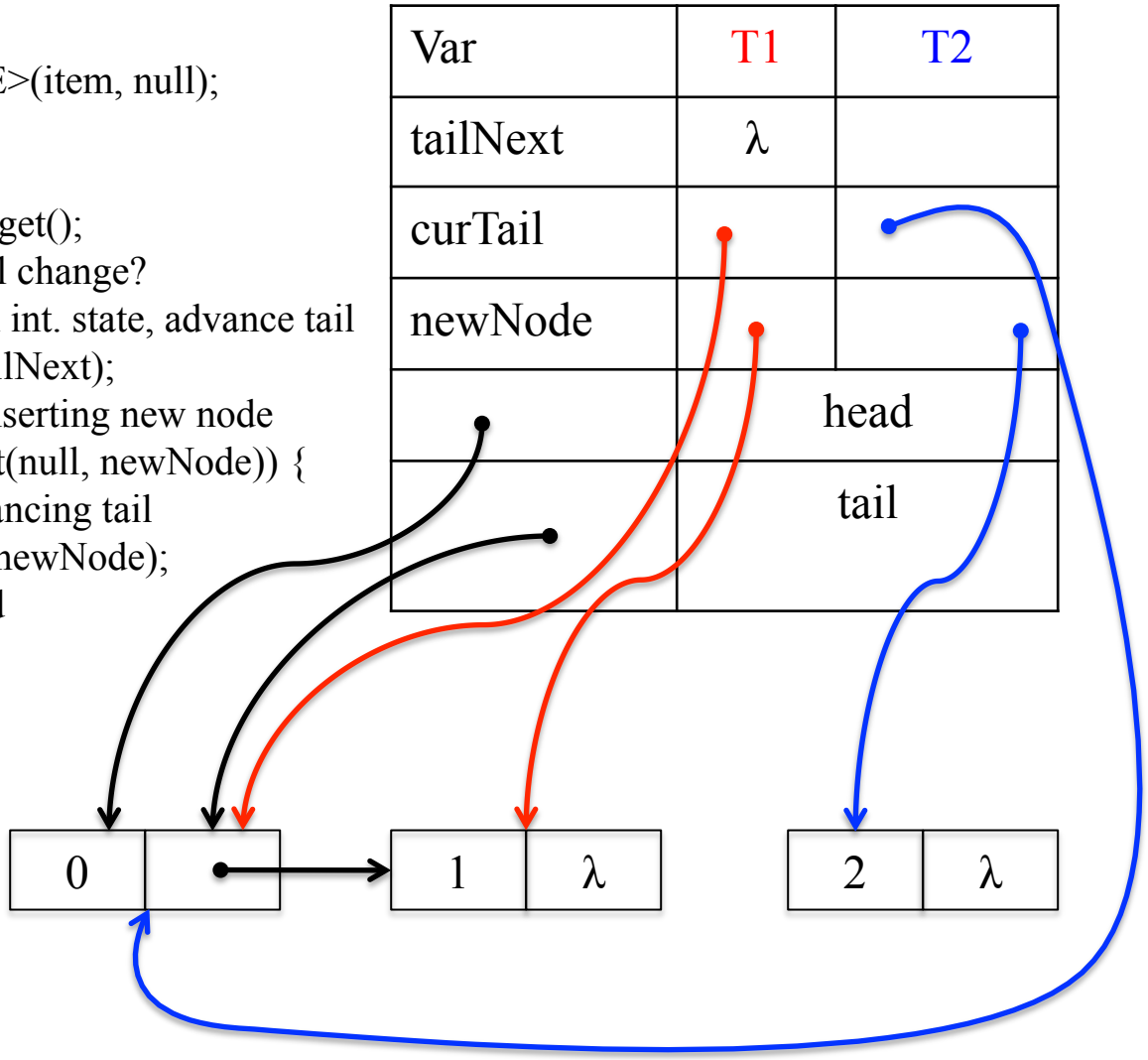
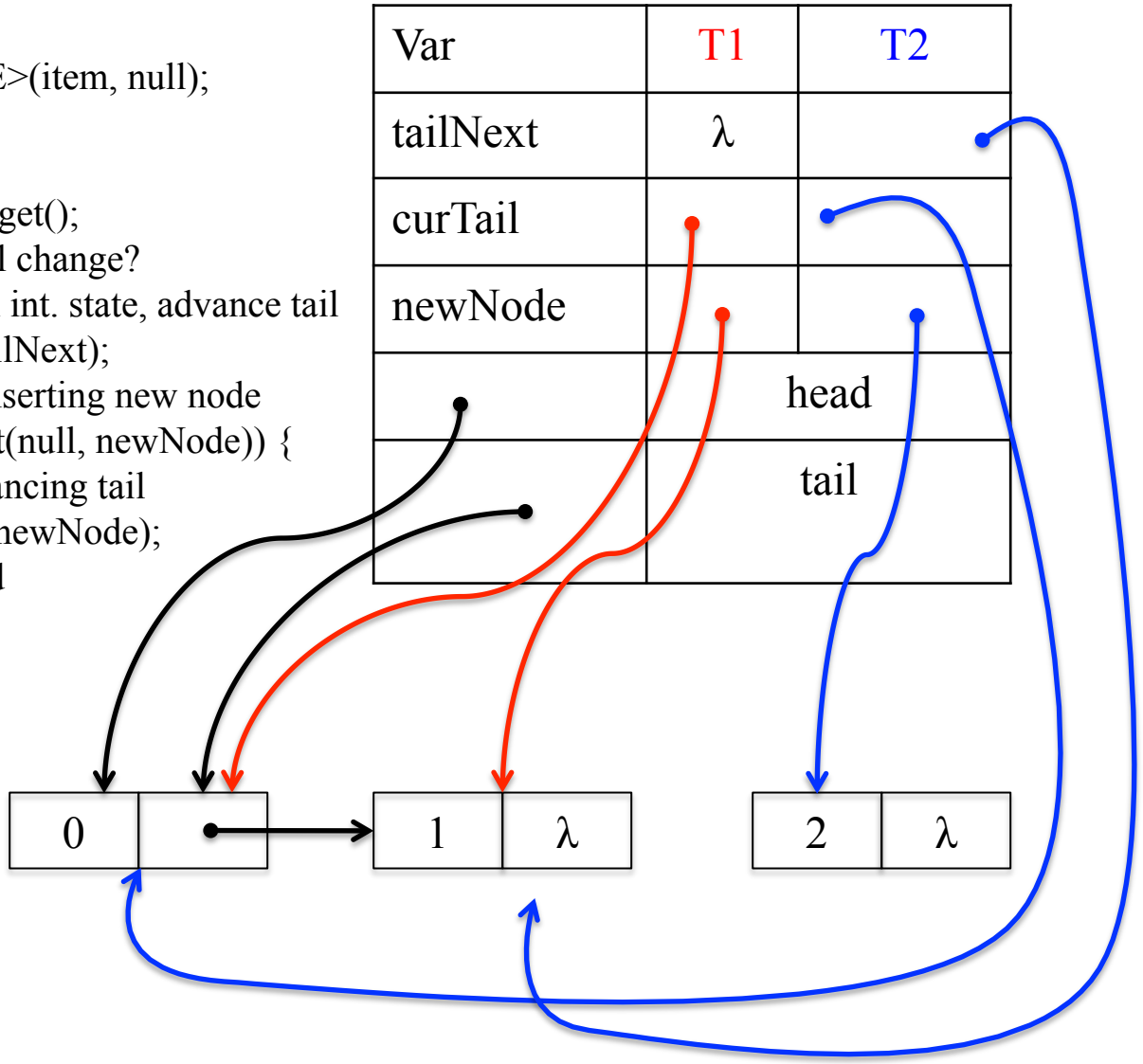



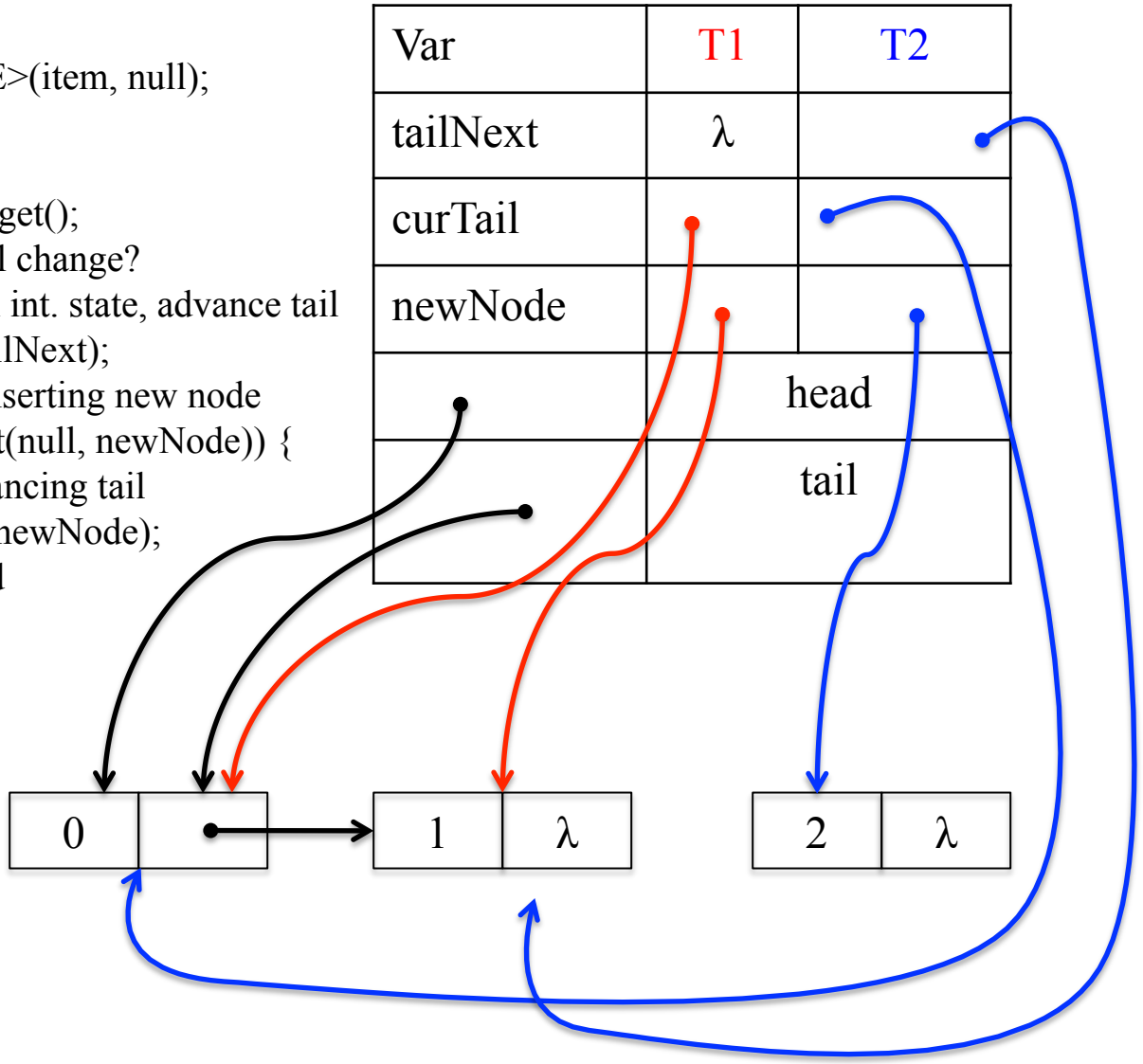
Trace 2

```
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
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;
            }
          }
        }
      }
    }
```
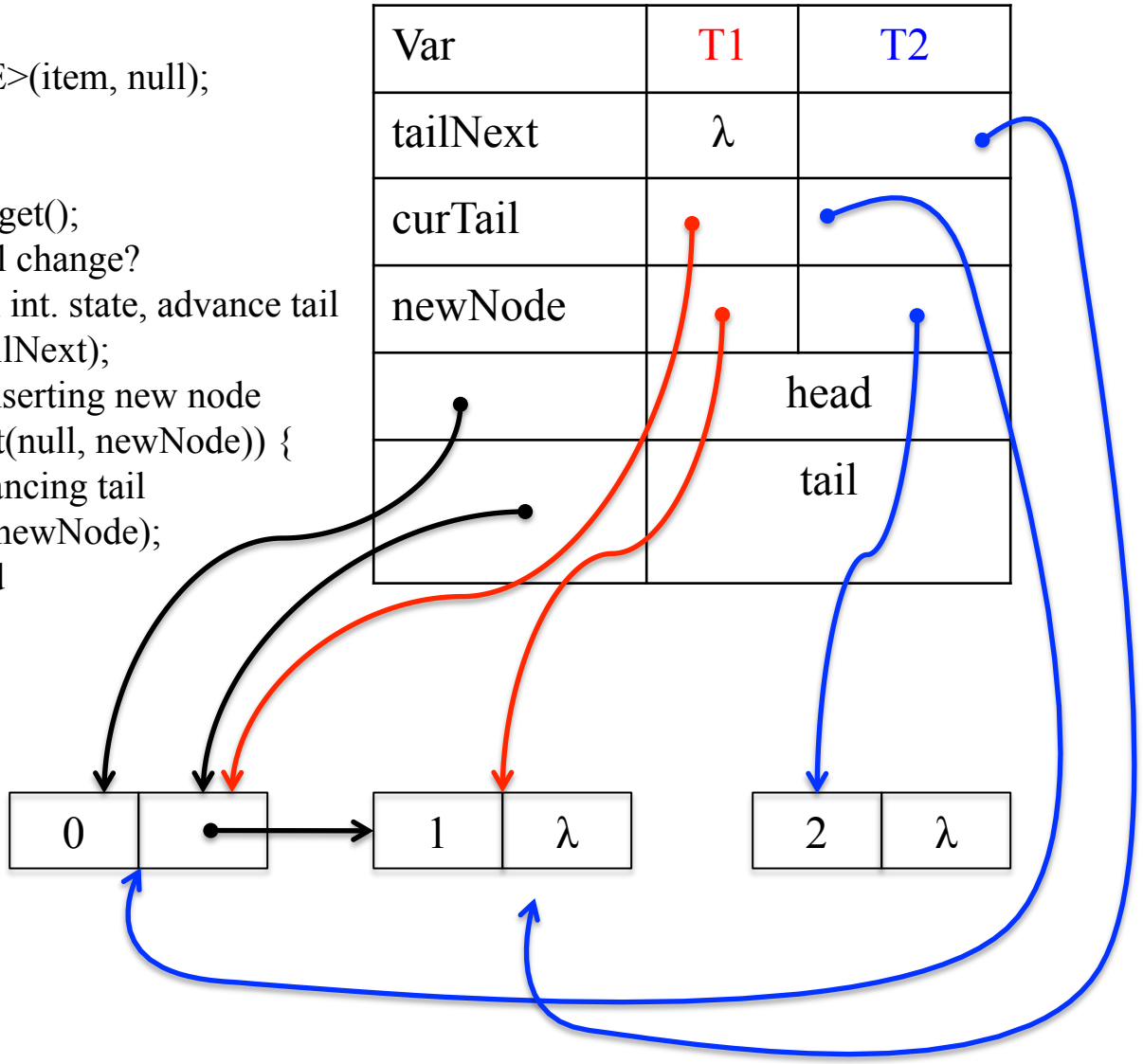
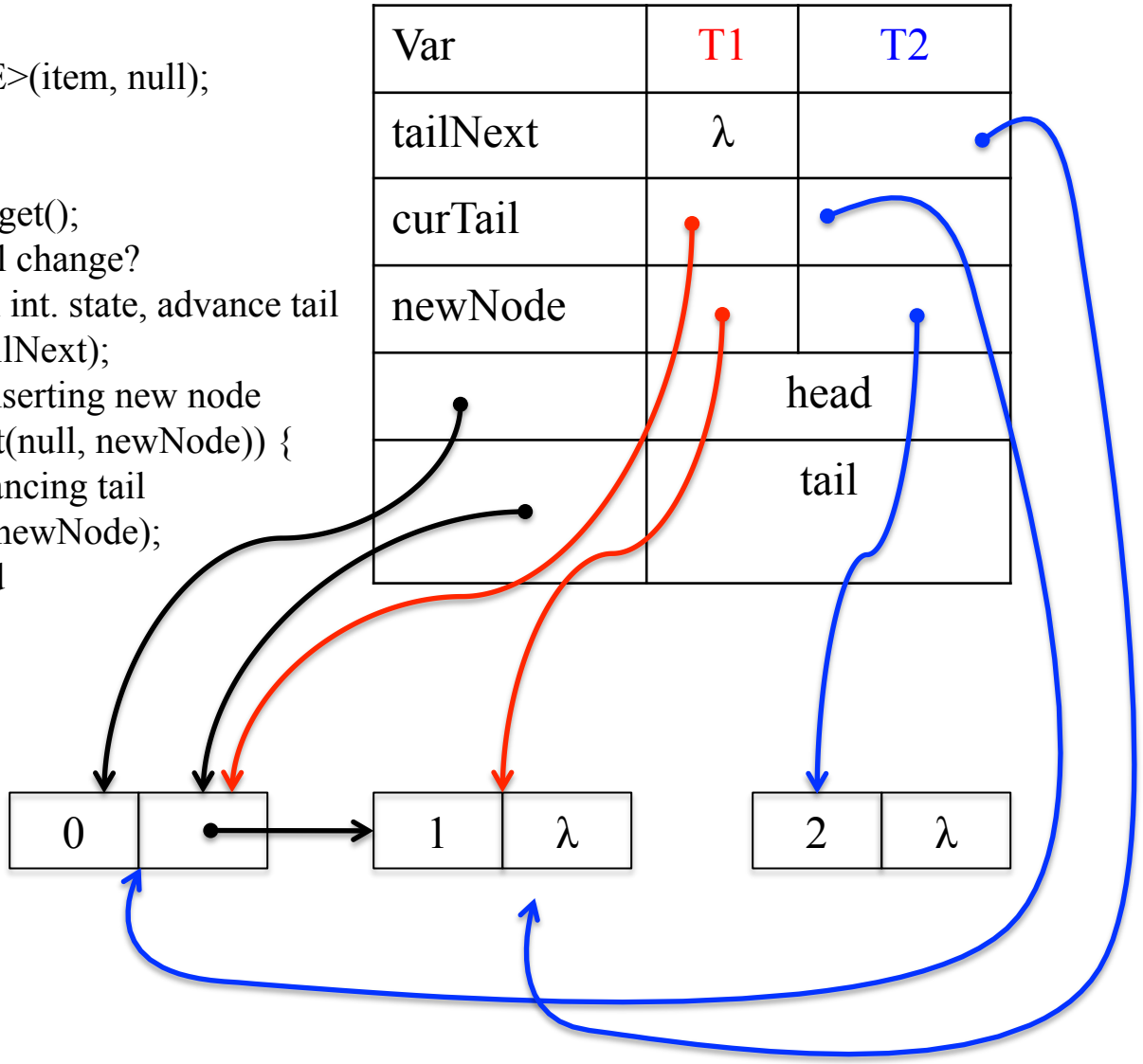



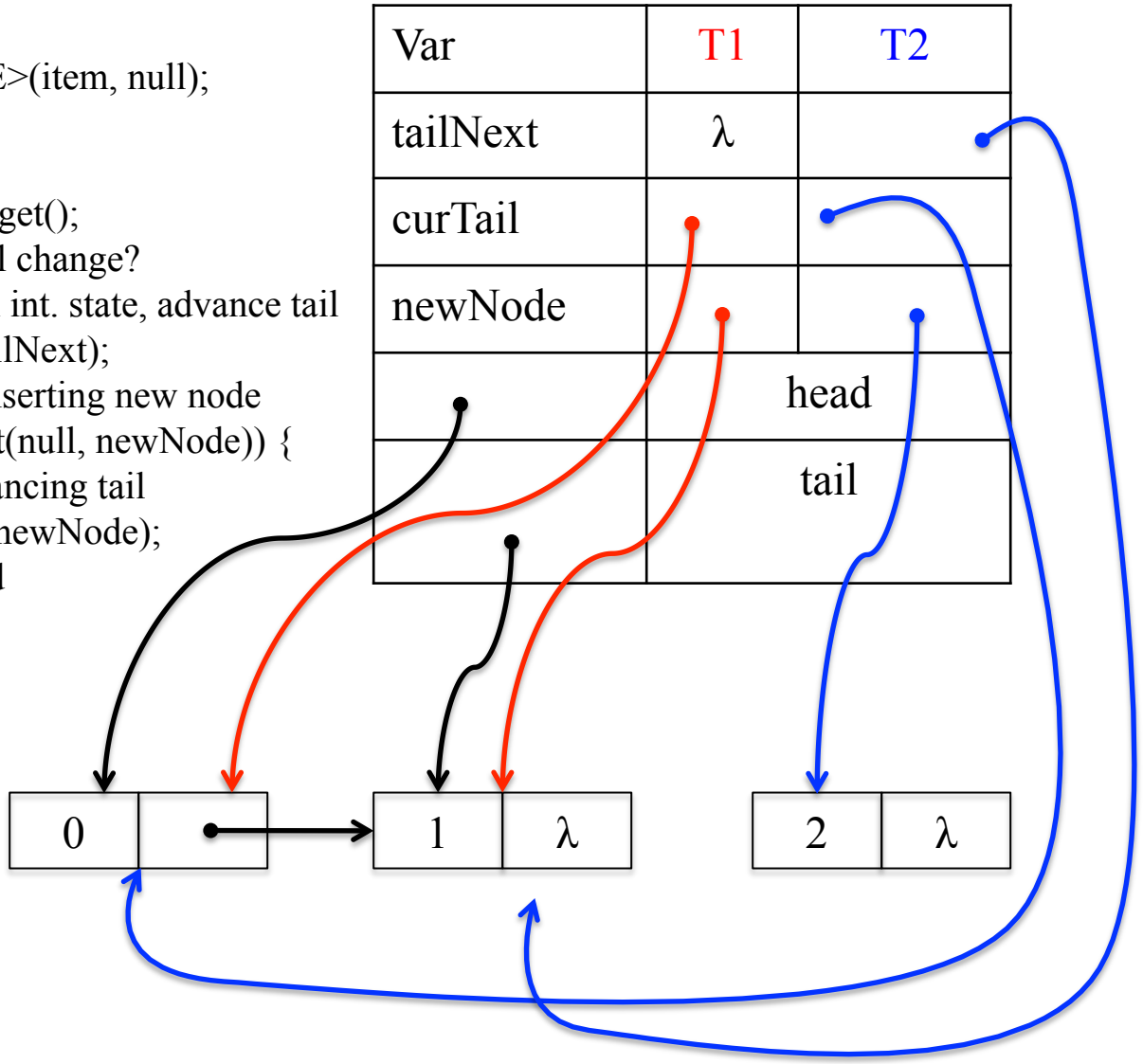
Trace 2:T2 wins

```
    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;
            }
          }
        }
      }
    }
```



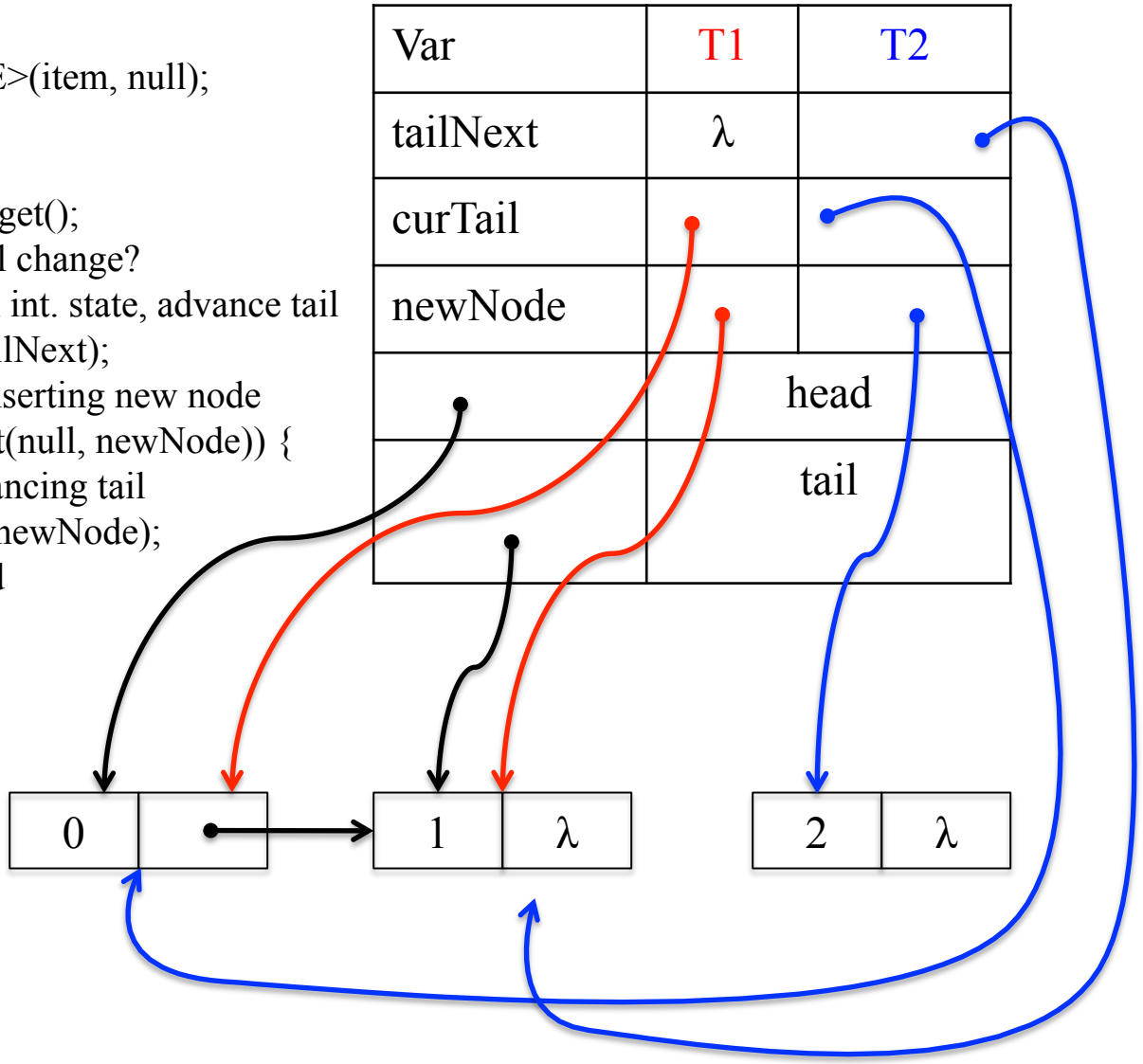
Trace 2: After CAS

```
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;
            }
          }
        }
      }
    }
```



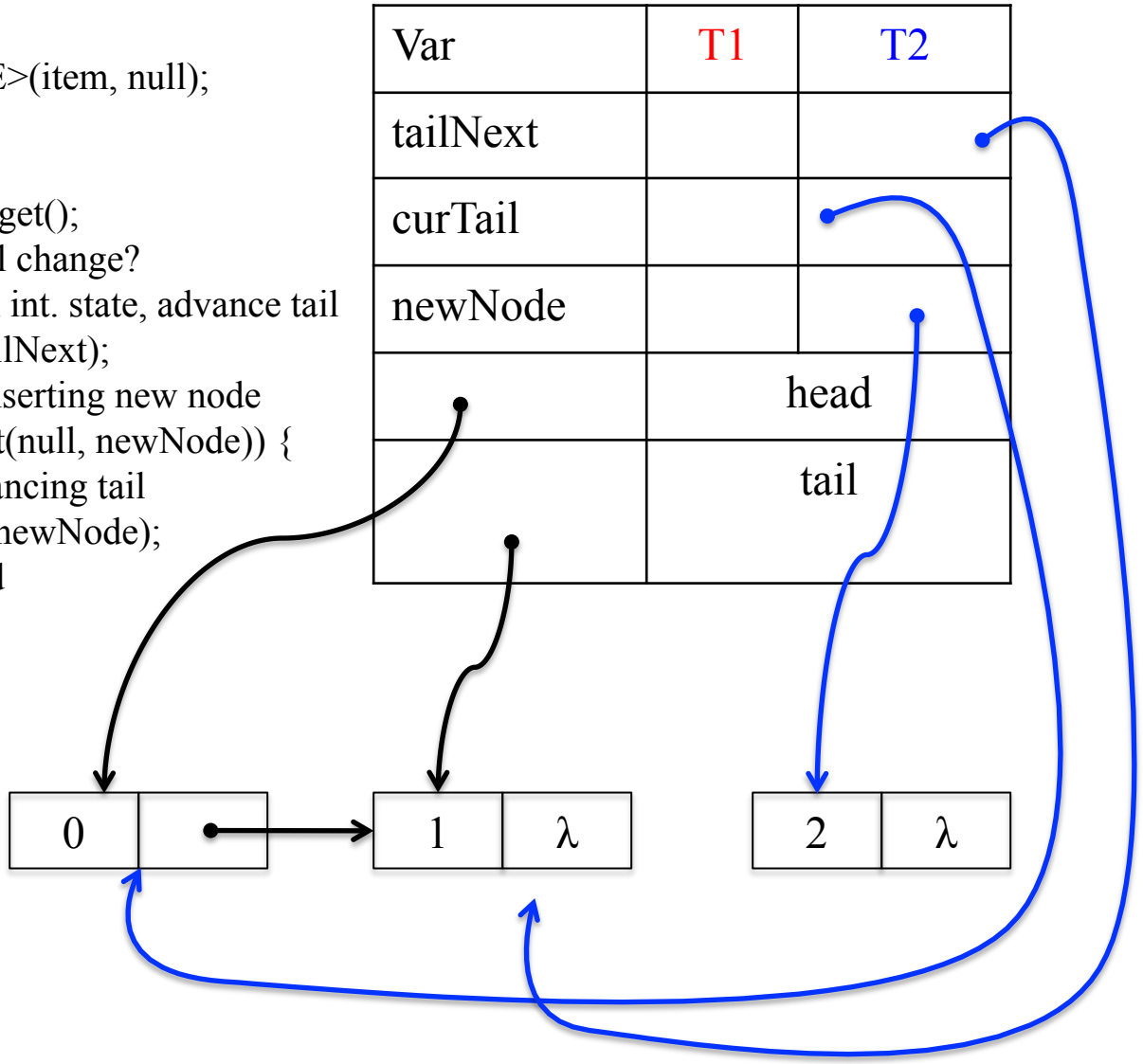
Trace 2: T1 continues: CAS fails

```
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;
            }
          }
        }
      }
    }
```



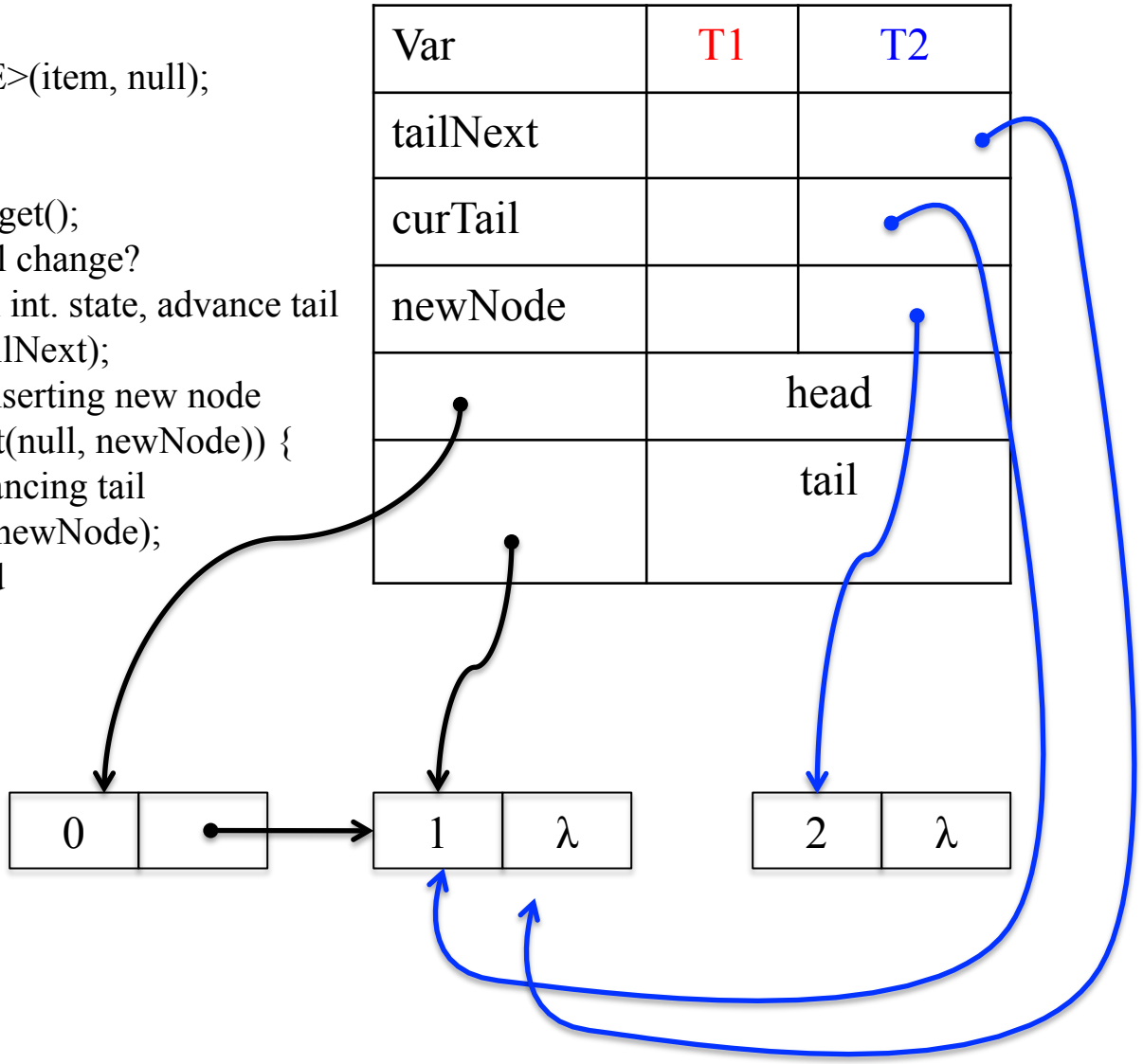
Trace 2: T1 exits

```
    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;
            }
          }
        }
      }
    }
```



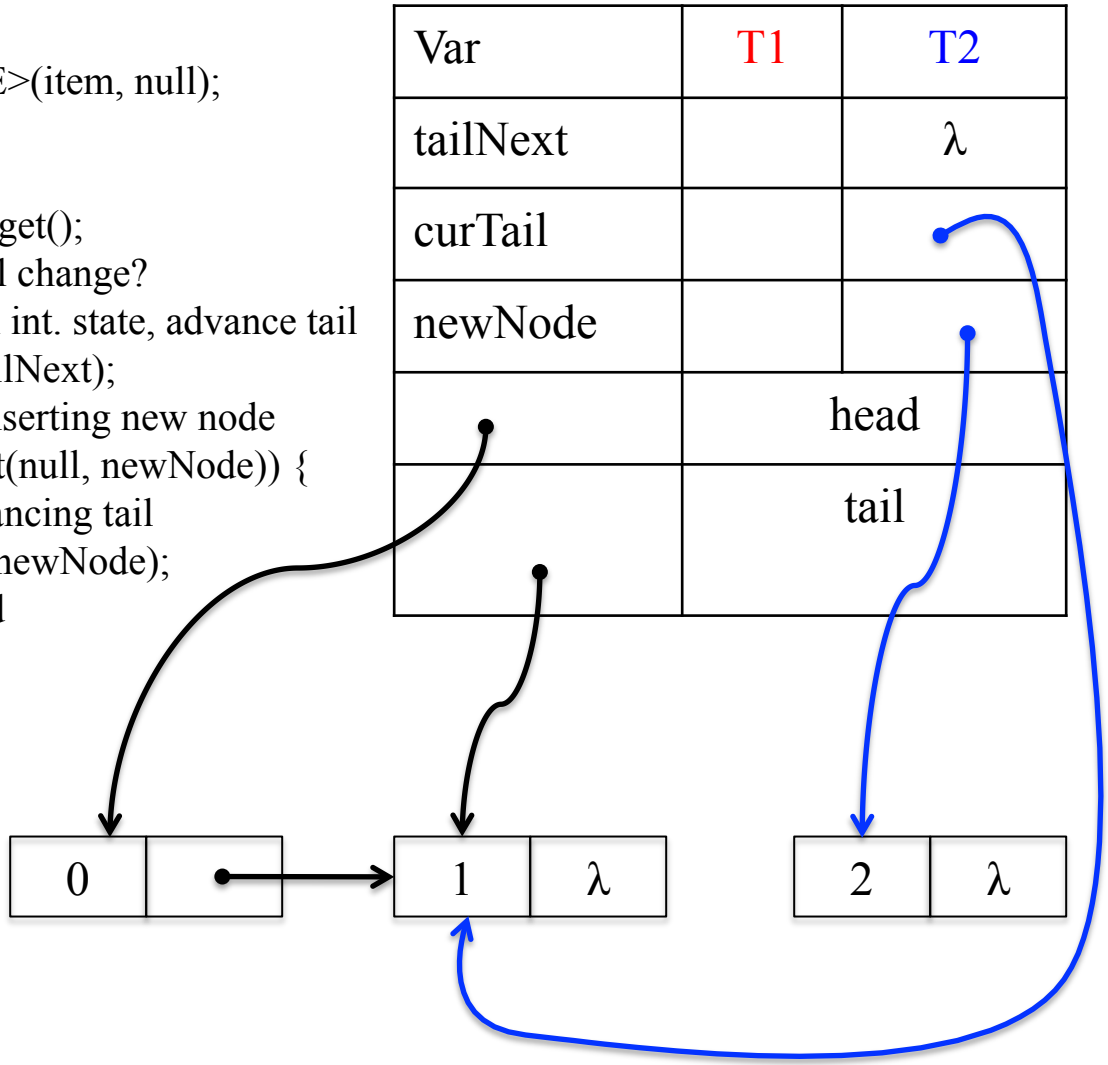
Trace 2: T2 continues

```
    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
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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;
            }
          }
        }
      }
    }
```

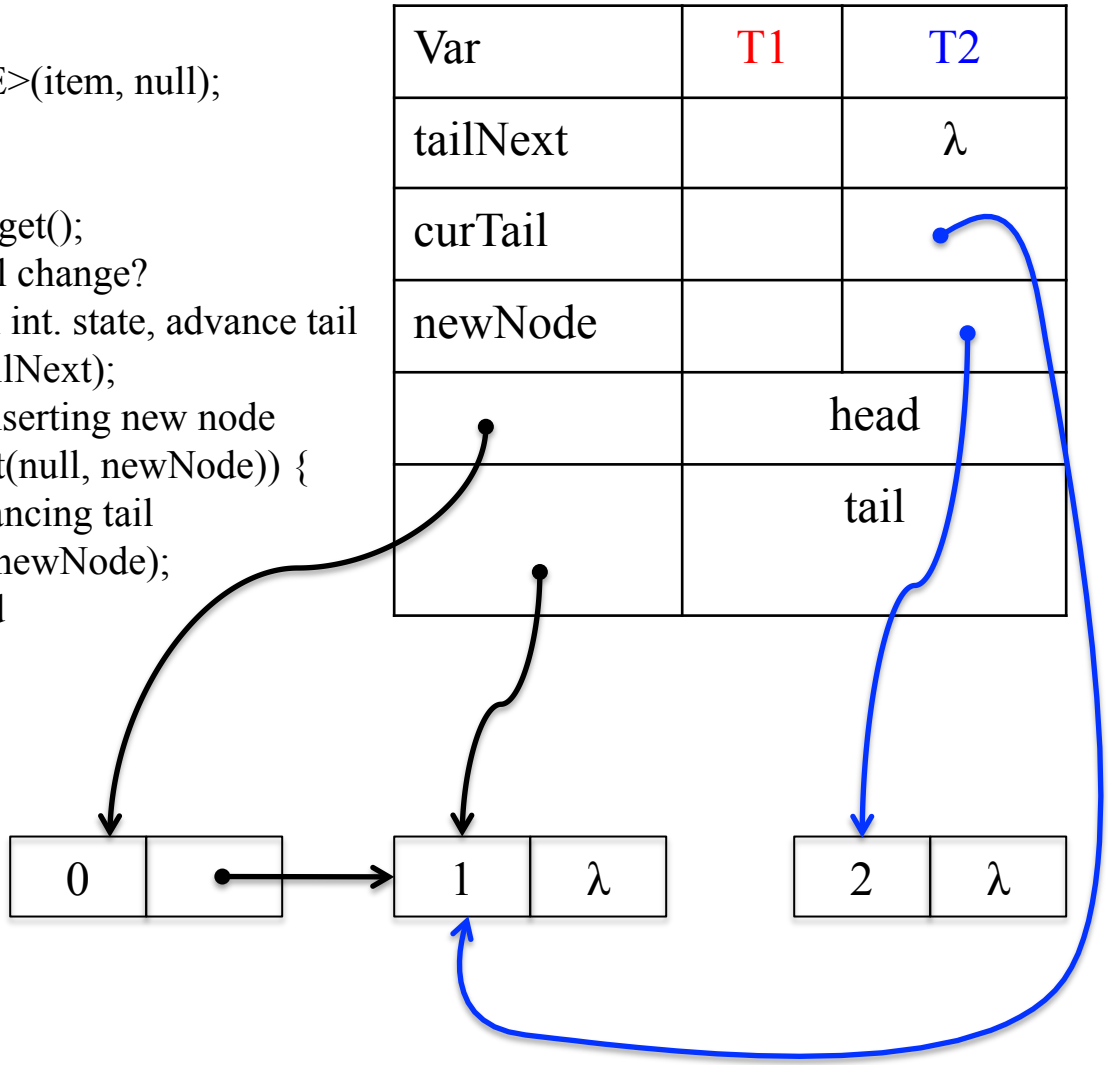

Trace 2: T2 continues

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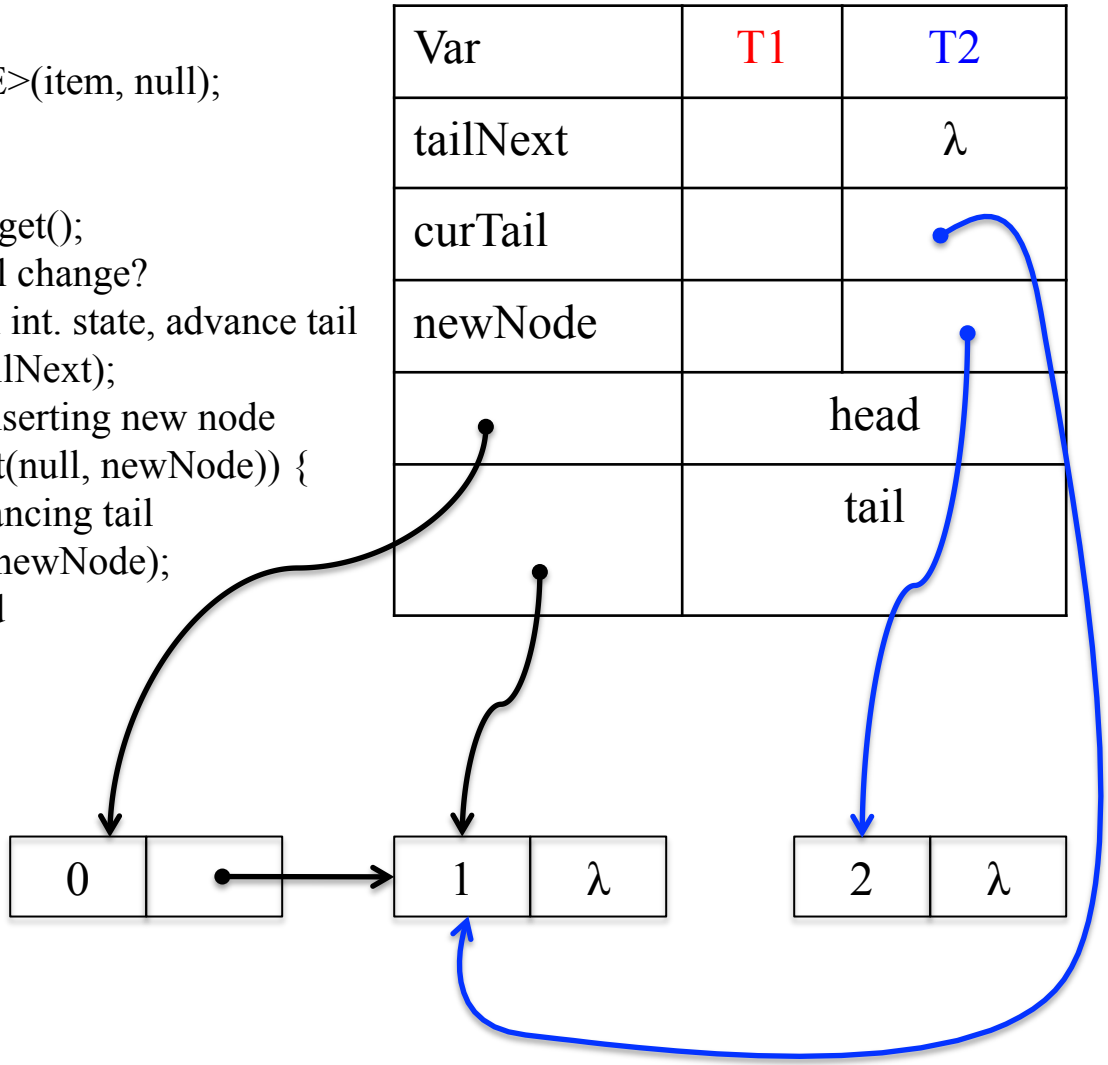
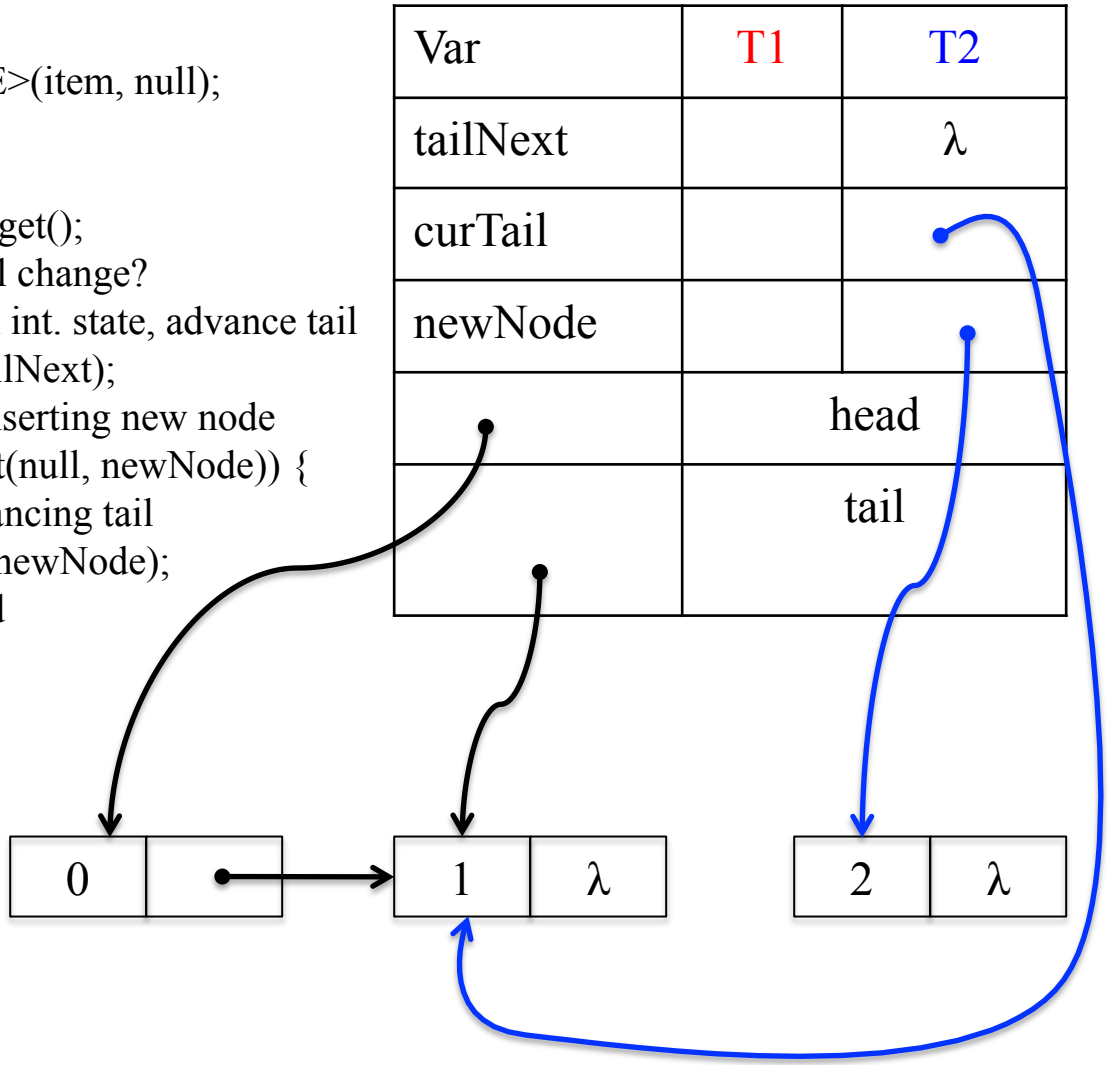



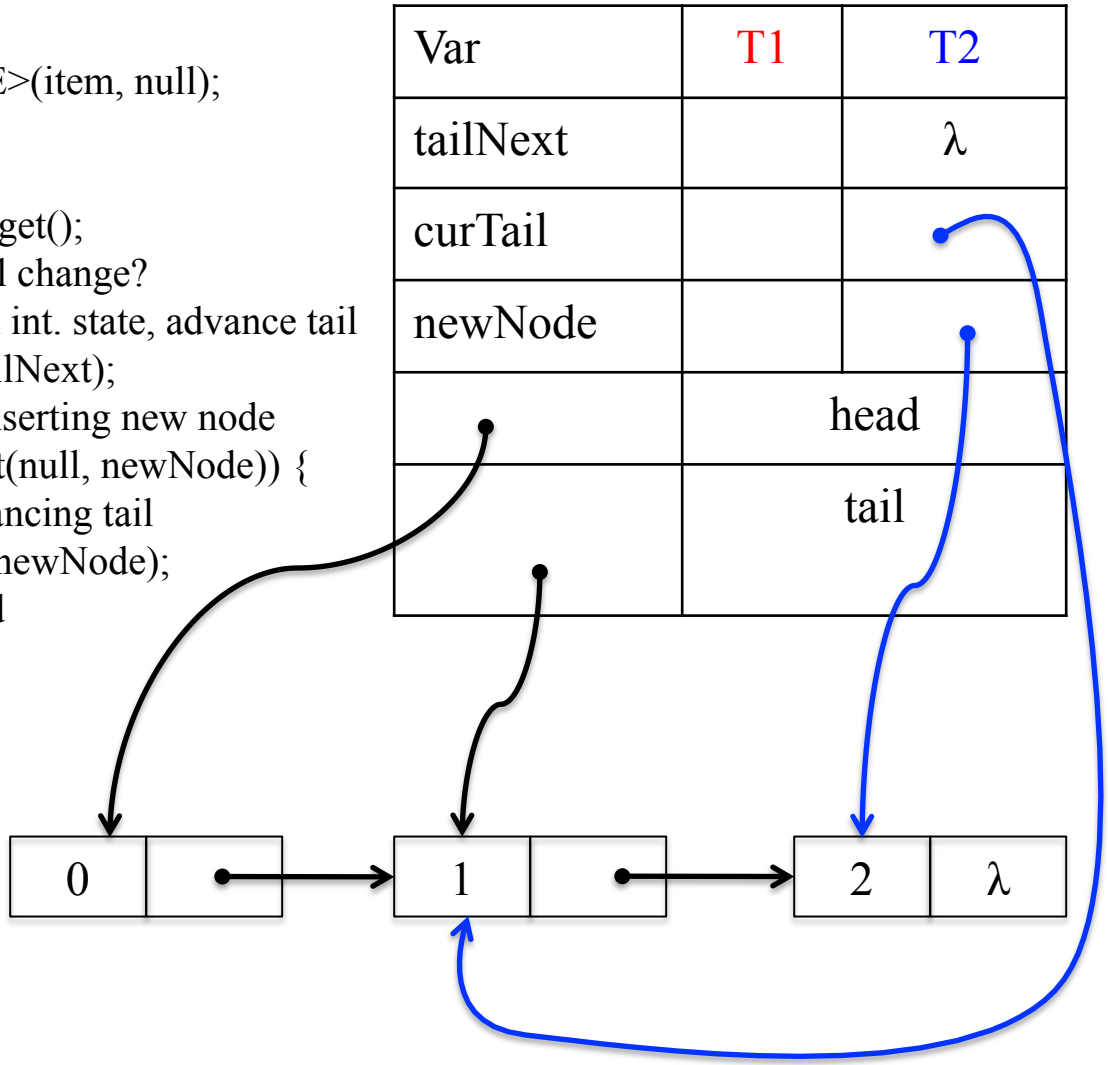
Trace 2: T2 continues

```
    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;
            }
          }
        }
      }
    }
```



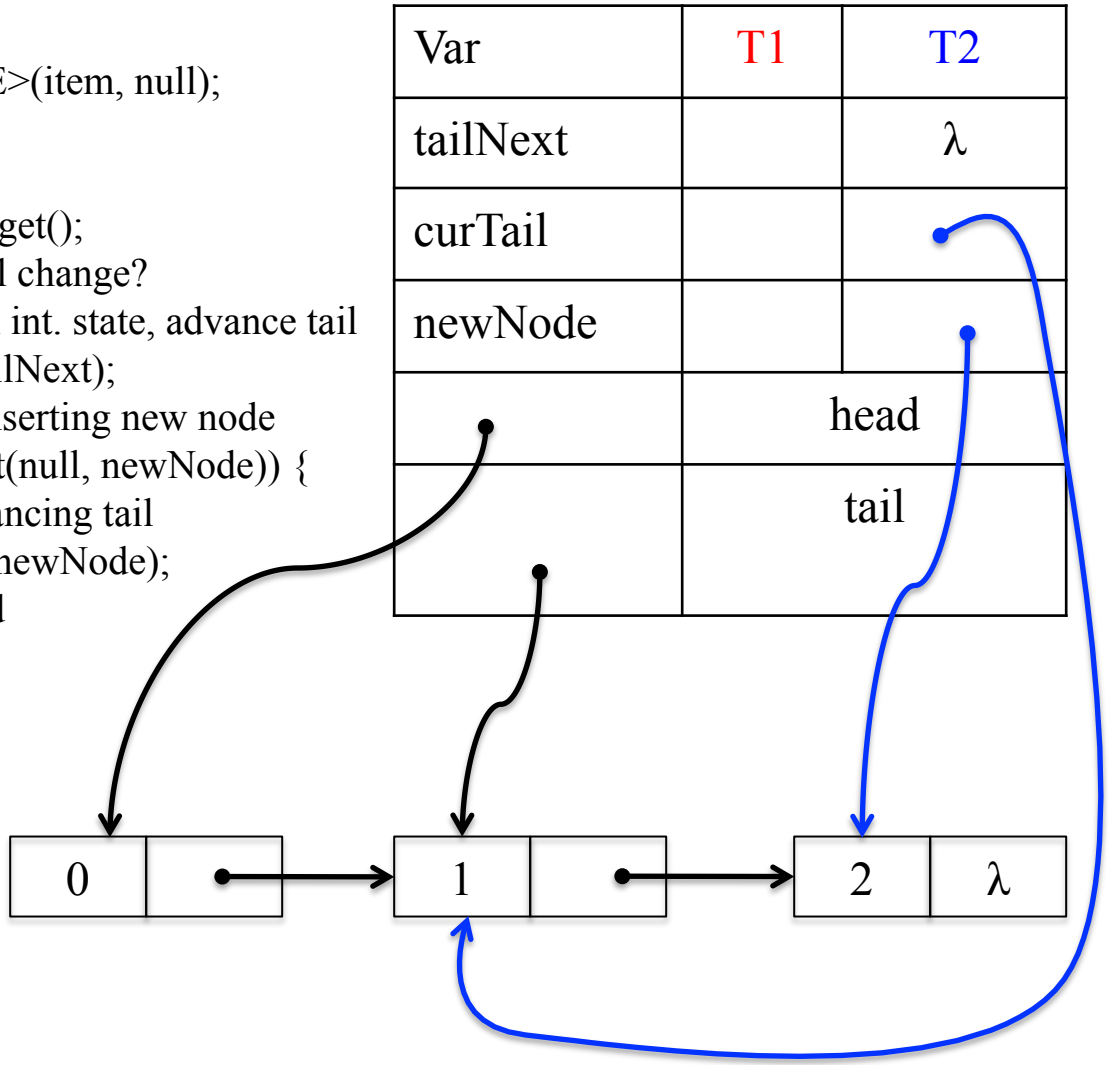
Trace 2: After CAS

```
    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;
            }
          }
        }
      }
    }
```



Trace 2: T2 continues

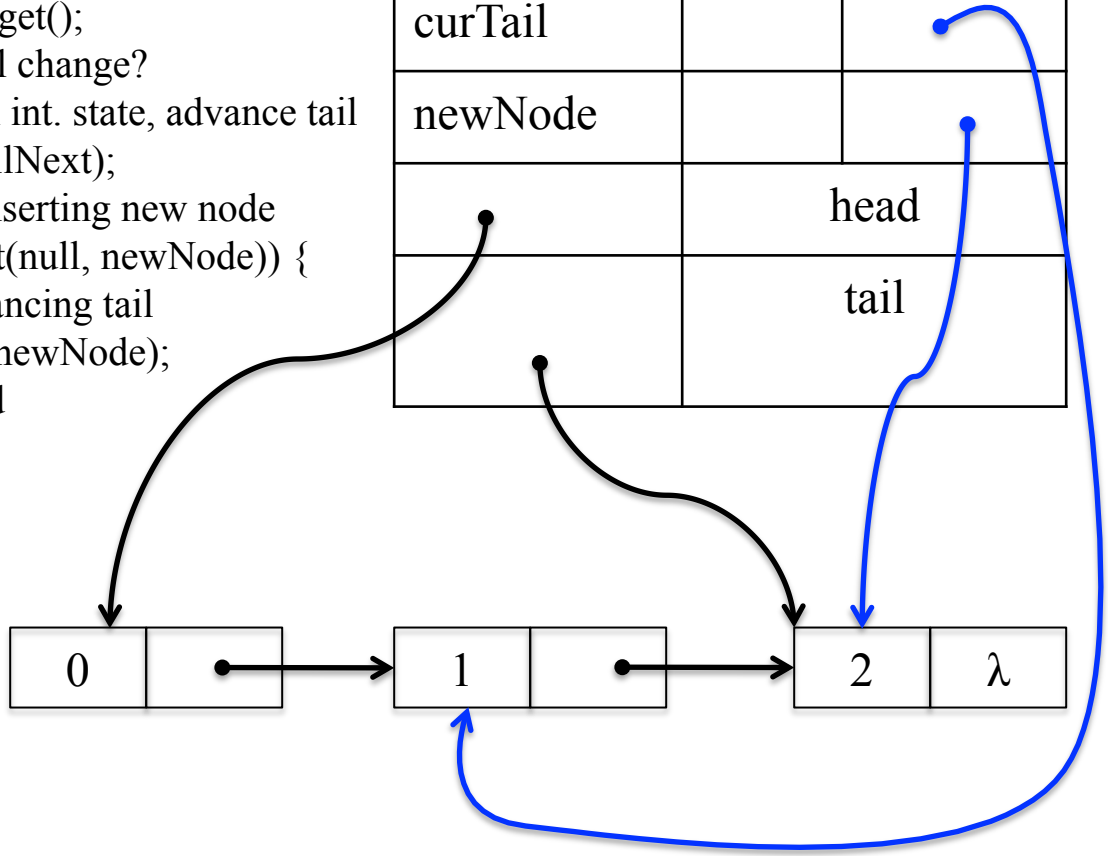
```
    public boolean put(E item) {
1     Node<E> newNode = new Node<E>(item, null);
2     while (true) {
3       Node<E> curTail = tail.get();
4       Node<E> tailNext = curTail.next.get();
5       if (curTail == tail.get()) {// did tail change?
6         if (tailNext != null) { // Queue in int. state,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