

YSC3248: Parallel, Concurrent and Distributed Programming

Concurrent Queues and the ABA Problem

The Five-Fold Path

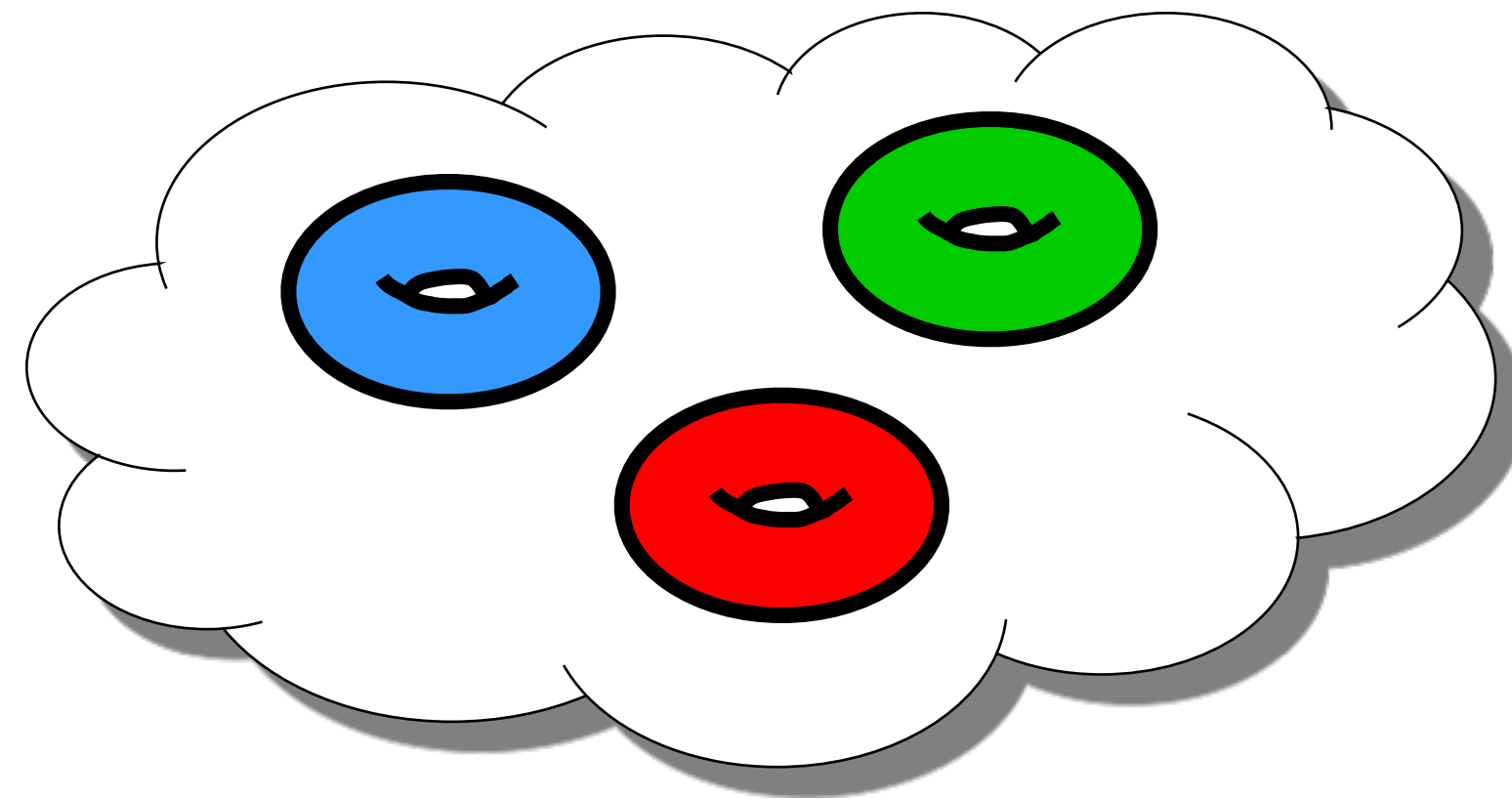
- Coarse-grained locking
- Fine-grained locking
- Optimistic synchronization
- Lazy synchronization
- Lock-free synchronization (a glimpse of)

Another Fundamental Problem

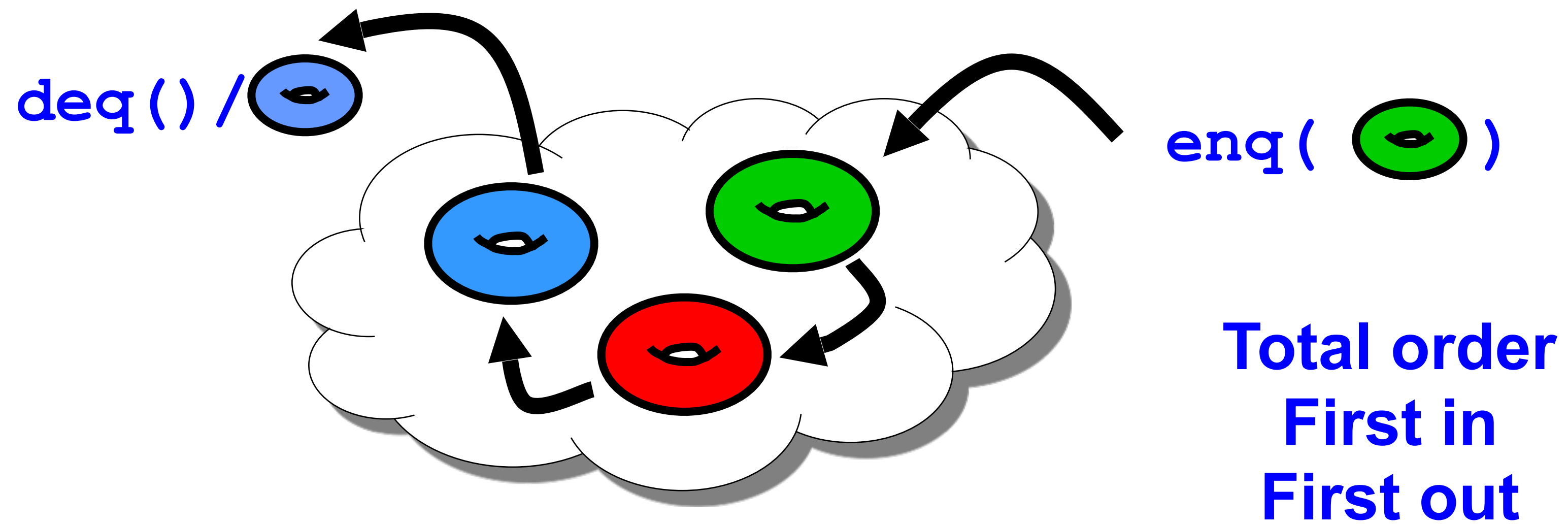
- We learned about
 - Sets implemented by linked lists
- Next: queues
- After that: stacks

Queues & Stacks

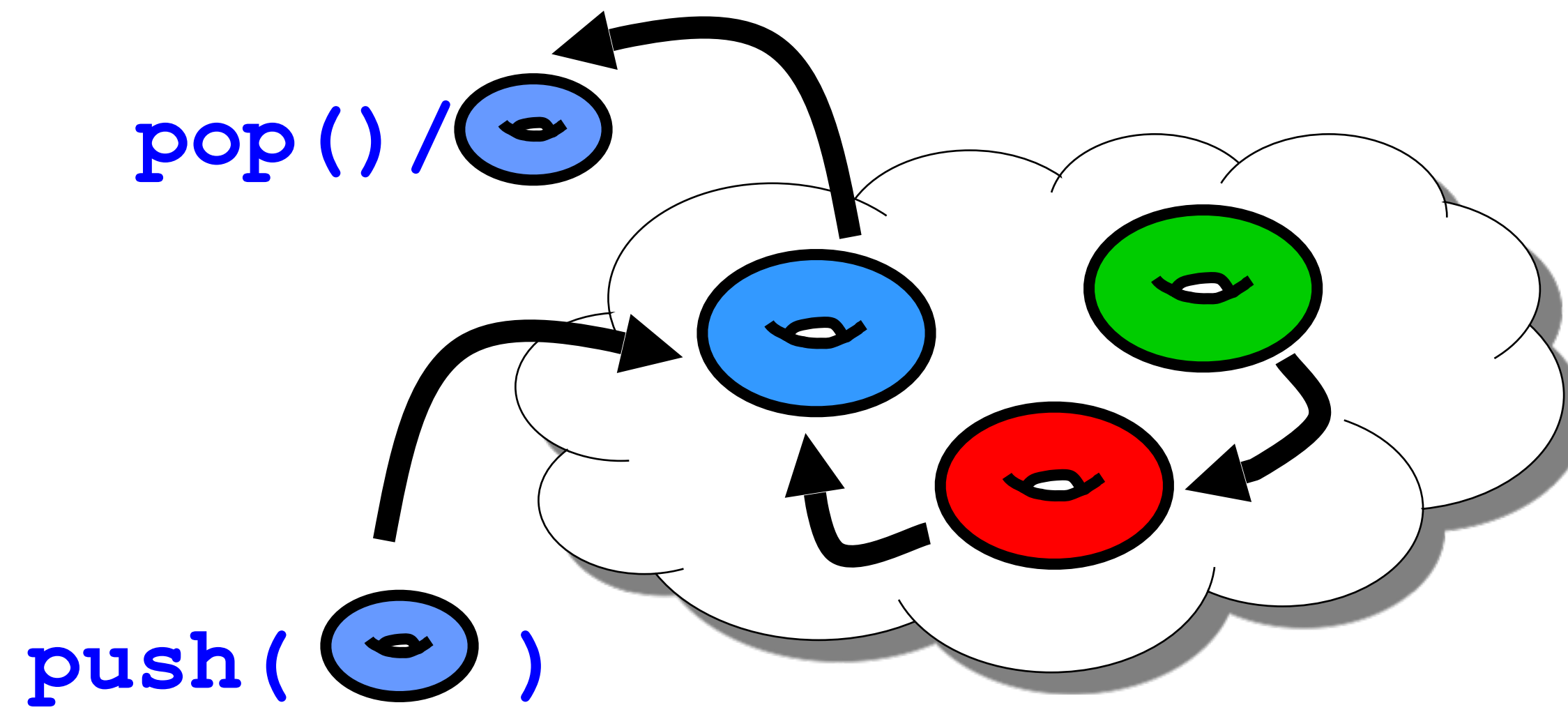
- pool of items



Queues



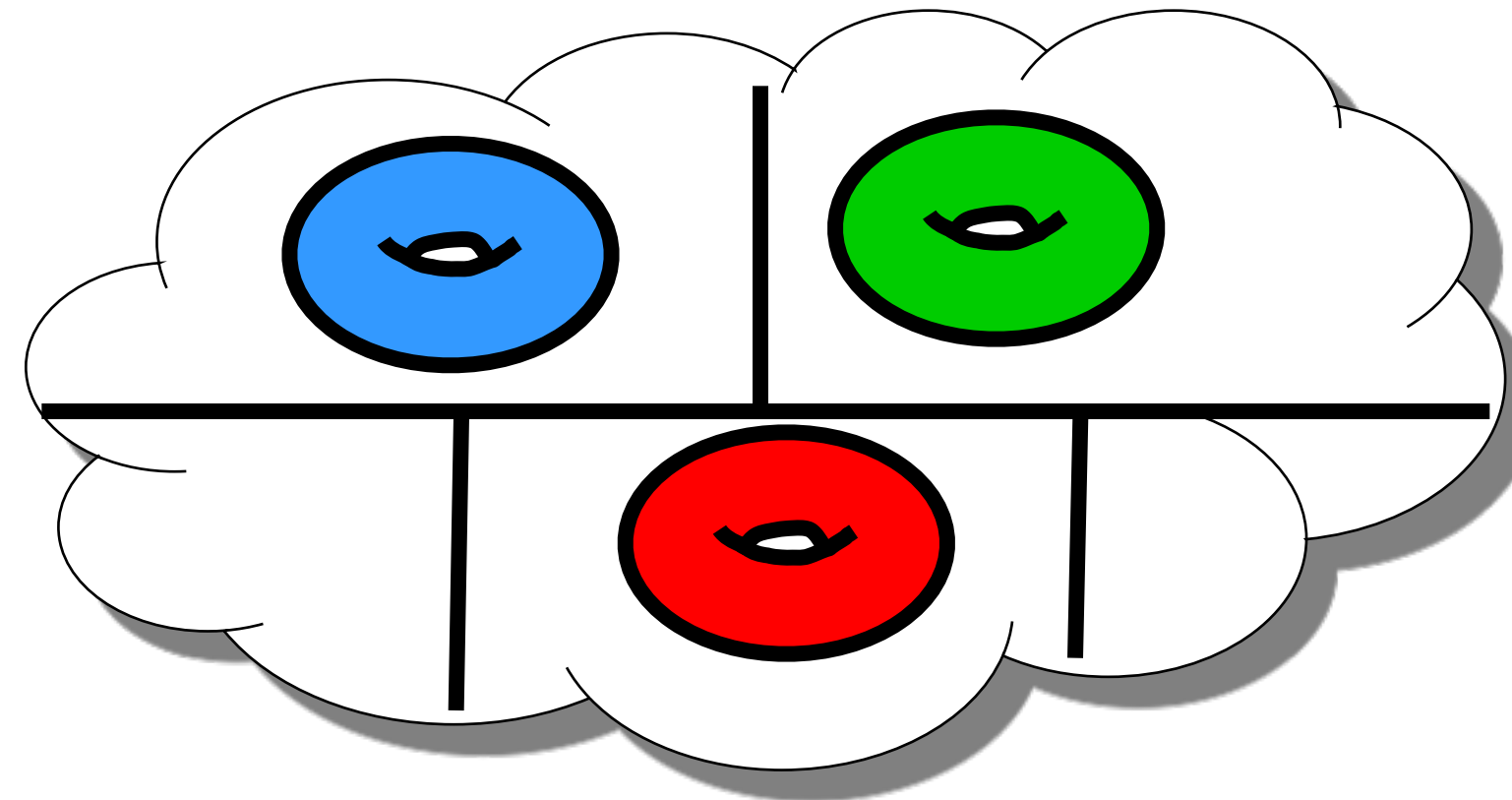
Stacks



Total order
Last in
First out

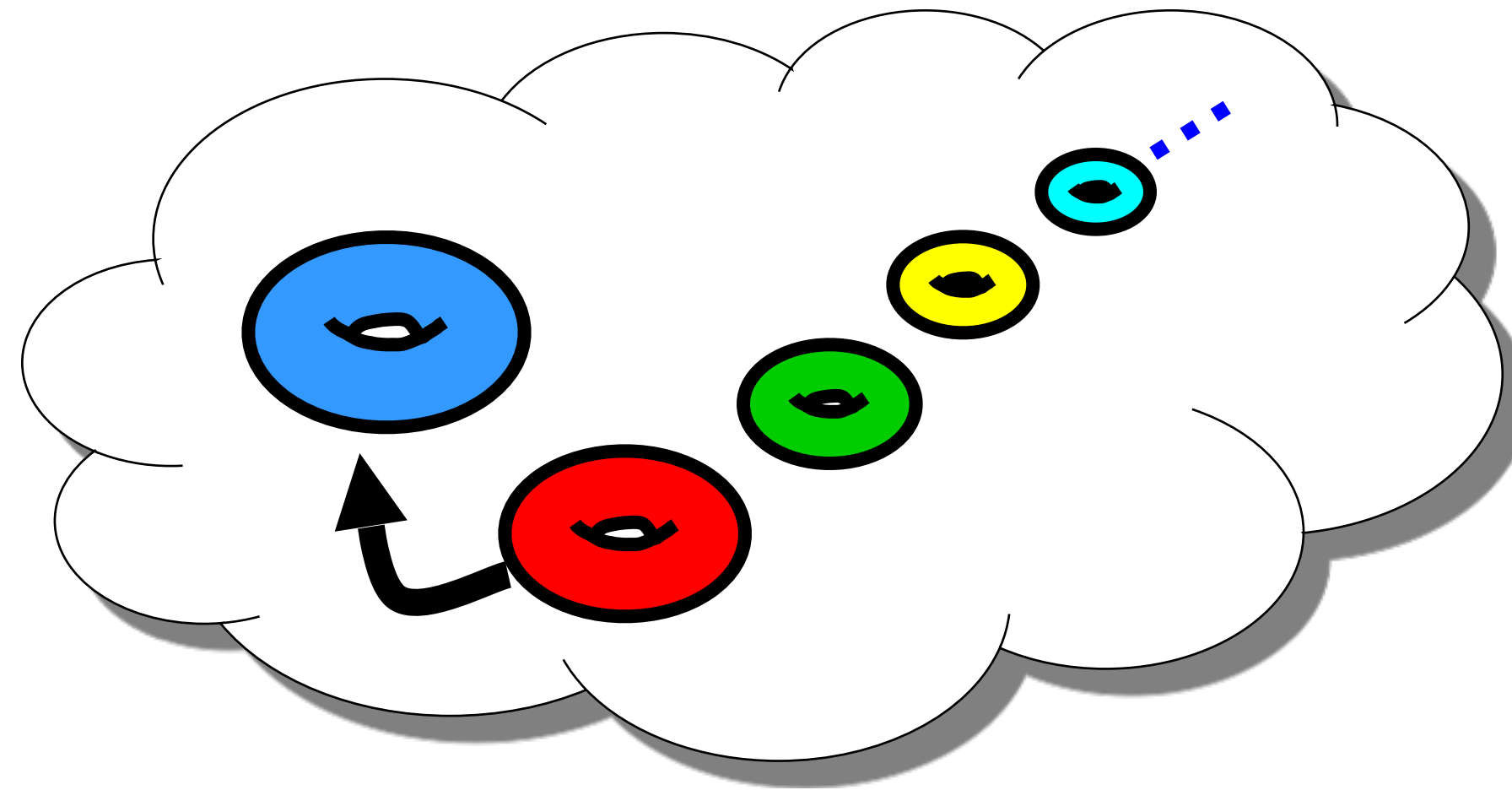
Bounded

- Fixed capacity
- Good when resources an issue

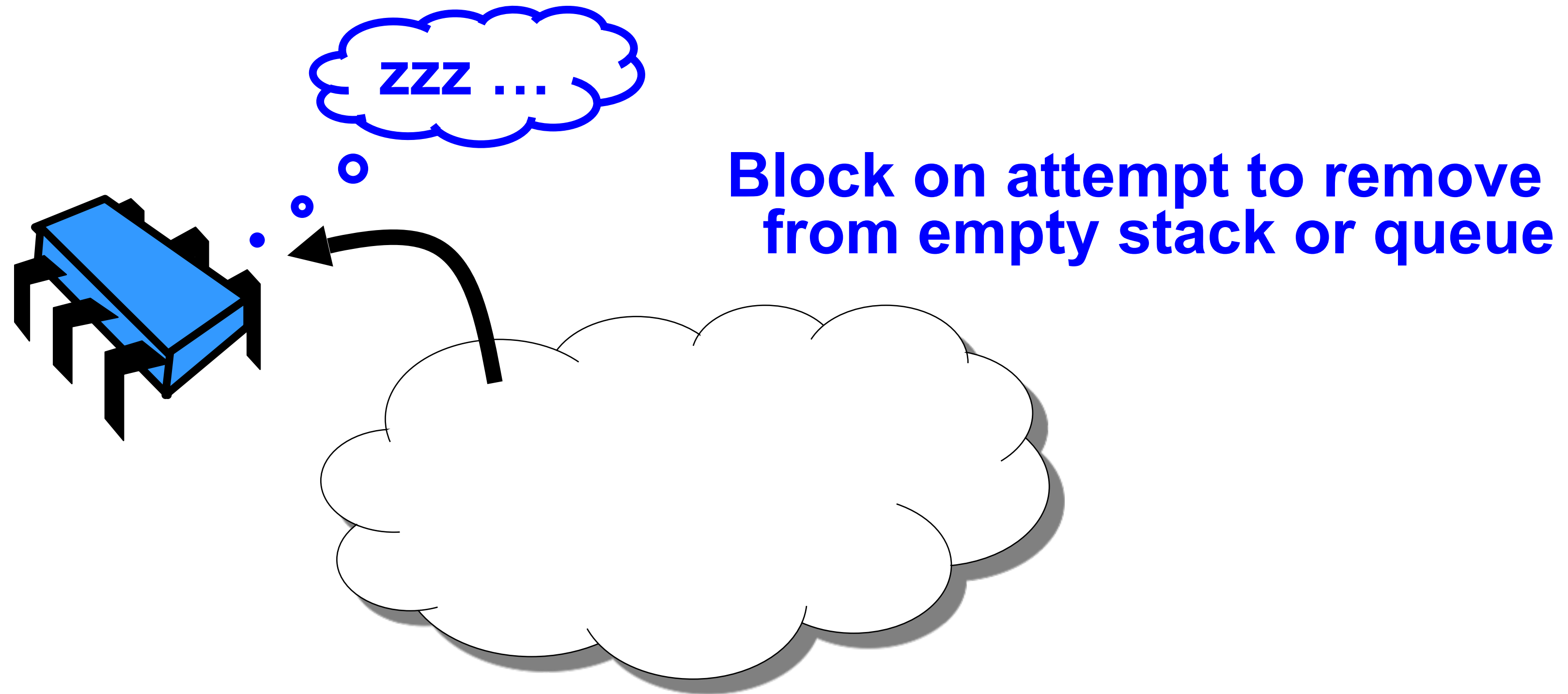


Unbounded

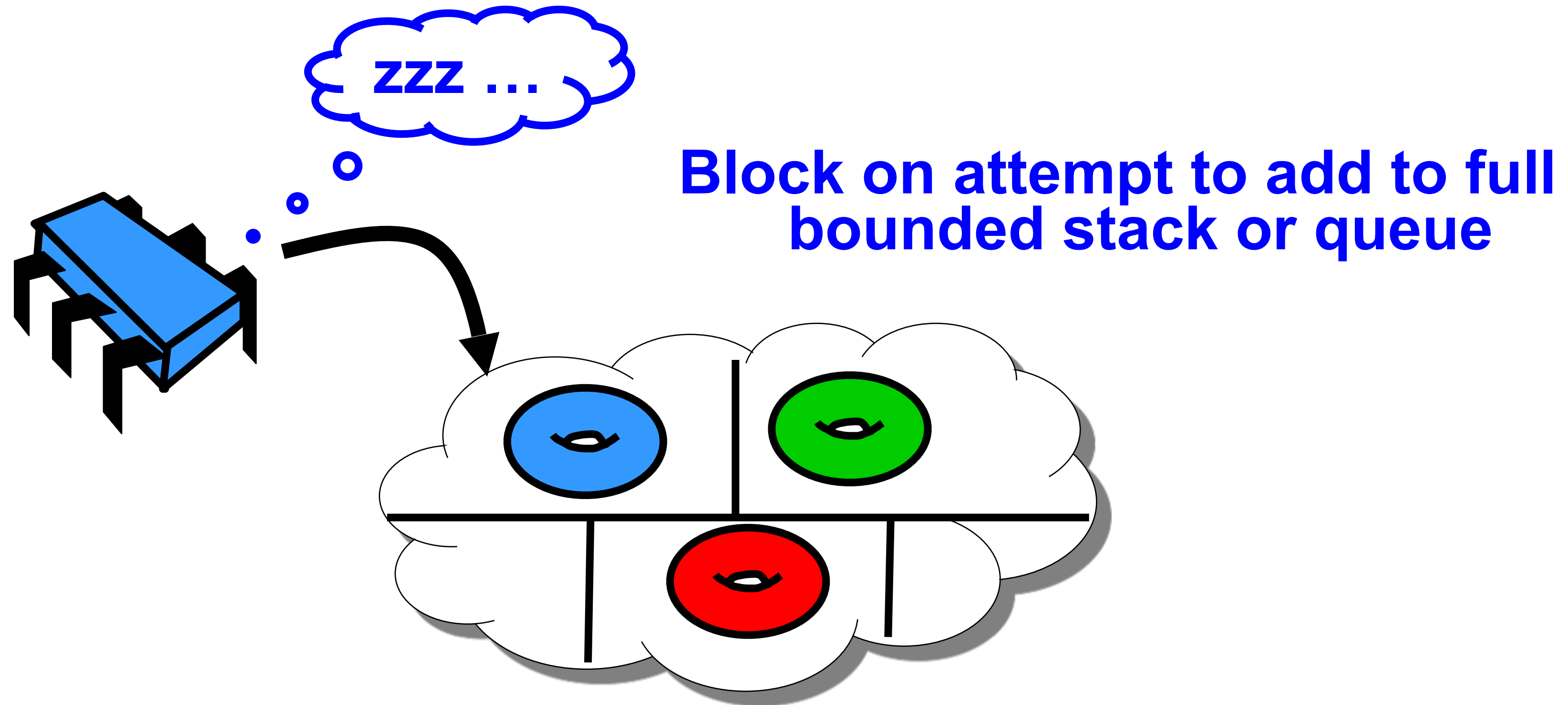
- Unlimited capacity
- Often more convenient



Blocking



Blocking



Non-Blocking



This and Next Lecture

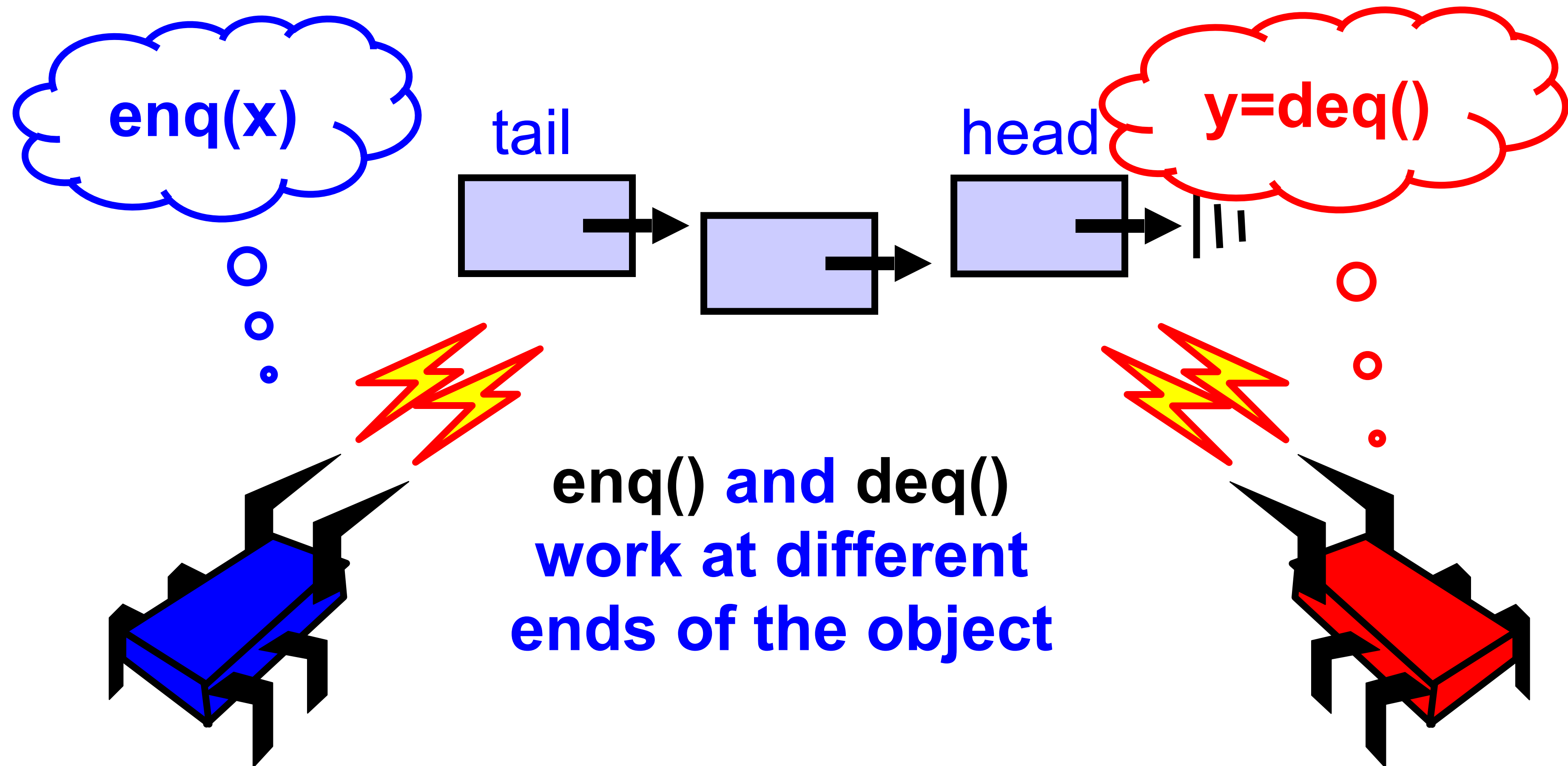
- Queue
 - Bounded, blocking, lock-based
 - Unbounded, non-blocking, lock-free
- Stack
 - Unbounded, non-blocking lock-free
 - Elimination-backoff algorithm

This Lecture

- Queue
 - Bounded, blocking, lock-based
 - Unbounded, non-blocking, lock-free
- Stack
 - Unbounded, non-blocking lock-free
 - Elimination-backoff algorithm

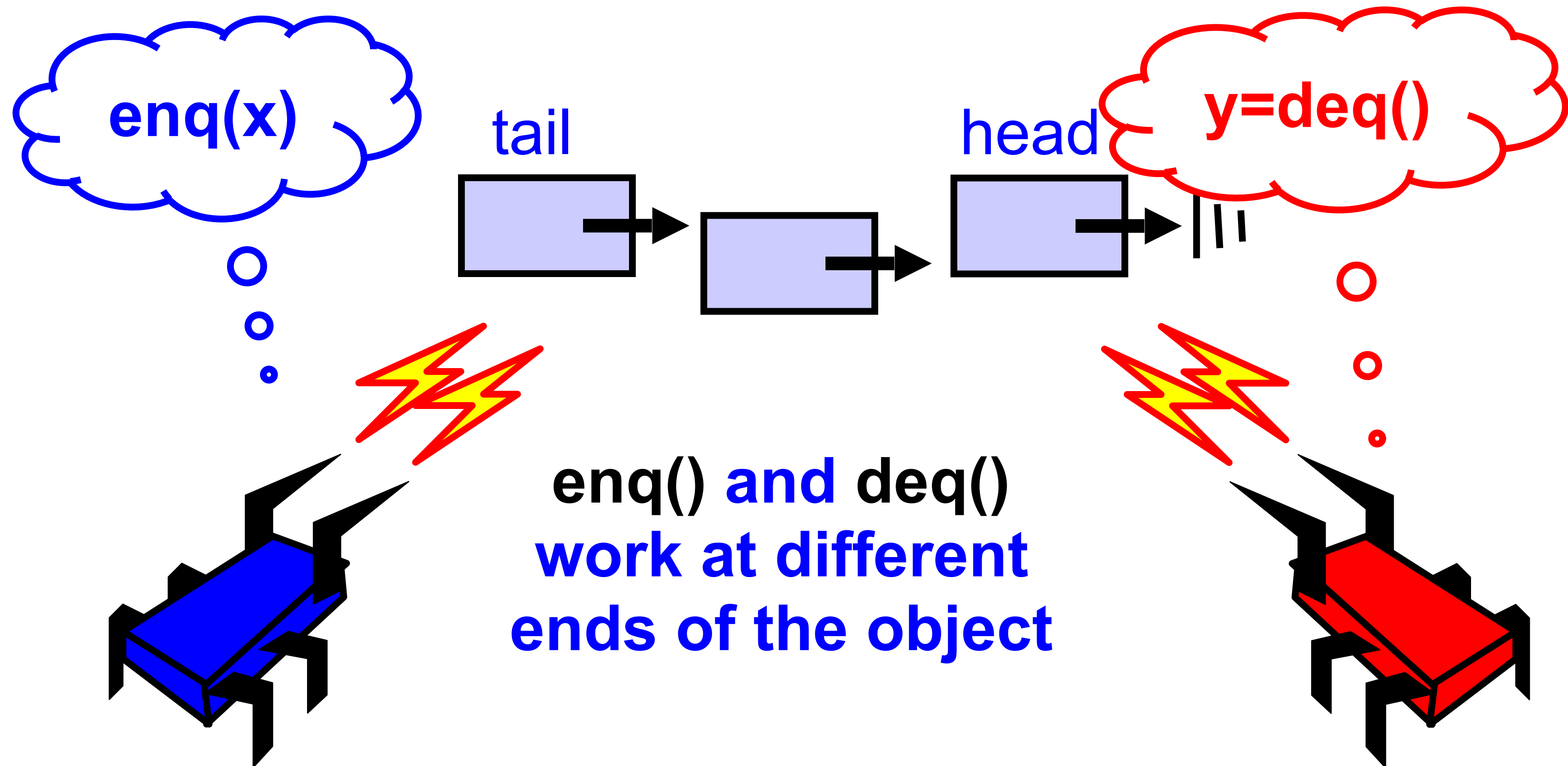
Warm-up:
Coarse-Grained Queues and Tests

Queue: Concurrency

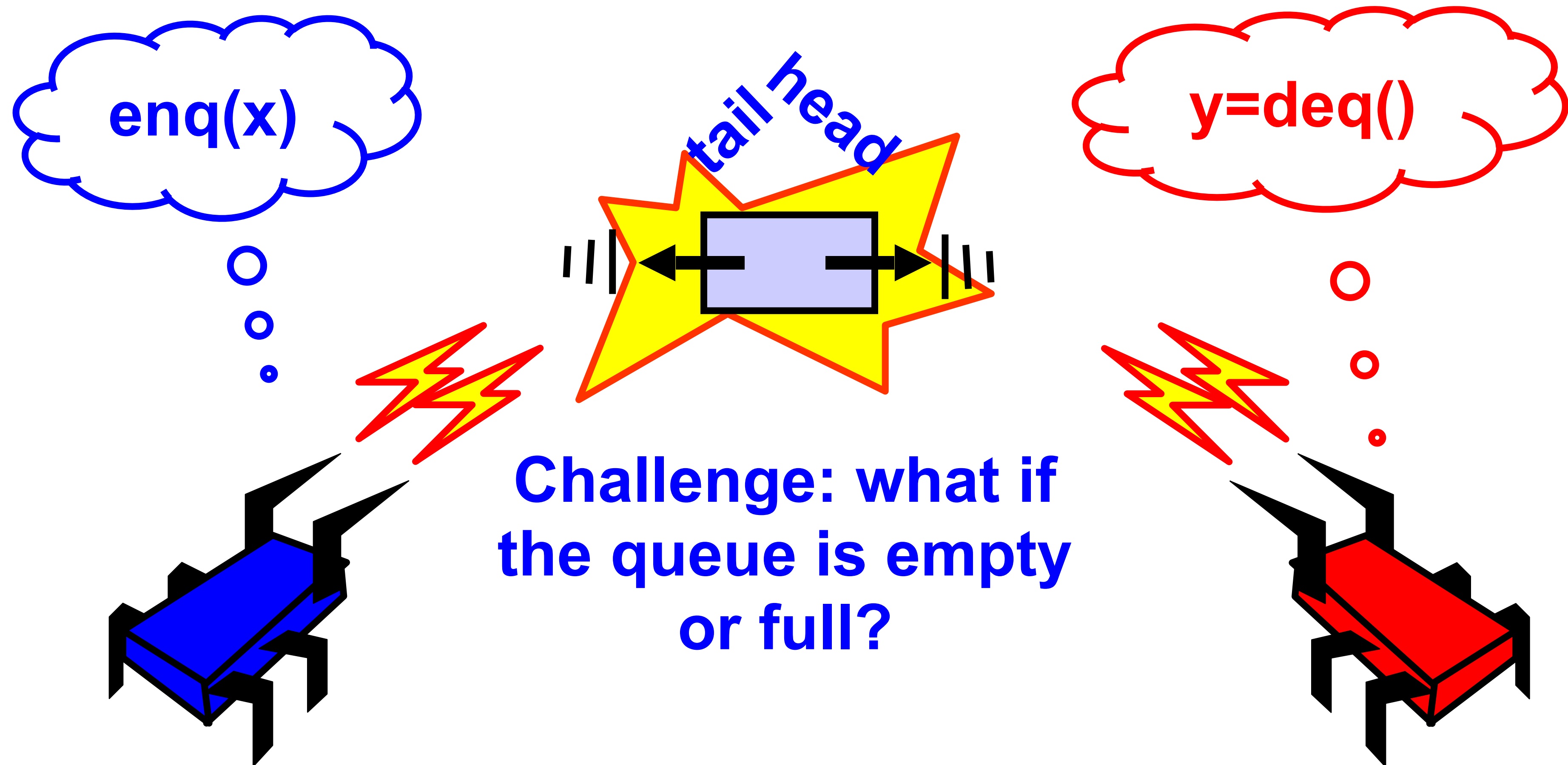


Let's Look at the Code:
Analysing Unbounded Queue

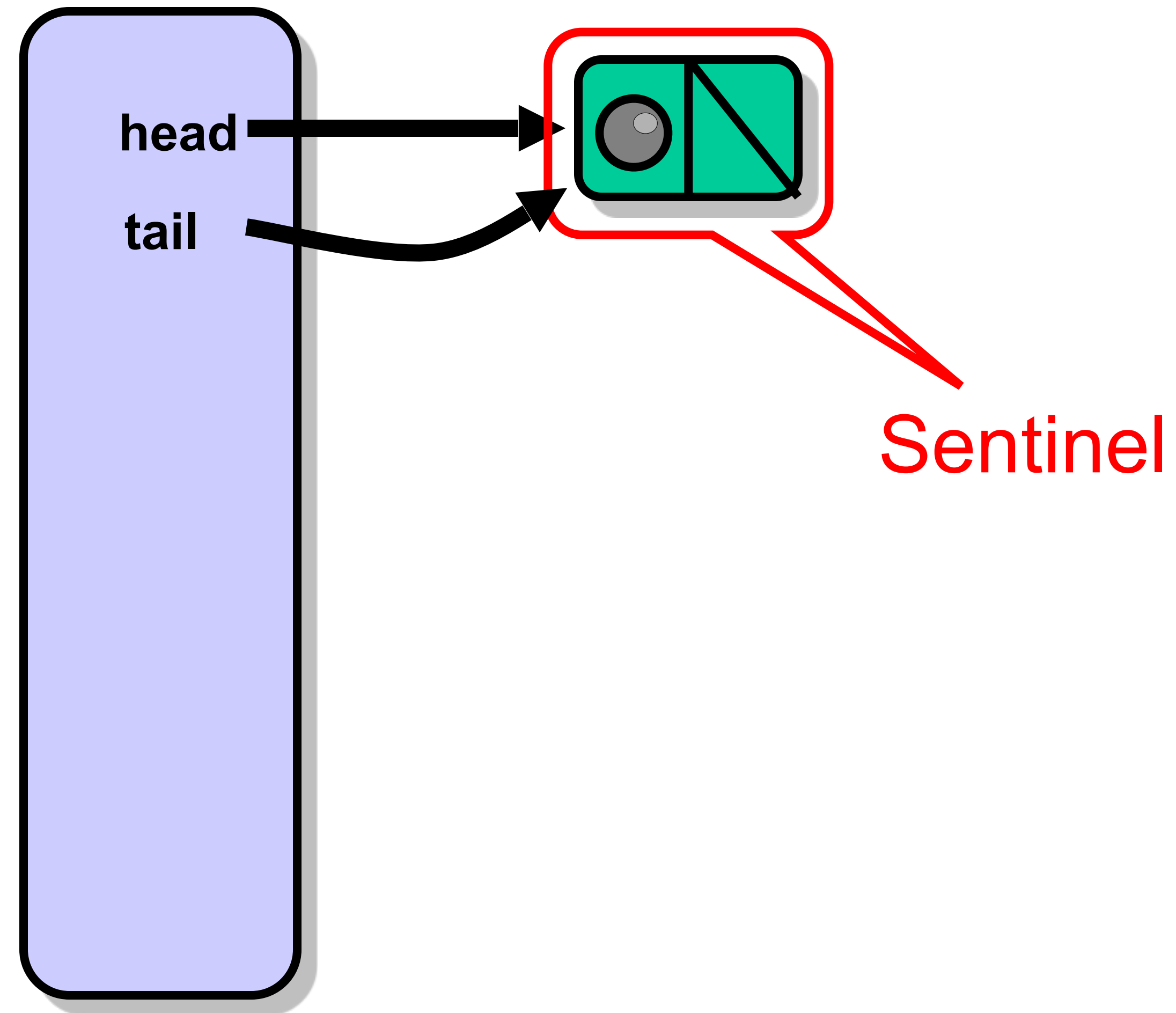
Queue: Concurrency



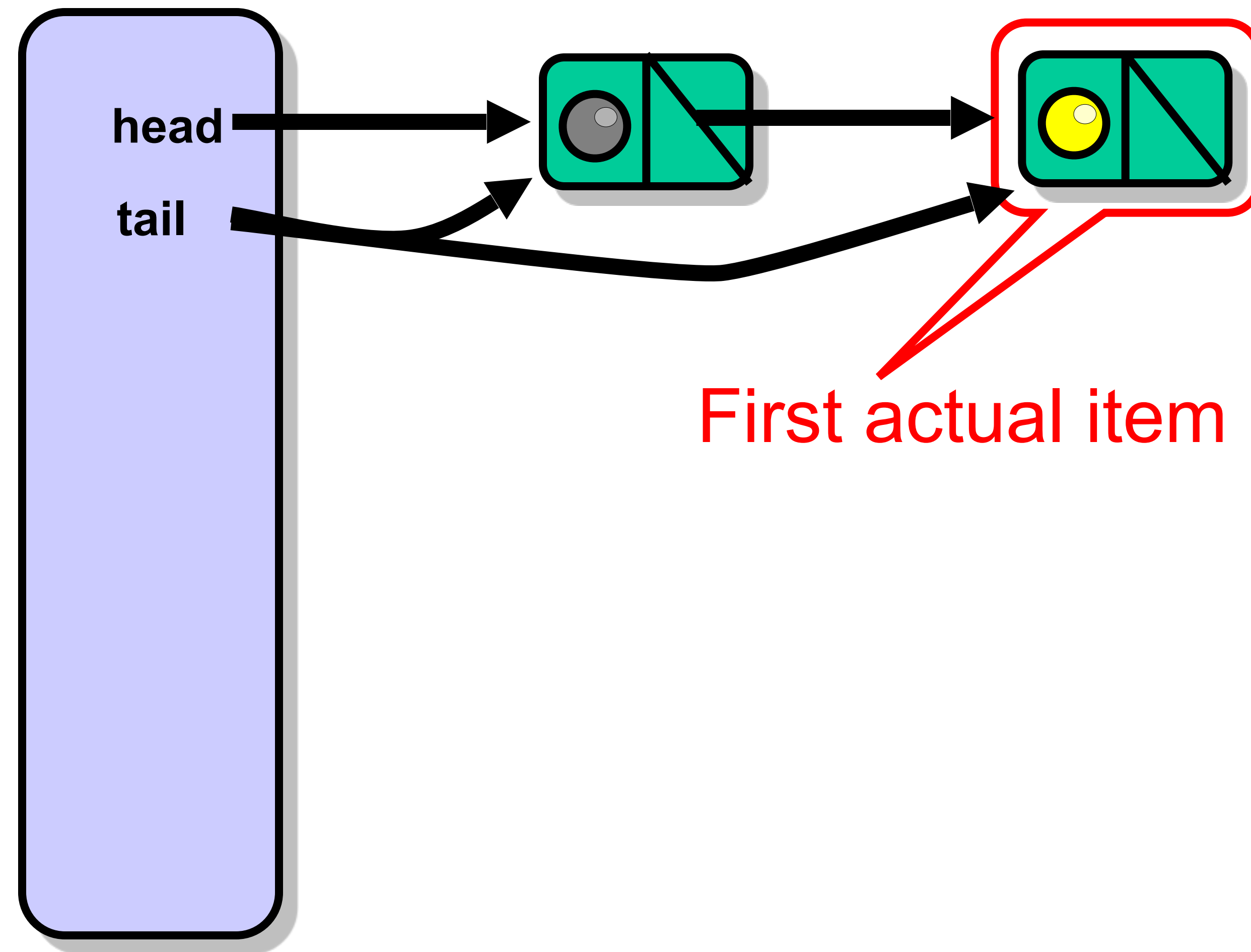
Concurrency



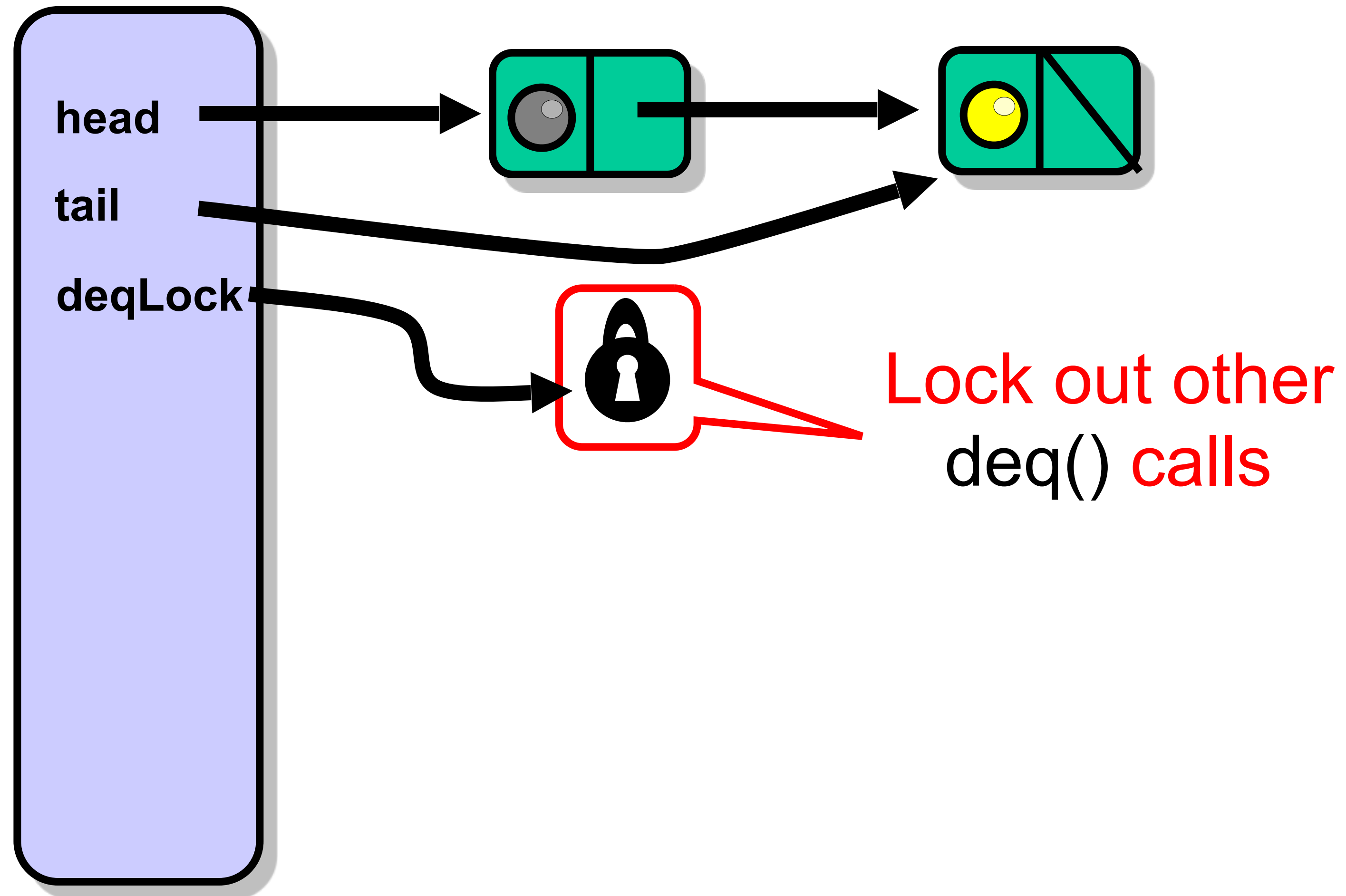
Bounded Queue



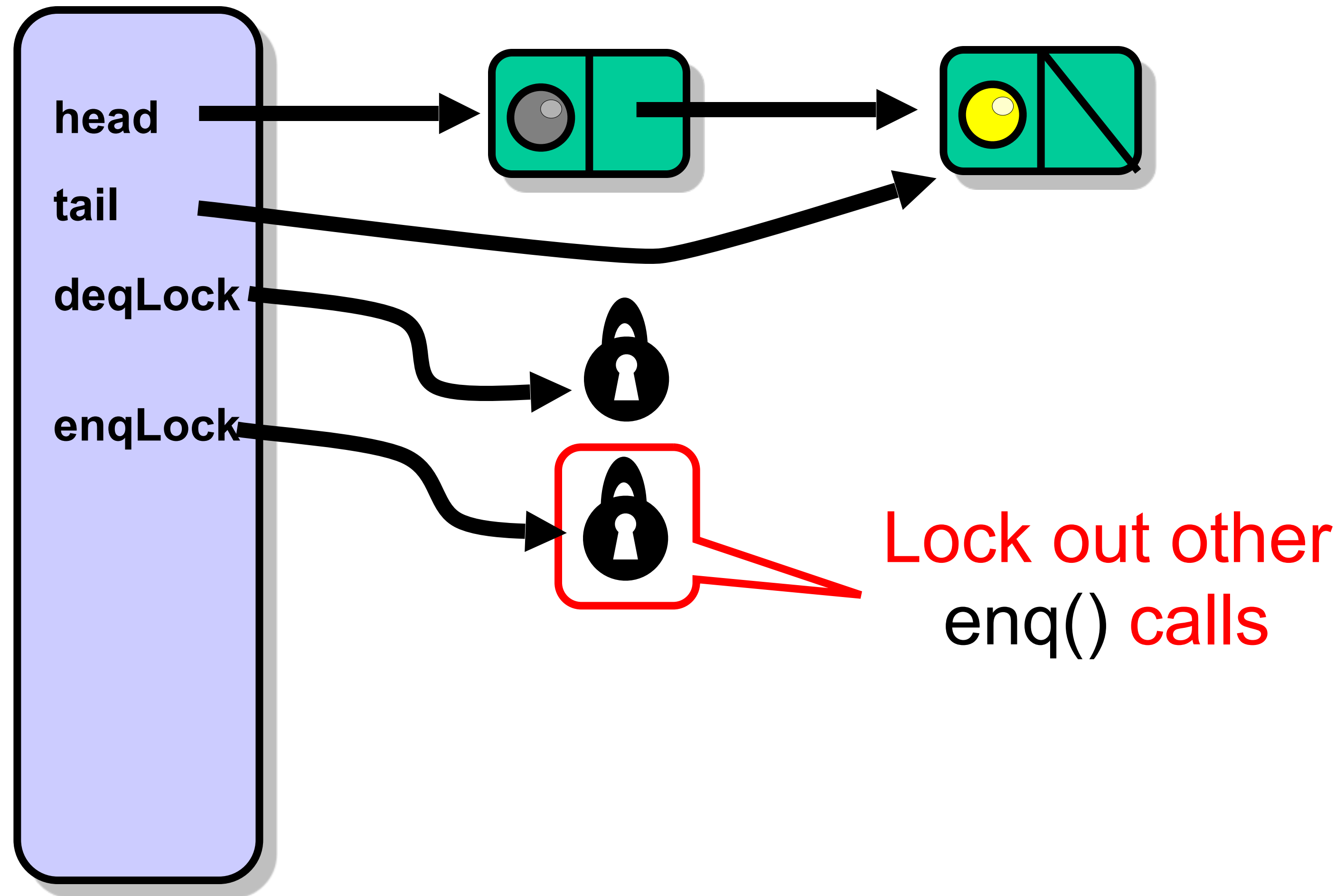
Bounded Queue



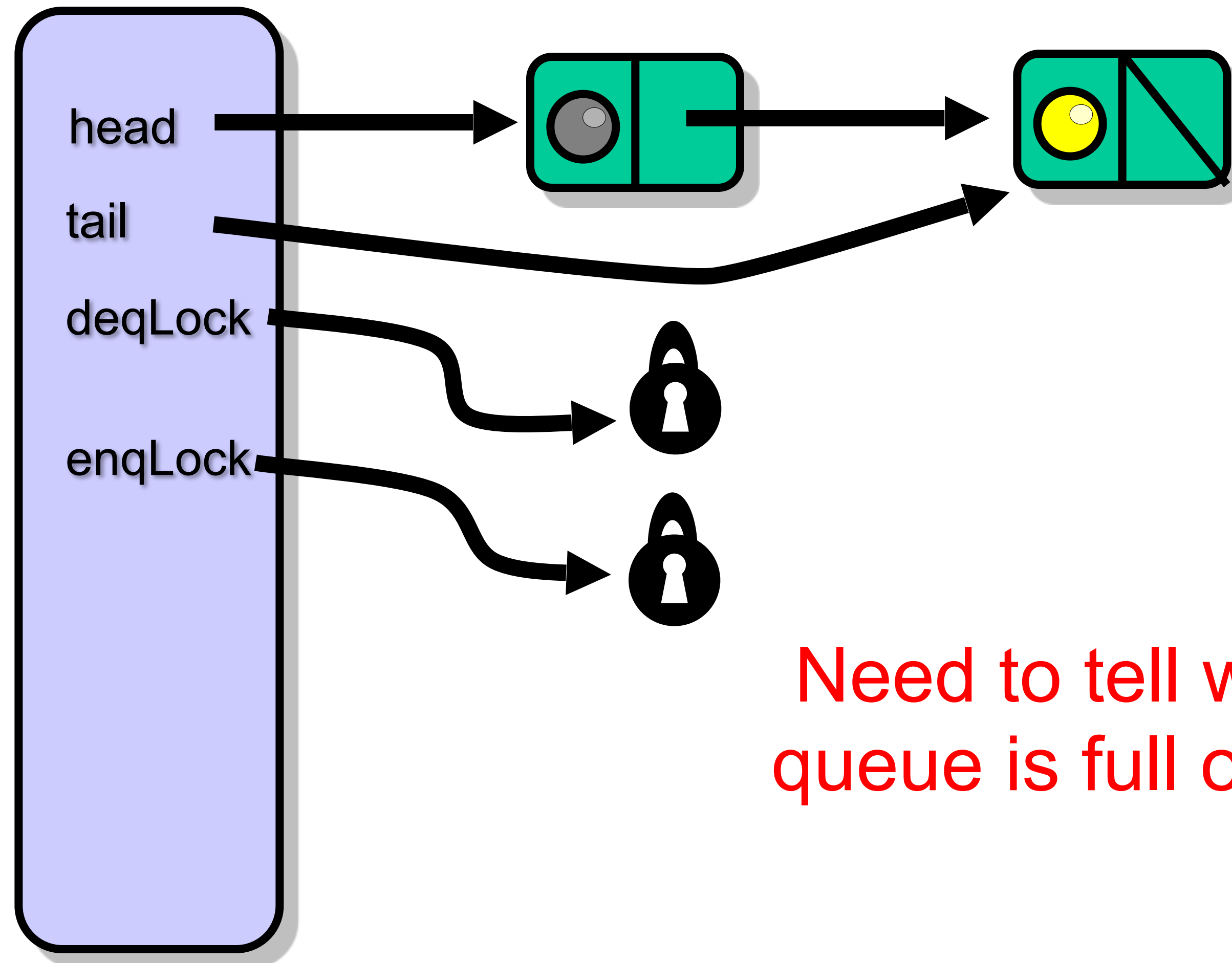
Bounded Queue



Bounded Queue

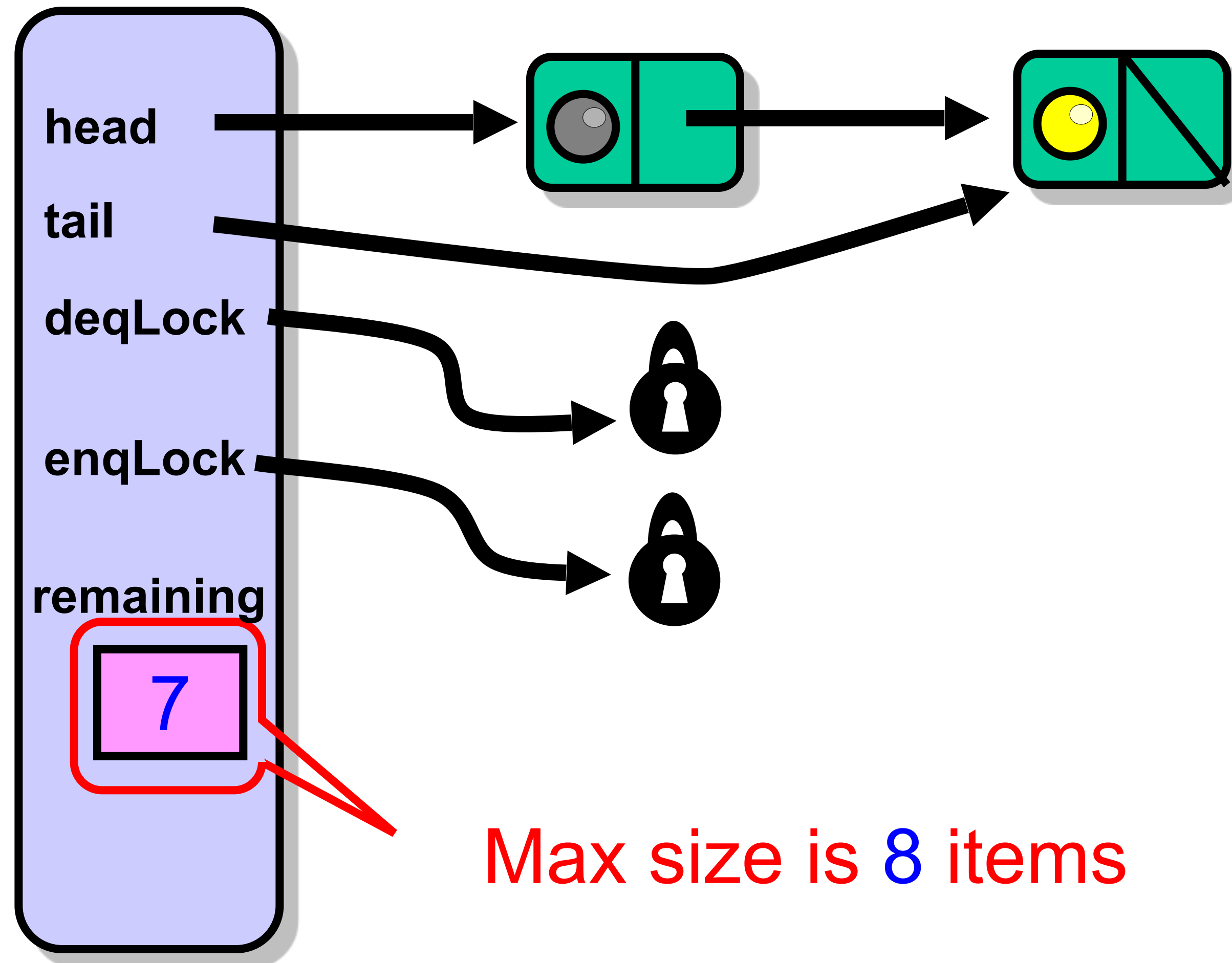


Not Done Yet

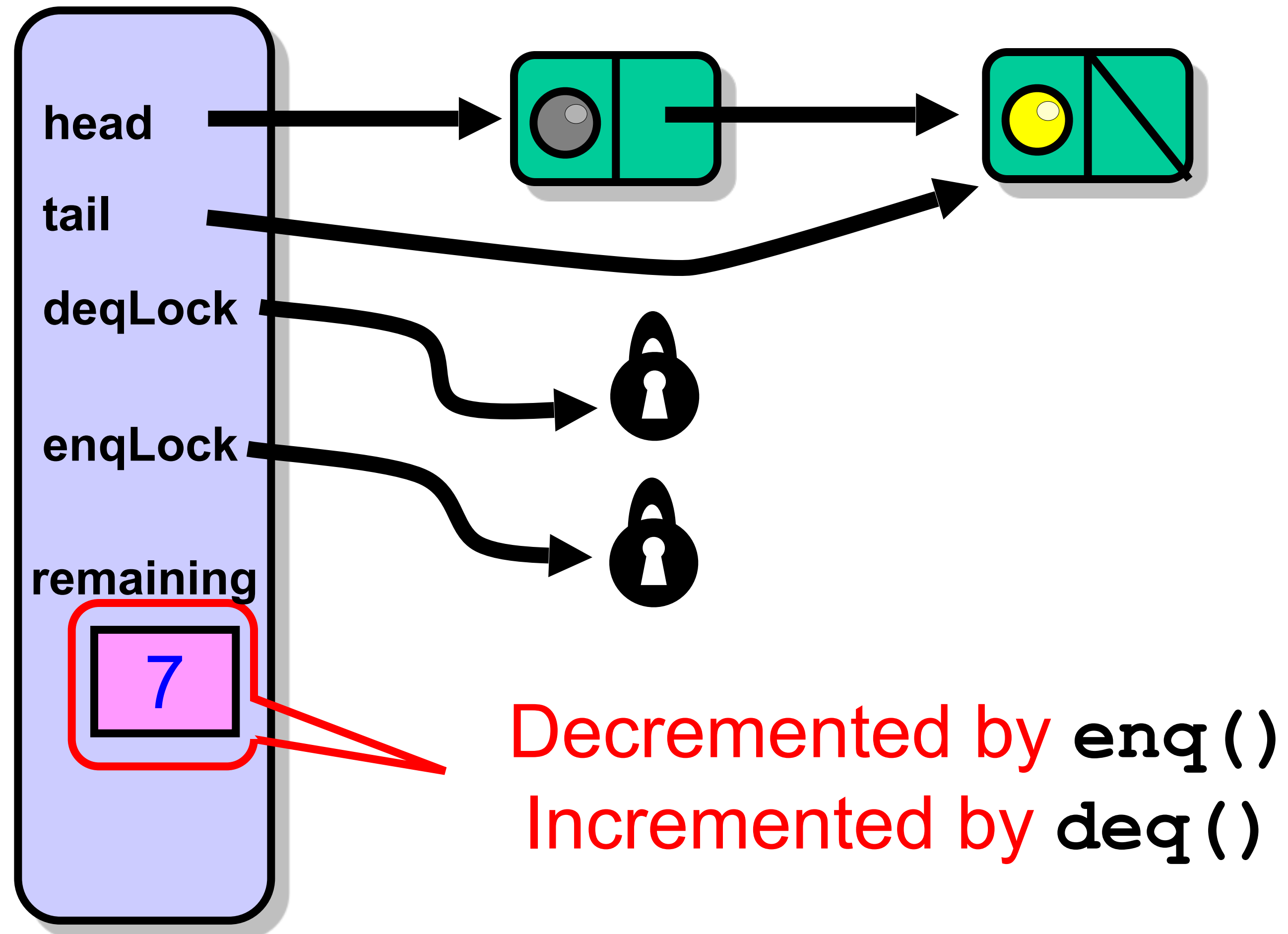


Need to tell whether
queue is full or empty

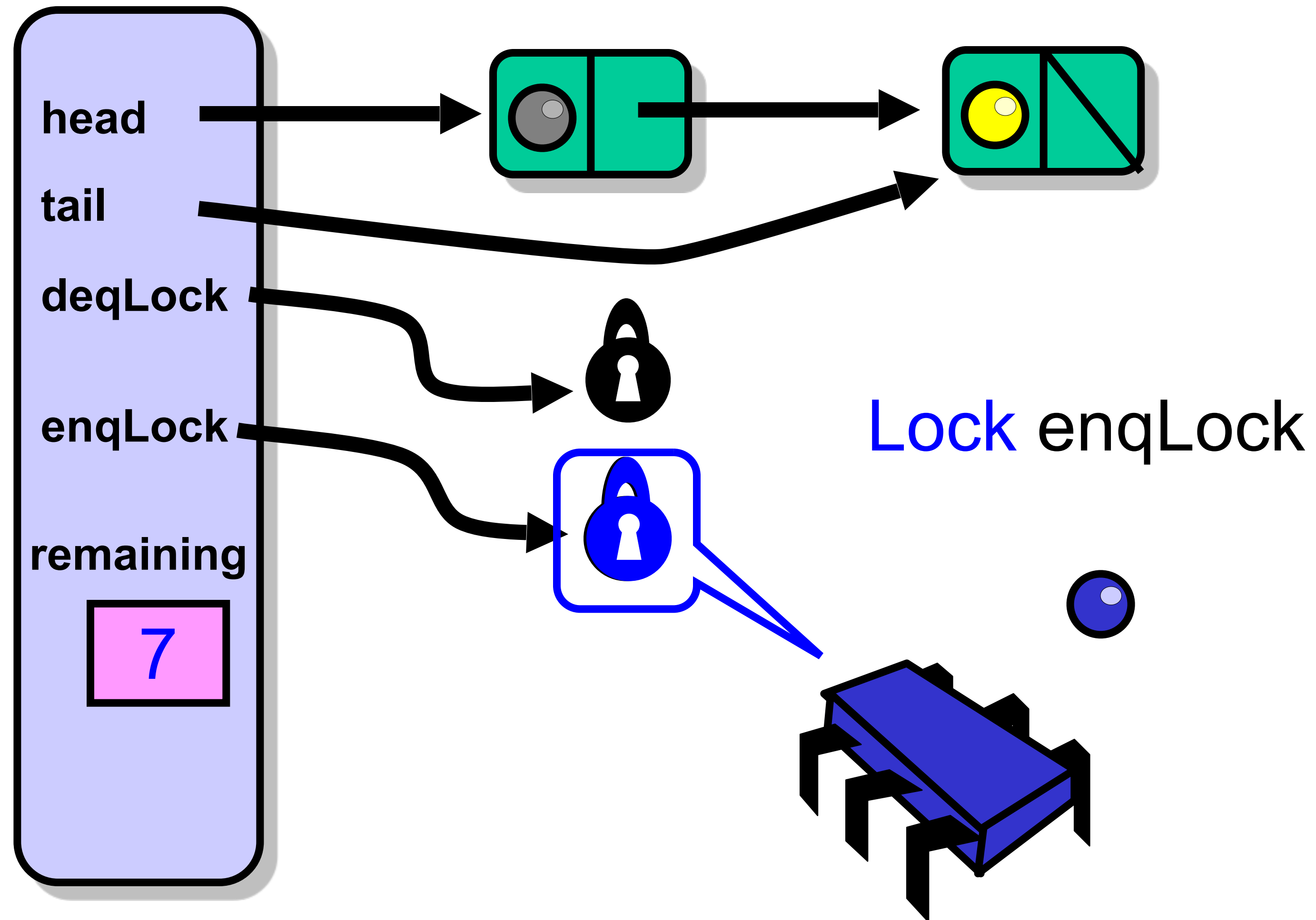
Not Done Yet



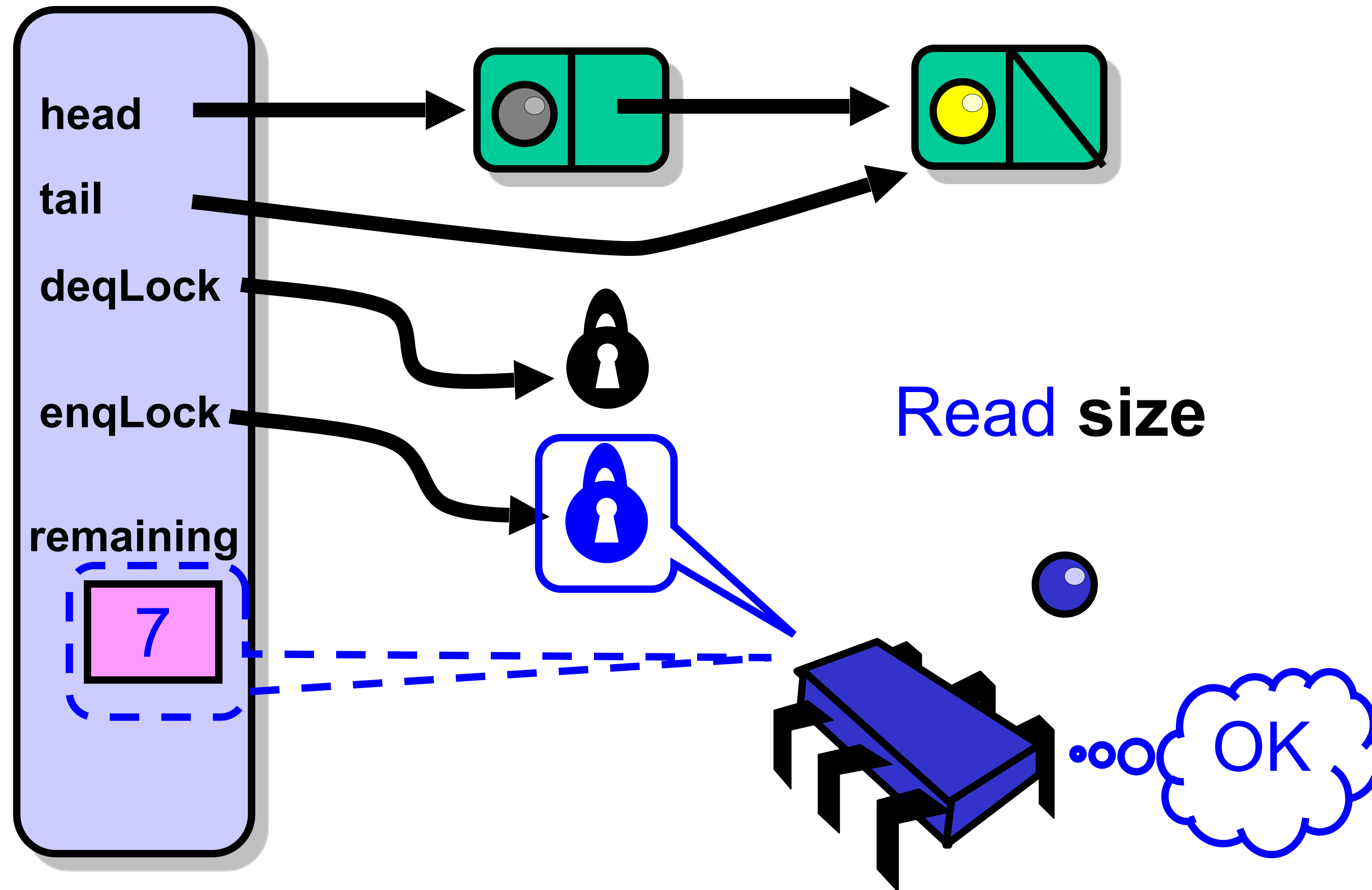
Not Done Yet



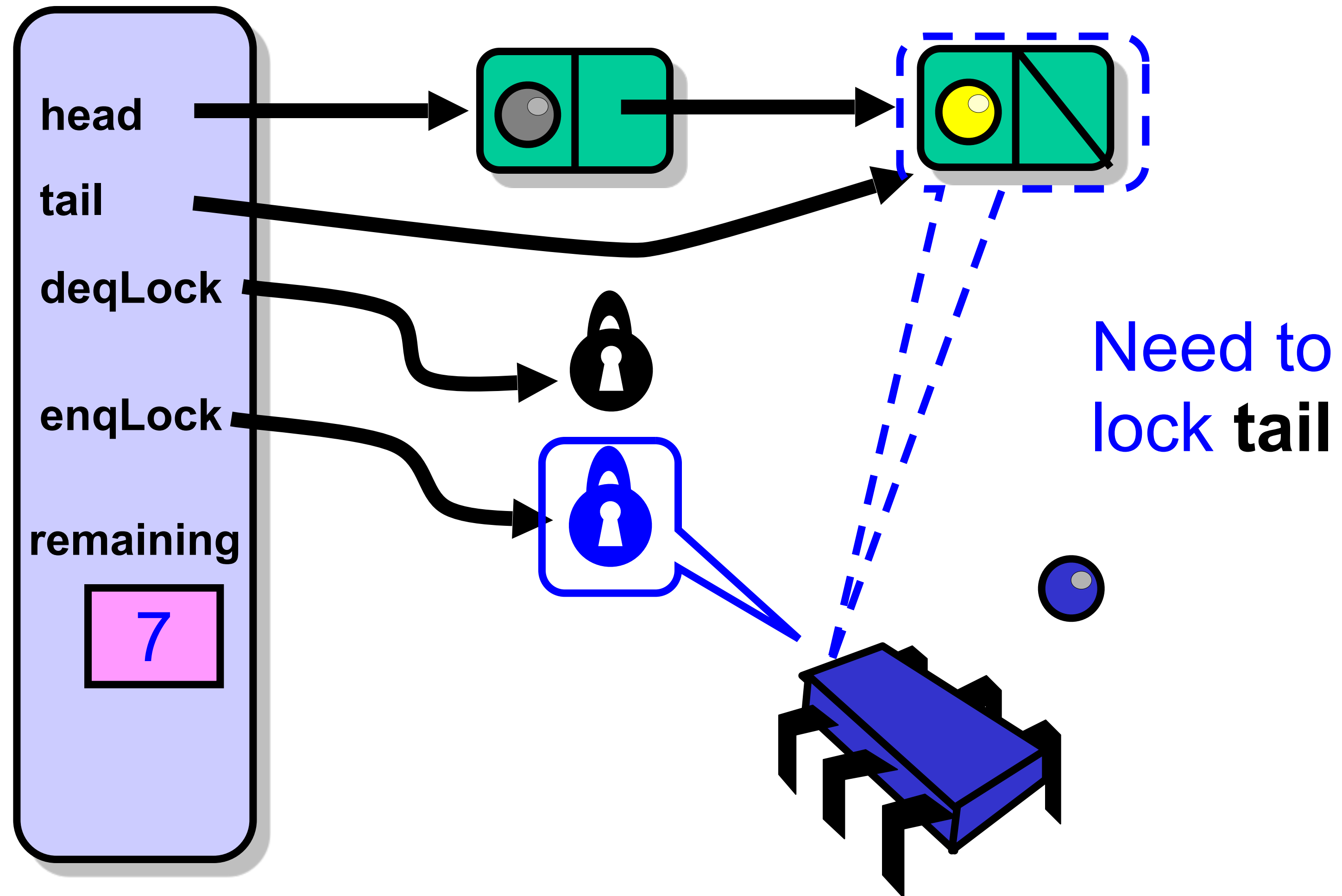
Enqueuer



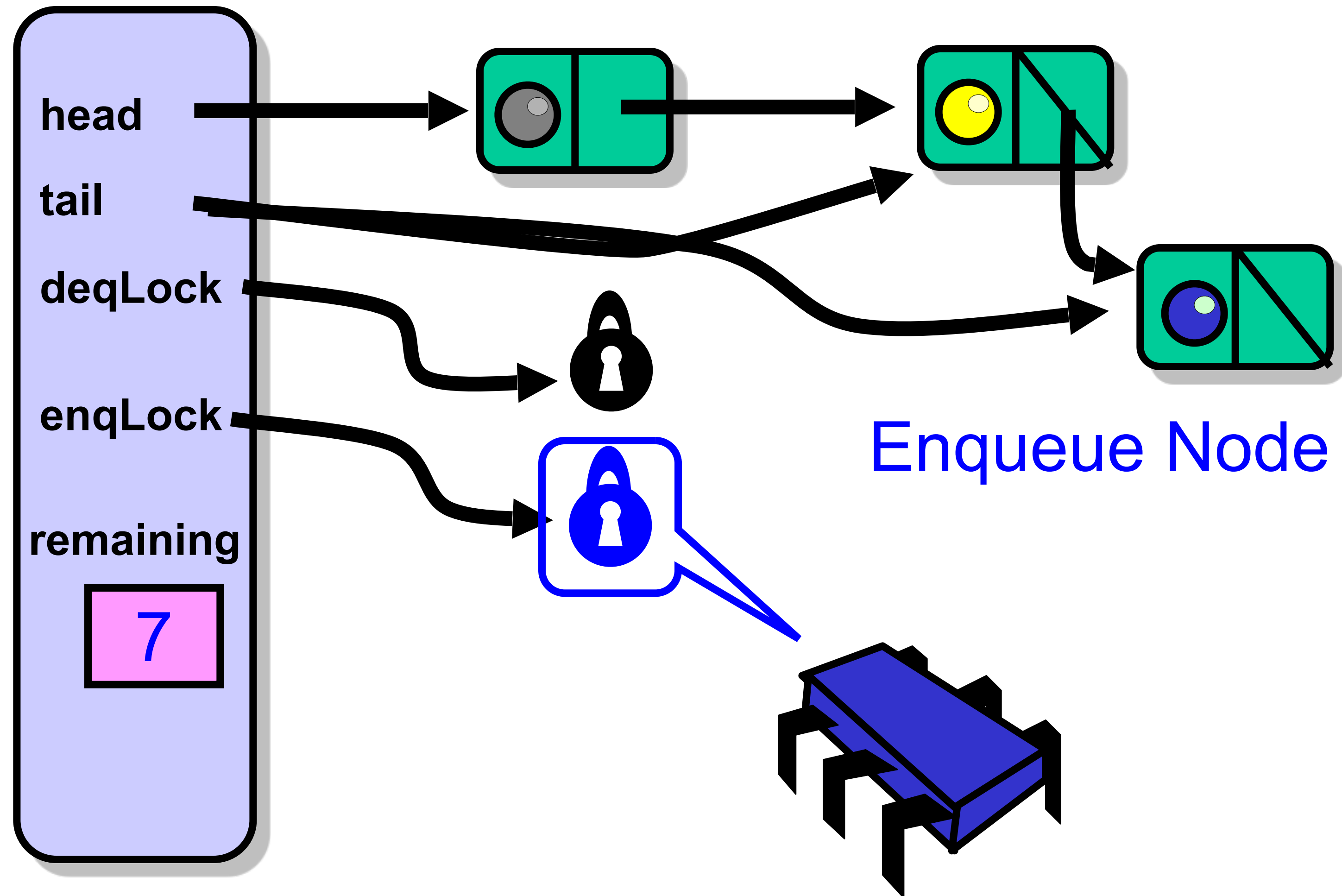
Enqueuer



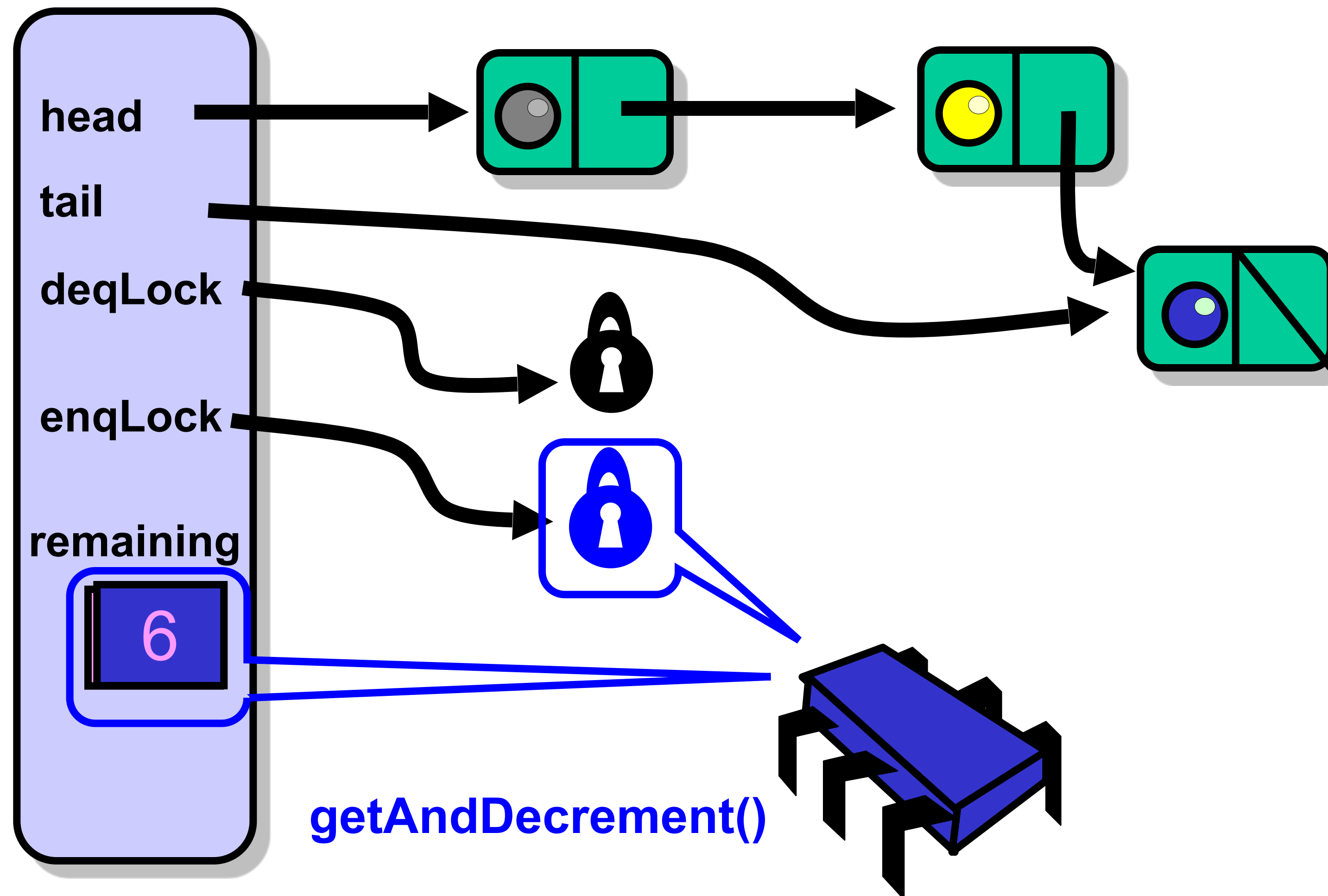
Enqueuer



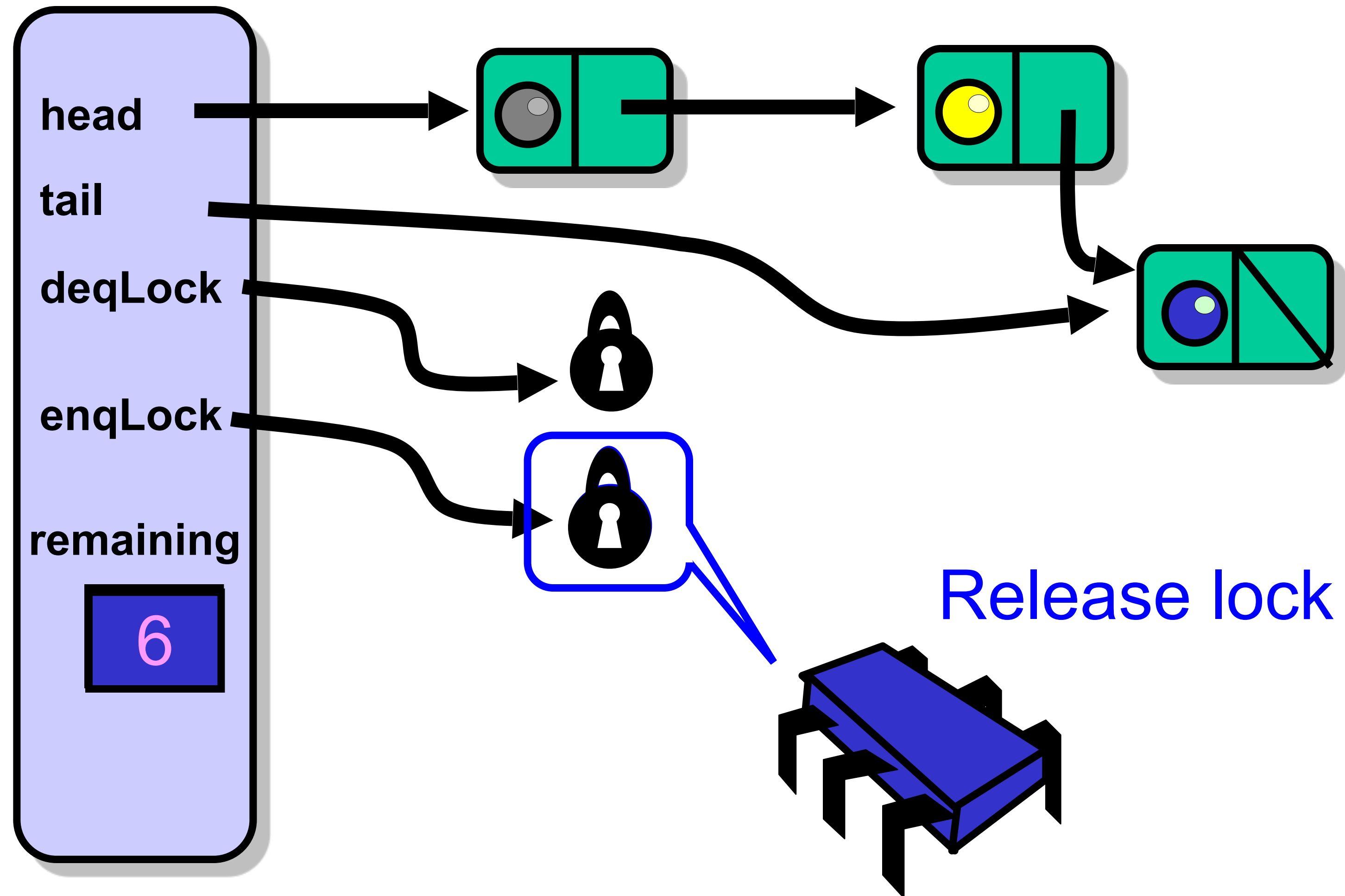
Enqueuer



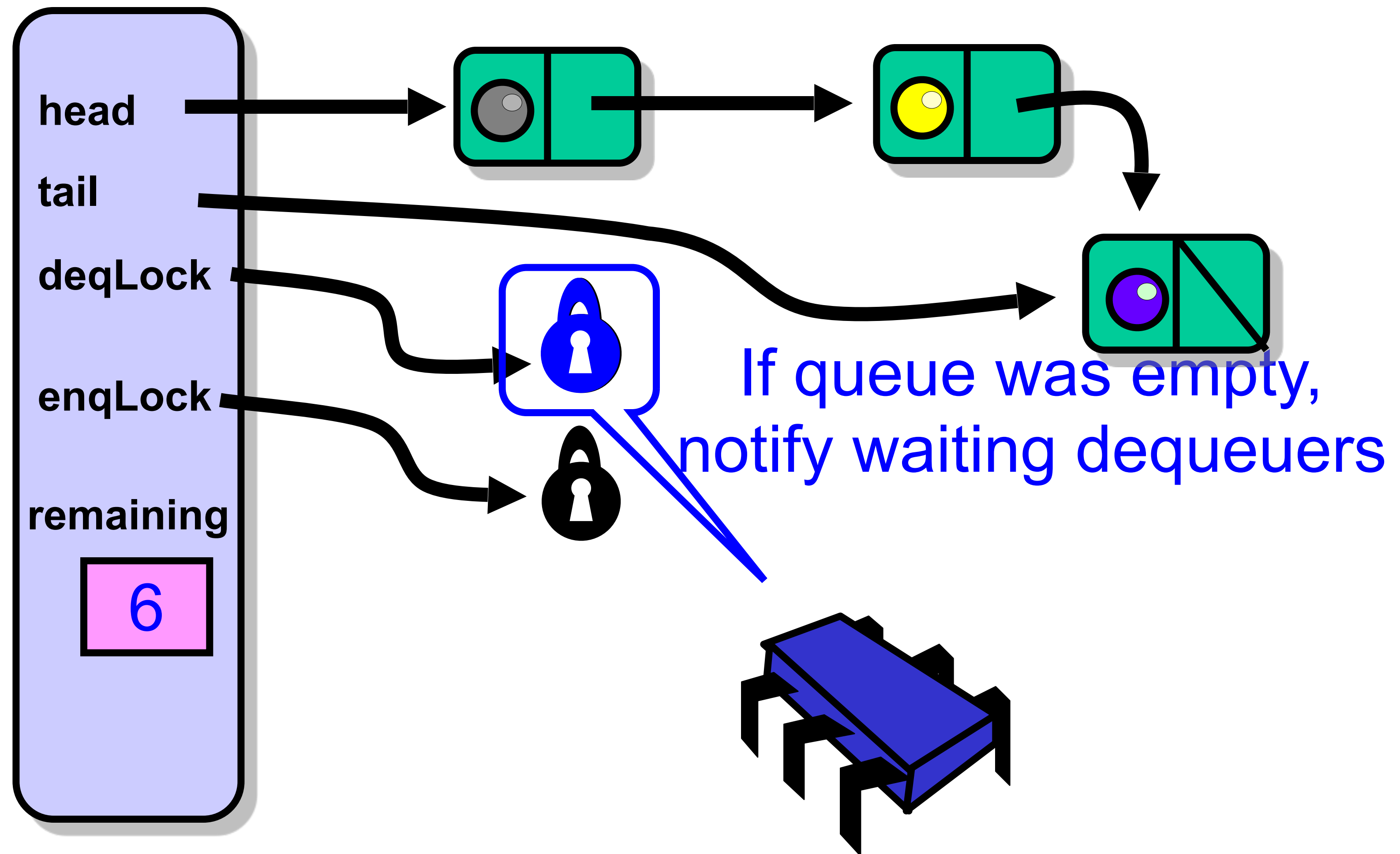
Enqueuer



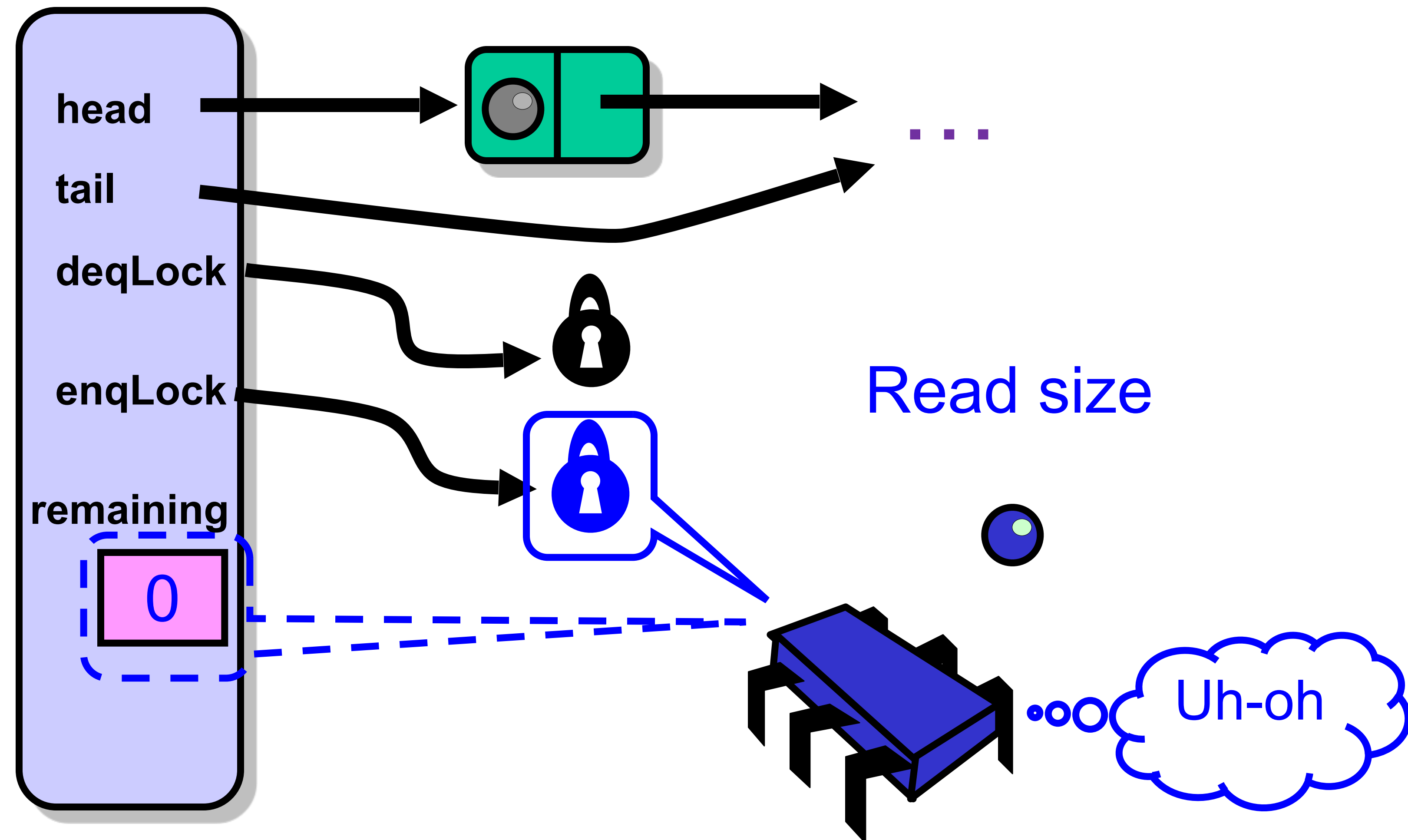
Enqueuer



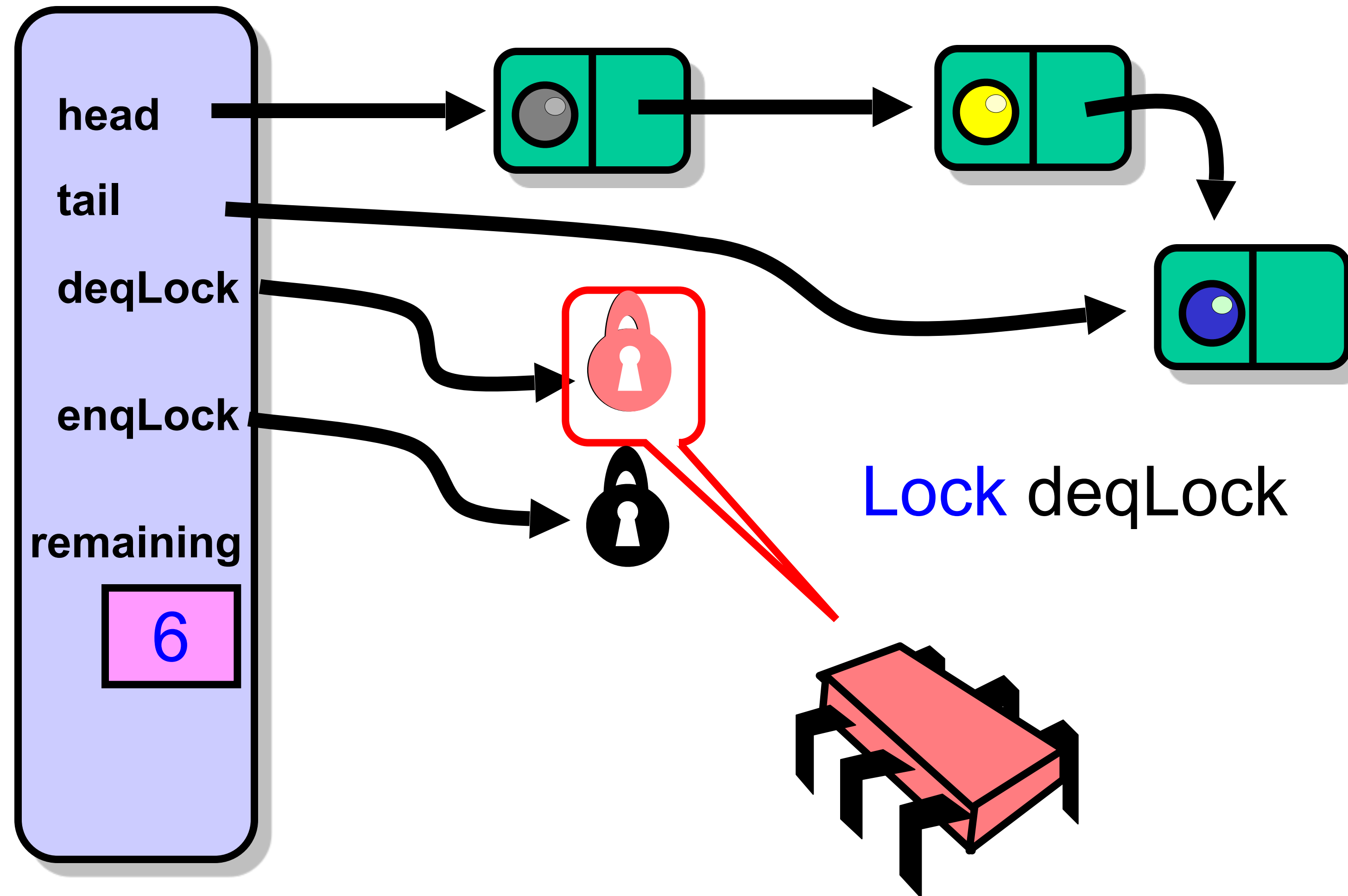
Enqueuer



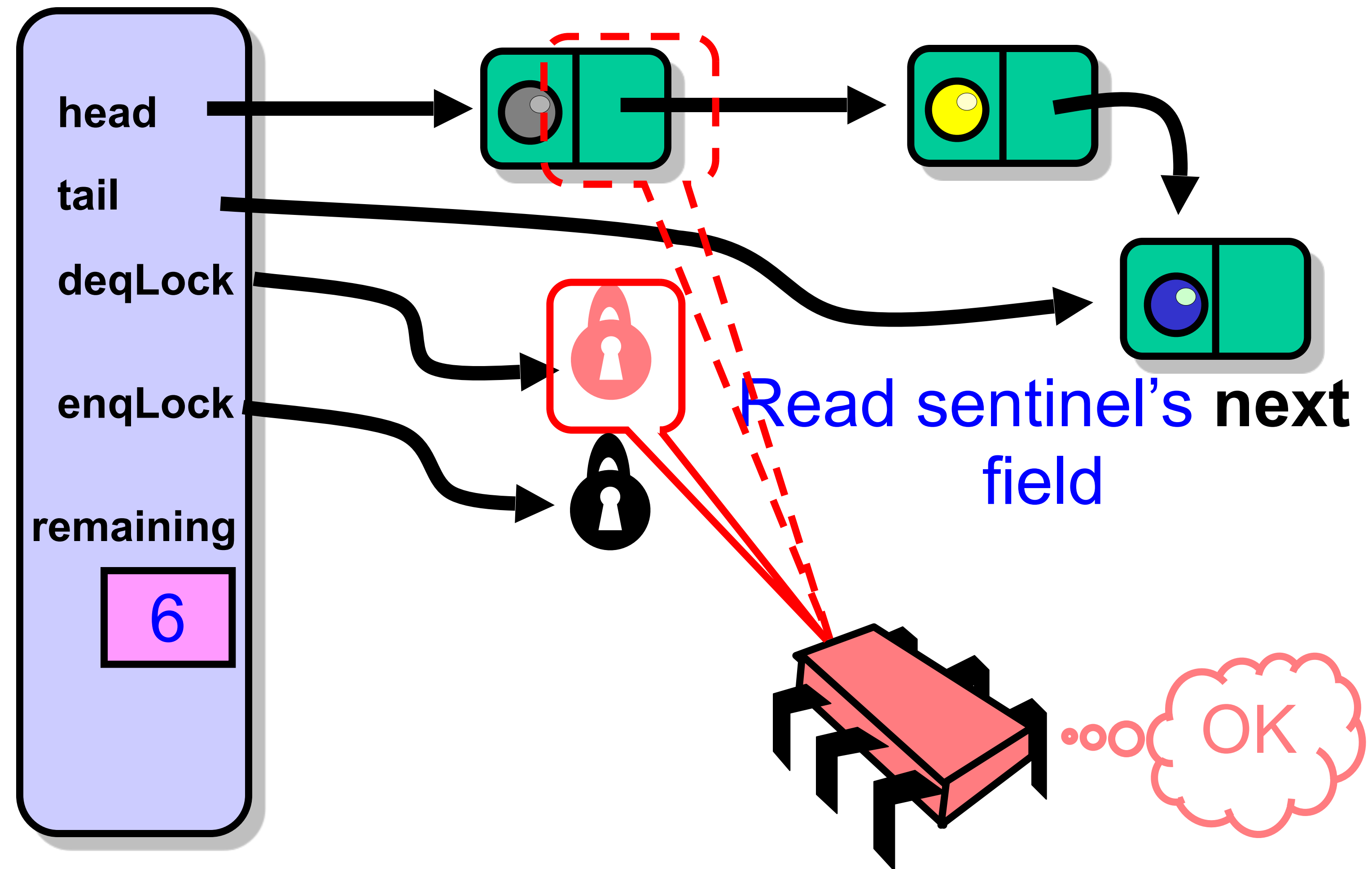
Unsuccessful Enqueuer



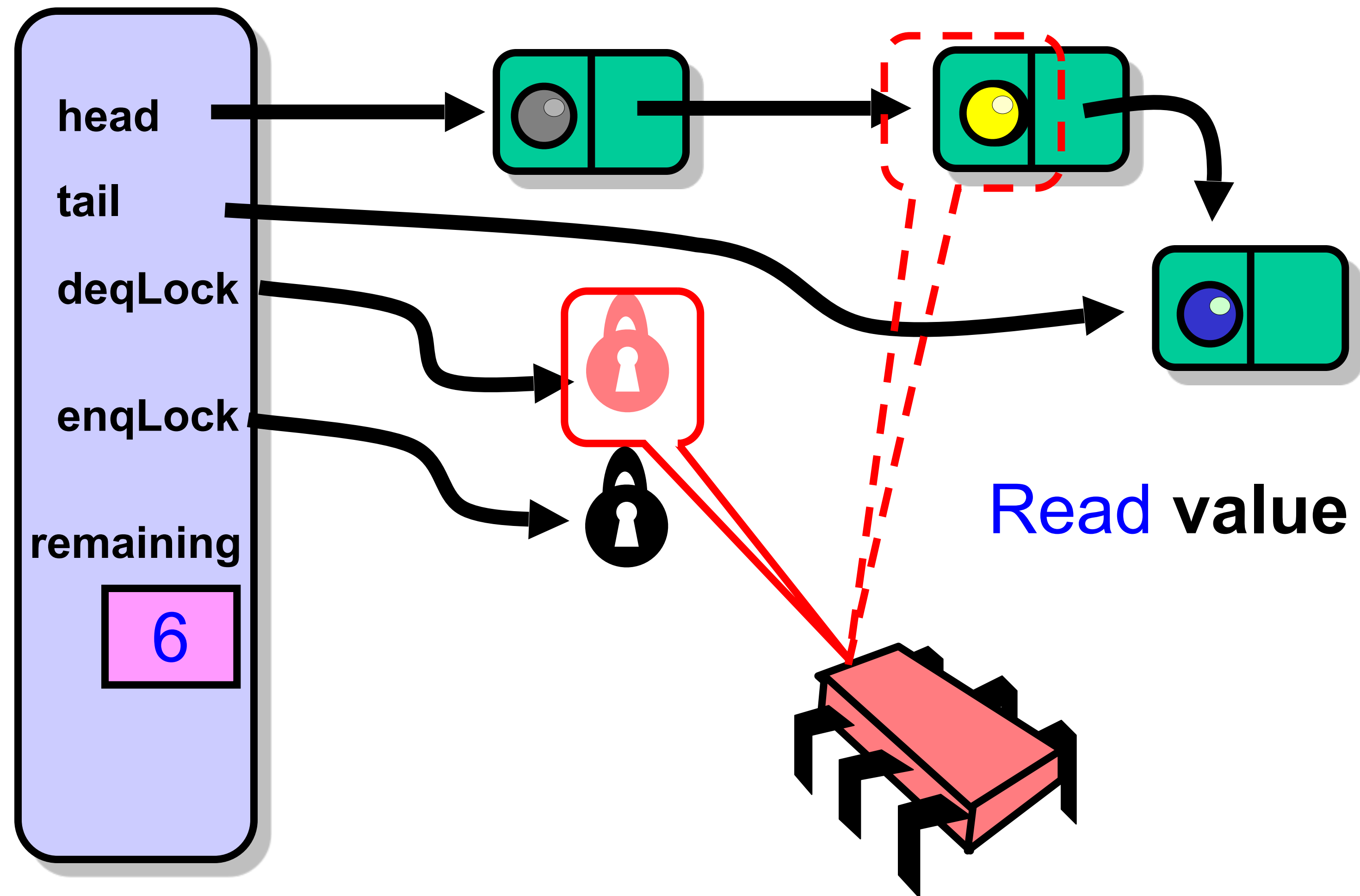
Dequeuer



Dequeuer

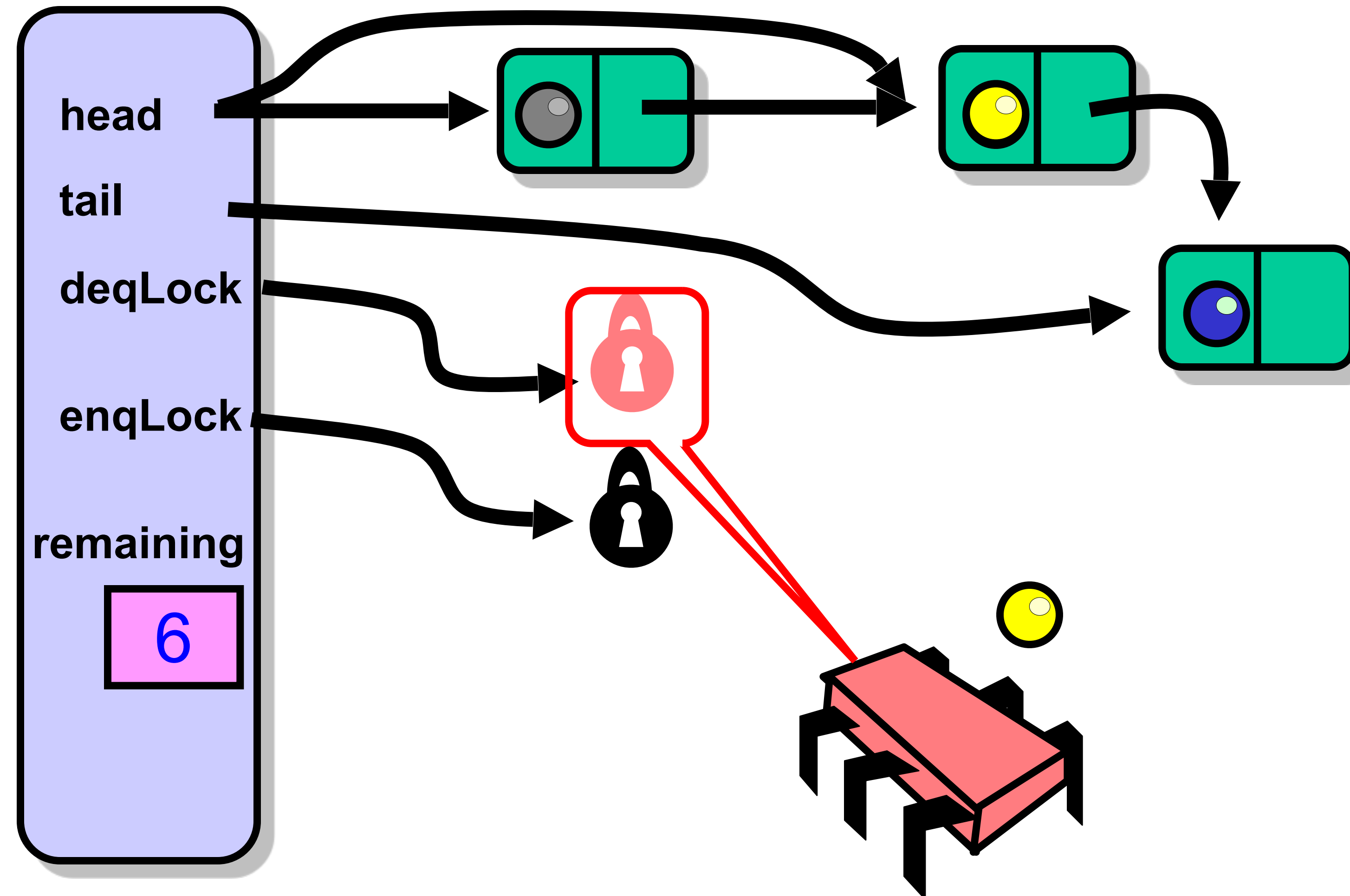


Dequeuer

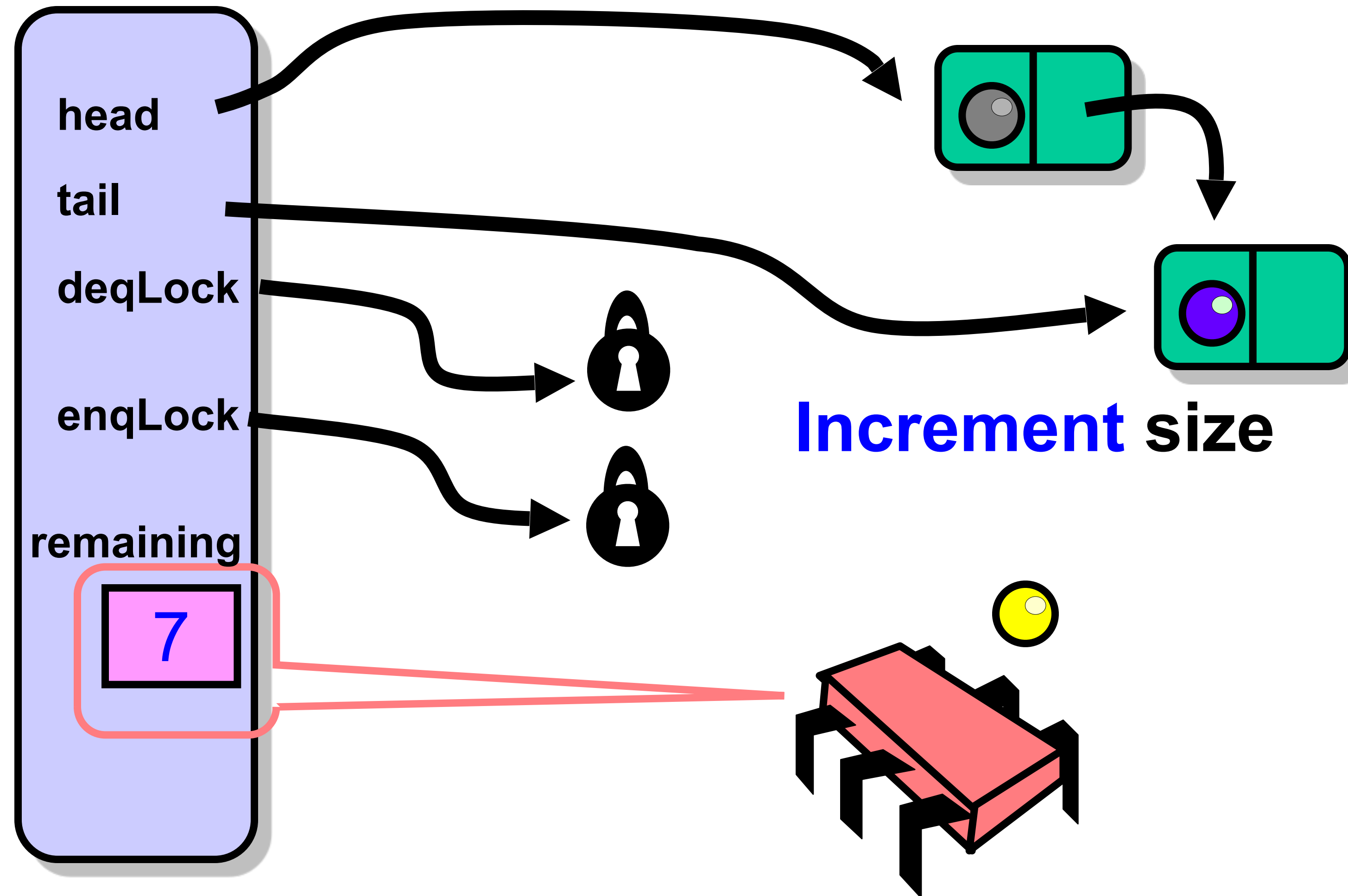


Make first Node new
sentinel

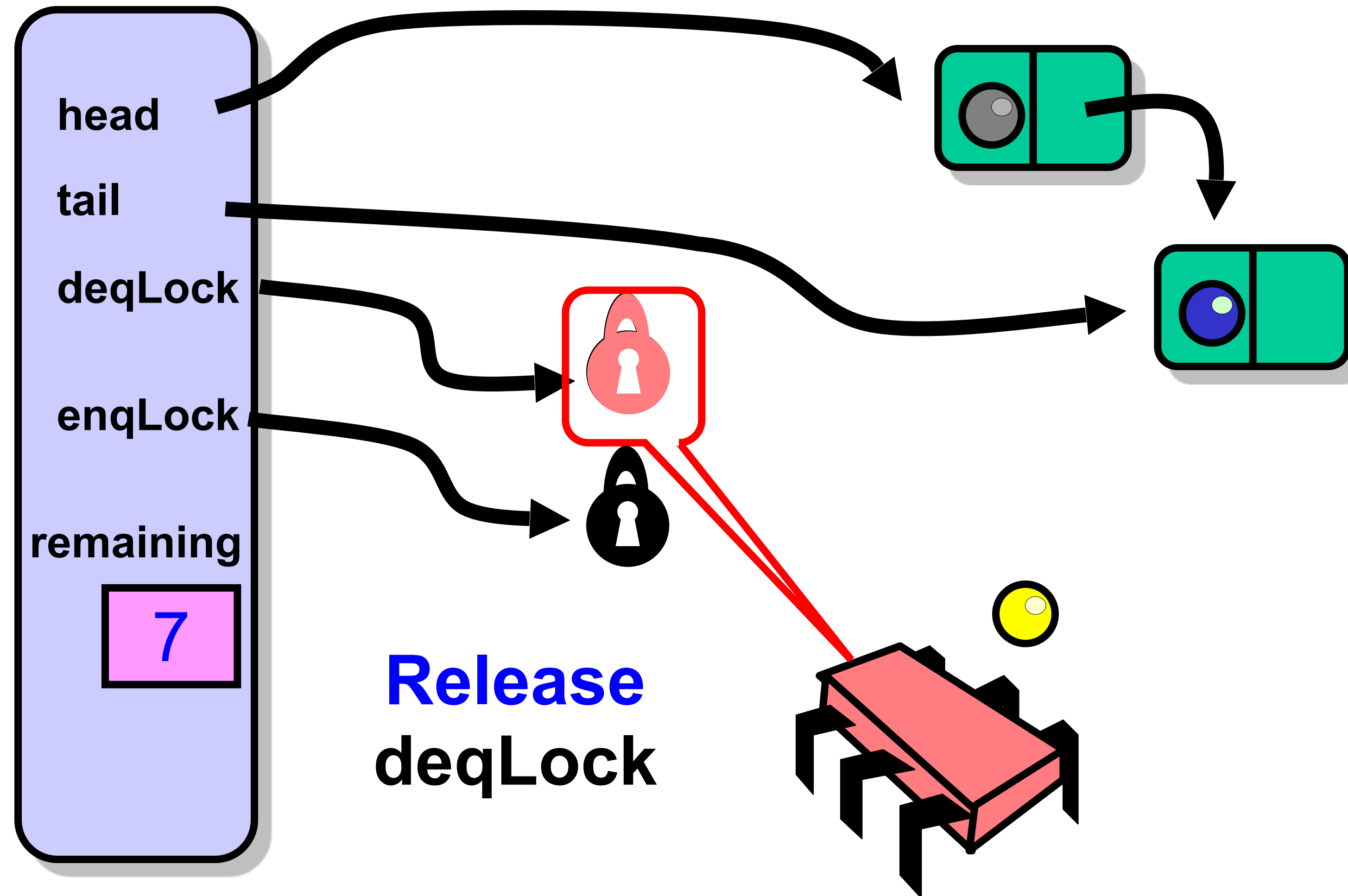
Dequeuer



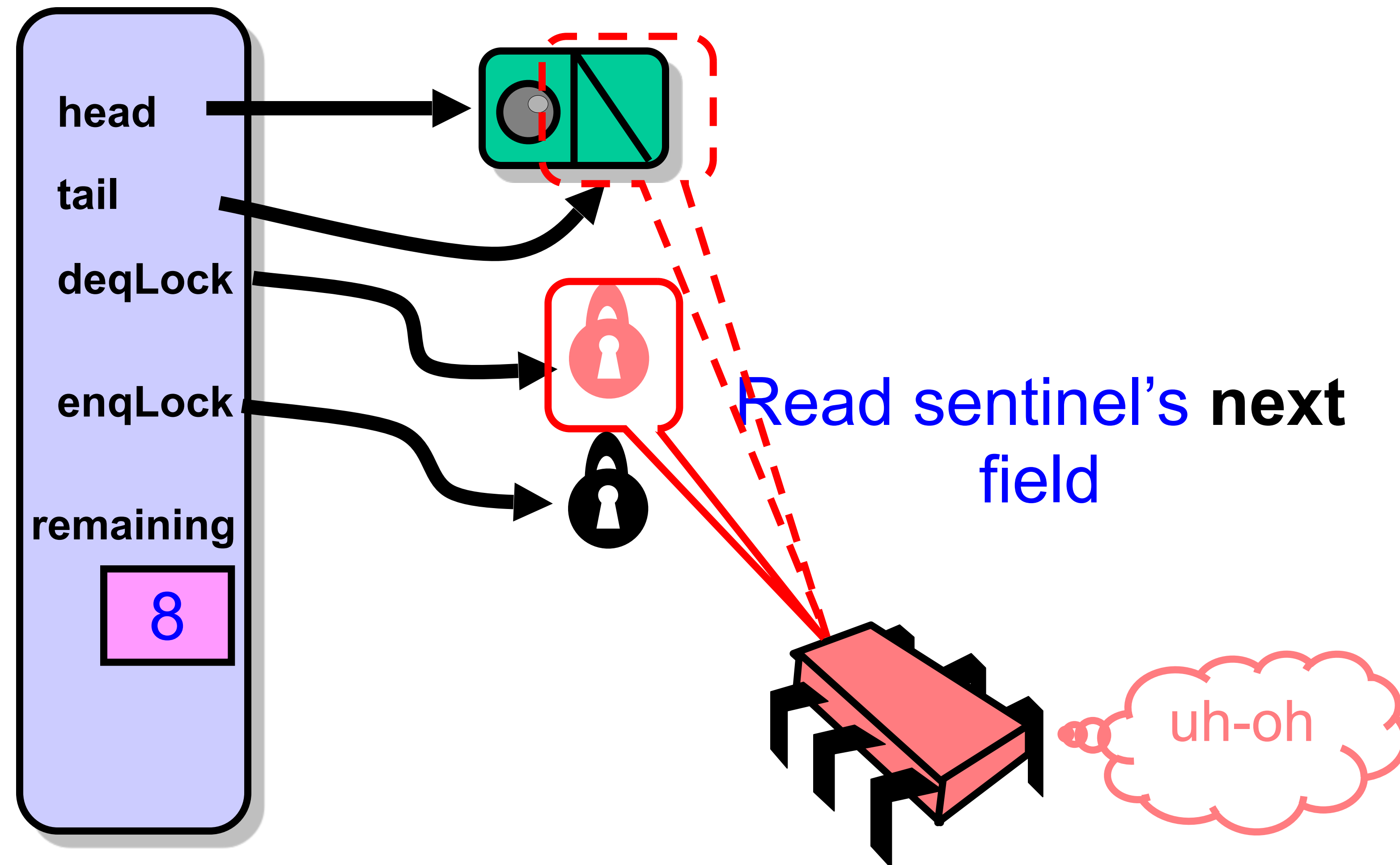
Dequeuer



Dequeuer



Unsuccessful Dequeueer



The Bounded Queue

```
class BoundedQueue[T] (private val capacity: Int)
    extends ConcurrentQueue[T] {

    private val enqLock = new ReentrantLock()
    private val deqLock = new ReentrantLock()

    private val notFullCondition = enqLock.newCondition()
    private val notEmptyCondition = deqLock.newCondition()

    private val remaining = new AtomicInteger(capacity)
    private val head: Node = new Node(null)
    private val tail: Node = head
```

Bounded Queue Fields

```
class BoundedQueue[T] (private val capacity: Int)
  extends ConcurrentQueue[T] {

  private val enqLock = new ReentrantLock()
  private val deqLock = new ReentrantLock()

  private val notFullCondition = enqLock.newCondition()
  private val notEmptyCondition = deqLock.newCondition()

  private val remaining = new AtomicInteger(capacity)
  private val head: Node = new Node(null)
  private val tail: Node = head
```

Enq & deq locks

Bounded Queue Fields

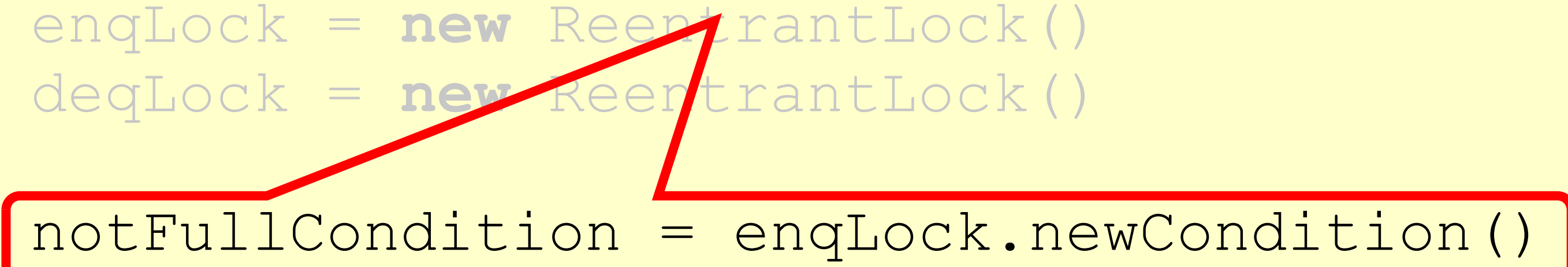
```
class BoundedQueue[T] (private val capacity: Int)
  extends ConcurrentQueue[T] {

  private val enqLock = new ReentrantLock()
  private val deqLock = new ReentrantLock()

  private val notFullCondition = enqLock.newCondition()
  private val notEmptyCondition = deqLock.newCondition()

  private val remaining = new AtomicInteger(capacity)
  private val head: Node = new Node(null)
  private val tail: Node = head
}
```

Enq lock's associated condition



Bounded Queue Fields

```
class BoundedQueue[T] (private val capacity: Int)
  extends ConcurrentQueue[T] {

  private val enqLock = new ReentrantLock()
  private val deqLock = new ReentrantLock()

  private val notFullCondition = enqLock.newCondition()
  private val notEmptyCondition = deqLock.newCondition()

  private val remaining = new AtomicInteger(capacity)
  private val head: Node = new Node(null)
  private val tail: Node = head
```

remaining slots: capacity to 0

Bounded Queue Fields

```
class BoundedQueue[T] (private val capacity: Int)
  extends ConcurrentQueue[T] {

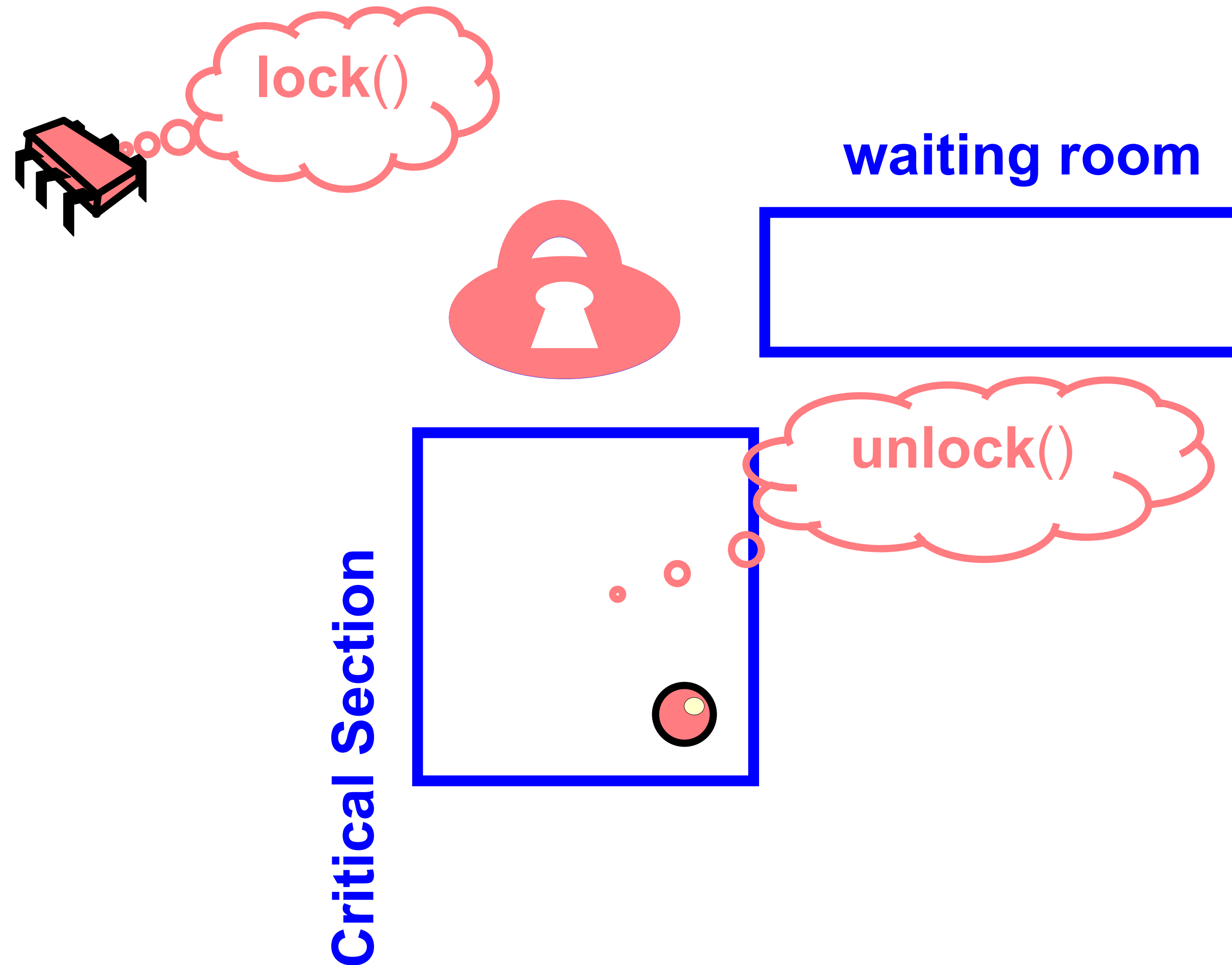
  private val enqLock = new ReentrantLock()
  private val deqLock = new ReentrantLock()

  private val notFullCondition = enqLock.newCondition()
  private val notEmptyCondition = deqLock.newCondition()

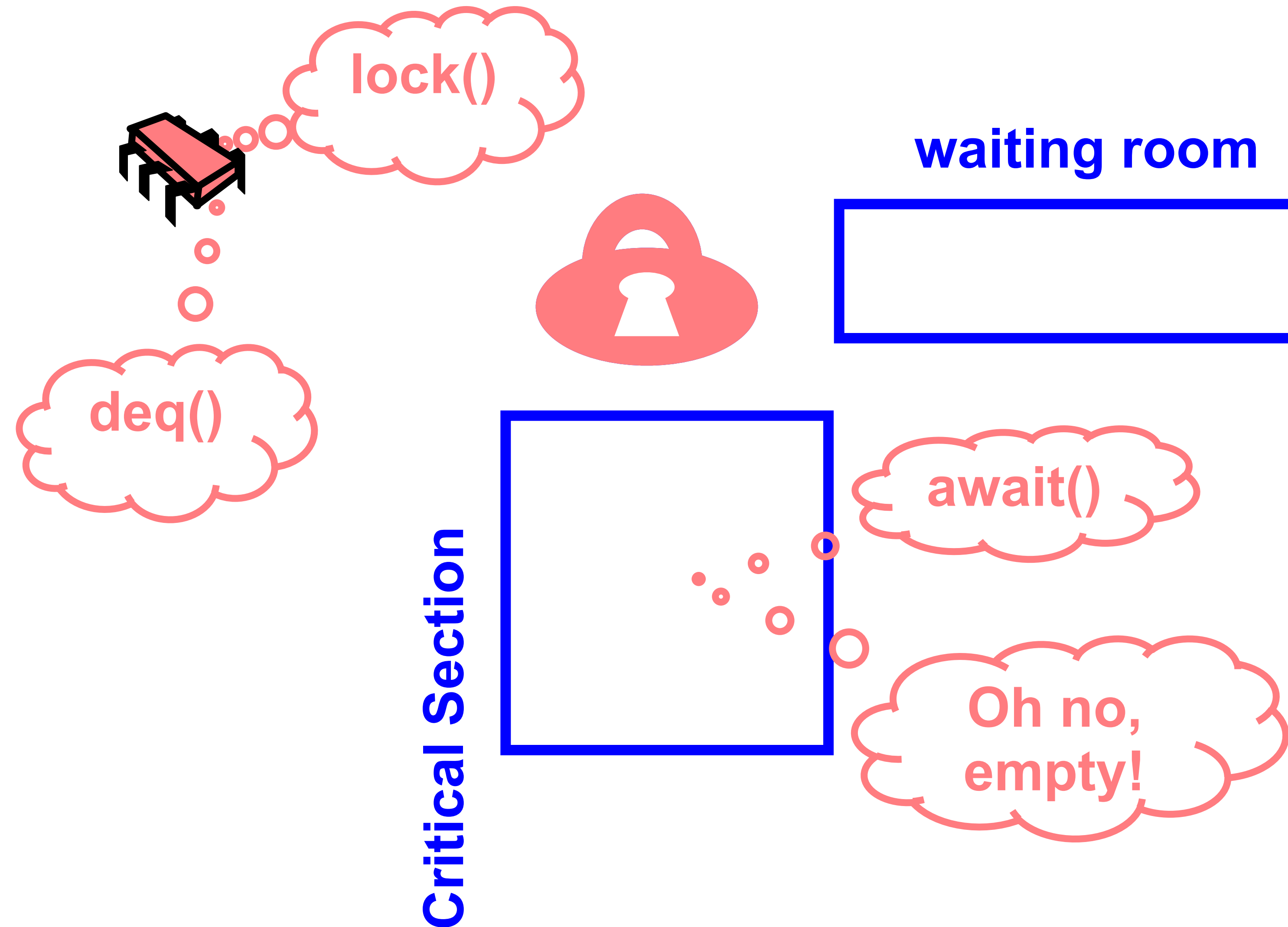
  private val remaining = new AtomicInteger(capacity)
  private val head: Node = new Node(null)
  private val tail: Node = head
```

Head and Tail

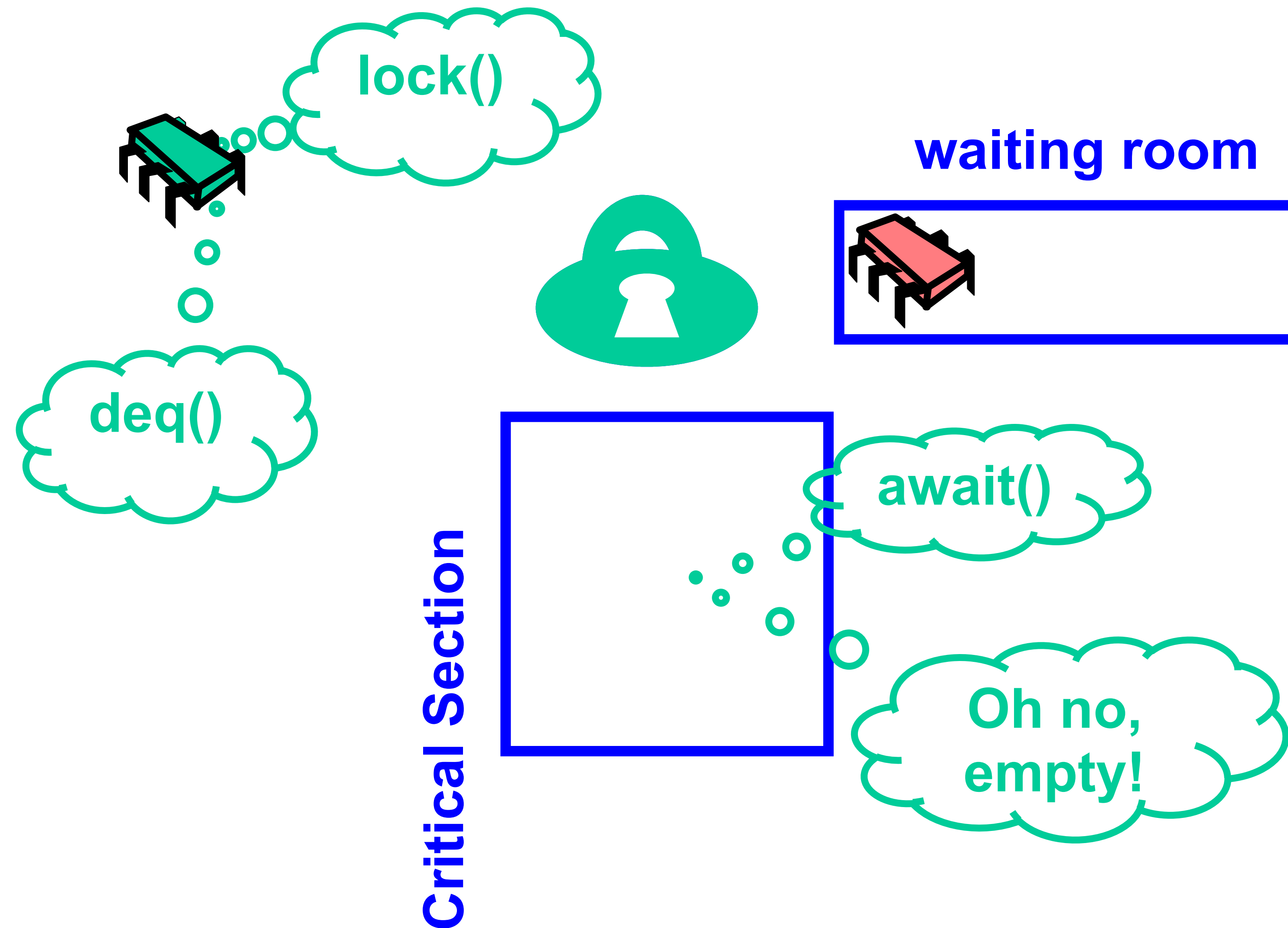
A Monitor Lock



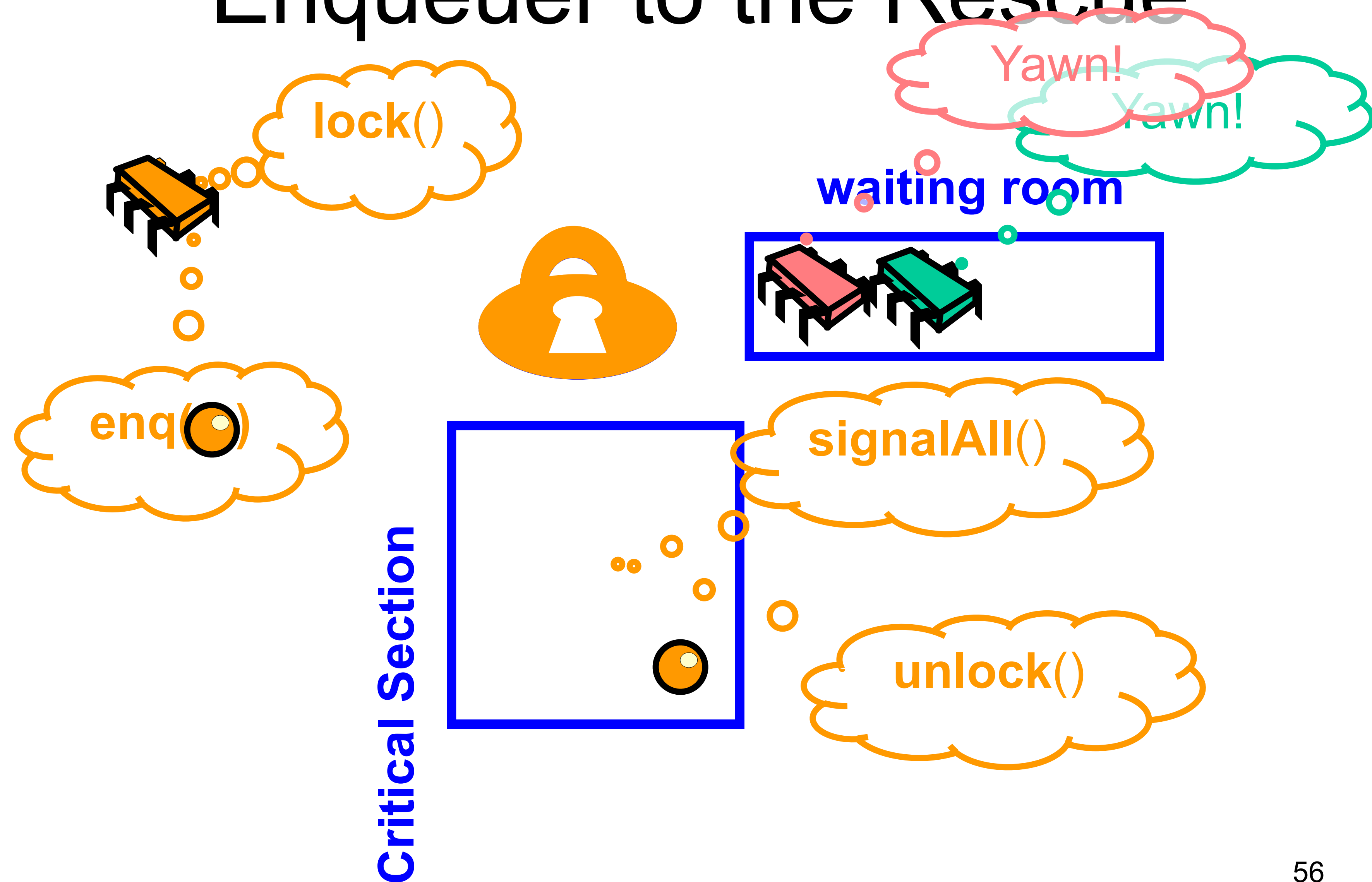
Unsuccessful Deq



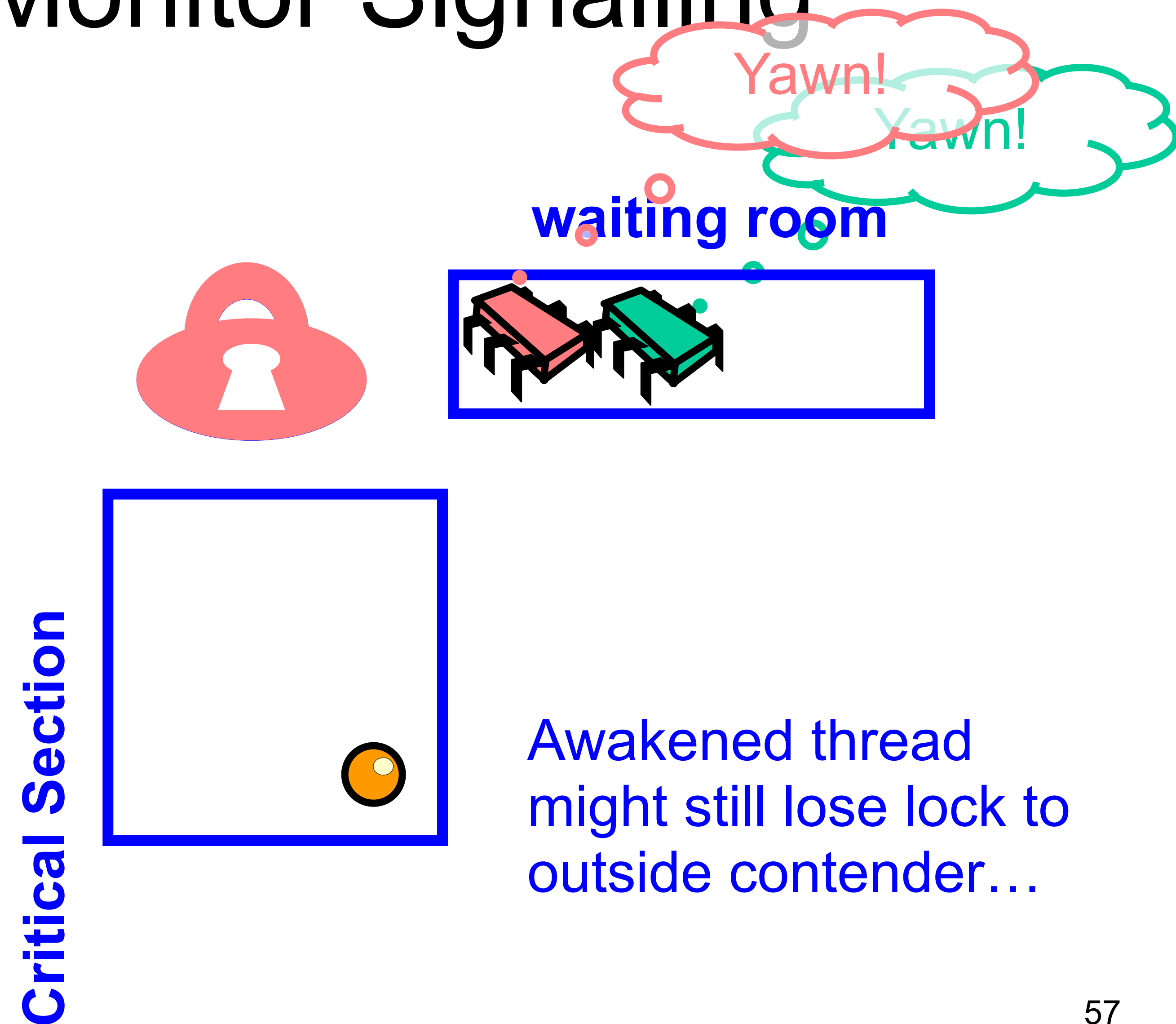
Another One



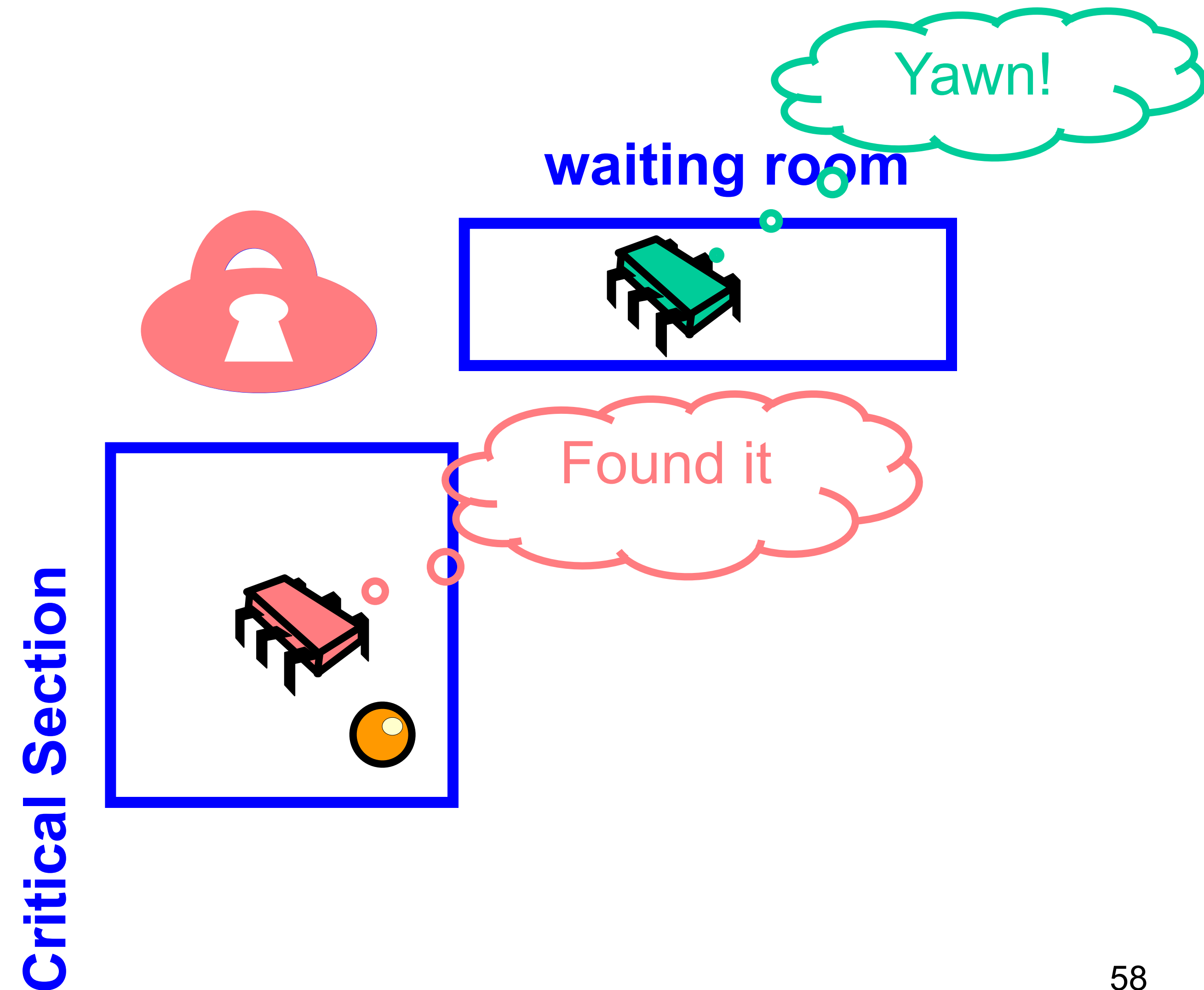
Enqueuer to the Rescue



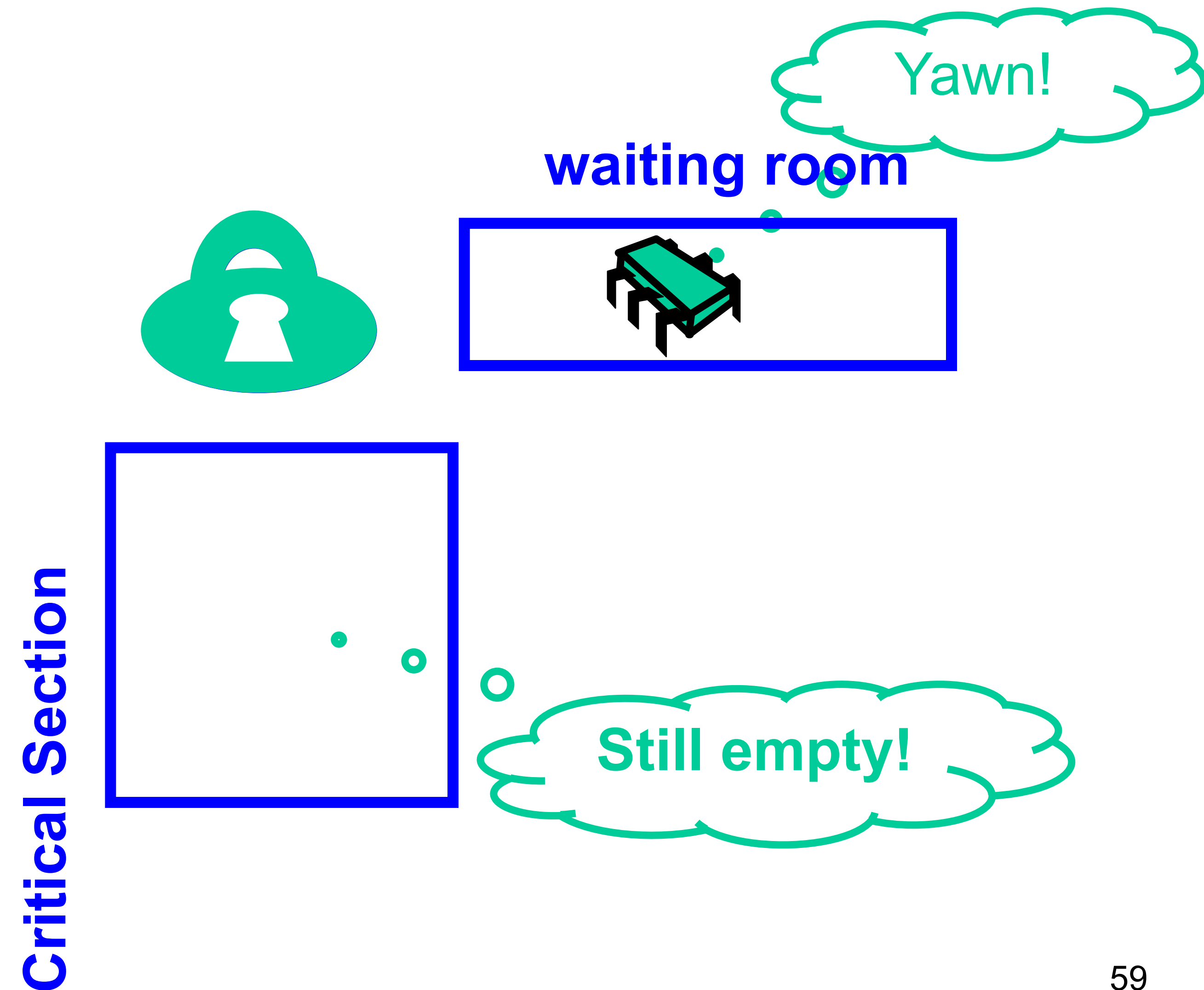
Monitor Signalling



Dequeuers Signalled

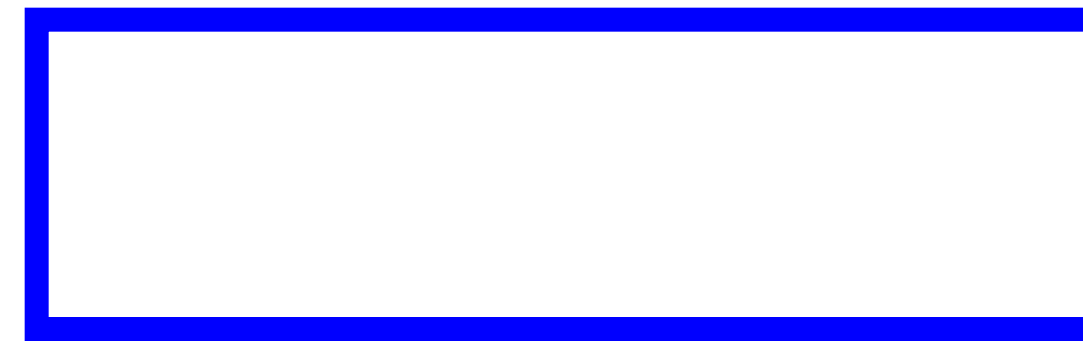


Dequeuers Signaled

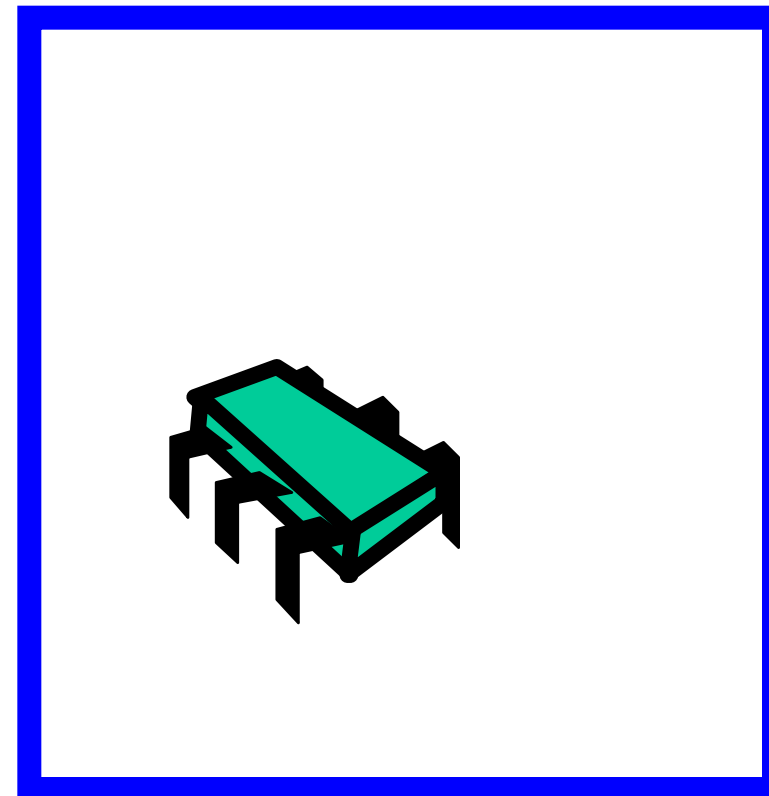


Dollar Short + Day Late

waiting room



Critical Section



Enq Method Part One

```
def enq(x: T): Unit = {  
  var mustWakeDequeuers = false  
  enqLock.lock()  
  try {  
    while (remaining.get == 0) {  
      notFullCondition.await()  
    }  
    val e = new Node(x)  
    tail.next = e  
    tail = e  
    if (remaining.getAndDecrement == capacity)  
      mustWakeDequeuers = true  
  } finally {  
    enqLock.unlock()  
  }  
  // ...  
}
```

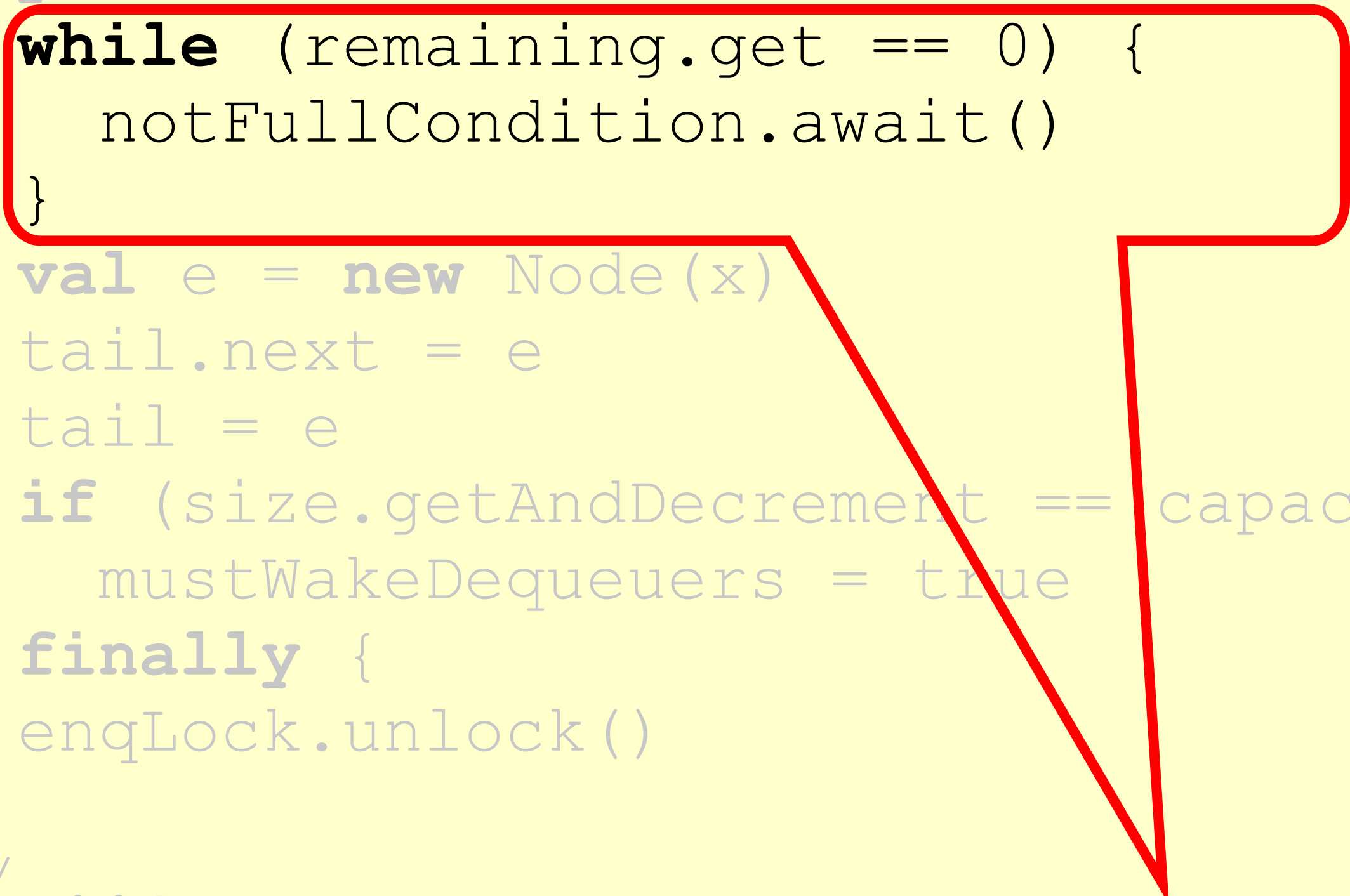
Enq Method Part One

```
def enq(x: T): Unit = {  
  var mustWakeDequeuers = false  
  enqLock.lock()  
  try {  
    while (remaining.get == 0)  
      notFullCondition.await()  
    }  
    val e = new Node(x)  
    tail.next = e  
    tail = e  
    if (remaining.getAndDecrement == capacity)  
      mustWakeDequeuers = true  
  } finally {  
    enqLock.unlock()  
  }  
  // ...  
}
```

**Lock and unlock
enq lock**

Enq Method Part One

```
def enq(x: T): Unit = {  
  var mustWakeDequeuers = false  
  enqLock.lock()  
  try {  
    while (remaining.get == 0) {  
      notFullCondition.await()  
    }  
    val e = new Node(x)  
    tail.next = e  
    tail = e  
    if (size.getAndDecrement == capacity)  
      mustWakeDequeuers = true  
  } finally {  
    enqLock.unlock()  
  }  
  // ...  
}
```



Wait while queue is full ...

Enq Method Part One

```
def enq(x: T): Unit = {  
  var mustWakeDequeuers = false  
  enqLock.lock()  
  try {  
    while (remaining.get == 0) {  
      notFullCondition.await()  
    }  
    val e = new Node(x)  
    tail.next = e  
    tail = e  
    if (size.getAndDecrement == capacity)  
      mustWakeDequeuers = true  
  } finally {  
    enqLock.unlock()  
  }  
  // ...  
}
```

**when await() returns, you
might still fail the test!**

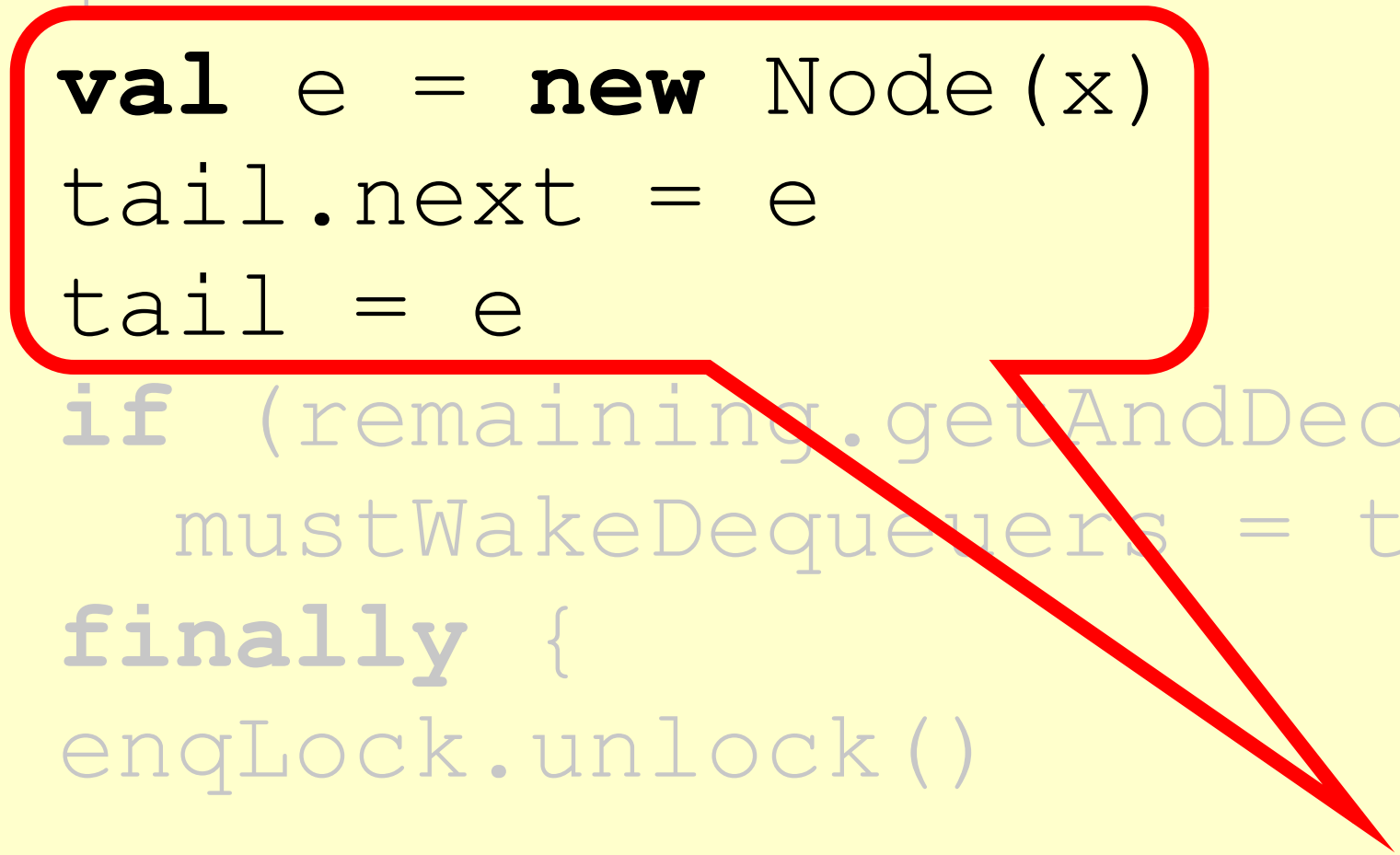
Be Afraid

```
def enq(x: T): Unit = {  
  var mustWakeDequeuers = false  
  enqLock.lock()  
  try {  
    while (remaining.get == 0) {  
      notFullCondition.await()  
    }  
    val e = new Node(x)  
    tail.next = e  
    tail = e  
    if (size.getAndDecrement == capacity)  
      mustWakeDequeuers = true  
  } finally {  
    enqLock.unlock()  
  }  
  // ...  
}
```

After the loop: how do we know the queue won't become full again?

Enq Method Part One

```
def enq(x: T): Unit = {  
  var mustWakeDequeuers = false  
  enqLock.lock()  
  try {  
    while (remaining.get == 0) {  
      notFullCondition.await()  
    }  
    val e = new Node(x)  
    tail.next = e  
    tail = e  
    if (remaining.getAndDecrement == capacity)  
      mustWakeDequeuers = true  
  } finally {  
    enqLock.unlock()  
  }  
  // ...  
}
```



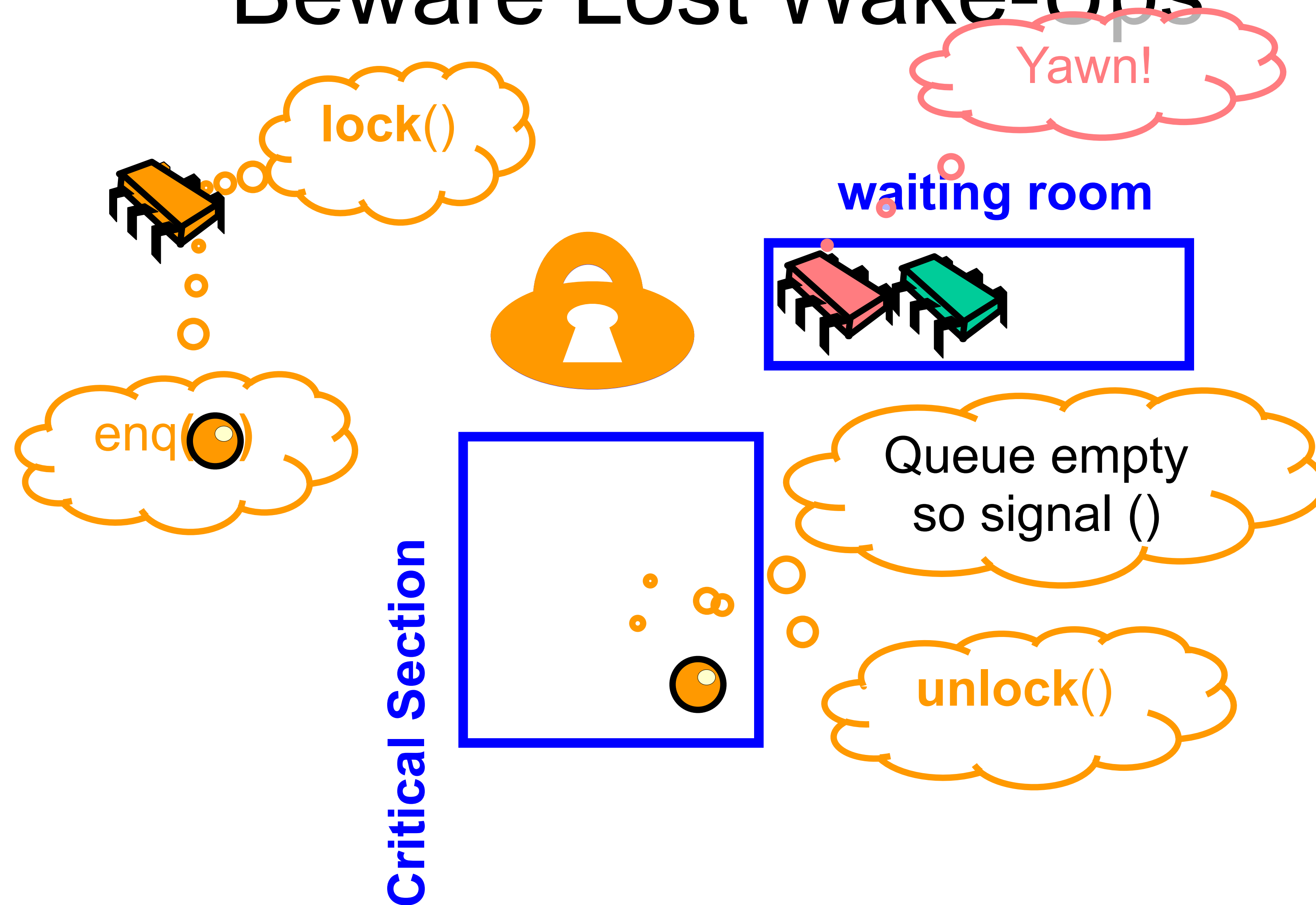
Add new node

Enq Method Part One

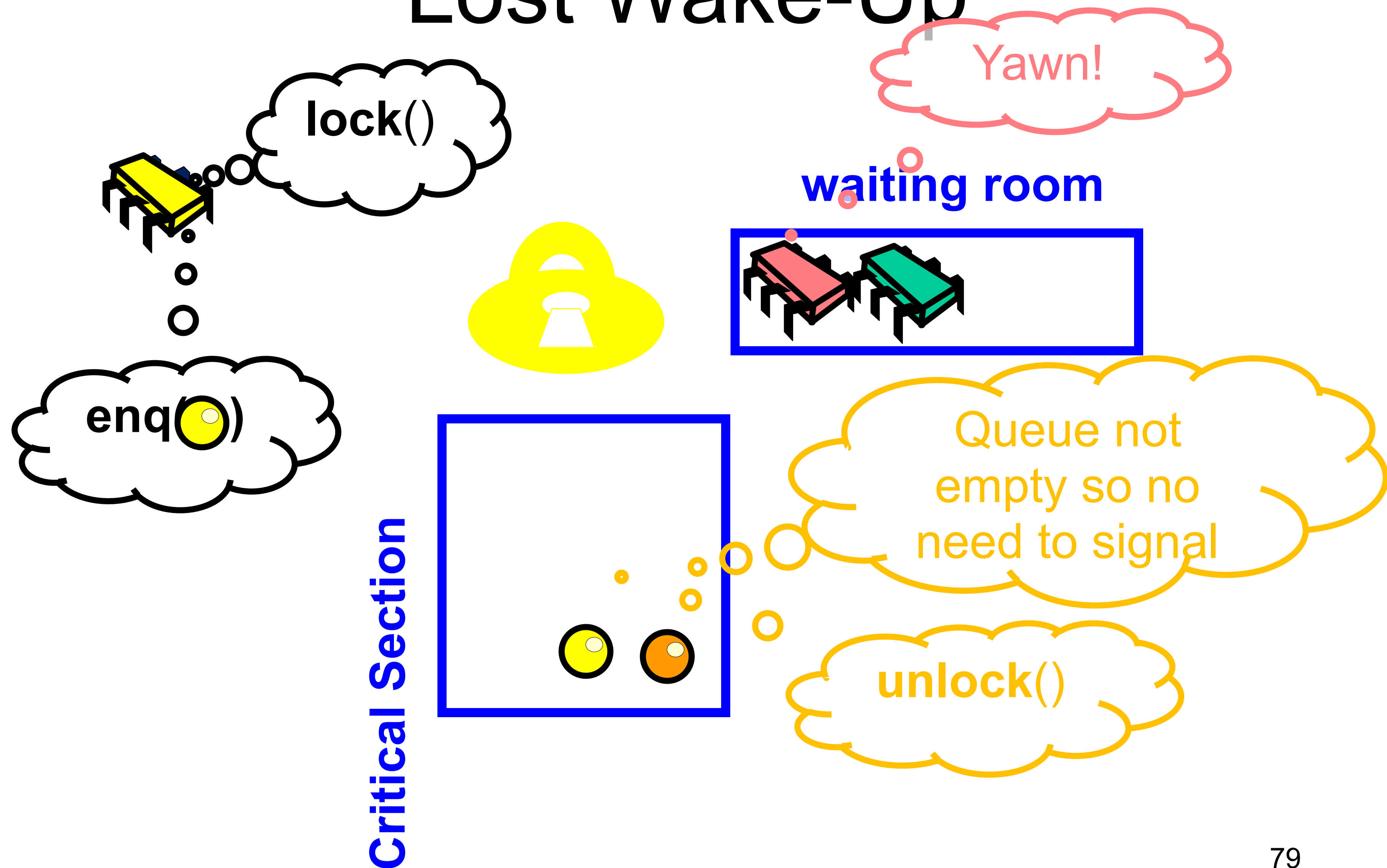
```
def enq(x: T): Unit = {  
  var mustWakeDequeuers = false  
  enqLock.lock()  
  try {  
    while (remaining.get == 0) {  
      notFullCondition.await()  
    }  
    val e = new Node(x)  
    tail.next = e  
    tail = e  
    if (remaining.getAndDecrement == capacity)  
      mustWakeDequeuers = true  
  } finally {  
    enqLock.unlock()  
  }  
  // ...  
}
```

**If queue was empty, wake
frustrated dequeuers**

Beware Lost Wake-Ups



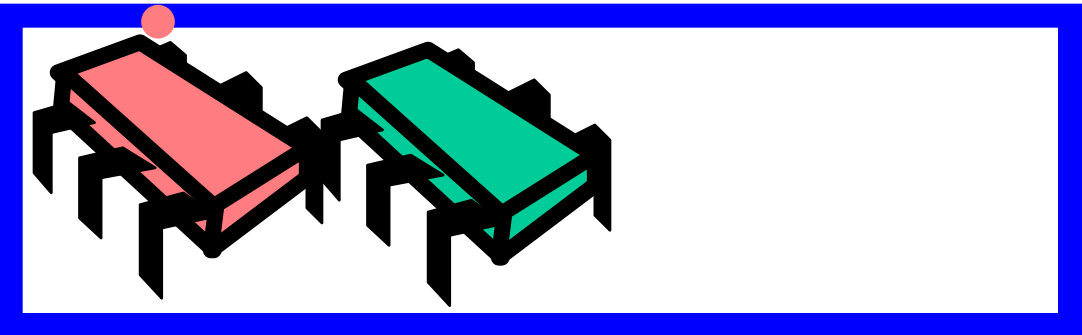
Lost Wake-Up



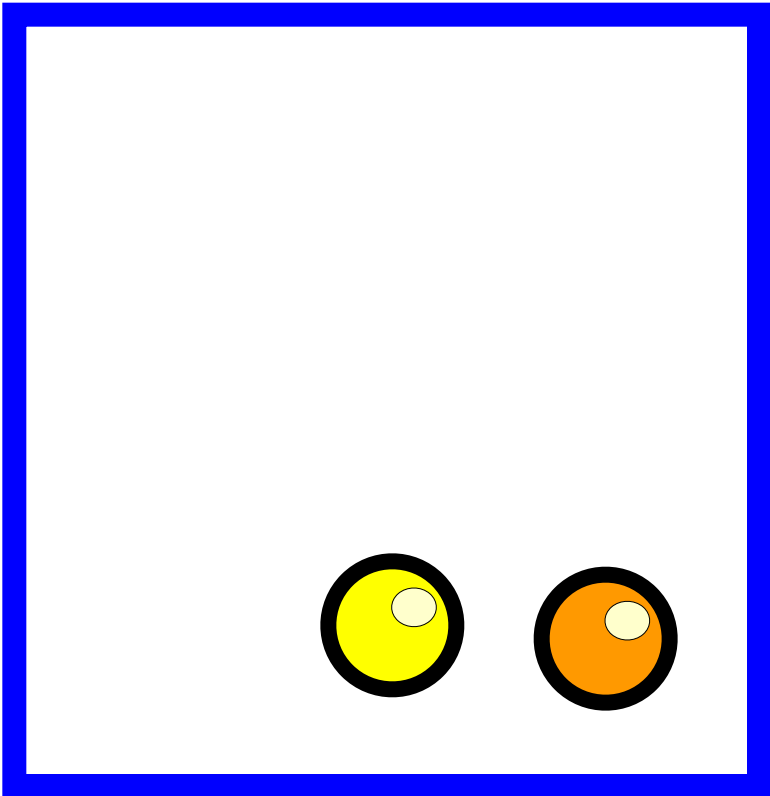
Lost Wake-Up



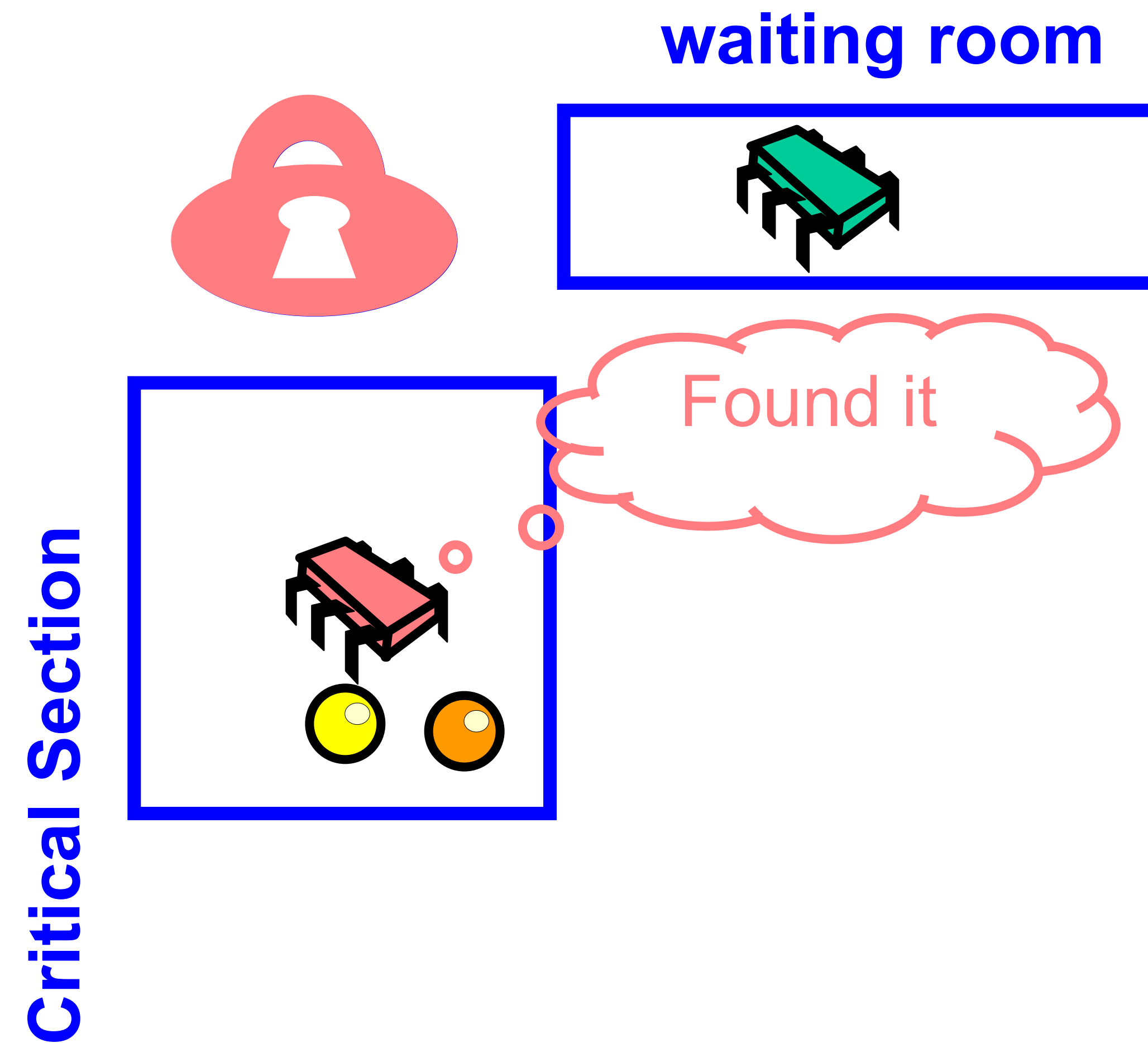
waiting room



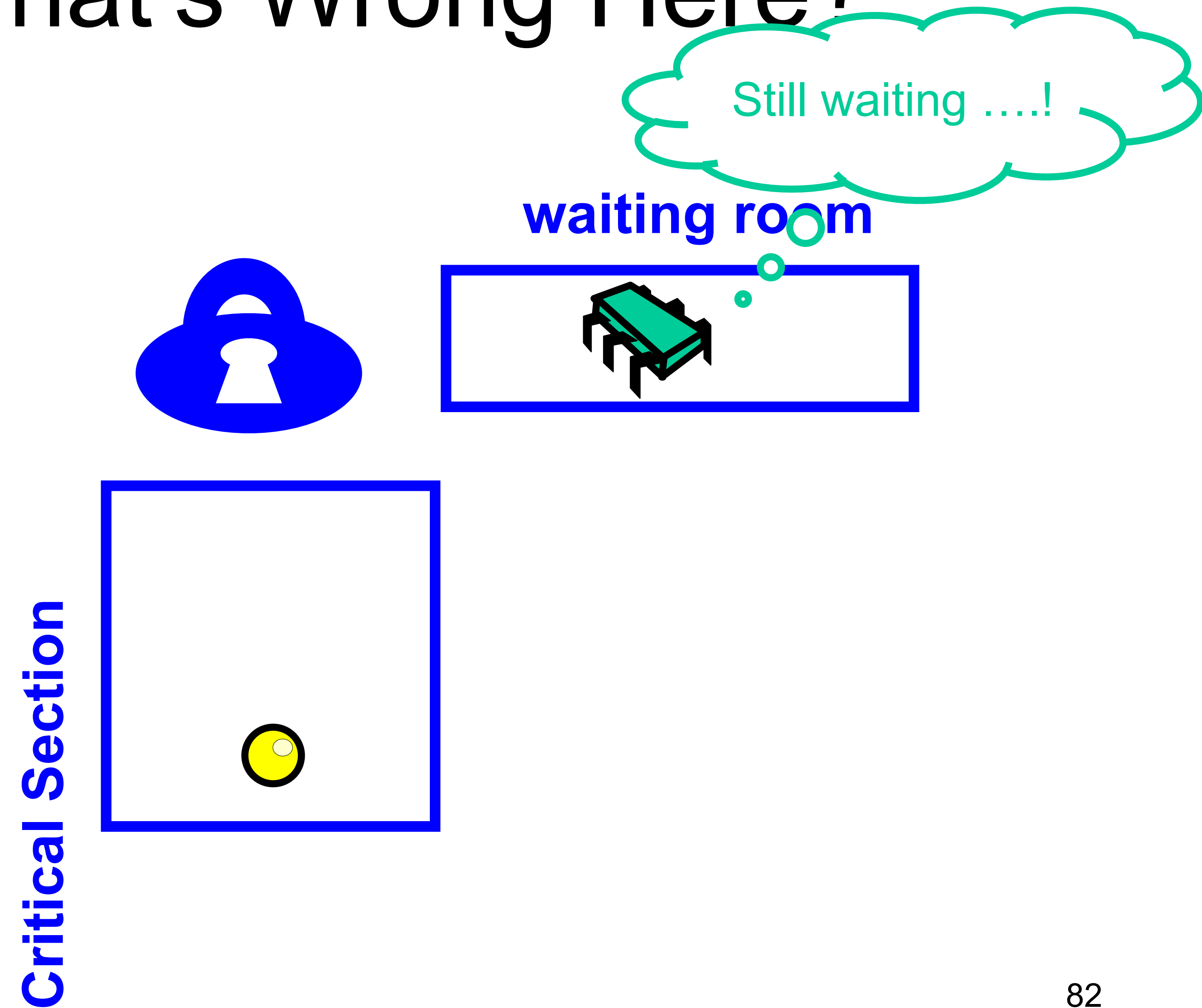
Critical Section



Lost Wake-Up



What's Wrong Here?



Solution to Lost Wakeup

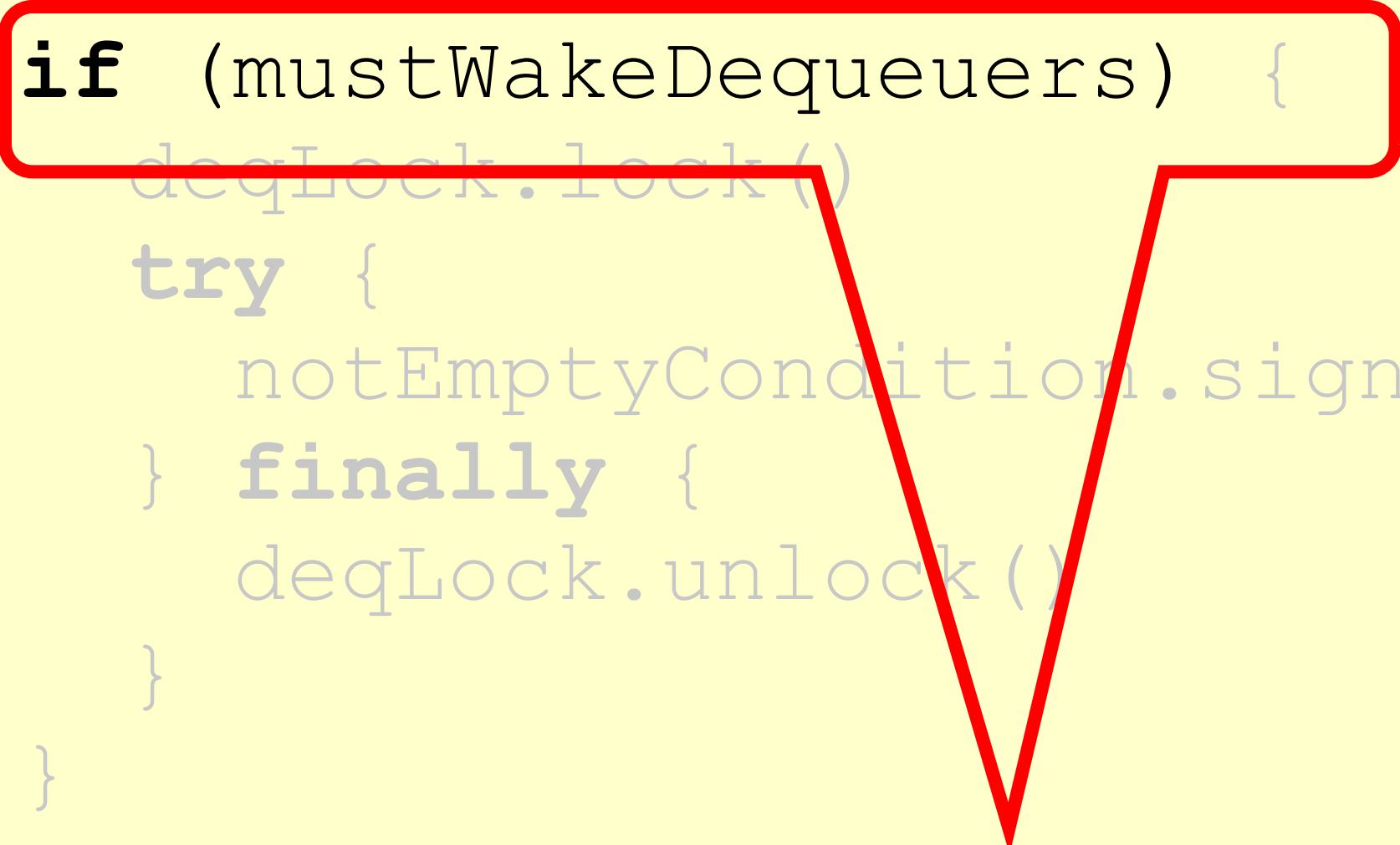
- Always use
 - `signalAll()` and `notifyAll()`
- Not
 - `signal()` and `notify()`

Enq Method Part Deux

```
def enq(x: T): Unit = {  
  // ...  
  if (mustWakeDequeuers) {  
    deqLock.lock()  
    try {  
      notEmptyCondition.signalAll()  
    } finally {  
      deqLock.unlock()  
    }  
  }  
}
```

Enq Method Part Deux

```
def enq(x: T): Unit = {  
  // ...  
  if (mustWakeDequeuers) {  
    deqLock.lock()  
    try {  
      notEmptyCondition.signalAll()  
    } finally {  
      deqLock.unlock()  
    }  
  }  
}
```



Are there dequeuers to be signaled?

Enq Method Part Deux

```
def enq(x: T): Unit = {  
  // ...  
  if (mustWakeDequeue) {  
    deqLock.lock()  
    try {  
      notEmptyCondition.signalAll()  
    } finally {  
      deqLock.unlock()  
    }  
  }  
}
```

**Lock and unlock
deq lock**



Enq Method Part Deux

**Signal dequeuers that
queue is no longer empty**

```
if (mustWakeDequeuers) {  
    deqLock.lock()  
    try {  
        notEmptyCondition.signalAll()  
    } finally {  
        deqLock.unlock()  
    }  
}
```

The `enq()` & `deq()` Methods

- Share no locks
 - That's good
- But do share an atomic counter
 - Accessed on every method call
 - That's not so good
- Can we alleviate this bottleneck?

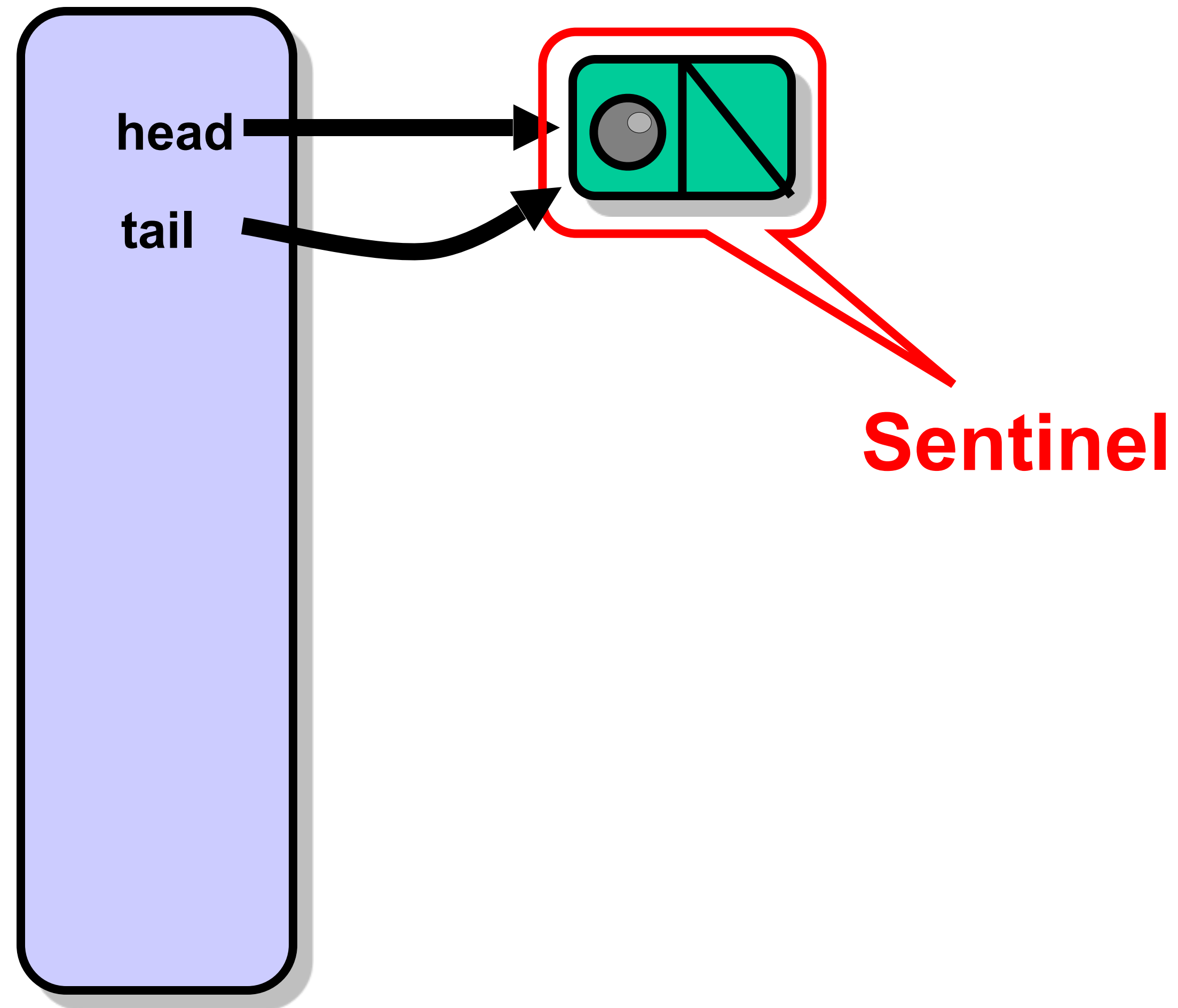
Split the Counter

- The **enq()** method
 - Increments only
 - Cares only if value is **capacity**
- The **deq()** method
 - Decrements only
 - Cares only if value is **zero**

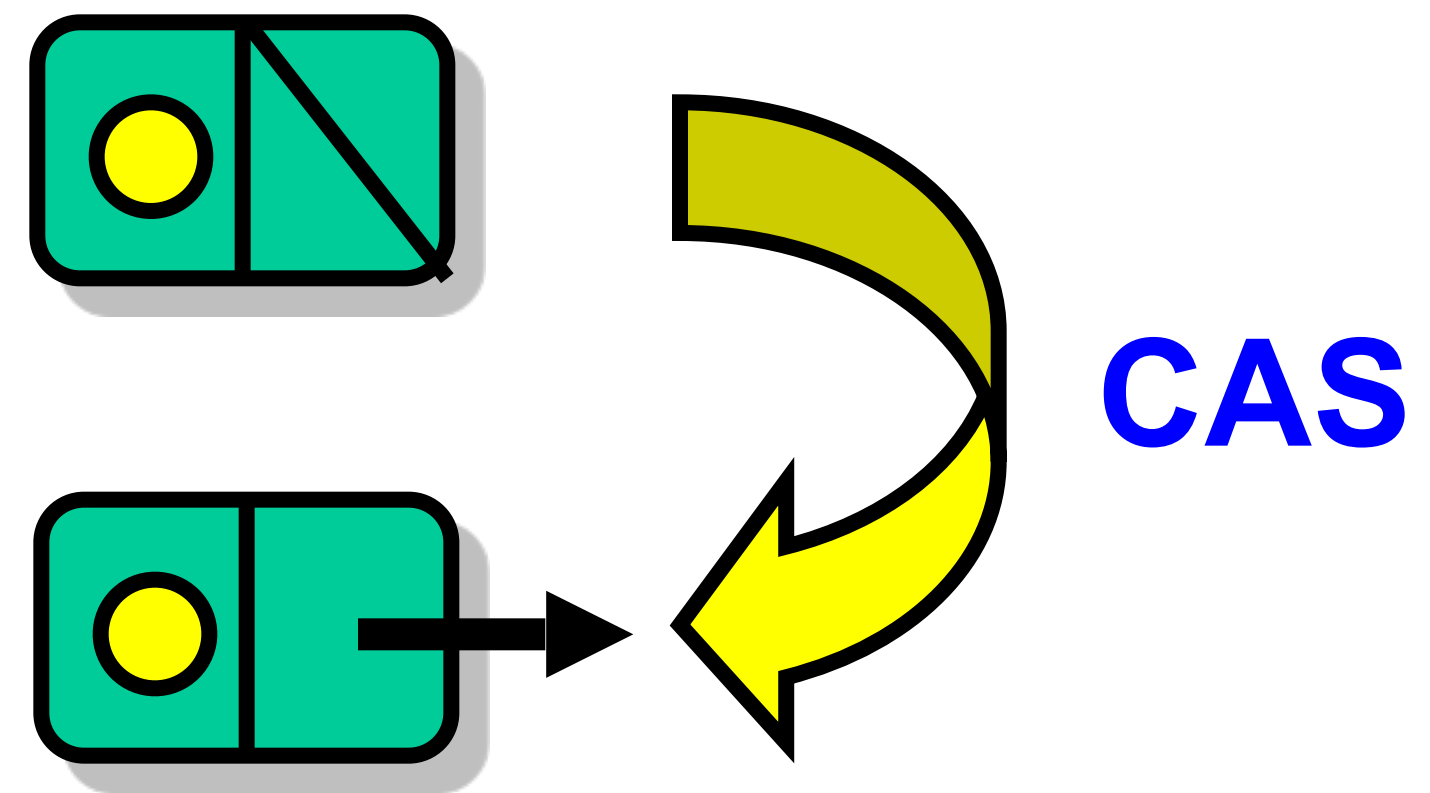
Split Counter

- Enqueueer increments **enqSize**
- Dequeueer increments **deqSize**
- When enqueueer hits capacity
 - Locks **deqLock**
 - Sets **size = enqSize - deqSize**
- Intermittent synchronization
 - Not with each method call
 - Need both locks! (careful ...)

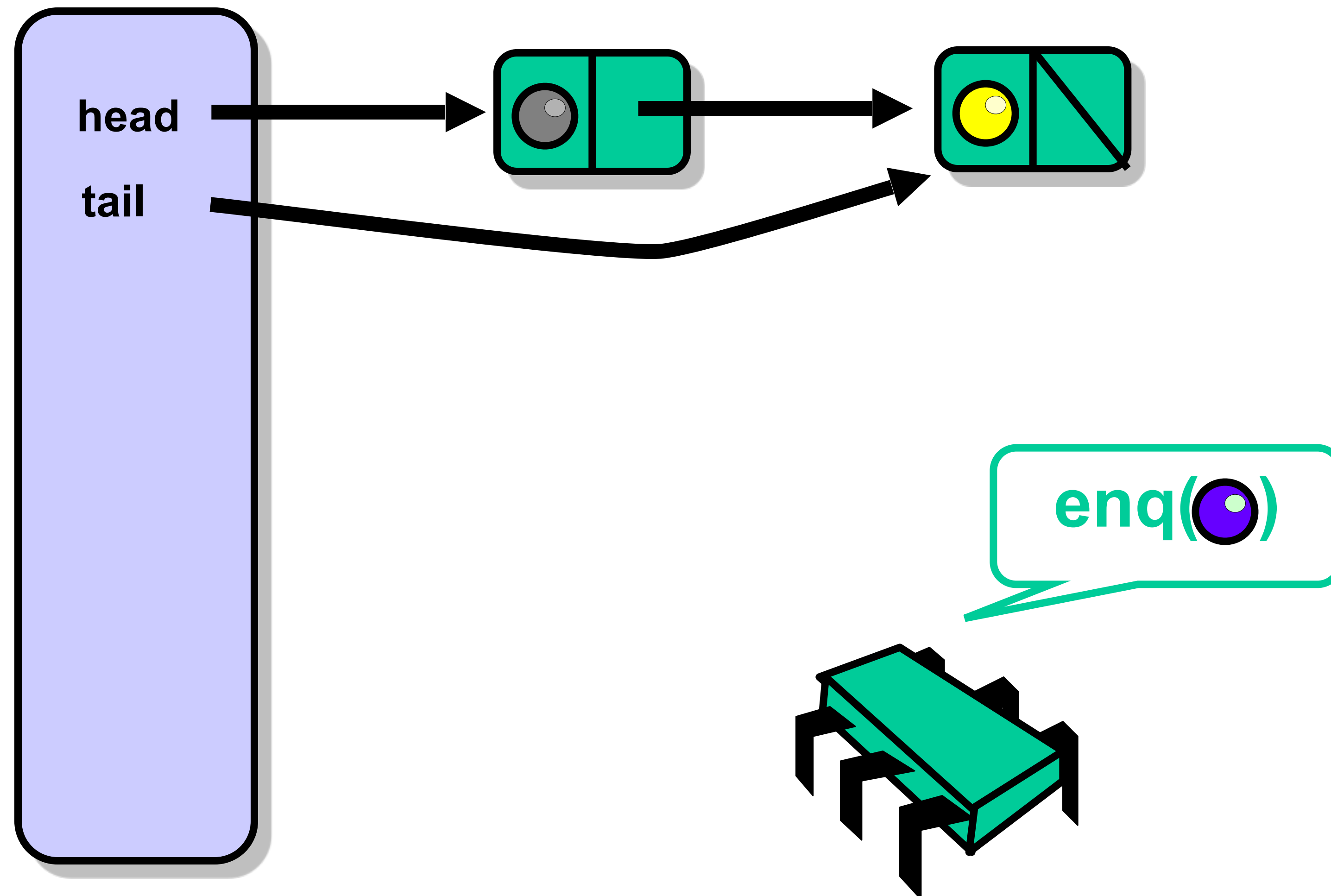
A Lock-Free Queue



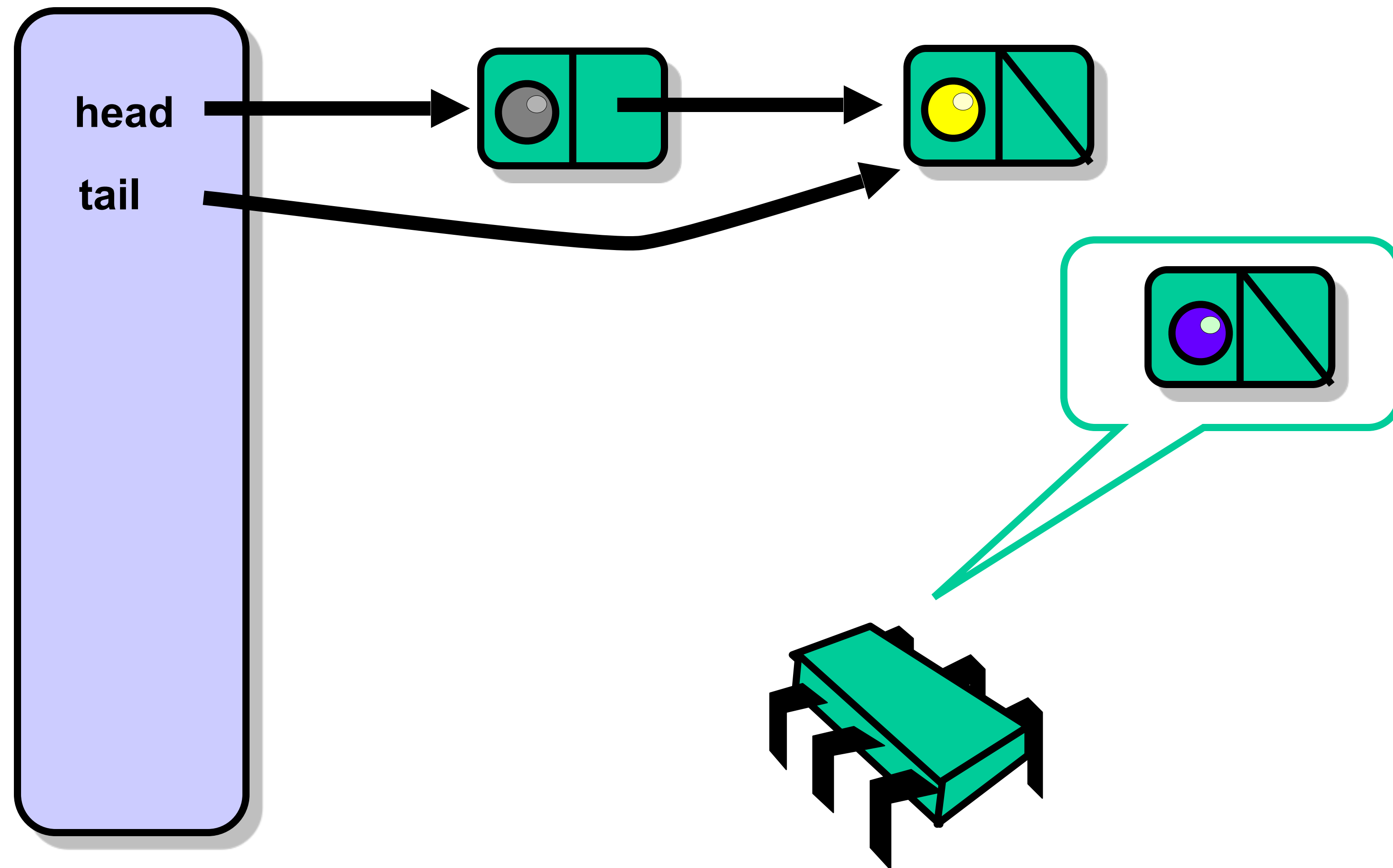
Compare and Set



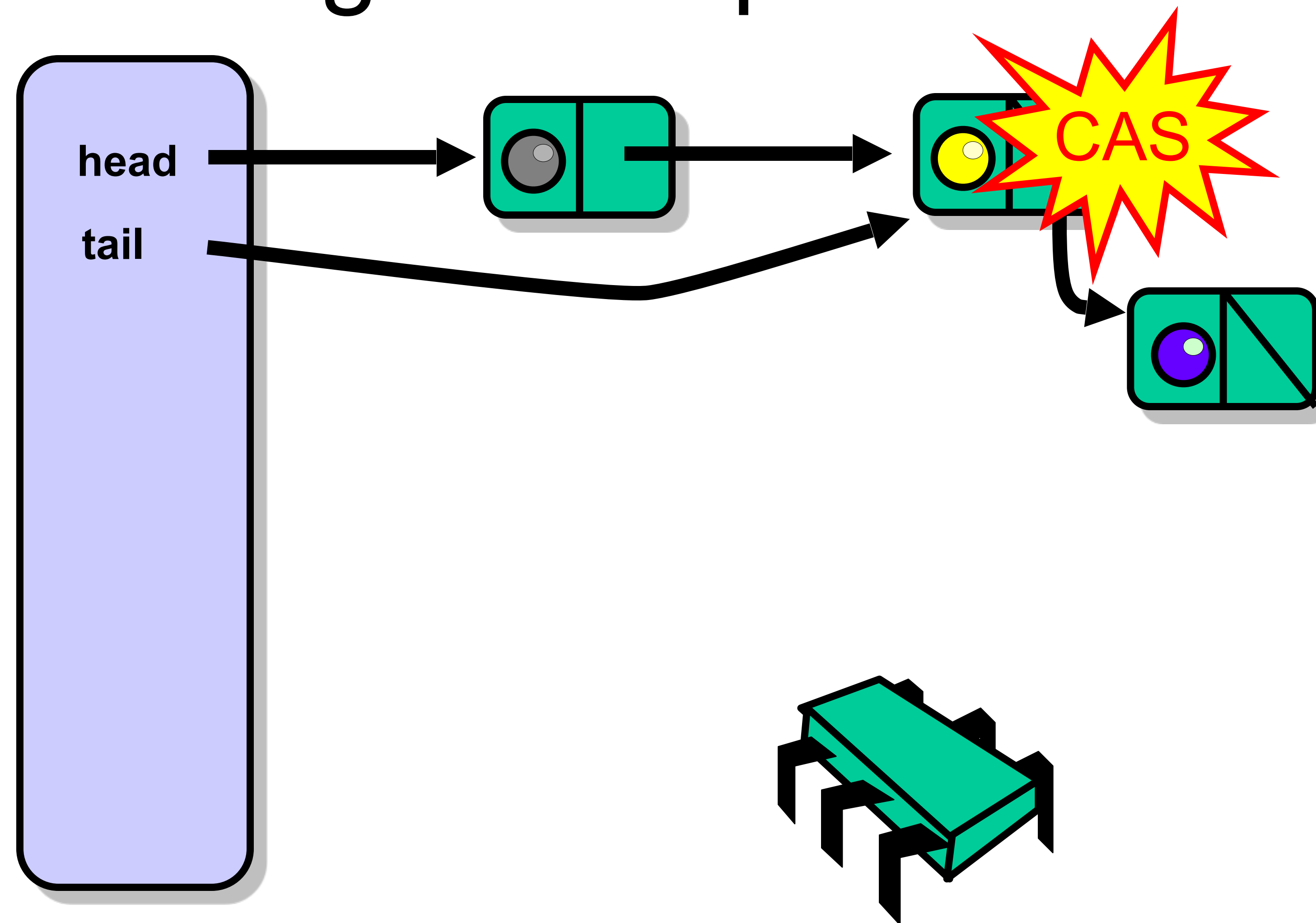
Enqueue



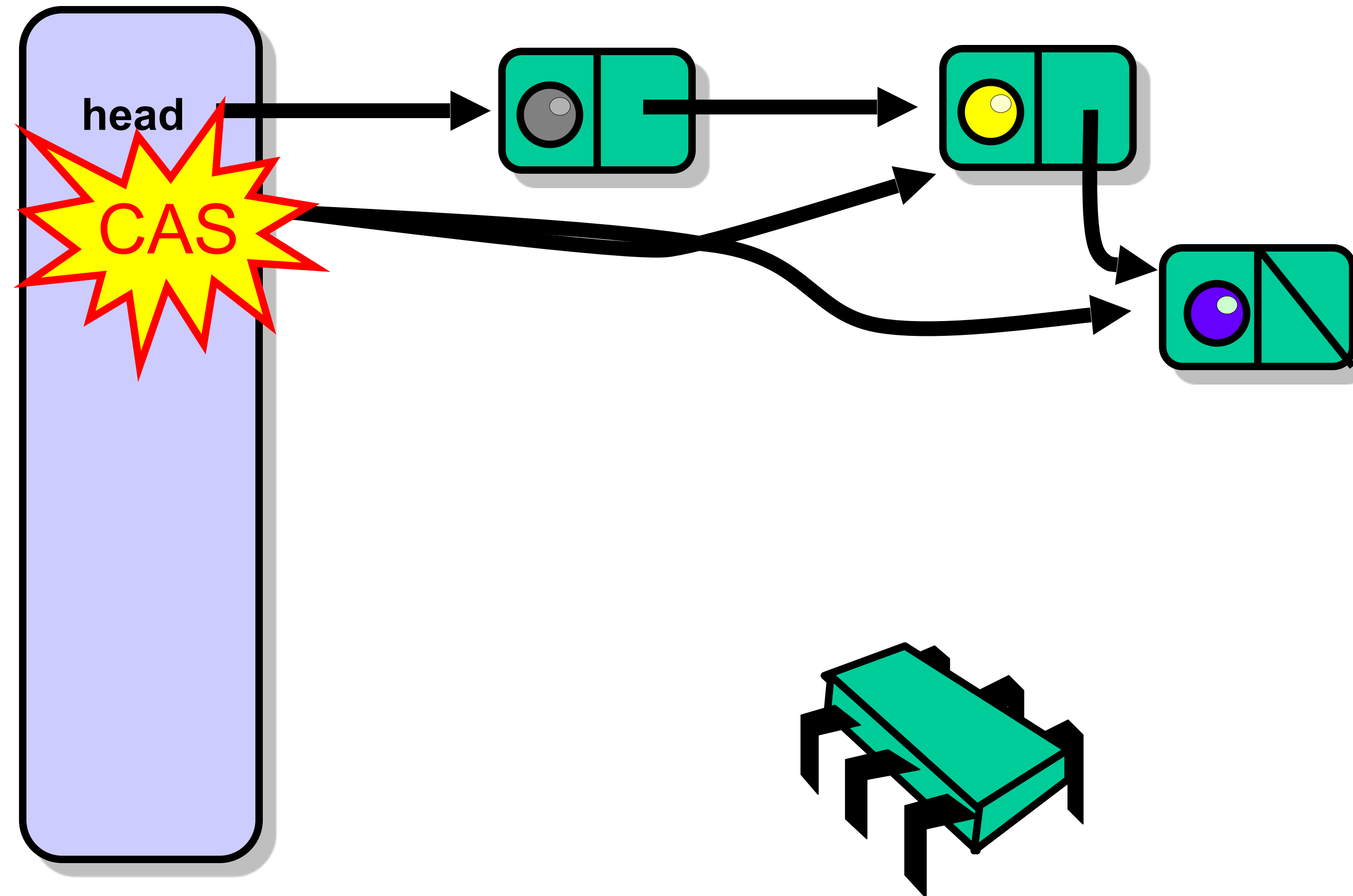
Enqueue



Logical Enqueue



Physical Enqueue



Enqueue

- These two steps are not atomic
- The tail field refers to either
 - Actual last Node (good)
 - Penultimate Node (not so good)
- Be prepared!

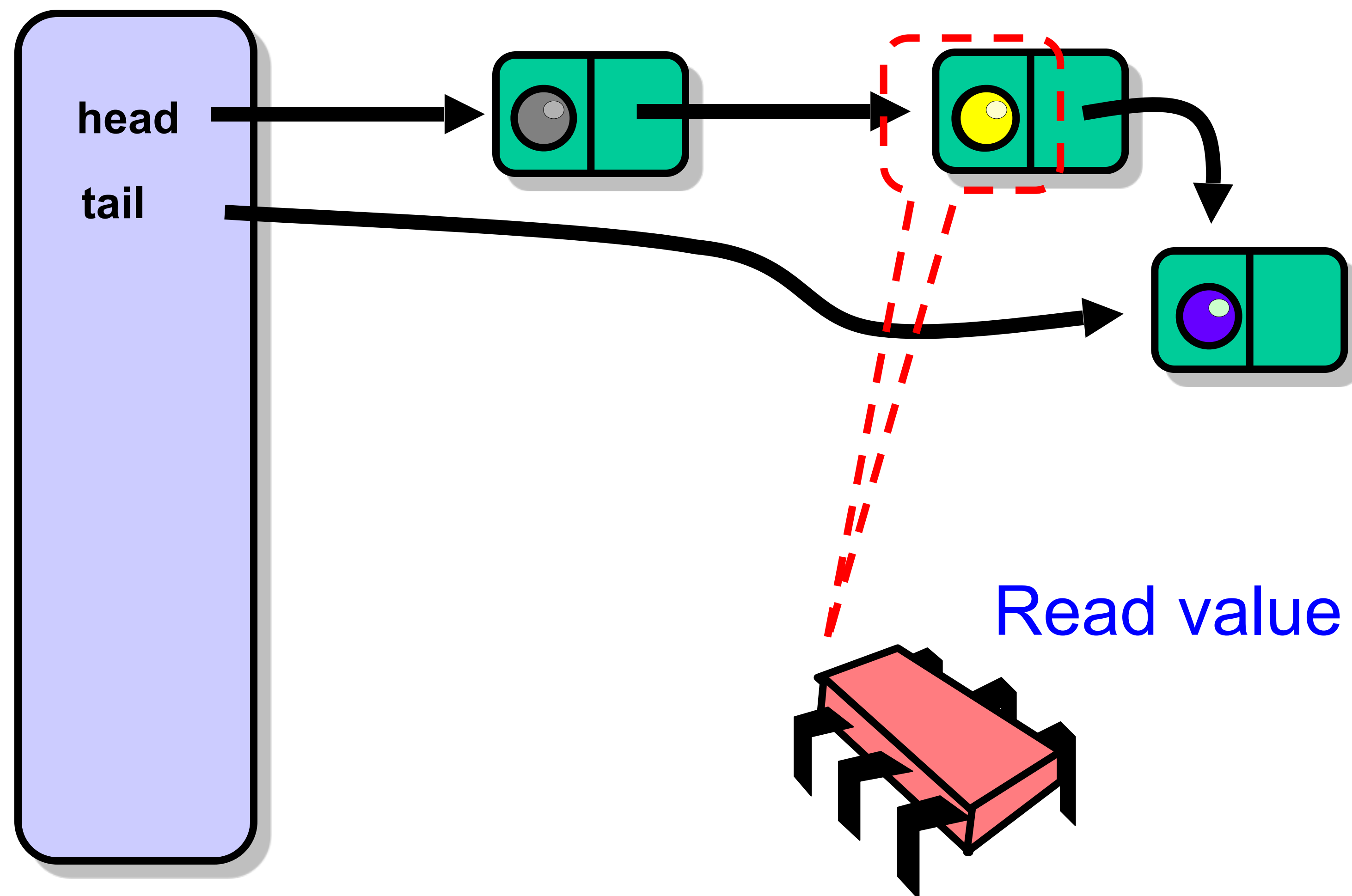
Enqueue

- What do you do if you find
 - A trailing **tail**?
- Stop and help fix it
 - If **tail** node has non-*null* next field
 - CAS the queue's **tail** field to **tail.next**
- As in the universal construction

When CASs Fail

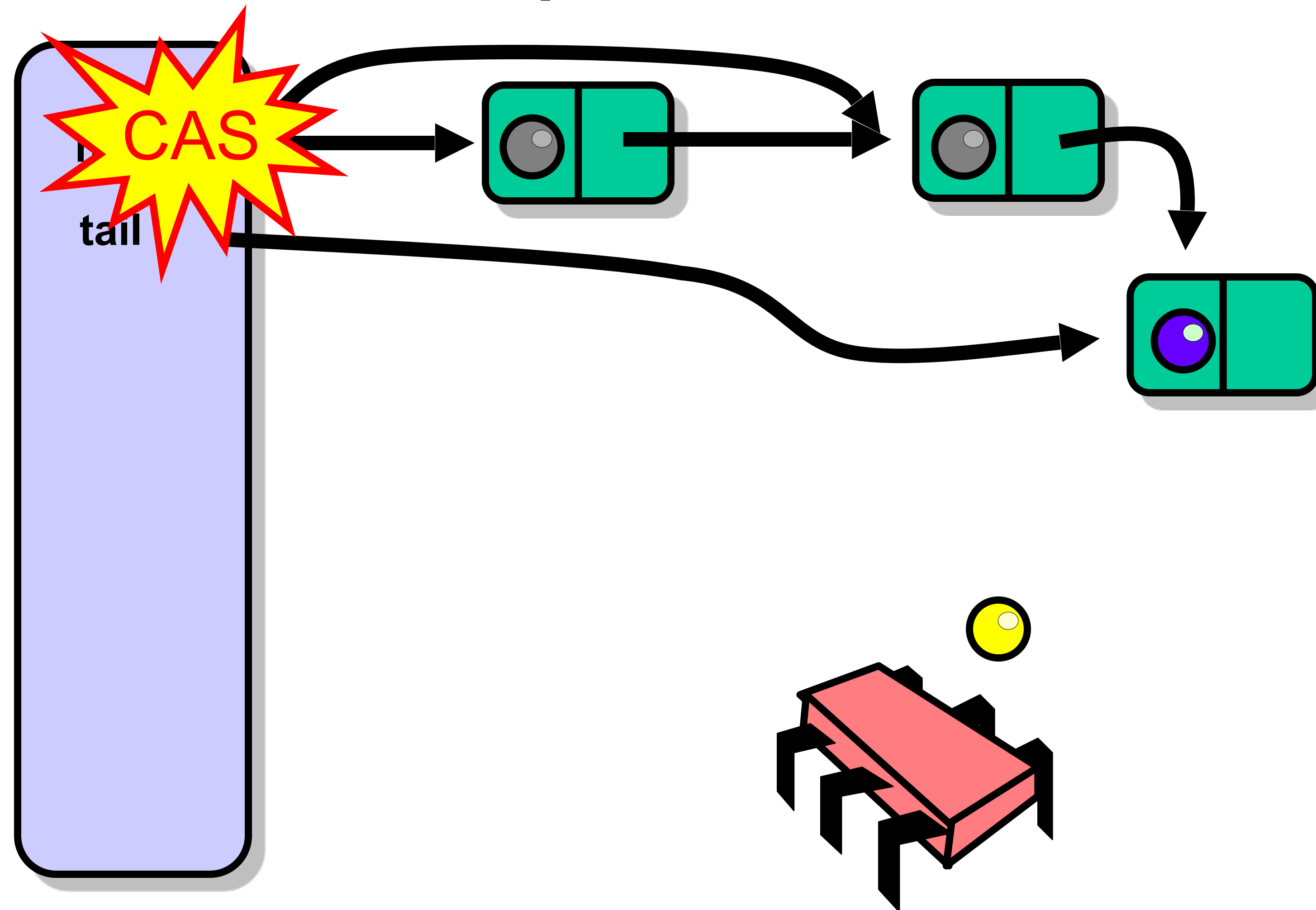
- During logical enqueue
 - Abandon hope, restart
 - Still lock-free (why?)
- During physical enqueue
 - Ignore it (why?)

Dequeuer



Make first Node new
sentinel

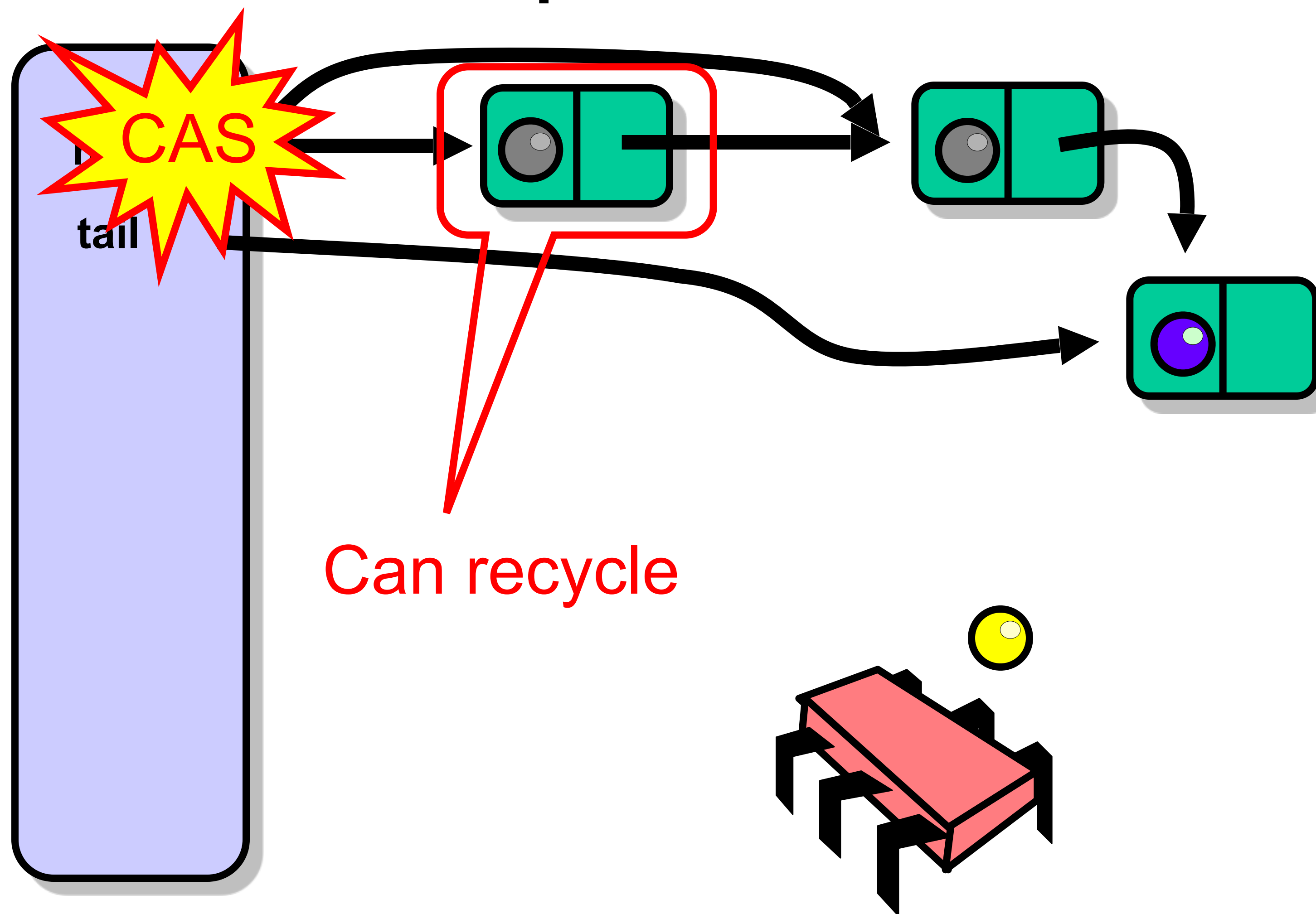
Dequeuer



Memory Reuse?

- What do we do with nodes after we dequeue them?
- Scala/Java: let garbage collector deal?
- Suppose there is no GC, or we prefer not to use it?

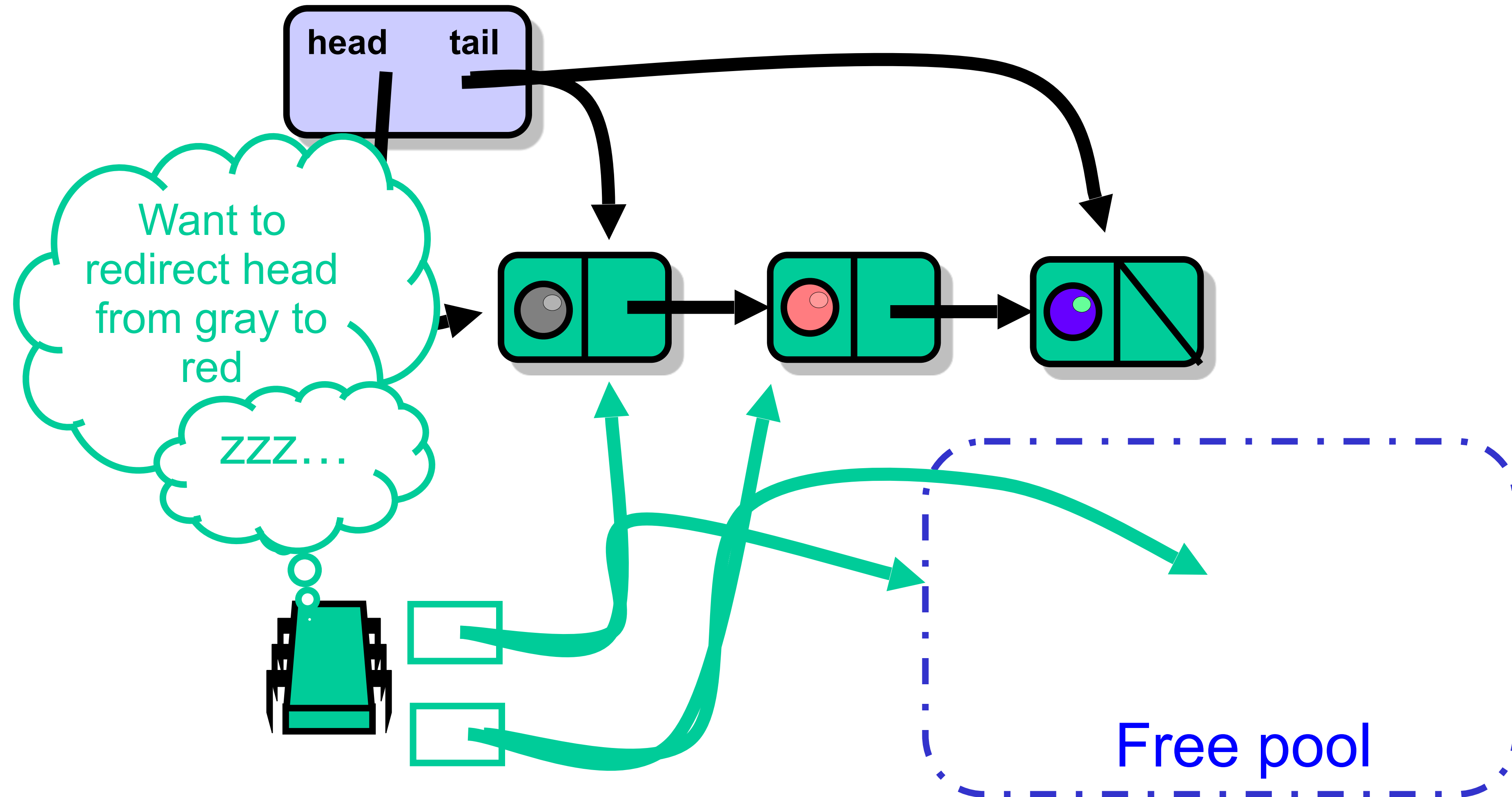
Dequeuer



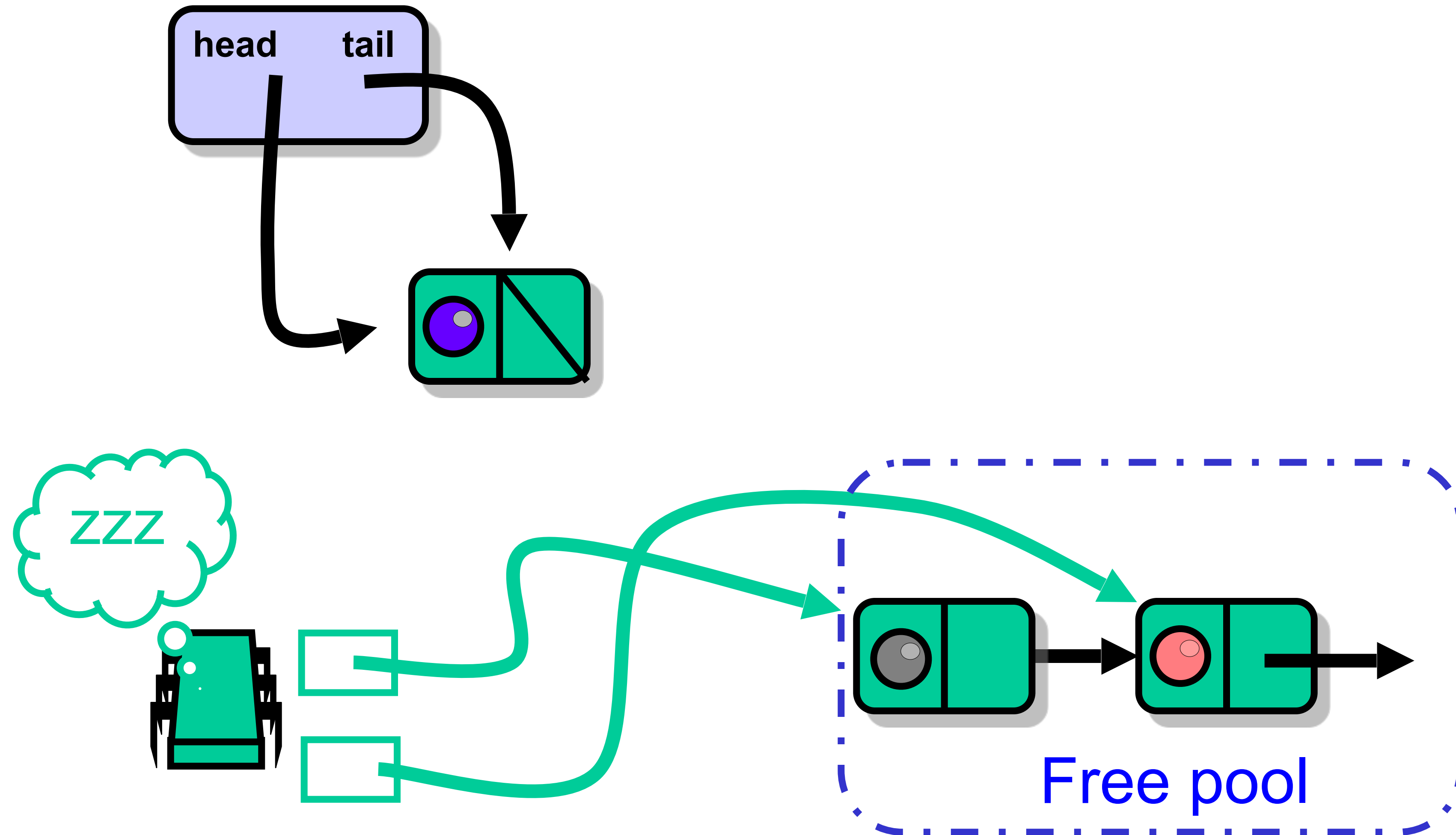
Simple Solution

- Each thread has a free list of unused queue nodes
- Allocate **node**: pop from list
- Free **node**: push onto list
- Deal with underflow somehow ...

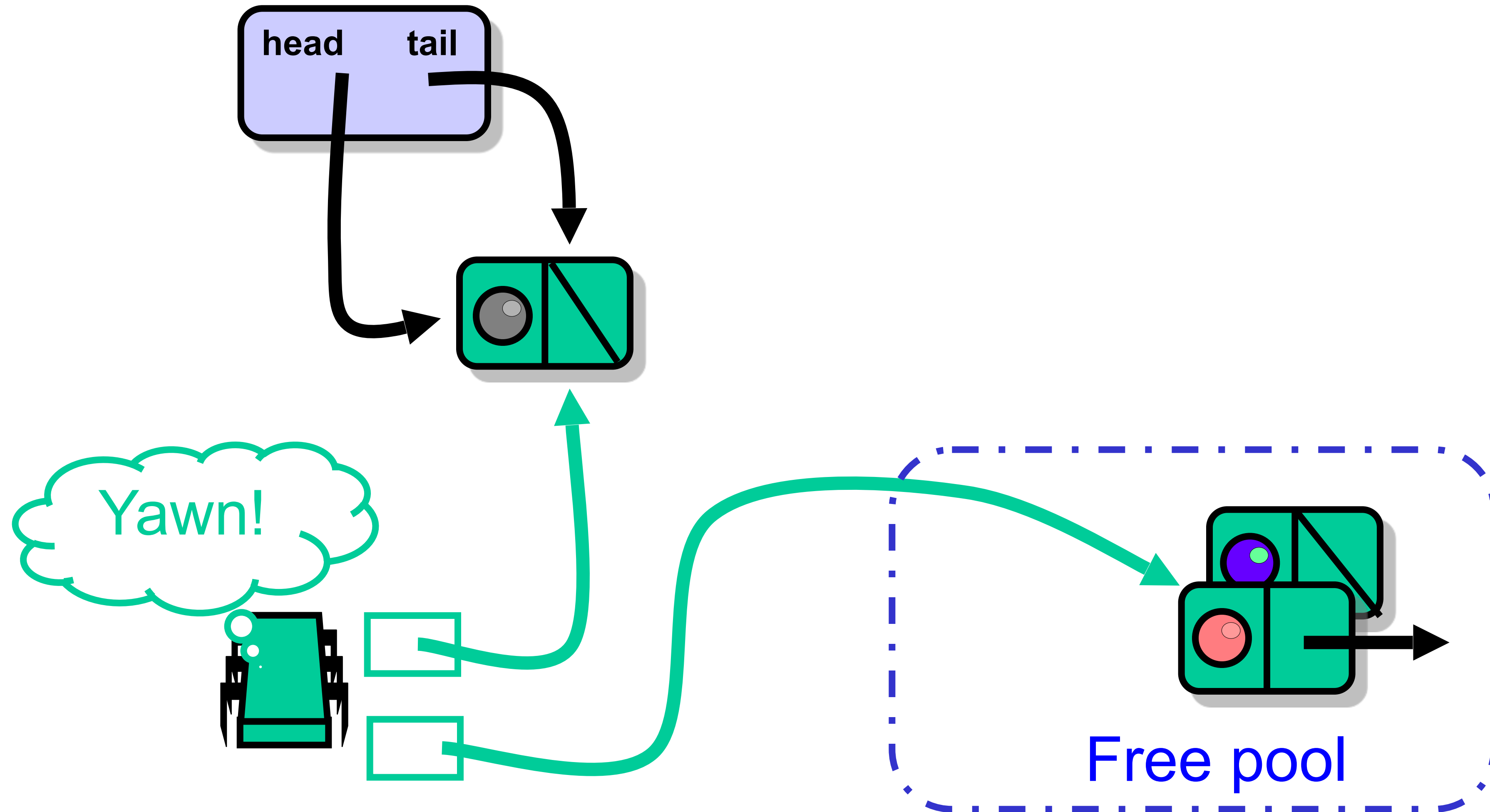
Why Recycling is Hard



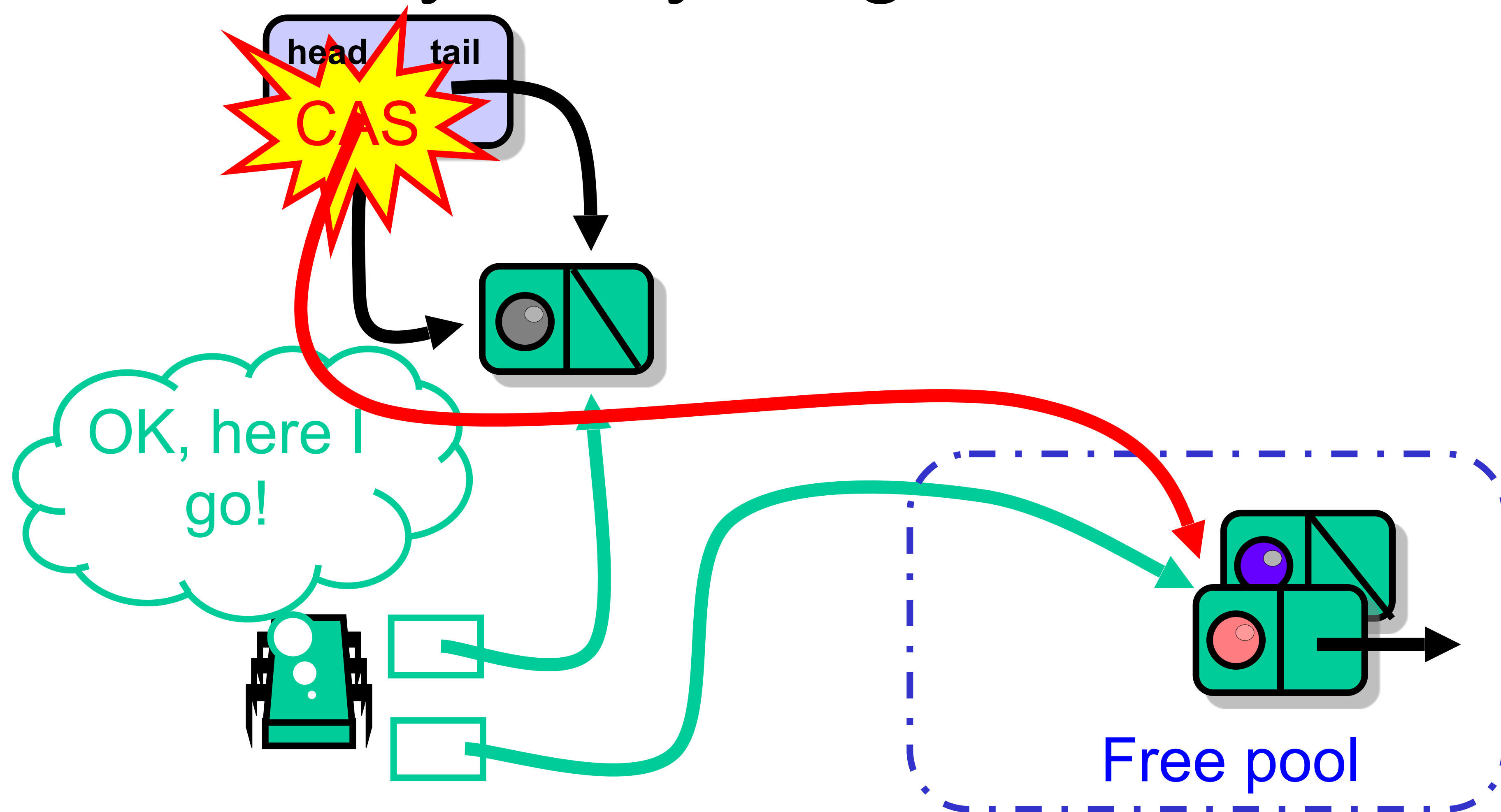
Both Nodes Reclaimed



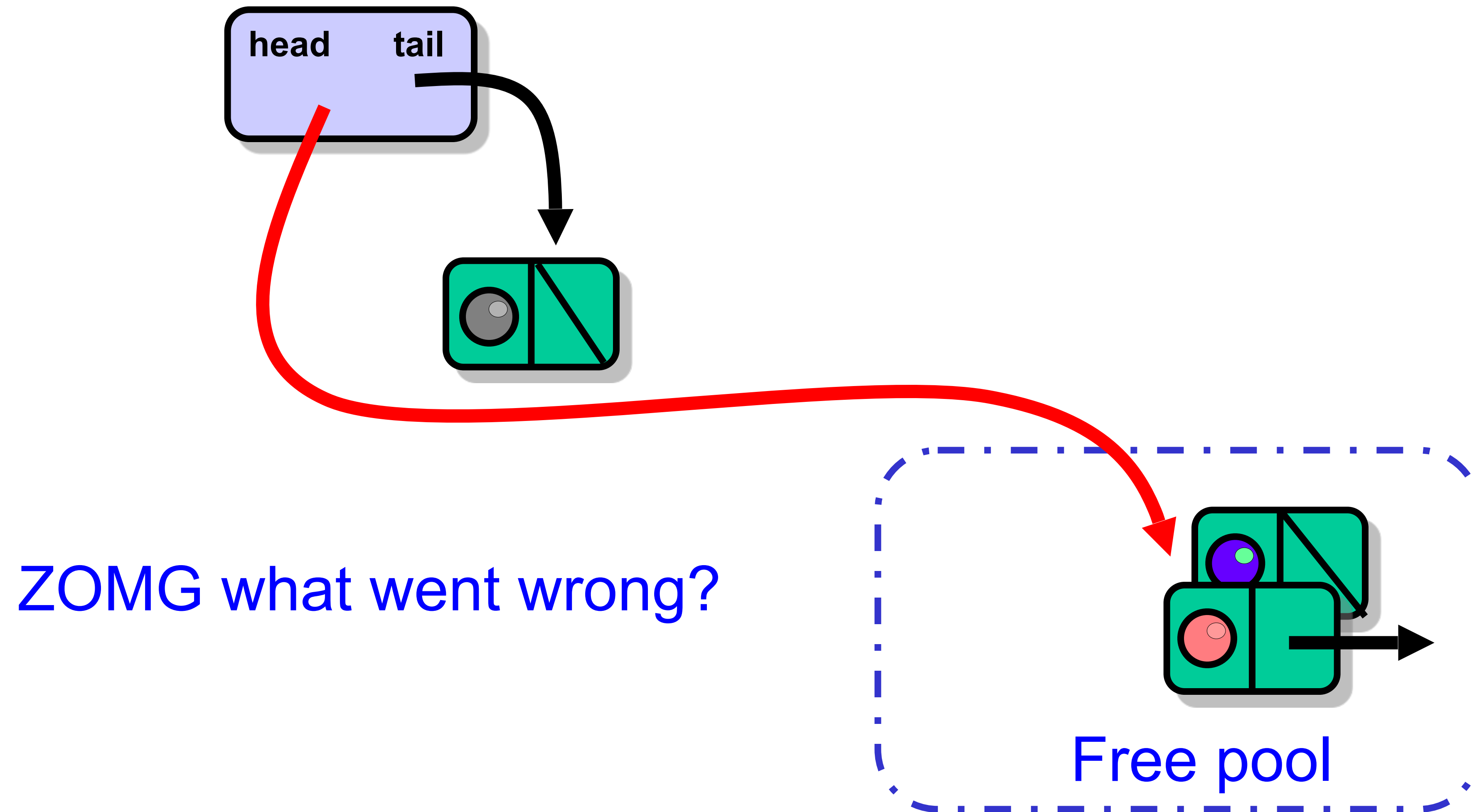
One Node Recycled



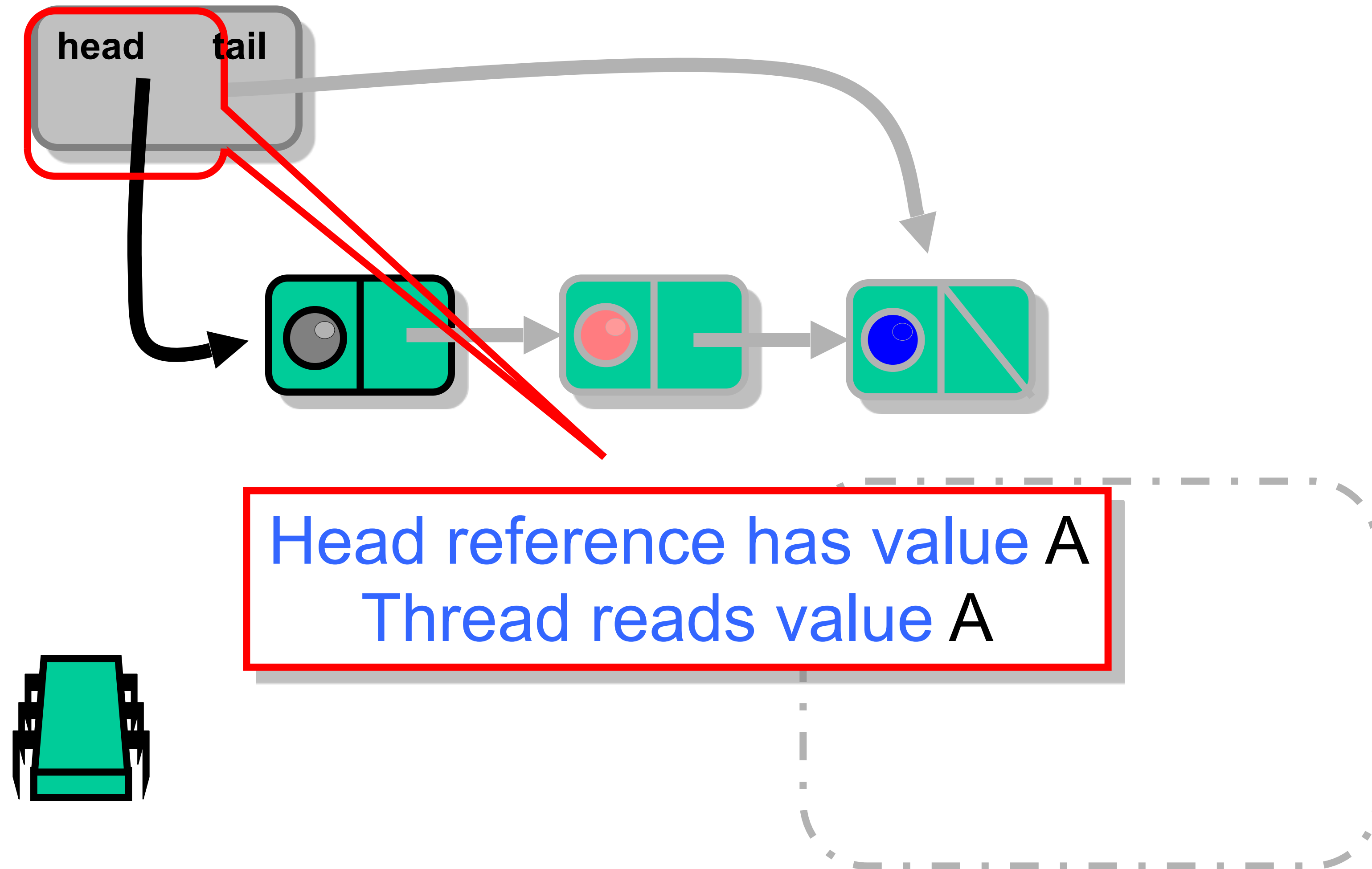
Why Recycling is Hard



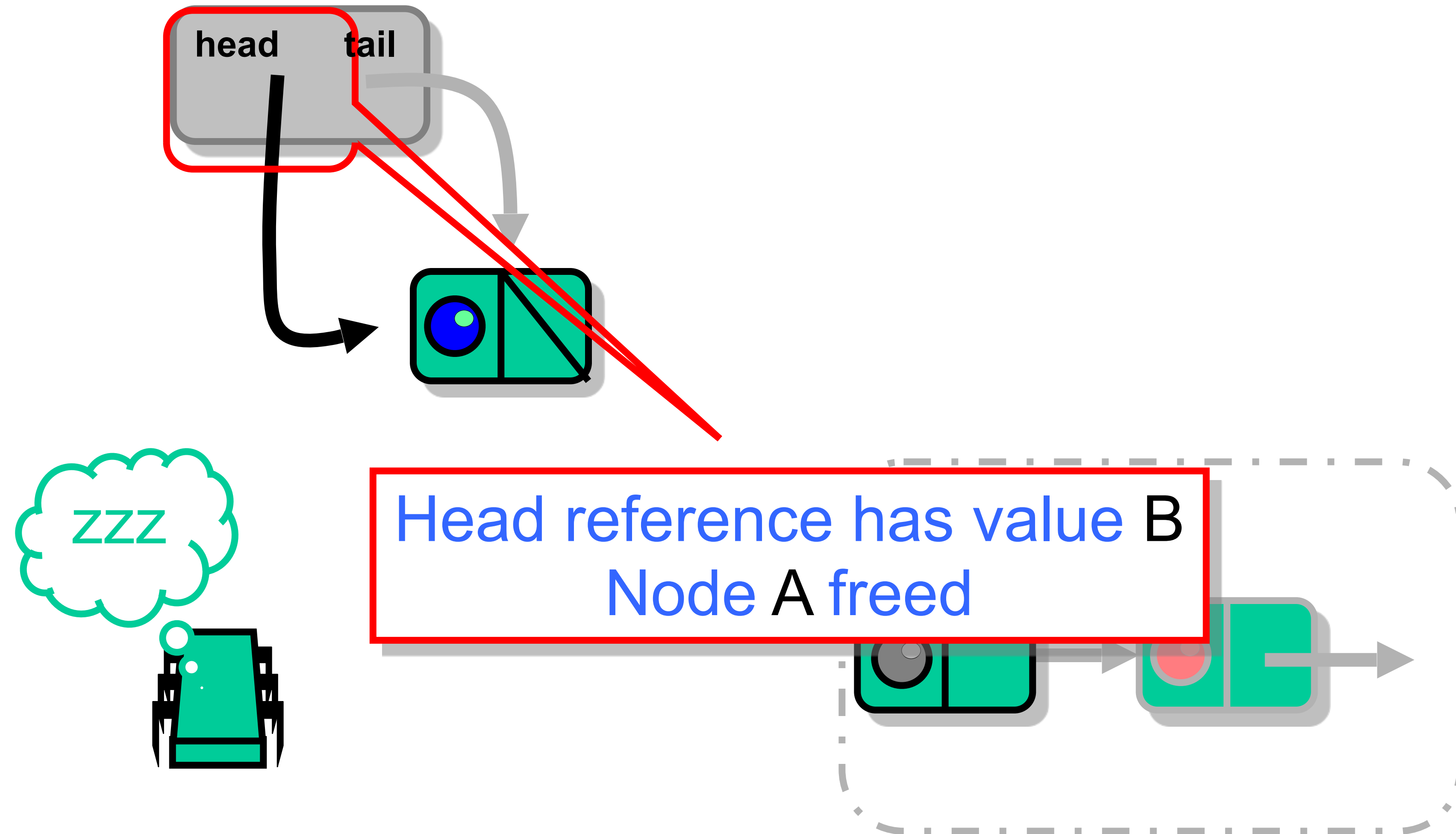
Recycle FAIL



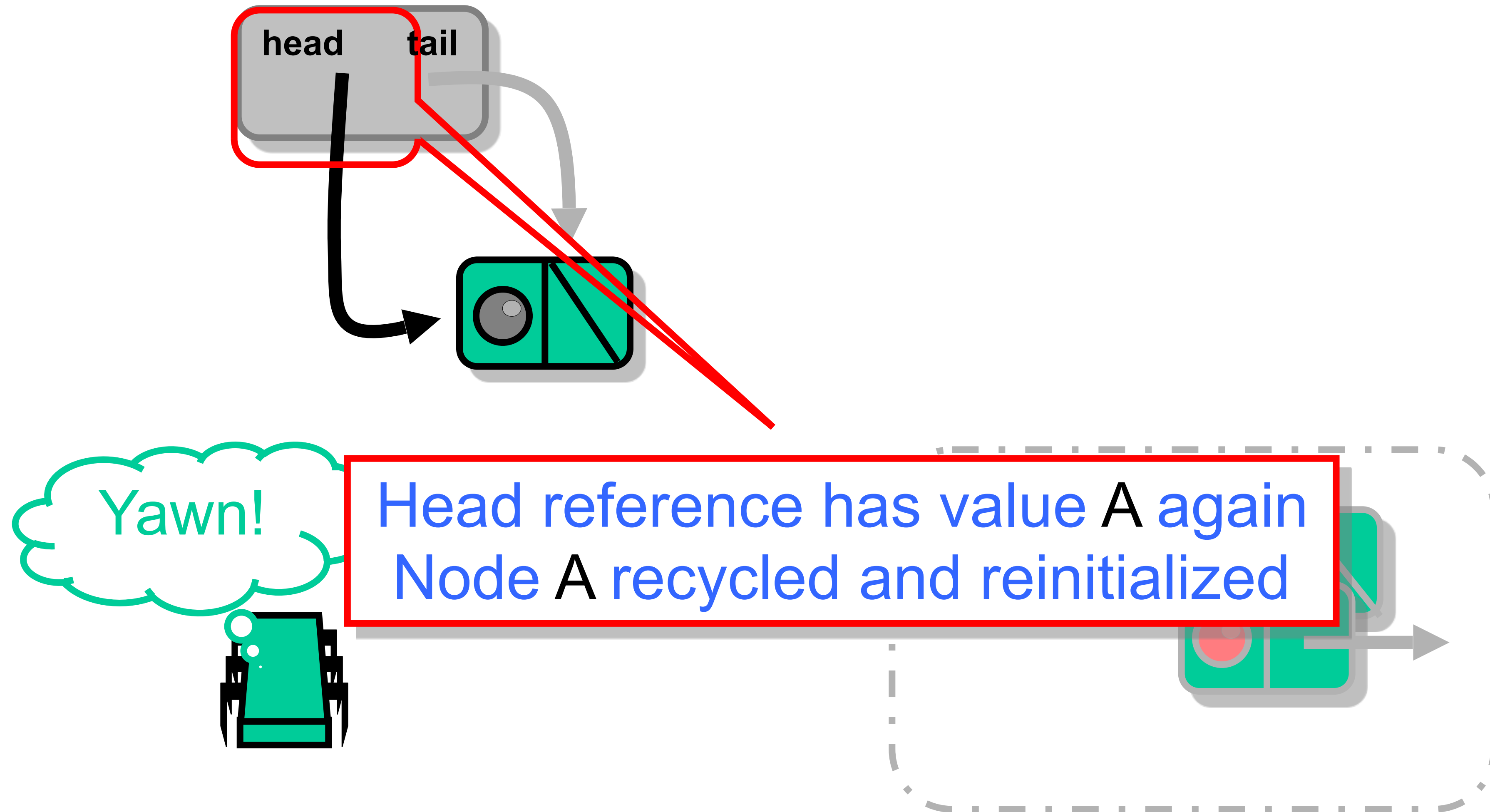
The Dreaded ABA Problem



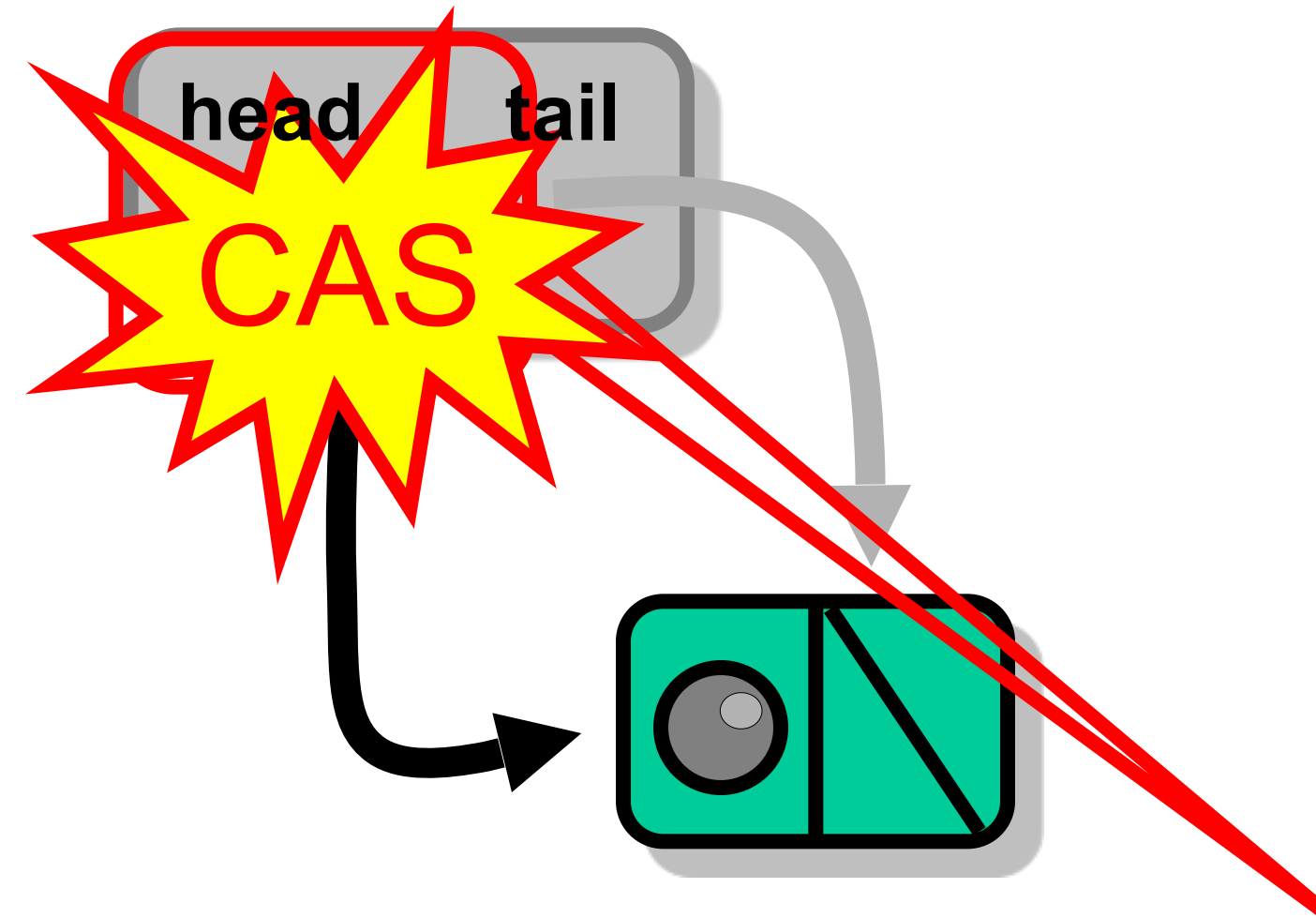
Dreaded ABA continued



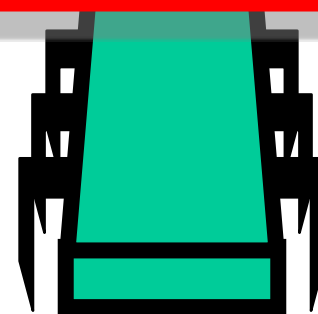
Dreaded ABA continued



Dreaded ABA continued



CAS succeeds because references match,
even though reference's meaning has changed



The Dreaded ABA FAIL

- Is a result of CAS() semantics
 - Oracle, Intel, AMD, ...
- Not with Load-Locked/Store-Conditional
 - IBM ...

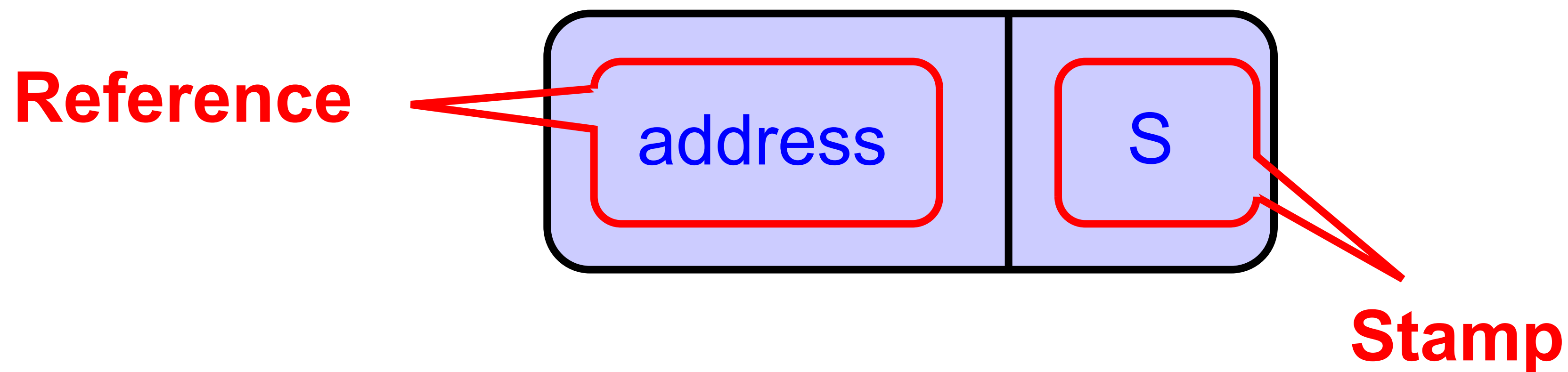
Dreaded ABA – A Solution

- Tag each pointer with a counter
- Unique over lifetime of node
- Pointer size vs word size issues
- Overflow?
 - Don't worry be happy?
 - Bounded tags?
- AtomicStampedReference class
- “Hazard Pointers”

Atomic Stamped Reference

- AtomicStampedReference **class**
 - Java.util.concurrent.atomic **package**

Can get reference & stamp atomically



Next Lecture:
Concurrent Stacks



This work is licensed under a [Creative Commons Attribution-ShareAlike 2.5 License](https://creativecommons.org/licenses/by-sa/3.0/).

- **You are free:**
 - **to Share** — to copy, distribute and transmit the work
 - **to Remix** — to adapt the work
- **Under the following conditions:**
 - **Attribution.** You must attribute the work to “The Art of Multiprocessor Programming” (but not in any way that suggests that the authors endorse you or your use of the work).
 - **Share Alike.** If you alter, transform, or build upon this work, you may distribute the resulting work only under the same, similar or a compatible license.
- For any reuse or distribution, you must make clear to others the license terms of this work. The best way to do this is with a link to
 - <http://creativecommons.org/licenses/by-sa/3.0/>.
- Any of the above conditions can be waived if you get permission from the copyright holder.
- Nothing in this license impairs or restricts the author's moral rights.