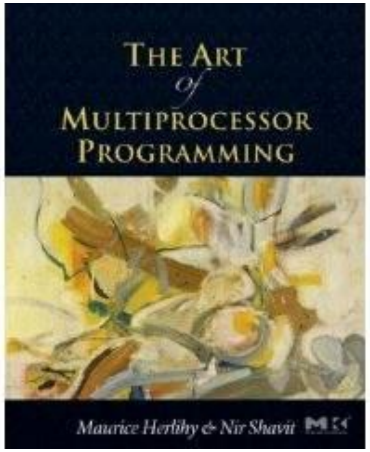
Programming Paradigms for Concurrency

Lecture 7 – Concurrent Queues and Stacks



Based on companion slides for
The Art of Multiprocessor Programming
by Maurice Herlihy & Nir Shavit

Modified by
Thomas Wies
New York University

The Five-Fold Path

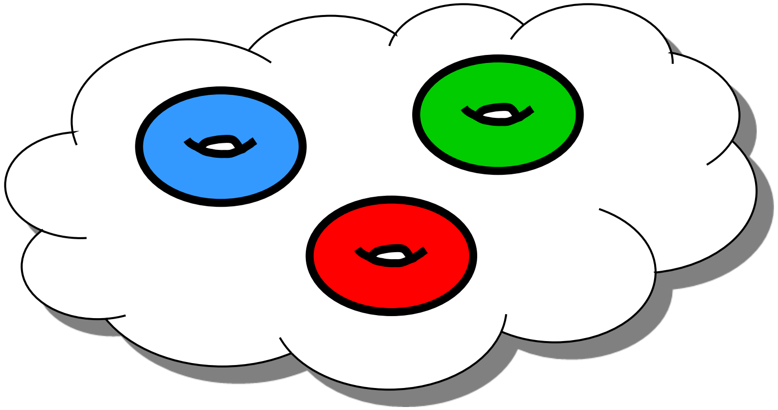
- Coarse-grained locking
- Fine-grained locking
- Optimistic synchronization
- Lazy synchronization
- Lock-free synchronization

Another Fundamental Problem

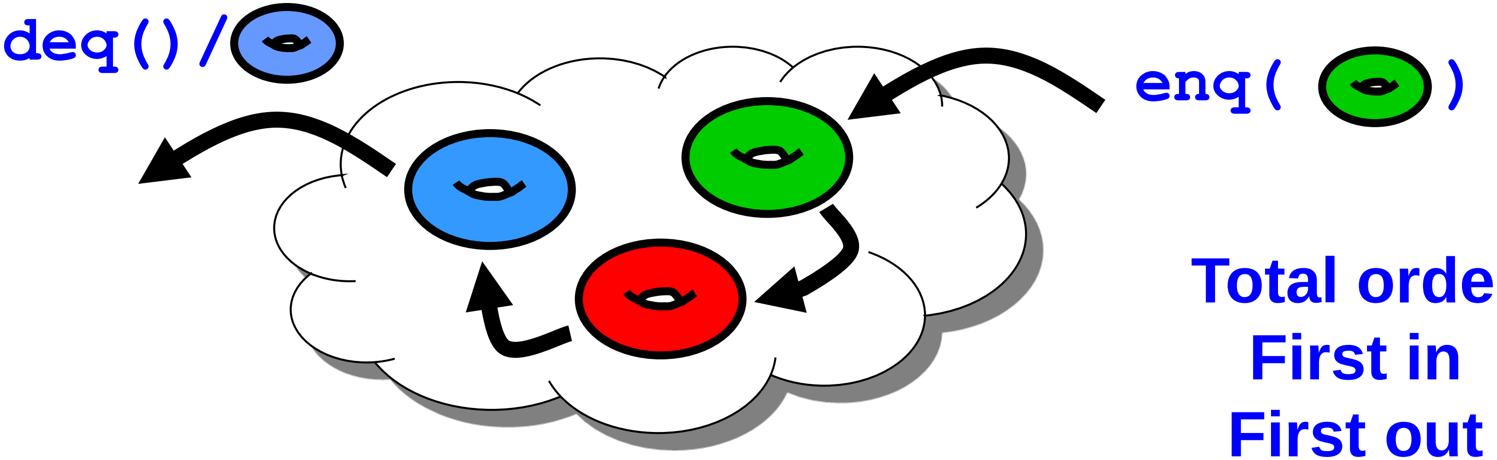
- I told you about
  - Sets implemented by linked lists
- Next: queues
- Next: stacks

Queues & Stacks

- pool of items

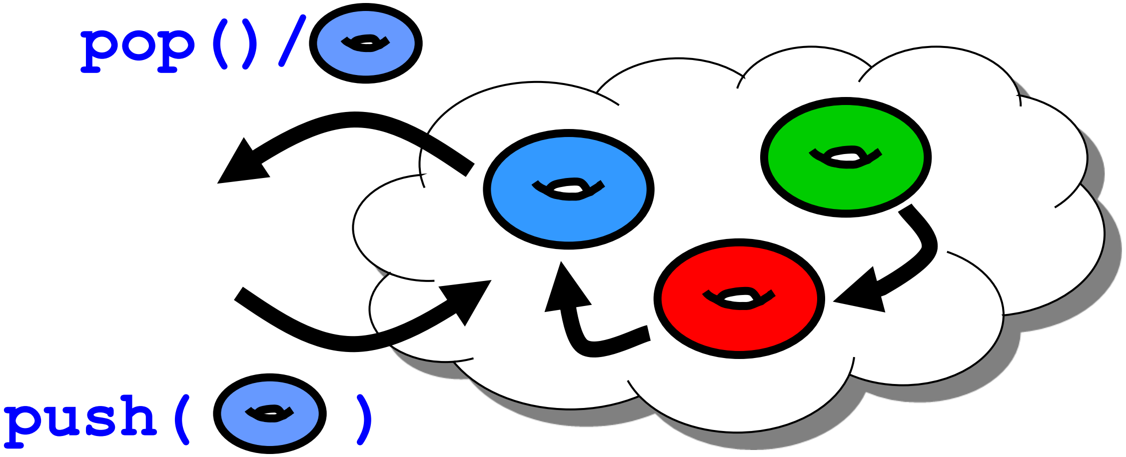


Queues



Total order
First in
First out

Stacks



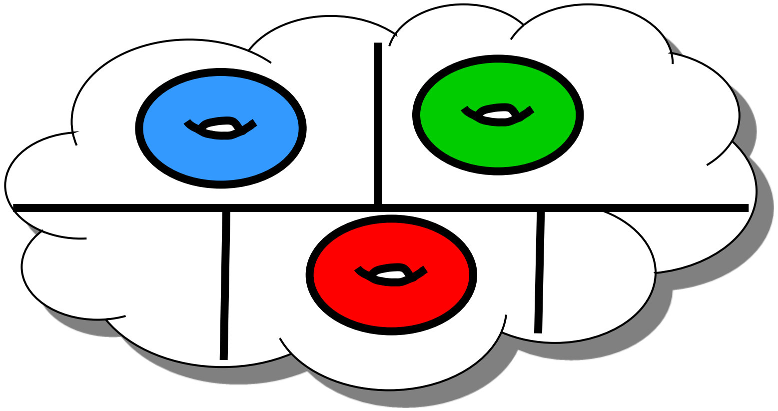
`pop()/`

`push( )`

Total order
Last in
First out

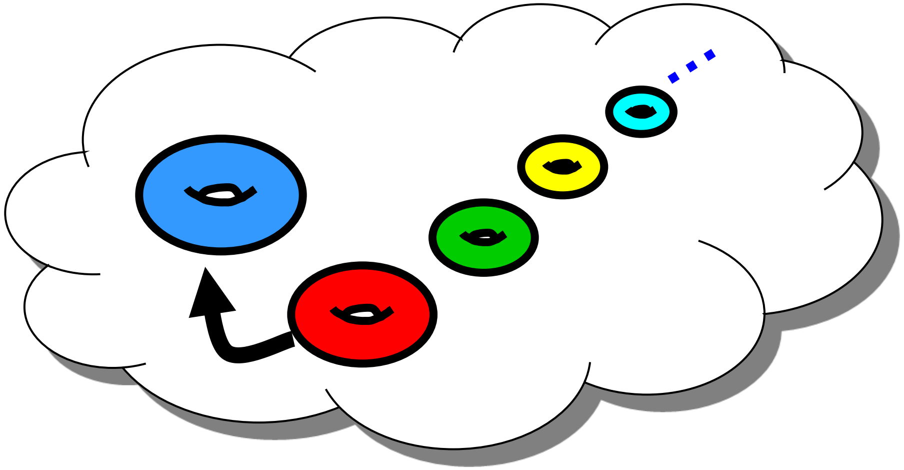
Bounded

- Fixed capacity
- Good when resources an issue

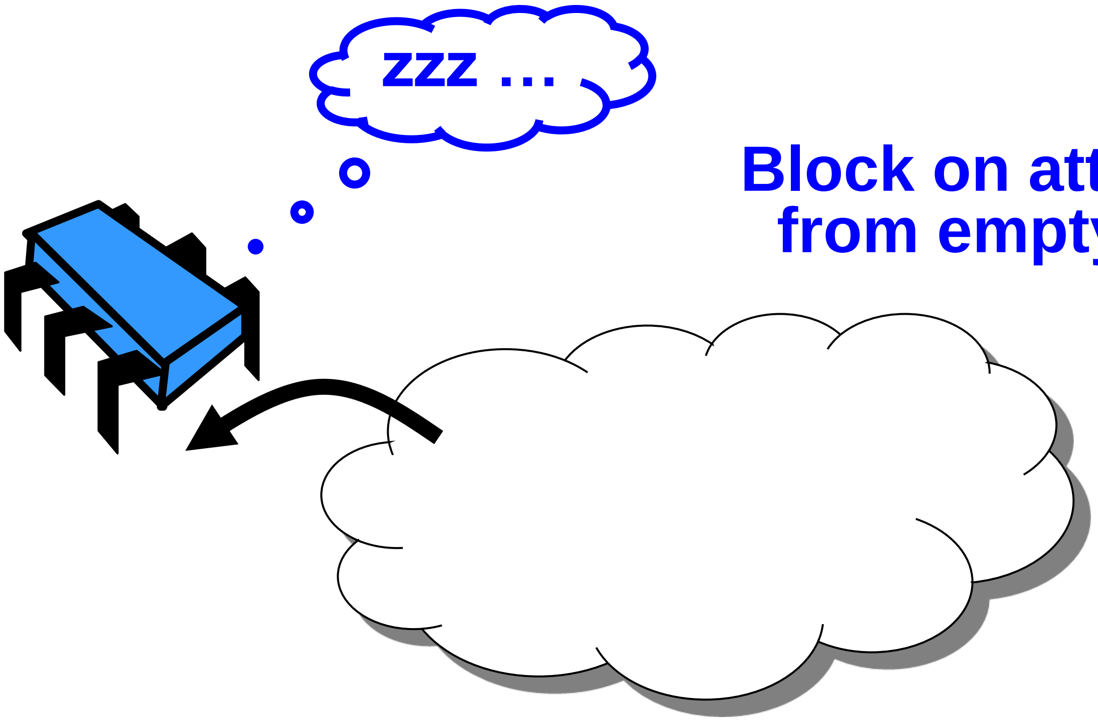


Unbounded

- Unlimited capacity
- Often more convenient

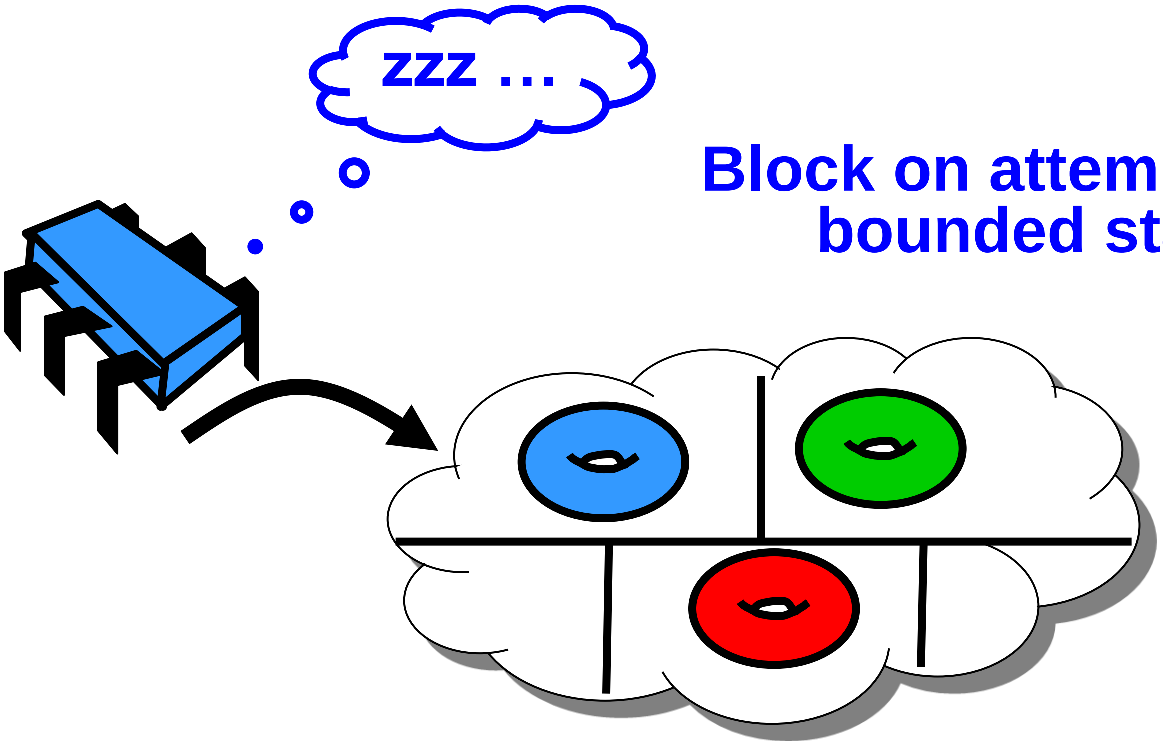


Blocking



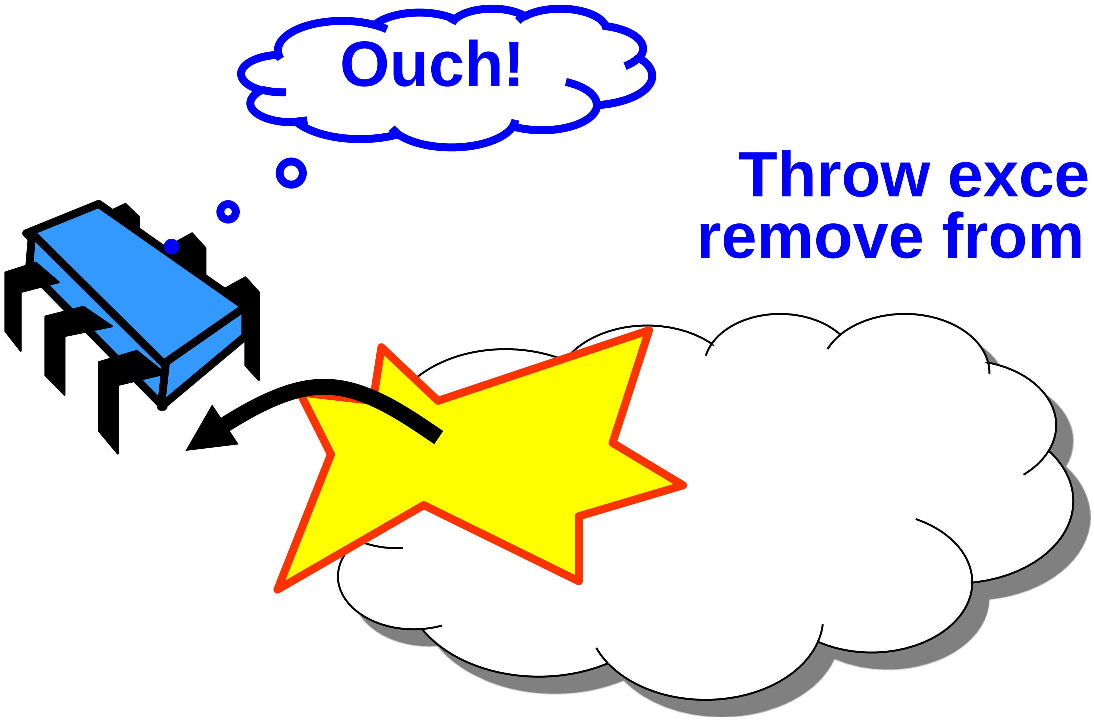
Block on attempt to remove from empty stack or queue

Blocking



Block on attempt to add to full bounded stack or queue

Non-Blocking

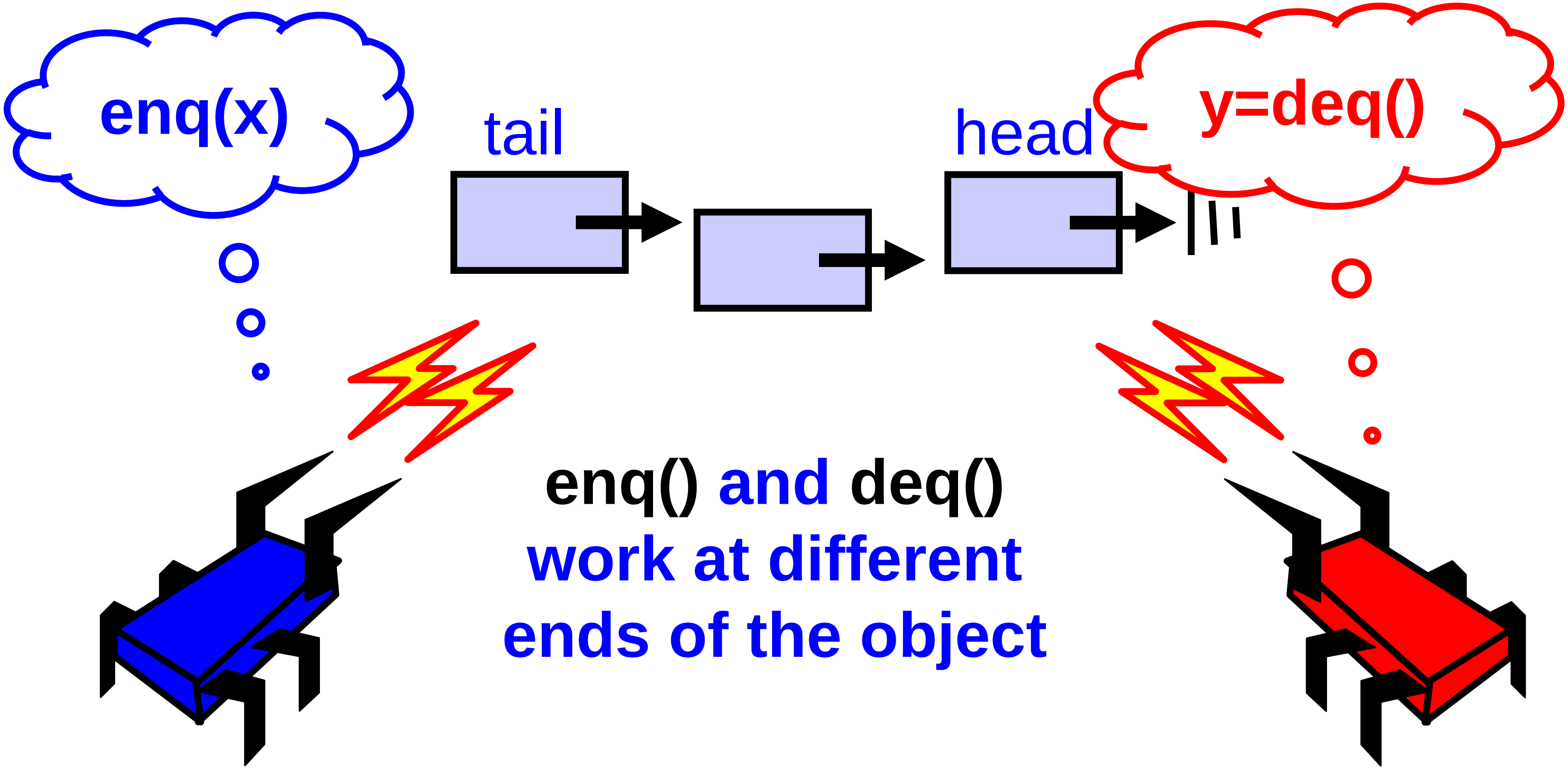


Throw exception on attempt to remove from empty stack or queue

This Lecture

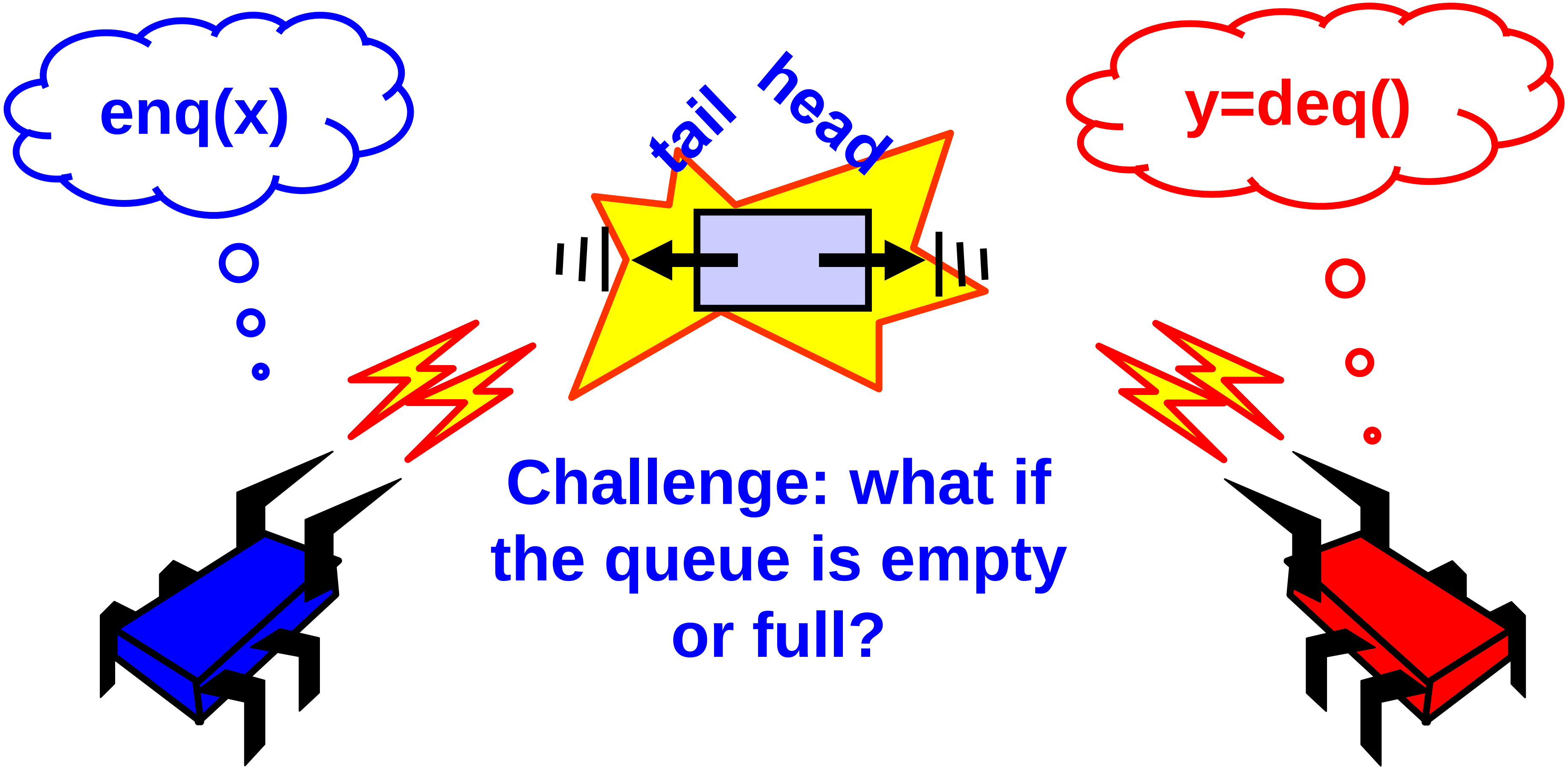
- Queue
  - – Bounded, blocking, lock-based
  - – Unbounded, non-blocking, lock-free
- Stack
  - – Unbounded, non-blocking lock-free
  - – Elimination-backoff algorithm

Queue: Concurrency



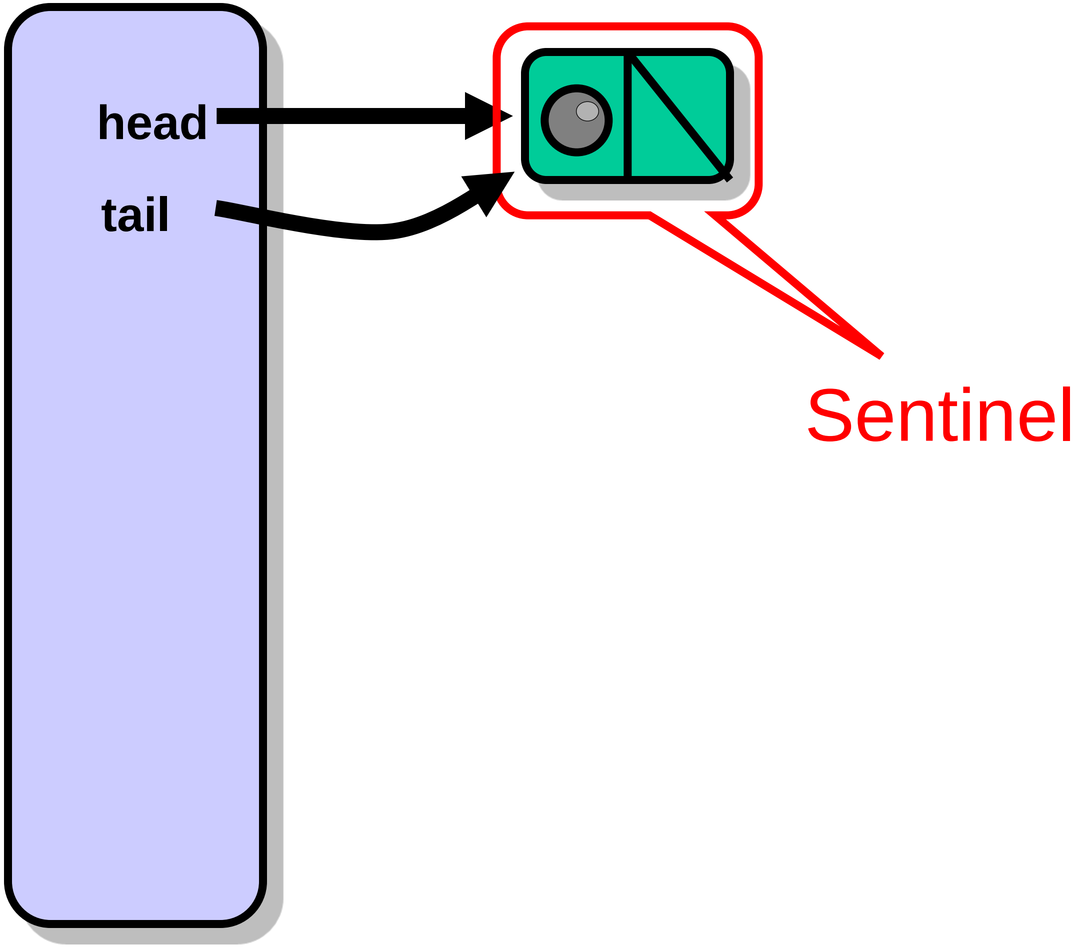
enq() and deq() work at different ends of the object

Concurrency

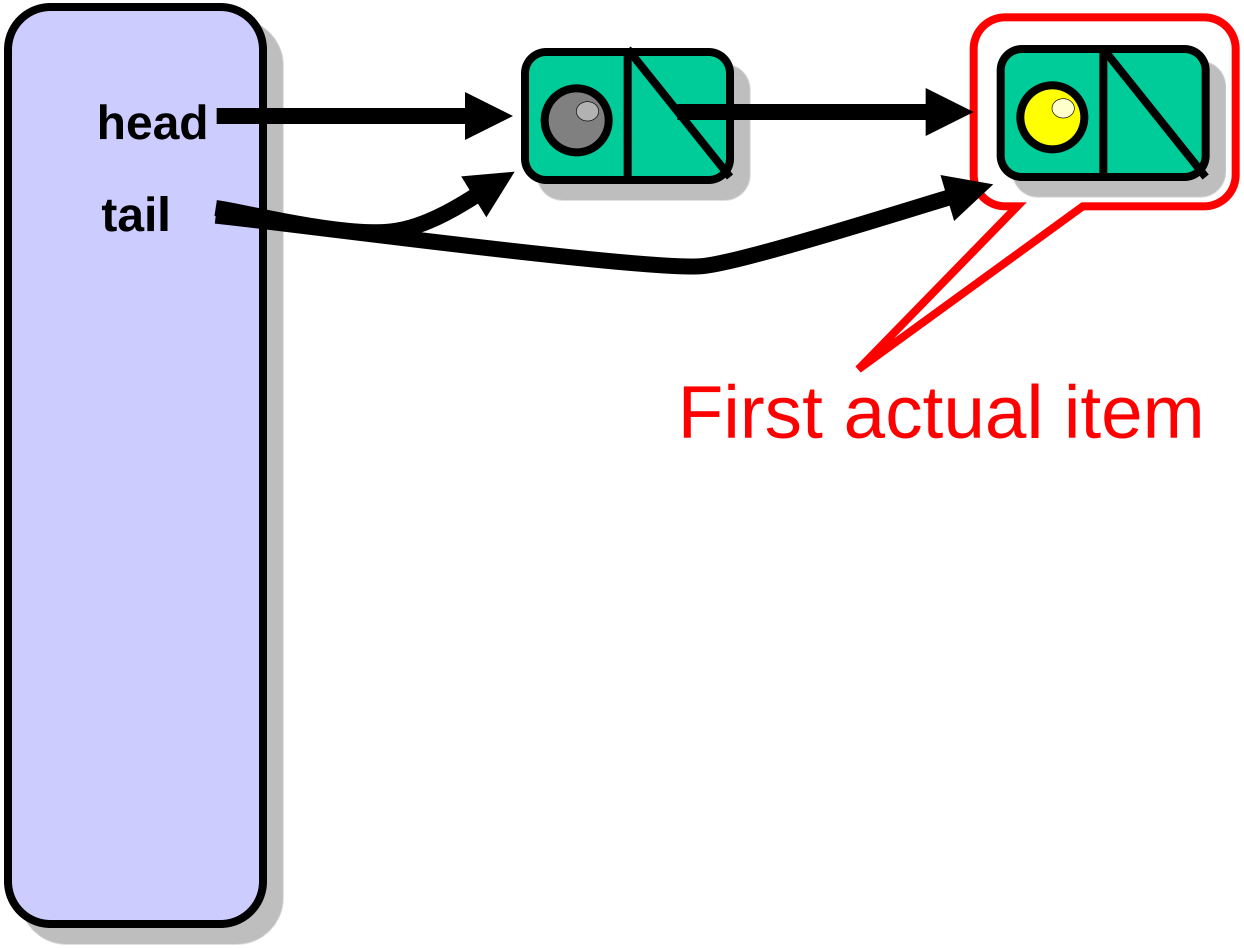


Challenge: what if the queue is empty or full?

Bounded Queue

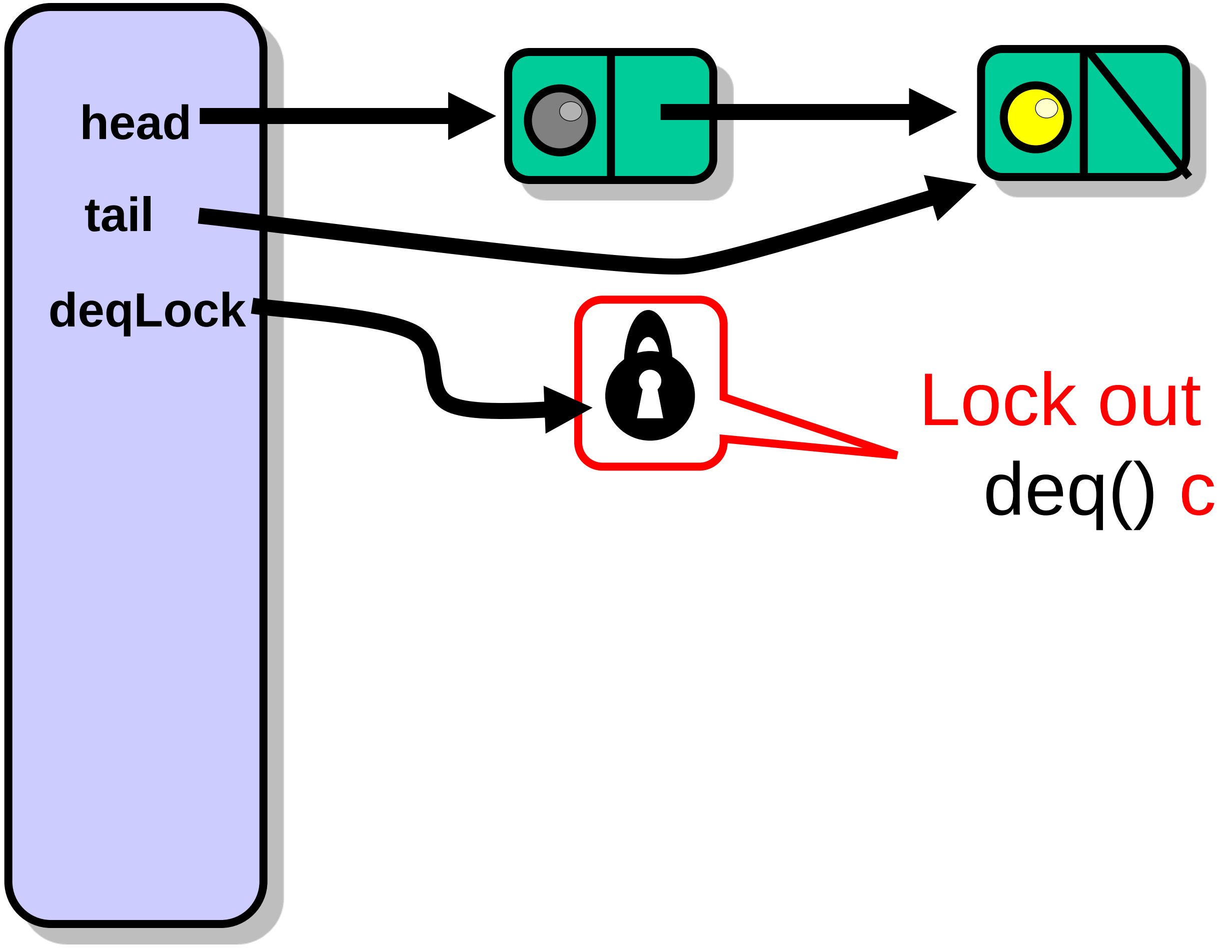


Bounded Queue



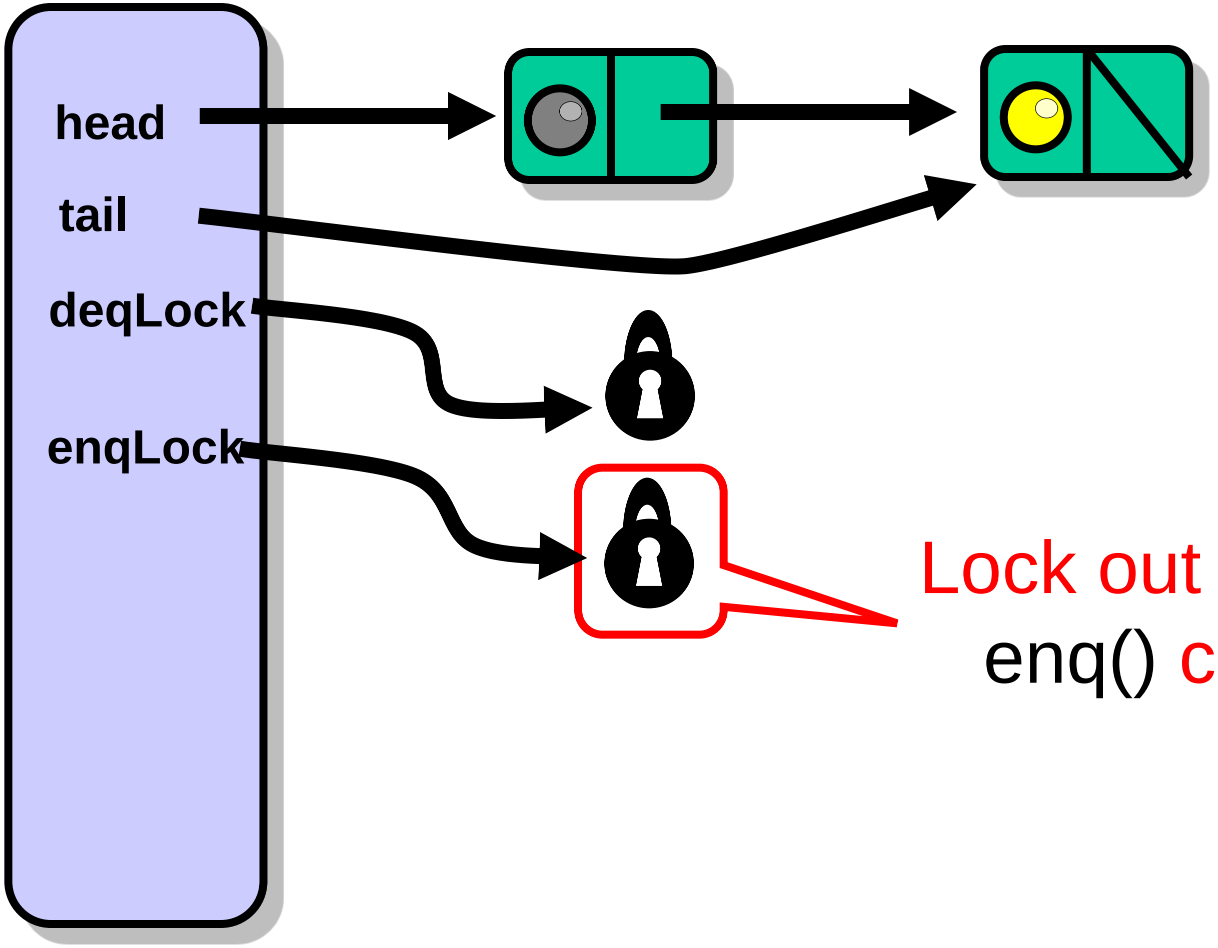
First actual item

Bounded Queue



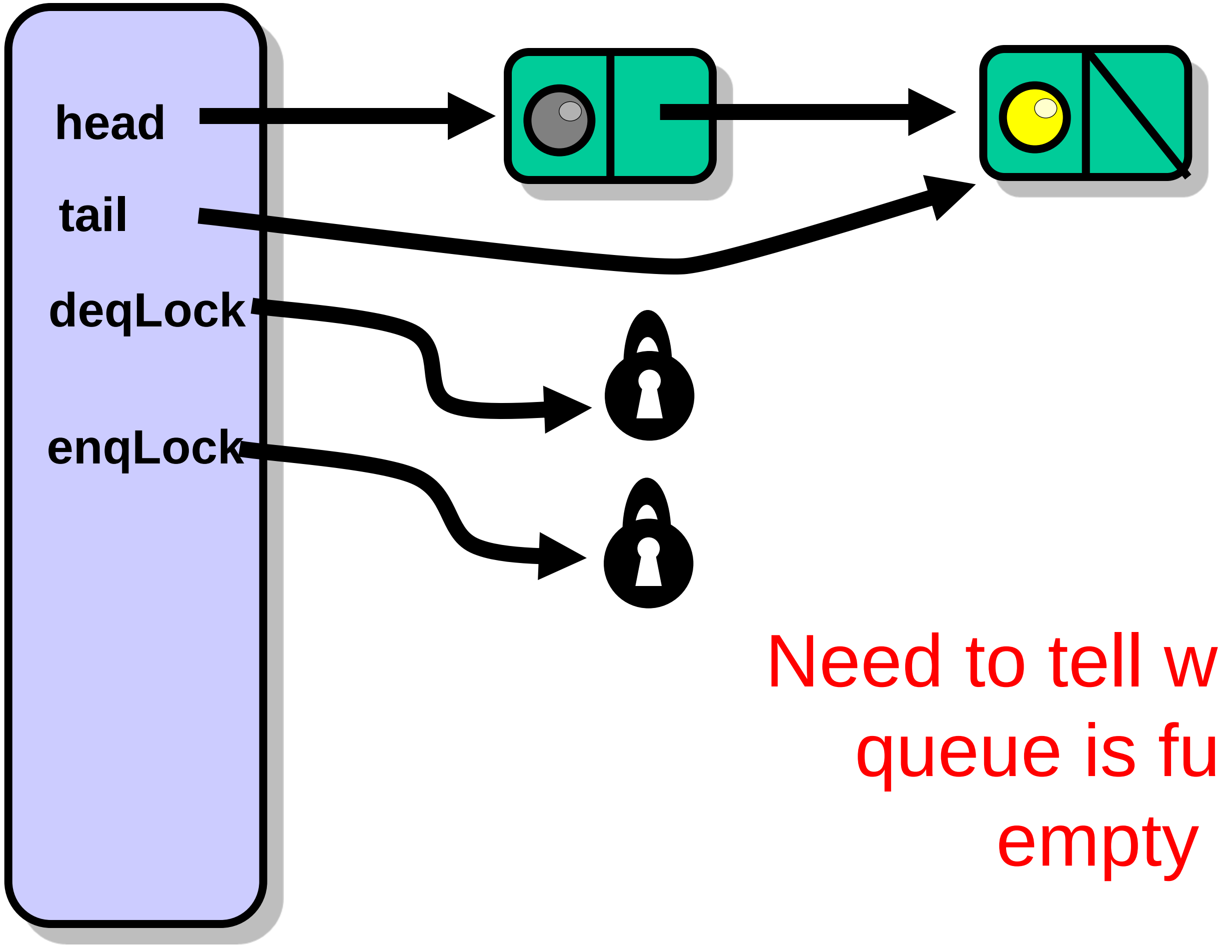
Lock out other deq() calls

Bounded Queue



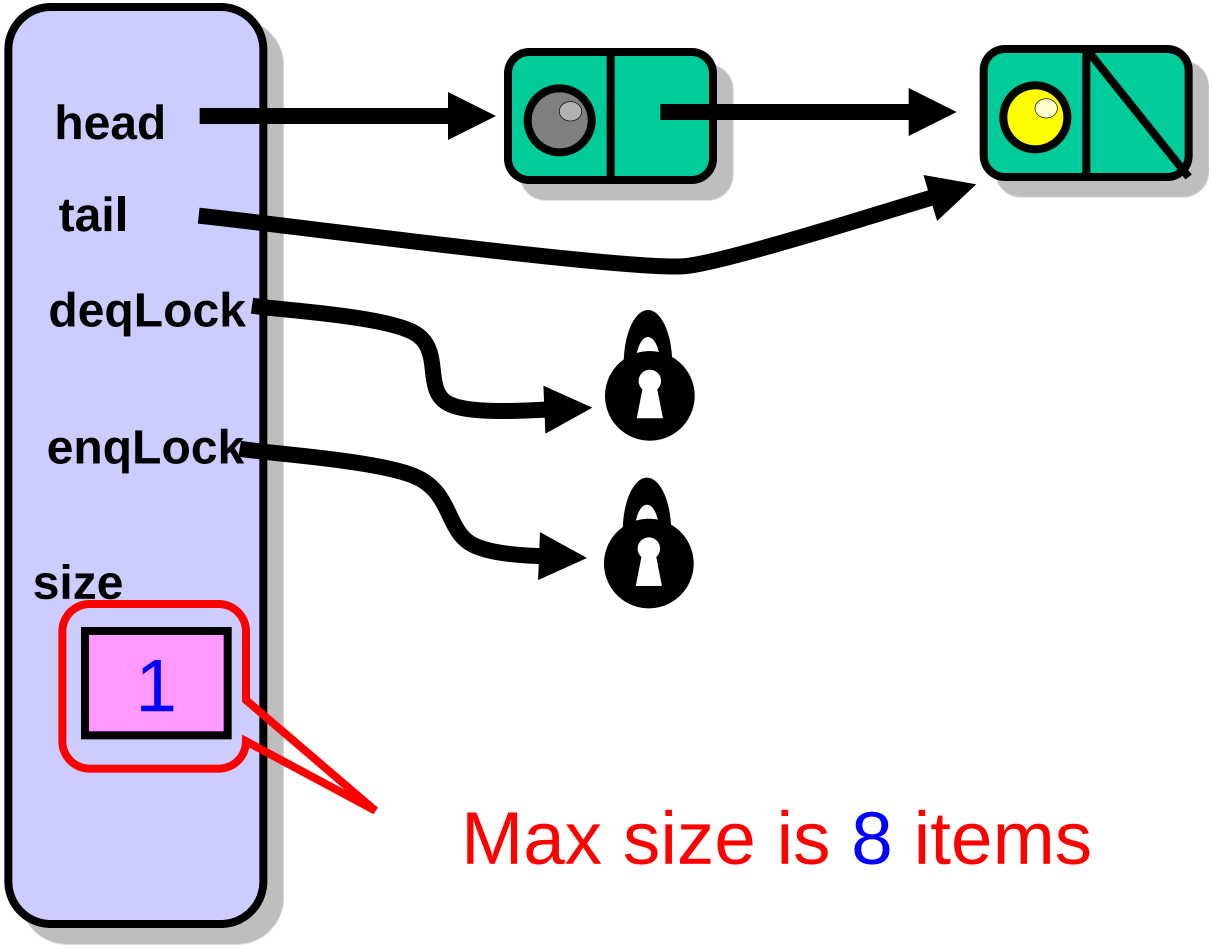
Lock out other enq() calls

Not Done Yet



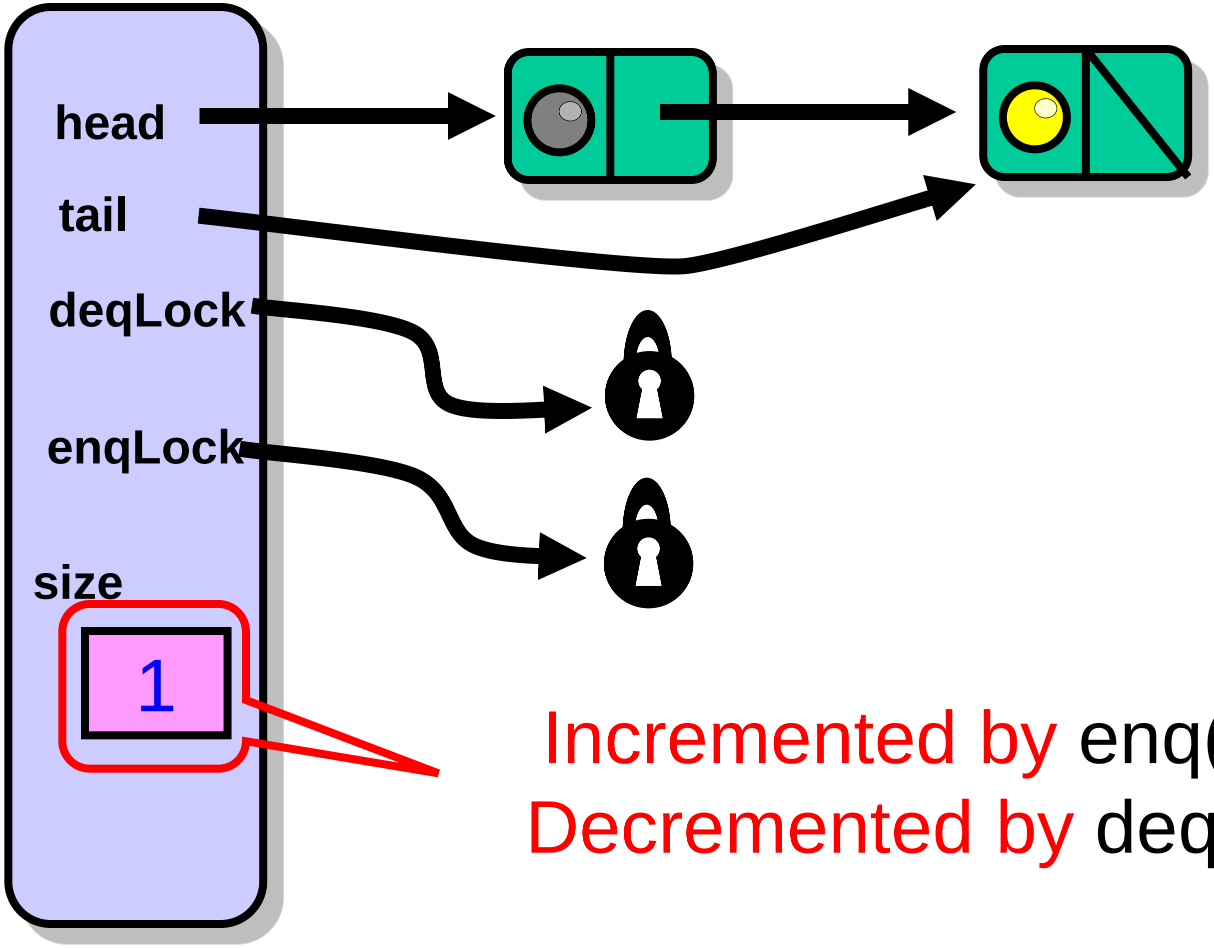
Need to tell whether queue is full or empty

Not Done Yet



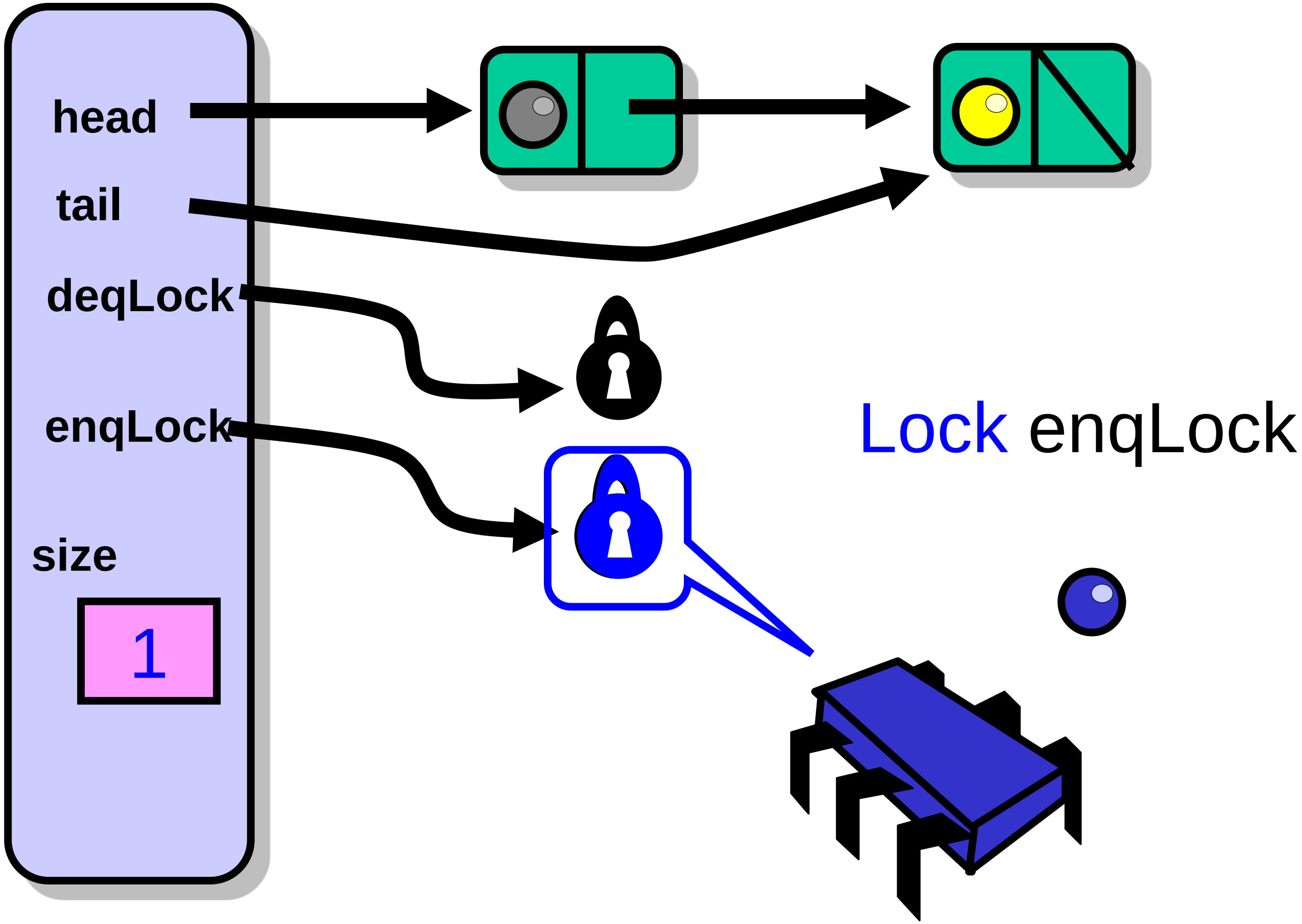
Max size is 8 items

Not Done Yet



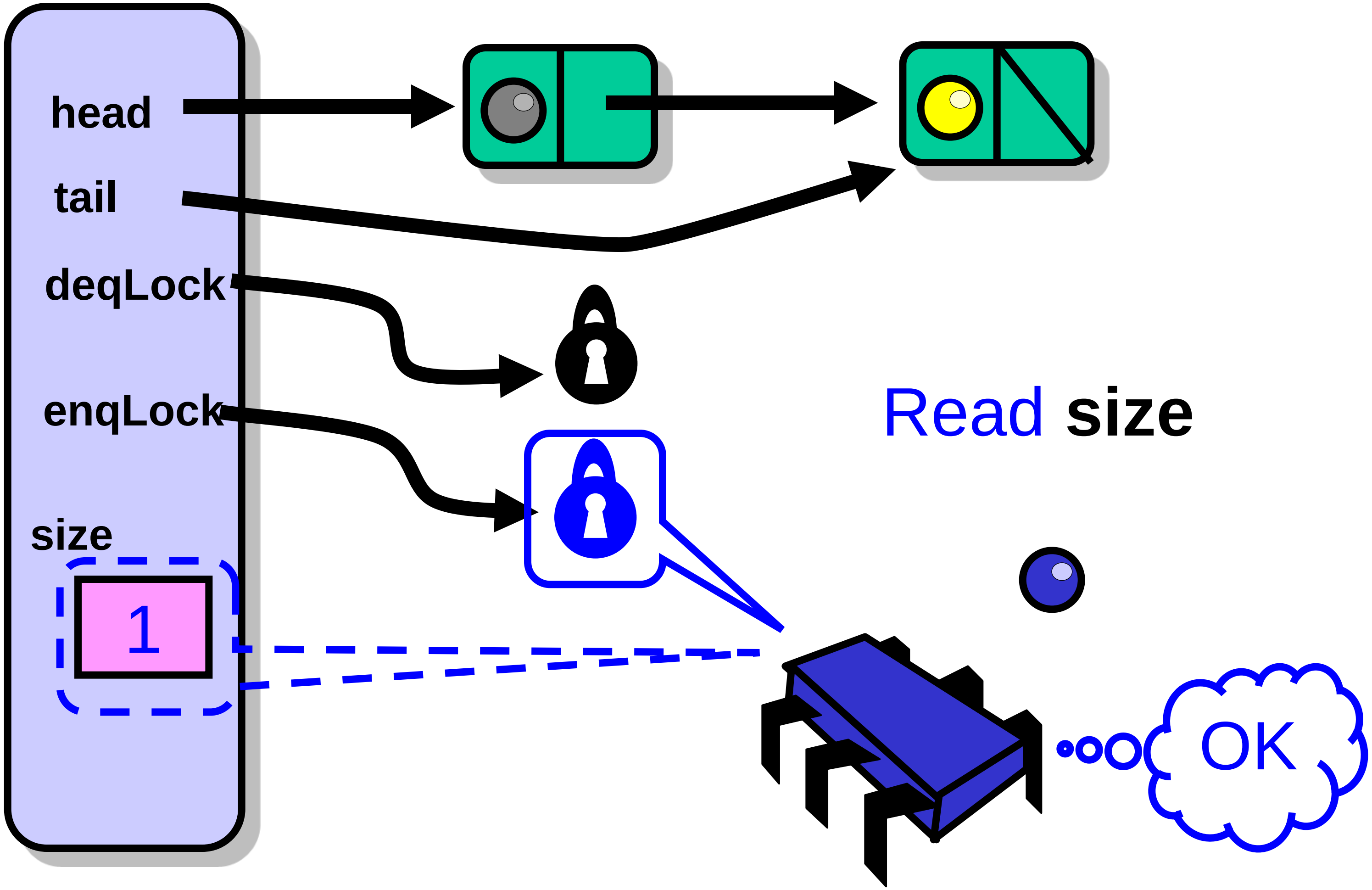
Incremented by enq()
Decremented by deq()

Enqueuer



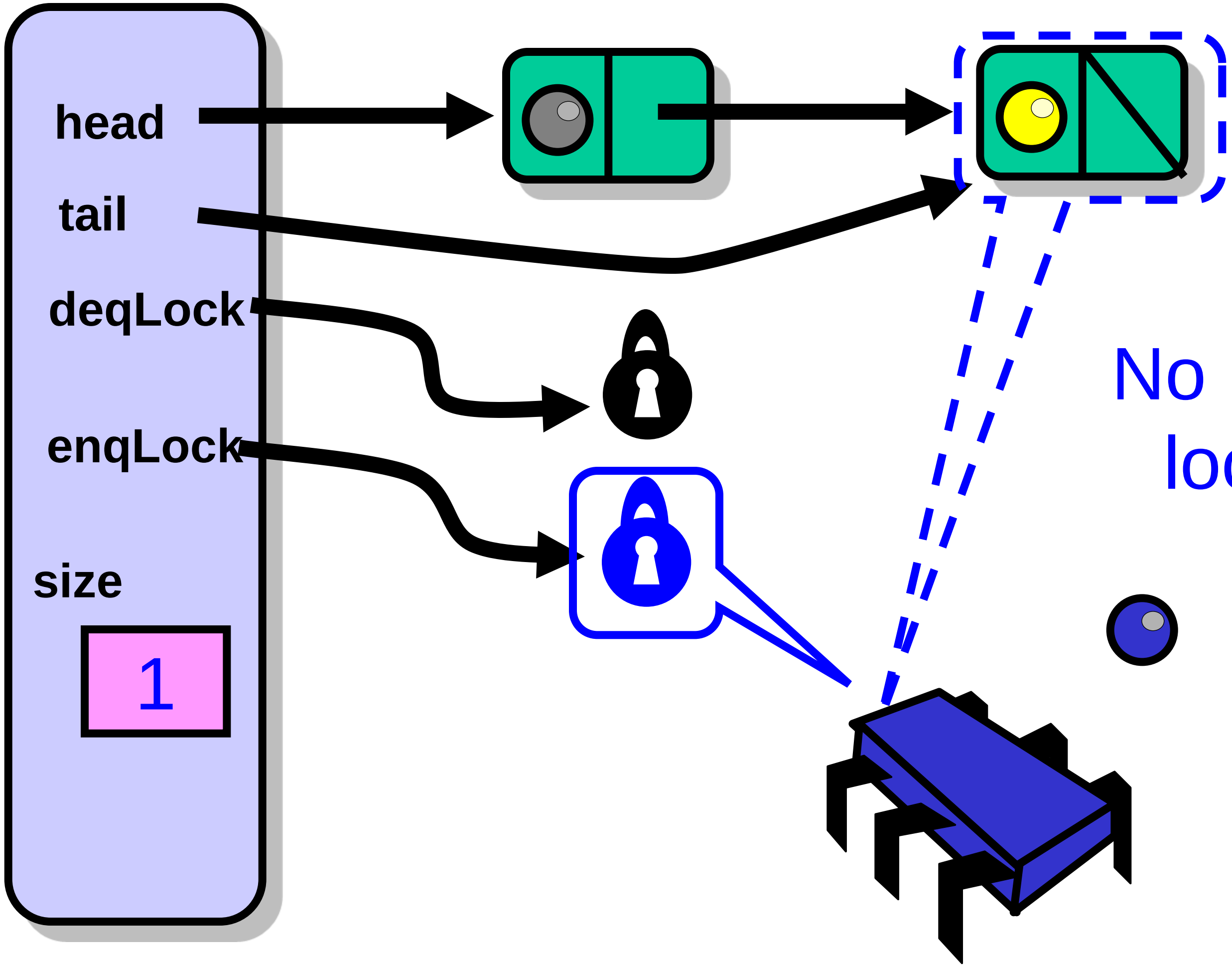
Lock enqLock

Enqueuer



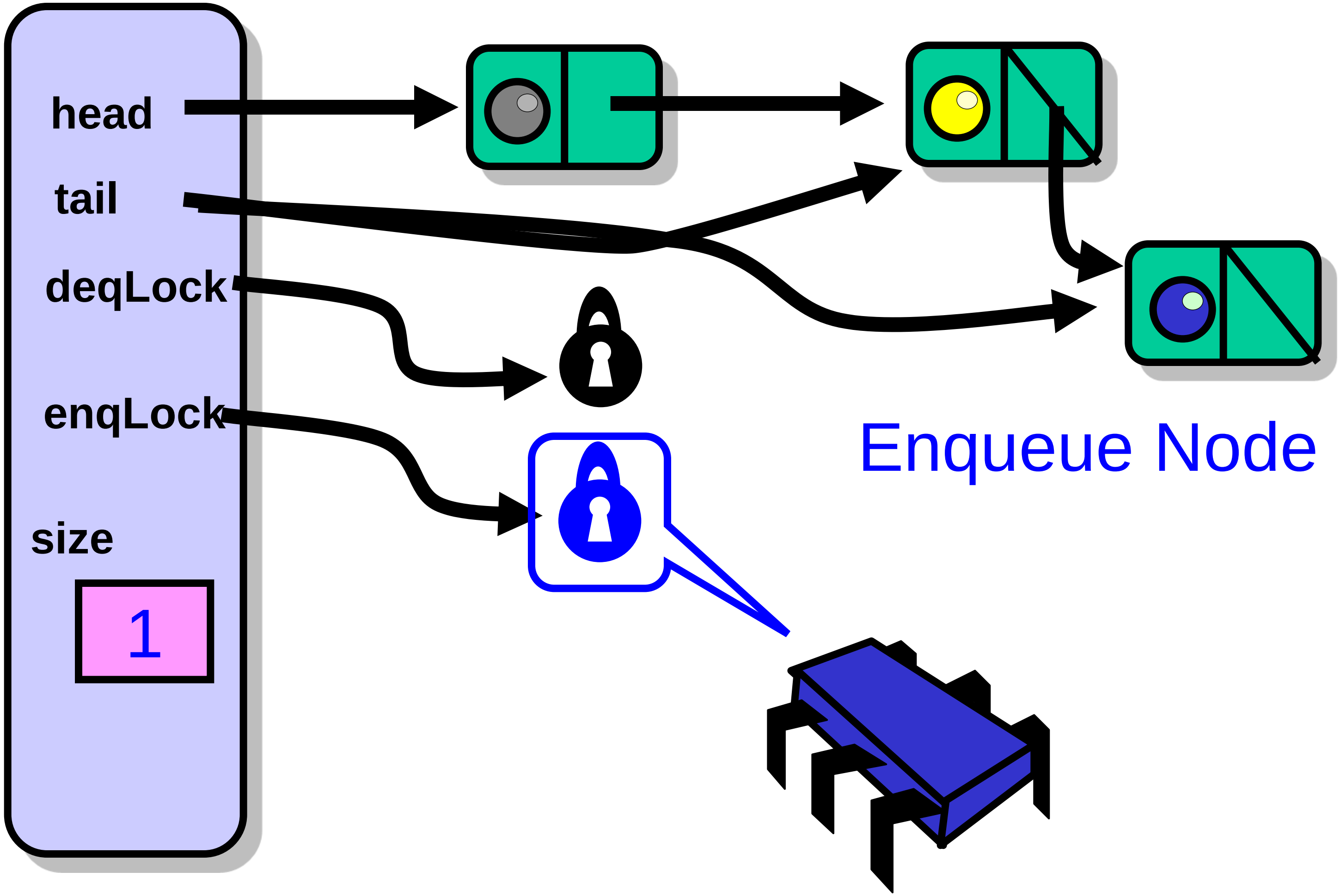
Read **size**

Enqueuer

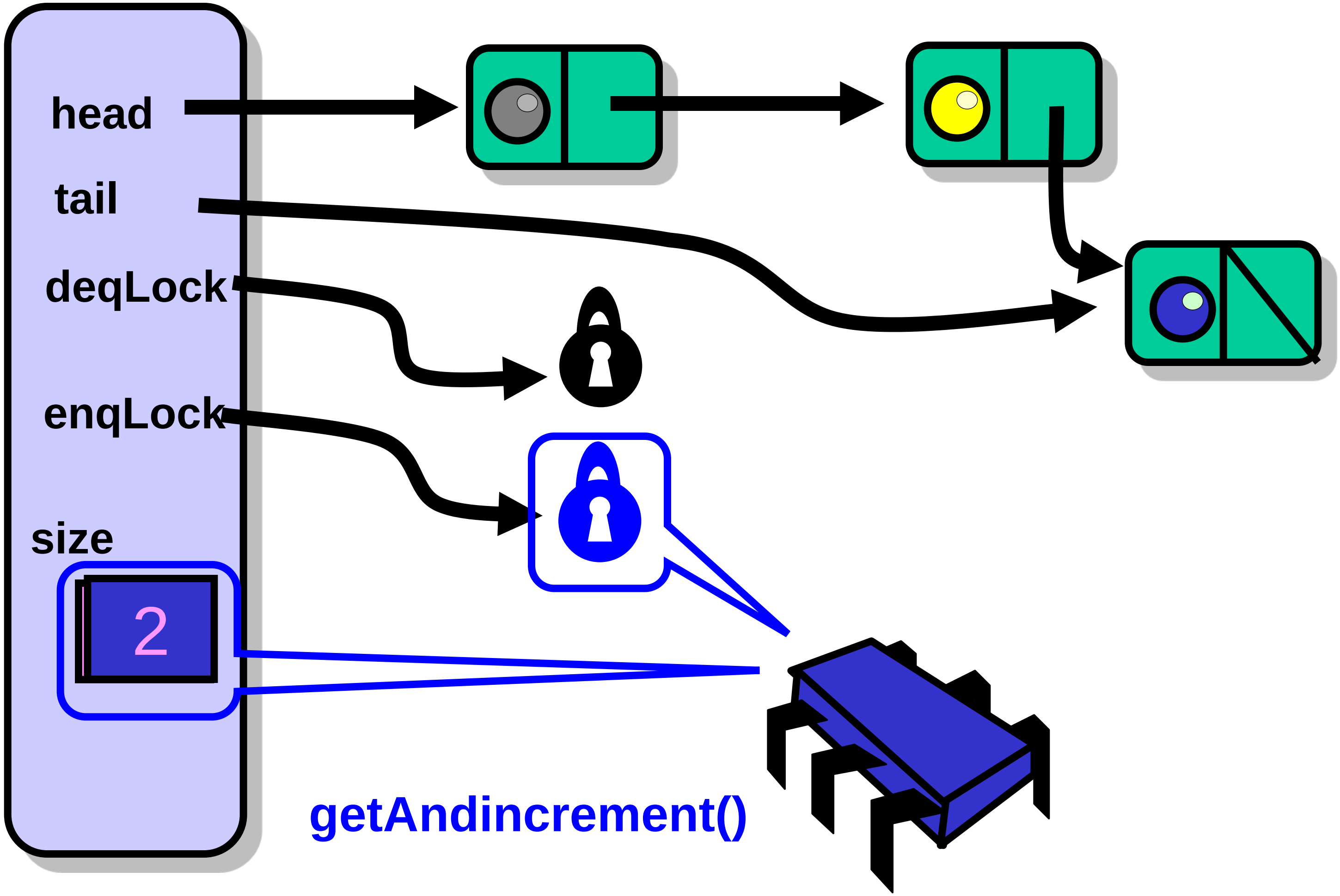


No need to lock **tail**

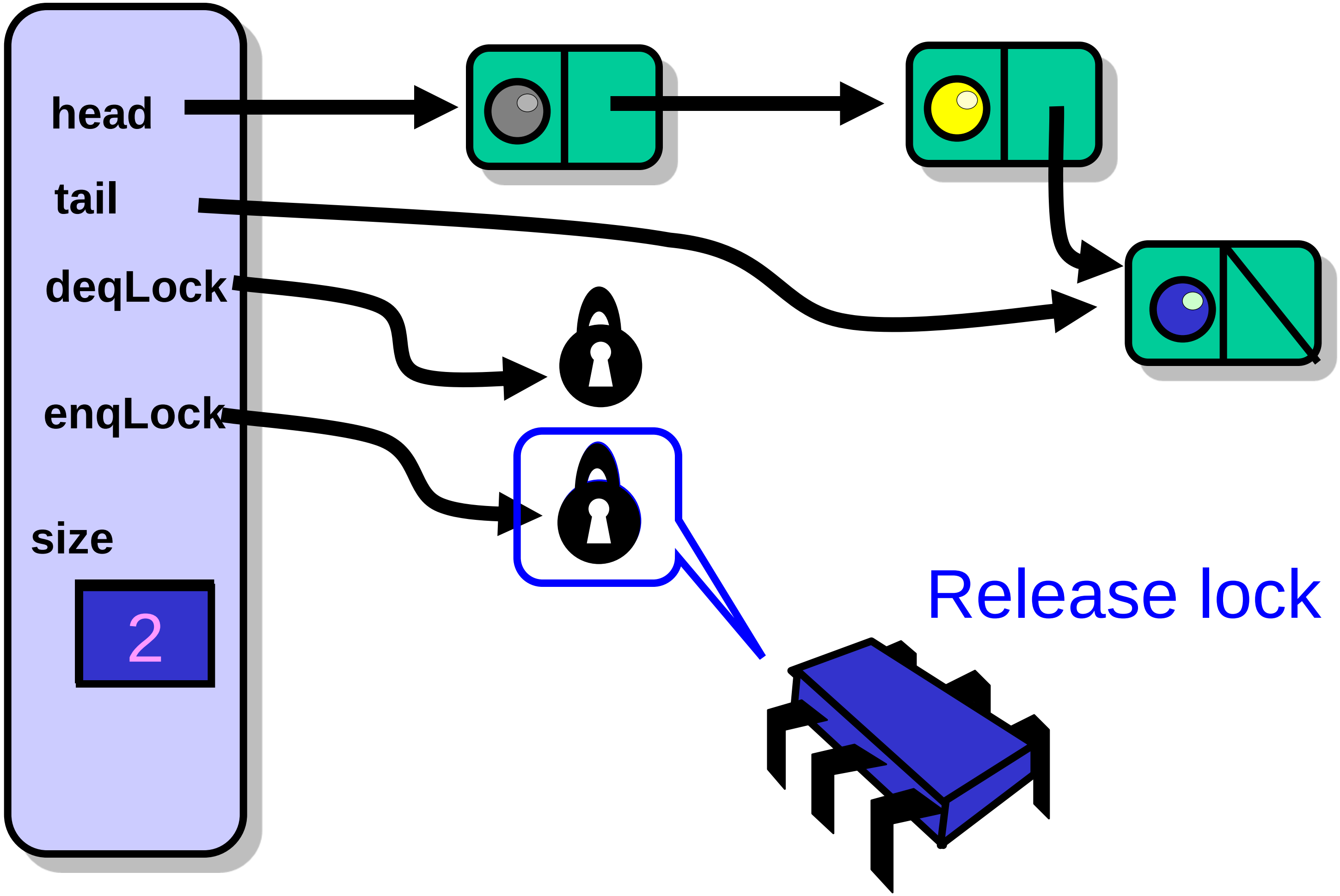
Enqueuer



Enqueuer

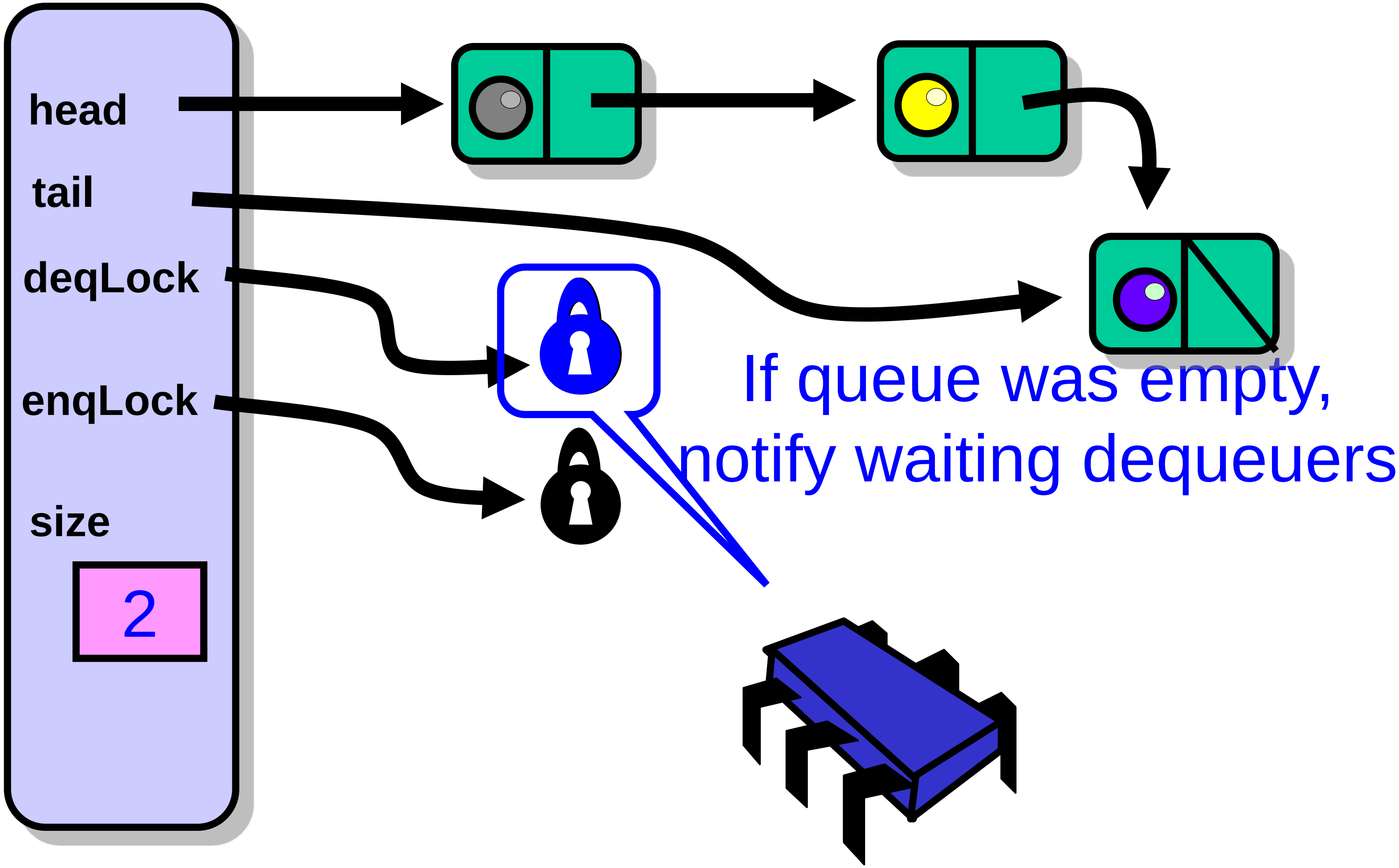


Enqueuer



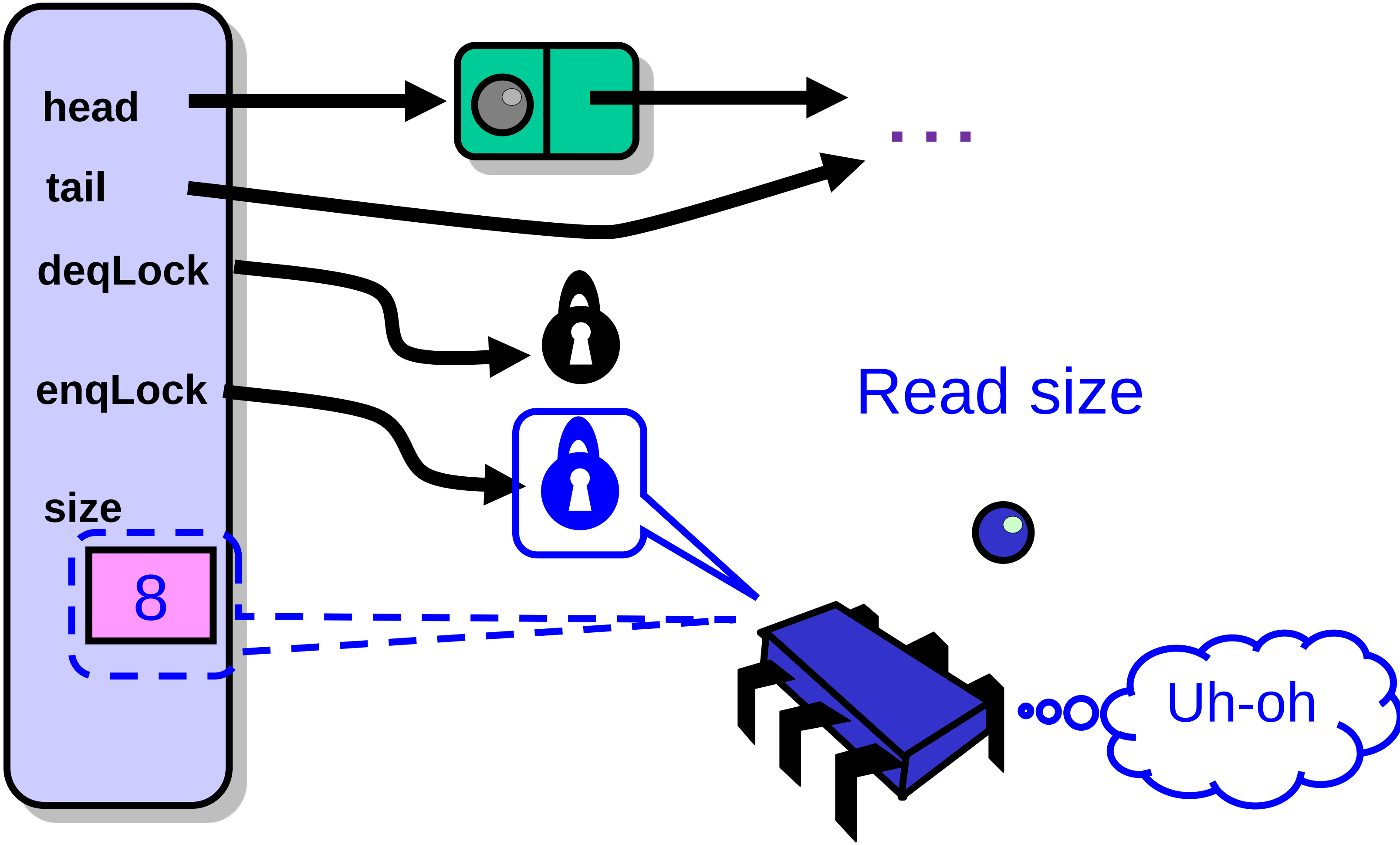
Release lock

Enqueuer

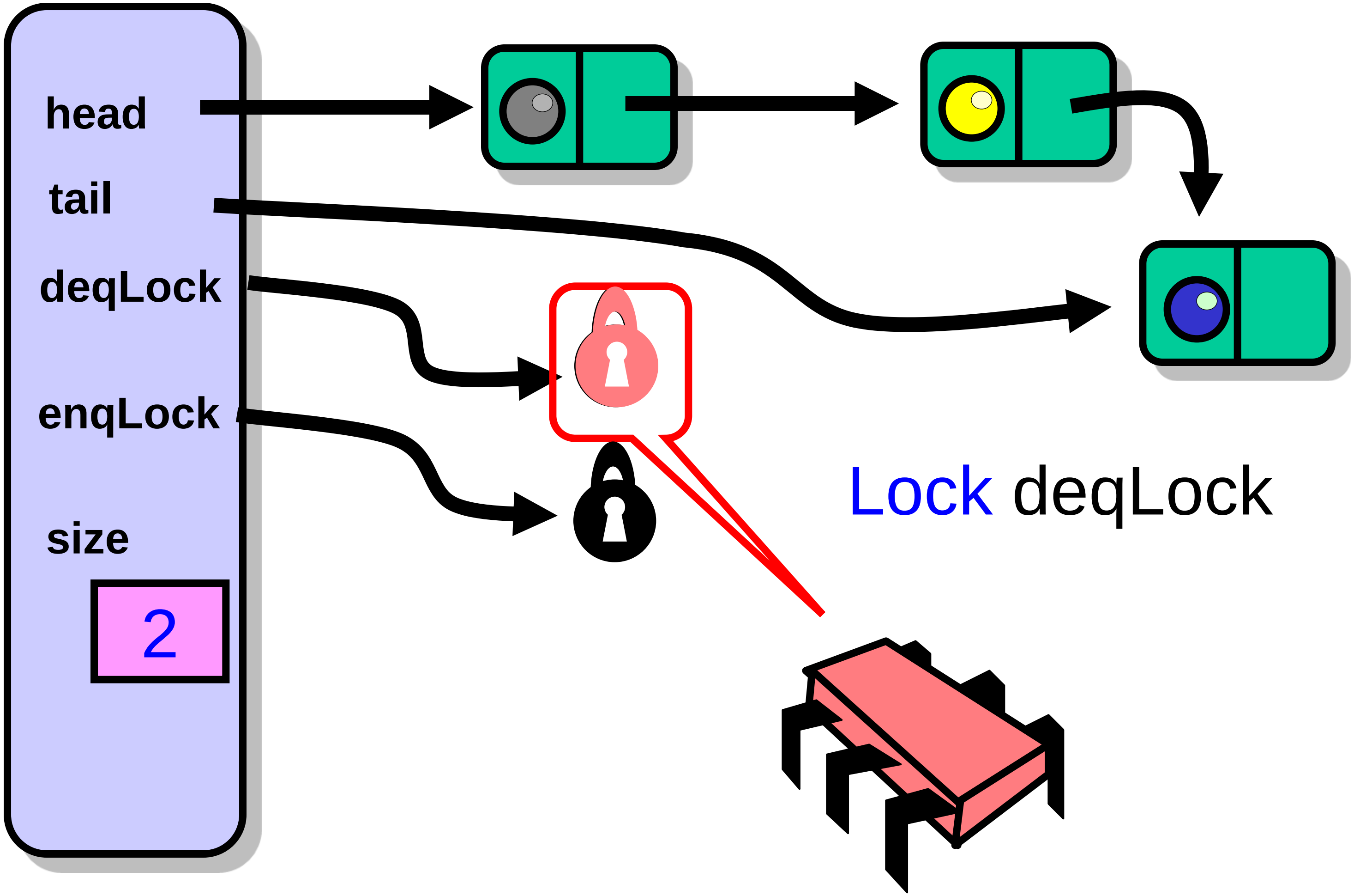


If queue was empty, notify waiting dequeuers

Unsuccesful Enqueuer

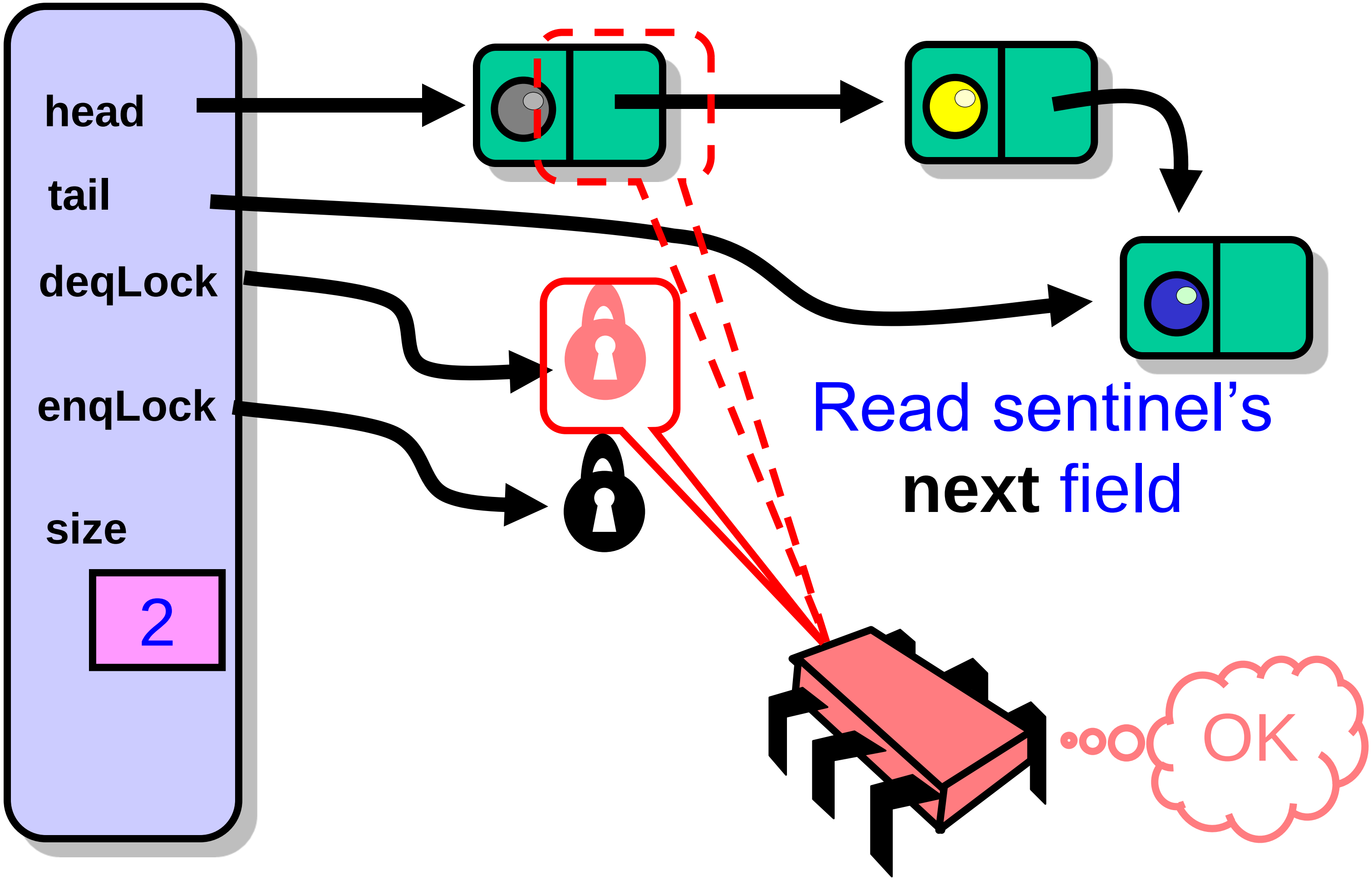


Dequeuer



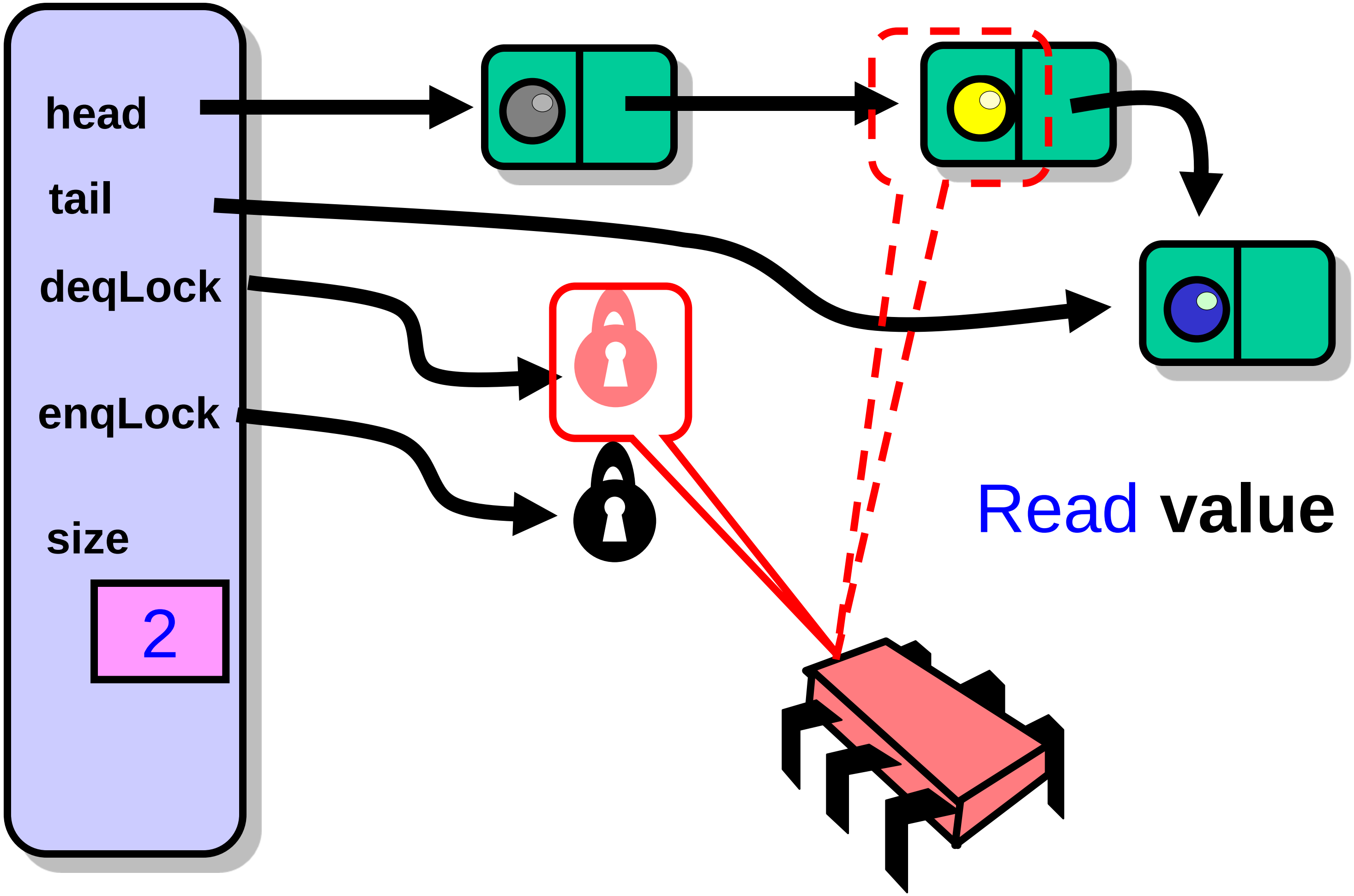
Lock deqLock

Dequeuer



Read sentinel's **next** field

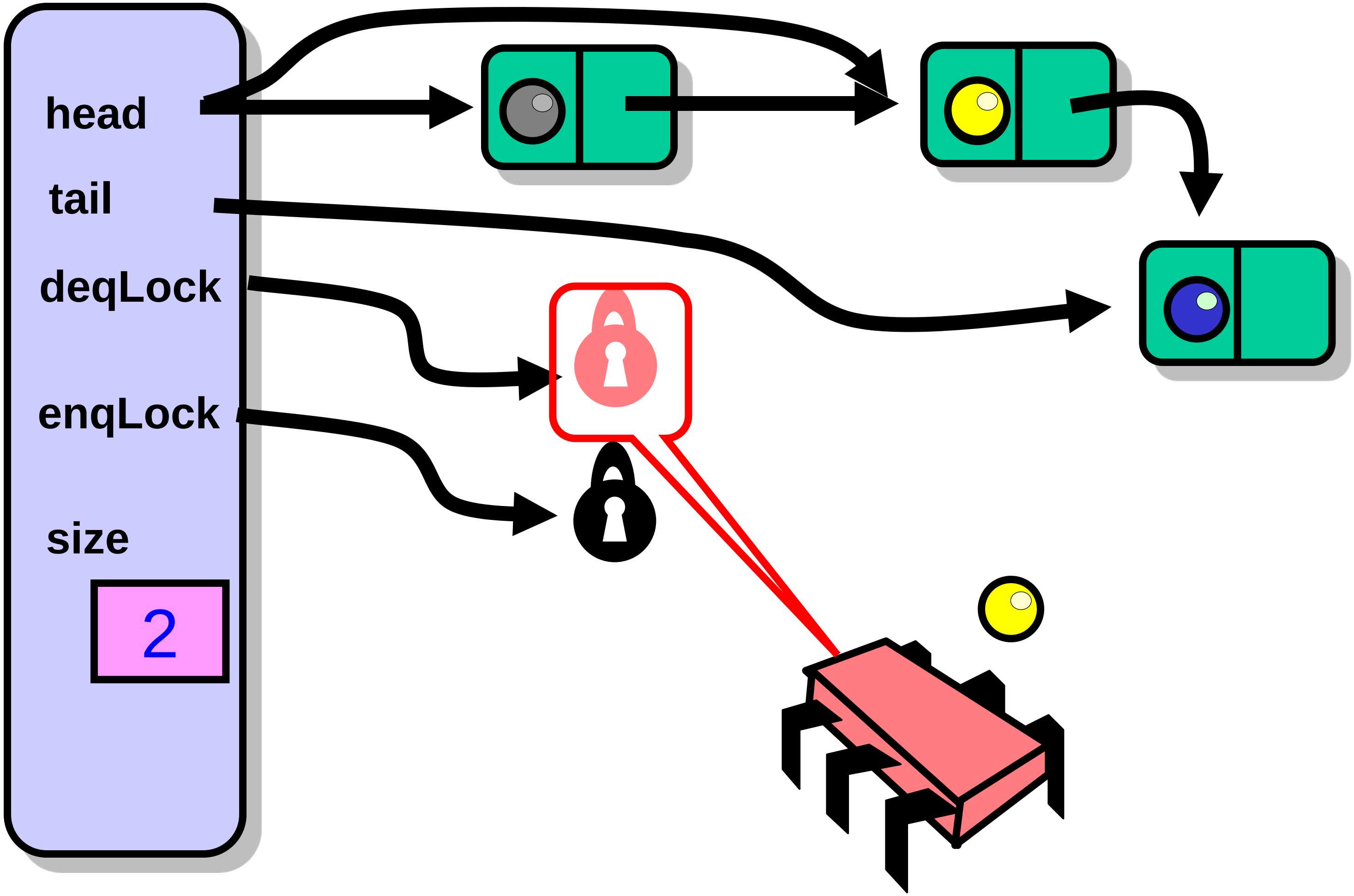
Dequeuer



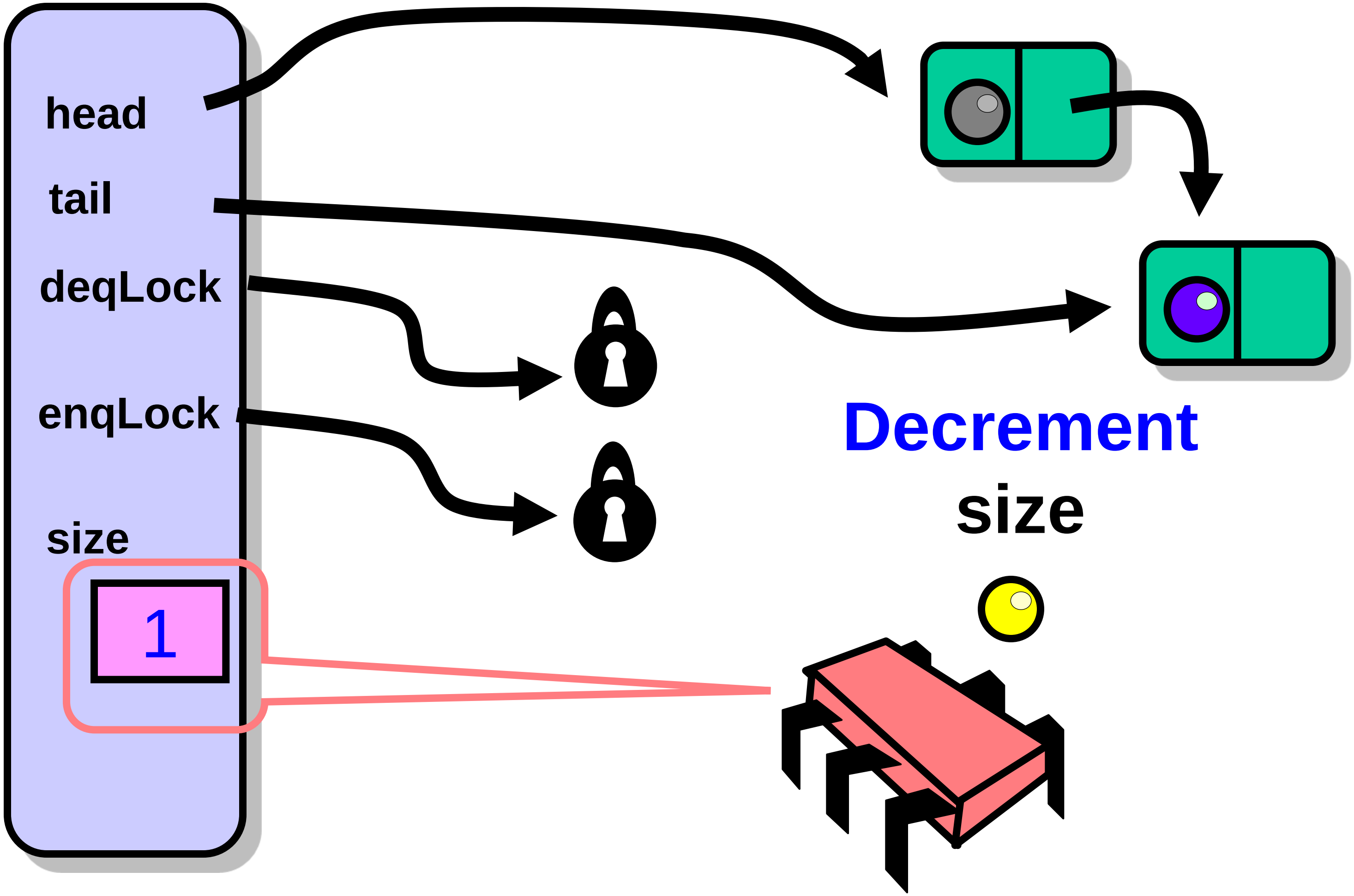
Read **value**

Dequeuer

Make first Node new sentinel



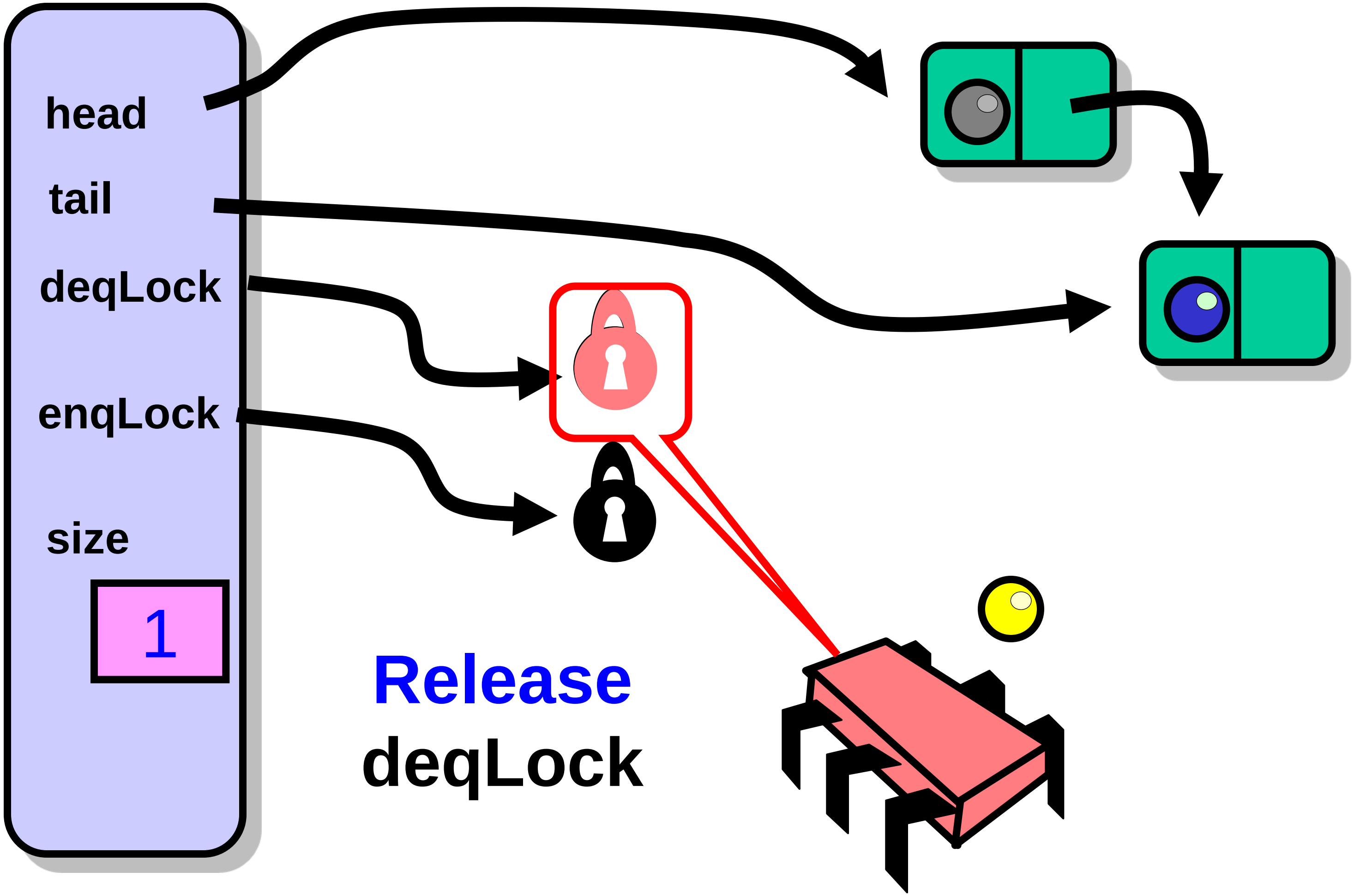
Dequeuer



Decrement

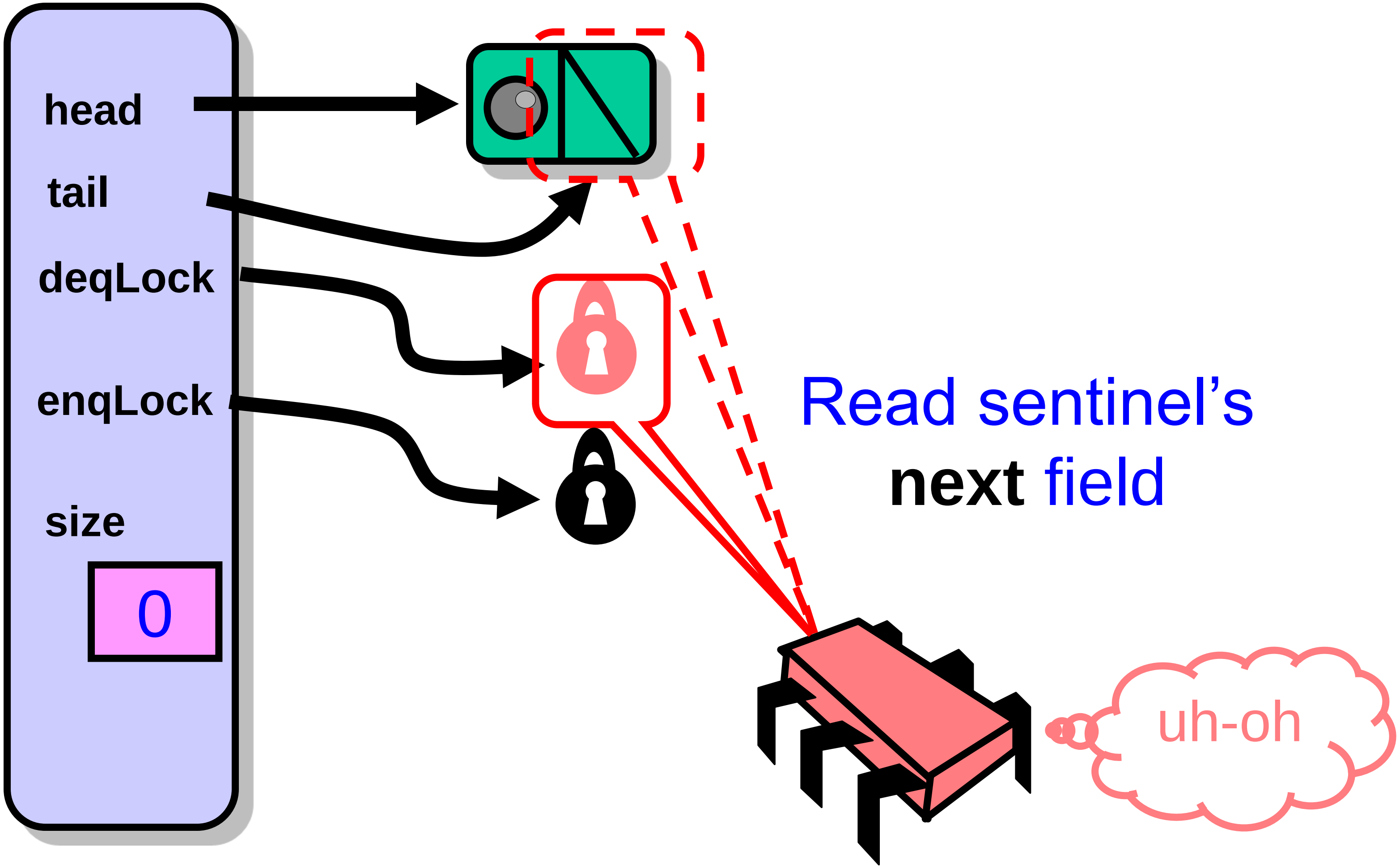
size

Dequeuer



Release deqLock

Unsuccesful Dequeuer



Read sentinel's **next** field

Bounded Queue

```
public class BoundedQueue<T> {
  ReentrantLock enqLock, deqLock;
  Condition notEmptyCondition, notFullCondition;
  AtomicInteger size;
  Node head;
  Node tail;
  int capacity;
  enqLock = new ReentrantLock();
  notFullCondition = enqLock.newCondition();
  deqLock = new ReentrantLock();
  notEmptyCondition = deqLock.newCondition();
}
```

Bounded Queue

```
public class BoundedQueue<T> {
  ReentrantLock enqLock, deqLock;
  Condition notEmptyCondition, notFullCondition;
  AtomicInteger size;
  Node head;
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  enqLock = new ReentrantLock();
  notFullCondition = enqLock.newCondition();
  deqLock = new ReentrantLock();
  notEmptyCondition = deqLock.newCondition();
}
```

enq & deq locks

Bounded Queue Fields

```
public class BoundedQueue<T> {
  ReentrantLock enqLock, deqLock;
  Condition notEmptyCondition, notFullCondition;
  AtomicInteger size;
  Node head;
  Node tail;
  int capacity;
  enqLock = new ReentrantLock();
  notFullCondition = enqLock.newCondition();
  deqLock = new ReentrantLock();
  notEmptyCondition = deqLock.newCondition();
}
```

Enq lock’s associated condition

Bounded Queue Fields

```
public class BoundedQueue<T> {
  ReentrantLock enqLock, deqLock;
  Condition notEmptyCondition, notFullCondition;
  AtomicInteger size;
  Node head;
  Node tail;
  int capacity;
  enqLock = new ReentrantLock();
  notFullCondition = enqLock.newCondition();
  deqLock = new ReentrantLock();
  notEmptyCondition = deqLock.newCondition();
}
```

size: 0 to capacity

Bounded Queue Fields

```
public class BoundedQueue<T> {
  ReentrantLock enqLock, deqLock;
  Condition notEmptyCondition, notFullCondition;
  AtomicInteger size;
  Node head;
  Node tail;
  int capacity;
  enqLock = new ReentrantLock();
  notFullCondition = enqLock.newCondition();
  deqLock = new ReentrantLock();
  notEmptyCondition = deqLock.newCondition();
}
```

Head and Tail

Enq Method Part One

```
public void enq(T x) {
 boolean mustWakeDequeuers = false;
 enqLock.lock();
 try {
  while (size.get() == Capacity)
    notFullCondition.await();
  Node e = new Node(x);
  tail.next = e;
  tail = tail.next;
  if (size.getAndIncrement() == 0)
   mustWakeDequeuers = true;
 } finally {
   enqLock.unlock();
 }
 …
}
```

Enq Method Part One

```
public void enq(T x) {
 boolean mustWakeDequeuers = false;
 enqLock.lock();
 try {
  while (size.get() == capacity)
    notFullCondition.await();
  Node e = new Node(x);
  tail.next = e;
  tail = tail.next;
  if (size.getAndIncrement() == 0)
   mustWakeDequeuers = true;
 } finally {
   enqLock.unlock();
 }
 …
}
```

Lock and unlock enq lock

Enq Method Part One

```
public void enq(T x) {
 boolean mustWakeDequeuers = false;
 enqLock.lock();
 try {
  while (size.get() == capacity)
    notFullCondition.await();
  Node e = new Node(x);
  tail.next = e;
  tail = tail.next;
  if (size.getAndIncrement() == 0)
   mustWakeDequeuers = true;
 } finally {
   enqLock.unlock();
 }
 …
}
```

Wait while queue is full …

Enq Method Part One

```
public void enq(T x) {
 boolean mustWakeDequeuers = false;
 enqLock.lock();
 try {
  while (size.get() == capacity)
    notFullCondition.await();
  Node e = new Node(x);
  tail.next = e;
  tail = tail.next;
  if (size.getAndIncrement() == 0)
   mustWakeDequeuers = true;
 } finally {
   enqLock.unlock();
 }
 …
}
```

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

Be Afraid

```
public void enq(T x) {
 boolean mustWakeDequeuers = false;
 enqLock.lock();
 try {
  while (size.get() == capacity)
    notFullCondition.await();
  Node e = new Node(x);
  tail.next = e;
  tail = tail.next;
  if (size.getAndIncrement() == 0)
   mustWakeDequeuers = true;
 } finally {
   enqLock.unlock();
 }
 …
}
```

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

Enq Method Part One

```
public void enq(T x) {
 boolean mustWakeDequeuers = false;
 enqLock.lock();
 try {
  while (size.get() == capacity)
    notFullCondition.await();
  Node e = new Node(x);
  tail.next = e;
  tail = tail.next;
  if (size.getAndIncrement() == 0)
   mustWakeDequeuers = true;
 } finally {
   enqLock.unlock();
 }
 …
}
```

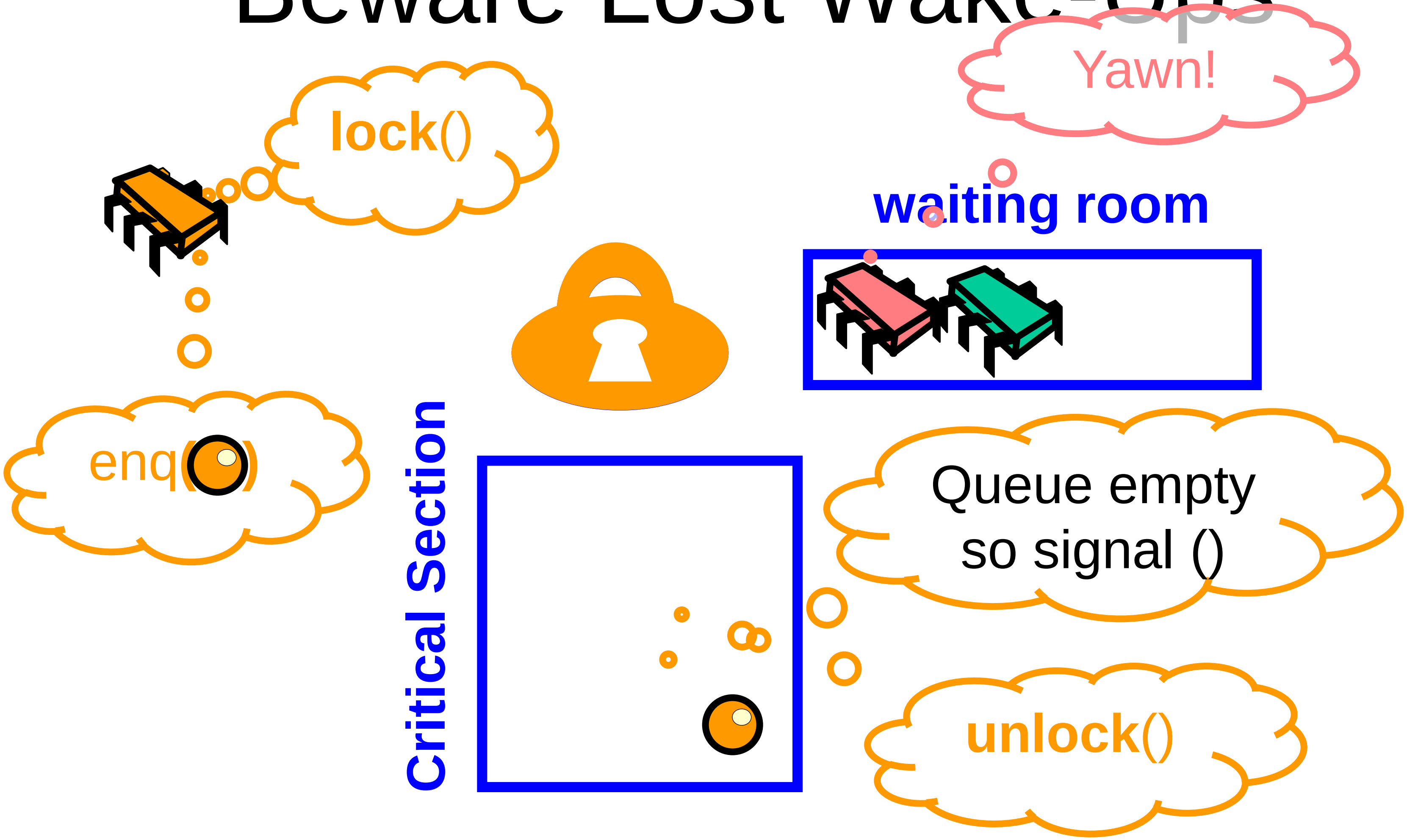
Add new node

Enq Method Part One

```
public void enq(T x) {
 boolean mustWakeDequeuers = false;
 enqLock.lock();
 try {
  while (size.get() == capacity)
    notFullCondition.await();
  Node e = new Node(x);
  tail.next = e;
  tail = tail.next;
  if (size.getAndIncrement() == 0)
   mustWakeDequeuers = true;
 } finally {
   enqLock.unlock();
 }
 …
}
```

If queue was empty, wake frustrated dequeuers

Beware Lost Wake-Ups



Lost Wake-Up

lock()
enq( )
Yawn!
waiting room
Critical Section
Queue not empty so no need to signal
unlock()

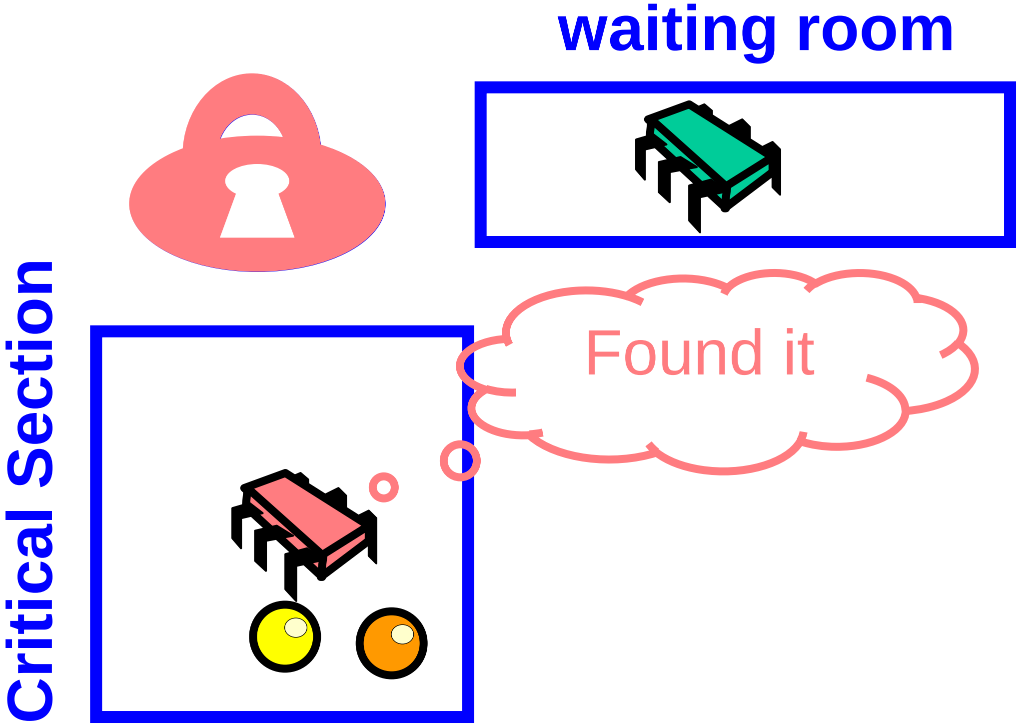
Lost Wake-Up

Yawn!

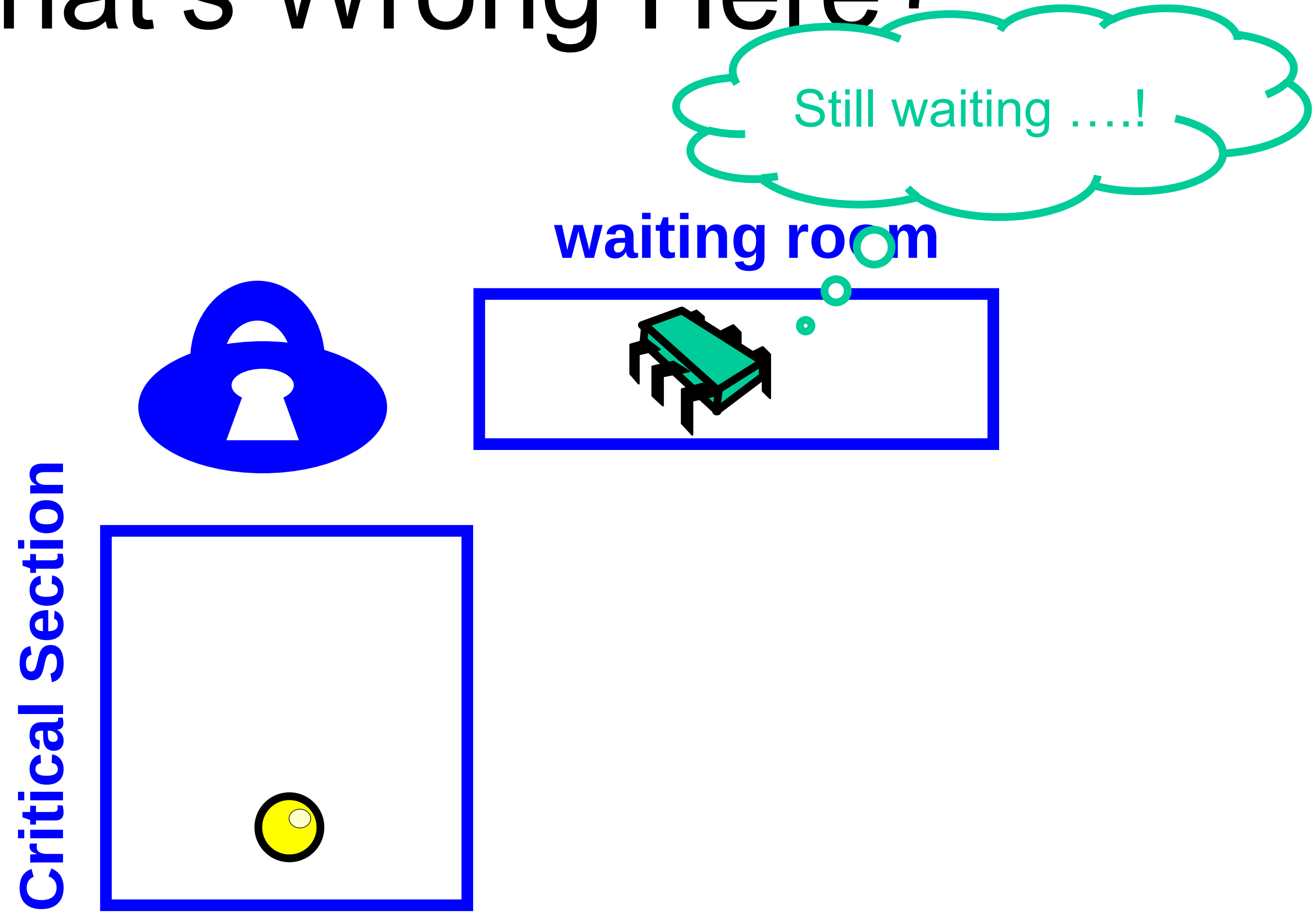
waiting room

Critical Section

Lost Wake-Up



What’s Wrong Here?



Still waiting ….!

waiting room

Critical Section

Enq Method Part Deux

```
public void enq(T x) {
 …
    if (mustWakeDequeuers) {
      deqLock.lock();
      try {
        notEmptyCondition.signalAll();
      } finally {
        deqLock.unlock();
      }
    }
  }
```

Enq Method Part Deux

```
public void enq(T x) {
 …
  if (mustWakeDequeuers) {
   deqLock.lock();
   try {
    notEmptyCondition.signalAll();
   } finally {
    deqLock.unlock();
   }
  }
 }
```

Are there dequeuers to be signaled?

Enq Method Part Deux

```
public void enq(T x) {
 …
    if (mustWakeDequeuers) {
      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

```
public void enq(T x) {
 ...
    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?

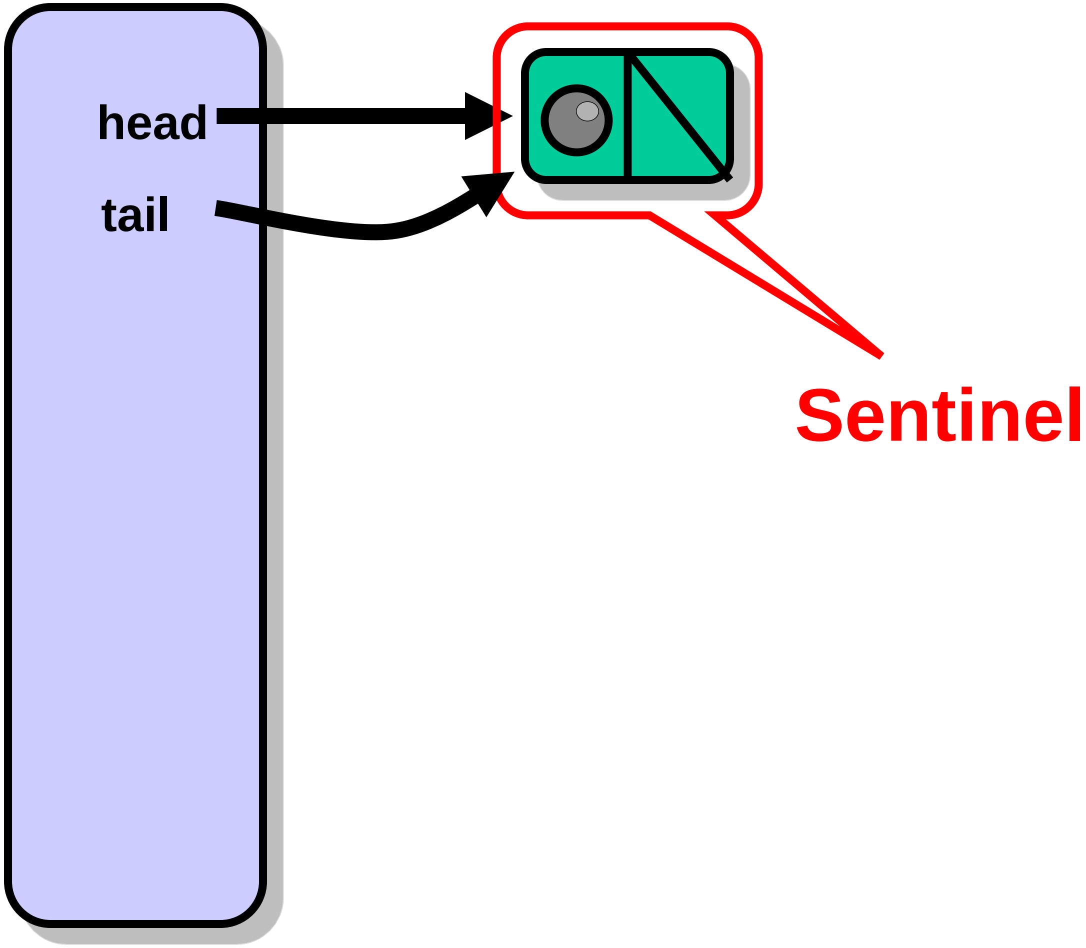
Split the Counter

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

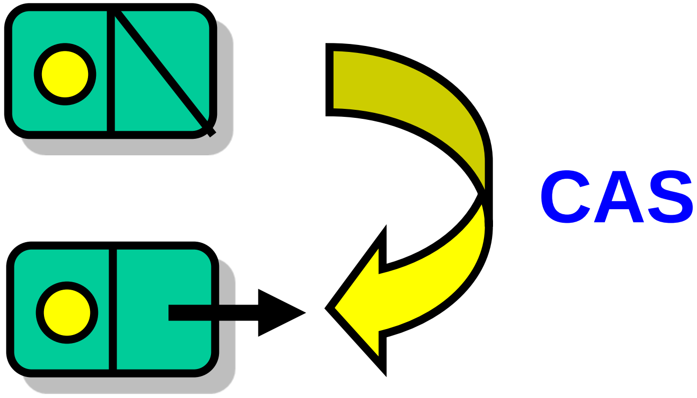
Split Counter

- Enqueuer increments enqSize
- Dequeuer decrements deqSize
- When enqueuer runs out
  - Locks **deqLock**
  - computes size = enqSize - DeqSize
- Intermittent synchronization
  - Not with each method call
  - Need both locks! (careful …)

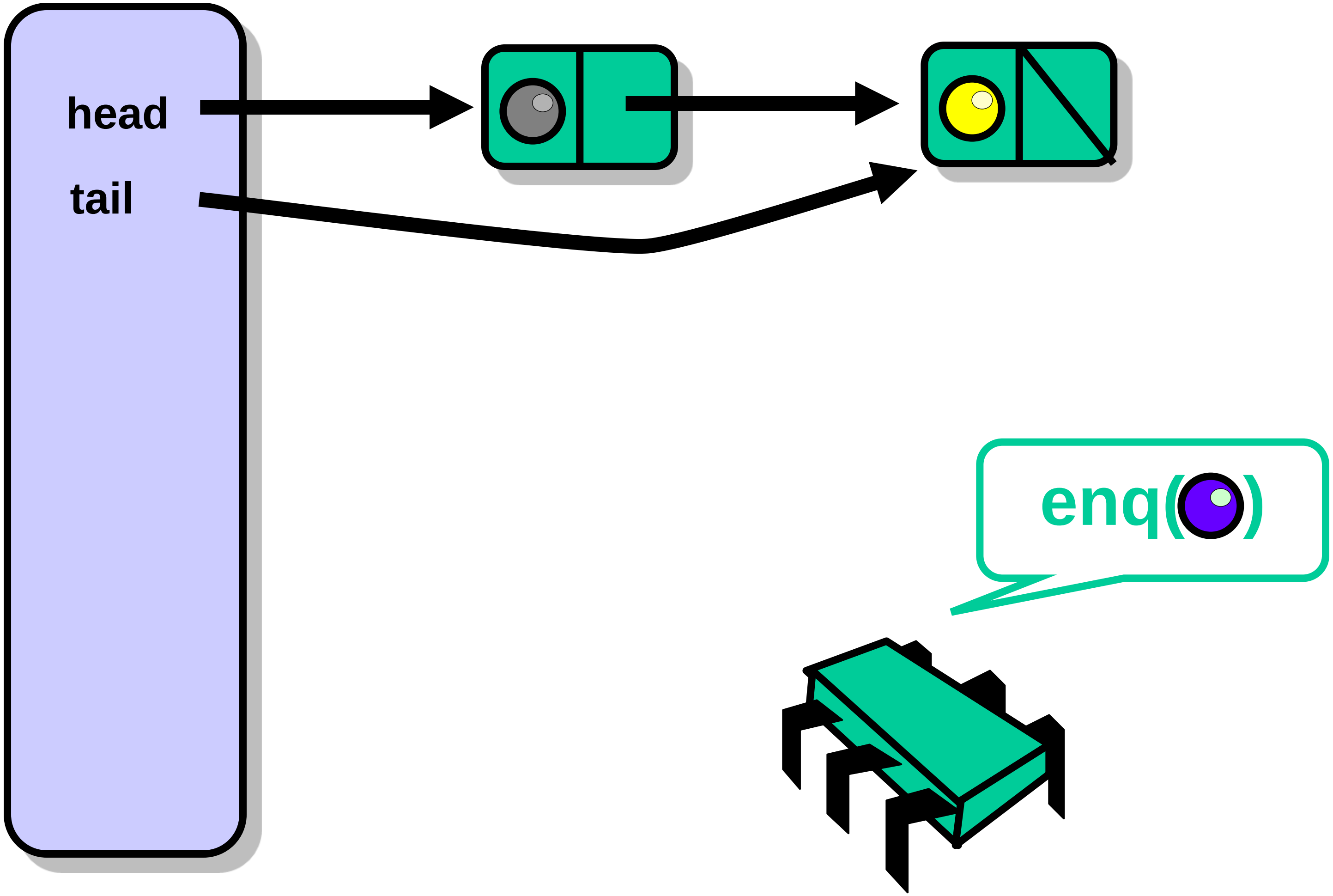
A Lock-Free Queue



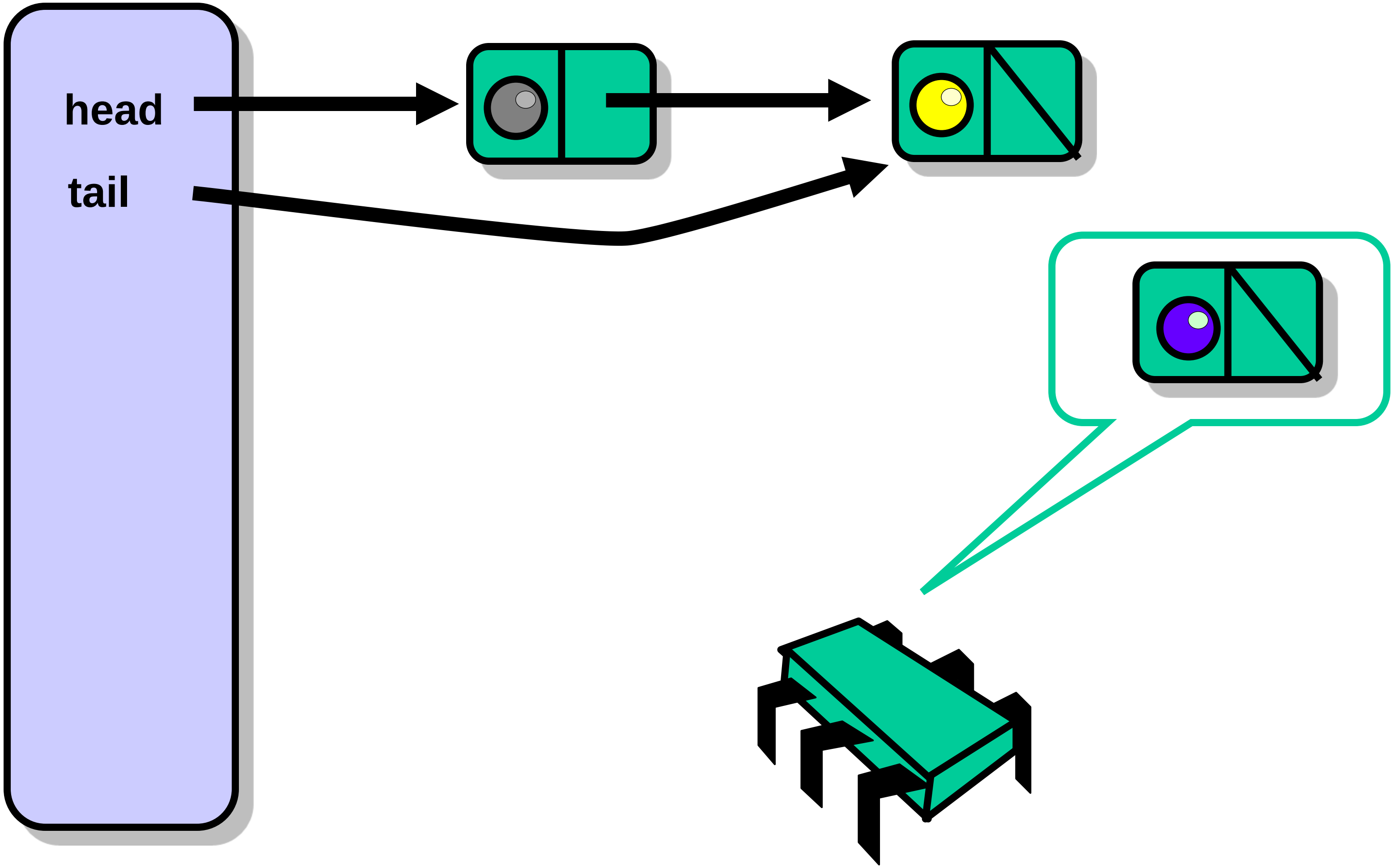
Compare and Set



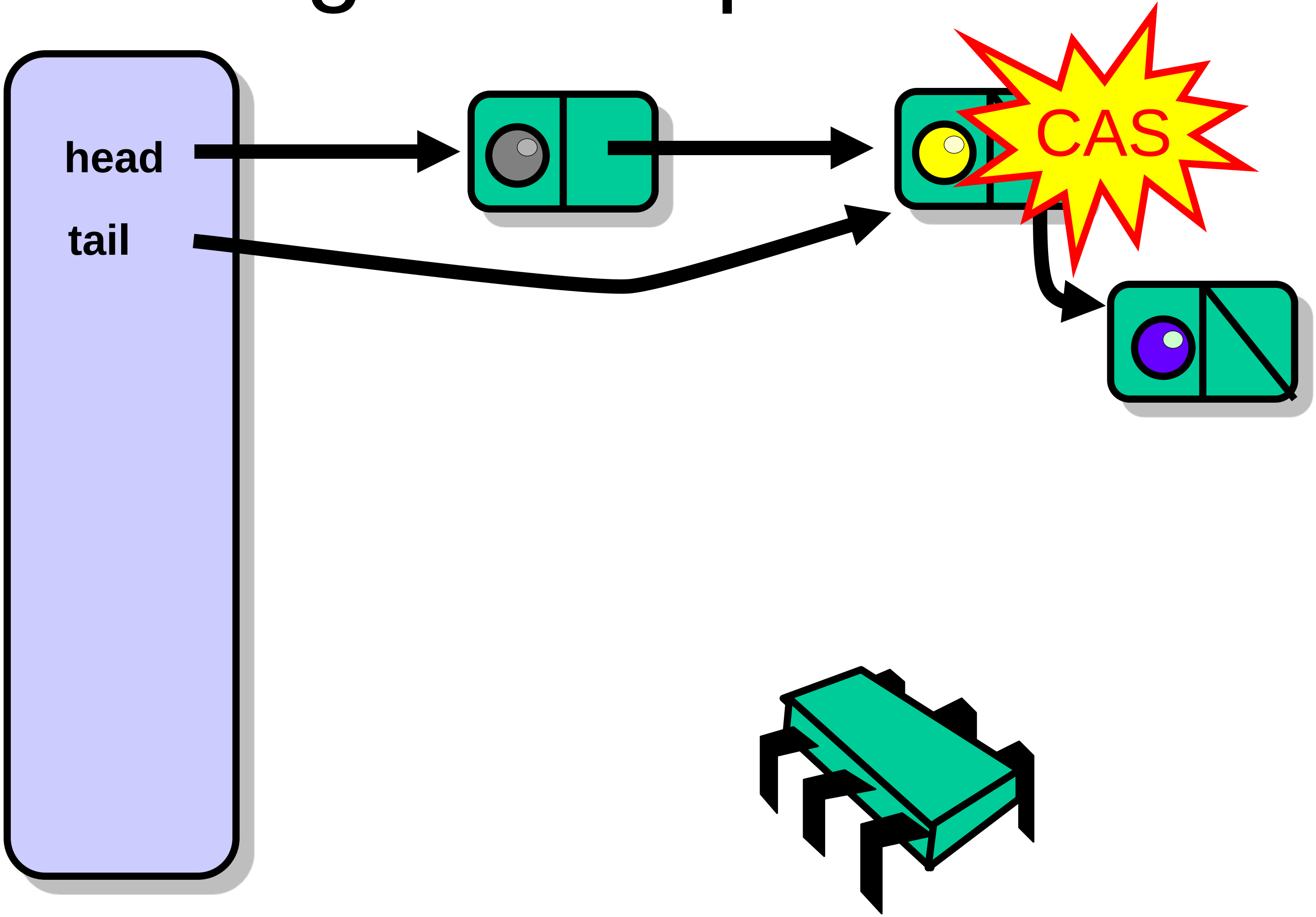
Enqueue



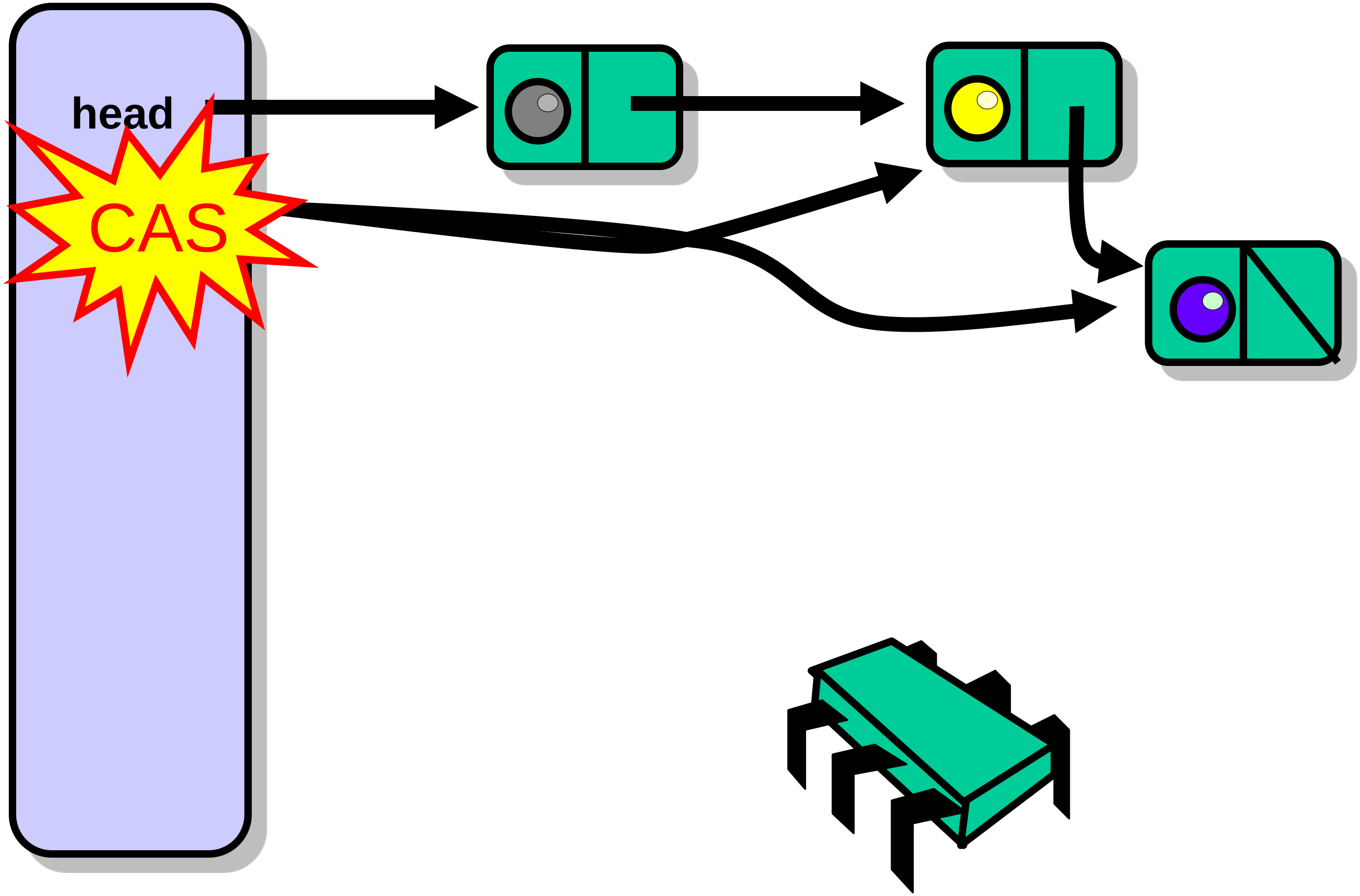
Enqueue



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!

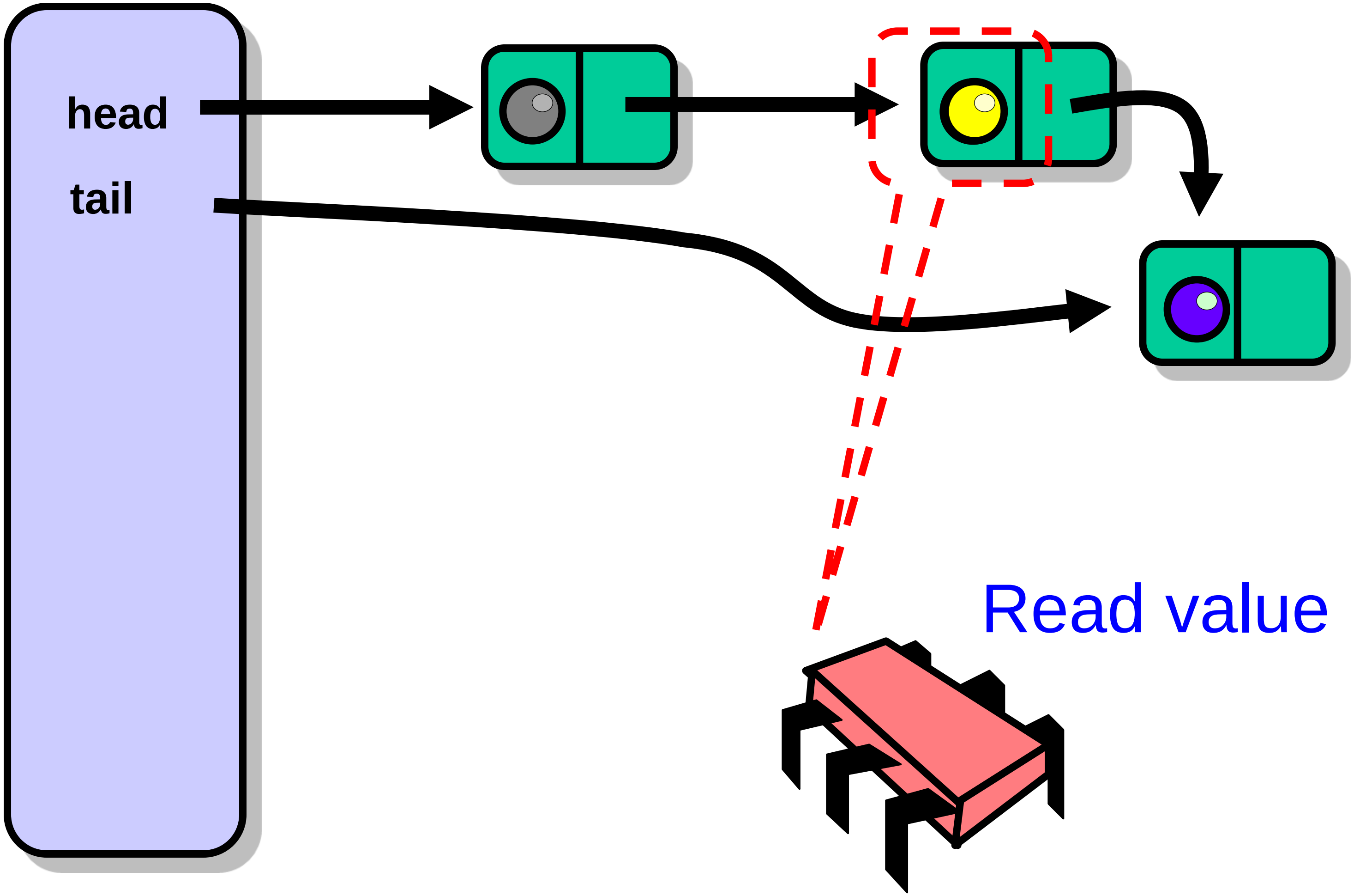
Enqueue

- 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**

When CASs Fail

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

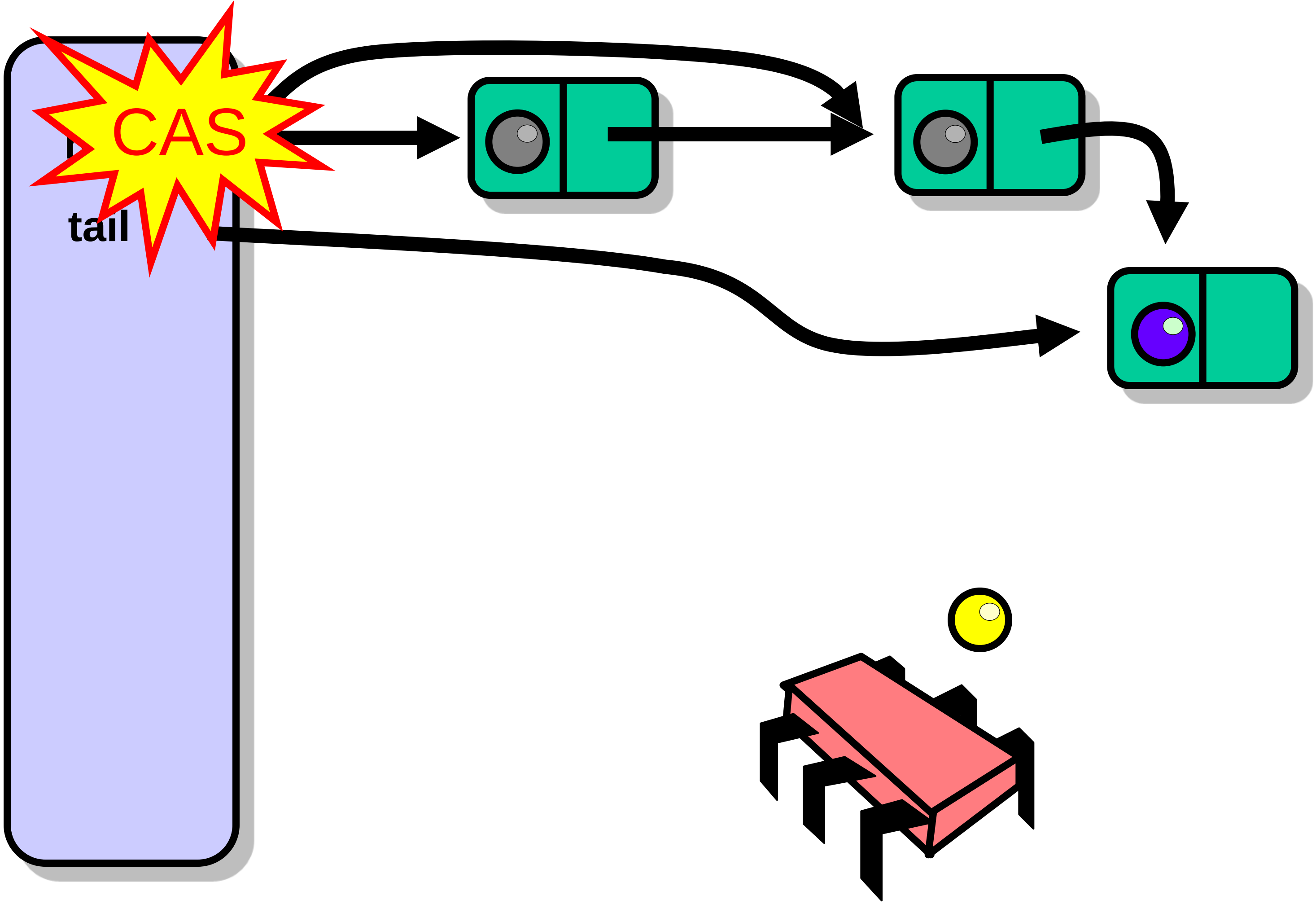
Dequeuer



Read value

Dequeuer

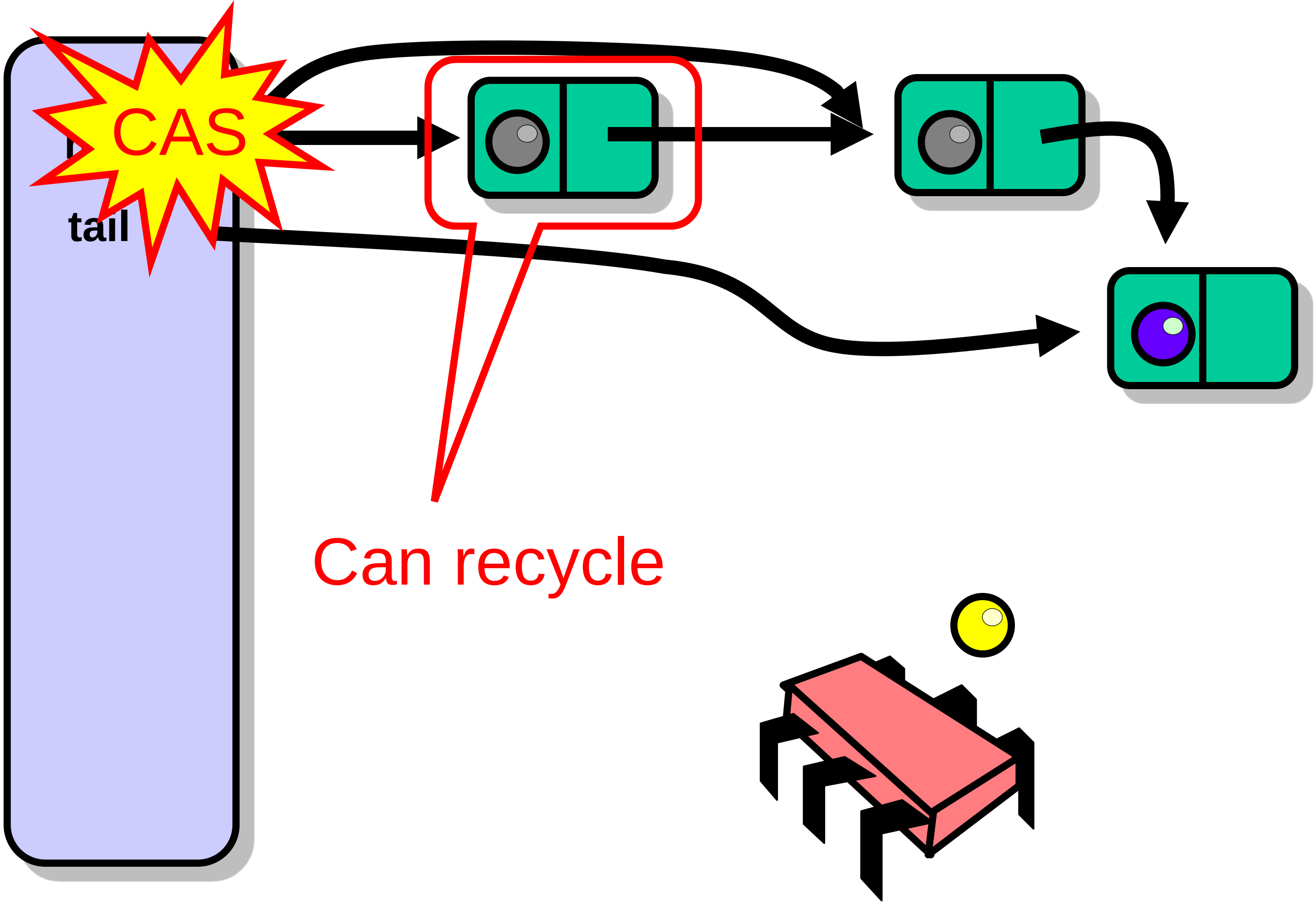
Make first Node
new sentinel



Memory Reuse?

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

Dequeuer

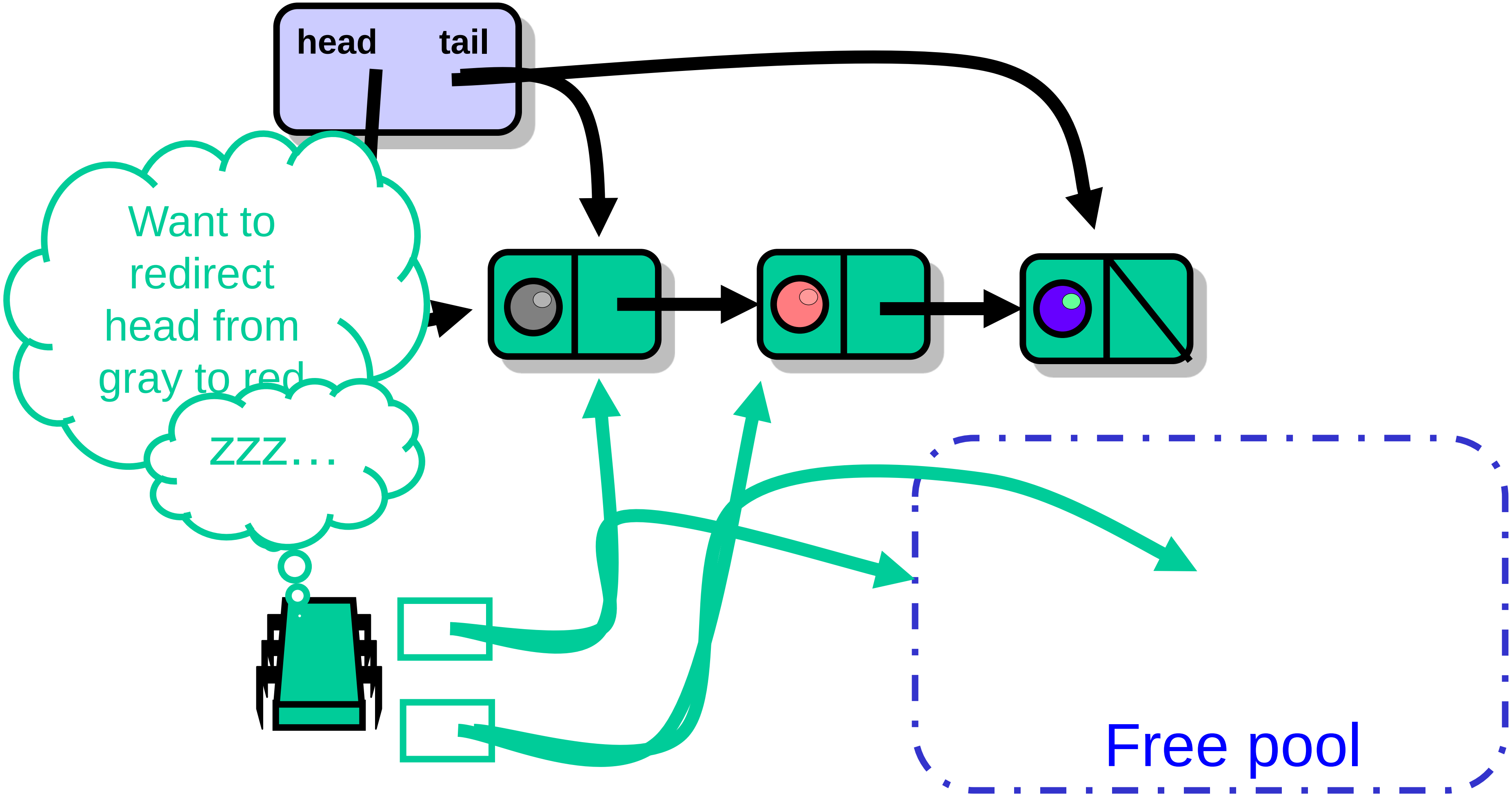


Can recycle

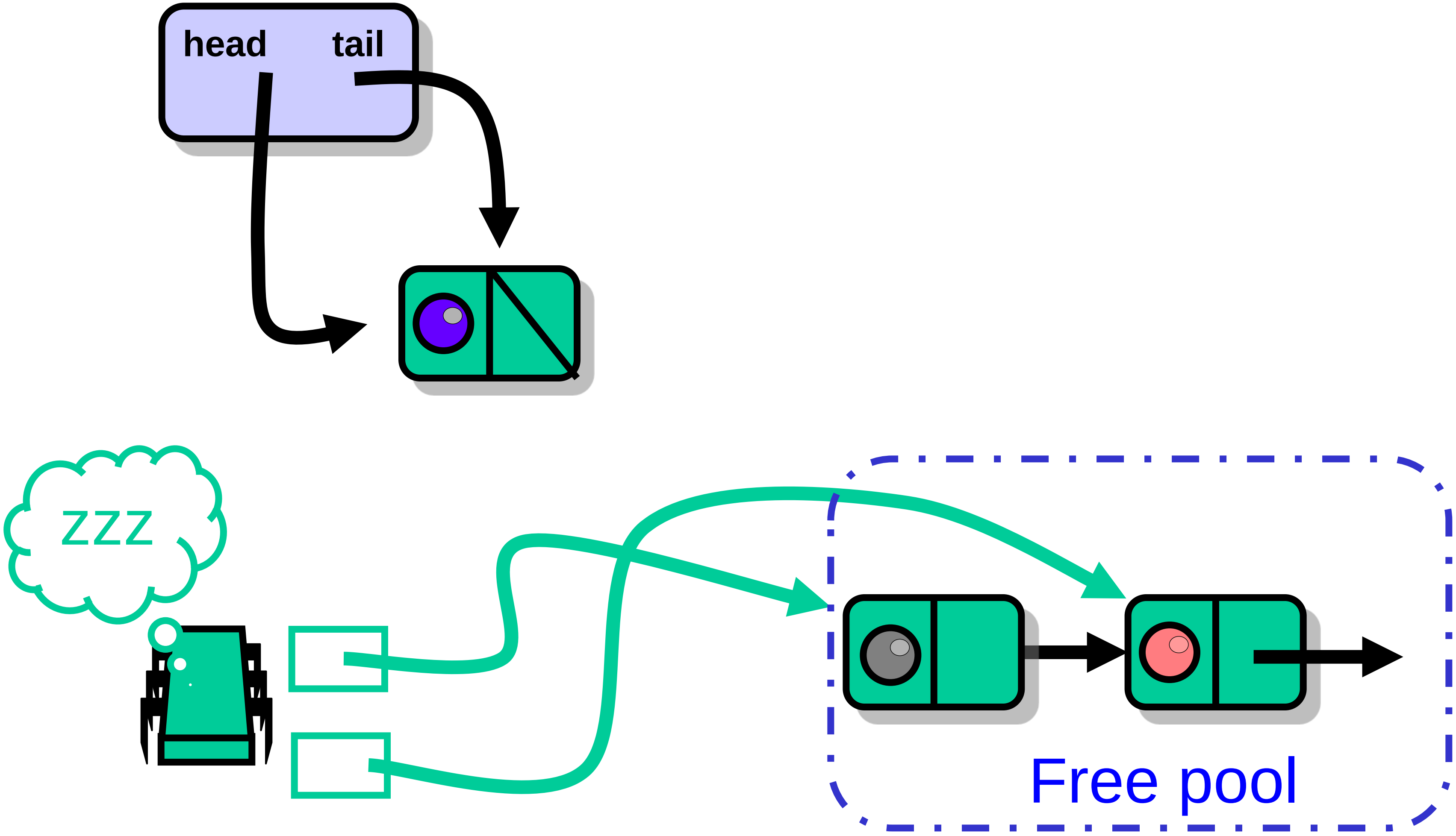
Simple Solution

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

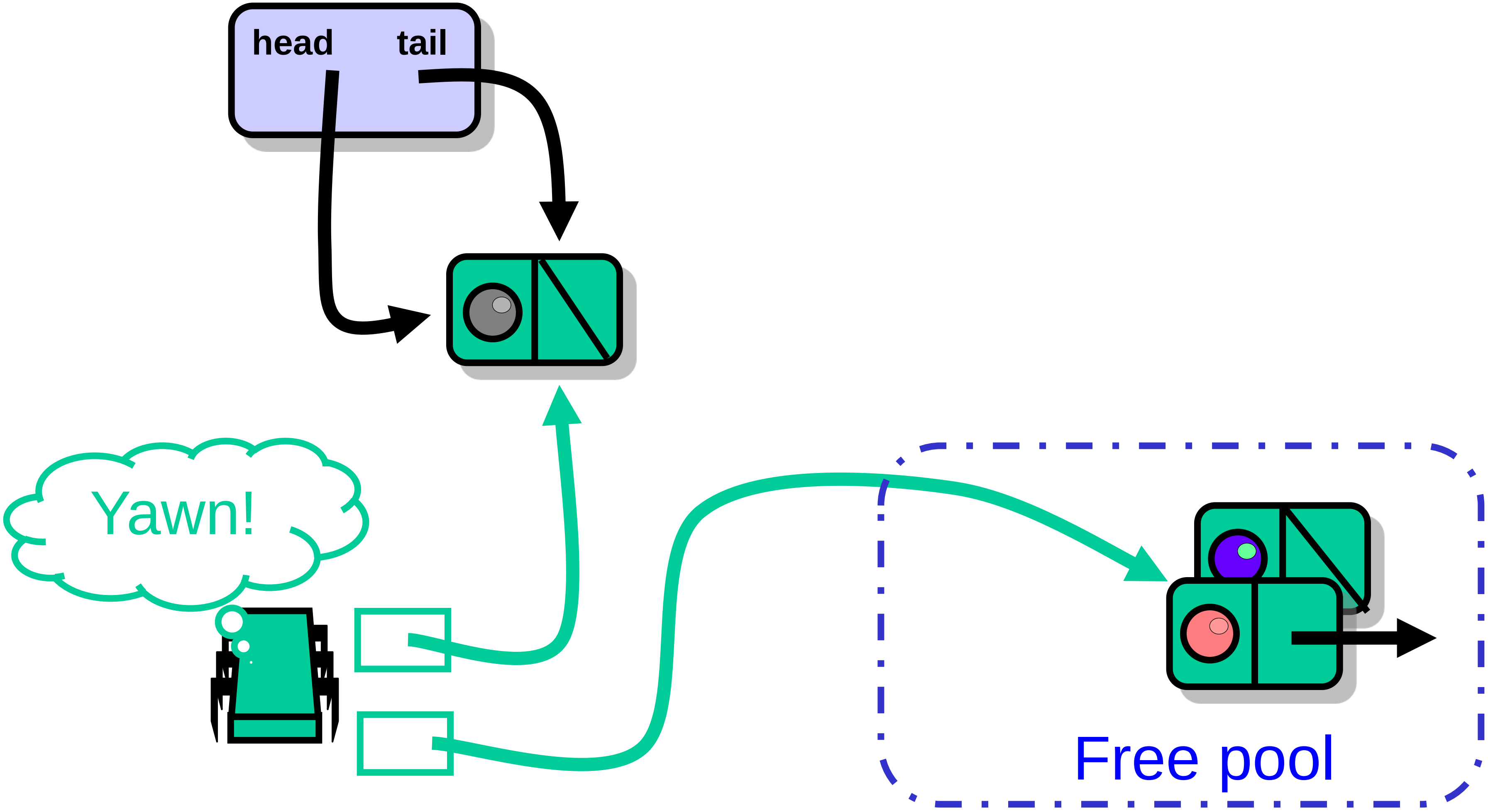
Why Recycling is Hard



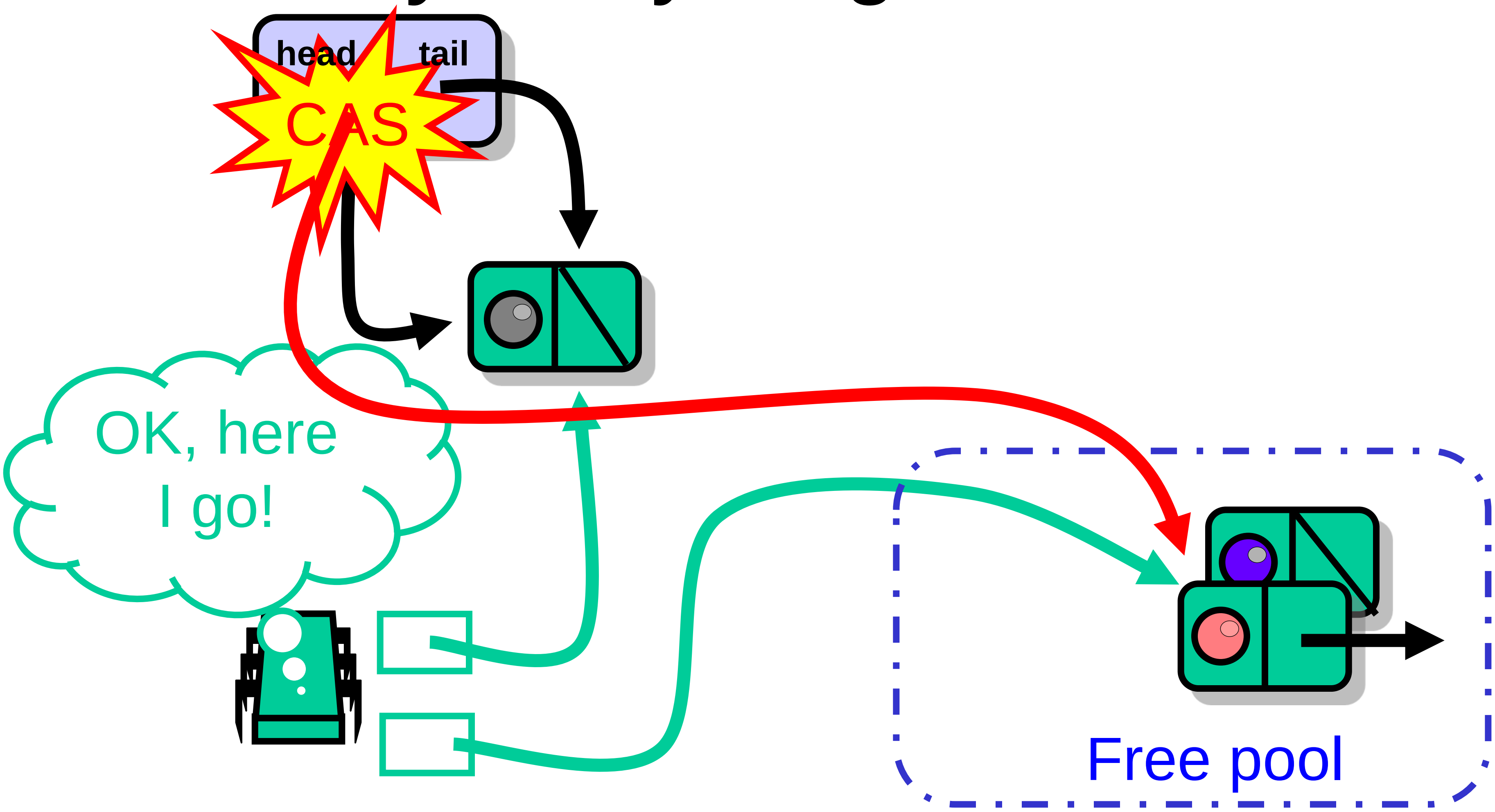
Both Nodes Reclaimed



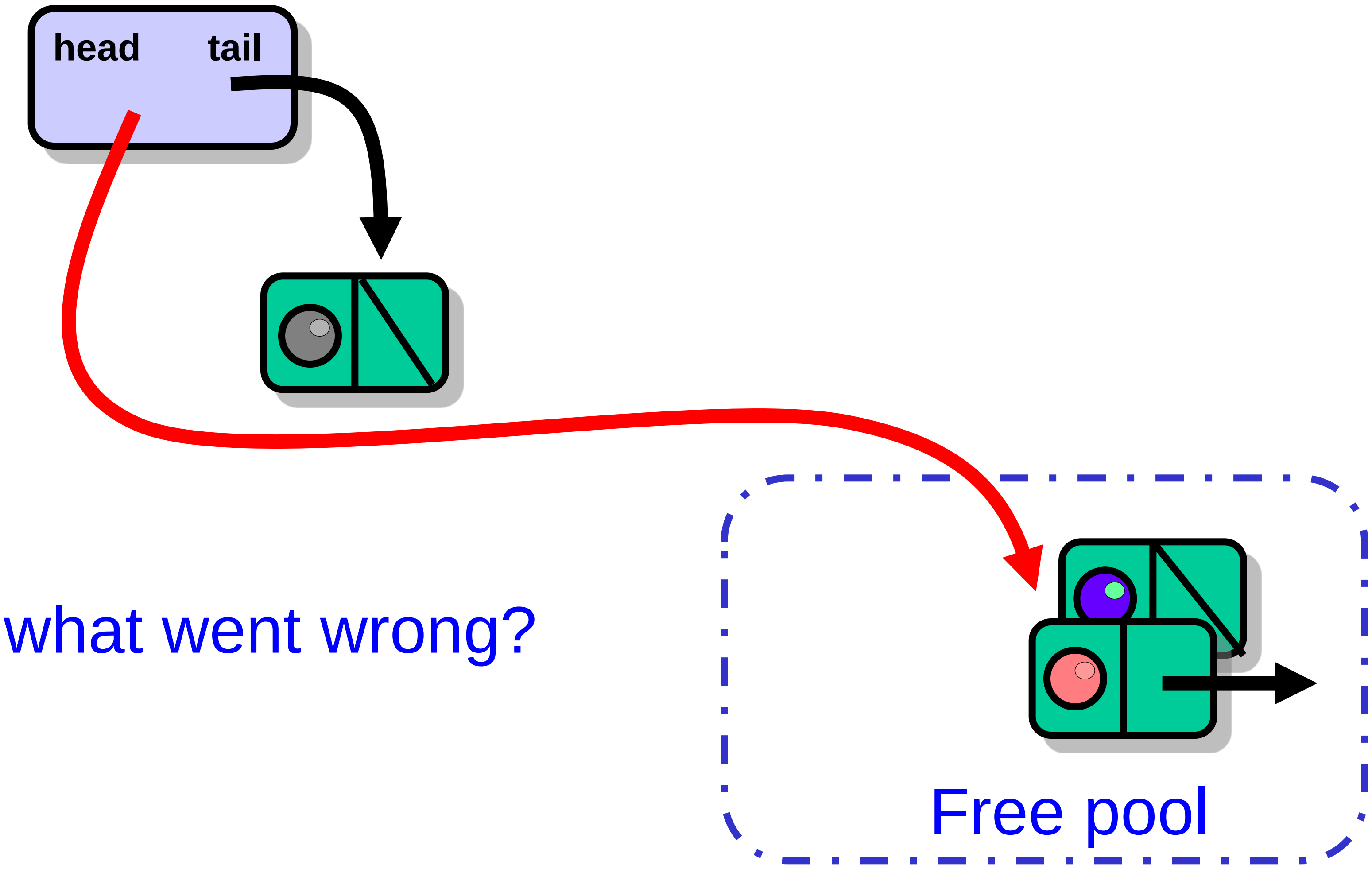
One Node Recycled



Why Recycling is Hard



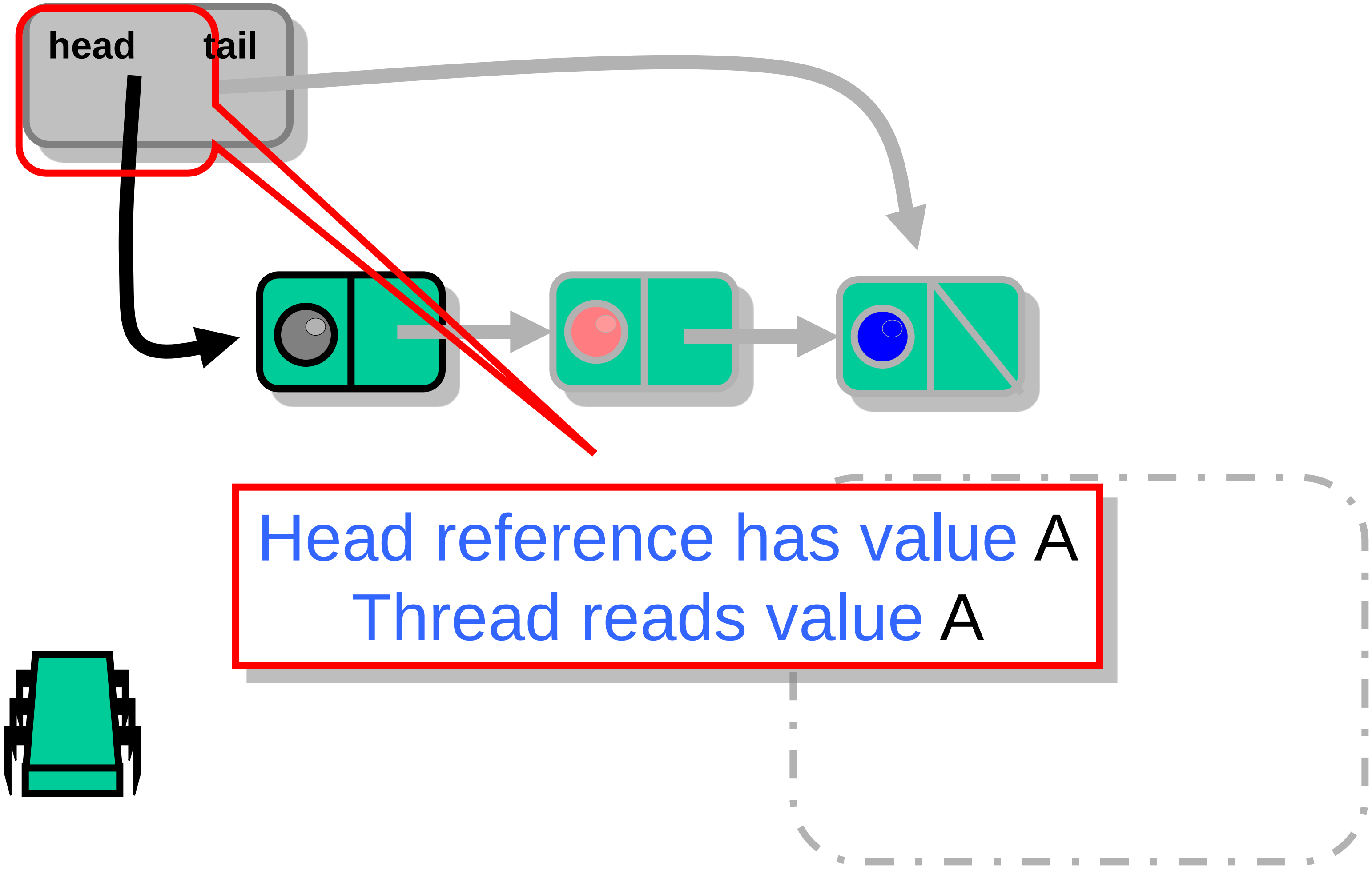
Recycle FAIL



Free pool

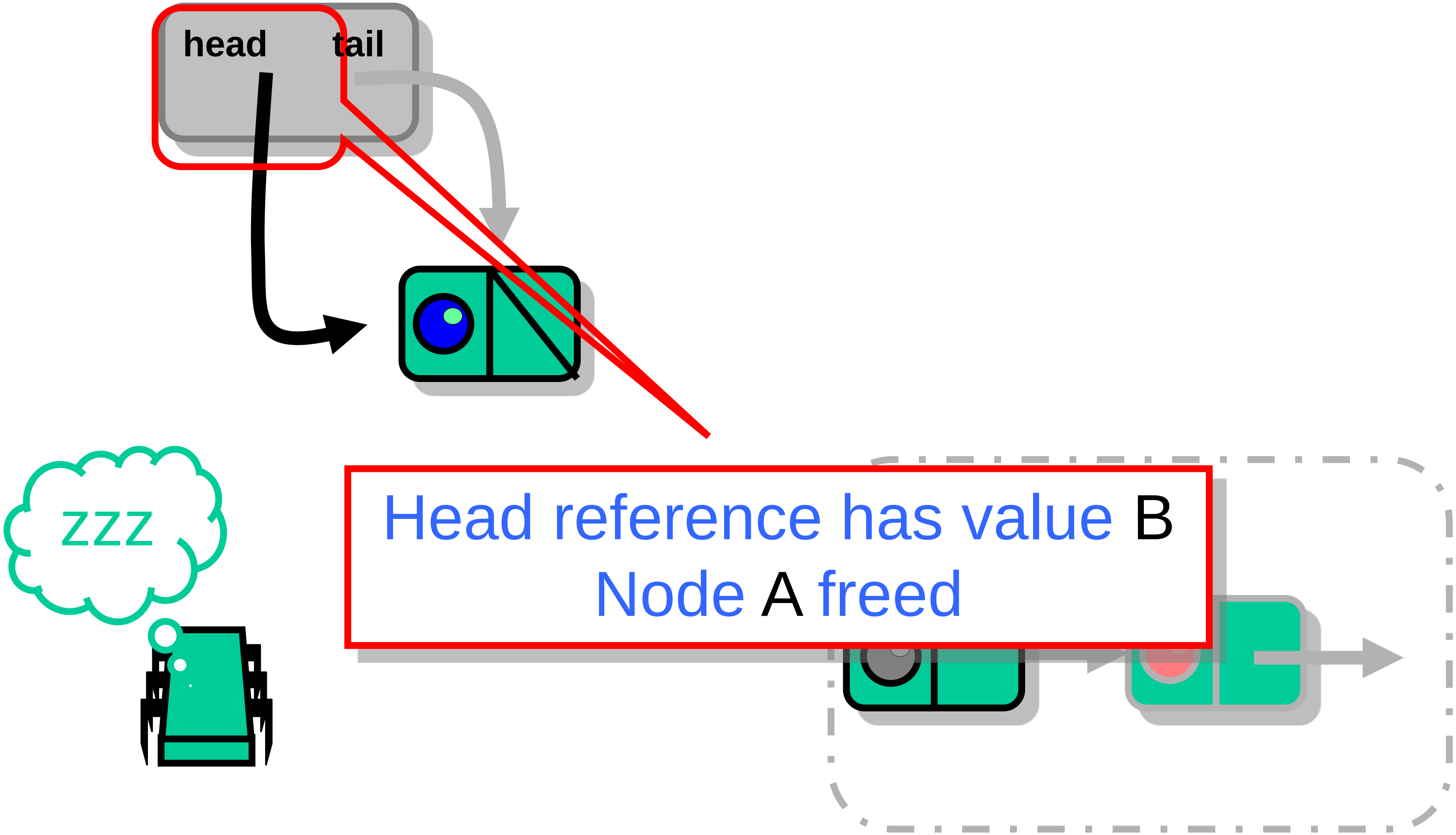
OMG what went wrong?

The Dreaded ABA Problem



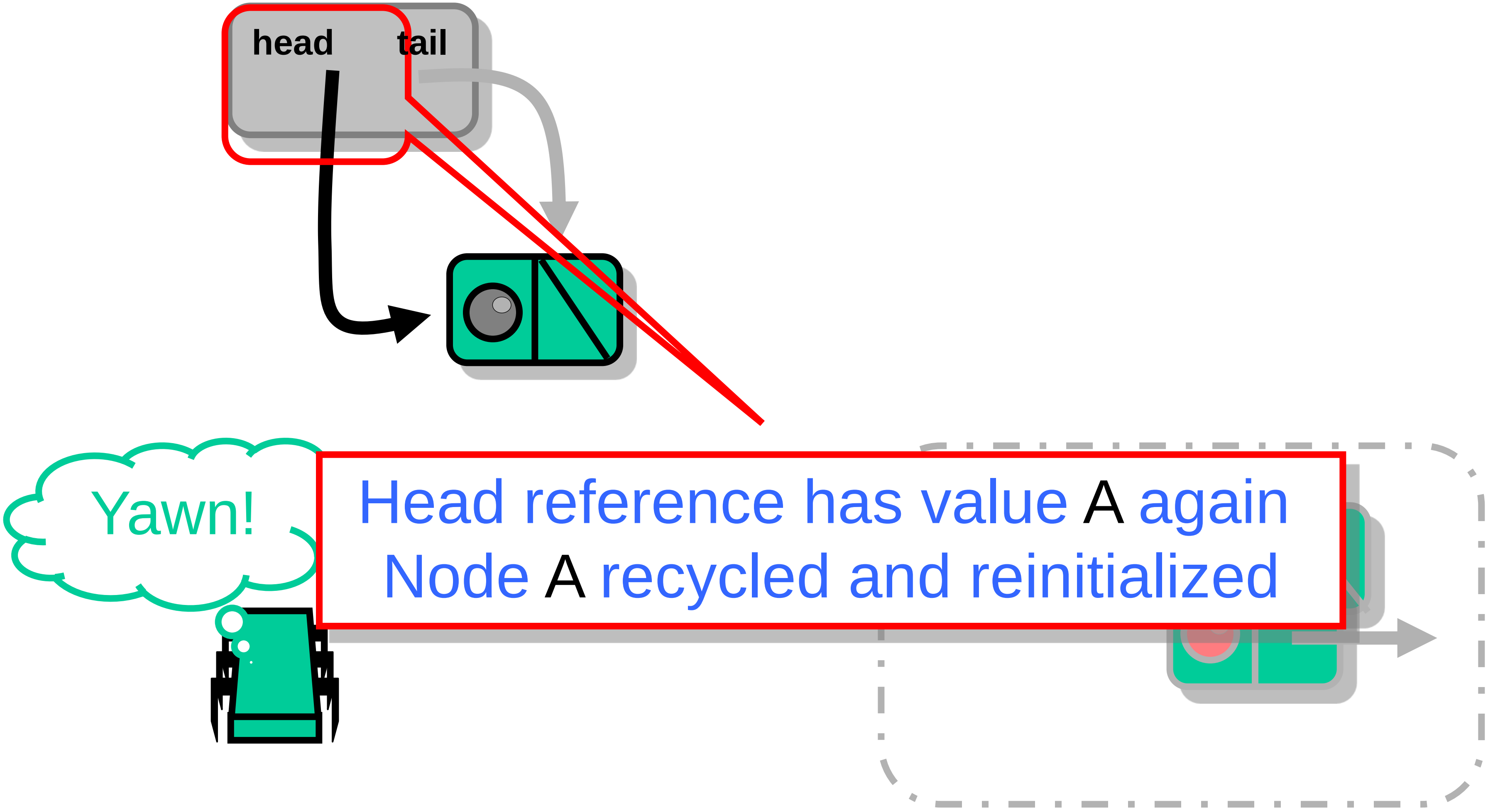
Head reference has value A
Thread reads value A

Dreaded ABA continued



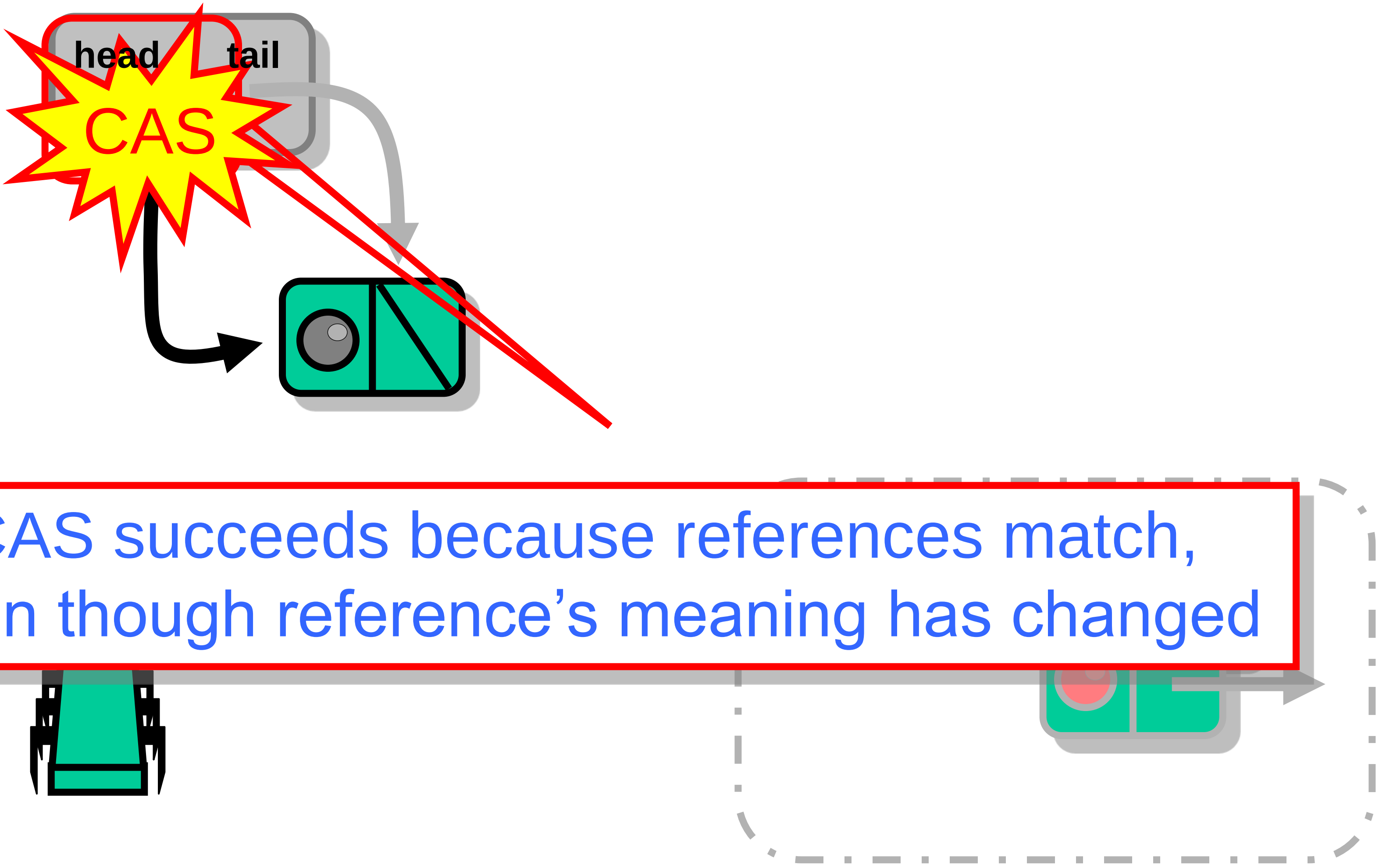
Head reference has value B
Node A freed

Dreaded ABA continued



Head reference has value A again
Node A recycled and reinitialized

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
  - – blame Sun, Intel, AMD, …
- Not with Load-Locked/Store-Conditional
  - – Good for IBM, ARM?

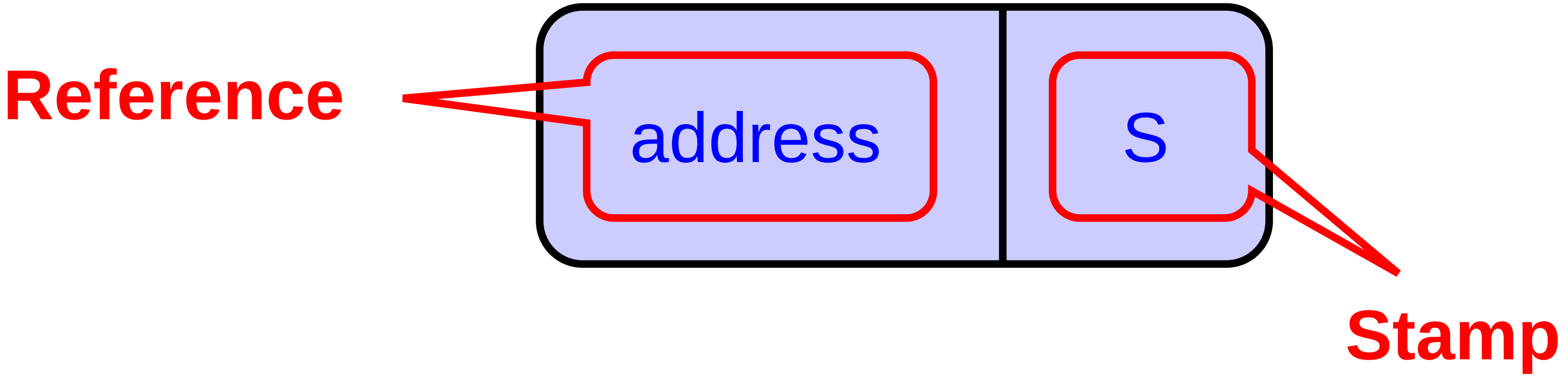
Dreaded ABA – A Solution

- 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

Atomic Stamped Reference

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

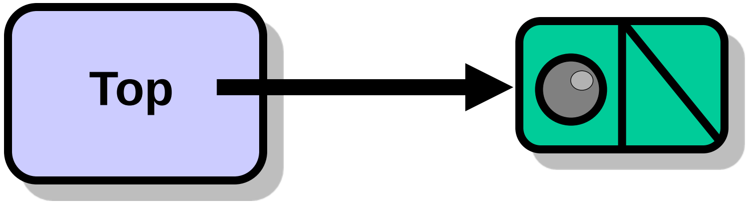
Can get reference & stamp atomically



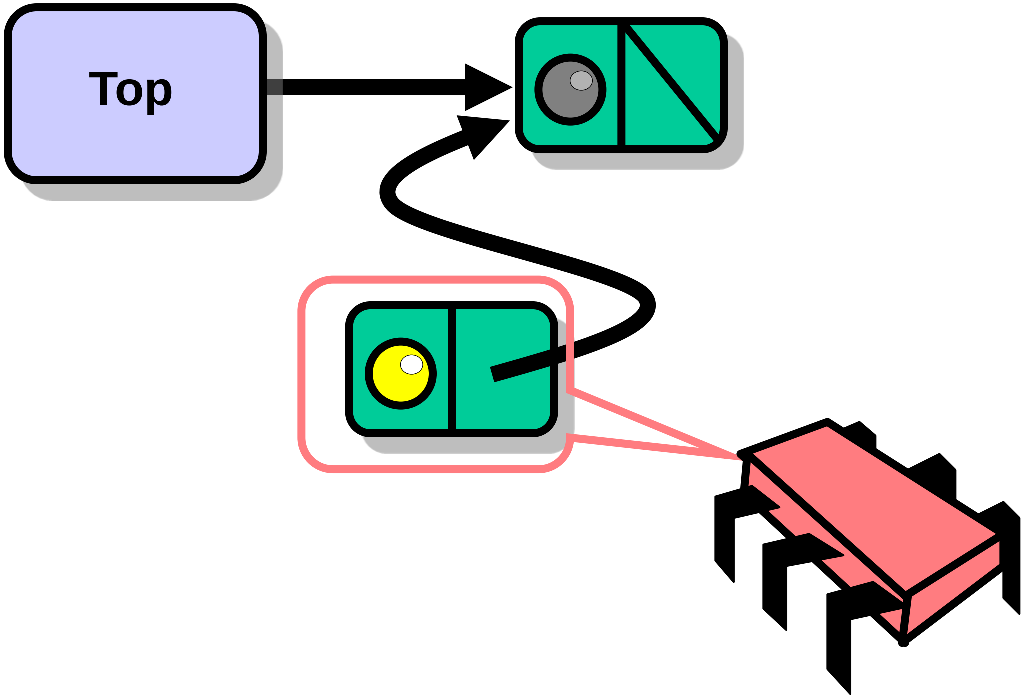
Concurrent Stack

- Methods
  - **push(x)**
  - **pop()**
- Last-in, First-out (LIFO) order
- Lock-Free!

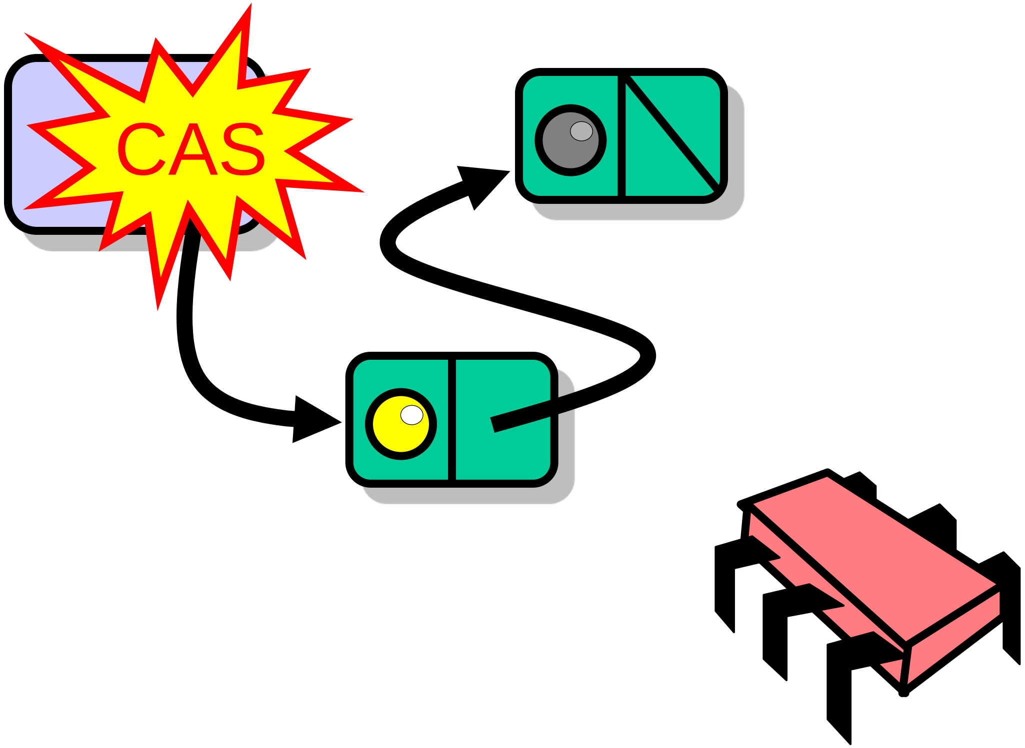
Empty Stack



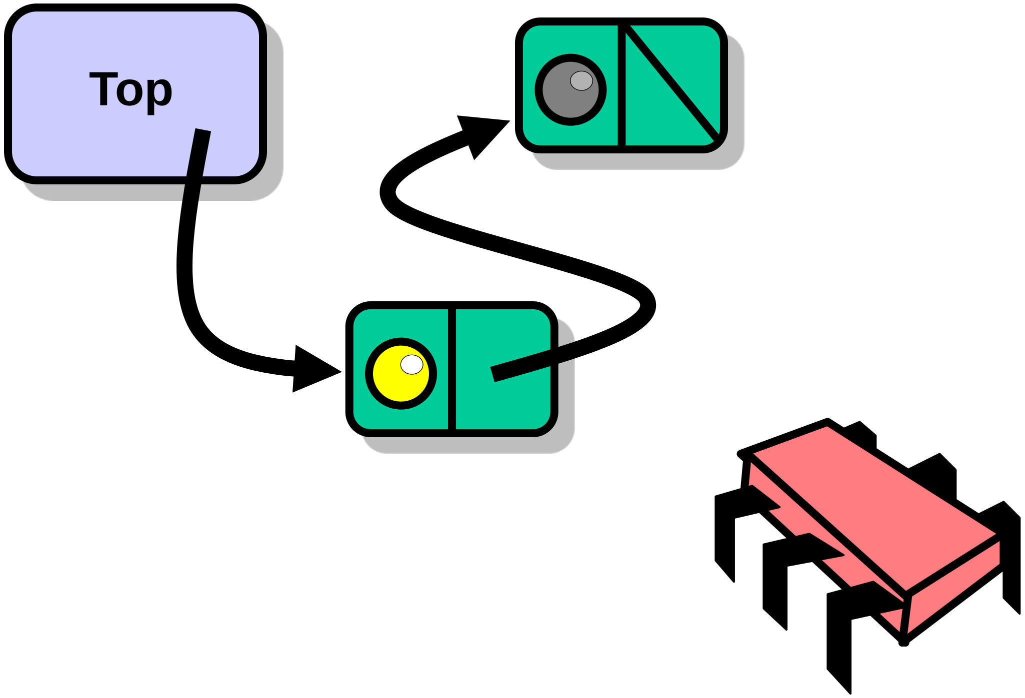
Push



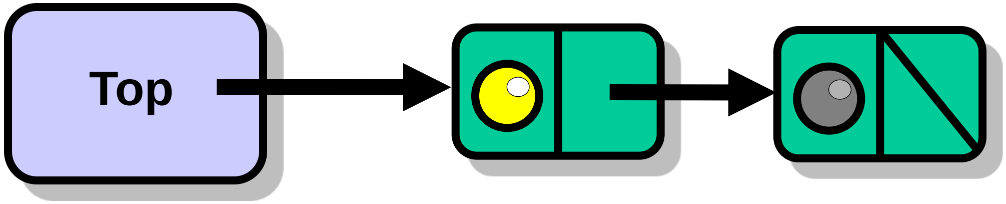
Push

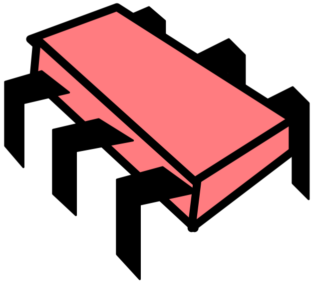


Push

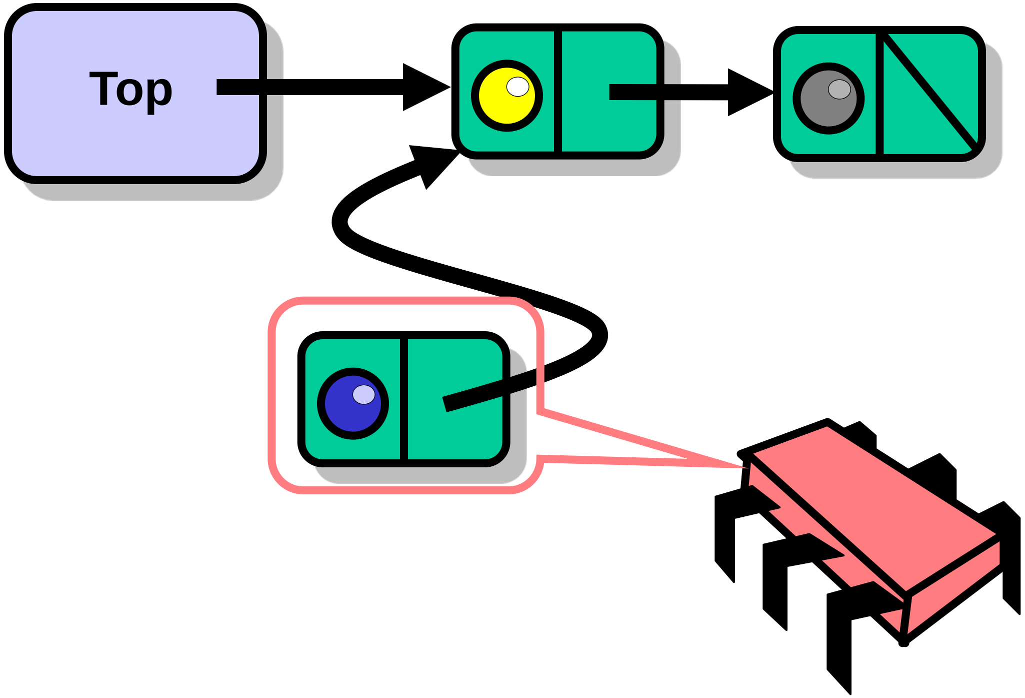


Push

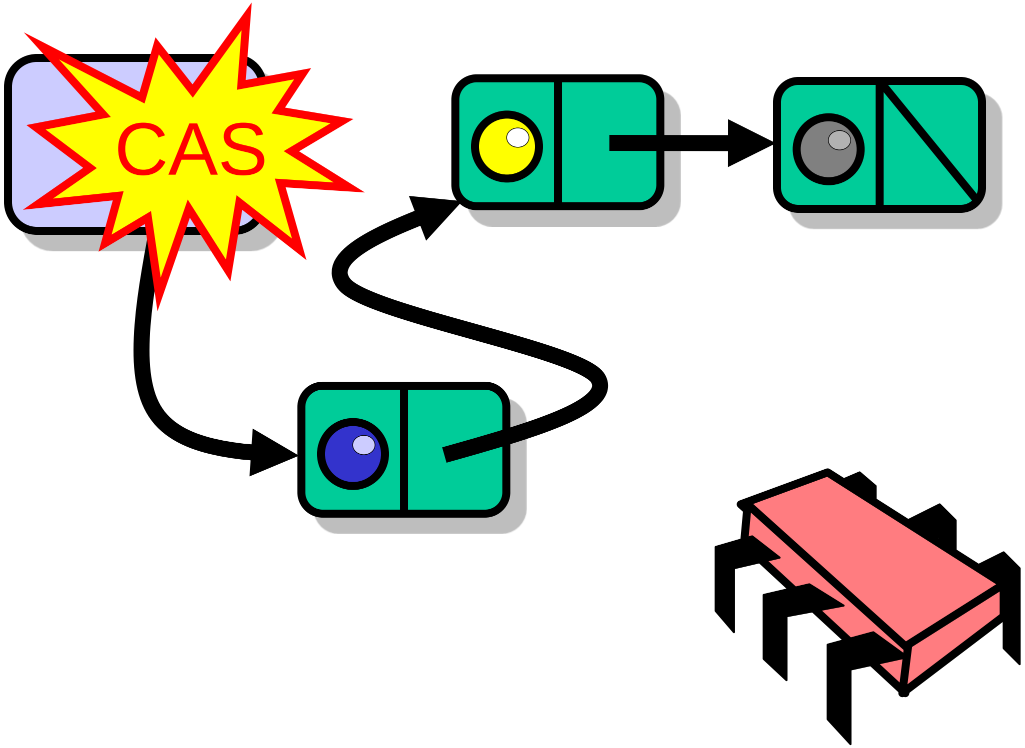




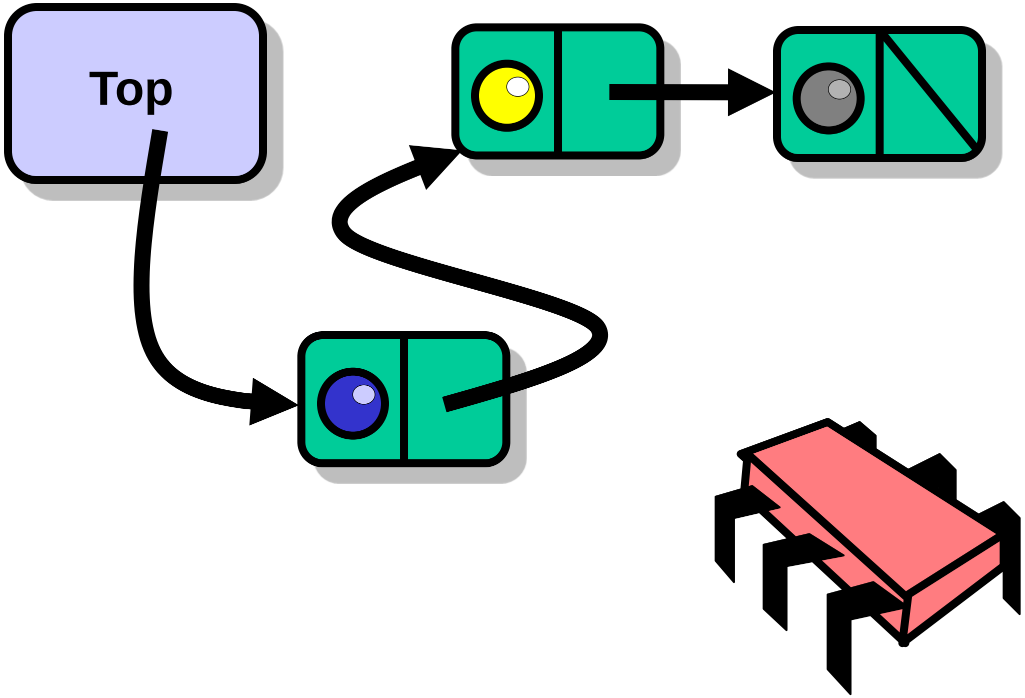
Push



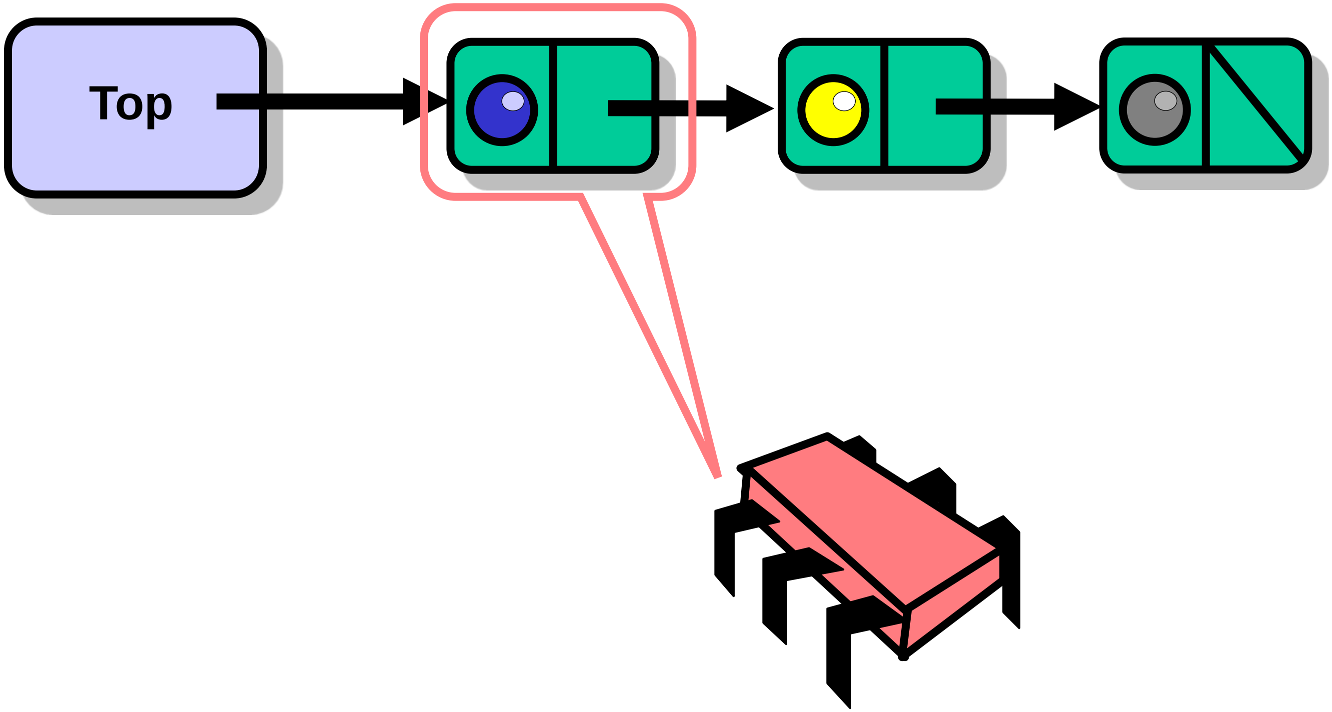
Push



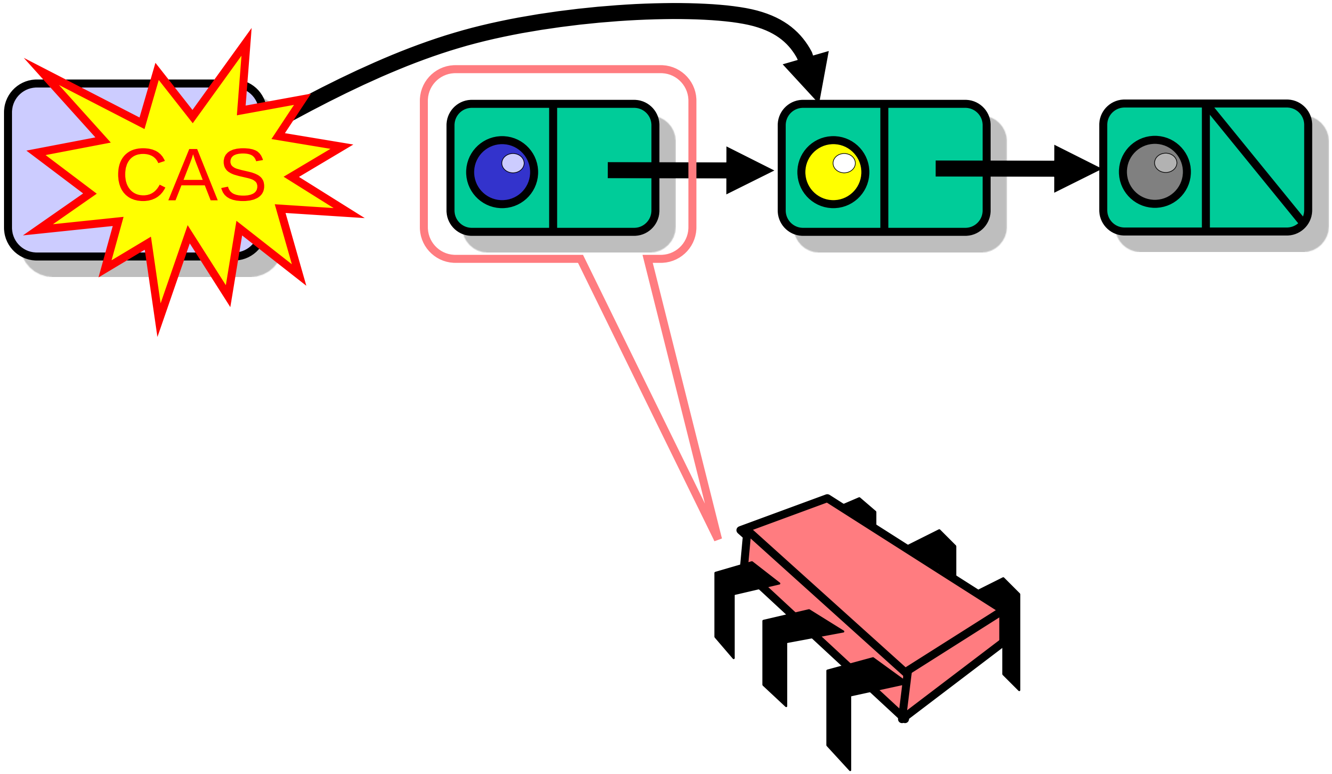
Push



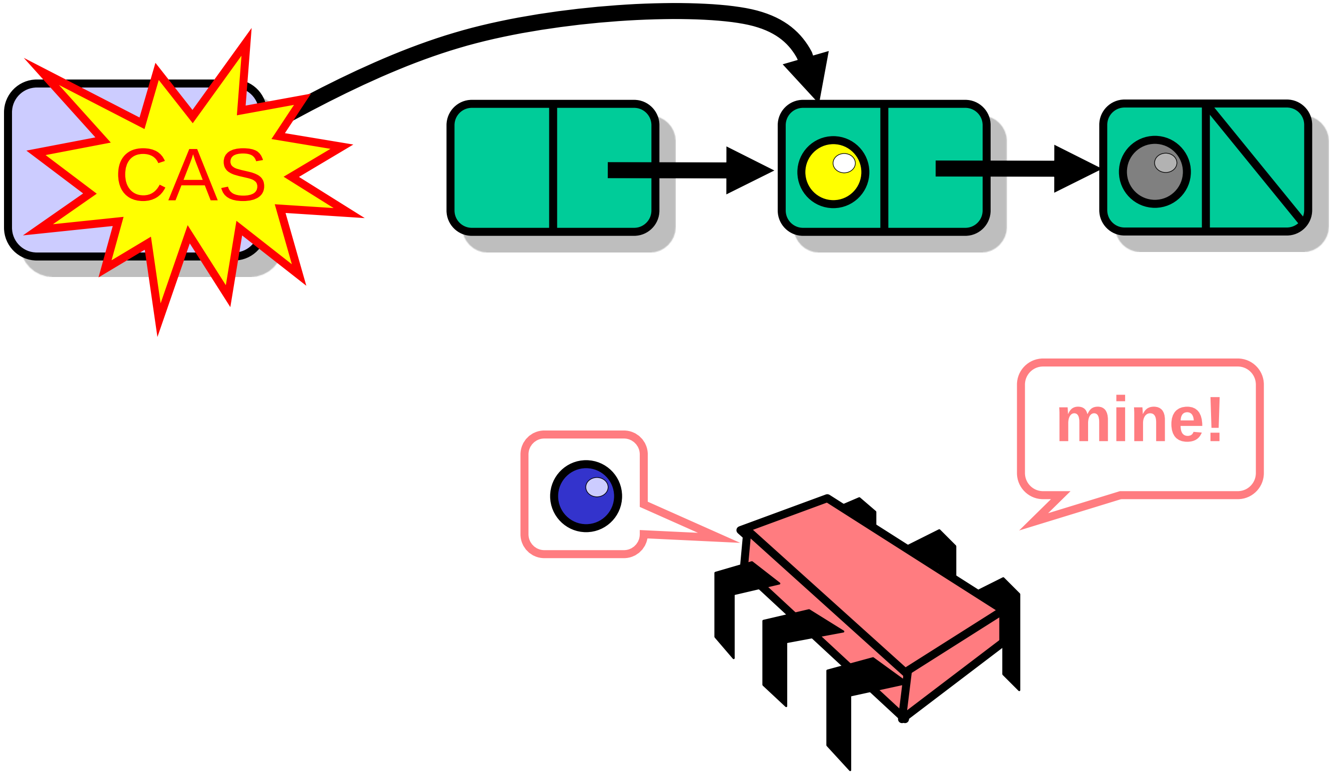
Pop



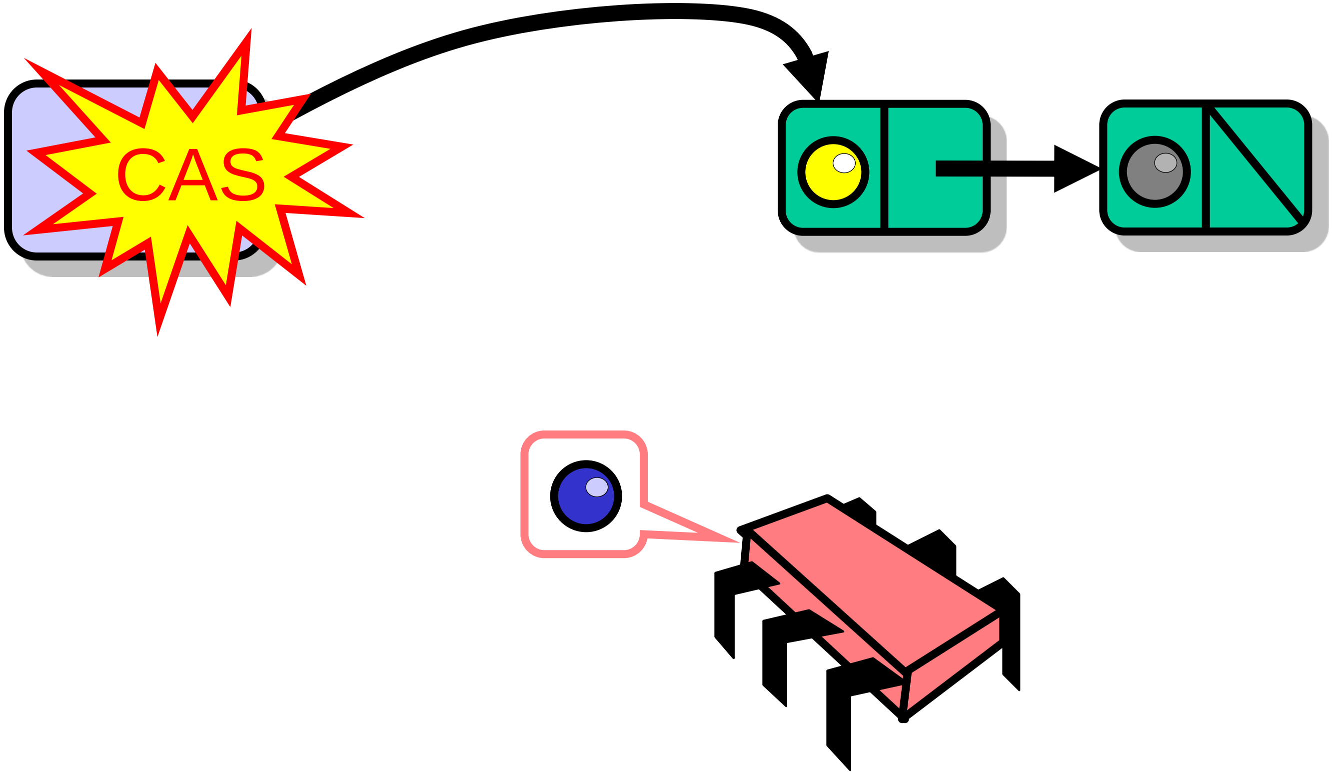
Pop



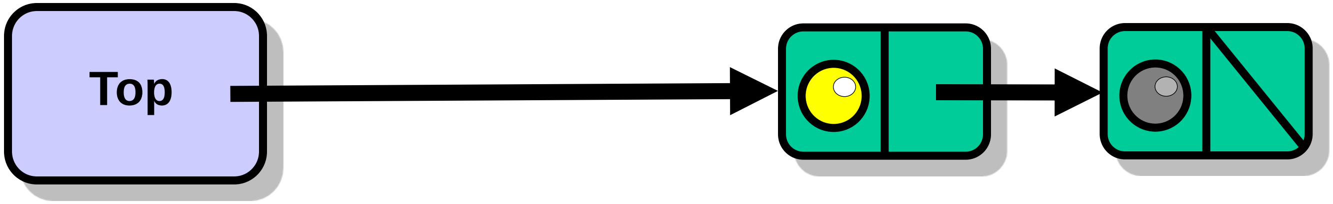
Pop

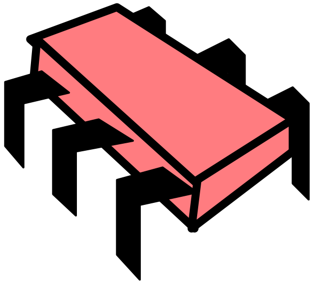


Pop



Pop





Lock-free Stack

```
public class LockFreeStack {
  private AtomicReference top =
    new AtomicReference(null);
  public boolean tryPush(Node node){
    Node oldTop = top.get();
    node.next = oldTop;
    return(top.compareAndSet(oldTop, node))
  }
  public void push(T value) {
  Node node = new Node(value);
    while (true) {
      if (tryPush(node)) {
        return;
      } else backoff.backoff();
  }}
```

Lock-free Stack

```
public class LockFreeStack {
  private AtomicReference top = new
AtomicReference(null);
public Boolean tryPush(Node node){
      Node oldTop = top.get();
      node.next = oldTop;
      return(top.compareAndSet(oldTop, node))
    }
public void push(T value) {
  Node node = new Node(value);
  while (true) {
      if (tryPush(node)) {
        return;

}}
```

tryPush attempts to push a node

Lock-free Stack

```
public class LockFreeStack {
  private AtomicReference top = new
AtomicReference(null);
public boolean tryPush(Node node){
      Node oldTop = top.get();
      node.next = oldTop;
      return(top.compareAndSet(oldTop, node))
    }
public void push(T value) {
  Node node = new Node(value);
  while (true) {
      if (tryPush(node)) {
        return;
      } else backoff.backoff()
}}
```

Read top value

Lock-free Stack

```
public class LockFreeStack {
  private AtomicReference top = new
AtomicReference(null);
public boolean tryPush(Node node){
      Node oldTop = top.get();
      node.next = oldTop;
      return(top.compareAndSet(oldTop, node))
    }
public void push(T value) {
  Node node = new Node(value);
  while (true) {
      if (tryPush(node)) {
        return;
}}
```

current top will be new node's successor

Lock-free Stack

```
public class LockFreeStack {
  private AtomicReference top = new
AtomicReference(null);
public boolean tryPush(Node node){
      Node oldTop = top.get();
      node.next = oldTop;
      return(top.compareAndSet(oldTop, node))
    }
public void push(T value) {
  Node node = new Node(value);
  while (true) {
      if (tryPush(node)) {
        return;
      } else backoff.backoff()
}}
```

Try to swing top, return success or failure

Lock-free Stack

```
public class LockFreeStack {
  private AtomicReference top = new
AtomicReference(null);
public boolean tryPush(Node node){
      Node oldTop = top.get();
      node.next = oldTop;
      return(top.compareAndSet(oldTop, node))
    }
public void push(T value) {
  Node node = new Node(value);
  while (true) {
      if (tryPush(node)) {
        return;
      } else backoff.backoff()
}}
```

Push calls tryPush

Lock-free Stack

```
public class LockFreeStack {
  private AtomicReference top = new
AtomicReference(null);
public boolean tryPush(Node node){
      Node oldTop = top.get();
      node.next = oldTop;
      return(top.compareAndSet(oldTop, node))
    }
public void push(T value) {
  Node node = new Node(value);
  while (true) {
      if (tryPush(node)) {
        return;
      } else backoff.backoff()
}}
```

Create new node

Lock-free Stack

```
public class LockFreeStack {
  private AtomicReference top = new
AtomicReference(null);
public boolean tryPush(Node node){
      Node oldTop = top.get();
      node.next = oldTop;
      return(top.compareAndSet(oldTop, node))
    }
public void push(T value) {
  Node node = new Node(value);
  while (true) {
      if (tryPush(node)) {
        return;
      } else backoff.backoff()
}}
```

If tryPush() fails, back off before retrying

Lock-free Stack

- Good
  - No locking
- Bad
  - Without GC, fear ABA
  - Without backoff, huge contention at top
  - In any case, no parallelism

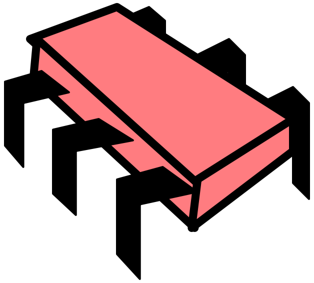
Big Question

- Are stacks *inherently* sequential?
- Reasons why
  - Every **pop()** call fights for top item
- Reasons why not
  - Stay tuned …

Elimination-Backoff Stack

- How to
  - “turn contention into parallelism”
- Replace familiar
  - **exponential backoff**
- With alternative
  - **elimination-backoff**

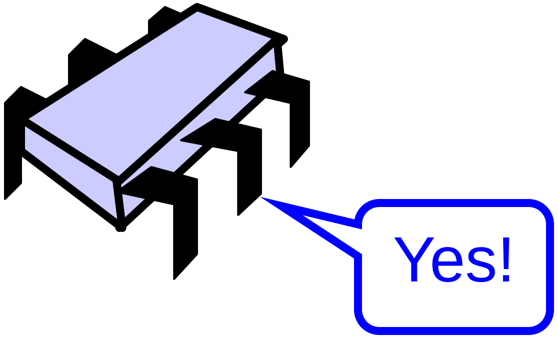
Observation



Push(●)

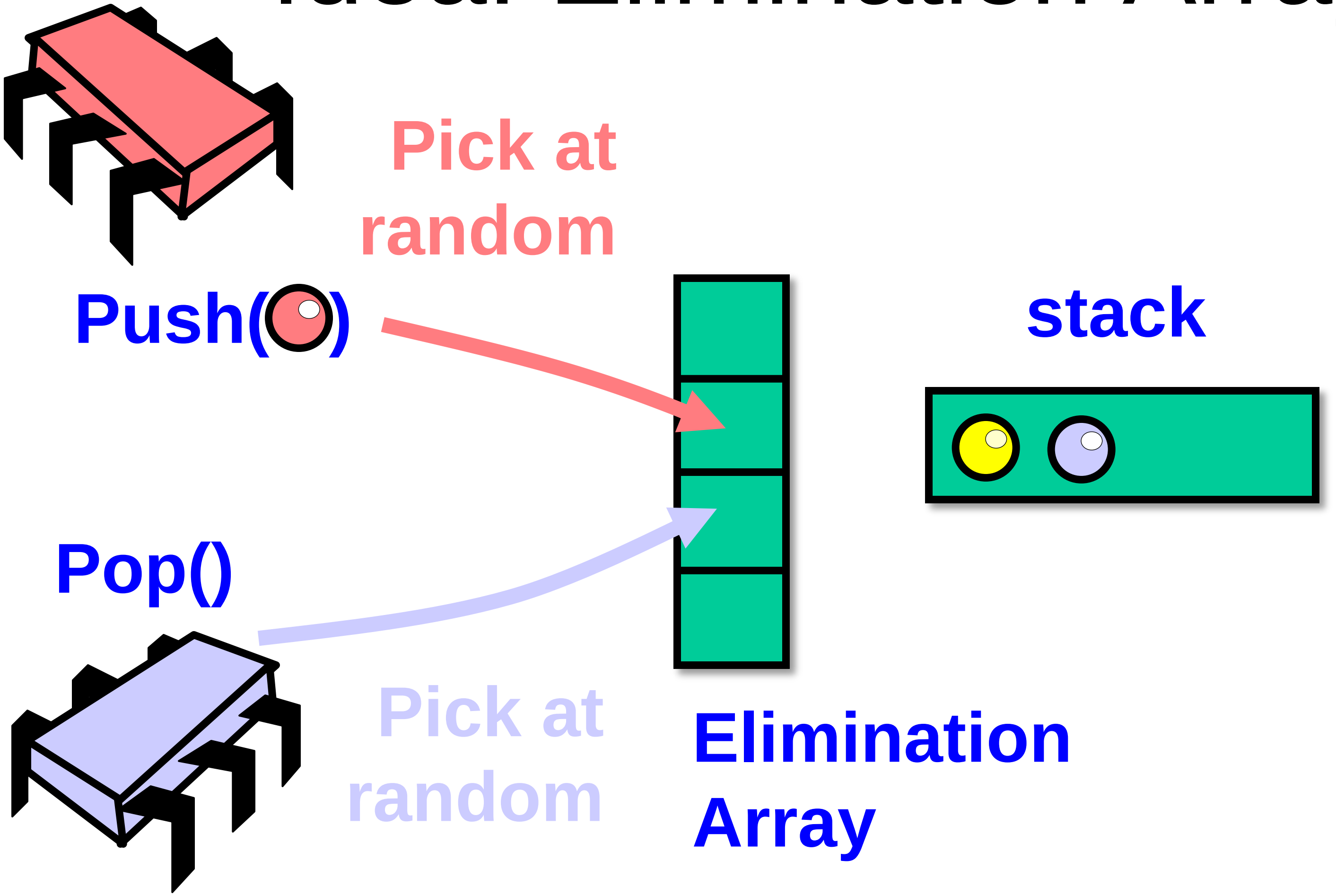
linearizable stack

Pop()



After an equal number of pushes and pops, stack stays the same

Idea: Elimination Array



Pick at random

Push( )

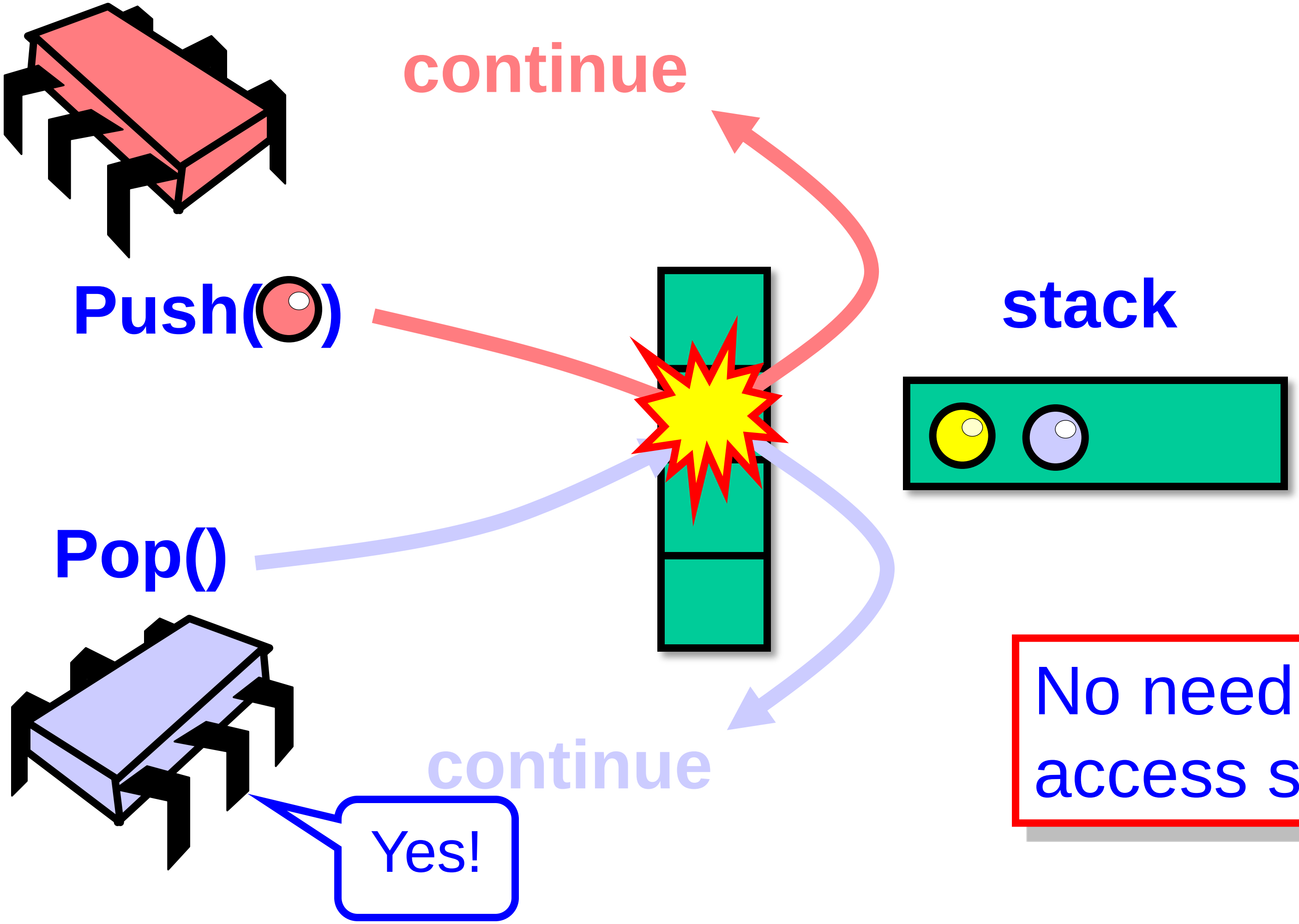
stack

Pop()

Pick at random

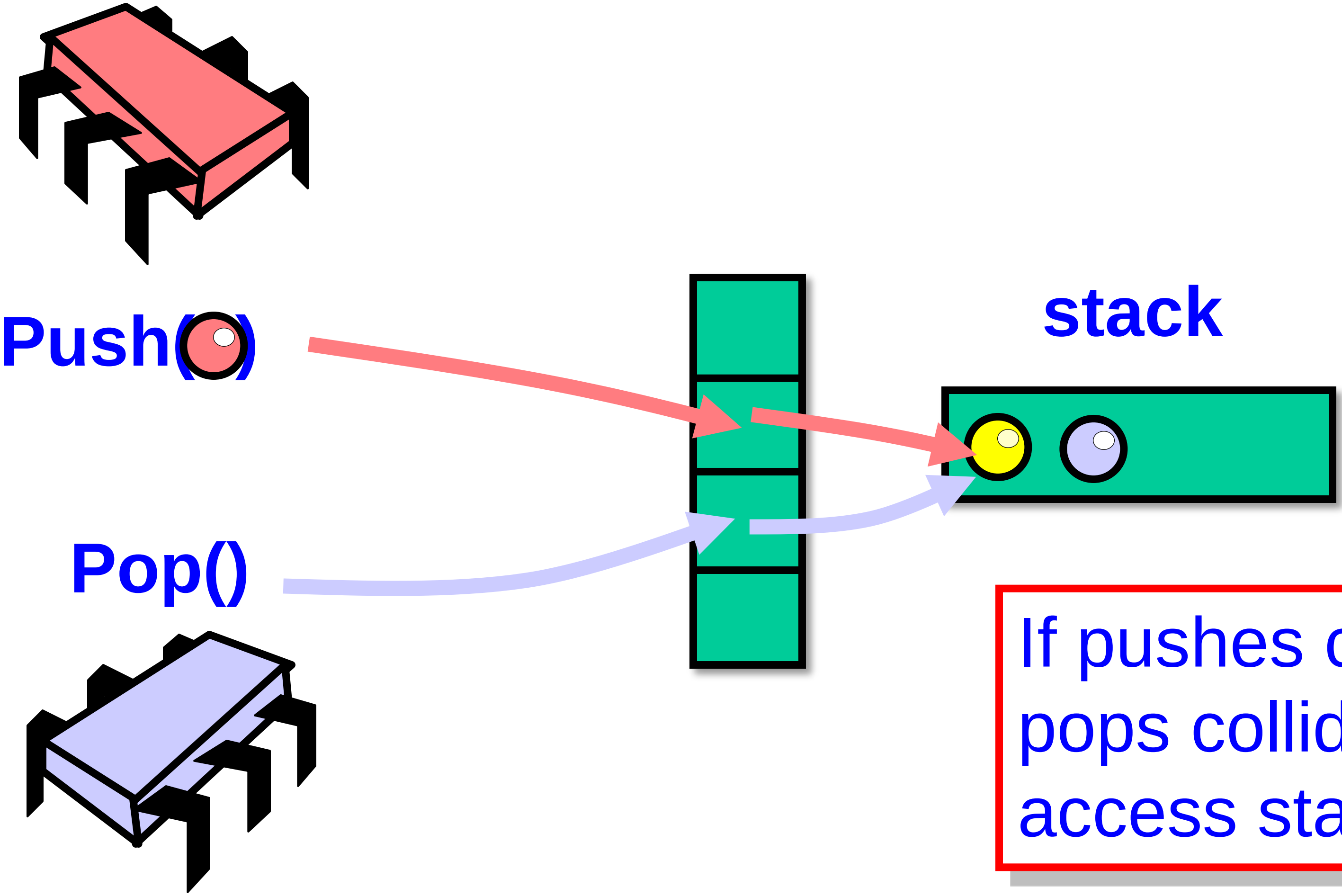
Elimination Array

Push Collides With Pop



No need to access stack

No Collision

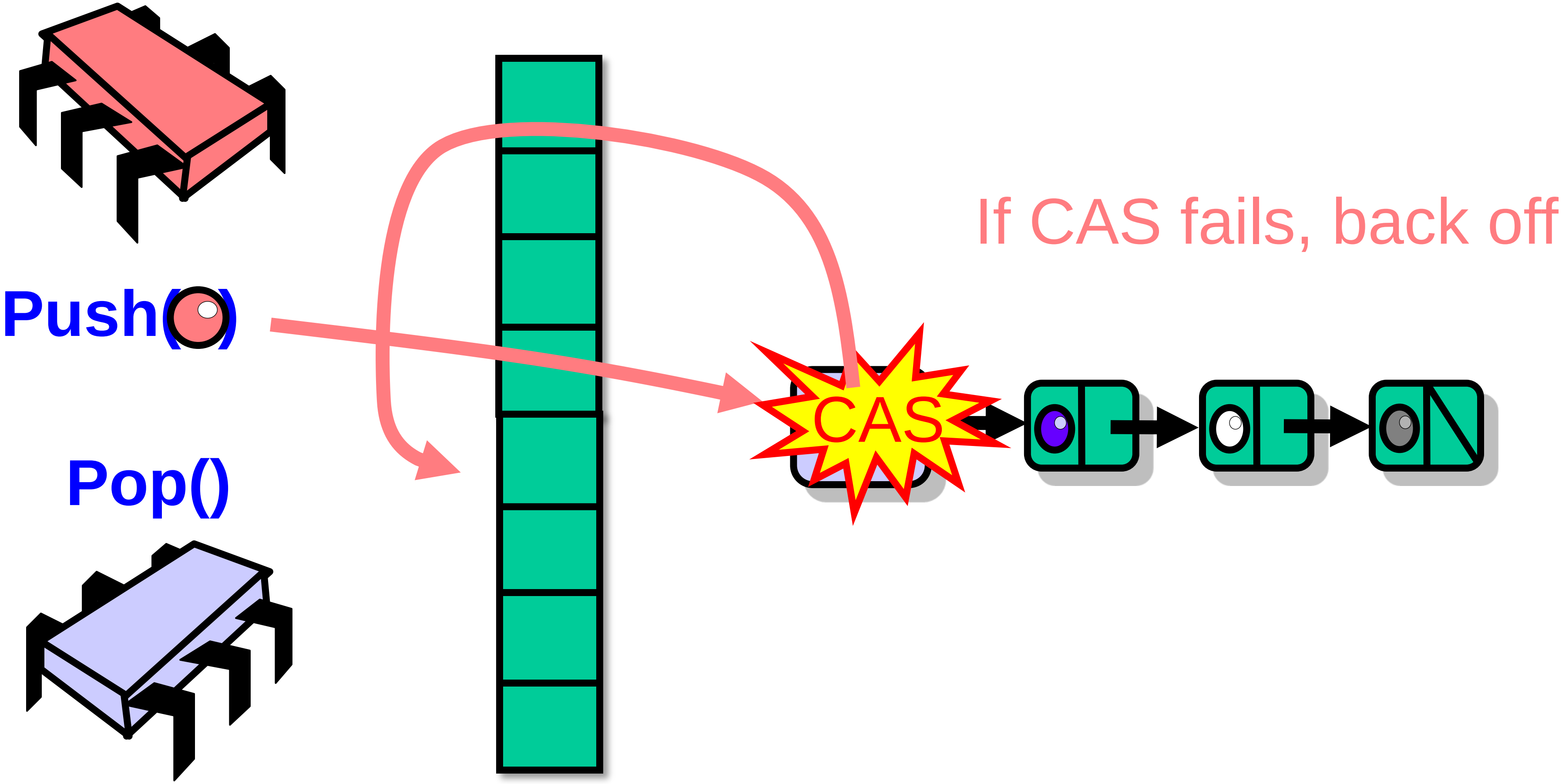


If pushes collide or pops collide access stack

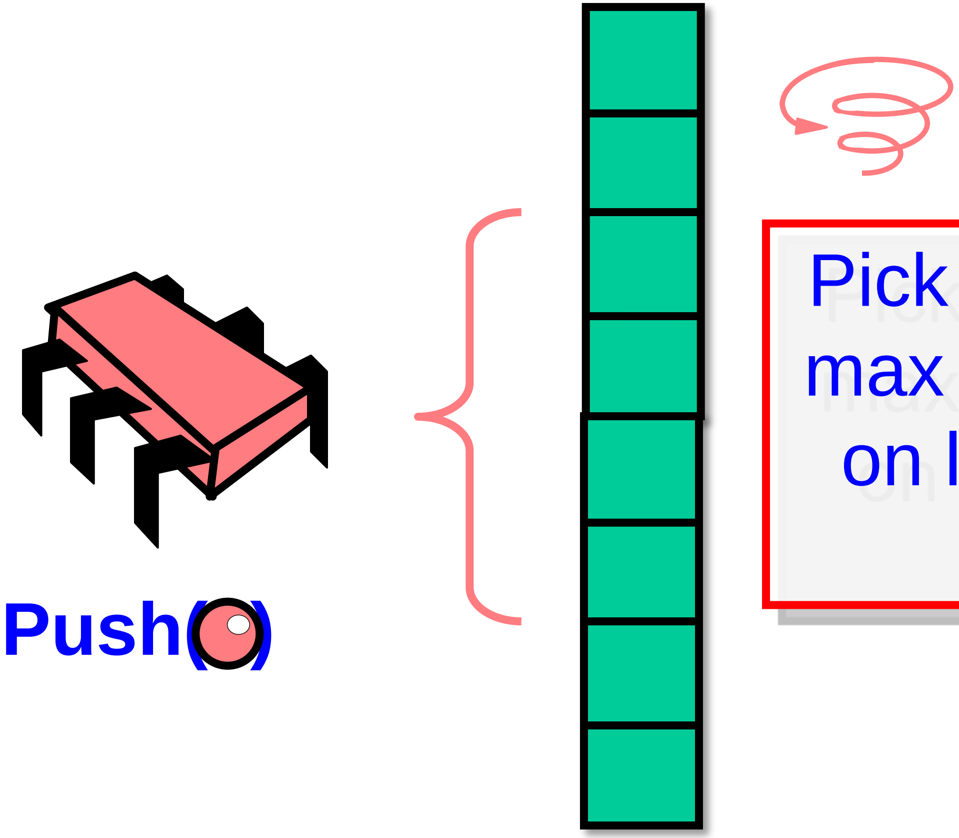
Elimination-Backoff Stack

- Lock-free stack + elimination array
- Access Lock-free stack,
  - If **uncontended**, apply operation
  - if **contended**, back off to elimination array and attempt elimination

Elimination-Backoff Stack



Dynamic Range and Delay

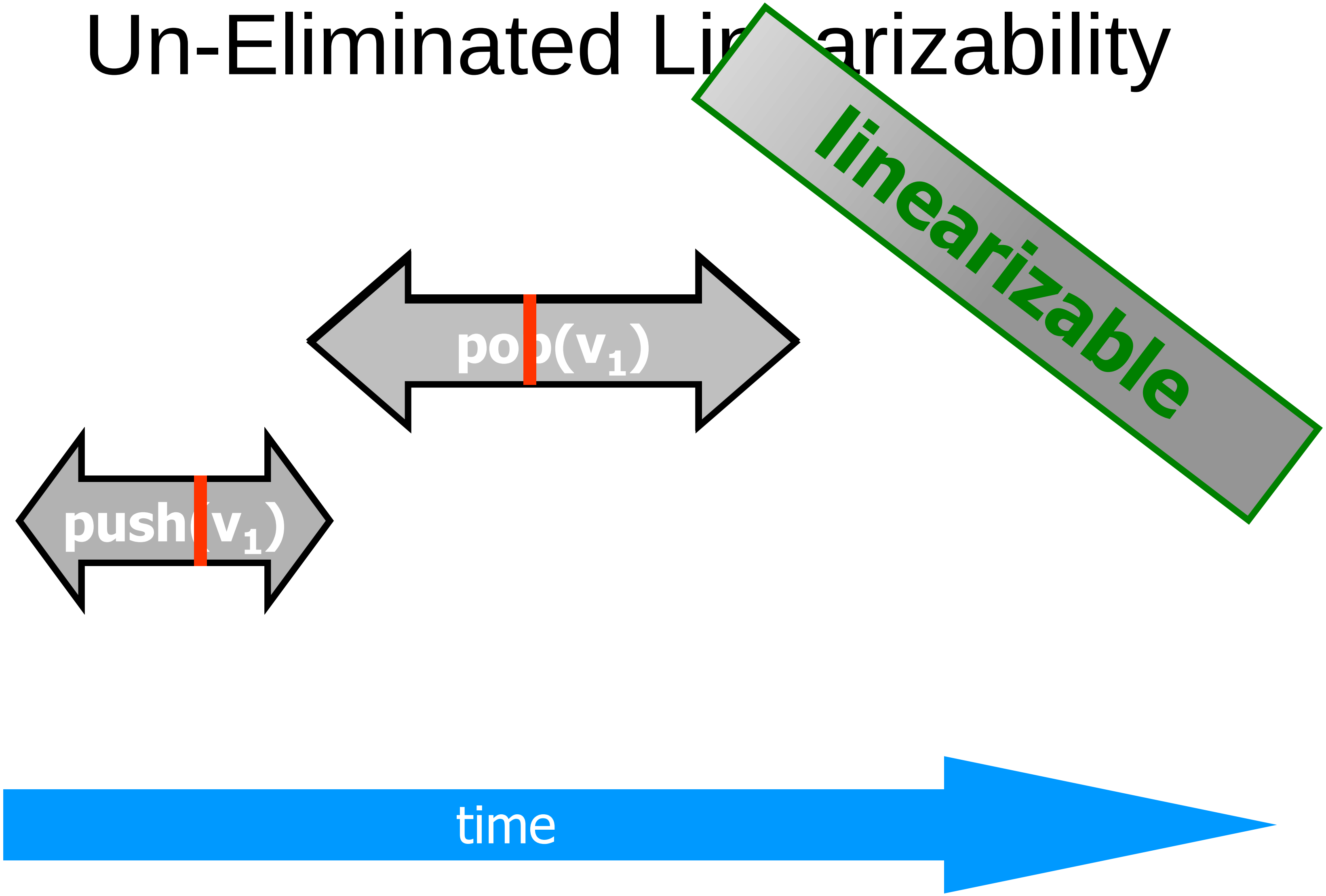


Pick random range and max waiting time based on level of contention encountered

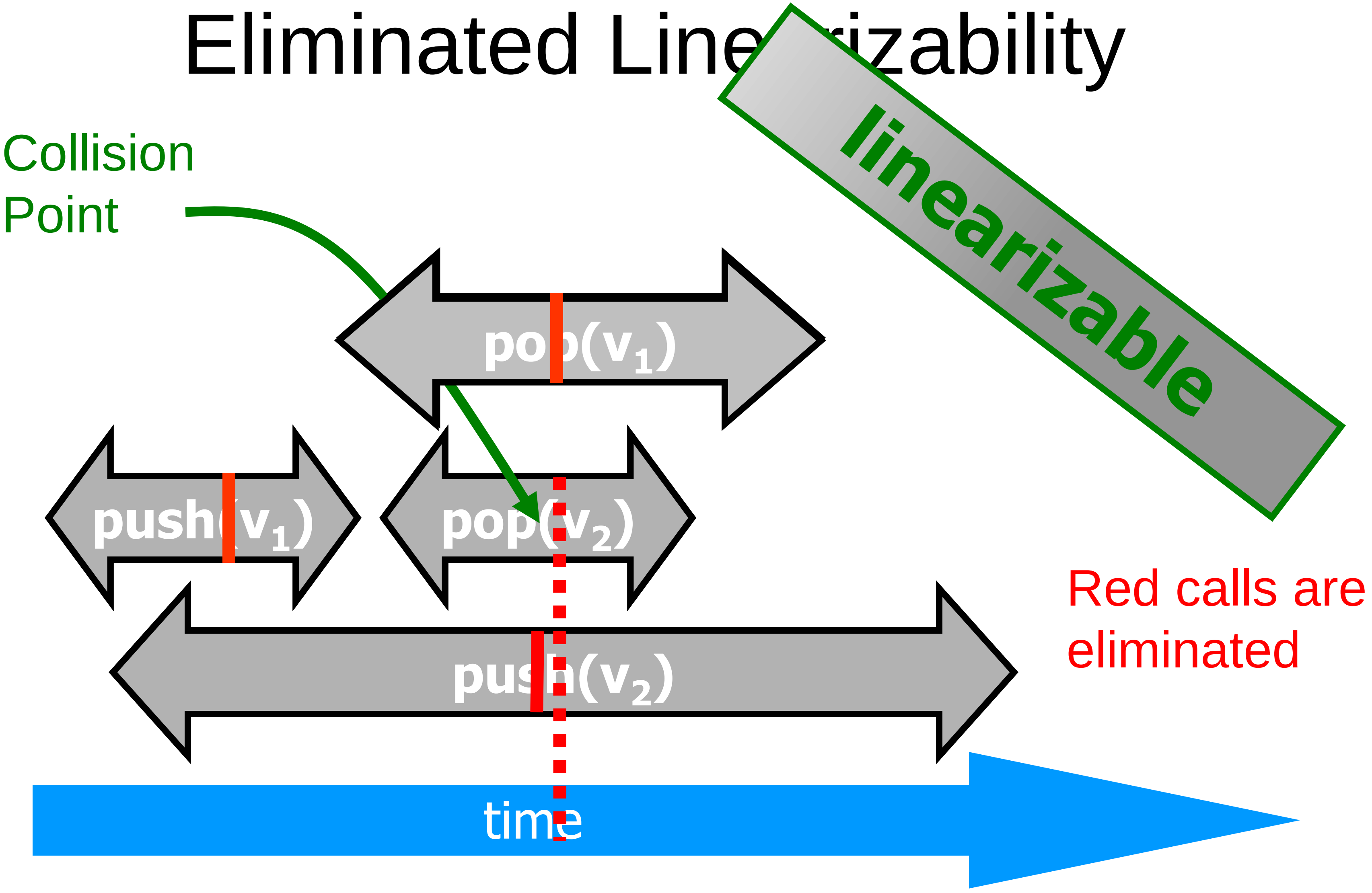
Linearizability

- **Un-eliminated calls**
  - **linearized as before**
- **Eliminated calls:**
  - **linearize pop() immediately after matching push()**
- **Combination is a linearizable stack**

Un-Eliminated Linearizability



Eliminated Linearizability



Red calls are eliminated

Backoff Has Dual Effect

- Elimination introduces parallelism
- Backoff to array cuts contention on lock-free stack
- Elimination in array cuts down number of threads accessing lock-free stack

Elimination Array

```
public class EliminationArray {
 private static final int duration = ...;
 private static final int timeUnit = ...;
 Exchanger<T>[] exchanger;
 public EliminationArray(int capacity) {
  exchanger = new Exchanger[capacity];
  for (int i = 0; i < capacity; i++)
   exchanger[i] = new Exchanger<T>();
  …
  }
  …
}
```

Elimination Array

```
public class EliminationArray {
 private static final int duration = ...;
 private static final int timeUnit = ...;
 Exchanger<T>[] exchanger;
 public EliminationArray(int capacity) {
  exchanger = new Exchanger[capacity];
  for (int i = 0; i < capacity; i++)
   exchanger[i] = new Exchanger<T>();
   …
   }
   …
}
```

An array of *Exchangers*

Digression: A Lock-Free Exchanger

```
public class Exchanger<T> {
 AtomicStampedReference<T> slot
  = new AtomicStampedReference<T>(null, 0);
```

A Lock-Free Exchanger

```
public class Exchanger<T> {
 AtomicStampedReference<T> slot
   = new AtomicStampedReference<T>(null, 0);
```

Atomically modifiable reference + status

The Exchange

```
public T Exchange(T myItem, long nanos)
   throws TimeoutException {
 long timeBound = System.nanoTime() + nanos;
 int[] stampHolder = {EMPTY};
 while (true) {
  if (System.nanoTime() > timeBound)
    throw new TimeoutException();
  T herItem = slot.get(stampHolder);
  int stamp = stampHolder[0];
  switch(stamp) {
   case EMPTY: …   // slot is free
   case WAITING: … // someone waiting for me
   case BUSY: …    // others exchanging
  }
 }
```

The Exchange

```
public T Exchange(T myItem, long nanos)
   throws TimeoutException {
 long timeBound = System.nanoTime() + nanos;
 int[] stampHolder = {EMPTY};
 while (true) {
  if (System.nanoTime() > timeBound)
    throw new TimeoutException();
  T herItem = slot.get(stampHolder);
  int stamp = stampHolder[0];
  switch(stamp) {
   case EMPTY: …    // slot is free
   case WAITING: … // someone waiting for me
   case BUSY: …     // others exchanging
  }
 }
```

Item and timeout

The Exchange

```
public T Exchange(T myItem, long nanos)
   throws TimeoutException {
 long timeBound = System.nanoTime() + nanos;
 int[] stampHolder = {EMPTY};
 while (true) {
  if (System.nanoTime() > timeBound)
    throw new TimeoutException();
  T herItem = slot.get(stampHolder);
  int stamp = stampHolder[0];
  switch(stamp) {
   case EMPTY: …    // slot is free
   case WAITING: … // someone waiting for me
   case BUSY: …    // others exchanging
  }
 }
```

Array holds status

The Exchange

```
public T Exchange(T myItem, long nanos)
   throws TimeoutException {
 long timeBound = System.nanoTime() + nanos;
 int[] stampHolder = {EMPTY};
 while (true) {
  if (System.nanoTime() > timeBound)
    throw new TimeoutException();
  T herItem = slot.get(stampHolder);
  int stamp = stampHolder[0];
  switch(stamp) {
   case EMPTY: …    // slot is free
   case WAITING: … // someone waiting for me
   case BUSY: …    // others exchanging
  }
 }
```

Loop until timeout

The Exchange

```
public T Exchange(T myItem, long nanos)
   throws TimeoutException {
 long timeBound = System.nanoTime() + nanos;
 int[] stampHolder = {EMPTY};
 while (true) {
  if (System.nanoTime() > timeBound)
    throw new TimeoutException();
  T herItem = slot.get(stampHolder);
  int stamp = stampHolder[0];
  switch(stamp) {
   case EMPTY: …    // slot is free
   case WAITING: … // someone waiting for me
   case BUSY: …    // others exchanging
  }
 }
```

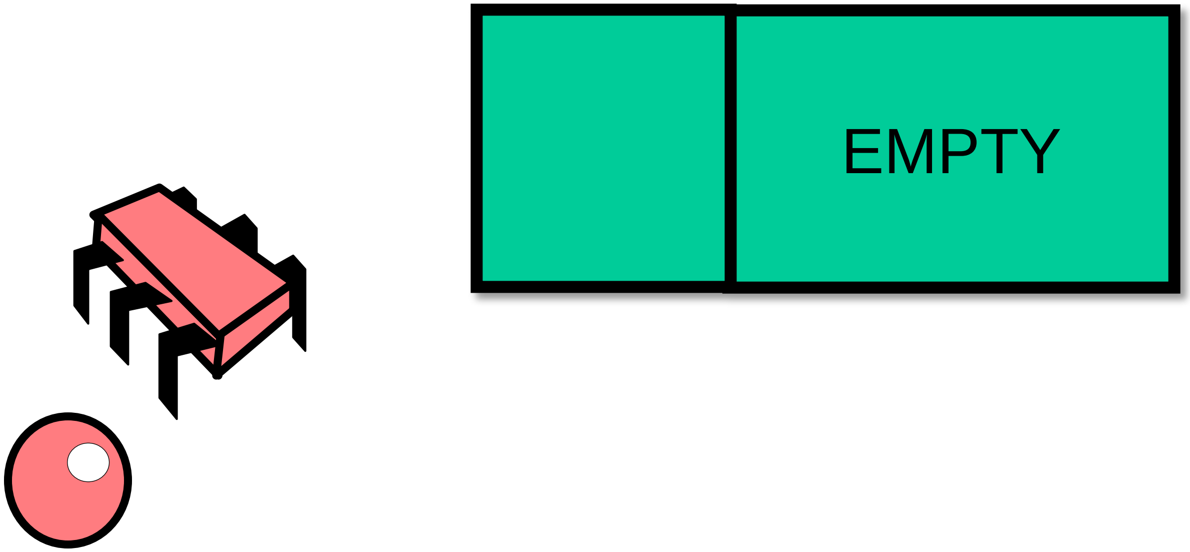
Get other’s item and status

The Exchange

```
public T Exchange(T myItem, long nanos)
   throws TimeoutException {
 long timeBound = System.nanoTime() + nanos;
 while (true) {
  if (System.nanoTime() > timeBound)
    throw new TimeoutException();
  T herItem = slot.get(stampHolder);
  int stamp = stampHolder[0];
  switch(stamp) {
   case EMPTY: …    // slot is free
   case WAITING: … // someone waiting for me
   case BUSY: …    // others exchanging
  }
 }
```

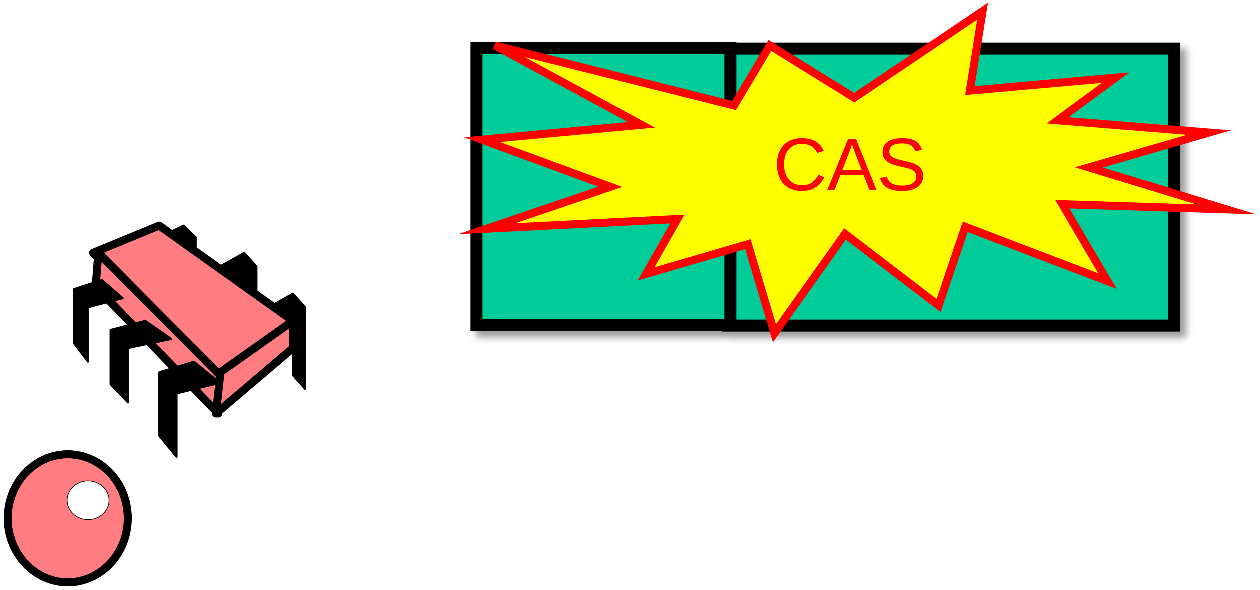
An *Exchanger* has three possible states

Lock-free Exchanger

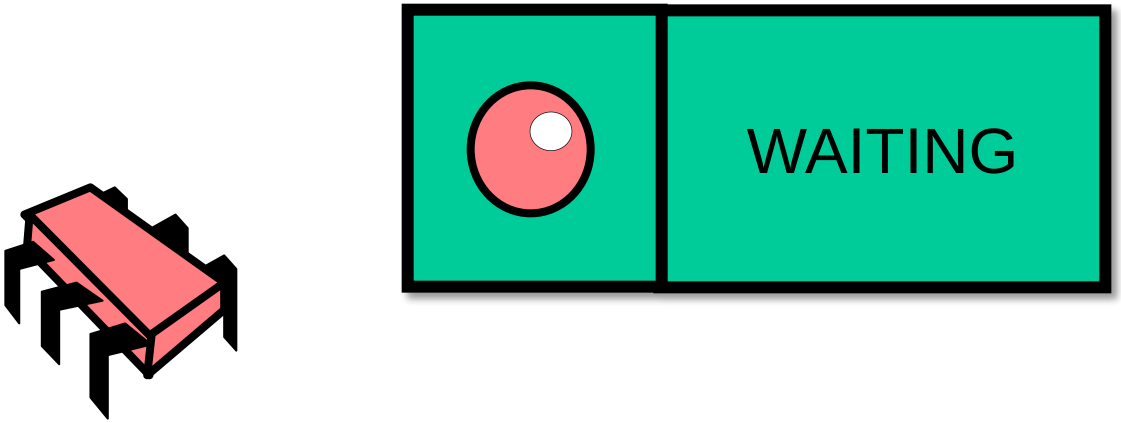


EMPTY

Lock-free Exchanger

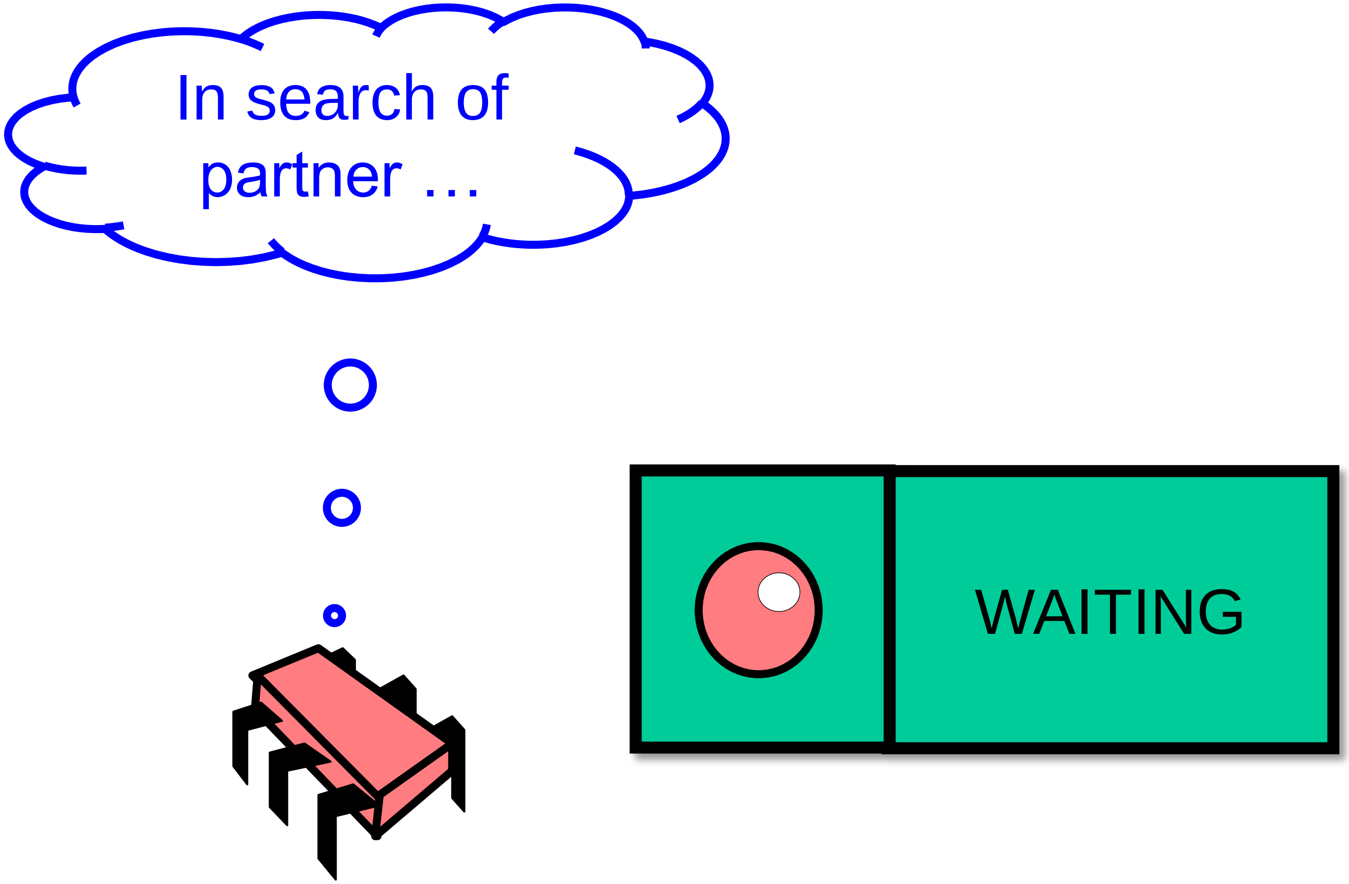


Lock-free Exchanger



WAITING

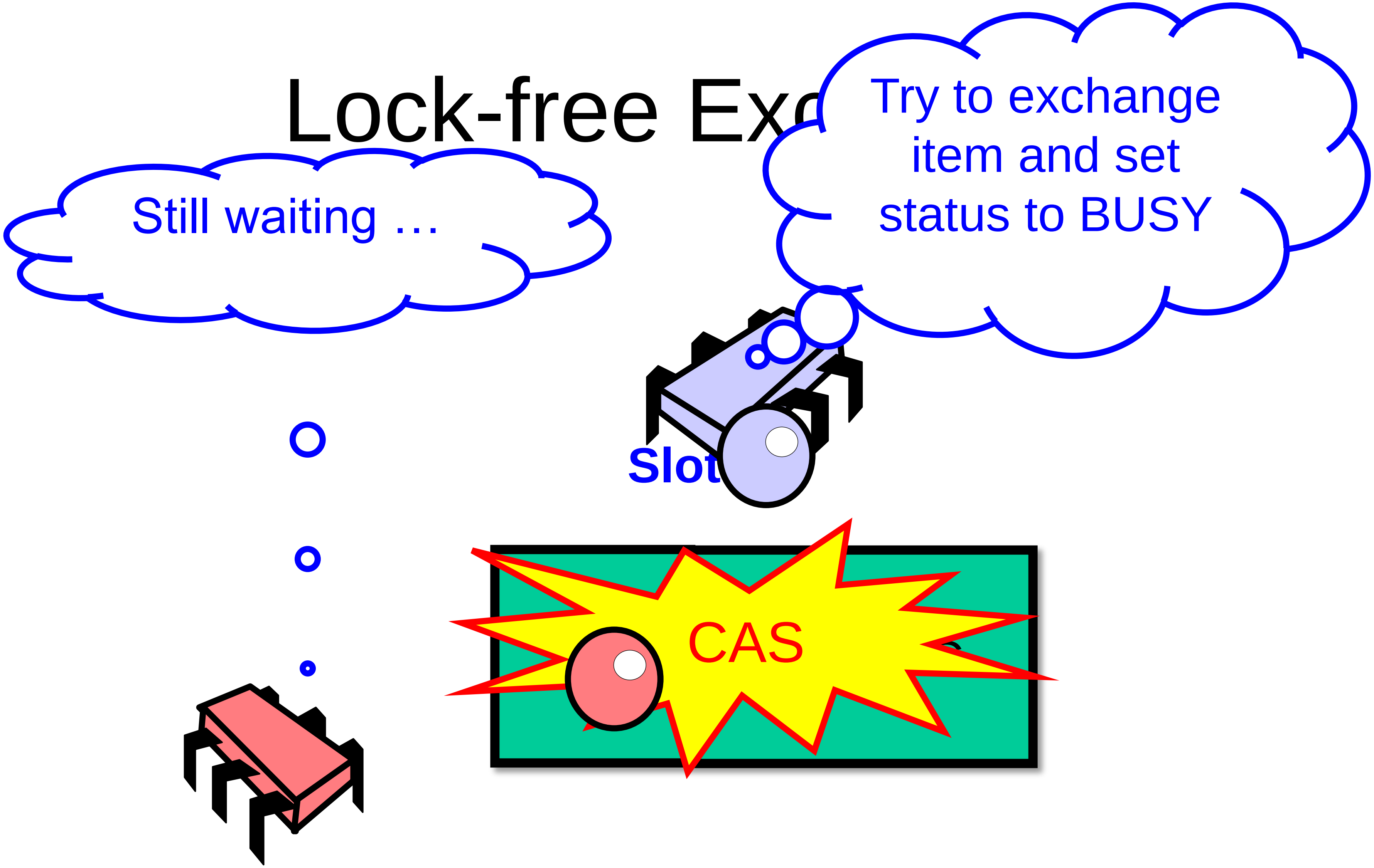
Lock-free Exchanger



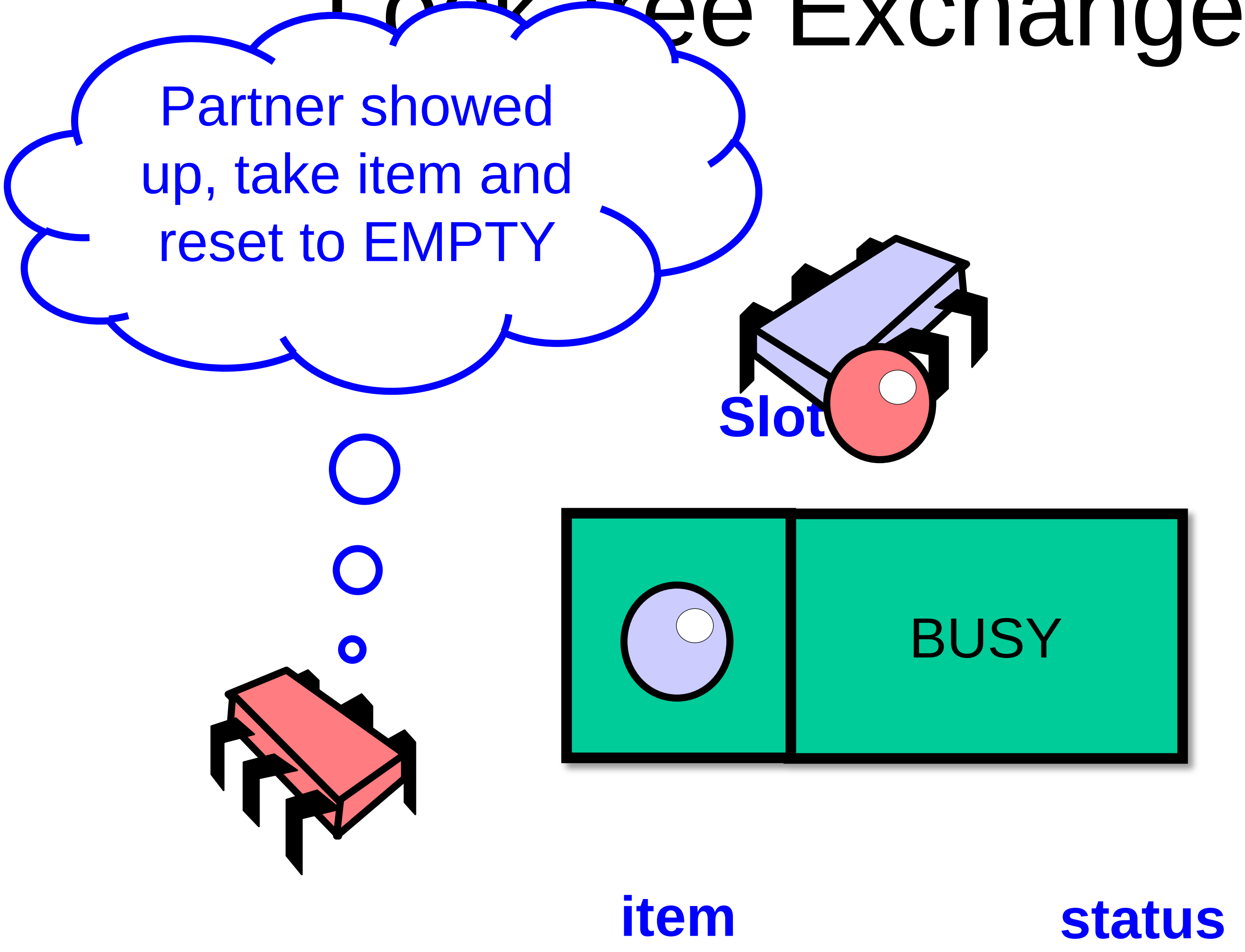
In search of partner …

WAITING

Lock-free Exc

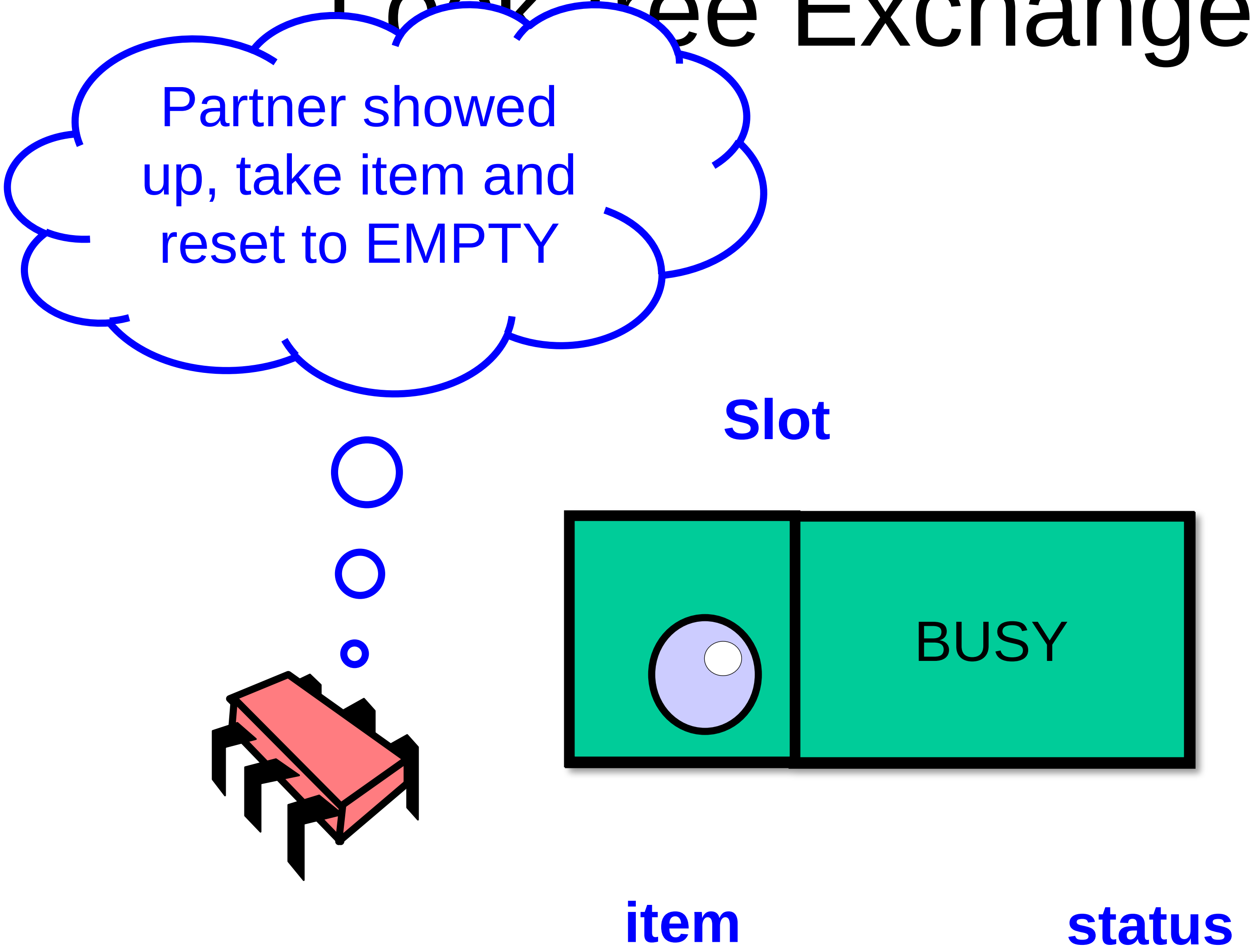


Lock-free Exchanger



Partner showed up, take item and reset to EMPTY

Lock-free Exchanger



Partner showed up, take item and reset to EMPTY

Slot

BUSY

item

status

Exchanger State EMPTY

```
case EMPTY: // slot is free
  if (slot.CAS(herItem, myItem, EMPTY, WAITING)) {
   while (System.nanoTime() < timeBound){
     herItem = slot.get(stampHolder);
     if (stampHolder[0] == BUSY) {
       slot.set(null, EMPTY);
       return herItem;
     }}
   if (slot.CAS(myItem, null, WAITING, EMPTY)){
      throw new TimeoutException();
   } else {
     herItem = slot.get(stampHolder);
     slot.set(null, EMPTY);
     return herItem;
   }
} break;
```

Exchanger State EMPTY

```
case EMPTY: // slot is free
  if (slot.CAS(herItem, myItem, EMPTY, WAITING)) {
   while (System.nanoTime() < timeBound){
     herItem = slot.get(stampHolder);
     if (stampHolder[0] == BUSY) {
       slot.set(null, EMPTY);
       return herItem;
     }}
   if (slot.CAS(myItem, null, WAITING, EMPTY)){
      throw new TimeoutException();
   } else {
     herItem = slot.get(stampHolder);
     slot.set(null, EMPTY);
     return herItem;
   }
} break;
```

Try to insert *myItem* and change state to *WAITING*

Exchanger State EMPTY

```
case EMPTY: // slot is free
  if (slot.CAS(herItem, myItem, EMPTY, WAITING)) {
   while (System.nanoTime() < timeBound){
     herItem = slot.get(stampHolder);
     if (stampHolder[0] == BUSY) {
       slot.set(null, EMPTY);
       return herItem;
     }}
   if (slot.CAS(myItem, null, WAITING, EMPTY)){
      throw new TimeoutException();
   } else {
     herItem = slot.get(stampHolder);
     slot.set(null, EMPTY);
     return herItem;
   }
} break;
```

Spin until either
myItem is taken or timeout

Exchanger State EMPTY

```
case EMPTY: // slot is free
  if (slot.CAS(herItem, myItem, EMPTY, WAITING)) {
   while (System.nanoTime() < timeBound){
     herItem = slot.get(stampHolder);
     if (stampHolder[0] == BUSY) {
       slot.set(null, EMPTY);
       return herItem;
     }}
   if (slot.CAS(myItem, null, WAITING, EMPTY)){
      throw new TimeoutException();
   } else {
     herItem = slot.get(stampHolder);
     slot.set(null, EMPTY);
     return herItem;
   }
} break;
```

myItem was taken,
so return *herItem*
that was put in its place

Exchanger State EMPTY

```
case EMPTY: // slot is free
  if (slot.CAS(herItem, myItem, EMPTY, WAITING)) {
    while (System.nanoTime() < timeBound){
      herItem = slot.get(stampHolder);
      if (stampHolder[0] == BUSY) {
        slot.set(null, EMPTY);
        return herItem;
      }}
    if (slot.CAS(myItem, null, WAITING, EMPTY)){
       throw new TimeoutException();
  } else {
    herItem = slot.get(stampHolder);
    slot.set(null, EMPTY);
    return herItem;
  }
} break;
```

Otherwise we ran out of time, try to reset status to EMPTY and time out

Exchanger State EMPTY

```
case EMPTY: // slot is free
   if (slot.CAS(herItem, myItem, WAITING, BUSY)) {
   while (System.nanoTime() < timeBound){
     herItem = slot.get(stampHolder);
     if
       slot.set(null, EMPTY);
       return herItem;
     }}
   if (slot.CAS(myItem, null, WAITING, EMPTY)){
     throw new TimeoutException();
   } else {
     herItem = slot.get(stampHolder)
     slot.set(null, EMPTY);
     return herItem;
   }
} break;
```

If reset failed,
someone showed up after all,
so take that item

Exchanger State EMPTY

```
case EMPTY: // slot is free
  if (slot.CAS(herItem, myItem, EMPTY, WAITING)) {
   while (System.nanoTime() < timeBound){
     herItem = slot.get(stampHolder);
     if (stampHolder[0] == BUSY) {
       slot.set(null, EMPTY);
       return herItem;
     }}
   if (slot.CAS(myItem, null, WAITING, EMPTY)){
      throw new TimeoutException();
   } else {
     herItem = slot.get(stampHolder);
     slot.set(null, EMPTY);
     return herItem;
   }
} break;
```

Clear slot and take that item

Exchanger State EMPTY

```
case EMPTY: // slot is free
  if (slot.CAS(herItem, myItem, EMPTY, WAITING)) {
   while (System.nanoTime() < timeBound){
     herItem = slot.get(stampHolder);
     if (stampHolder[0] == BUSY) {
       slot.set(null, EMPTY);
       return herItem;
     }}
   if (slot.CAS(myItem, null, WAITING, EMPTY)){
     throw new TimeoutException();
   } else {
     herItem = slot.get(stampHolder);
     slot.set(null, EMPTY);
     return herItem;
   }
} break;
```

If initial CAS failed,
then someone else changed status
from EMPTY to WAITING,
so retry from start

States WAITING and BUSY

```
case WAITING:    // someone waiting for me
  if (slot.CAS(herItem, myItem, WAITING, BUSY))
    return herItem;
  break;
case BUSY:       // others in middle of exchanging
  break;
default:         // impossible
  break;
        }
      }
    }
}
```

States WAITING and BUSY

```
case WAITING:    // someone waiting for me
  if (slot.CAS(herItem, myItem, WAITING, BUSY))
    return herItem;
  break;
case BUSY:       // others in middle of exchanging
  break;
default:         // impossible
  break;
      }
    }
  }
}
```

someone is waiting to exchange,
so try to CAS my item in
and change state to BUSY

States WAITING and BUSY

```
case WAITING:   // someone waiting for me
  if (slot.CAS(herItem, myItem, WAITING, BUSY))
    return herItem;
  break;
case BUSY:     // others in middle of exchanging
  break;
default:       // impossible
  break;
      }
    }
  }
}
```

If successful, return other’s item,
otherwise someone else took it,
so try again from start

States WAITING and BUSY

```
case WAITING:    // someone waiting for me
  if (slot.CAS(herItem, myItem, WAITING, BUSY))
    return herItem;
  break;
case BUSY:      // others in middle of exchanging
  break;
default:        // impossible
  break;
      }
    }
  }
}
```

If BUSY,
other threads exchanging,
so start again

The Exchanger Slot

- Exchanger is lock-free
- Because the only way an exchange can fail is if others repeatedly succeeded or no-one showed up
- The slot we need does not require symmetric exchange

Back to the Stack: the Elimination Array

```
public class EliminationArray {
…
public T visit(T value, int range)
  throws TimeoutException {
    int slot = random.nextInt(range);
    int nanodur = convertToNanos(duration, timeUnit));
    return (exchanger[slot].exchange(value, nanodur)
}}
```

Elimination Array

```
public class EliminationArray {
…
public T visit(T value, int range)
  throws TimeoutException {
    int slot = random.nextInt(range);
    int nanodur = convertToNanos(duration, timeUnit));
    return (exchanger[slot].exchange(value, nanodur)
}}
```

visit the elimination array with fixed value and range

Elimination Array

```
public class EliminationArray {
…
public T visit(T value, int range)
  throws TimeoutException {
    int slot = random.nextInt(range);
    int nanodur = convertToNanos(duration, timeUnit));
    return (exchanger[slot].exchange(value, nanodur)
}}
```

Pick a random array entry

Elimination Array

```
public class EliminationArray {
…
public T visit(T v
   throws TimeoutException {
     int slot = random.nextInt(range);
     int nanodur = convertToNanos(duration, timeUnit));
     return (exchanger[slot].exchange(value, nanodur)
}}
```

Exchange value or time out

Elimination Stack Push

```
public void push(T value) {
...
 while (true) {
  if (tryPush(node)) {
    return;
  } else try {
      T otherValue =
      eliminationArray.visit(value,policy.range);
      if (otherValue == null) {
         return;
    }
}
```

Elimination Stack Push

```
public void push(T value) {
...
 while (true) {
  if (tryPush(node)) {
    return;
  } else try {
      T otherValue =
      eliminationArray.visit(value,policy.range);
      if (otherValue == null) {
         return;
    }
}
```

First, try to push

Elimination Stack Push

```
public void push(T value) {
...
 while (true) {
  if (tryPush(node)) {
    return;
  } else try {
      T otherValue =
      eliminationArray.visit(value,policy.range);
      if (otherValue == null) {
         return;
      }
}
```

If I failed, backoff & try to eliminate

Elimination Stack Push

```
public void push(T value) {
...
 while (true) {
  if (tryPush(node)) {
    return;
  } else try {
      T otherValue =
      eliminationArray.visit(value,policy.range);
      if (otherValue == null) {
         return;
      }
}
```

Value pushed and range to try

Elimination Stack Push

```
public void push(T value) {
...
 while (true) {
  if (tryPush(node)) {
    return;
  } else try {
      T otherValue =
      eliminationArray.visit(value,policy.range);
      if (otherValue == null) {
         return;
    }
}
```

Only pop() leaves null,
so elimination was successful

Elimination Stack Push

```
public void push(T value) {
...
 while (true) {
  if (tryPush(node)) {
    return;
  } else try {
      T otherValue =
      eliminationArray.visit(value,policy.range);
      if (otherValue == null) {
         return;
    }
}
```

Otherwise, retry push() on lock-free stack

Elimination Stack Pop

```
public T pop() {
 ...
 while (true) {
  if (tryPop()) {
   return returnNode.value;
   } else
      try {
        T otherValue =
        eliminationArray.visit(null,policy.range;
        if (otherValue != null) {
         return otherValue;
         }
      }
}}
```

Elimination Stack Pop

```
public T pop() {
 ...
 while (true) {
  if (tryPop()) {
   return returnNode.value;
  } else
     try {
       T otherValue =
       eliminationArray.visit(null,policy.range;
       if ( otherValue != null) {
        return otherValue;
       }
     }
}}
```

If value not null, other thread is a push(), so elimination succeeded

Summary

- We saw both lock-based and lock-free implementations of
- queues and stacks
- Don’t be quick to declare a data structure inherently sequential
  - Linearizable stack is not inherently sequential (though it is in worst case)
- ABA is a real problem, pay attention

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