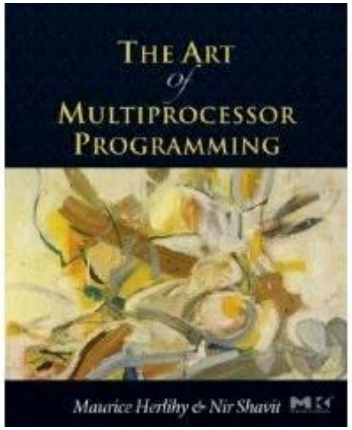
Concurrent Queues and Stacks



Companion slides for

The Art of Multiprocessor Programming

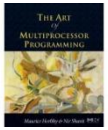
by Maurice Herlihy & Nir Shavit

The Five-Fold Path

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

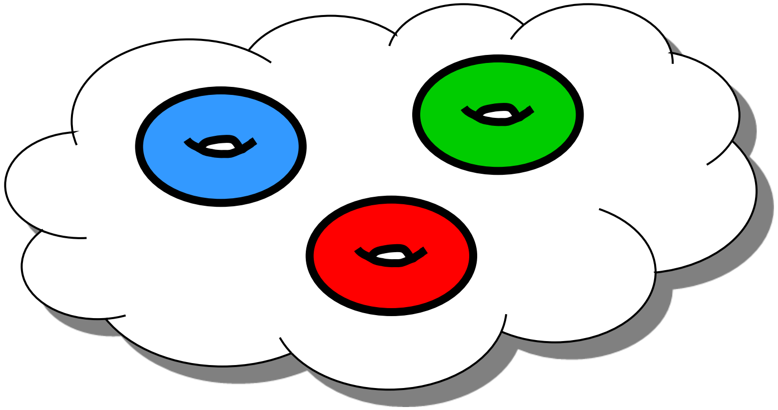
Another Fundamental Problem

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

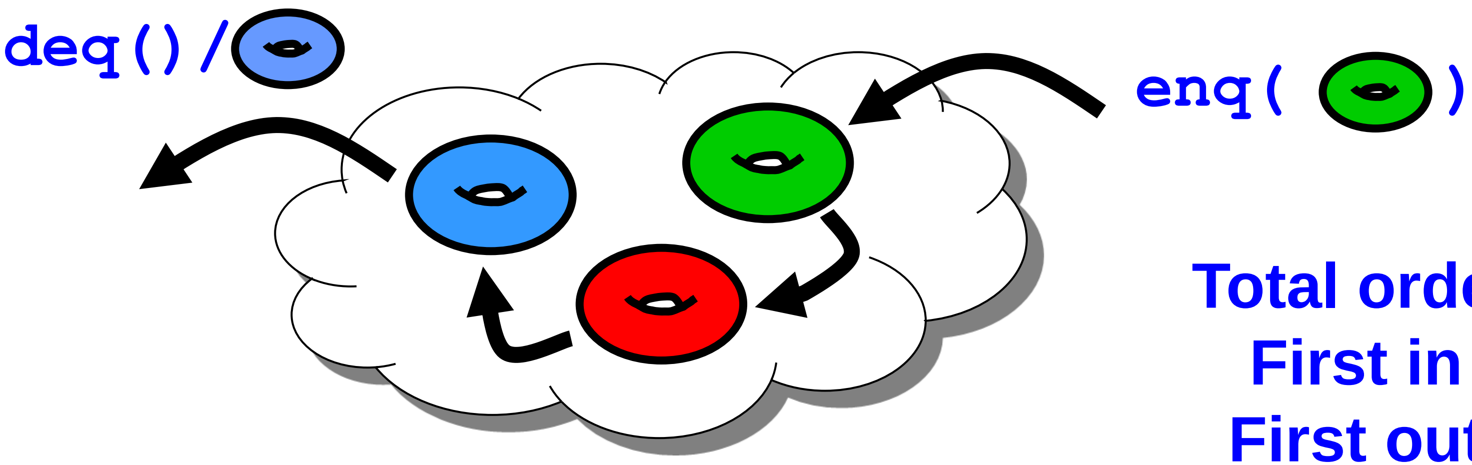


Queues & Stacks

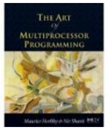
- pool of items



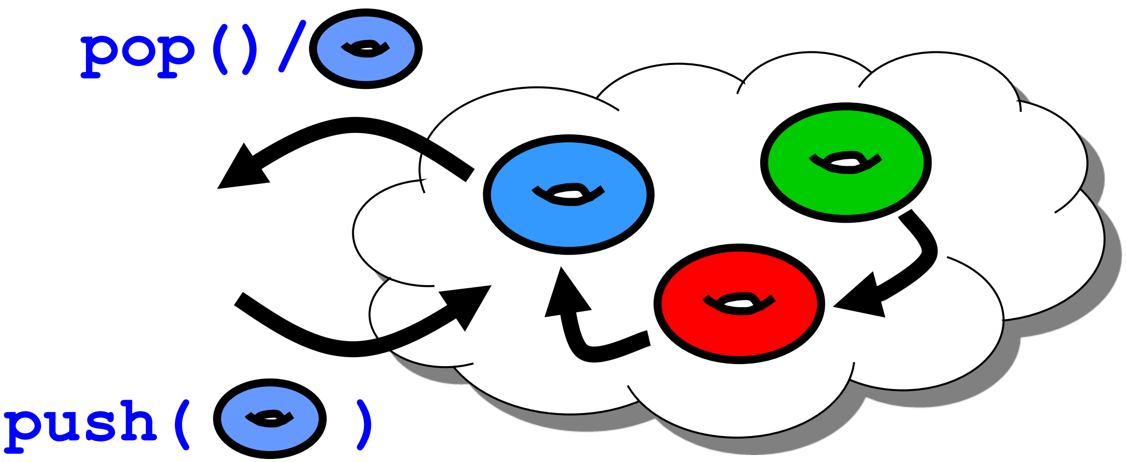
Queues



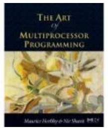
Total order
First in
First out



Stacks

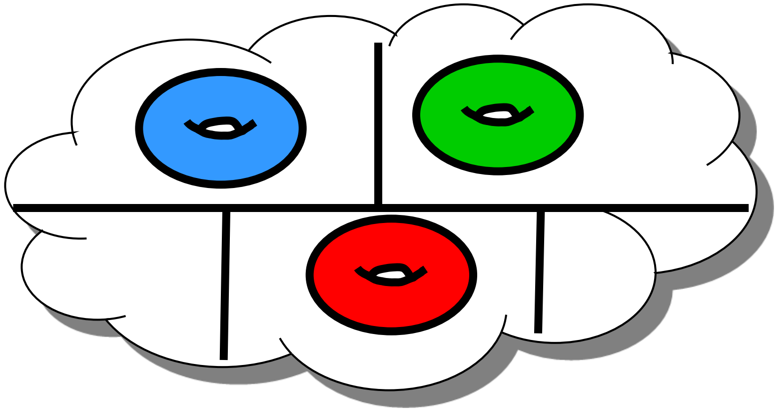


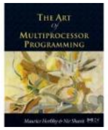
Total order
Last in
First out



Bounded

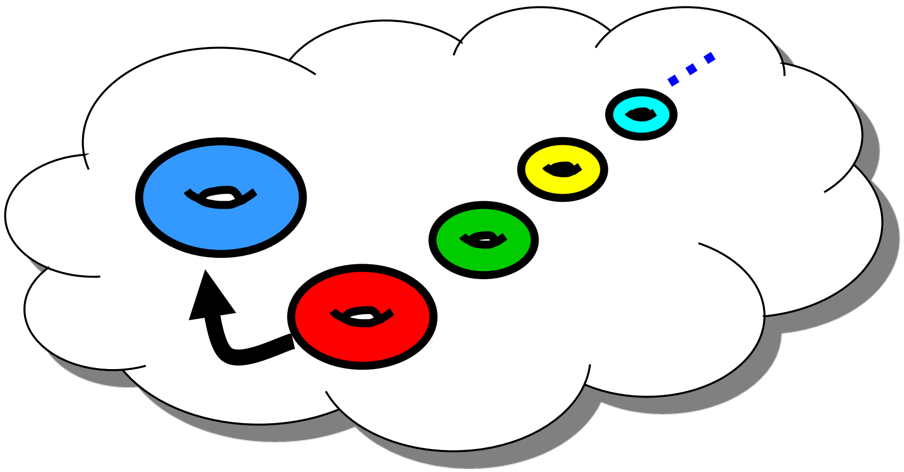
- Fixed capacity
- Good when resources an issue



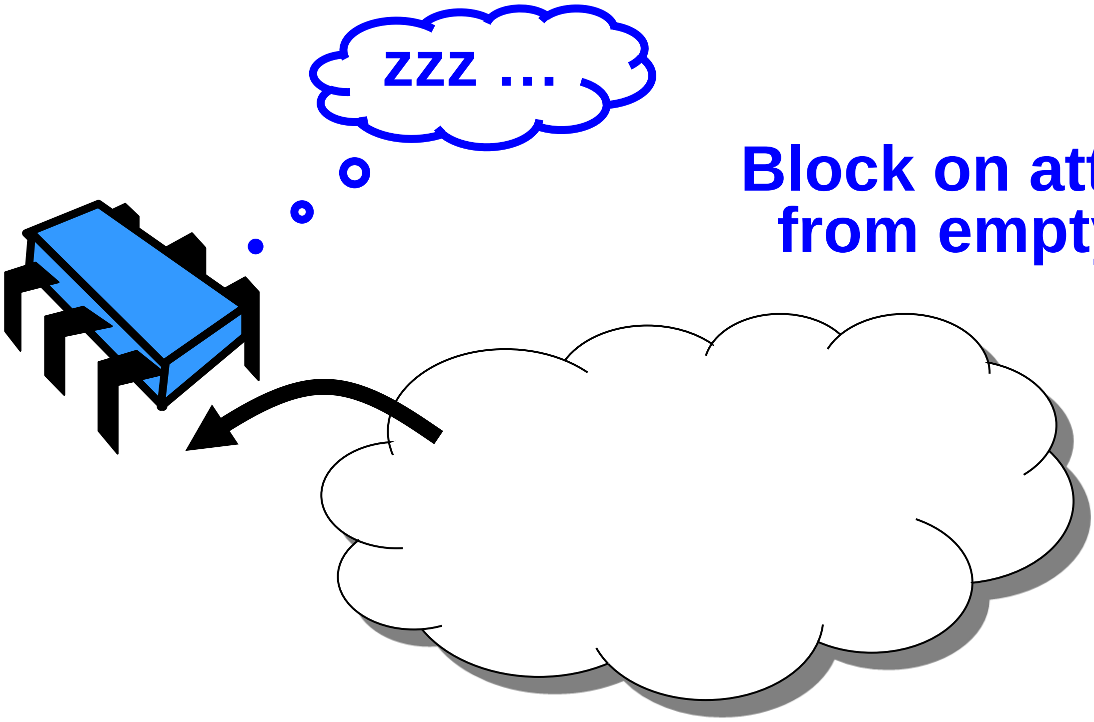


Unbounded

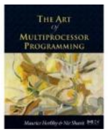
- Unlimited capacity
- Often more convenient



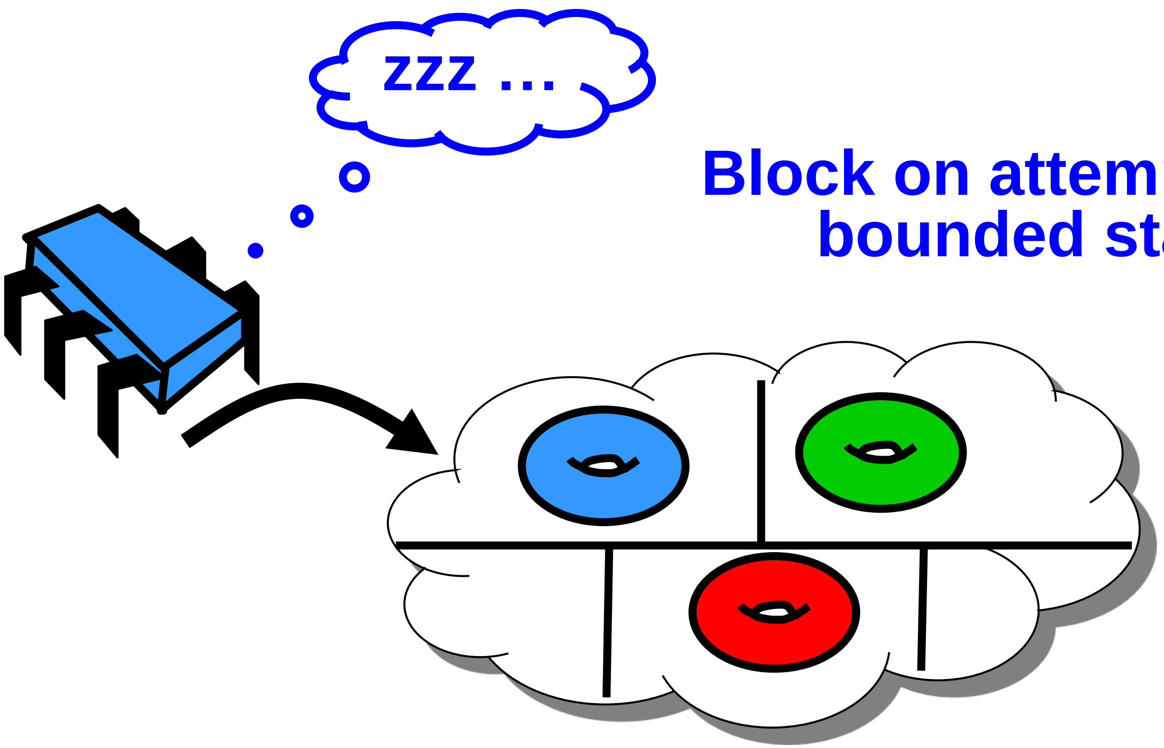
Blocking



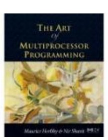
Block on attempt to remove from empty stack or queue



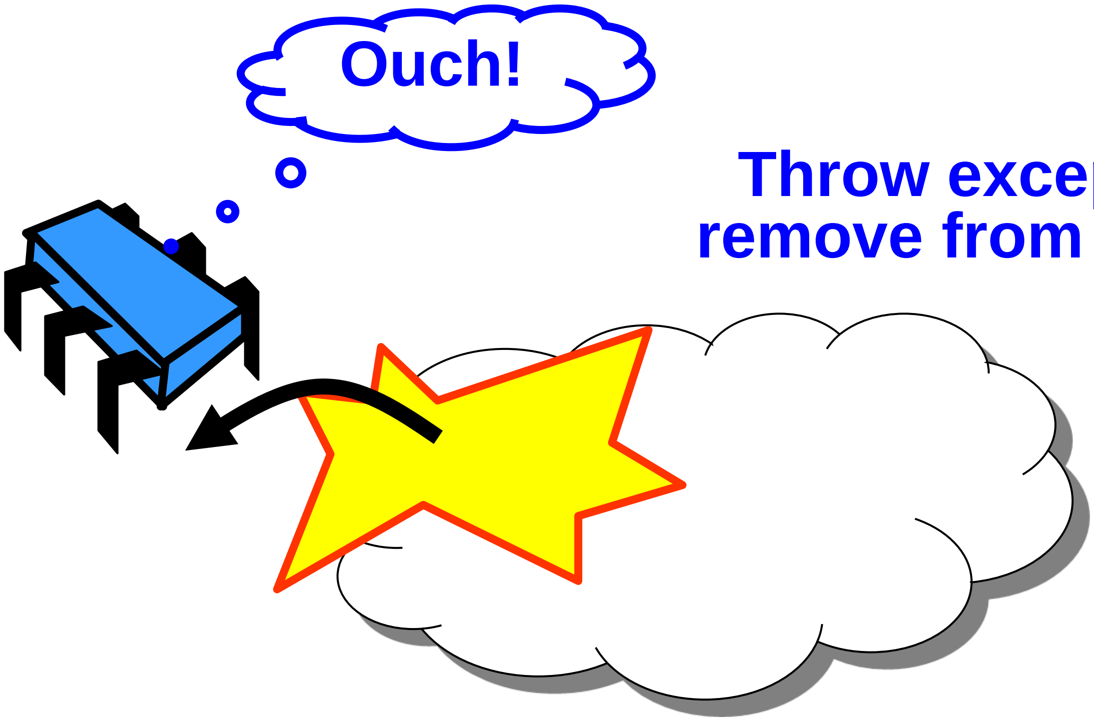
Blocking



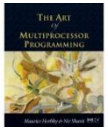
Block on attempt to add to full bounded stack or queue



Non-Blocking



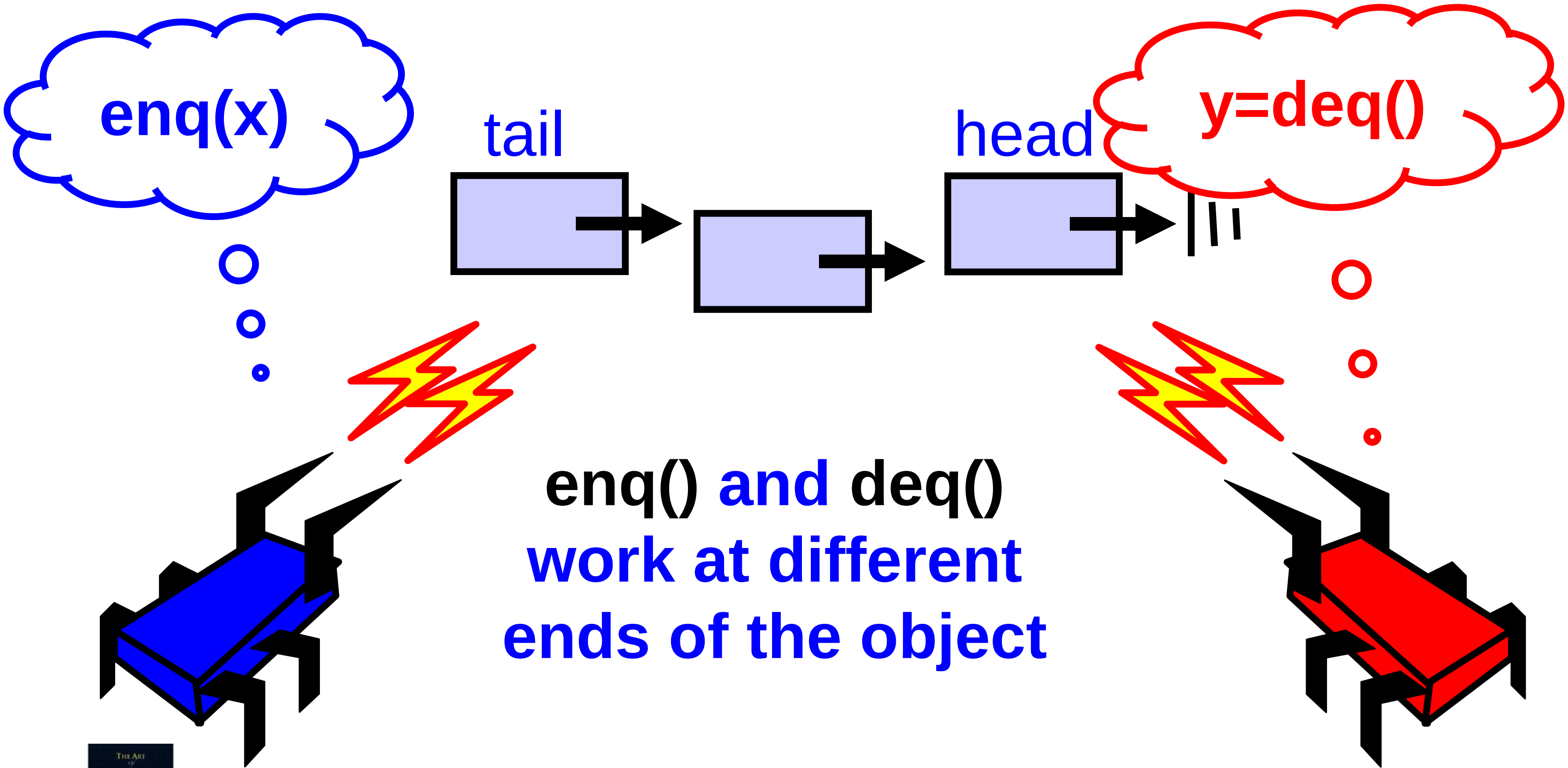
Throw exception on attempt to remove from empty stack or queue

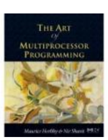


This Lecture

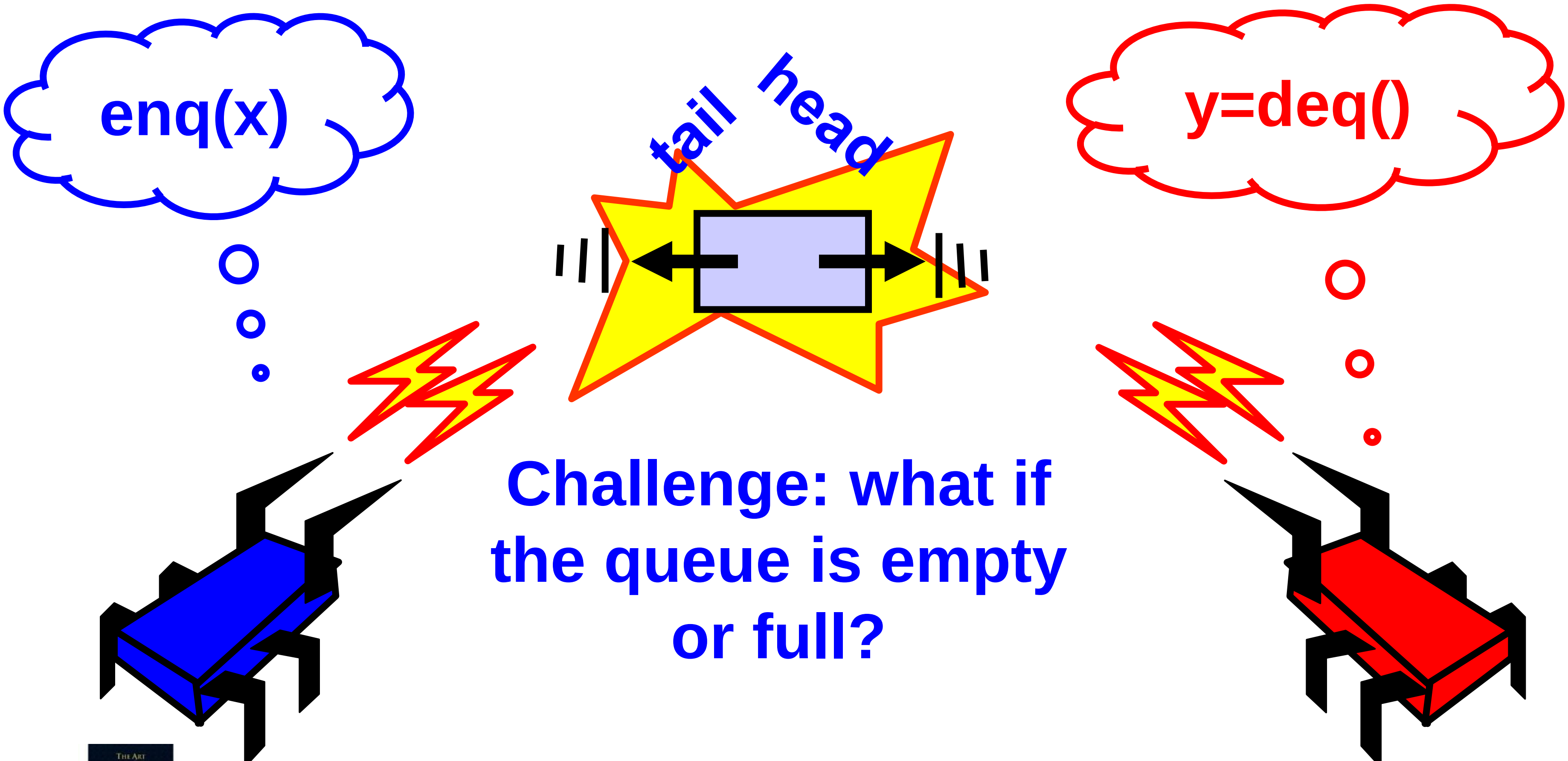
- Queue
  - Bounded, blocking, lock-based
  - Unbounded, non-blocking, lock-free
- Stack
  - Unbounded, non-blocking lock-free
  - Elimination-backoff algorithm

Queue: Concurrency

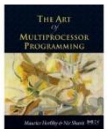




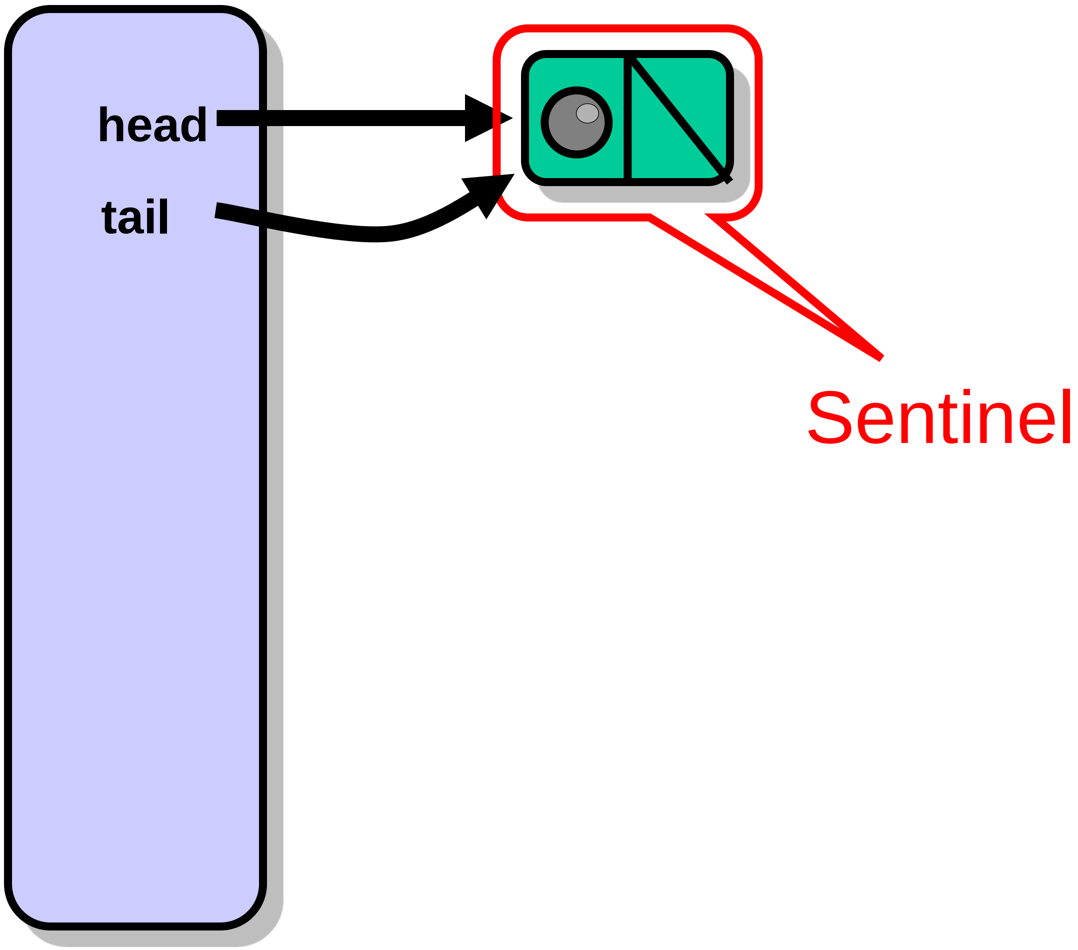
Concurrency

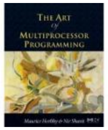


Challenge: what if the queue is empty or full?

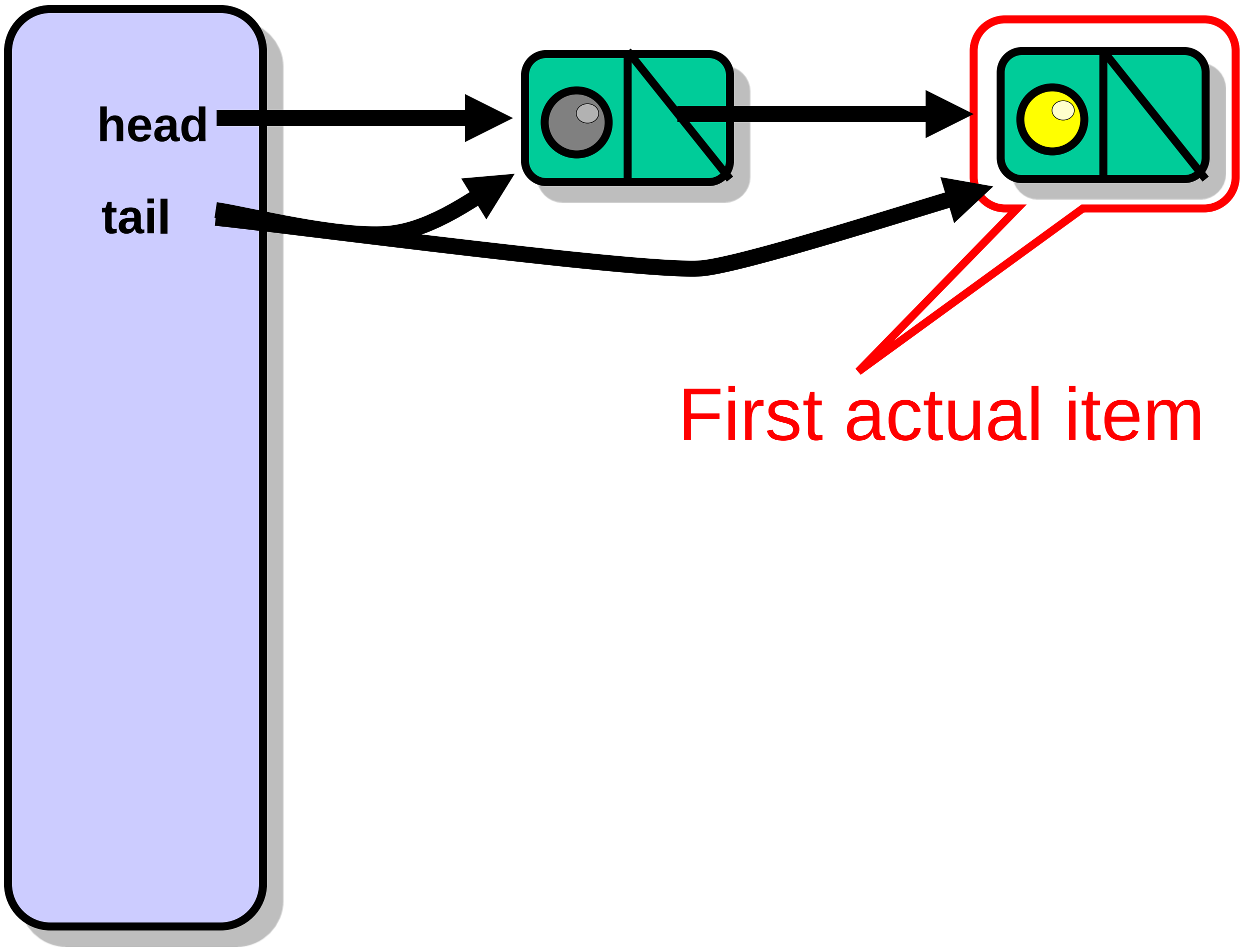


Bounded Queue

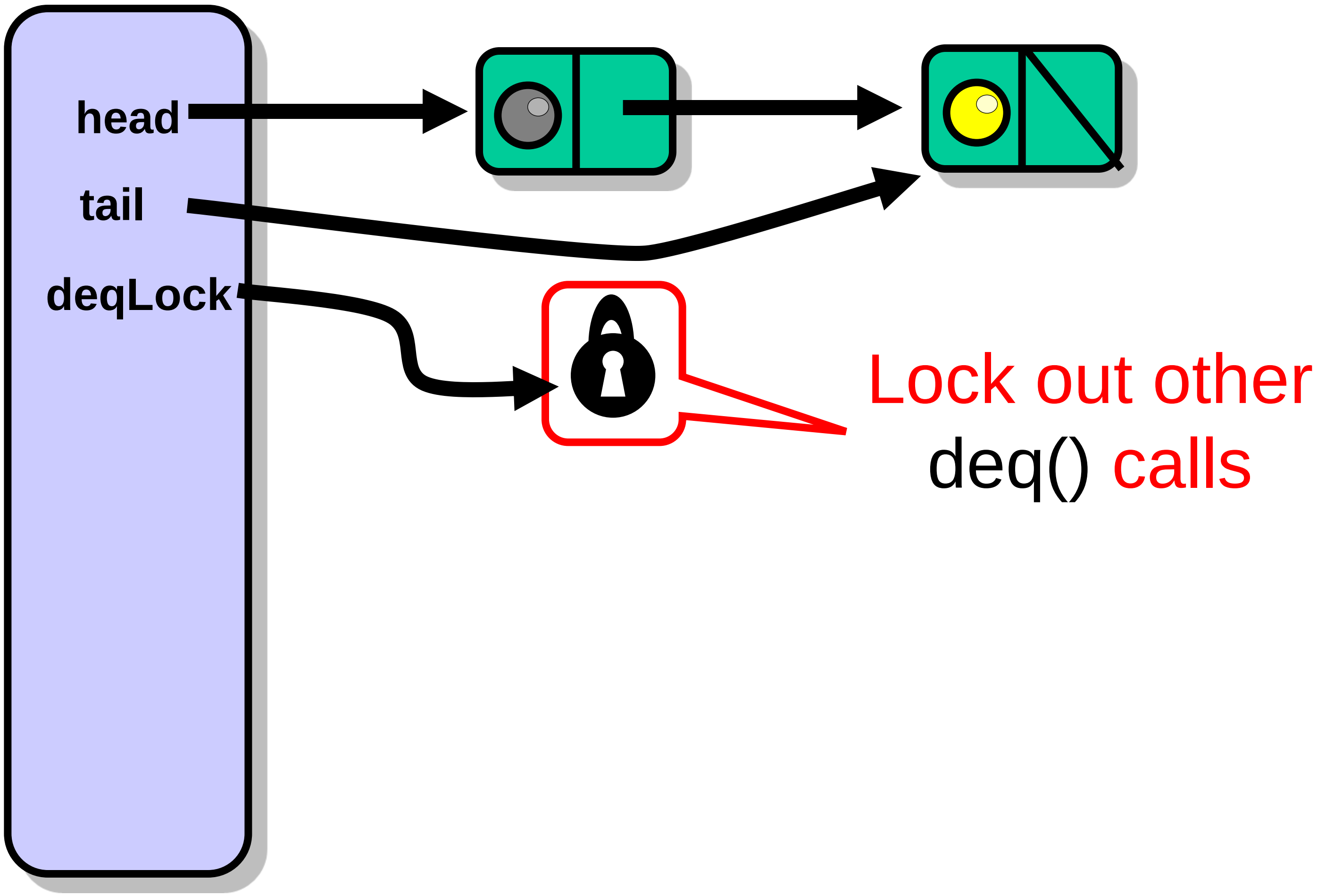


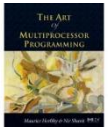


Bounded Queue

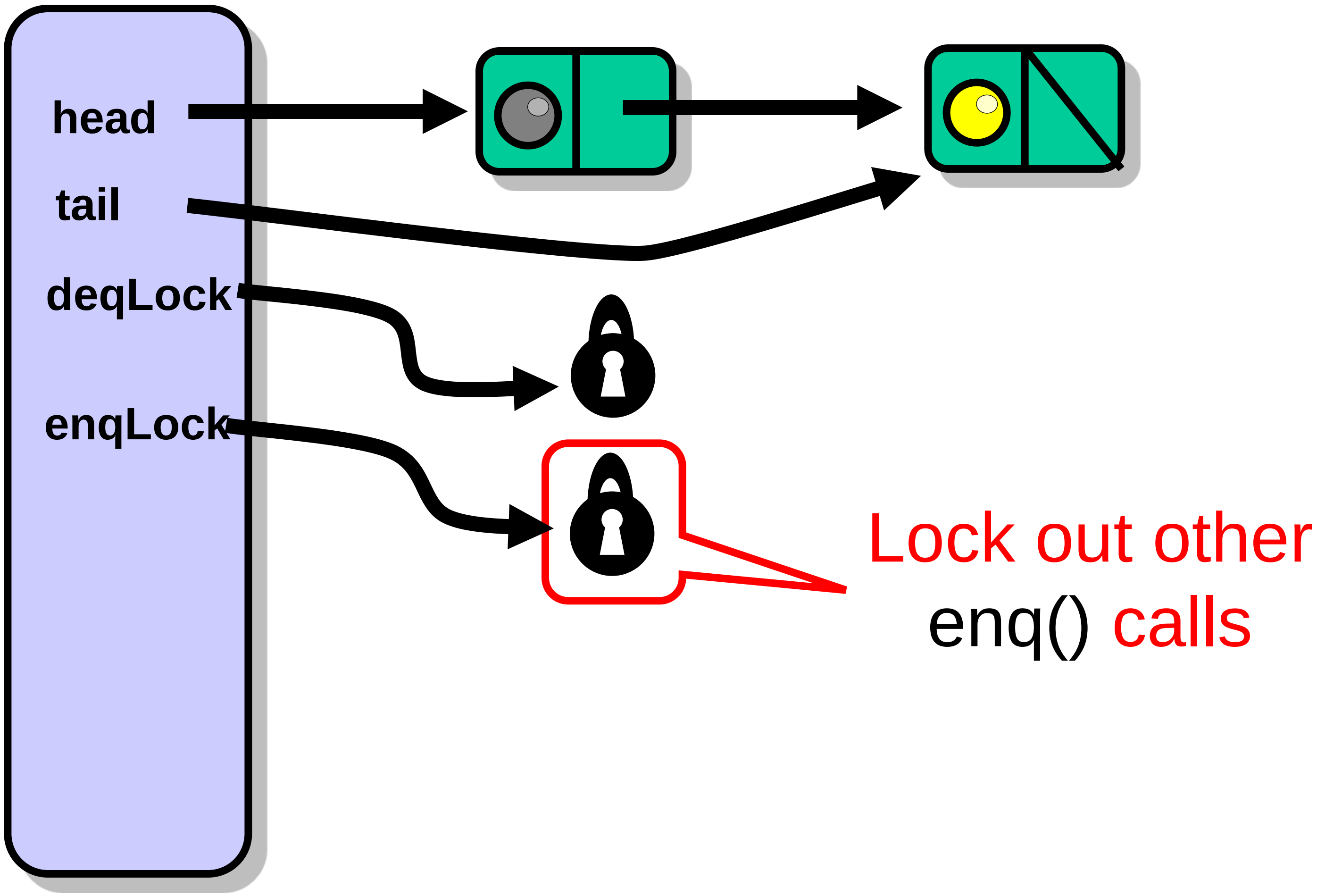


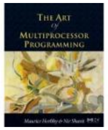
Bounded Queue



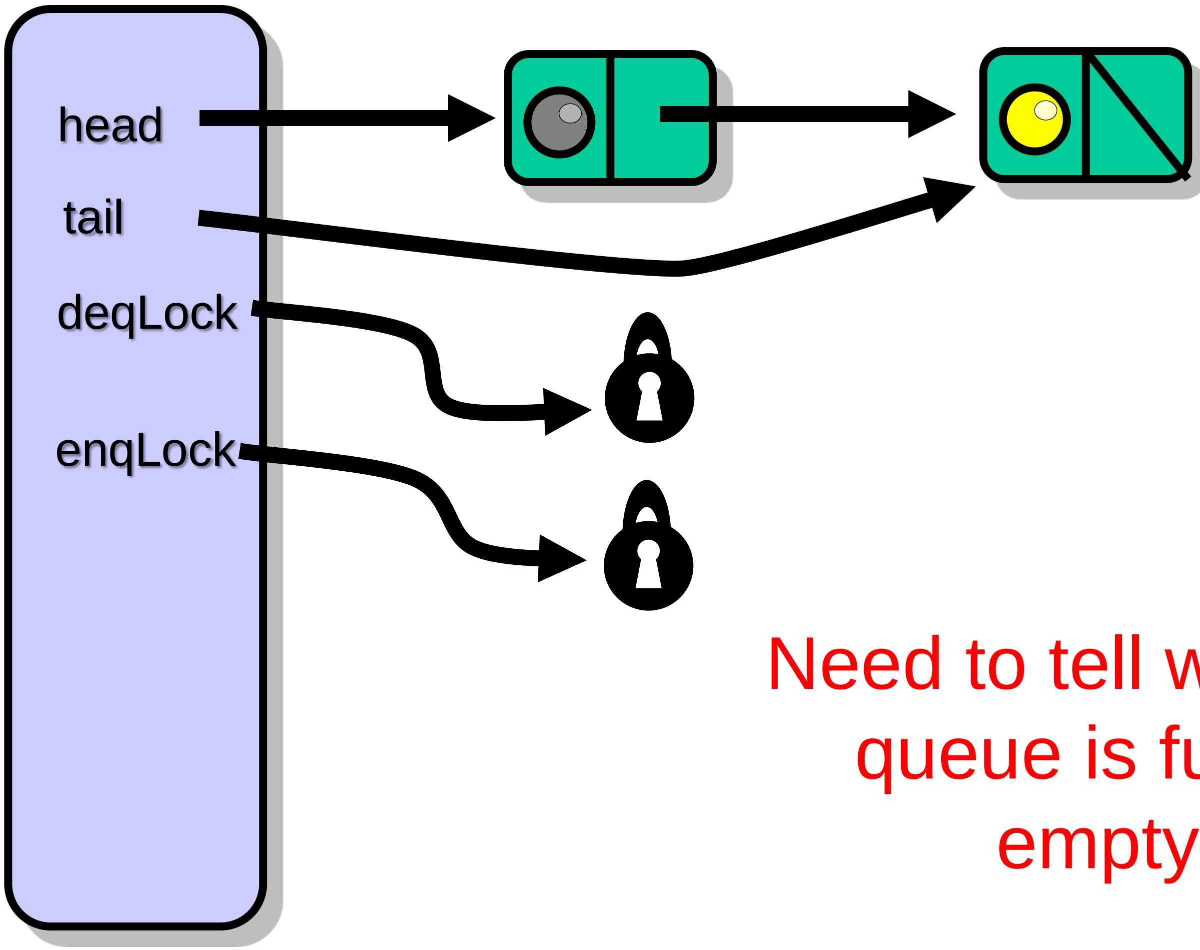


Bounded Queue

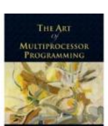




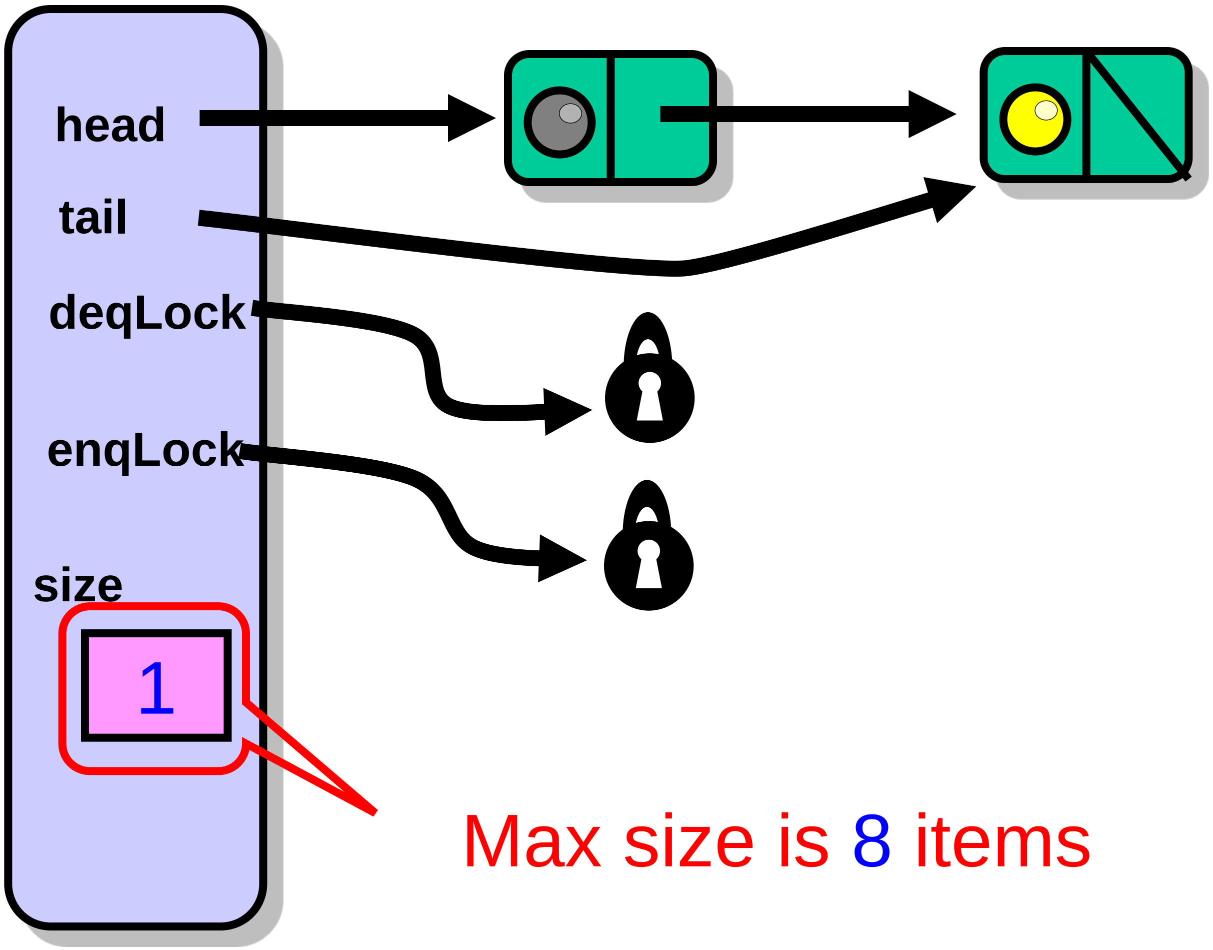
Not Done Yet

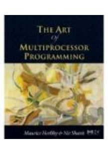


Need to tell whether queue is full or empty

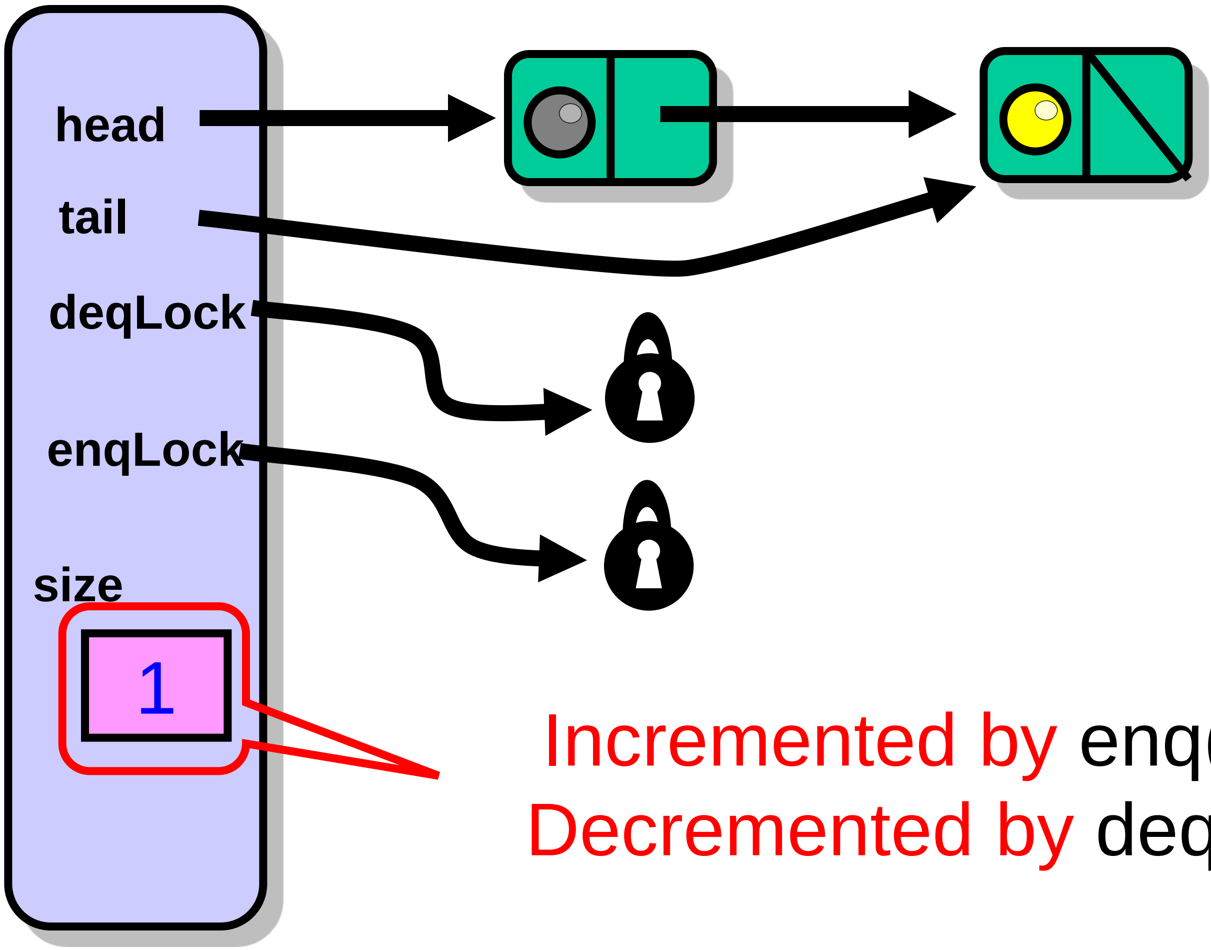


Not Done Yet

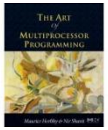




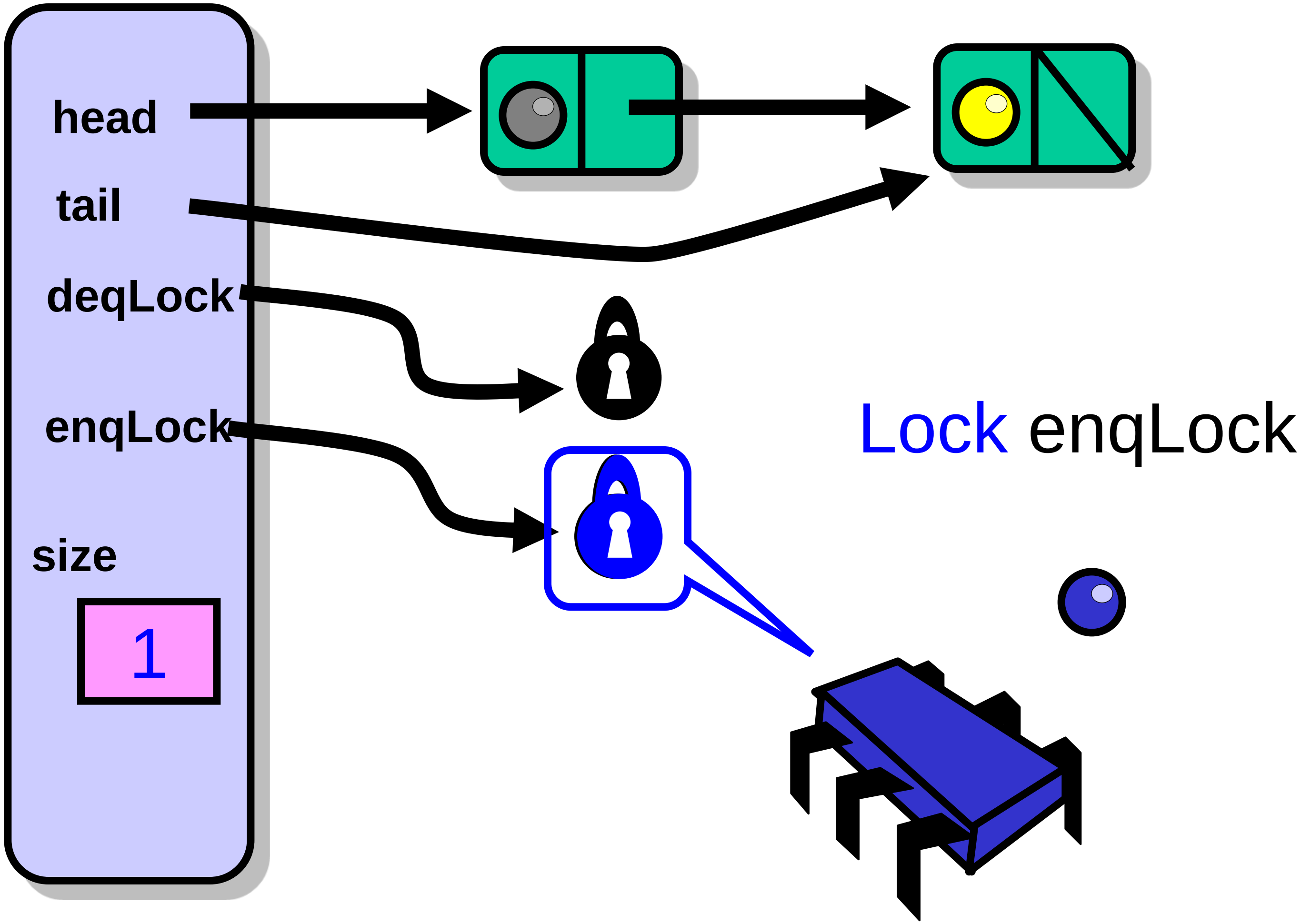
Not Done Yet

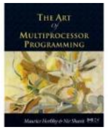


Incremented by enq()
Decremented by deq()

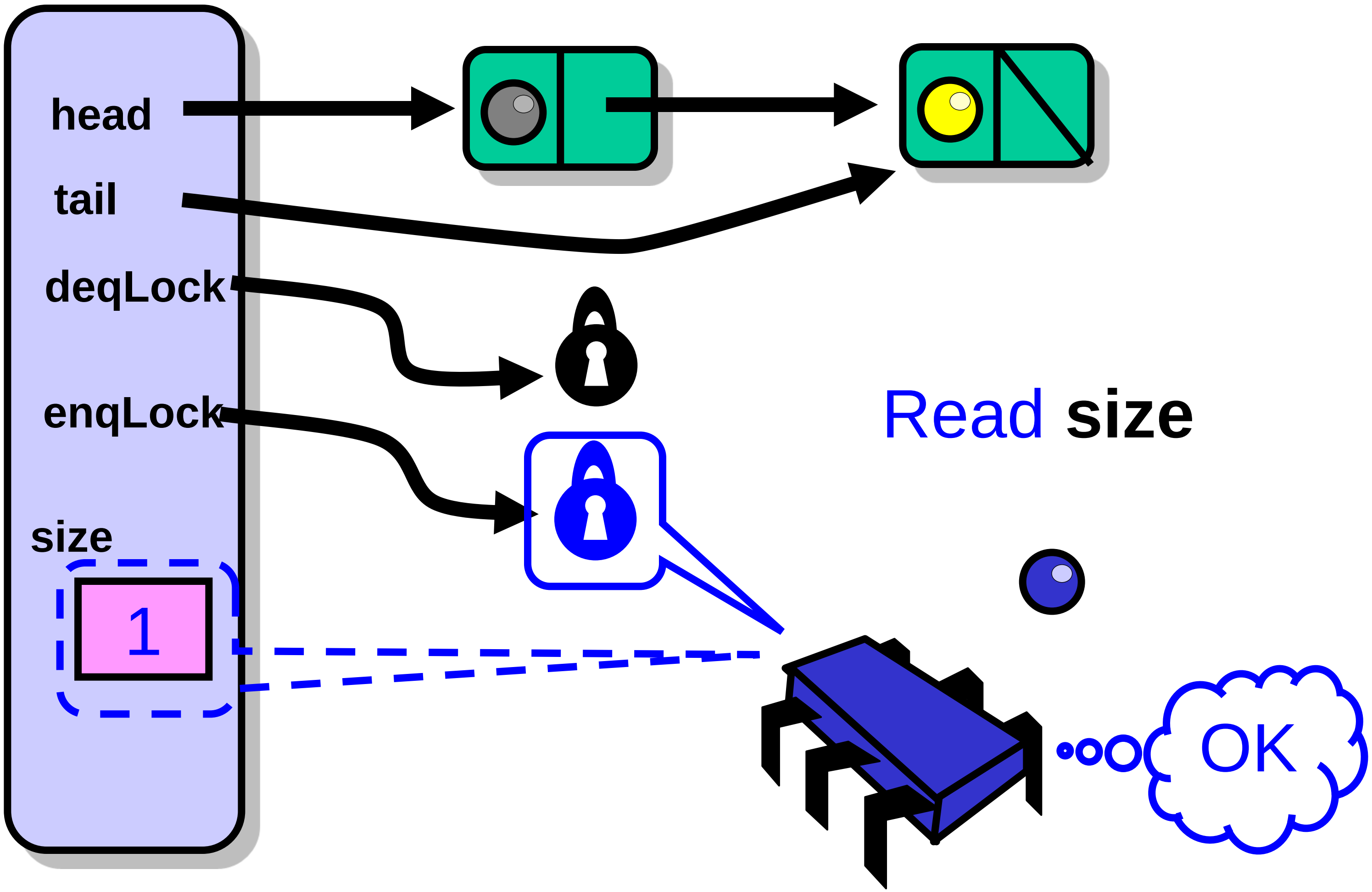


Enqueuer

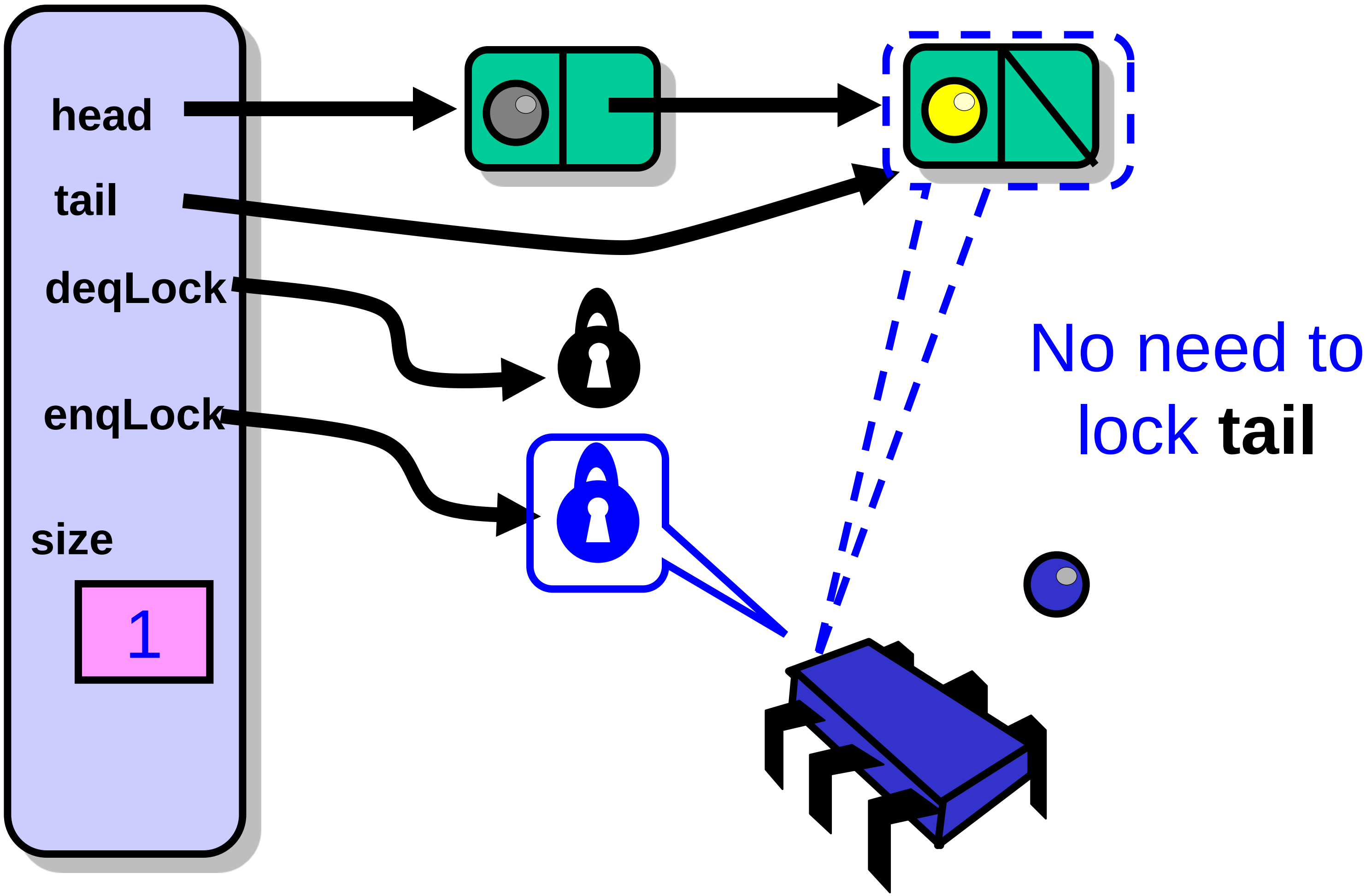


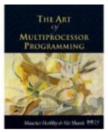


Enqueuer

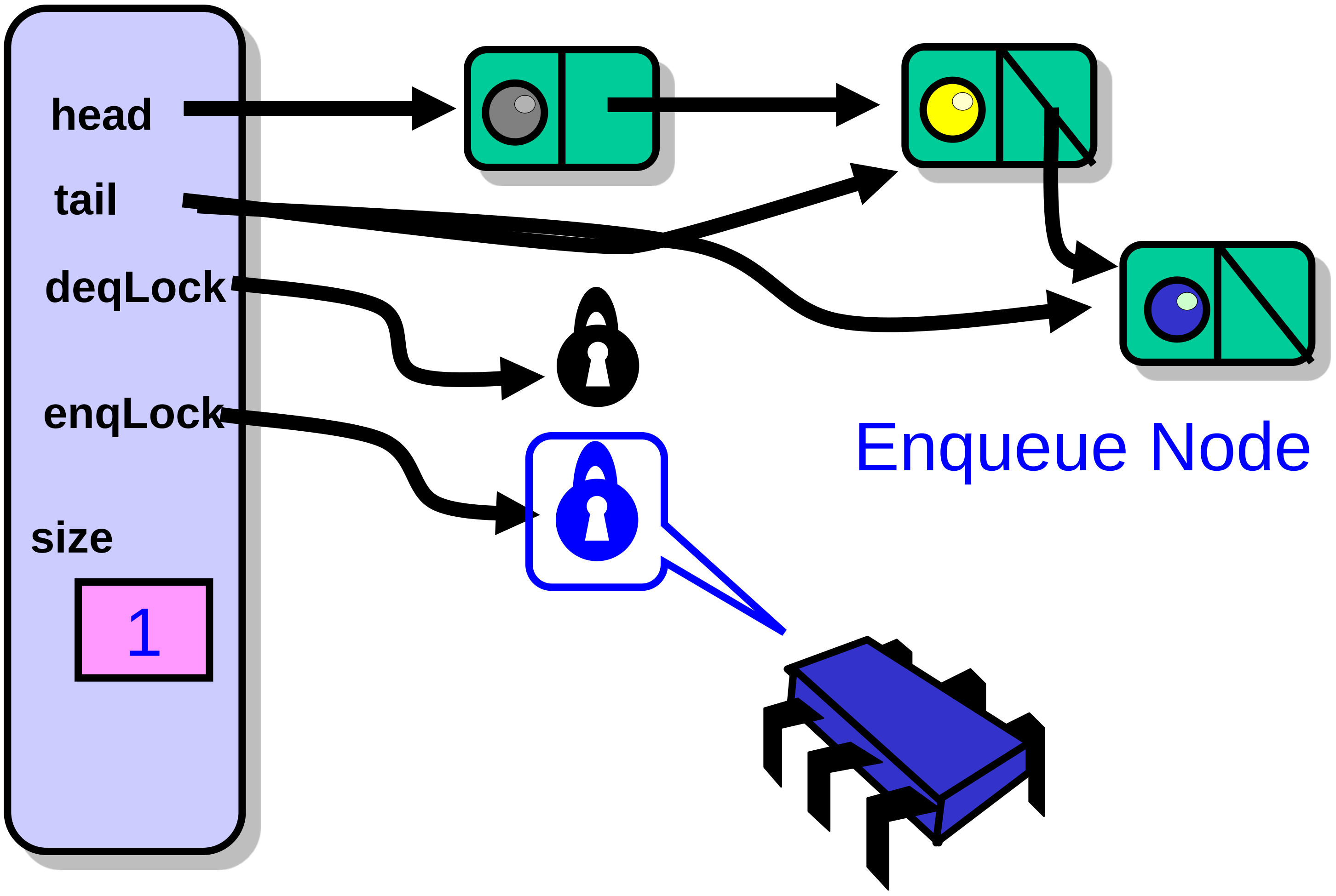


Enqueuer

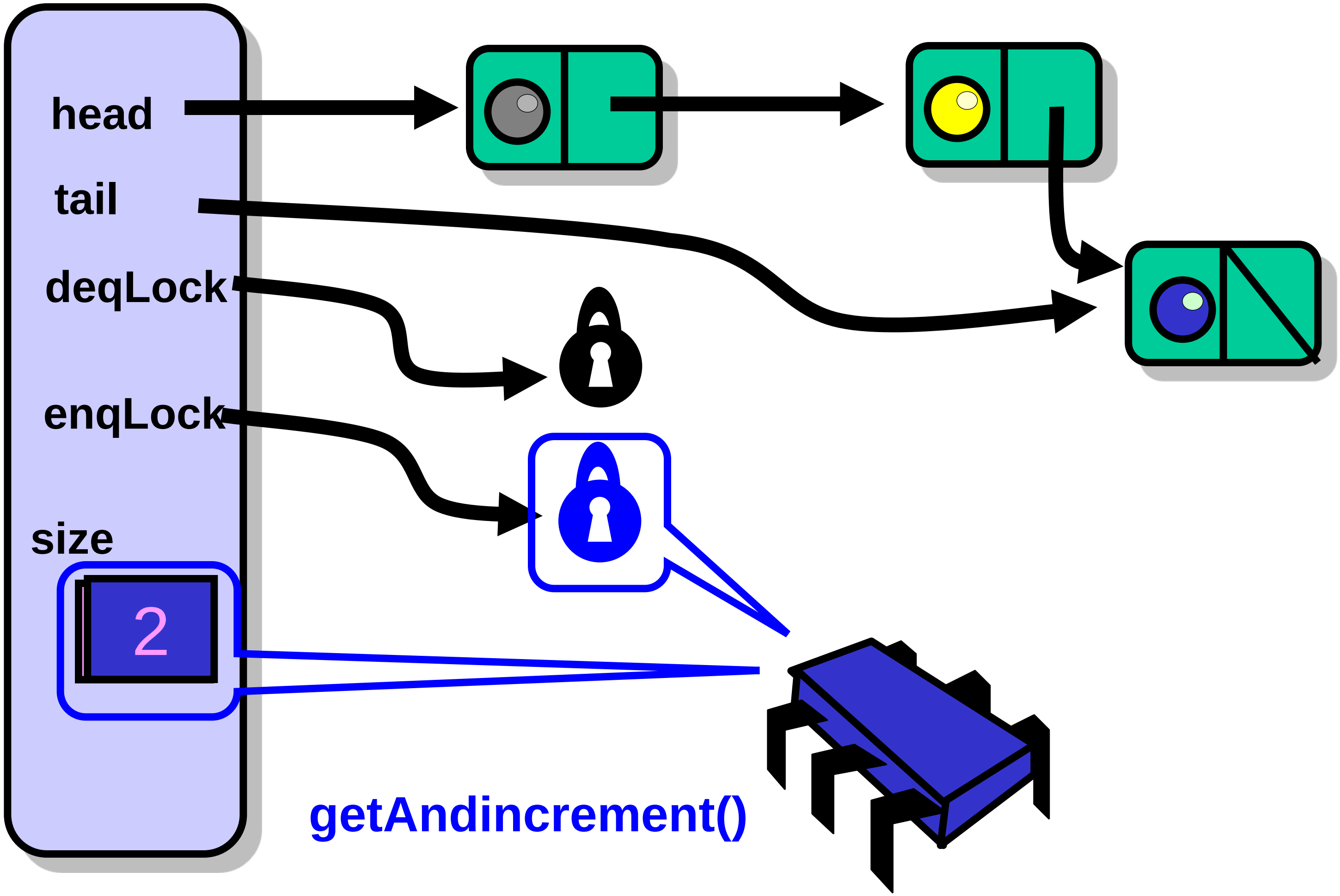




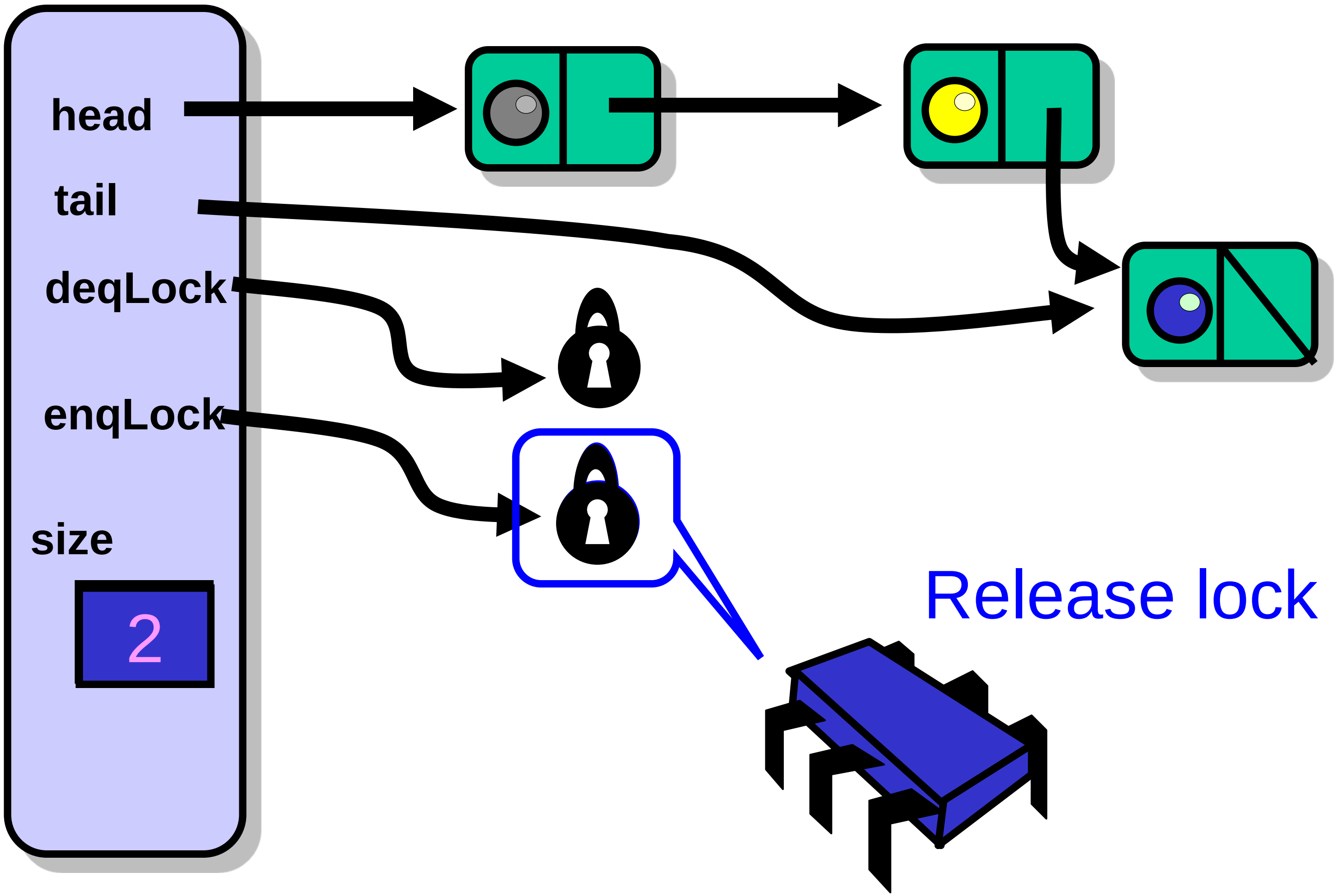
Enqueuer



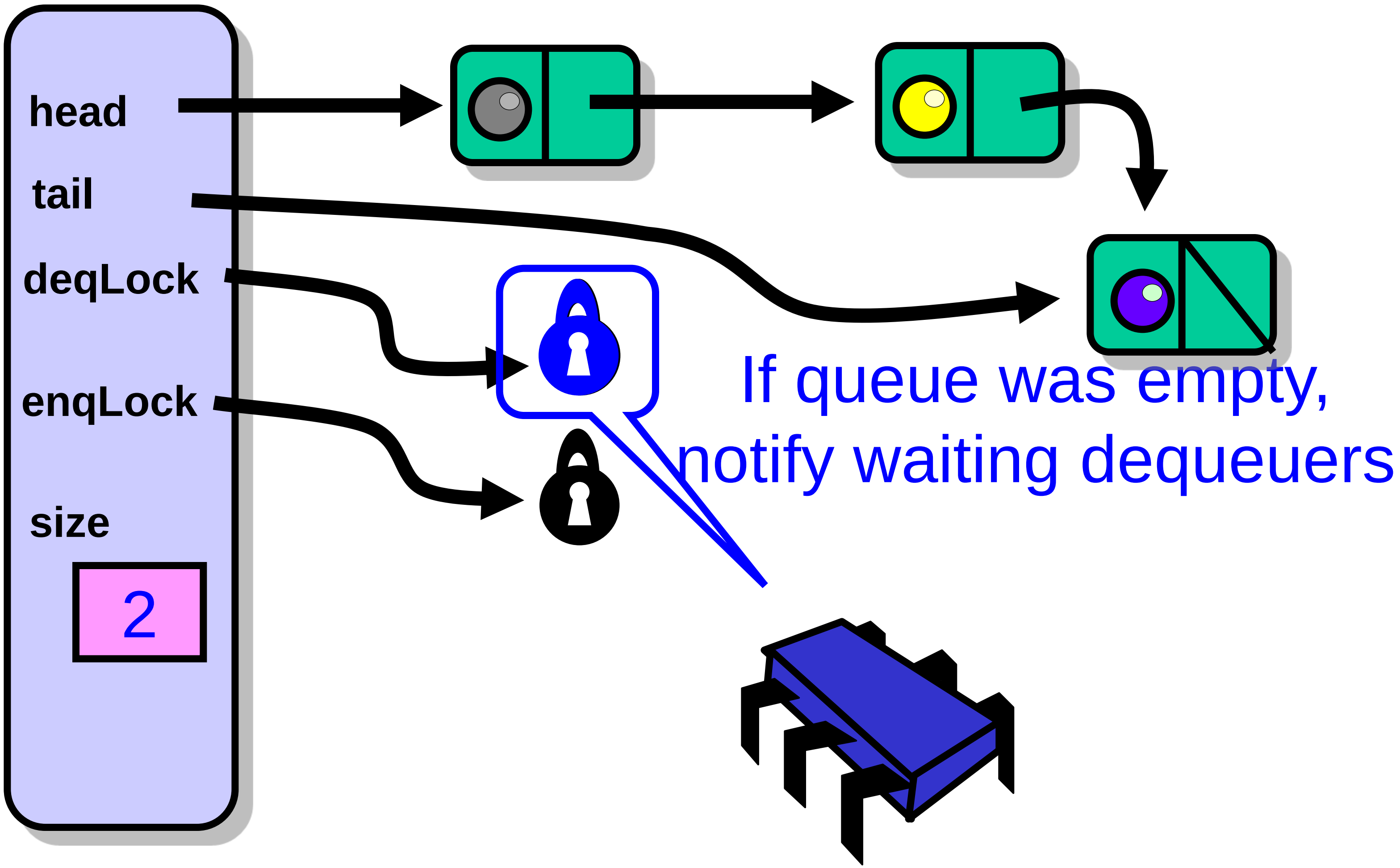
Enqueuer

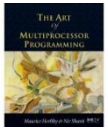


Enqueuer

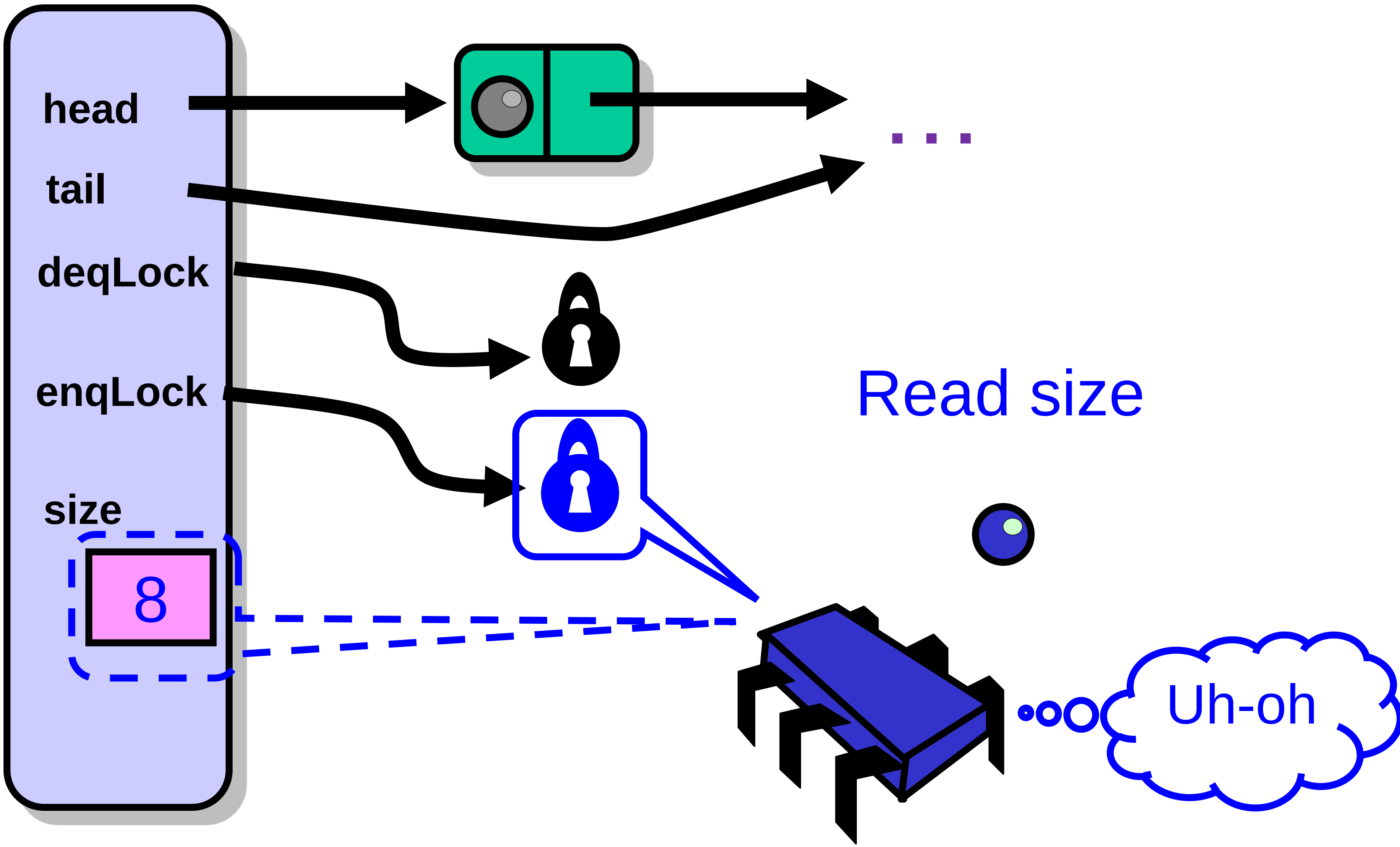


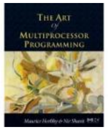
Enqueuer


head
tail
deqLock
enqLock
size
2
If queue was empty,
notify waiting dequeuers

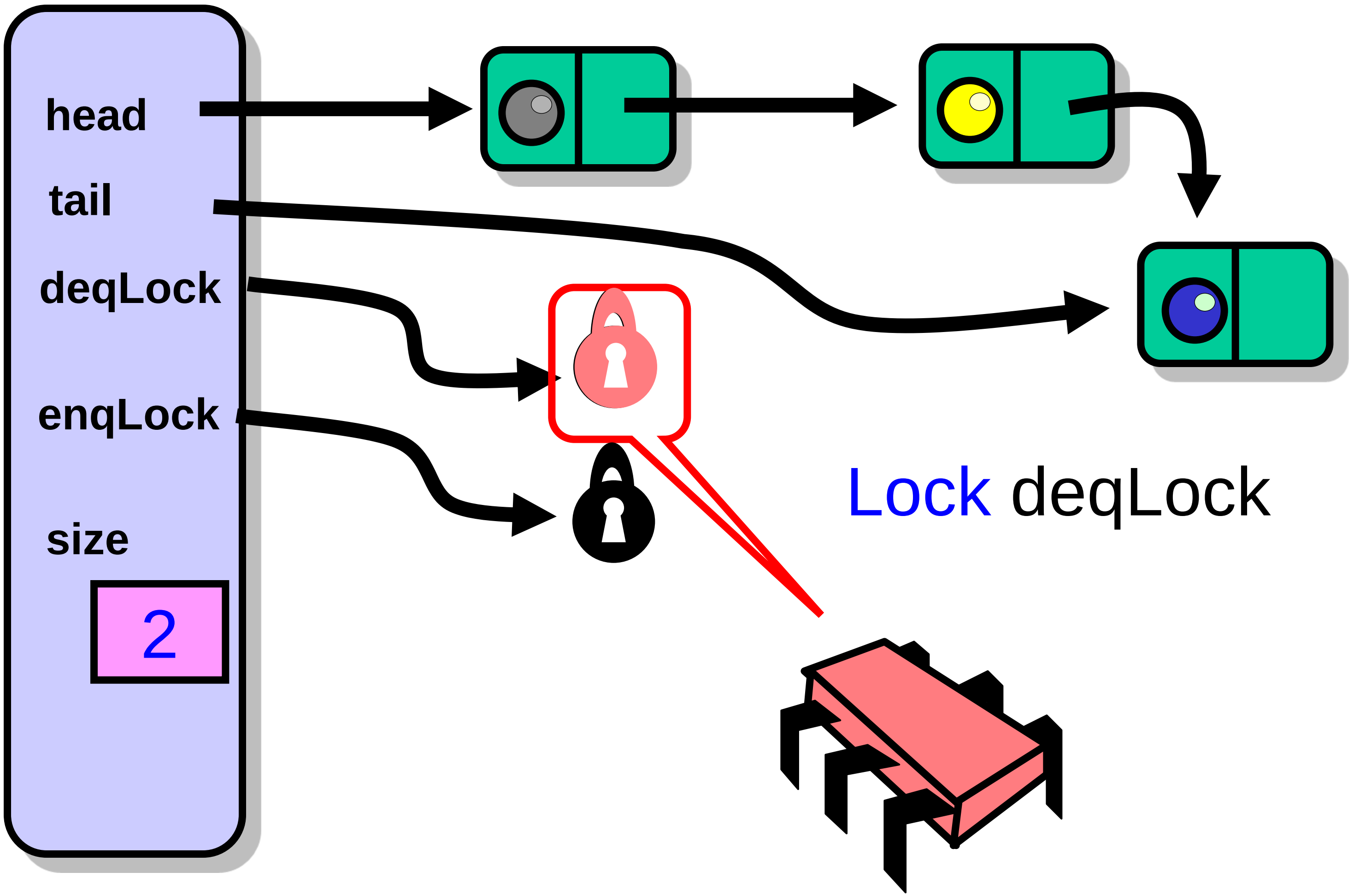


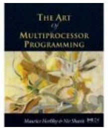
Unsuccesful Enqueuer



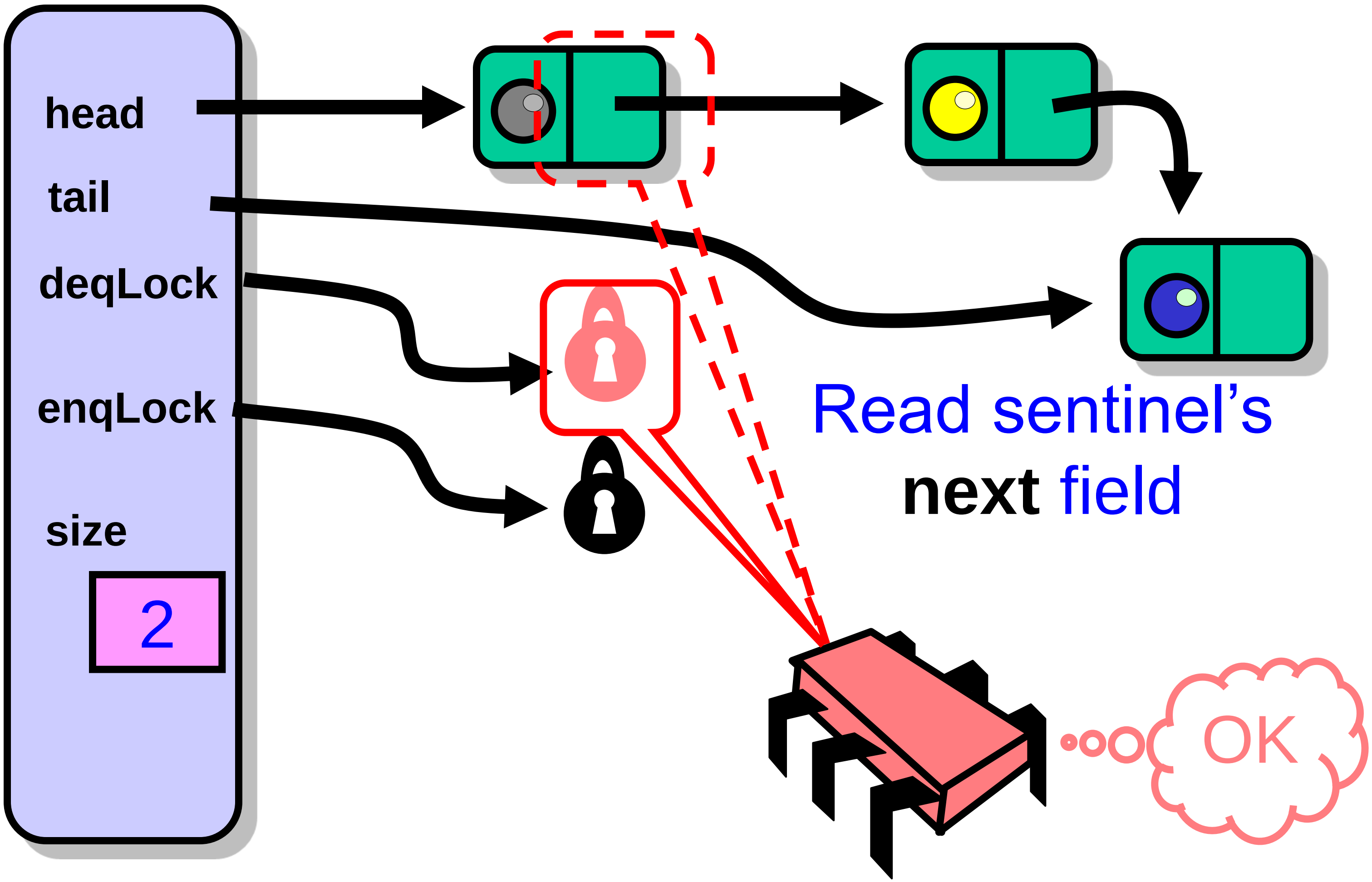


Dequeuer

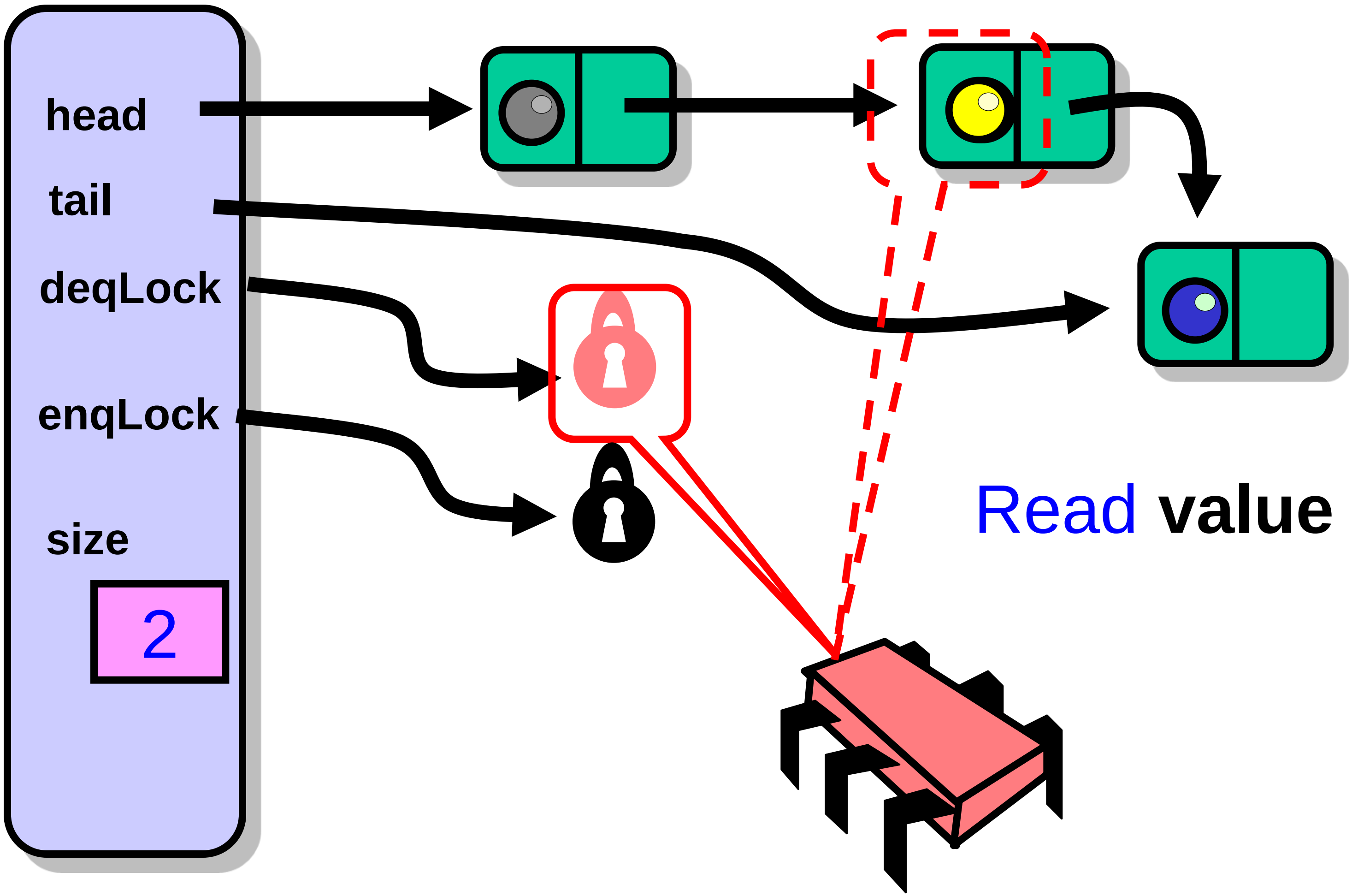


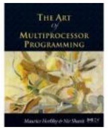


Dequeuer


head
tail
deqLock
enqLock
size
2
Read sentinel's
next field
OK

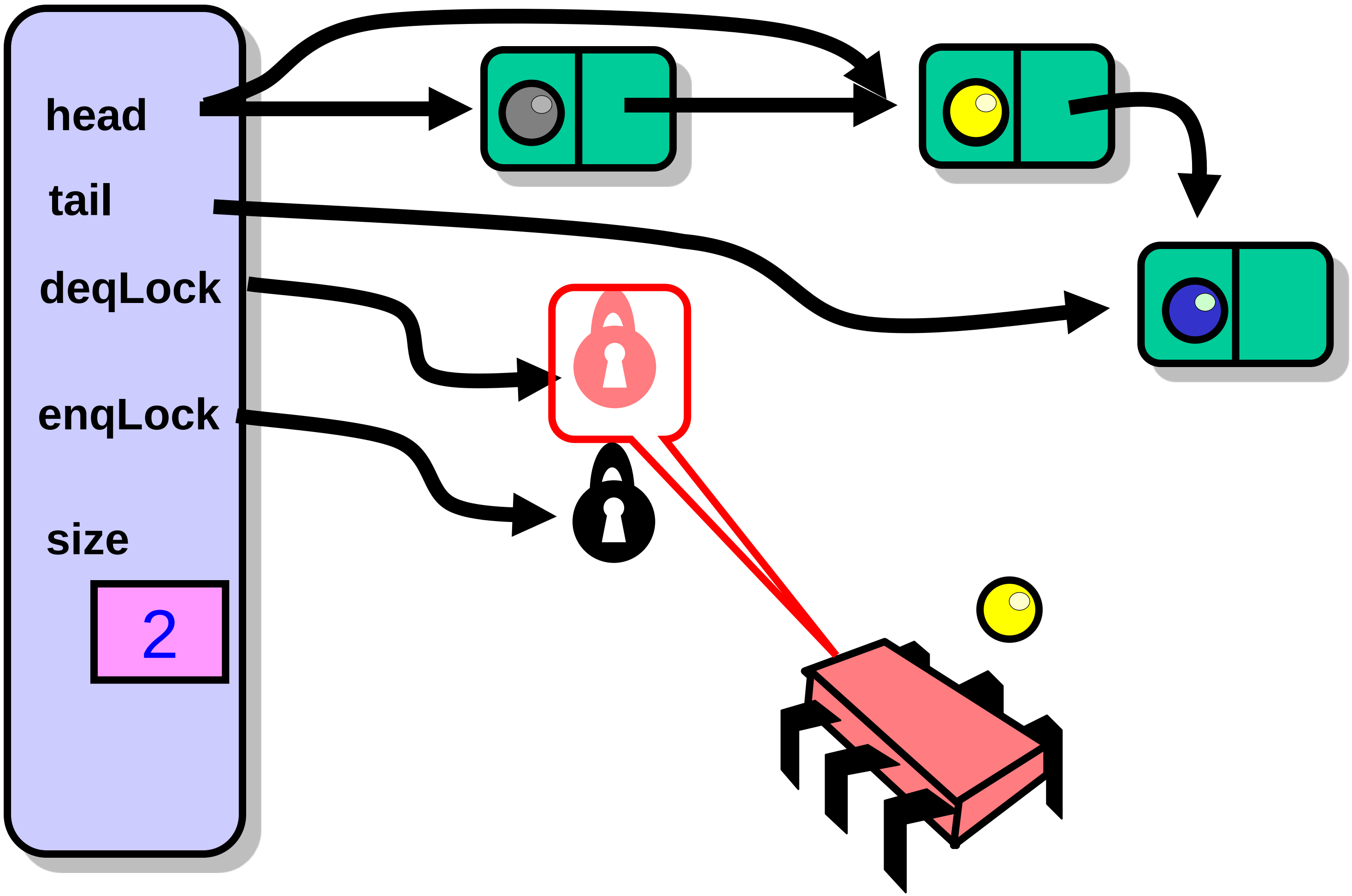
Dequeuer

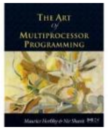




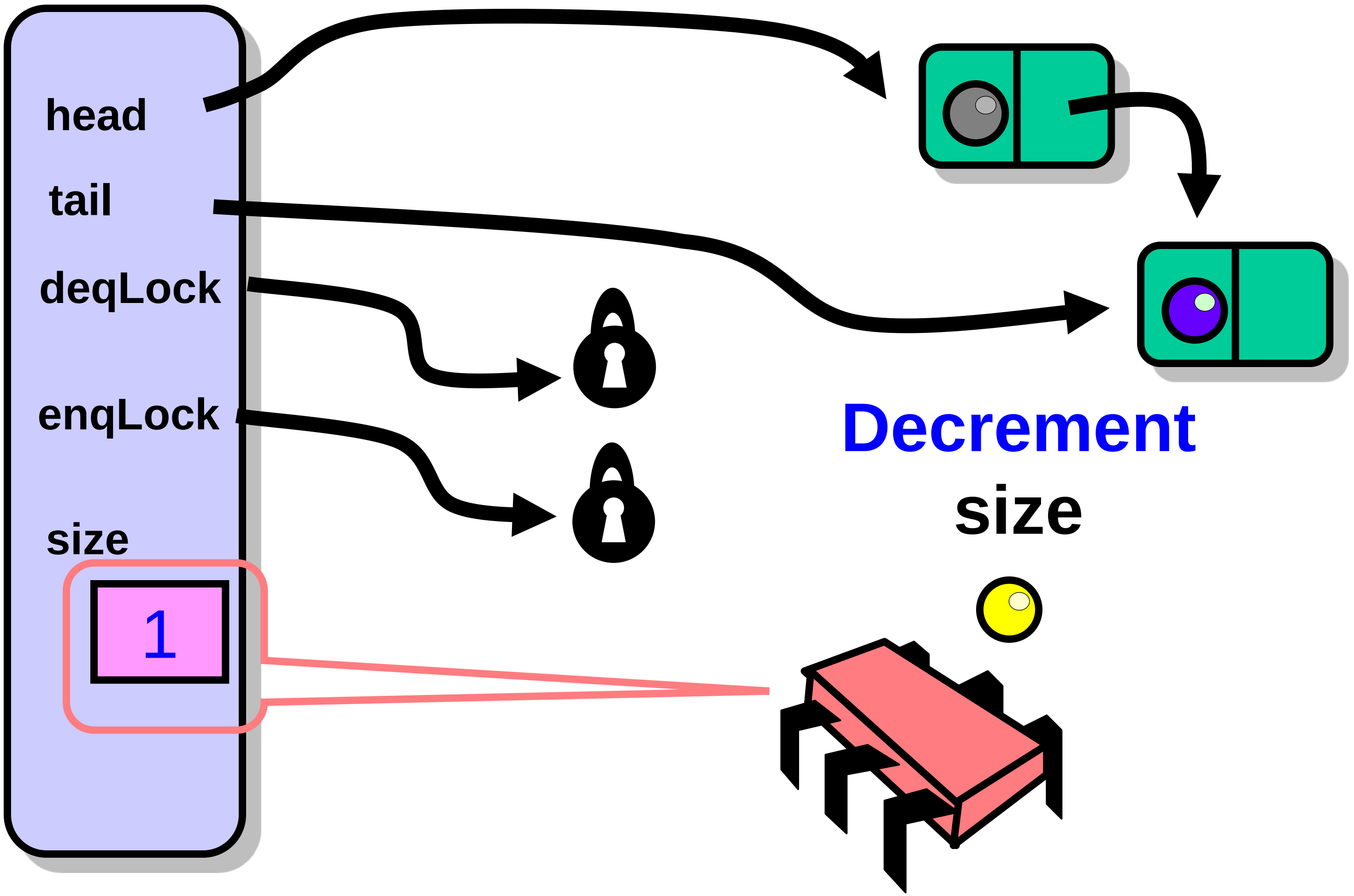
Dequeuer

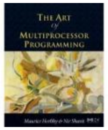
Make first Node
new sentinel



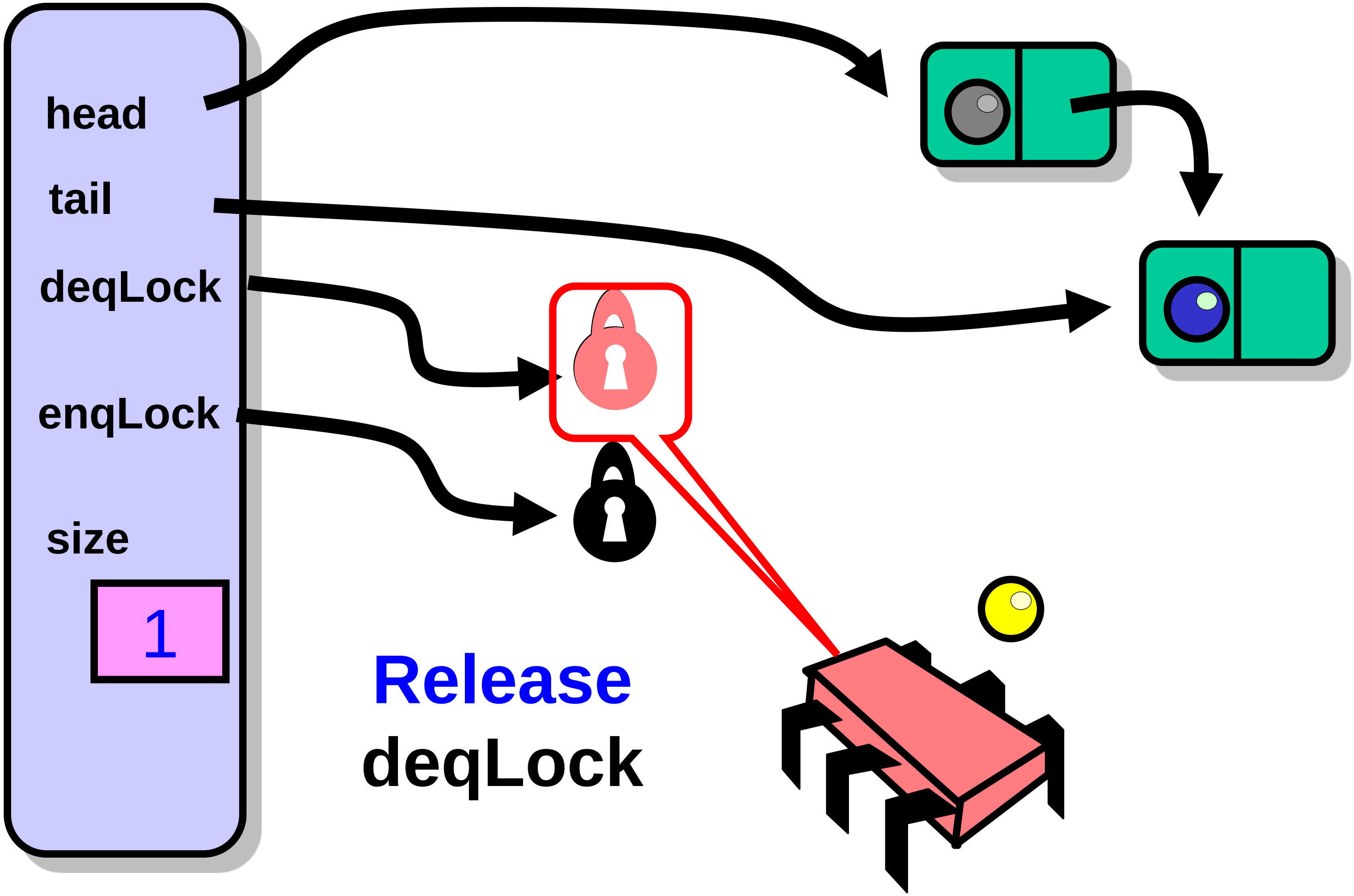


Dequeuer

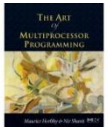




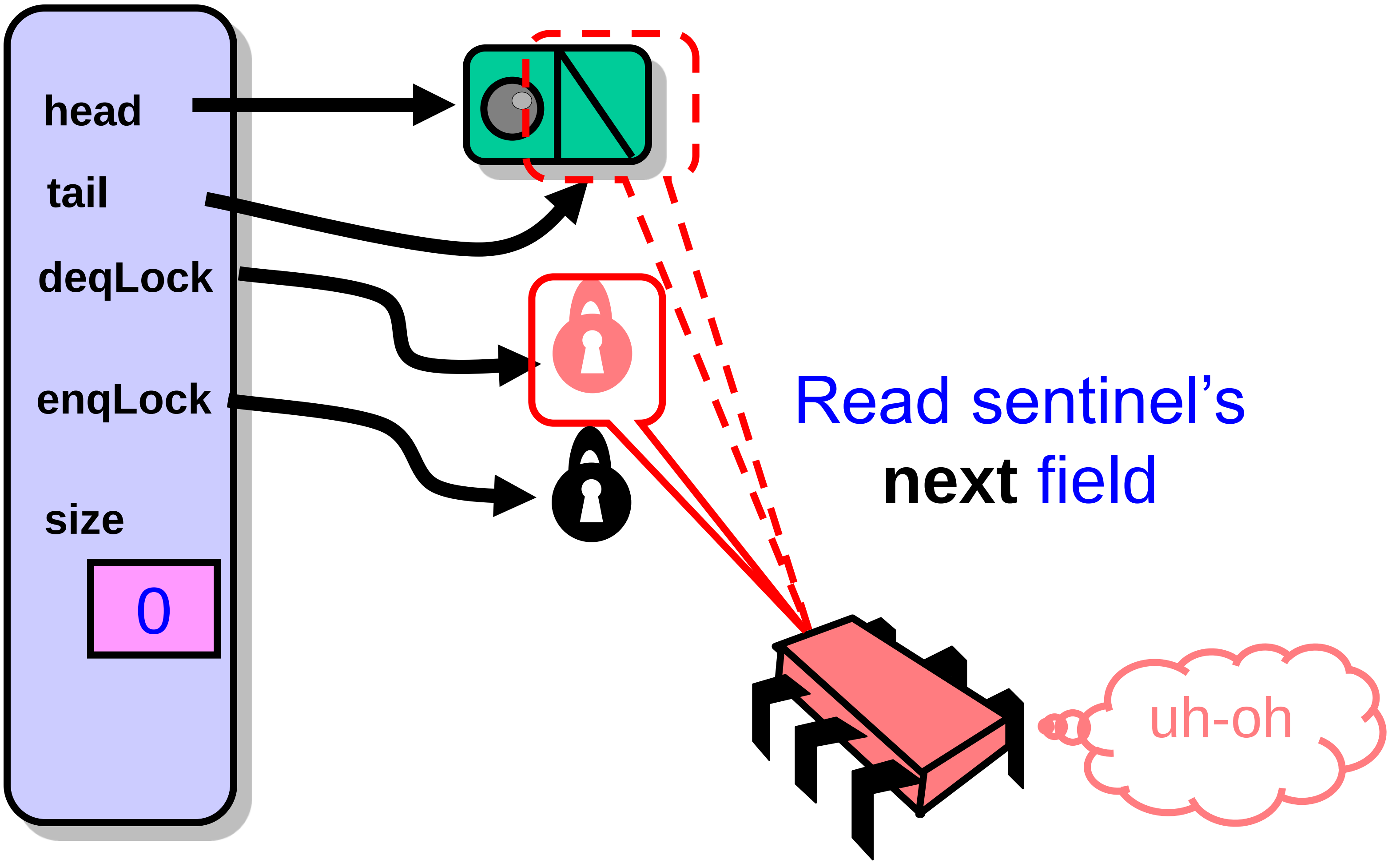
Dequeuer

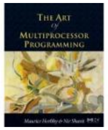


Release deqLock



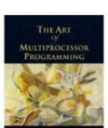
Unsuccesful Dequeuer





Digression: Monitor Locks

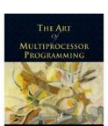
- Java **`synchronized`** objects and **`ReentrantLocks`** are monitors
- Allow blocking on a condition rather than spinning
- Threads:
  - acquire and release lock
  - wait on a condition



The Java Lock Interface

```
public interface Lock {
 void lock();
 void lockInterruptibly() throws InterruptedException;
 boolean tryLock();
 boolean tryLock(long time, TimeUnit unit);
 Condition newCondition();
 void unlock;
}
```

Acquire lock



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```
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 Condition newCondition();
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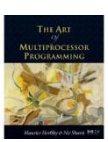
}
```

Release lock



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public interface Lock {
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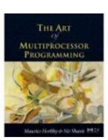
 boolean tryLock();
 boolean tryLock(long time, TimeUnit unit);
 Condition newCondition();
 void unlock;
}
```

Try for lock, but not too hard

The Java Lock Interface

```
public interface Lock {
 void lock();
 void lockInterruptibly() throws InterruptedException;
 boolean tryLock();
 boolean tryLock(long time, TimeUnit unit);
 Condition newCondition();
 void unlock;
}
```

Create condition to wait on



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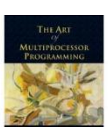
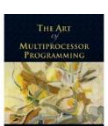
 boolean tryLock(long time, TimeUnit unit);
 Condition newCondition();
 void unlock;
}
```

Never mind what this method does



Lock Conditions

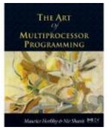
```
public interface Condition {
  void await();
  boolean await(long time, TimeUnit unit);
  …
  void signal();
  void signalAll();
 }
```



Lock Conditions

```
public interface Condition {
  void await();
  boolean await(long time, TimeUnit unit);
  …
  void signal();
  void signalAll();
}
```

Release lock and wait on condition



Lock Conditions

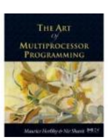
```
public interface Condition {
  void await();
  boolean await(long time, TimeUnit unit);
  …
  void signal();
  void signalAll();
 }
```

Wake up one waiting thread

Lock Conditions

```
public interface Condition {
  void await();
  boolean await(long time, TimeUnit unit);
  …
  void signal();
  void signalAll();
}
```

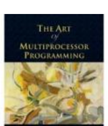
Wake up all waiting threads



Await

```
q.await()
```

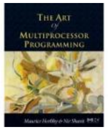
- Releases lock associated with q
- Sleeps (gives up processor)
- Awakens (resumes running)
- Reacquires lock & returns



Signal

```
q.signal();
```

- Awakens one waiting thread
  - Which will reacquire lock

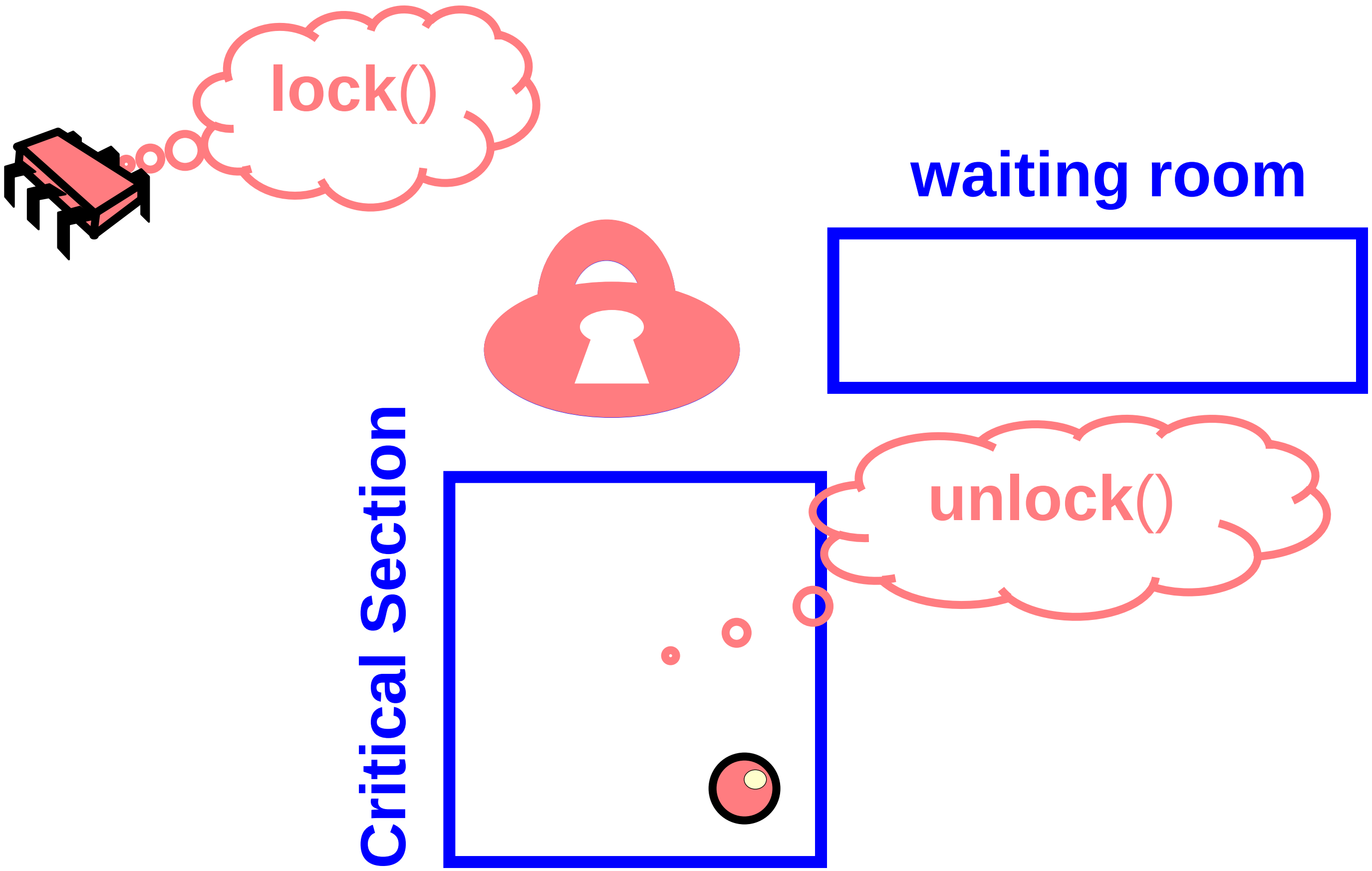


Signal All

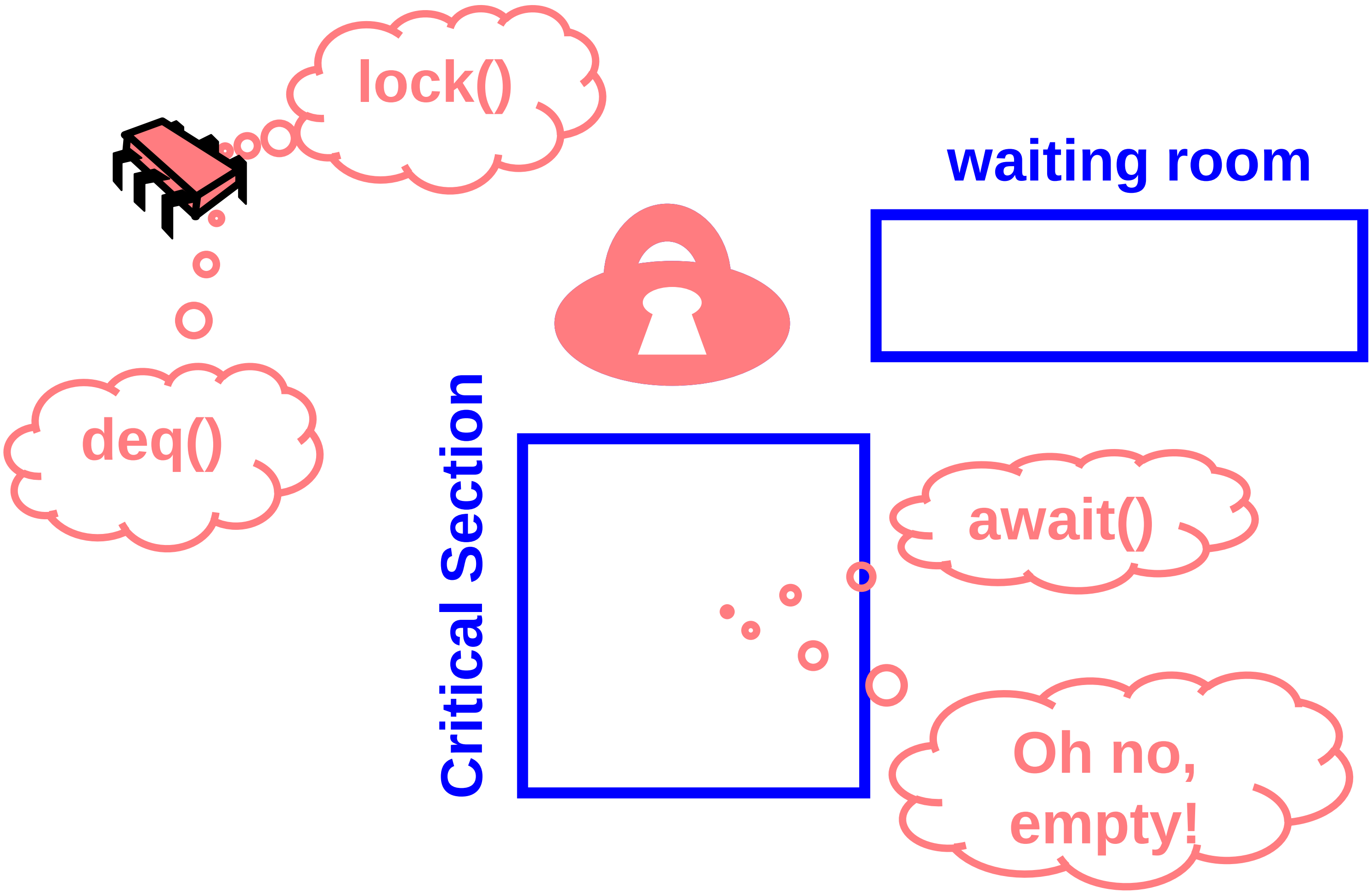
```
q.signalAll();
```

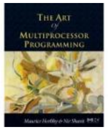
- Awakens all waiting threads
  - Which will each reacquire lock

A Monitor Lock

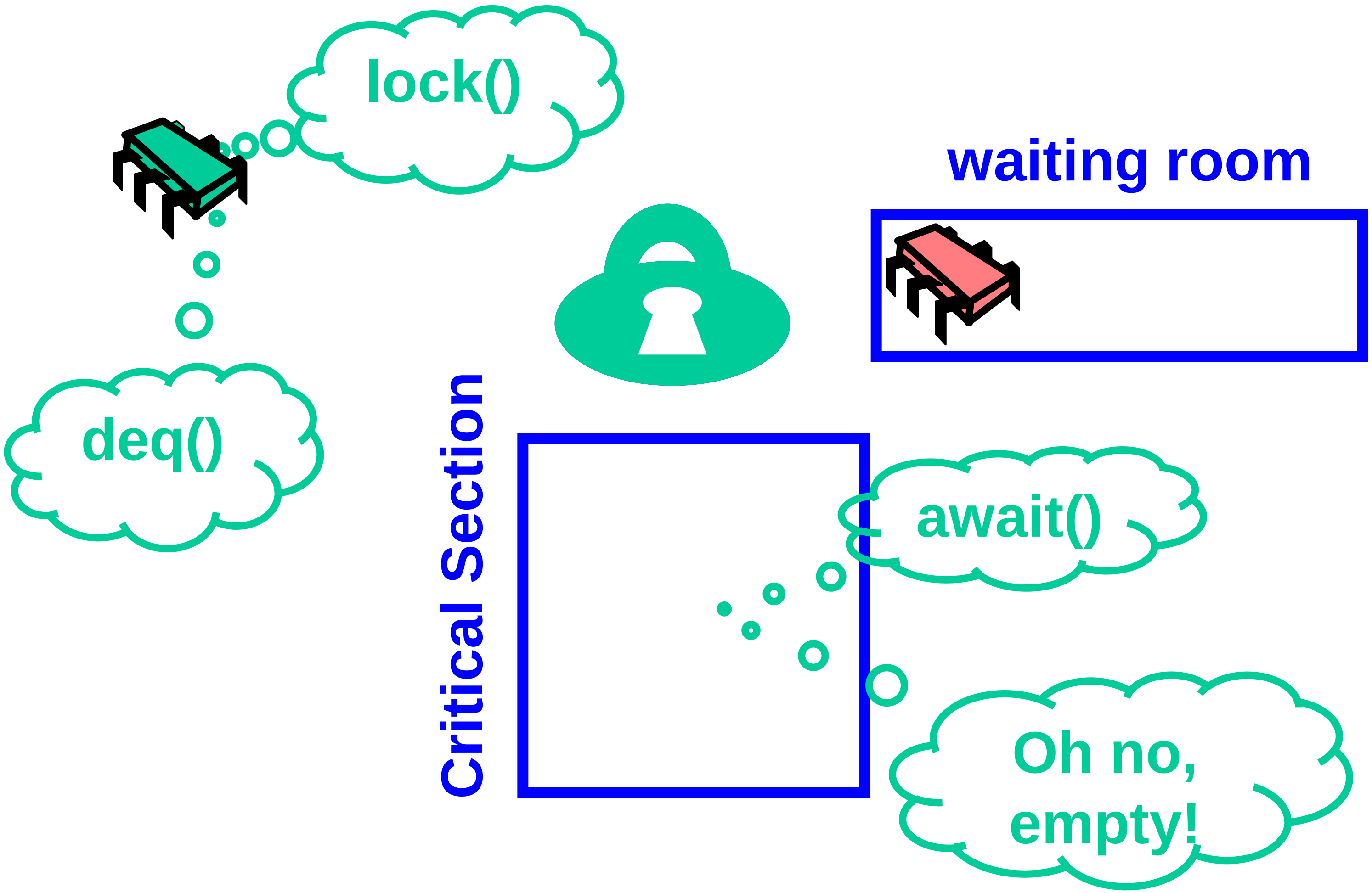


Unsuccessful Deq

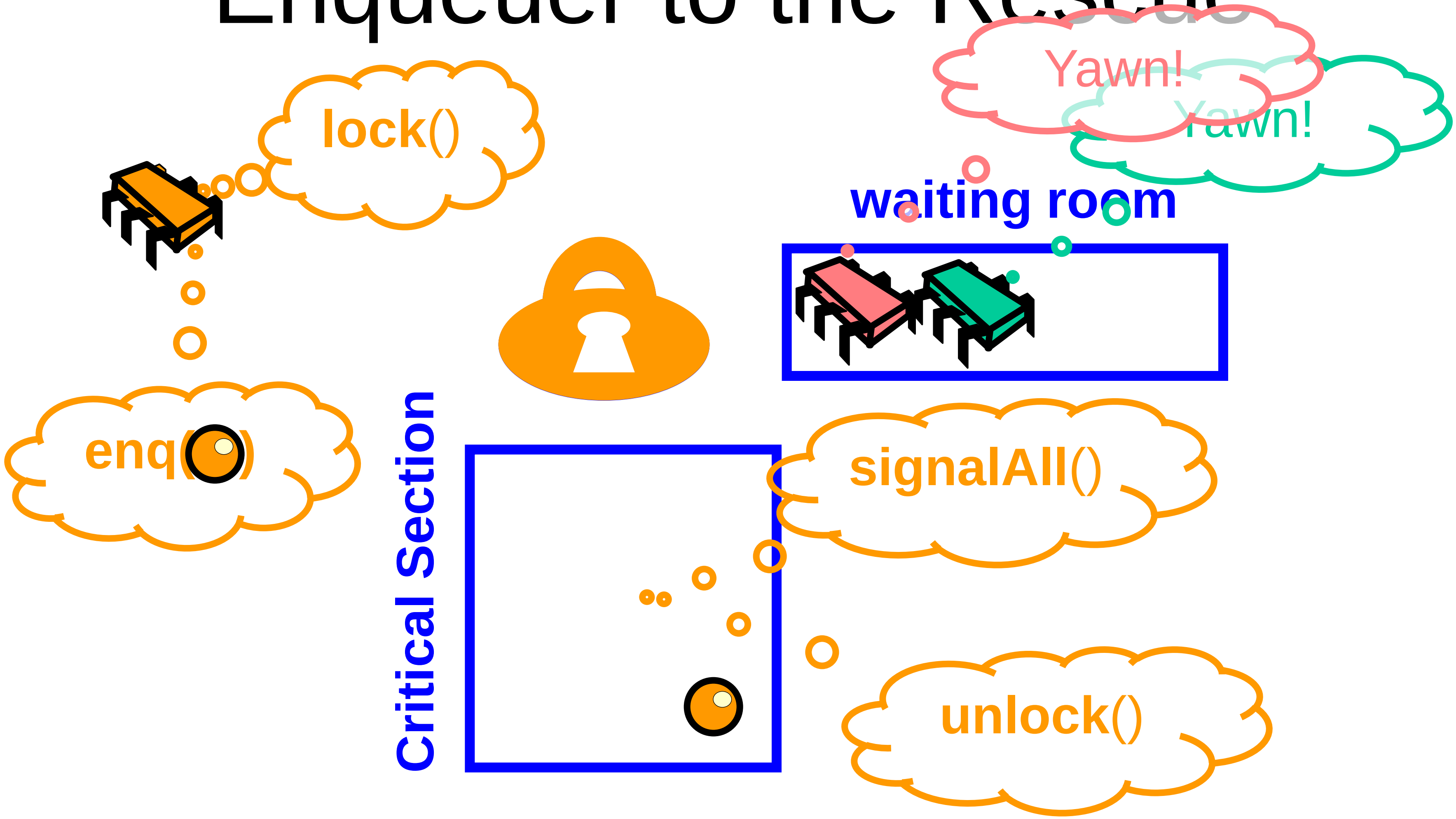




Another One



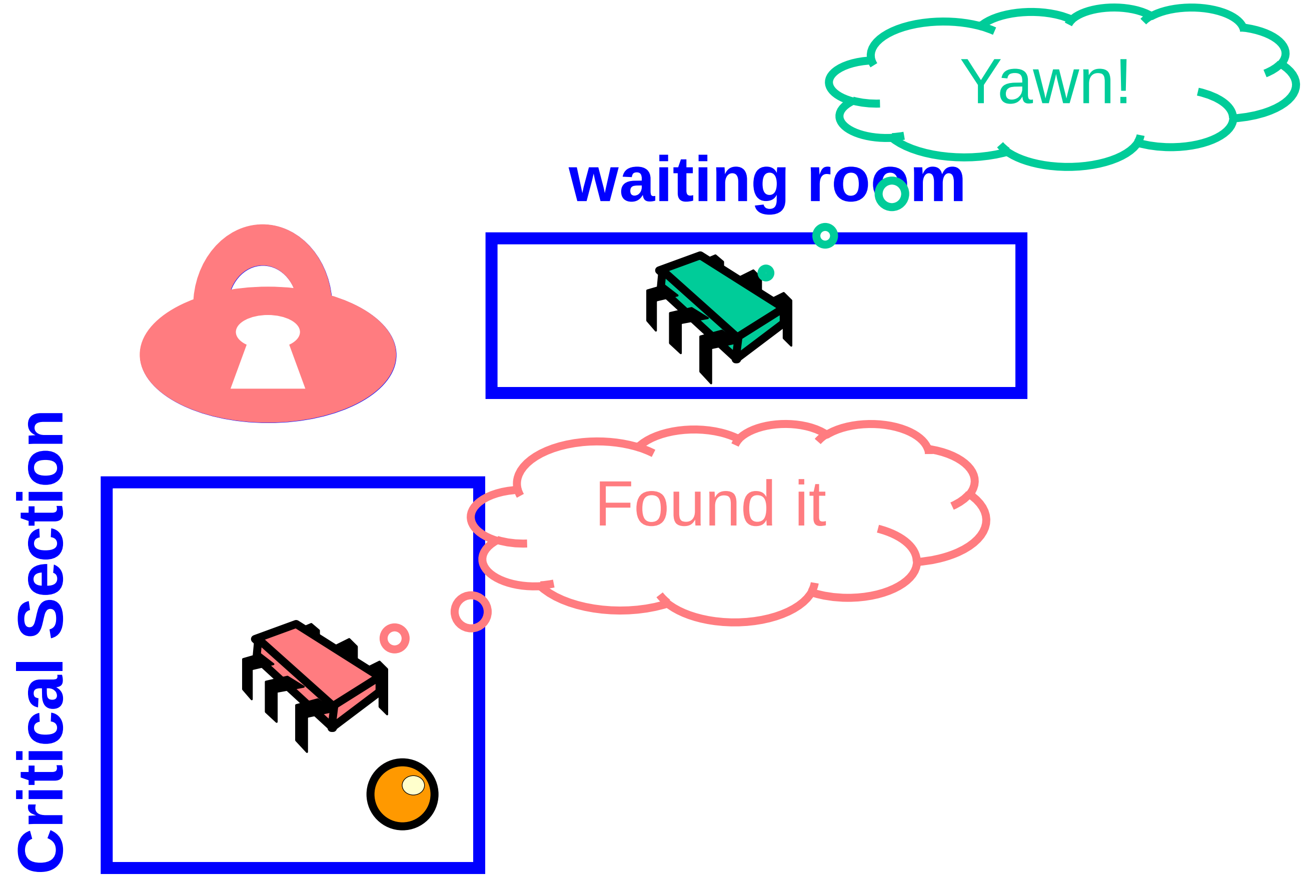
Enqueuer to the Rescue



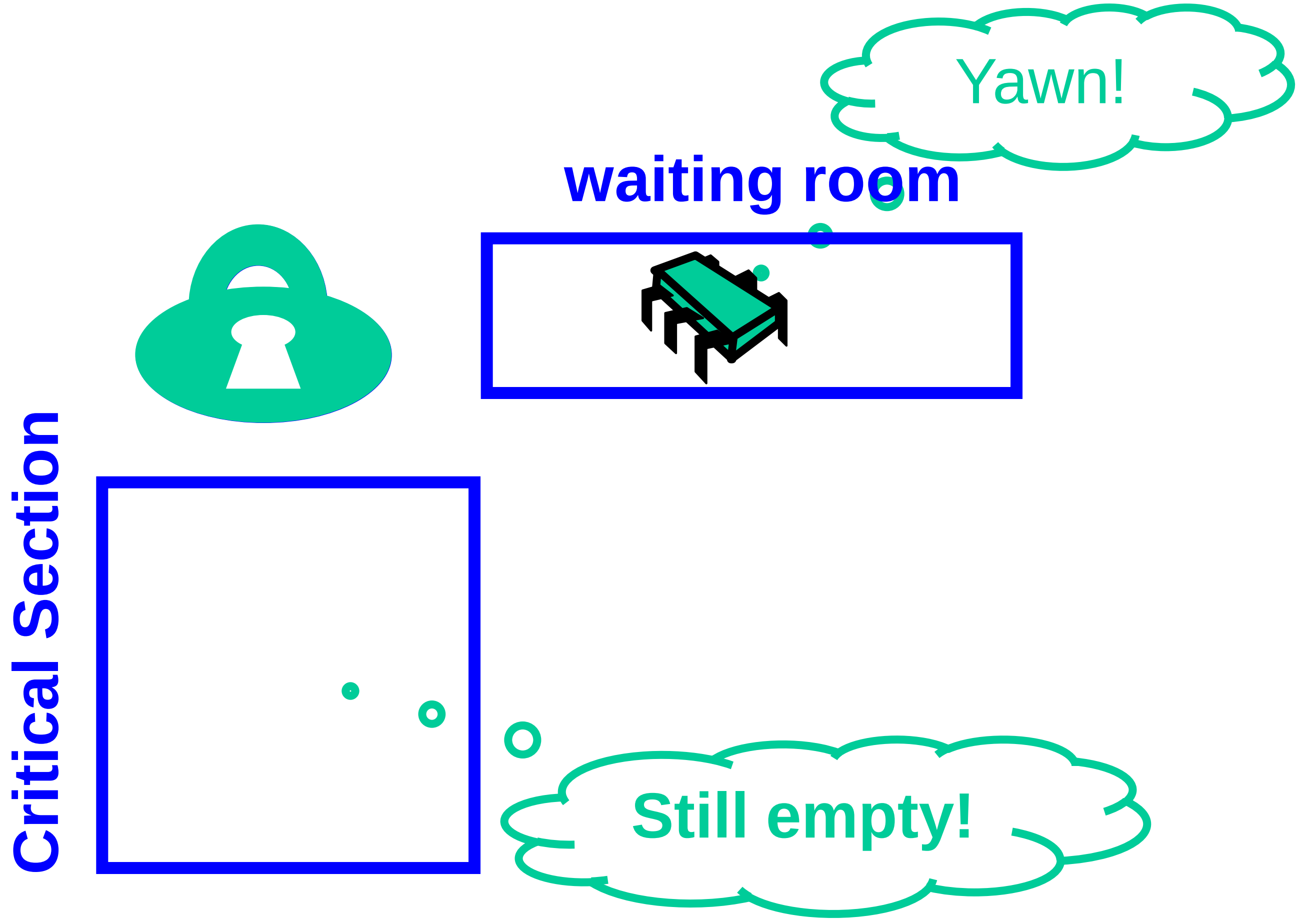
Monitor Signalling

Awakened thread might still lose lock to outside contender…

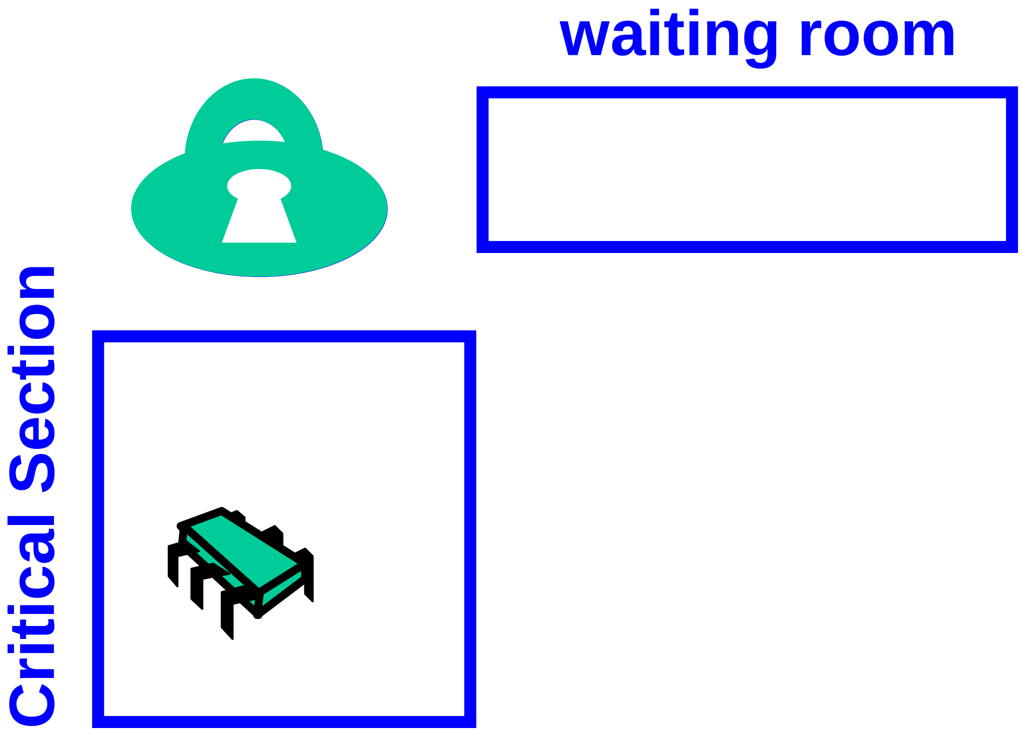
Dequeuers Signalled



Dequeuers Signaled



Dollar Short + Day Late

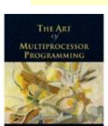


Java Synchronized Methods

```
public class Queue<T> {

  int head = 0, tail = 0;
  T[QSIZE] items;

  public synchronized T deq() {
   while (tail – head == 0)
     wait();
   T result = items[head % QSIZE]; head++;
   notifyAll();
   return result;
  }
  …
}}
```



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   return result;
  }
  …
}}
```

Each object has an implicit lock with an implicit condition

Java Synchronized Methods

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  public synchronized T deq() {
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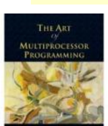
   T result = items[head % QSIZE]; head++;
   notifyAll();
   return result;
  }
  …
}}
```

Lock on entry, unlock on return



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   T result = items[head % QSIZE]; head++;
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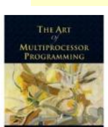
   return result;
  }
  …
}}
```

Wait on implicit condition



Java Synchronized Methods

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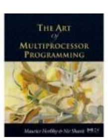
  public synchronized T deq() {
   while (tail – head == 0)
     this.wait();
   T result = items[head % QSIZE]; head++;
   notifyAll();
   return result;
  }
  …
}}
```

Signal all threads waiting on condition

(Pop!) The 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();
}
```

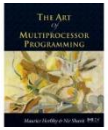


Beware Lost Wake-Ups

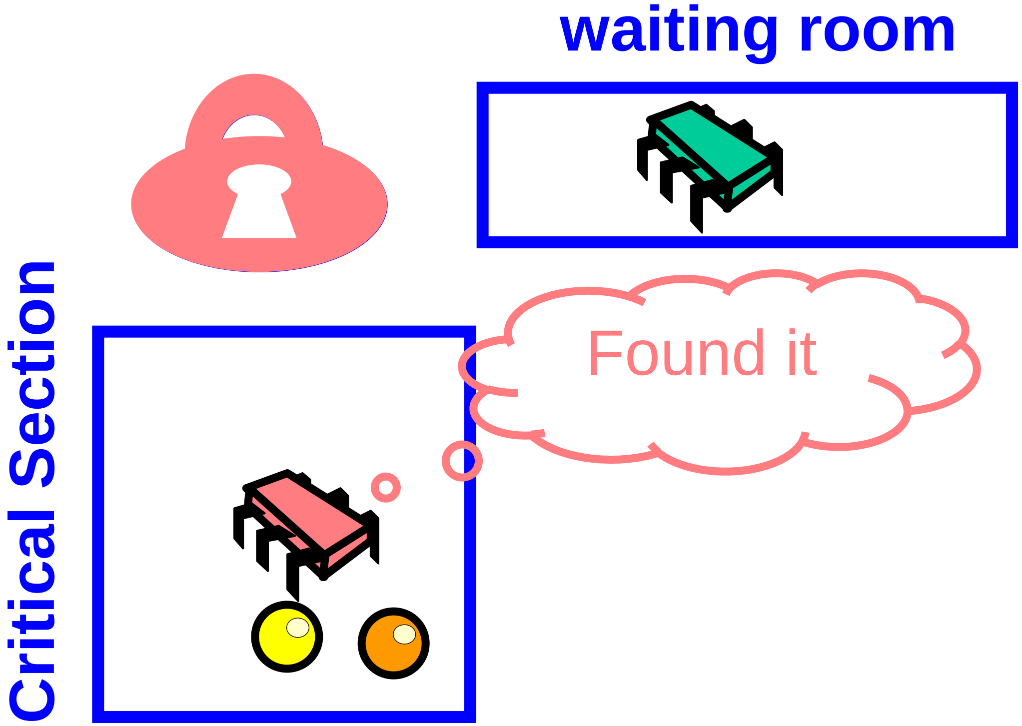
Lost Wake-Up

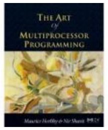

Yawn!
lock()
waiting room
enq( )
Critical Section
Queue not empty so no need to signal
unlock()

Lost Wake-Up

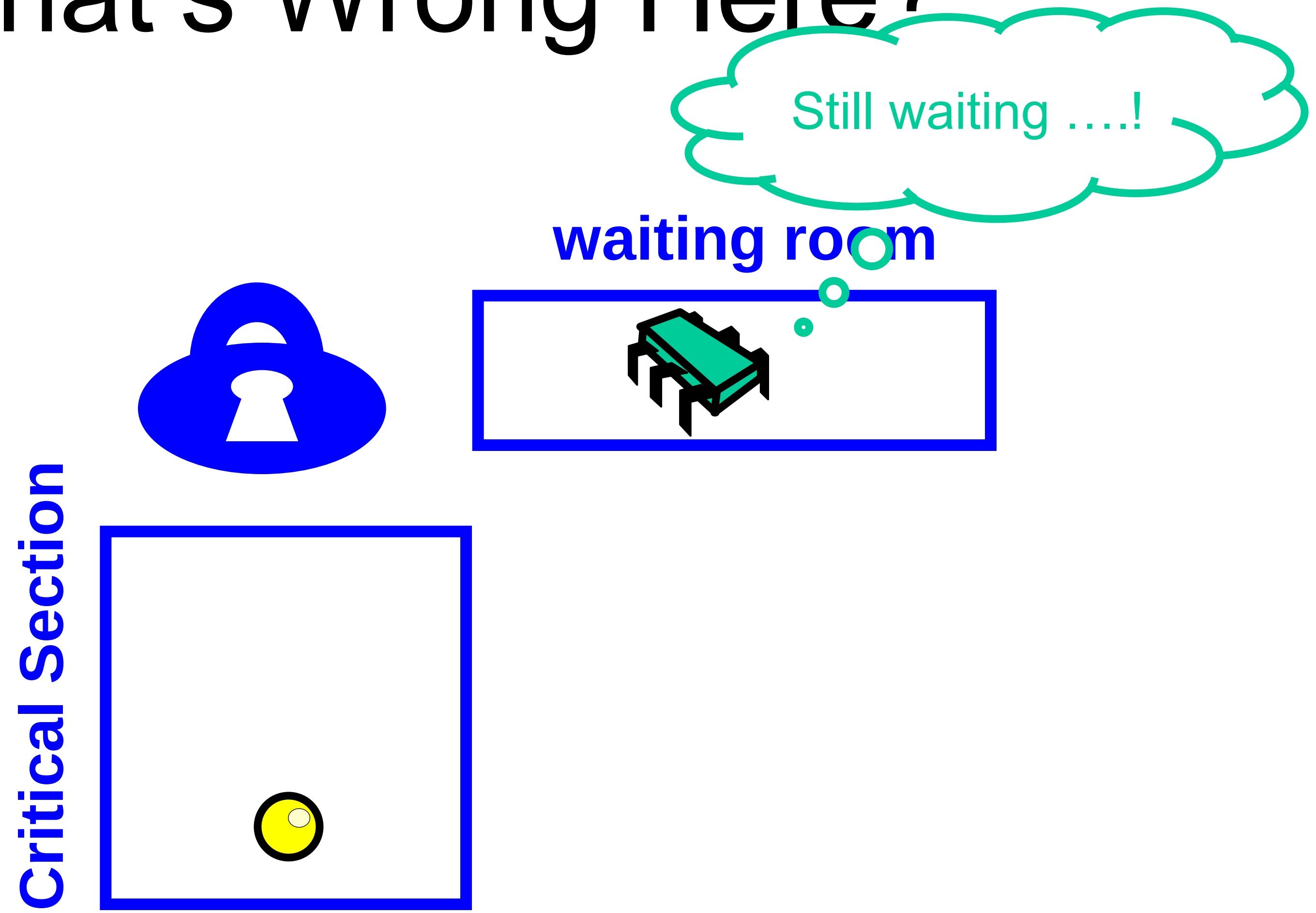


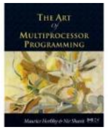
Lost Wake-Up





What's Wrong Here?



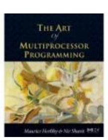


Solution to Lost Wakeup

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

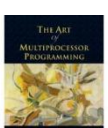
The **`enq()`** & **`deq()`** Methods

- 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?



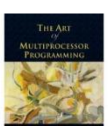
Split the Counter

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

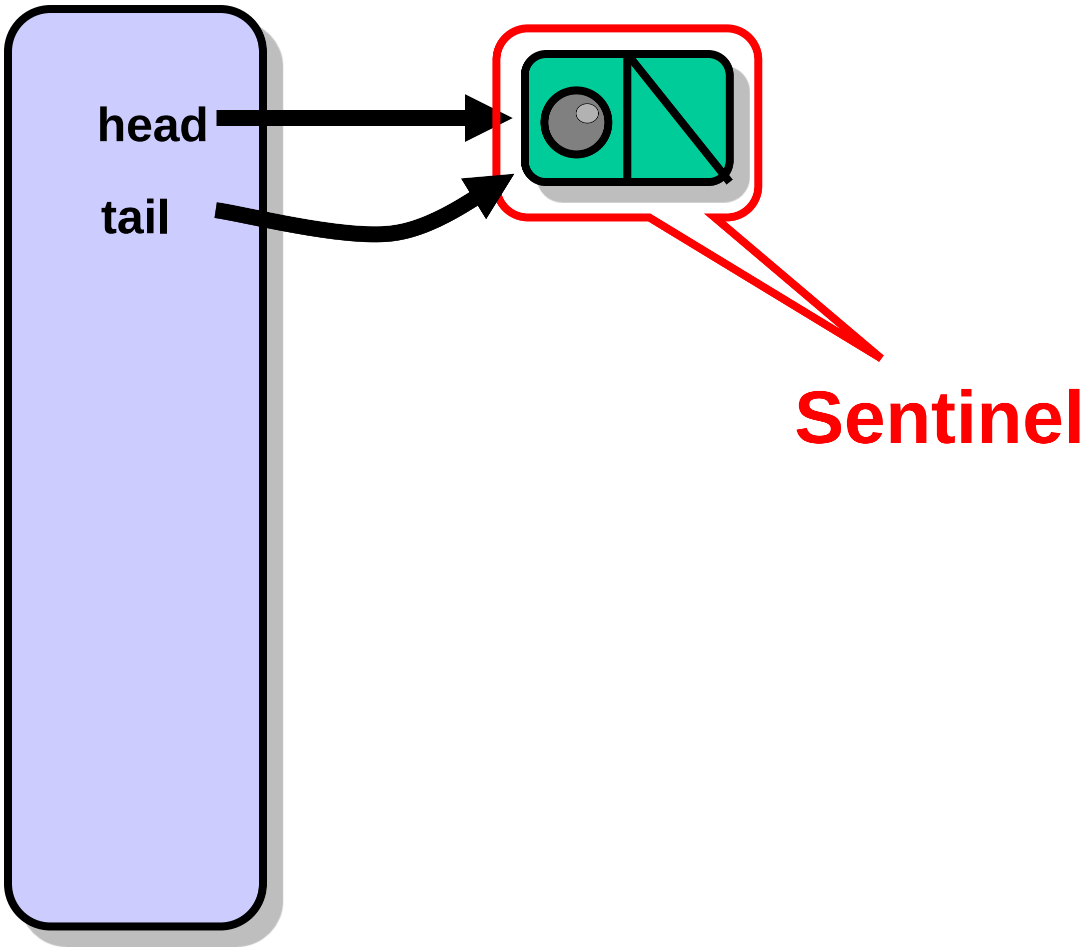


Split Counter

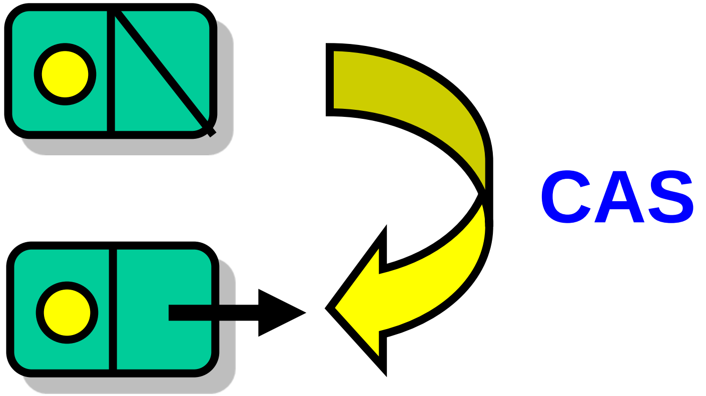
- Enqueuer increments enqSize
- Dequeuer decrements deqSize
- When enqueuer runs out
  - Locks **deqLock**
  - computes size = enqSize - DeqSize
- Intermittent synchronization
  - Not with each method call
  - Need both locks! (careful …)



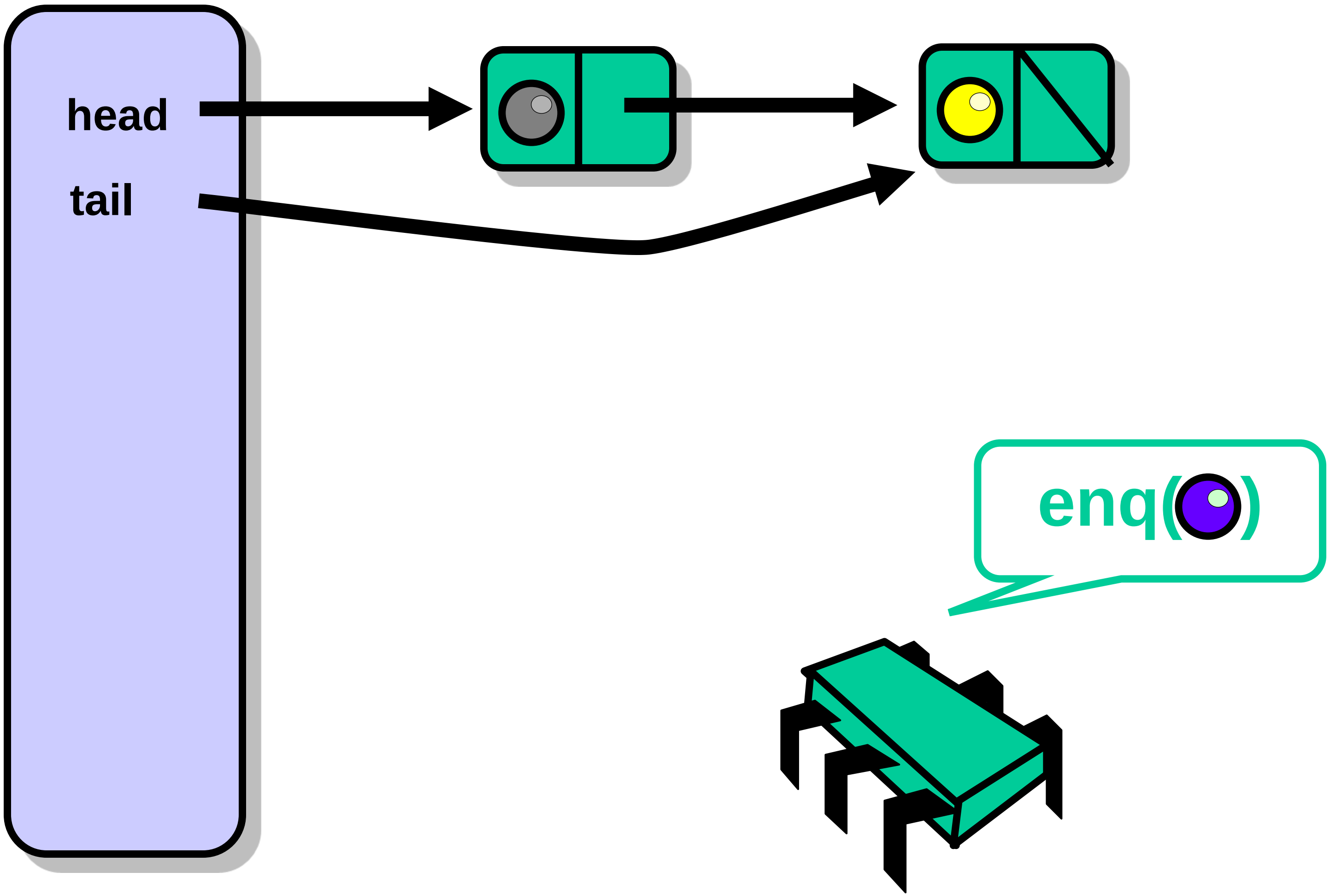
A Lock-Free Queue

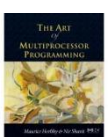


Compare and Set

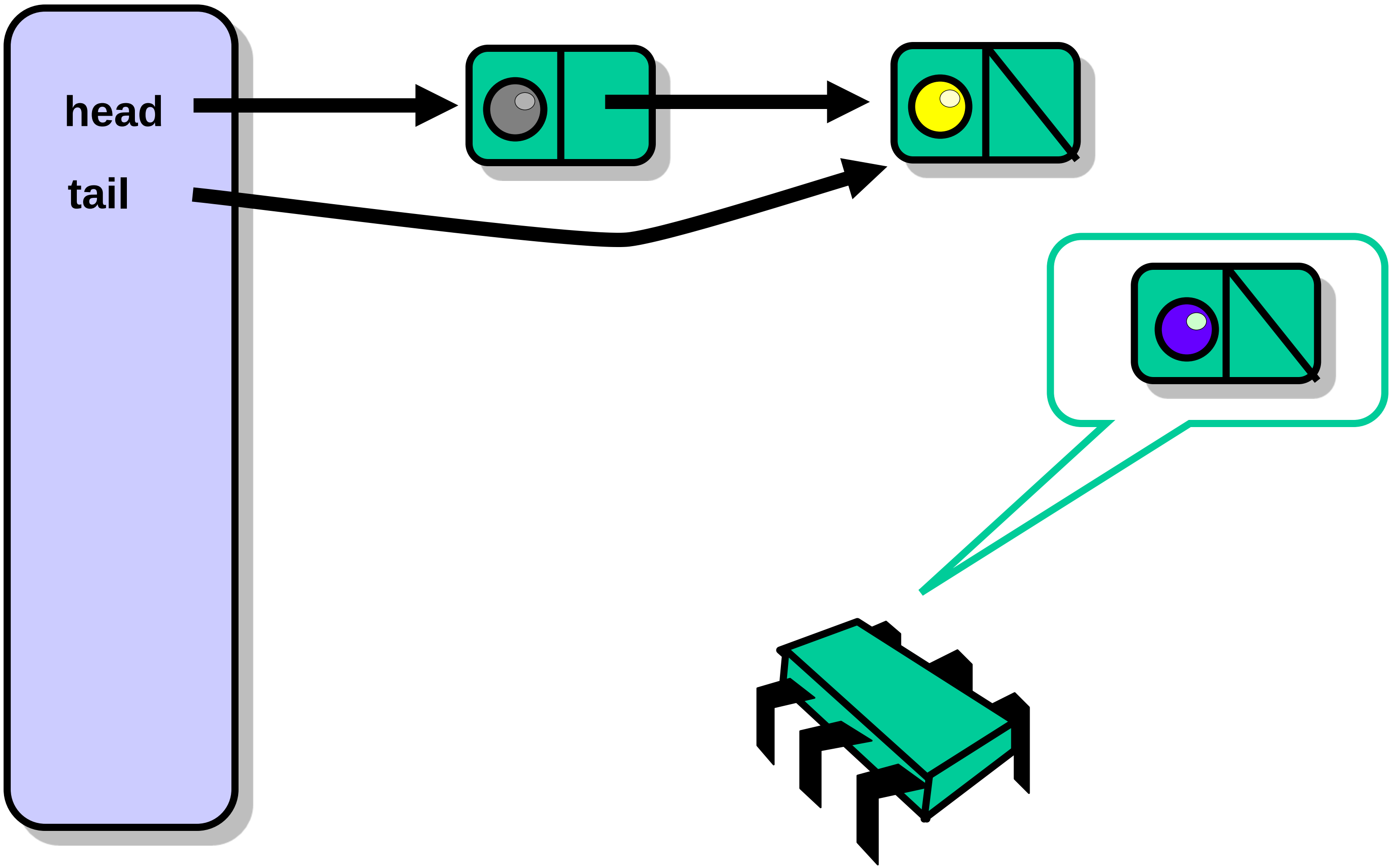


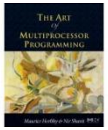
Enqueue



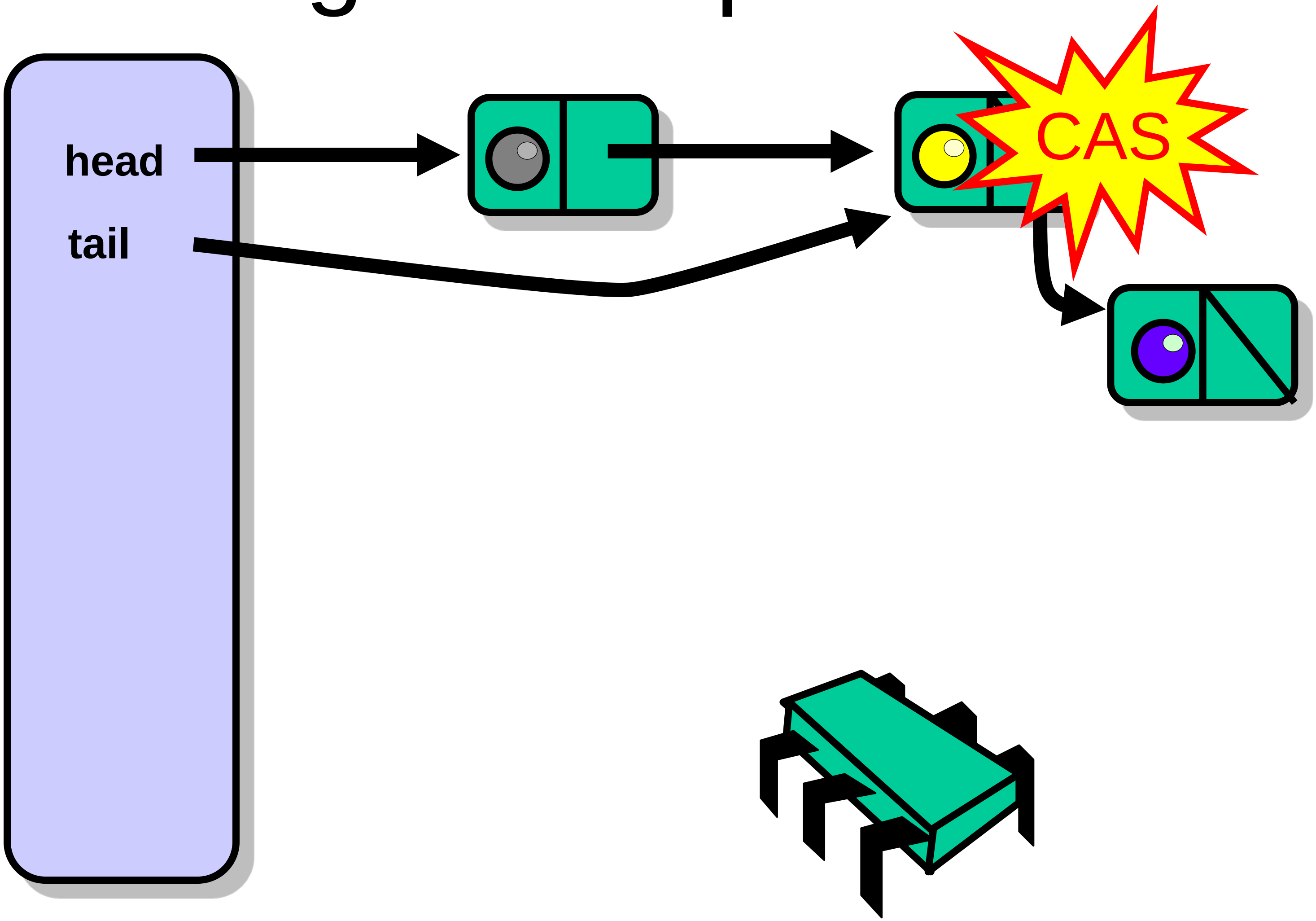


Enqueue

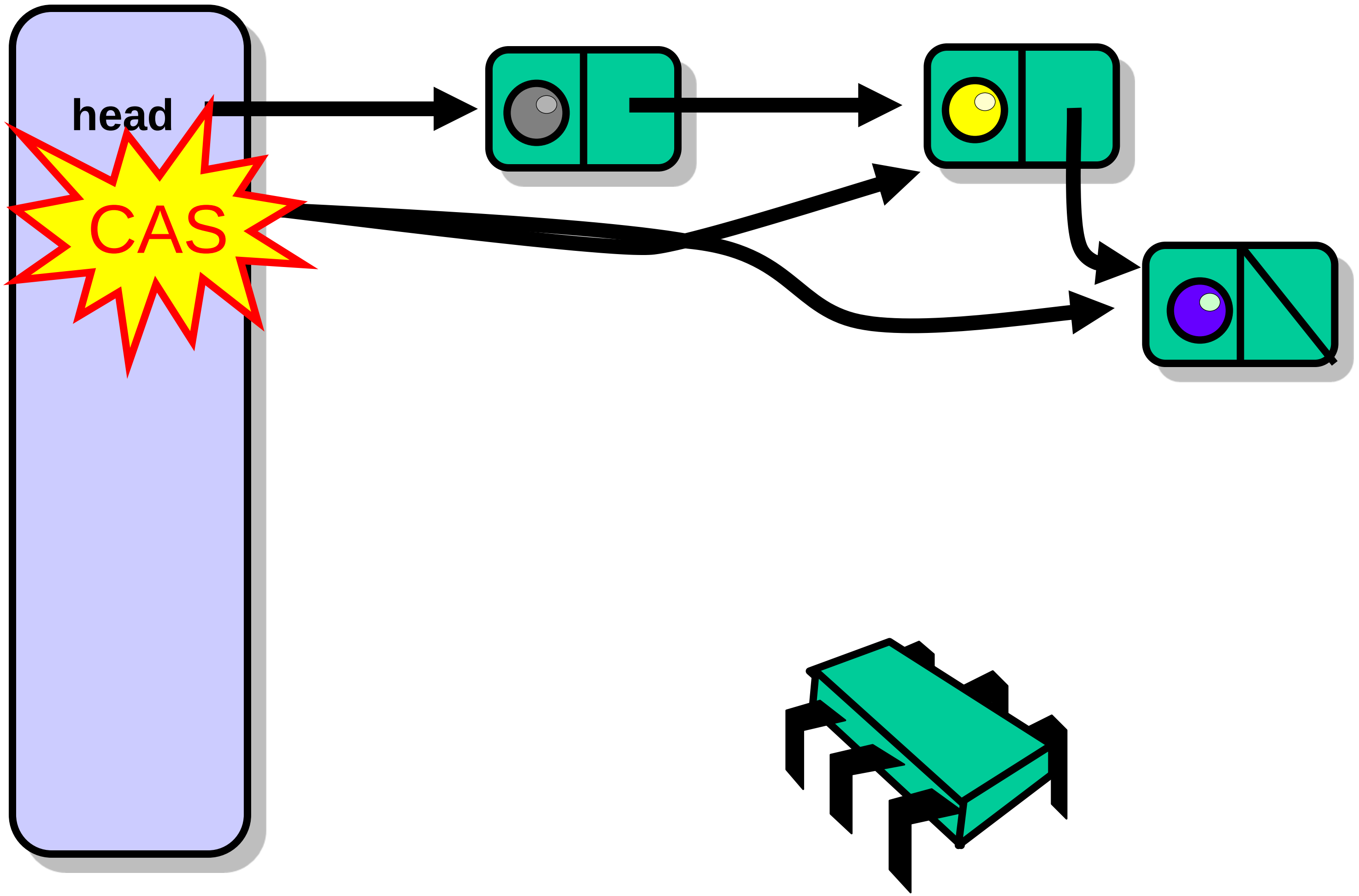


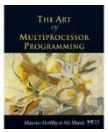


Logical Enqueue



Physical Enqueue





Enqueue

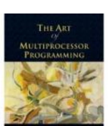
- These two steps are not atomic
- The tail field refers to either
  - Actual last Node (good)
  - Penultimate Node (not so good)
- Be prepared!

Enqueue

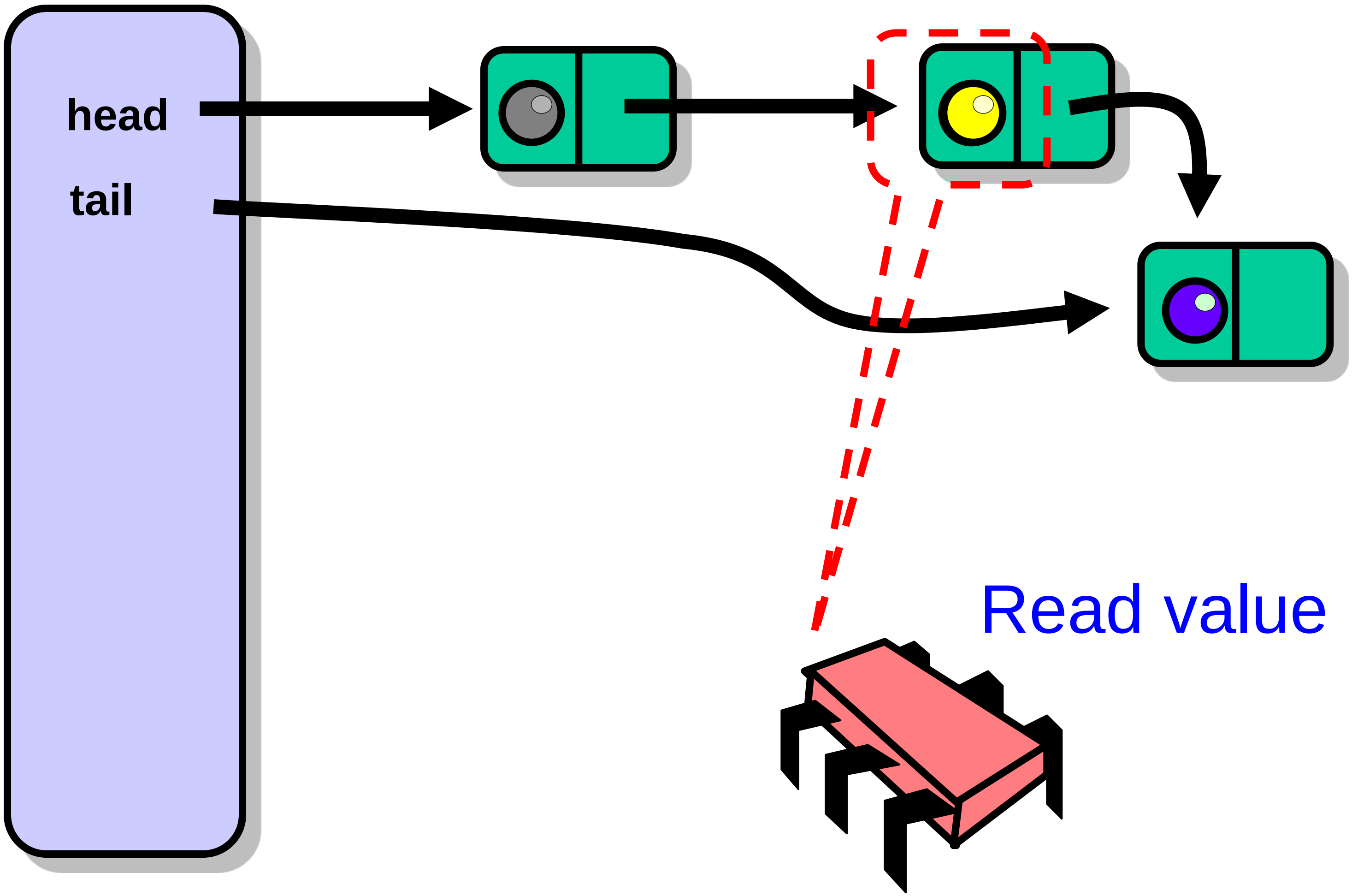
- What do you do if you find
  - A trailing **tail**?
- Stop and help fix it
  - If **tail** node has non-*null* next field
  - CAS the queue's **tail** field to **tail.next**
- As in the universal construction

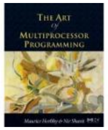
When CASs Fail

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



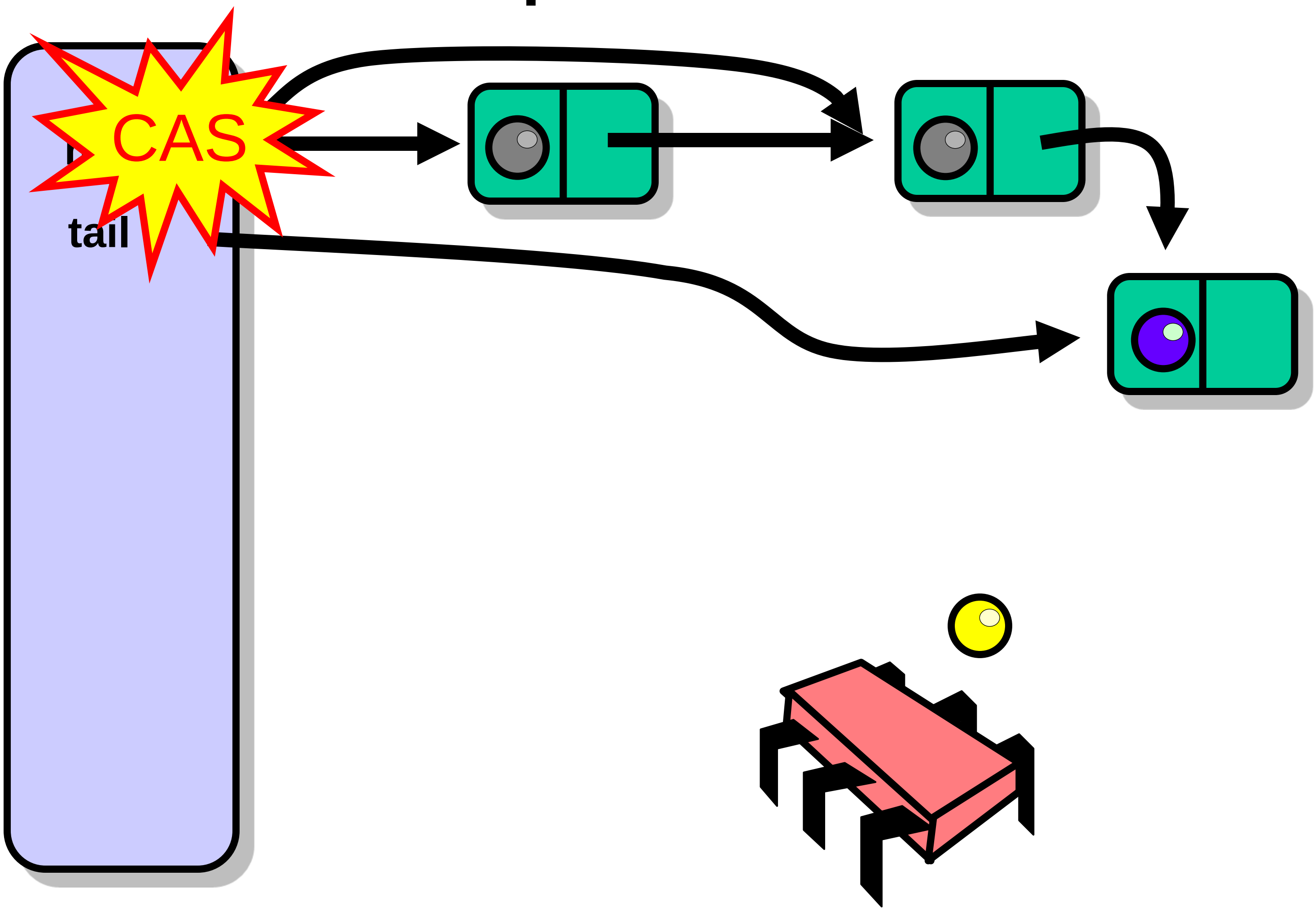
Dequeuer





Dequeuer

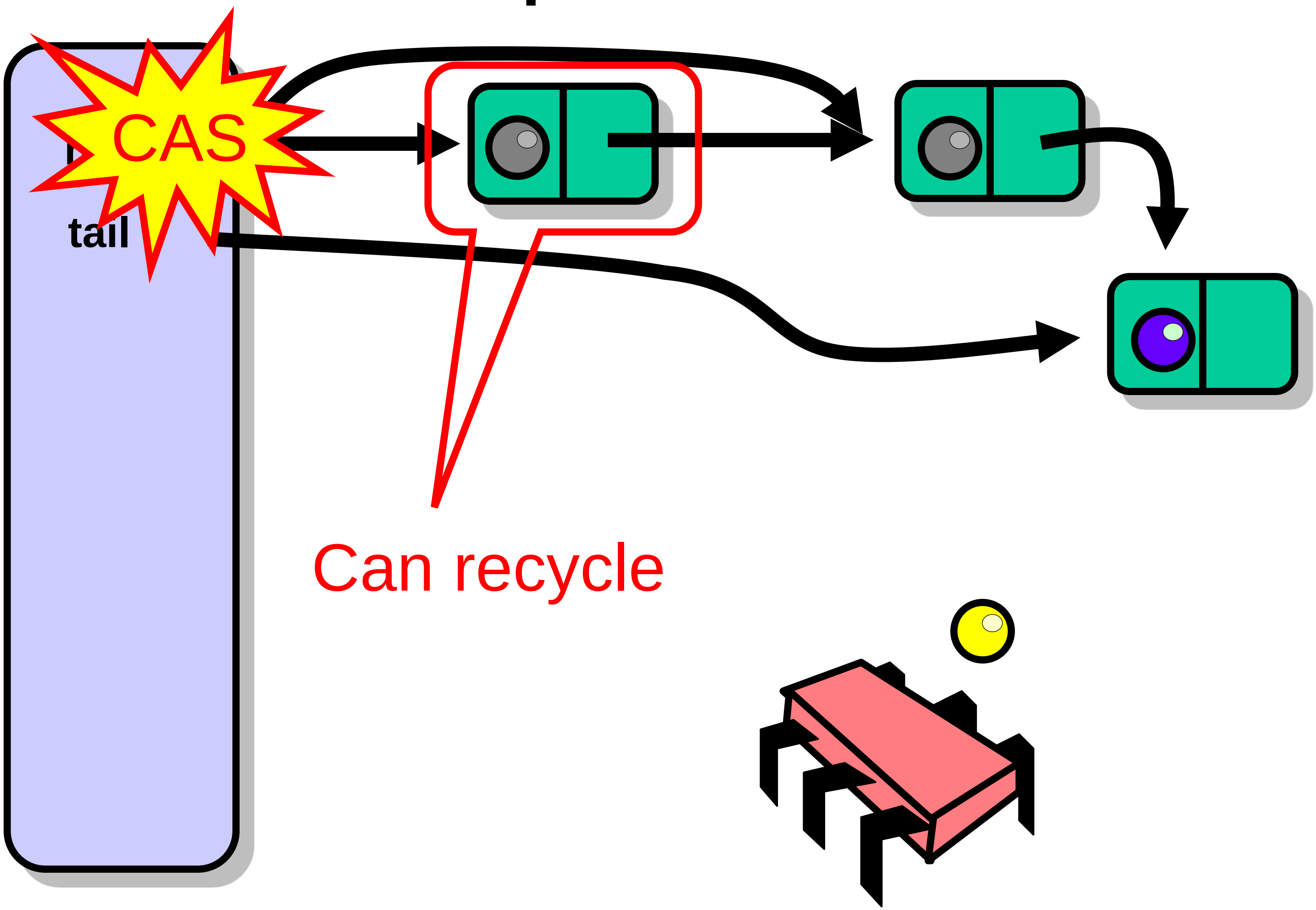
Make first Node new sentinel



Memory Reuse?

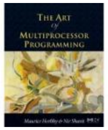
- What do we do with nodes after we dequeue them?
- Java: let garbage collector deal?
- Suppose there is no GC, or we prefer not to use it?

Dequeuer

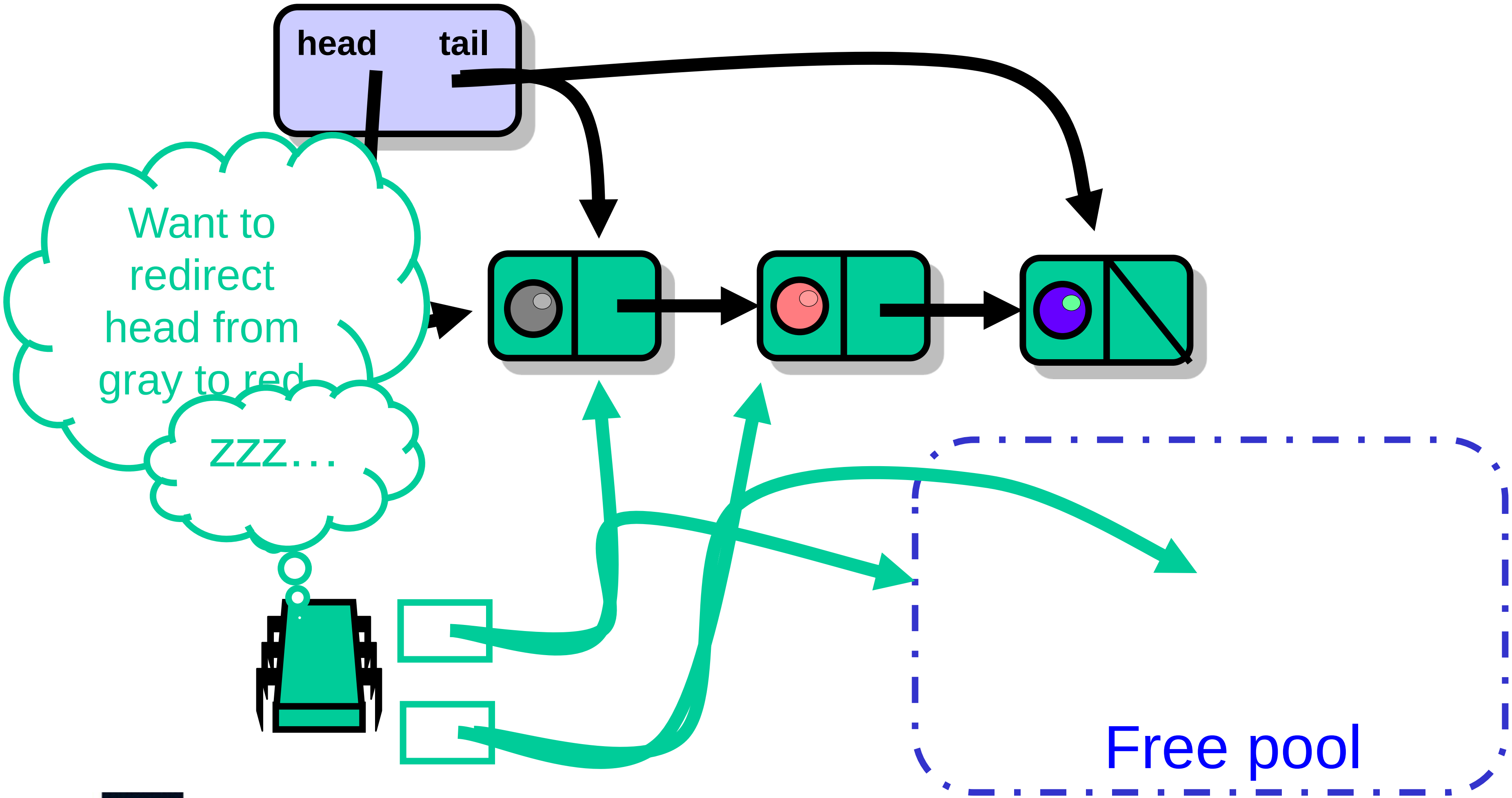


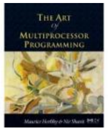
Simple Solution

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

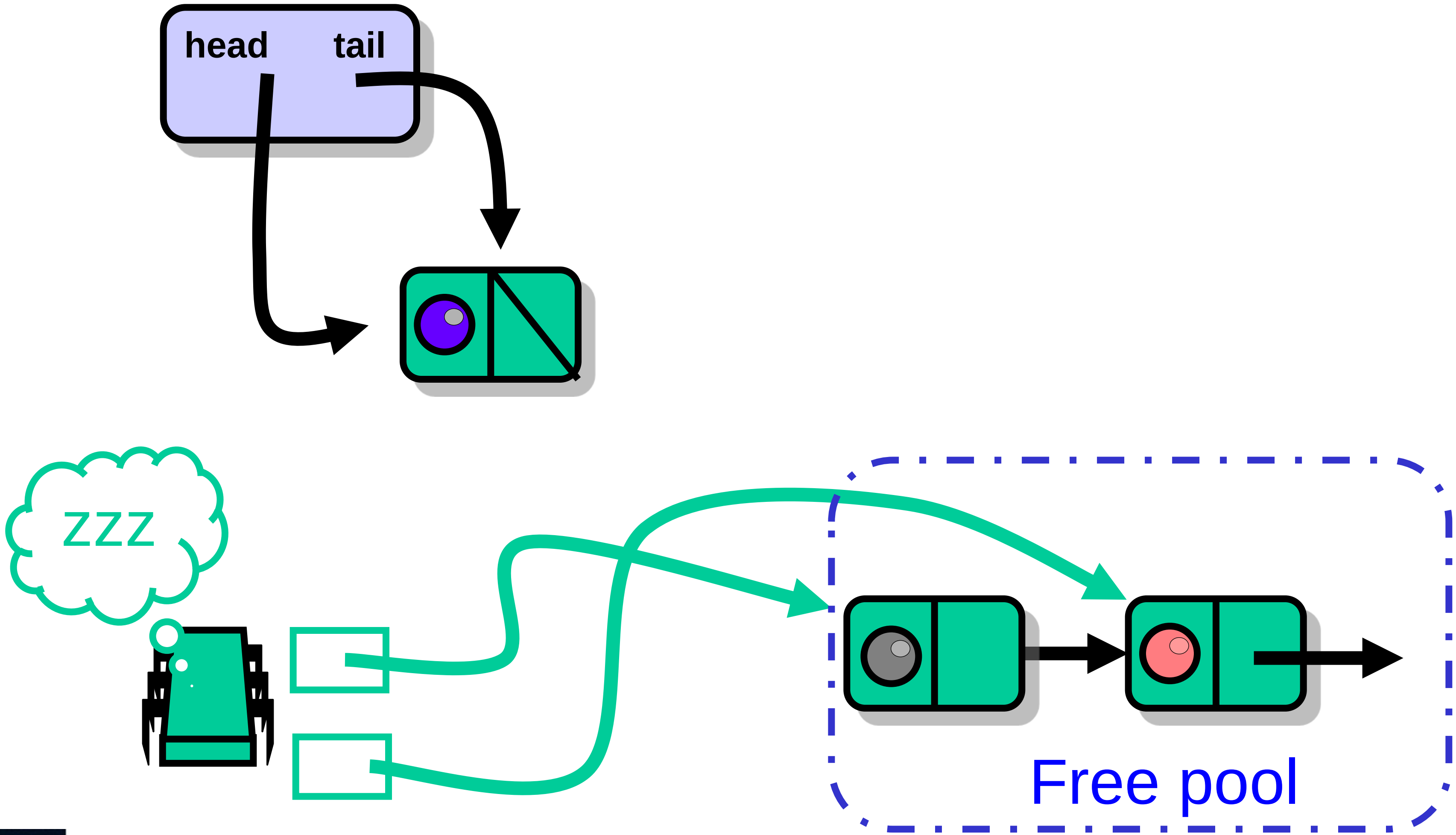


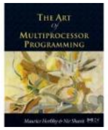
Why Recycling is Hard



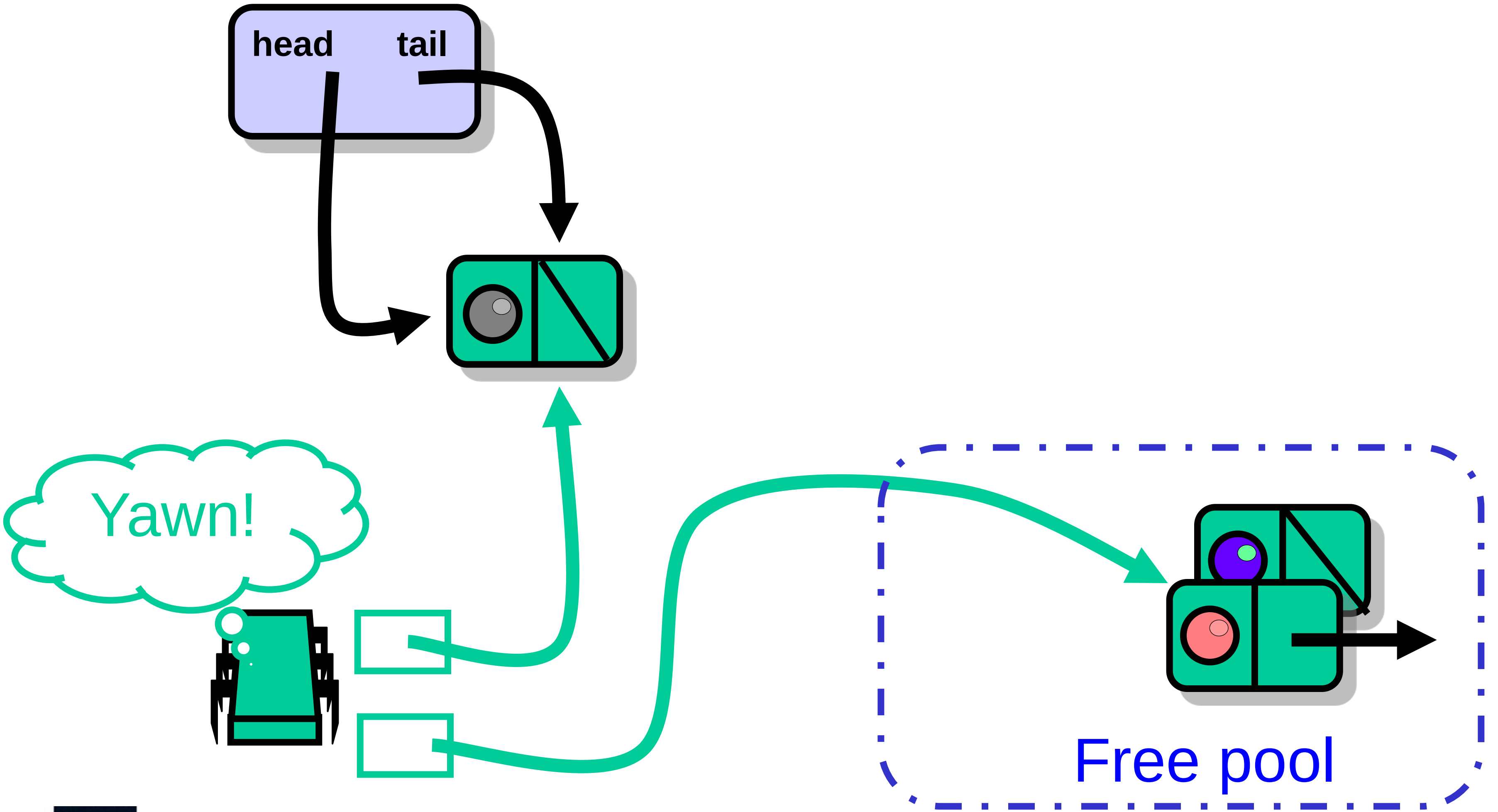


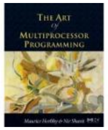
Both Nodes Reclaimed





One Node Recycled





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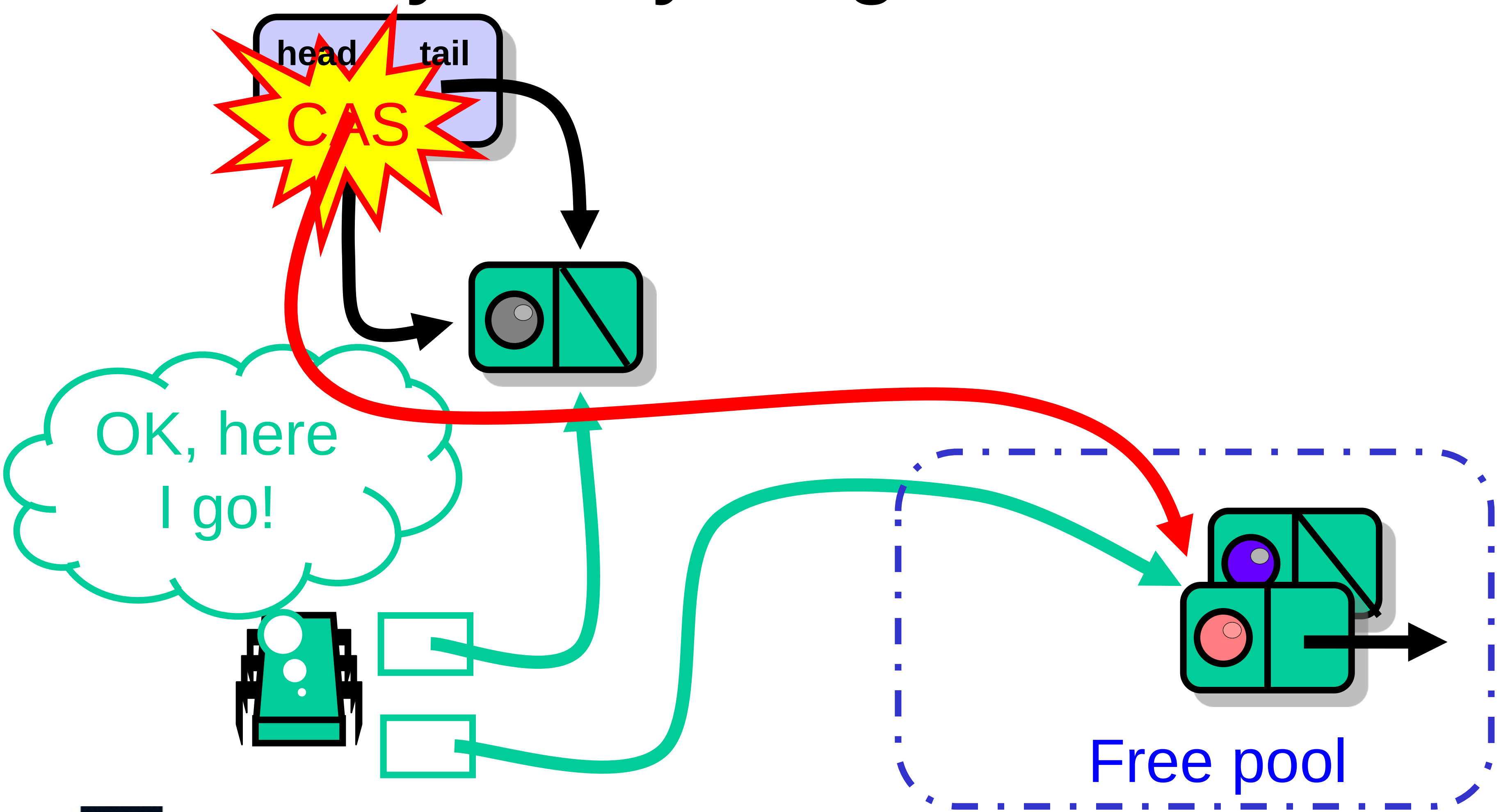
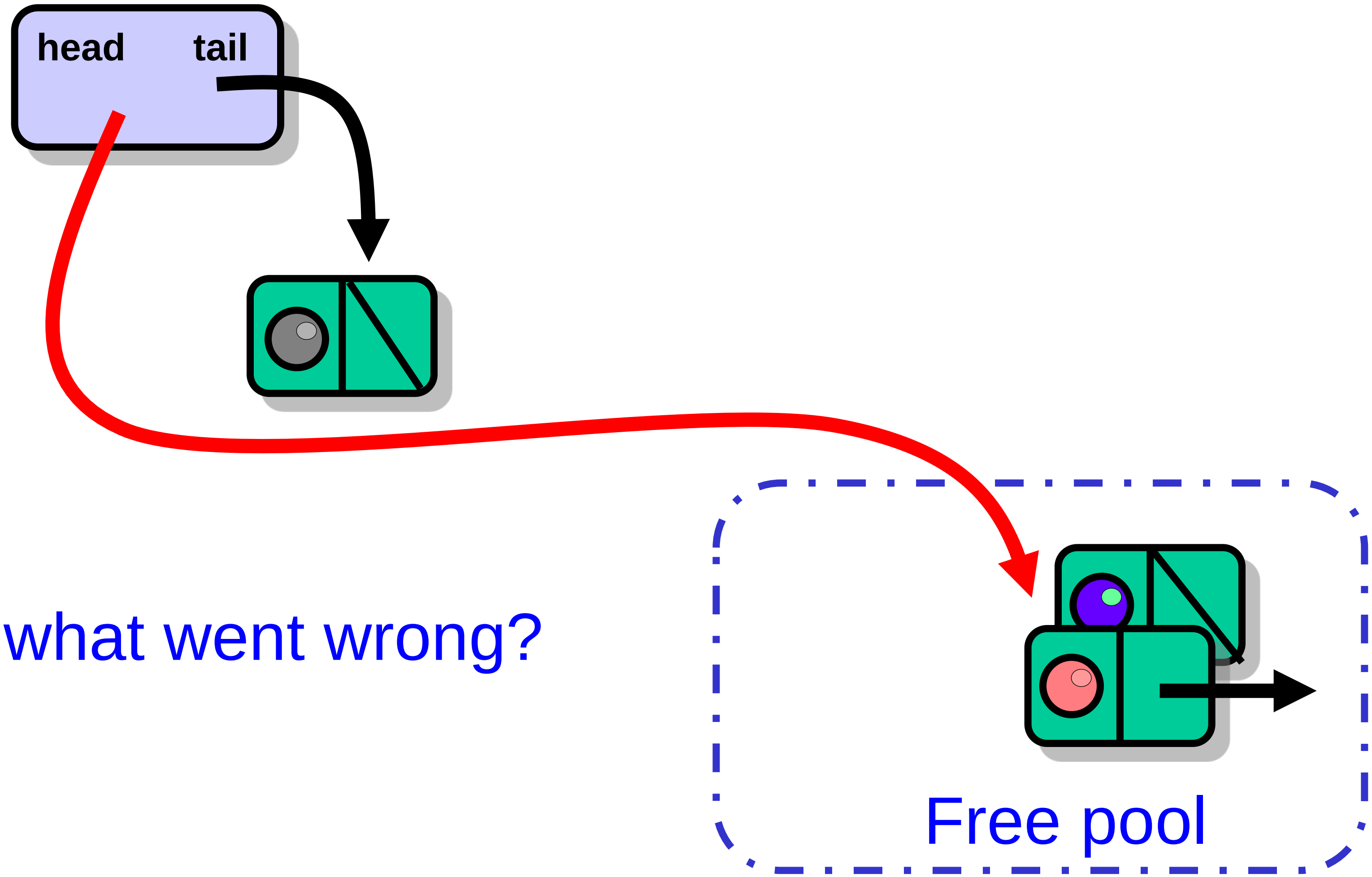
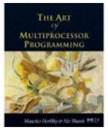


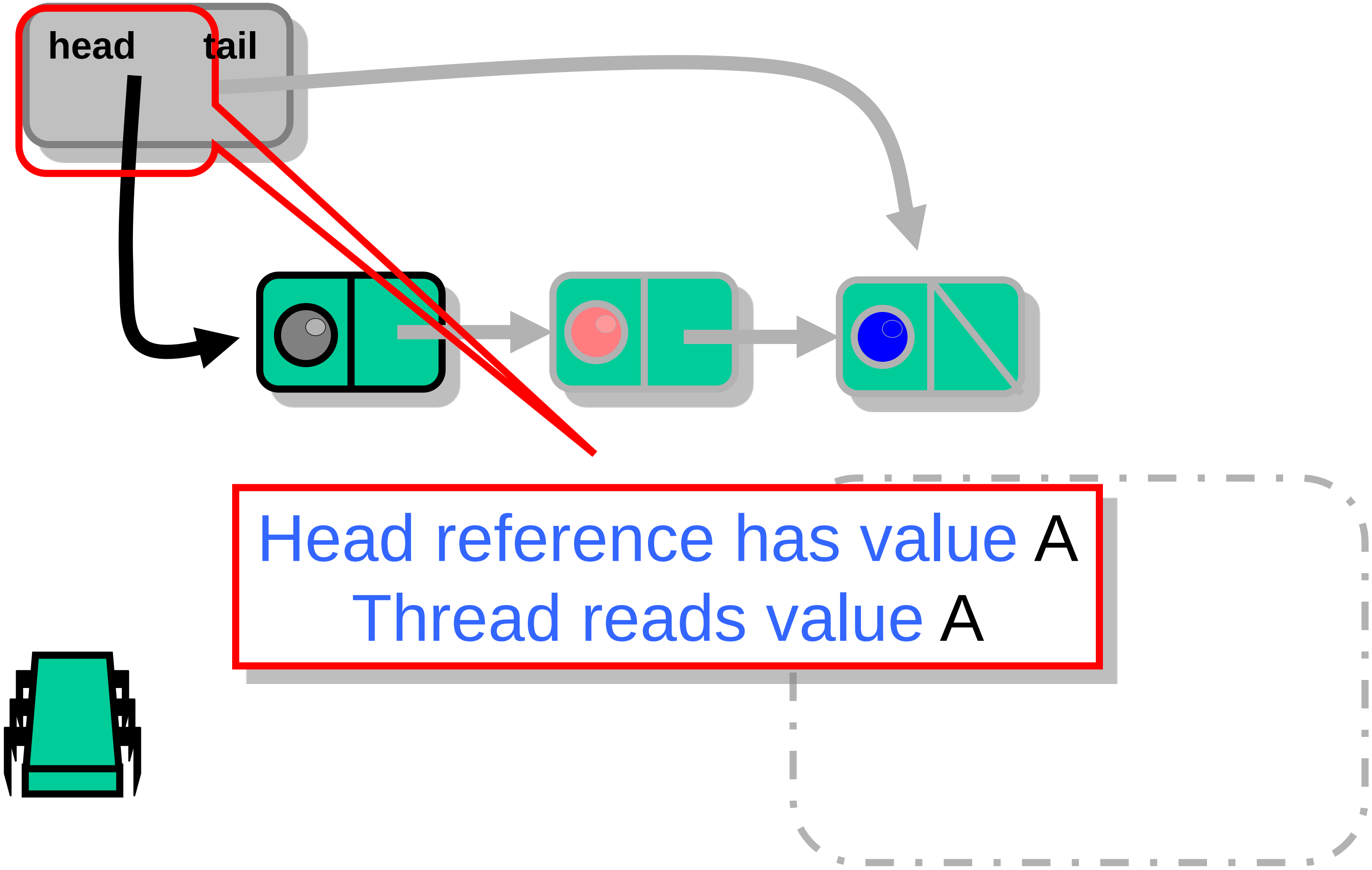
Recycle FAIL

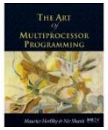


zOMG what went wrong?

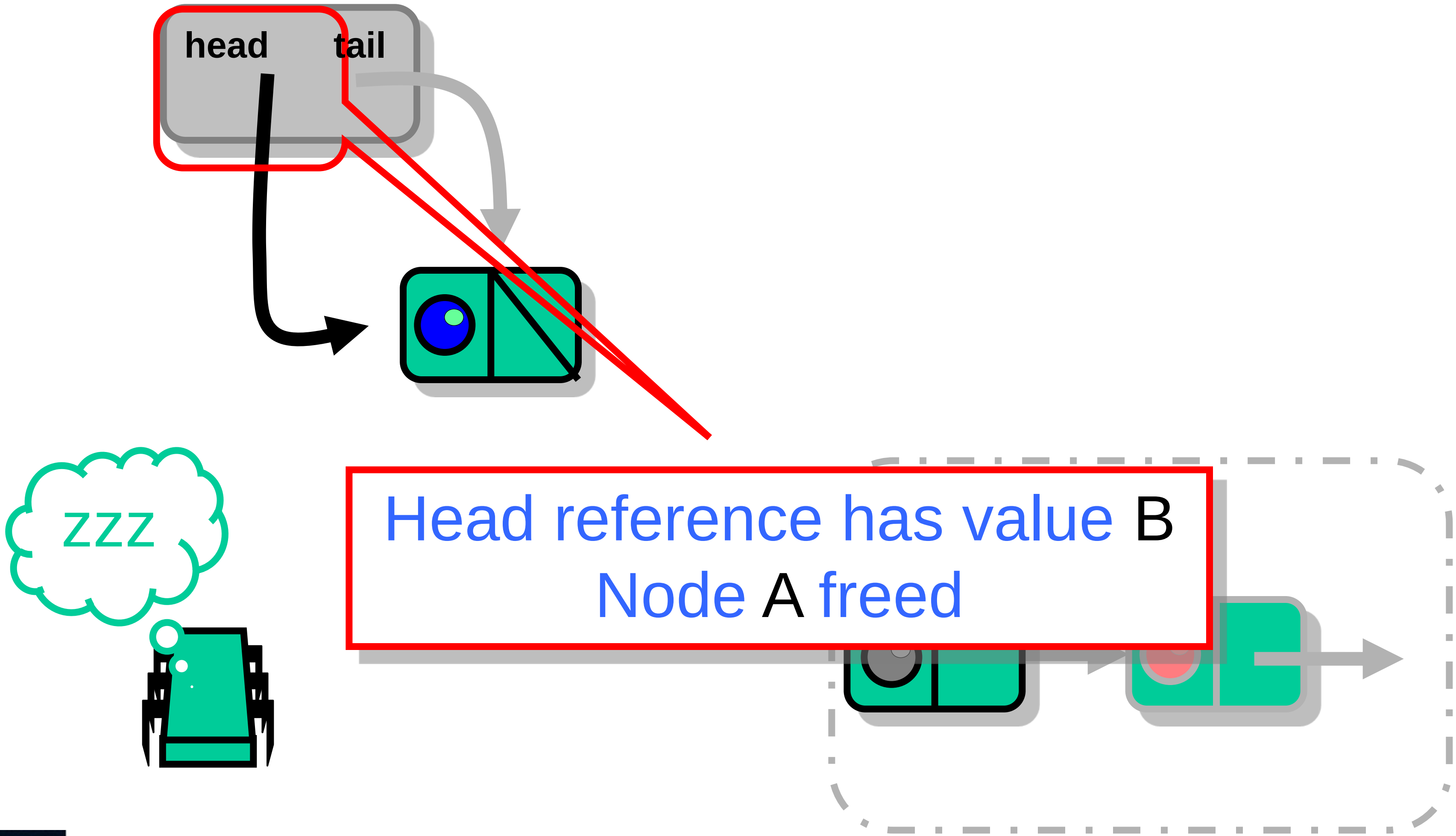


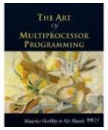
The Dreaded ABA Problem



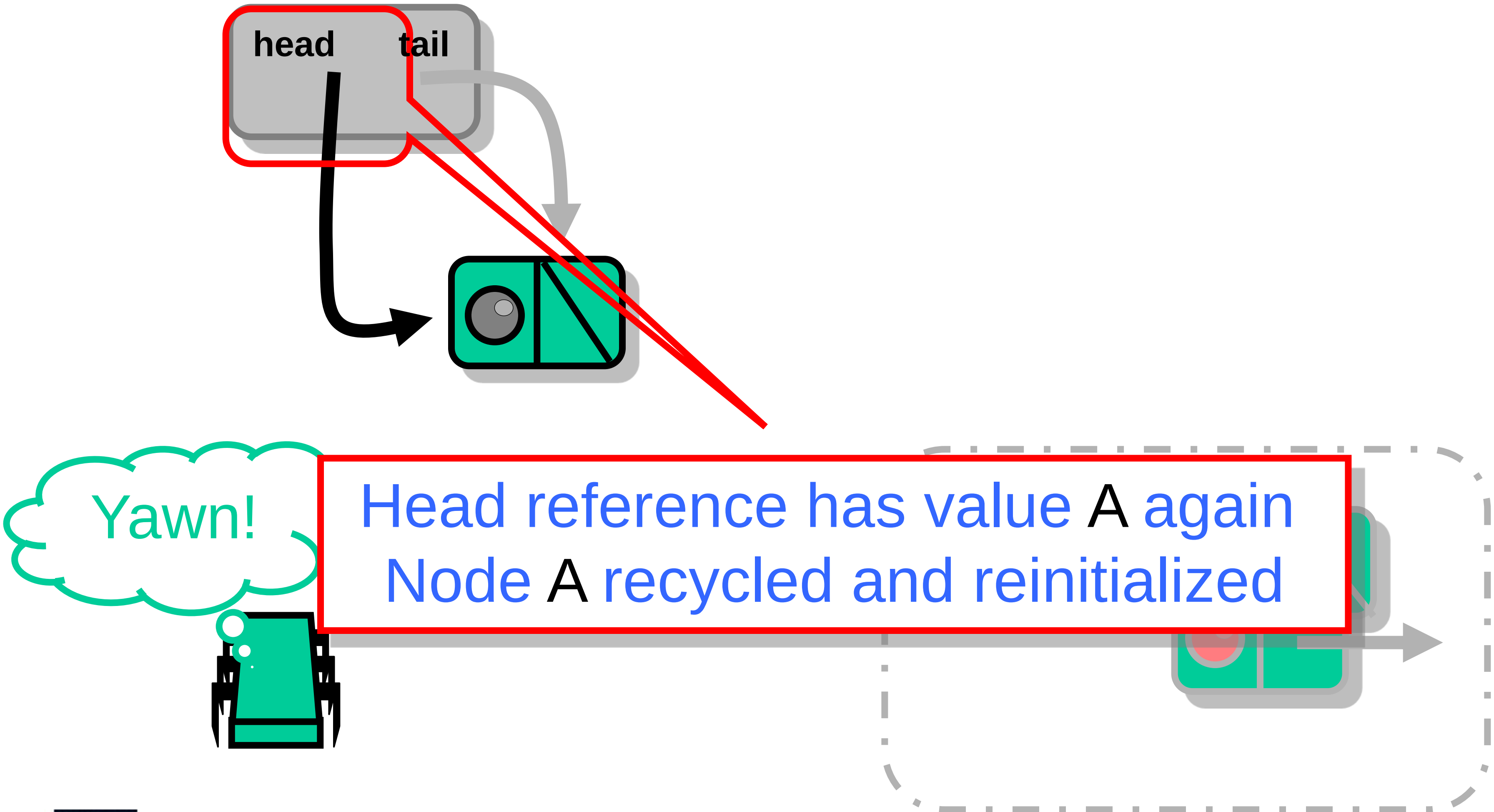


Dreaded ABA continued





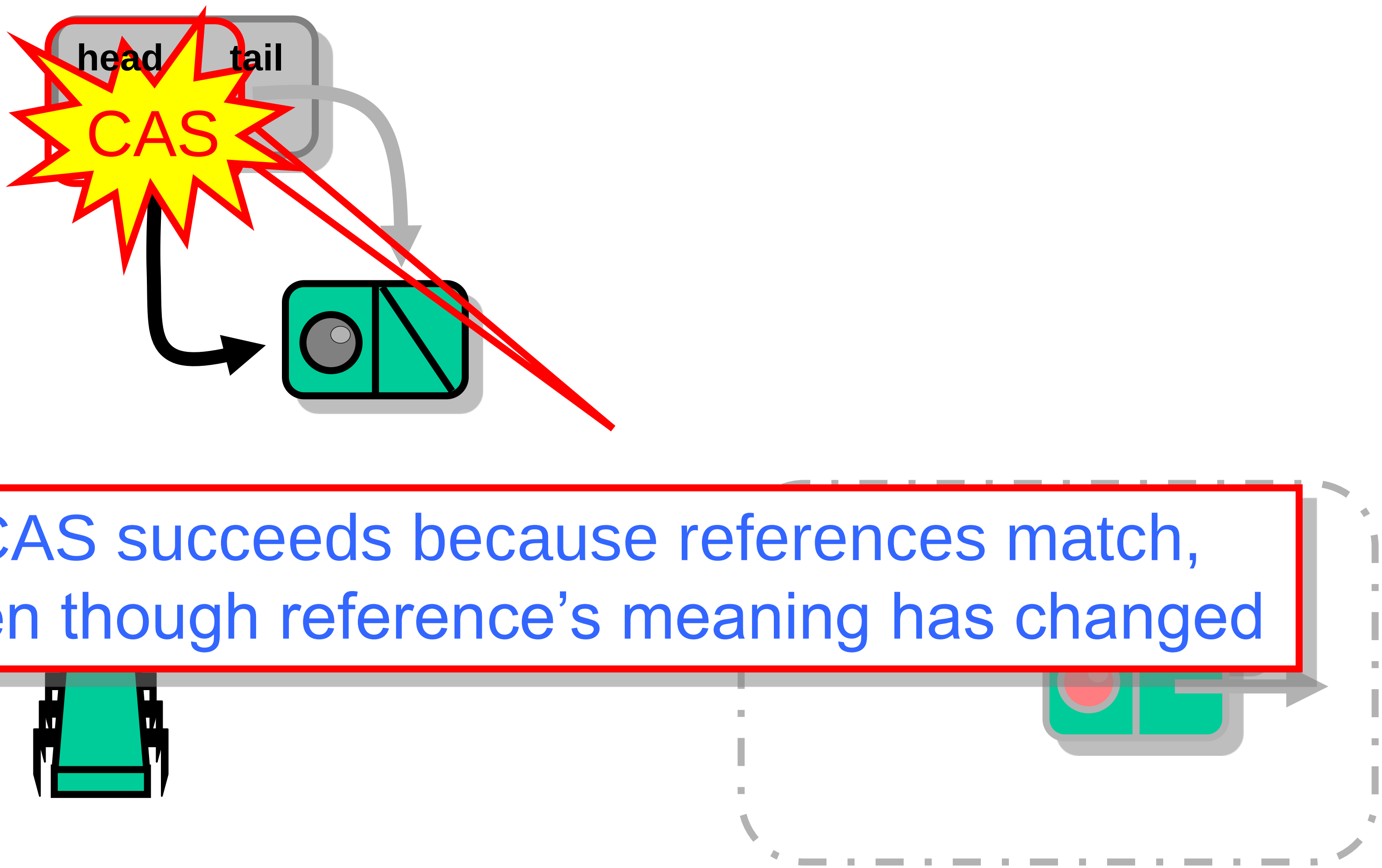
Dreaded ABA continued



Head reference has value A again

Node A recycled and reinitialized

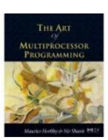
Dreaded ABA continued



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

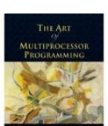
The Dreaded ABA FAIL

- Is a result of CAS() semantics
  - I blame Sun, Intel, AMD, …
- Not with Load-Locked/Store-Conditional
  - Good for IBM?



Dreaded ABA – A Solution

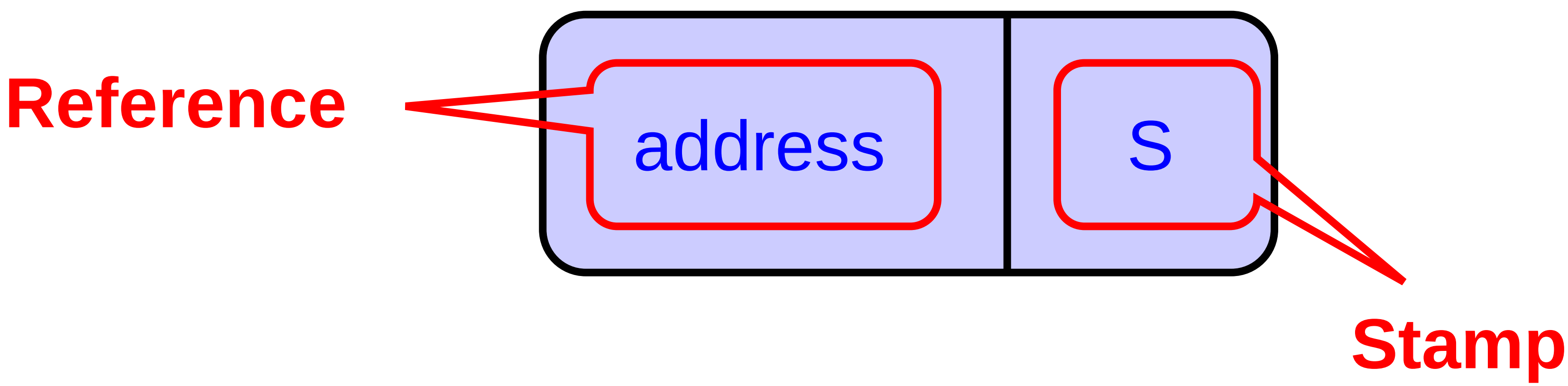
- Tag each pointer with a counter
- Unique over lifetime of node
- Pointer size vs word size issues
- Overflow?
  - Don’t worry be happy?
  - Bounded tags?
- AtomicStampedReference class

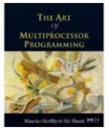


Atomic Stamped Reference

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

Can get reference & stamp atomically

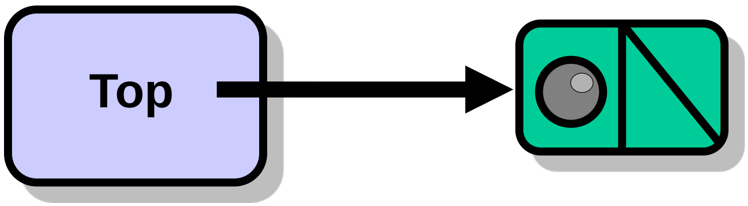


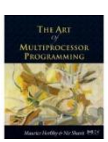


Concurrent Stack

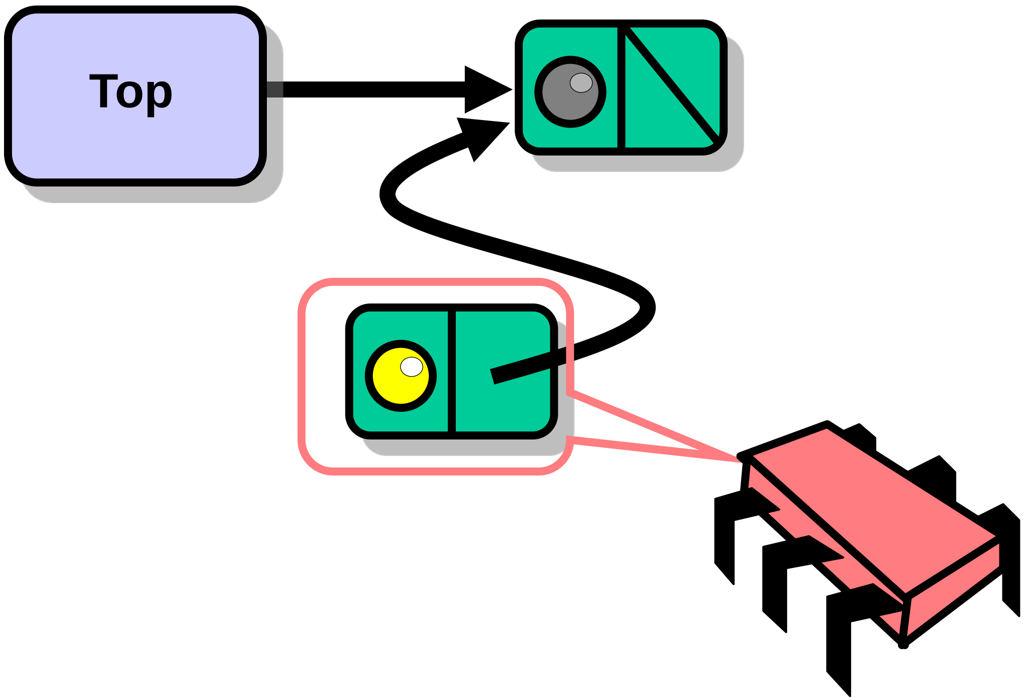
- Methods
  - **push(x)**
  - **pop()**
- Last-in, First-out (LIFO) order
- Lock-Free!

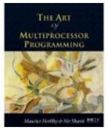
Empty Stack



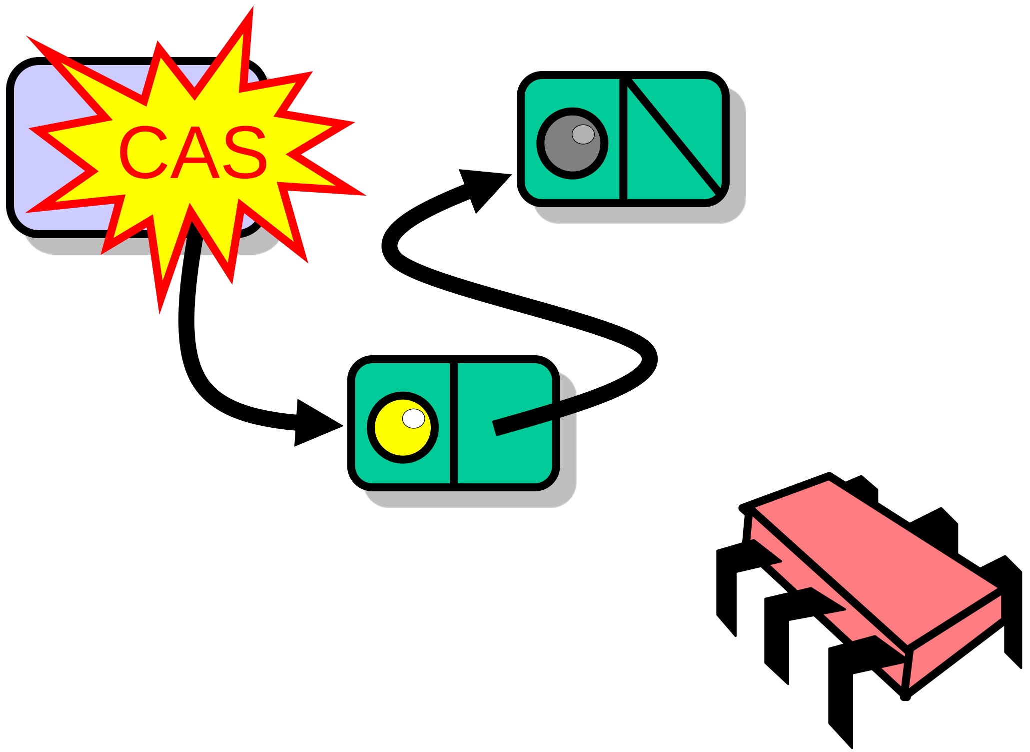


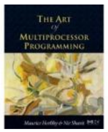
Push



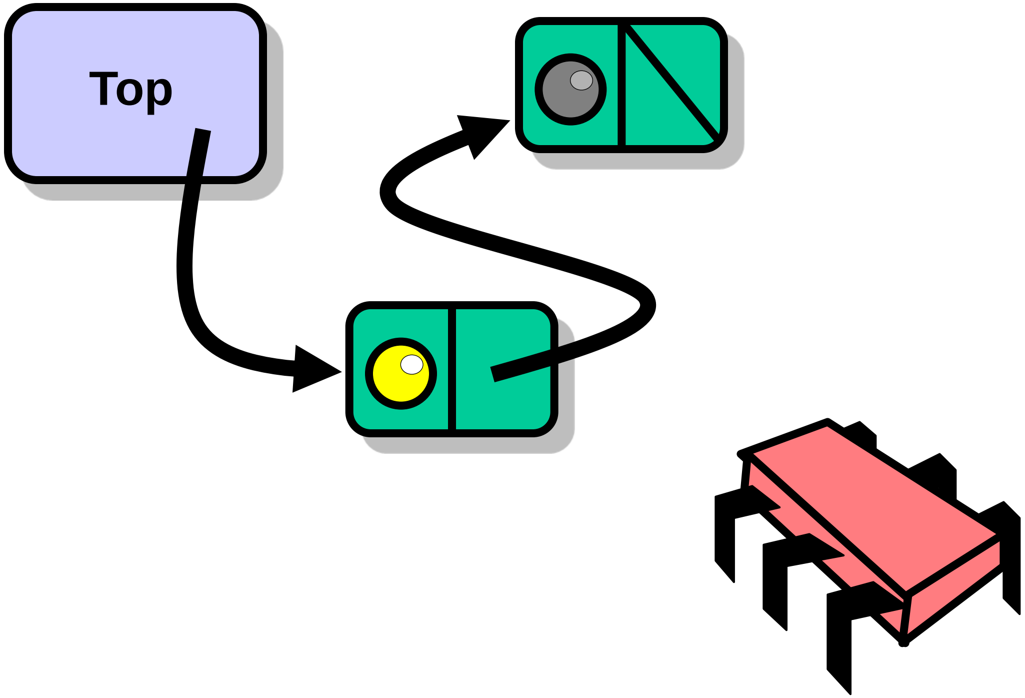


Push

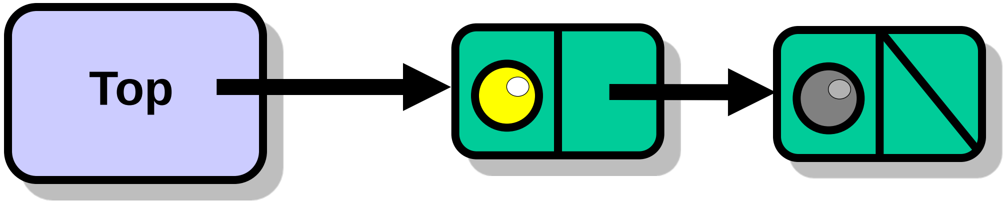


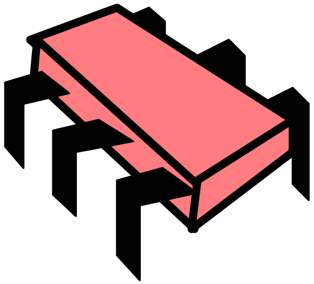


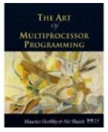
Push



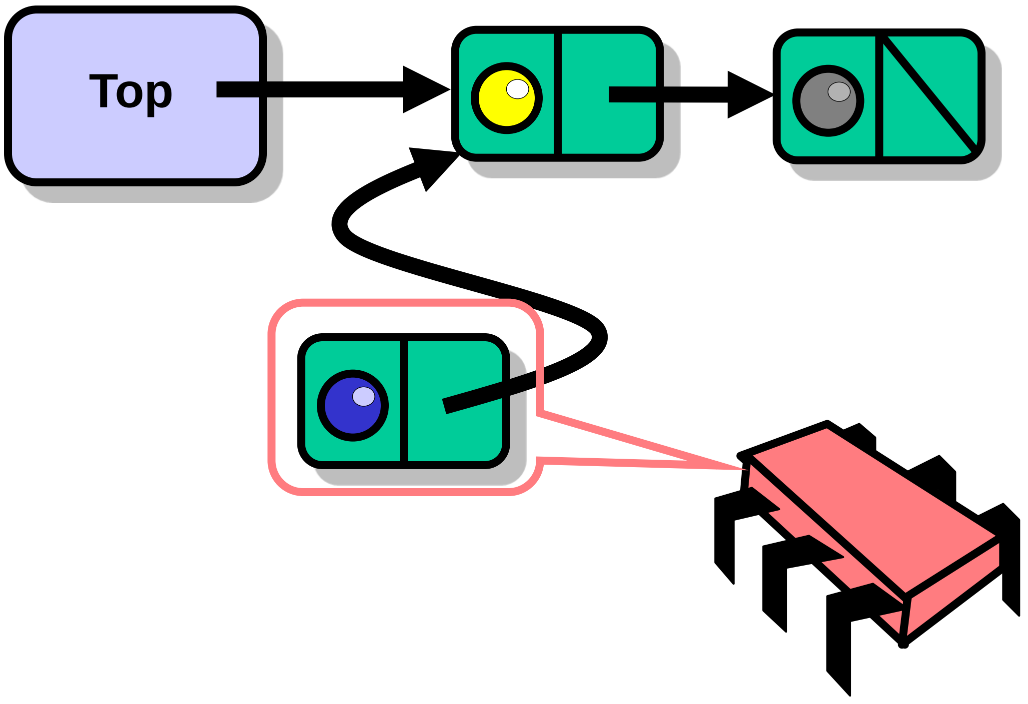
Push

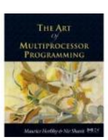




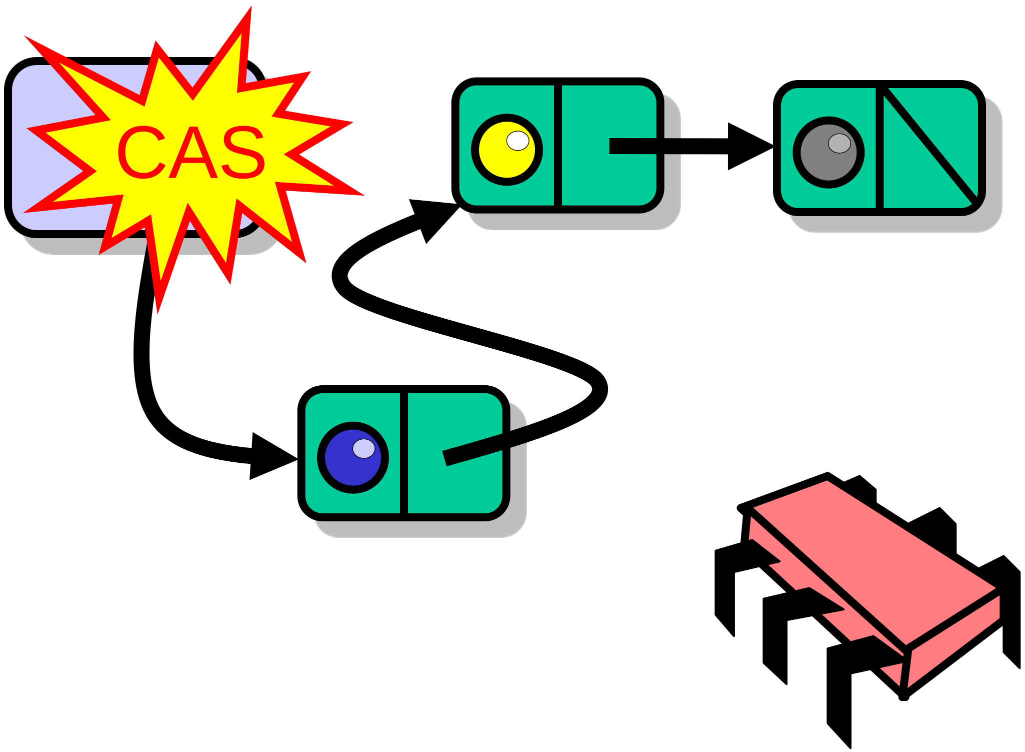


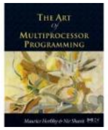
Push



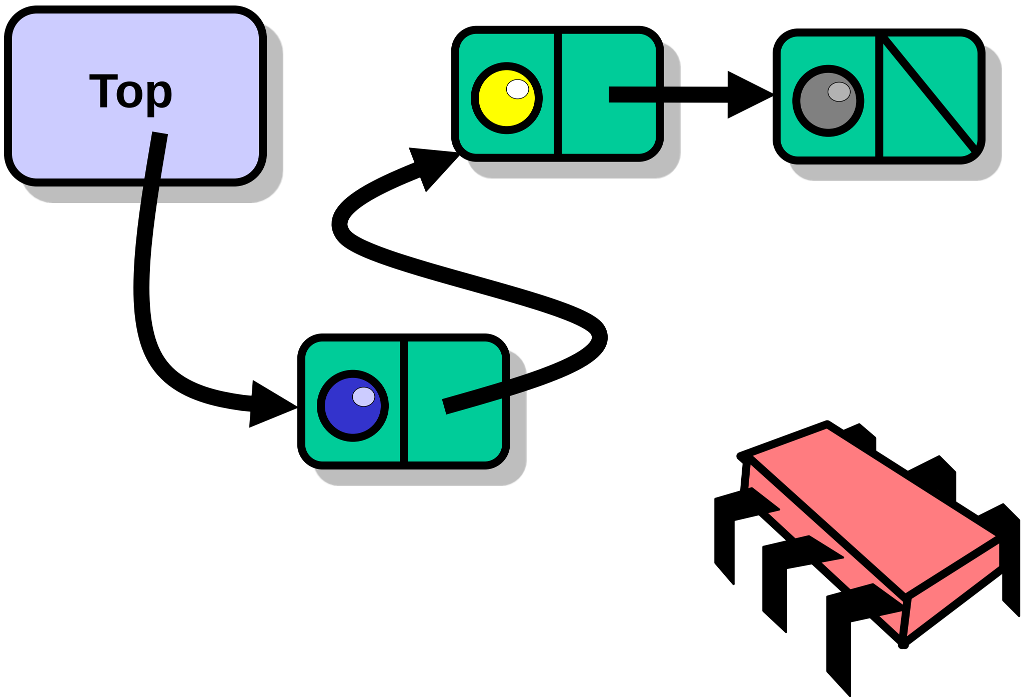


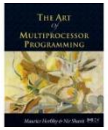
Push



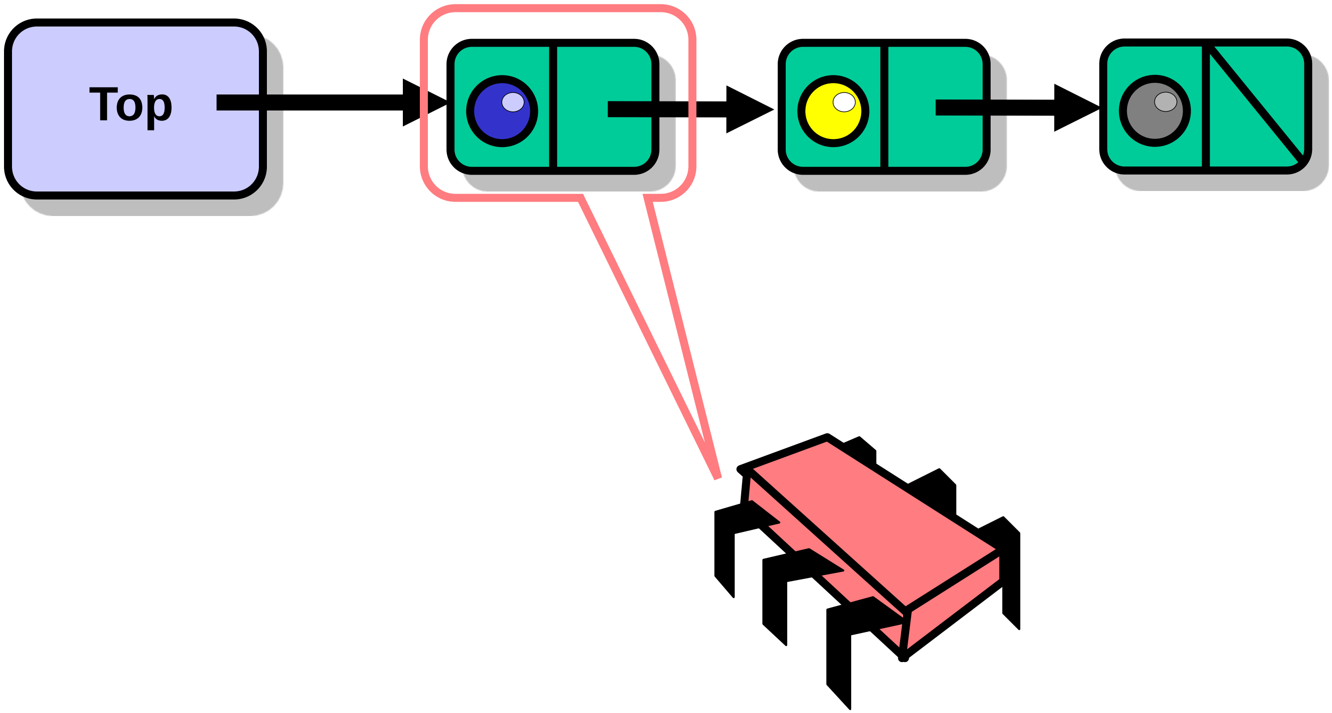


Push

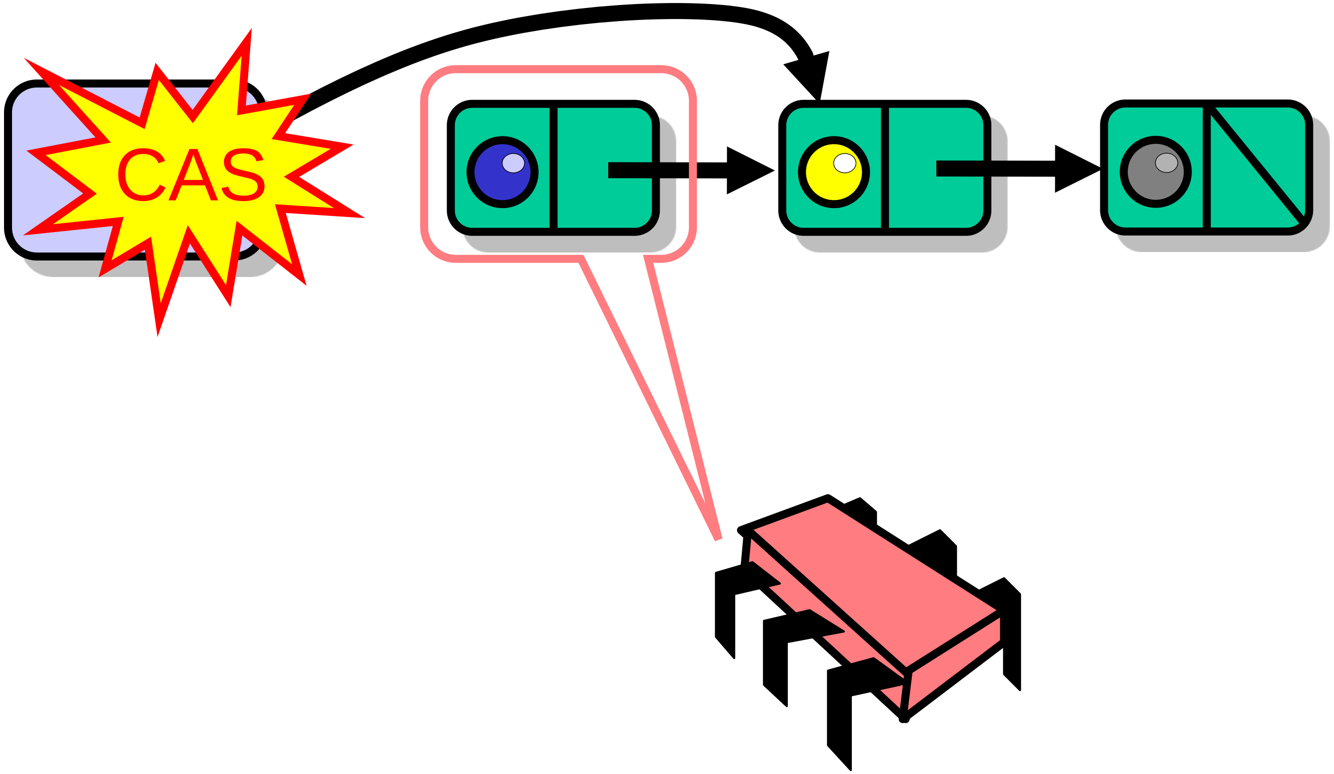


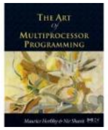


Pop

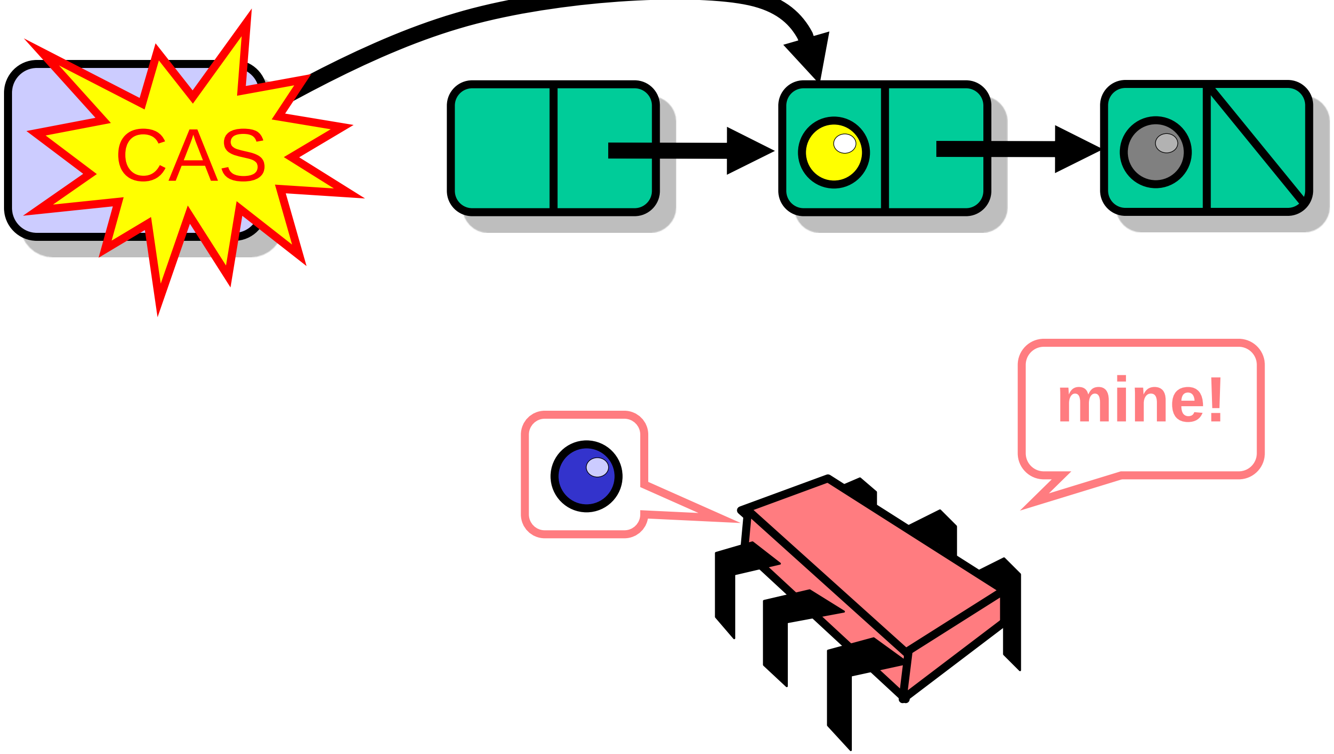


Pop

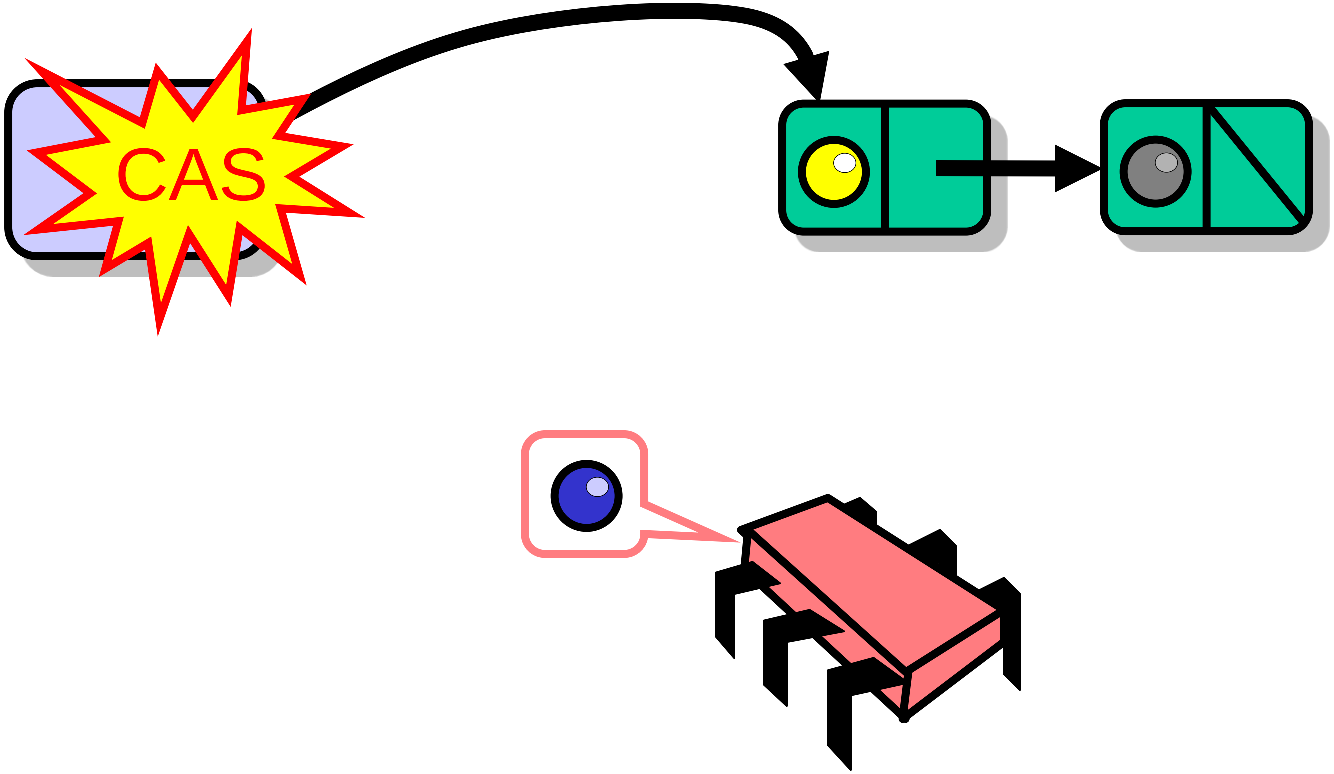




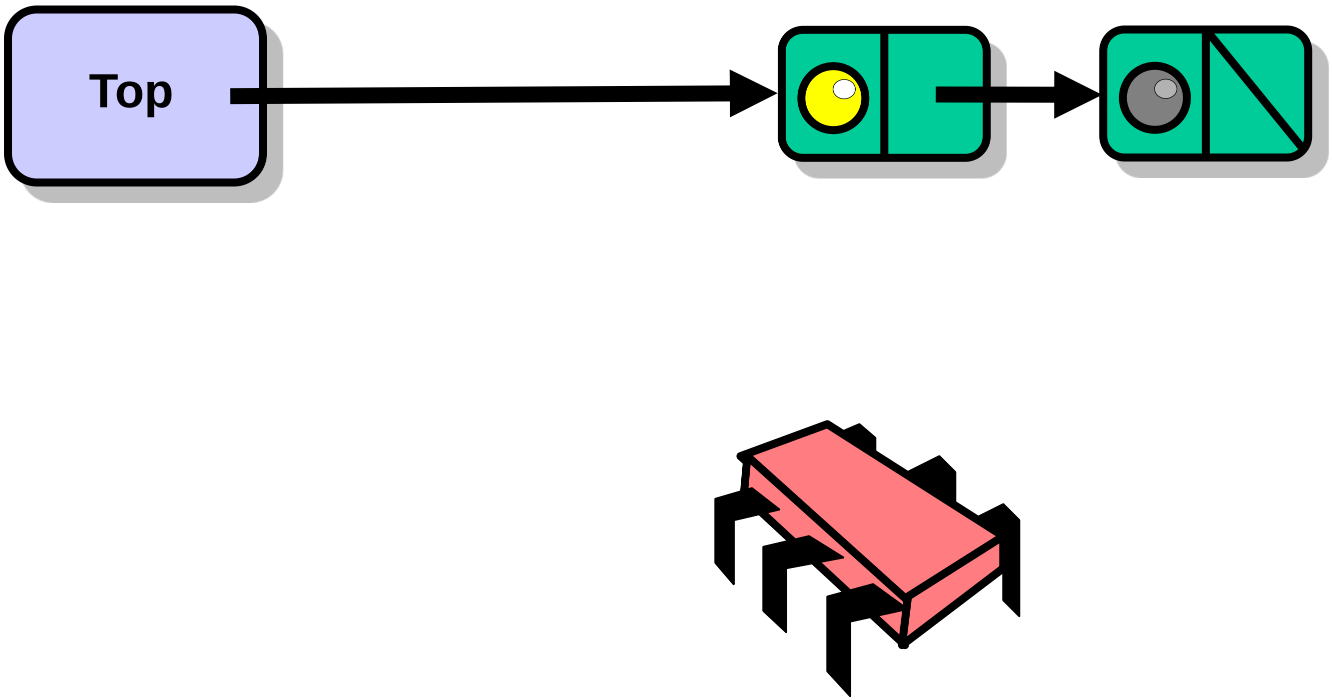
Pop

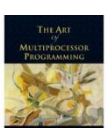


Pop



Pop



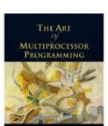


Lock-free Stack

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

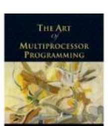
Big Question

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

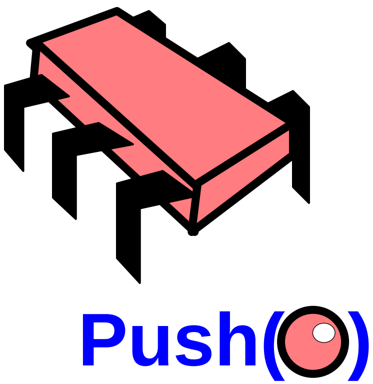


Elimination-Backoff Stack

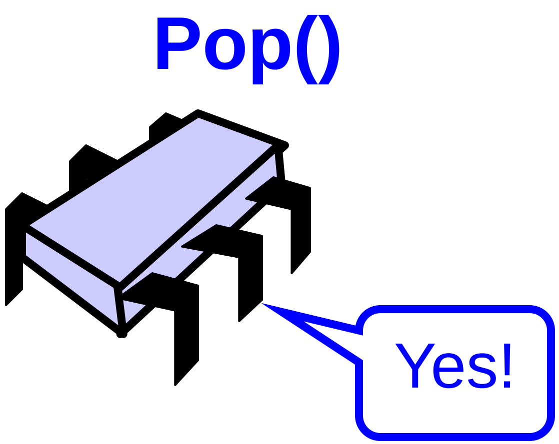
- How to
  - "turn contention into parallelism"
- Replace familiar
  - **exponential backoff**
- With alternative
  - **elimination-backoff**



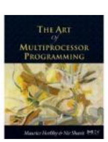
Observation



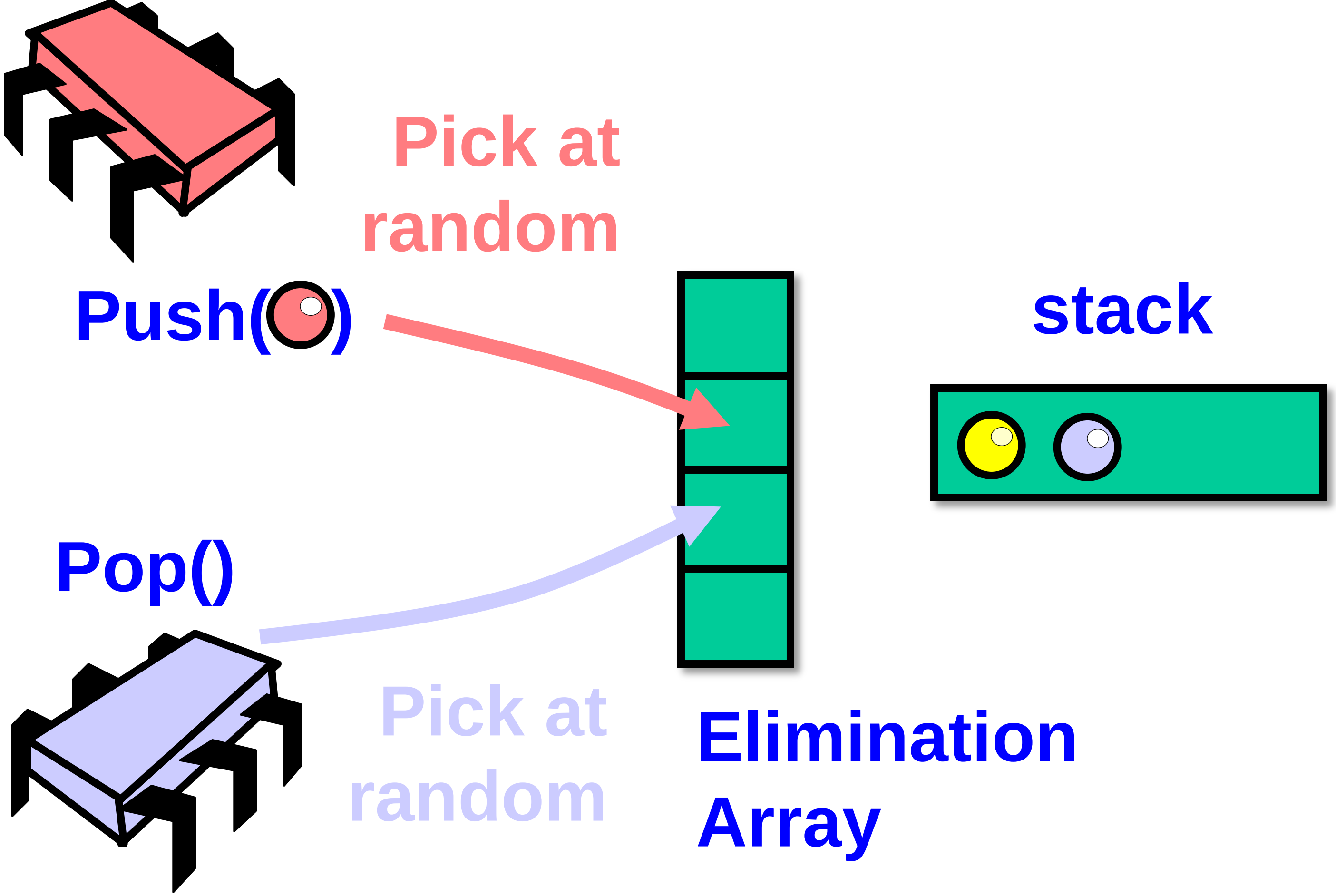
linearizable stack

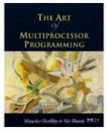


After an equal number of pushes and pops, stack stays the same

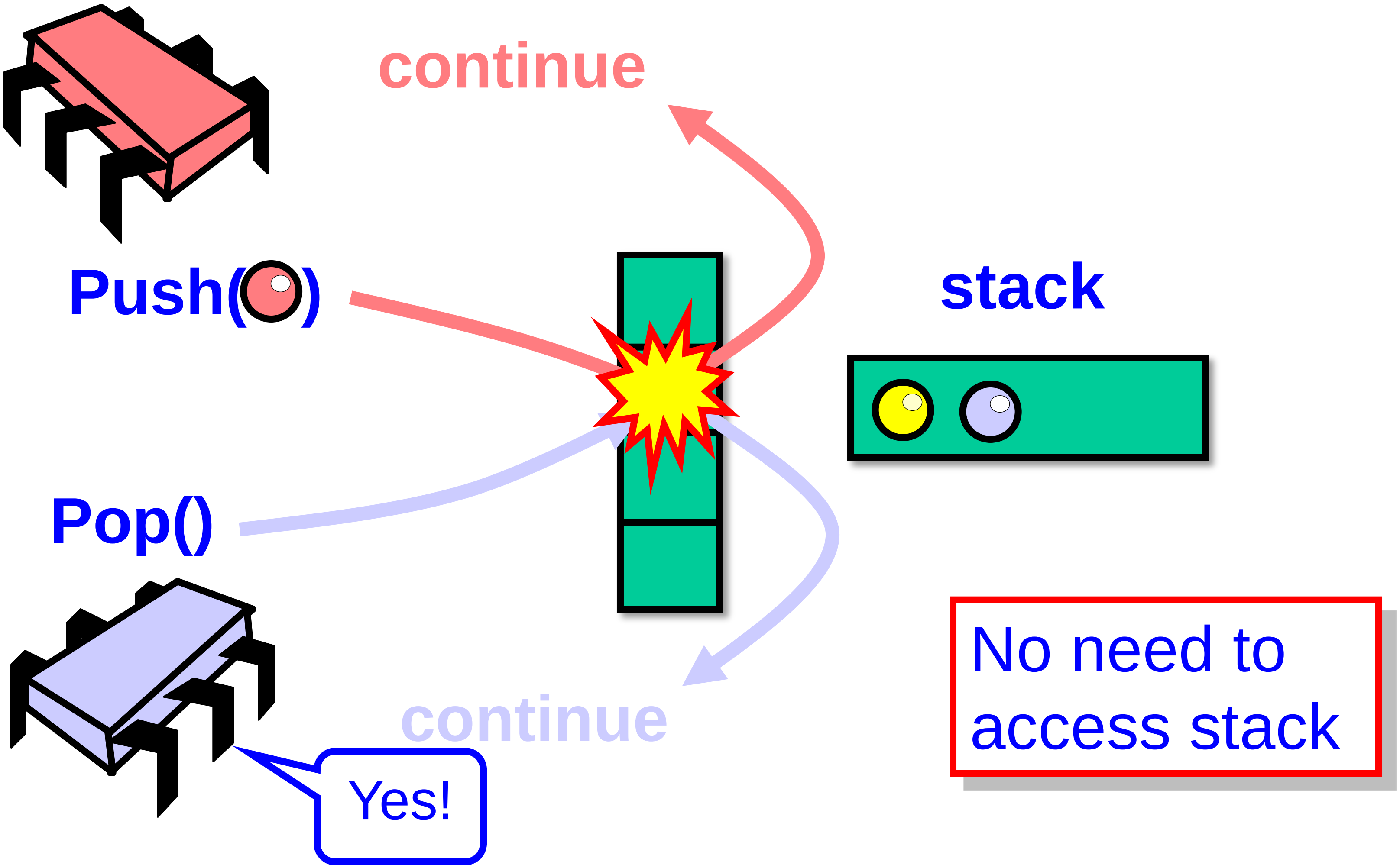


Idea: Elimination Array

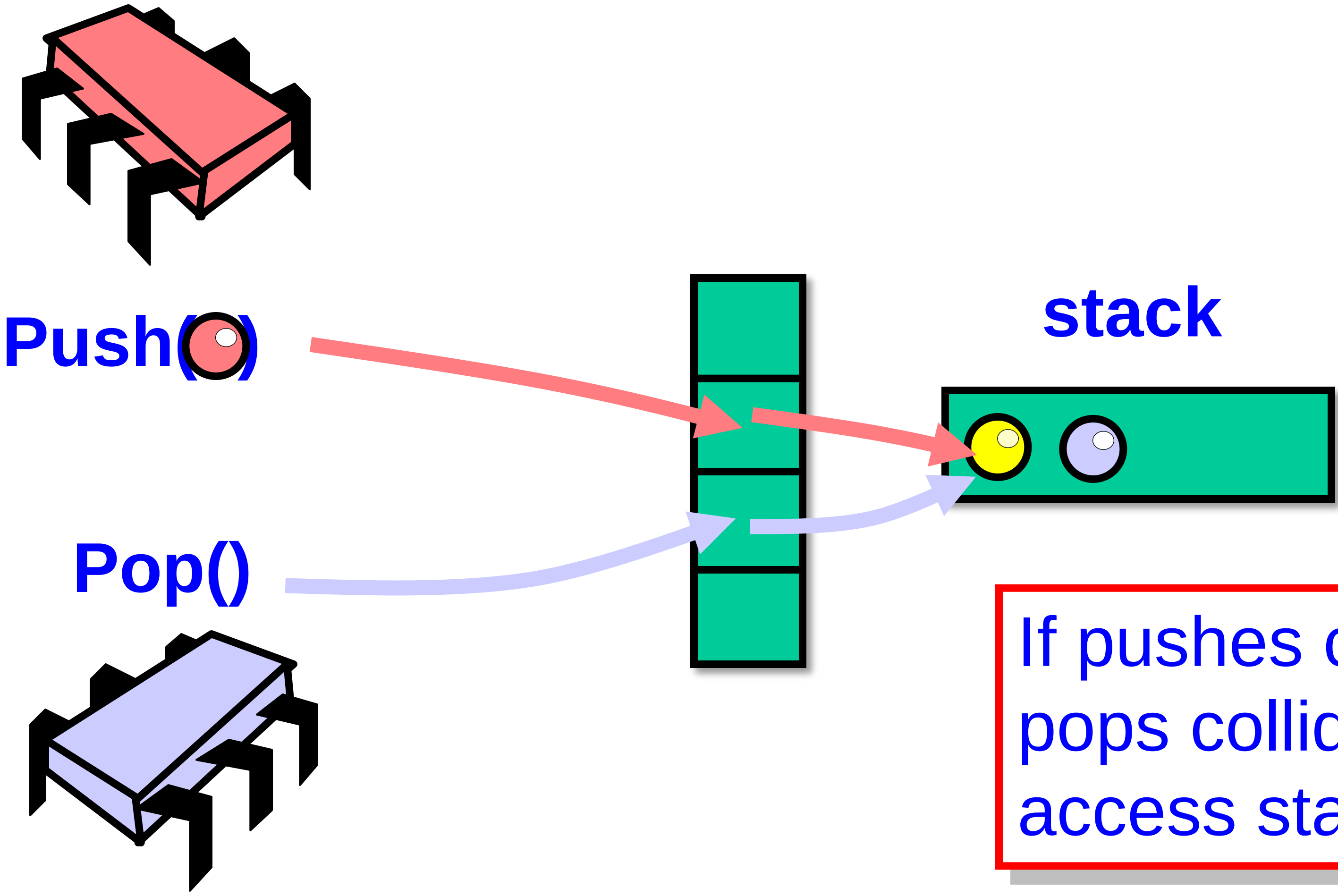




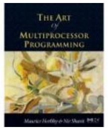
Push Collides With Pop



No Collision



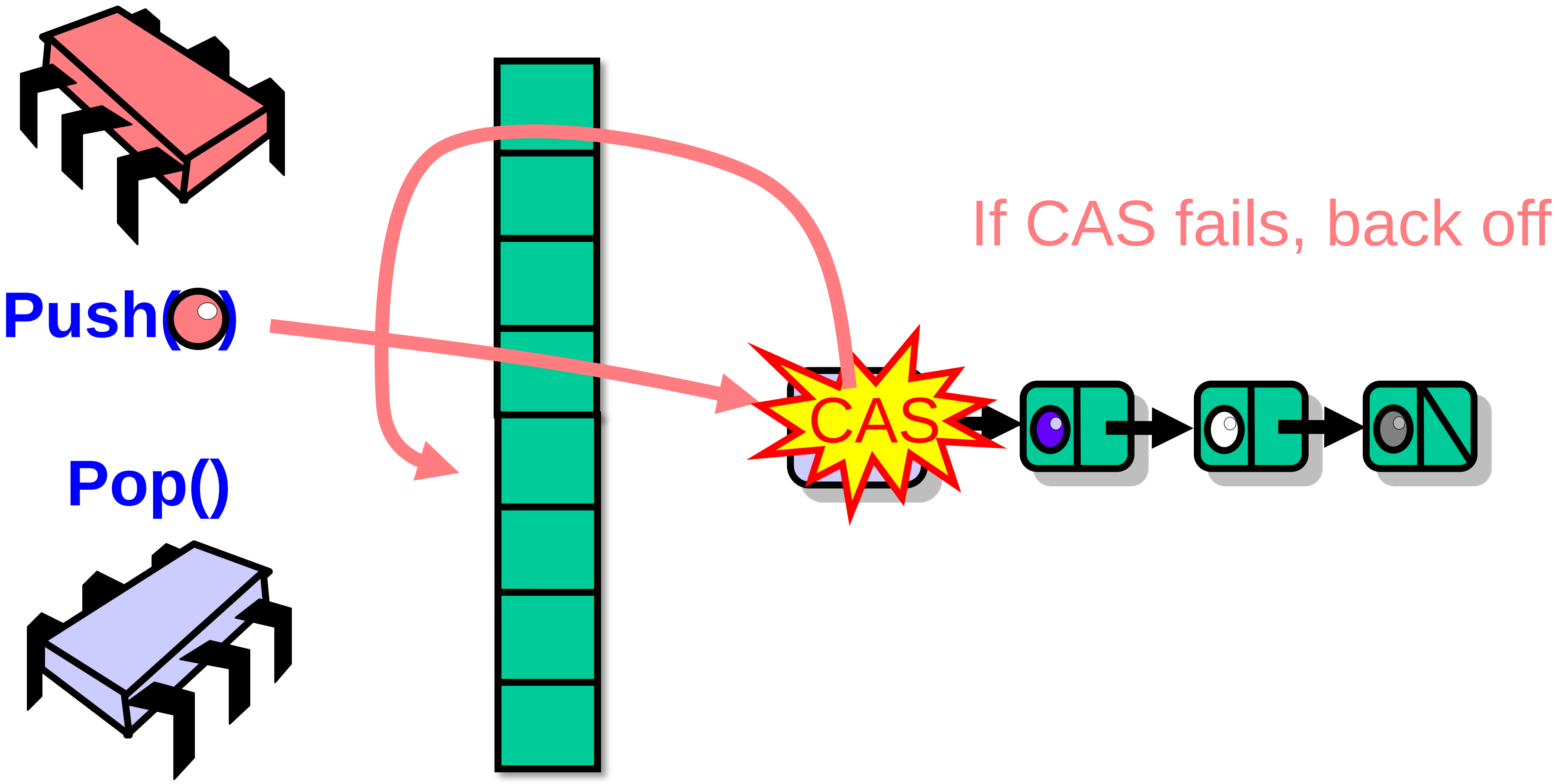
If pushes collide or pops collide access stack

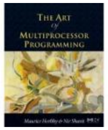


Elimination-Backoff Stack

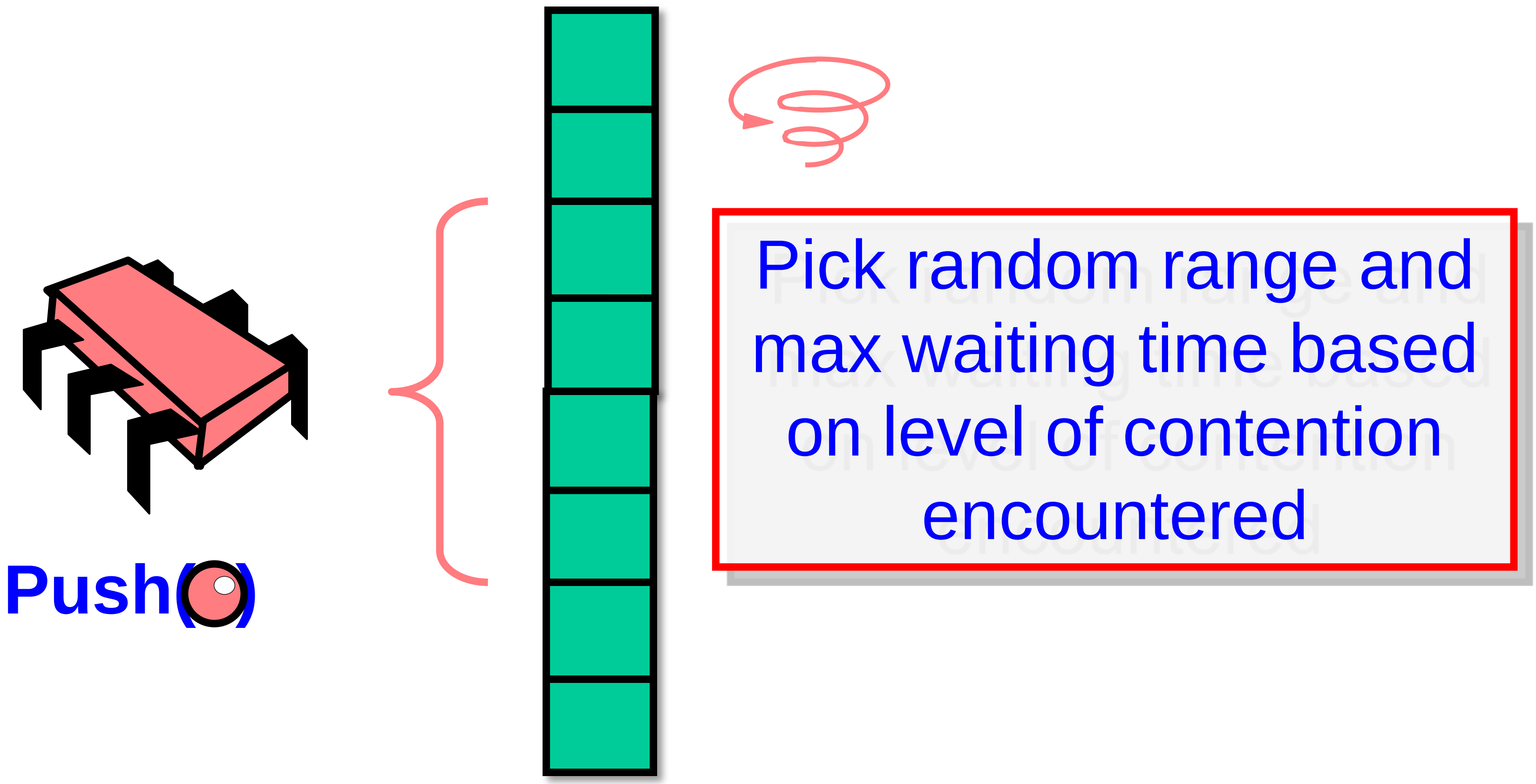
- Lock-free stack + elimination array
- Access Lock-free stack,
  - If **uncontended**, apply operation
  - if **contended**, back off to elimination array and attempt elimination

Elimination-Backoff Stack



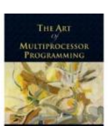


Dynamic Range and Delay

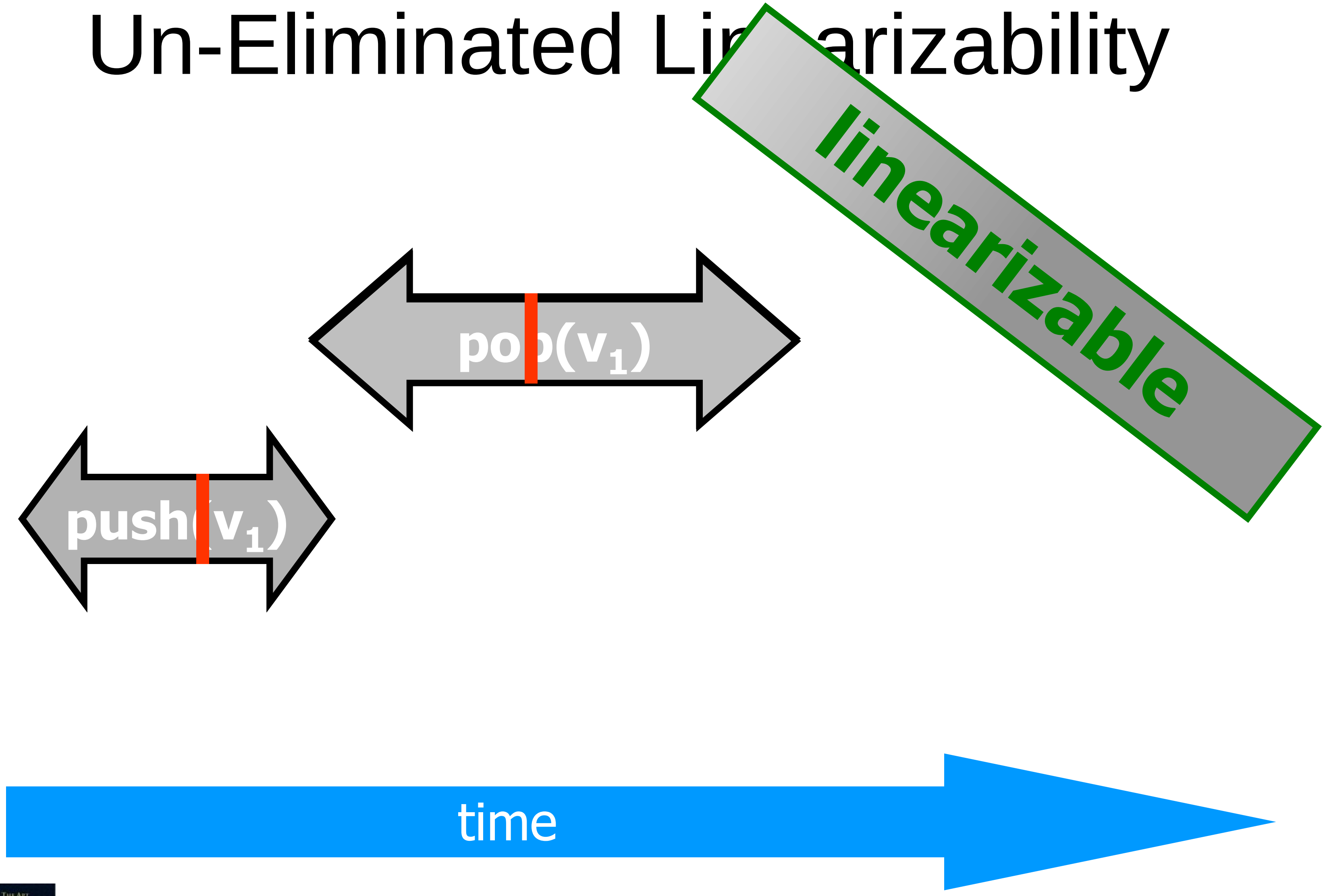


Linearizability

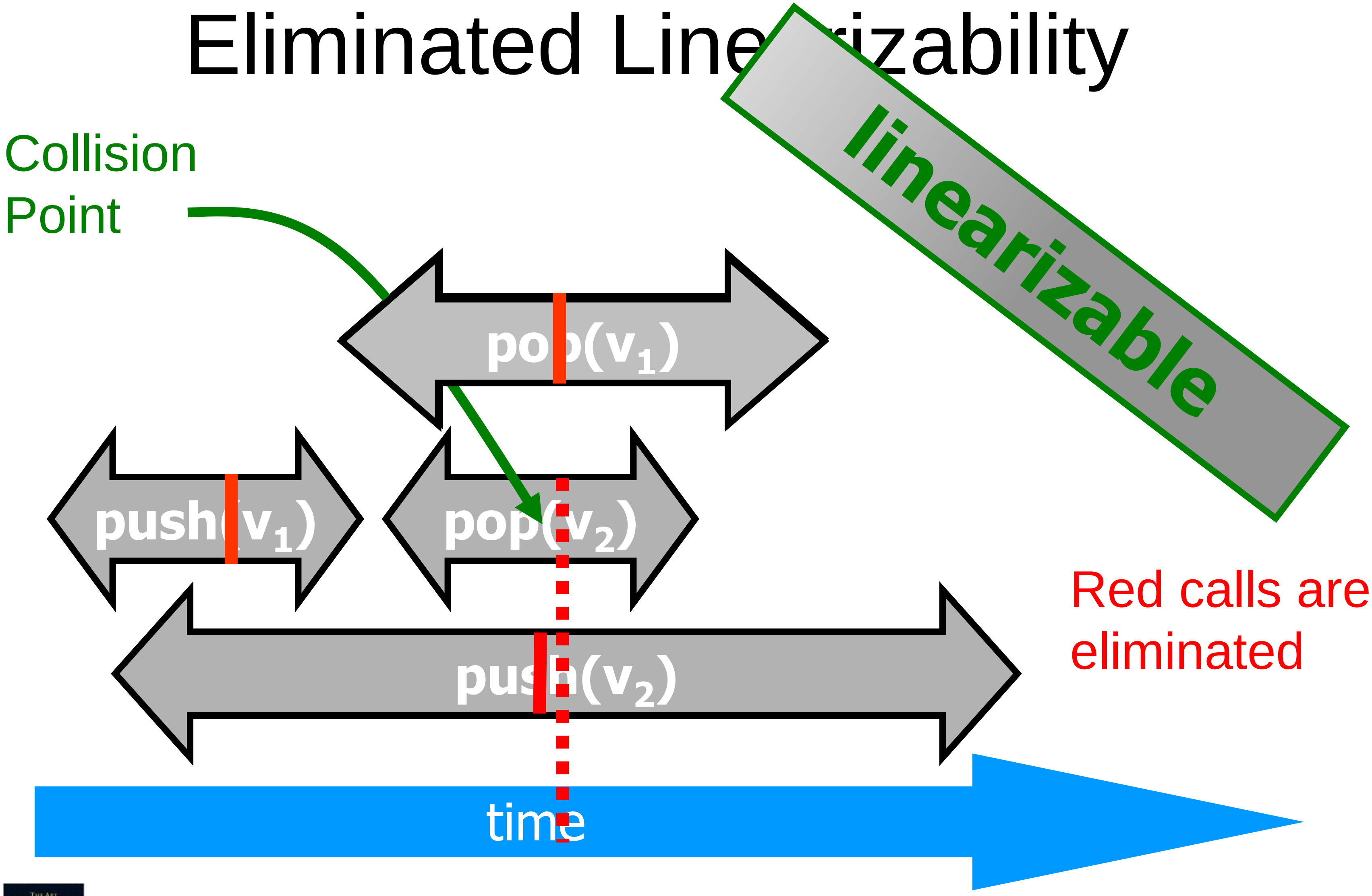
- **Un-eliminated calls**
  - **linearized as before**
- **Eliminated calls:**
  - **linearize pop() immediately after matching push()**
- **Combination is a linearizable stack**



Un-Eliminated Linearizability



Eliminated Linearizability

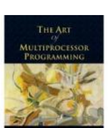


Backoff Has Dual Effect

- 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 = ...;
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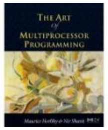
  Exchanger<T>[] exchanger;
  public EliminationArray(int capacity) {
   exchanger = new Exchanger[capacity];
   for (int i = 0; i < capacity; i++)
    exchanger[i] = new Exchanger<T>();
   …
   }
   …
}
```

An array of *Exchangers*



Digression: A Lock-Free Exchanger

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

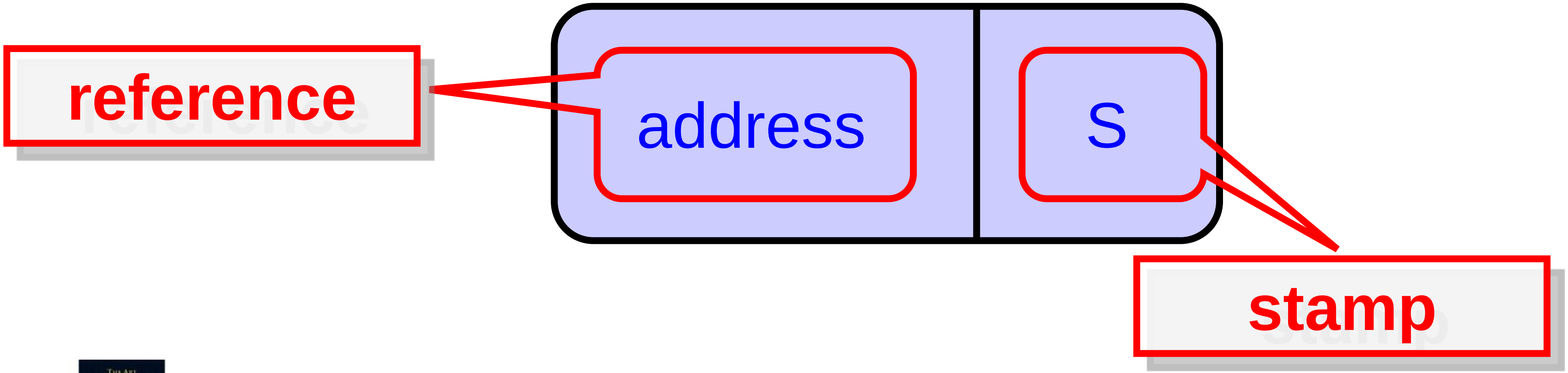
A Lock-Free Exchanger

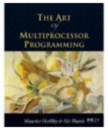
```
public class Exchanger<T> {
  AtomicStampedReference<T> slot
    = new AtomicStampedReference<T>(null, 0);
```

Atomically modifiable reference + status

Atomic Stamped Reference

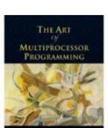
- **AtomicStampedReference** class
  - Java.util.concurrent.atomic package
- In C or C++:





Extracting Reference & Stamp

```
public T get(int[] stampHolder);
```

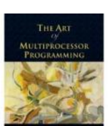


Extracting Reference & Stamp

```
public T get(int[] stampHolder);
```

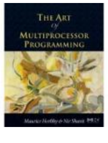
Returns reference to object of type T

Returns stamp at array index 0!



Exchanger Status

```
enum Status {EMPTY, WAITING, BUSY};
```



Exchanger Status

```
enum Status {EMPTY, WAITING, BUSY};
```

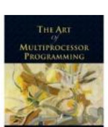
Nothing yet

Exchange Status

```
enum Status {EMPTY, WAITING, BUSY};
```

Nothing yet

One thread is waiting for rendez-vous



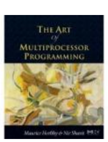
Exchange Status

```
enum Status {EMPTY, WAITING, BUSY};
```

- EMPTY: Nothing yet
- WAITING: One thread is waiting for rendez-vous
- BUSY: Other threads busy with rendez-vous

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
  }
 }
```



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  int stamp = stampHolder[0];
  switch(stamp) {
   case EMPTY: …    // slot is free
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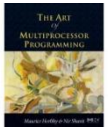
  }
 }
```

Item and timeout



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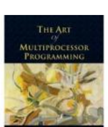
  int stamp = stampHolder[0];
  switch(stamp) {
   case EMPTY: …    // slot is free
   case WAITING: … // someone waiting for me
   case BUSY: …    // others exchanging
  }
 }
```

Array holds status



The Exchange

```
public T Exchange(T myItem, long nanos) throws
TimeoutException {
    long timeBound = System.nanoTime() + nanos;
    int[] stampHolder = {0};
    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

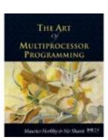
```
public T Exchange(T myItem, long nanos) throws
TimeoutException {
    long timeBound = System.nanoTime() + nanos;
    int[] stampHolder = {0};
    while (true) {
      if (System.nanoTime() > timeBound)
        throw new TimeoutException();
      T herItem = slot.get(stampHolder);
      int stamp = 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

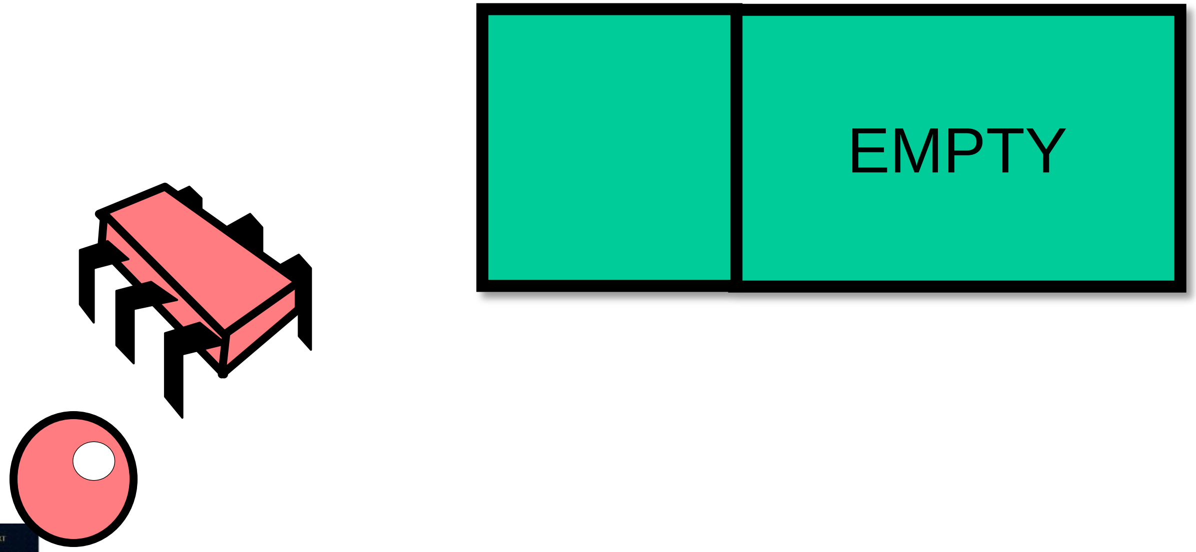
The Exchange

```
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
        }
    }}
```

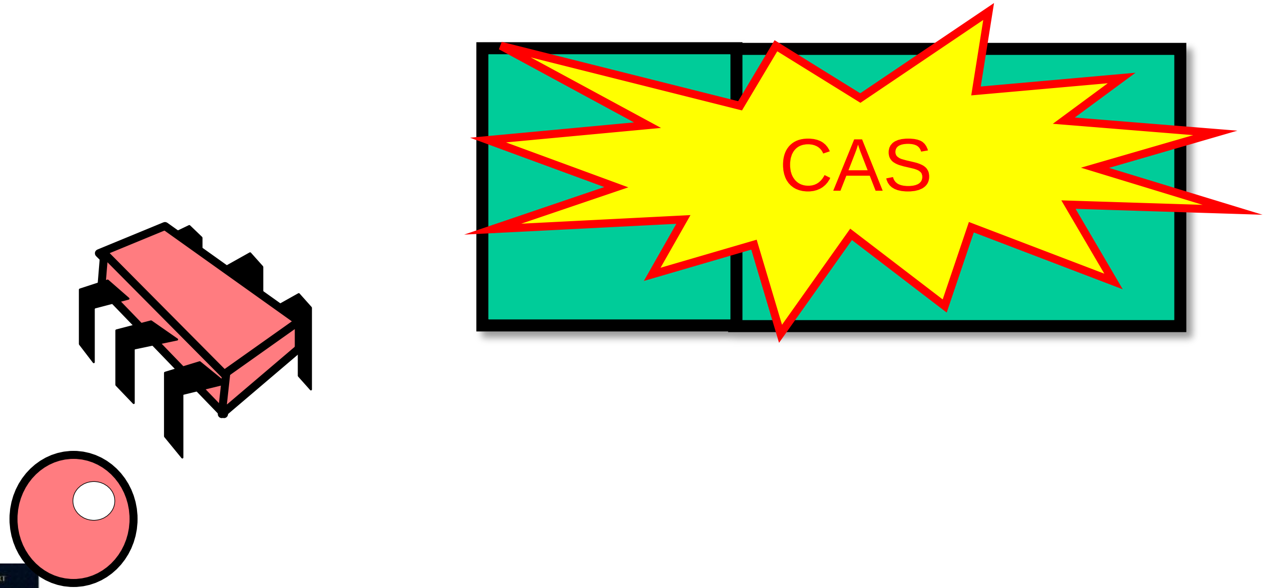
An *Exchanger* has three possible states



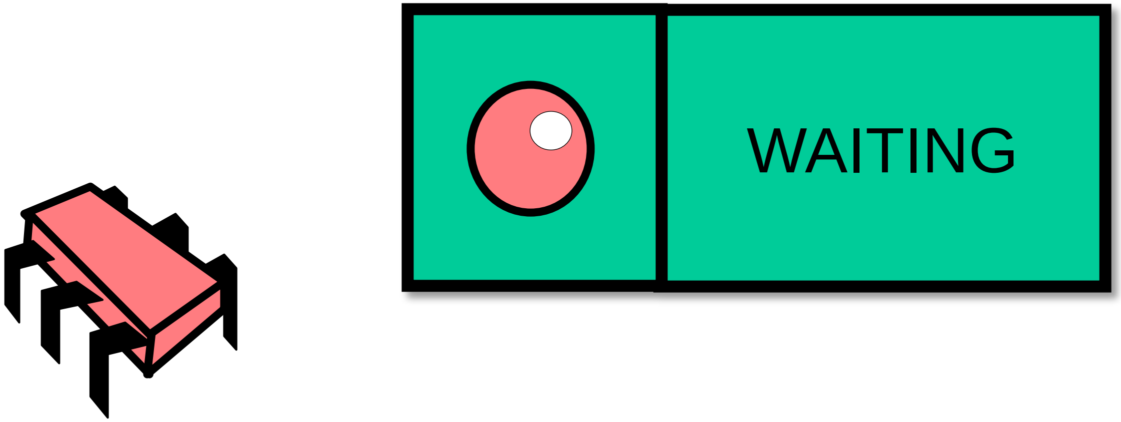
Lock-free Exchanger



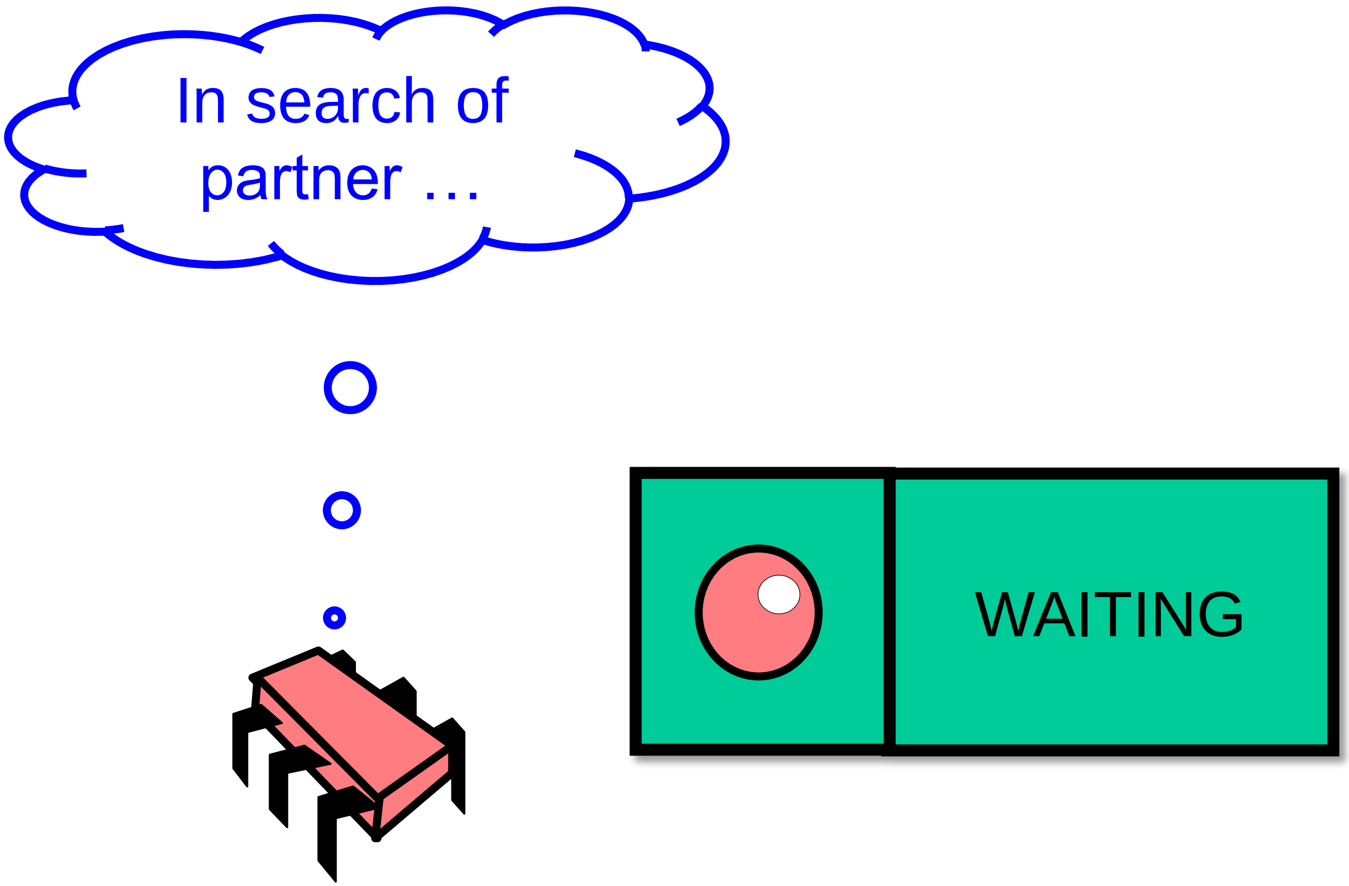
Lock-free Exchanger



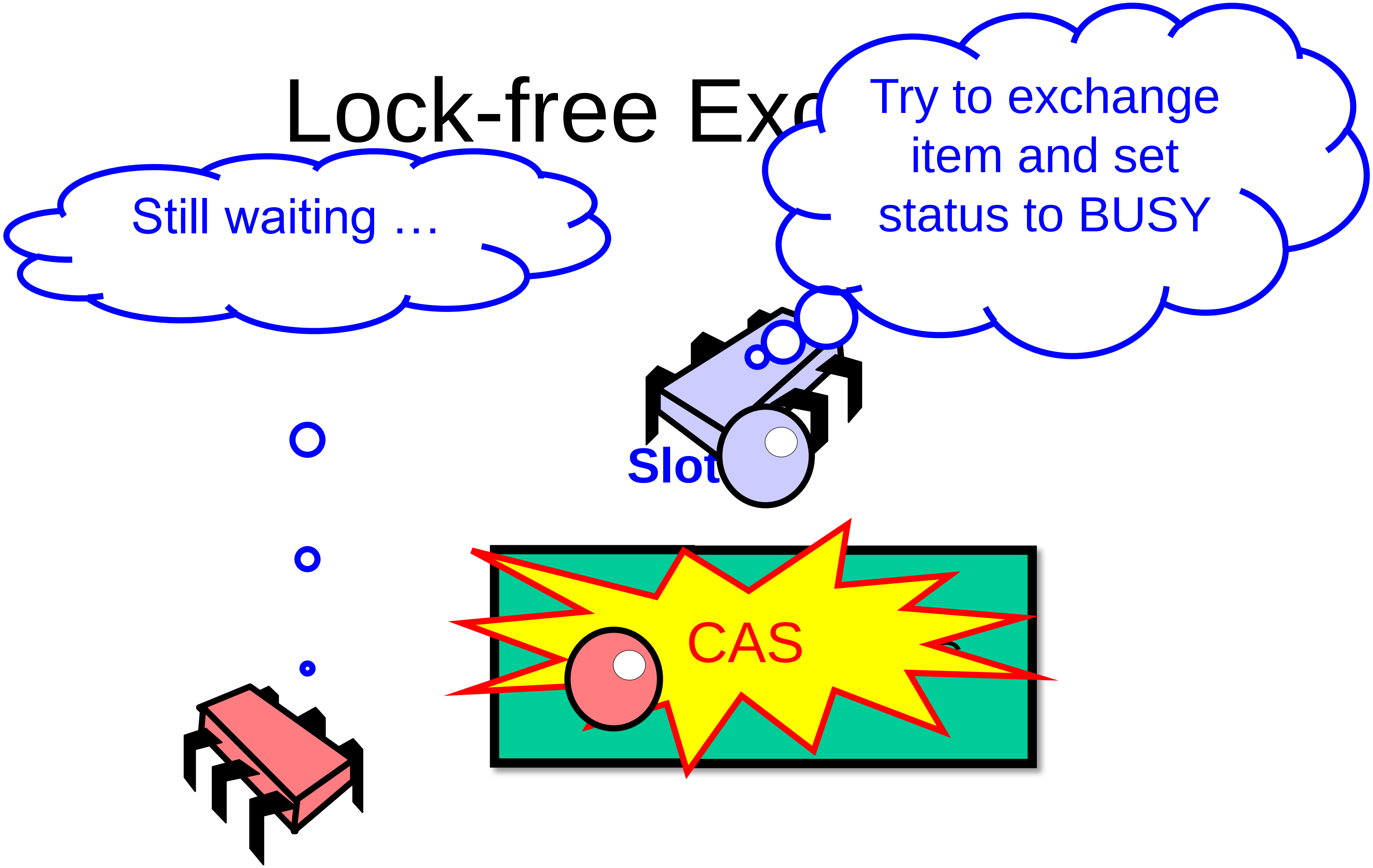
Lock-free Exchanger



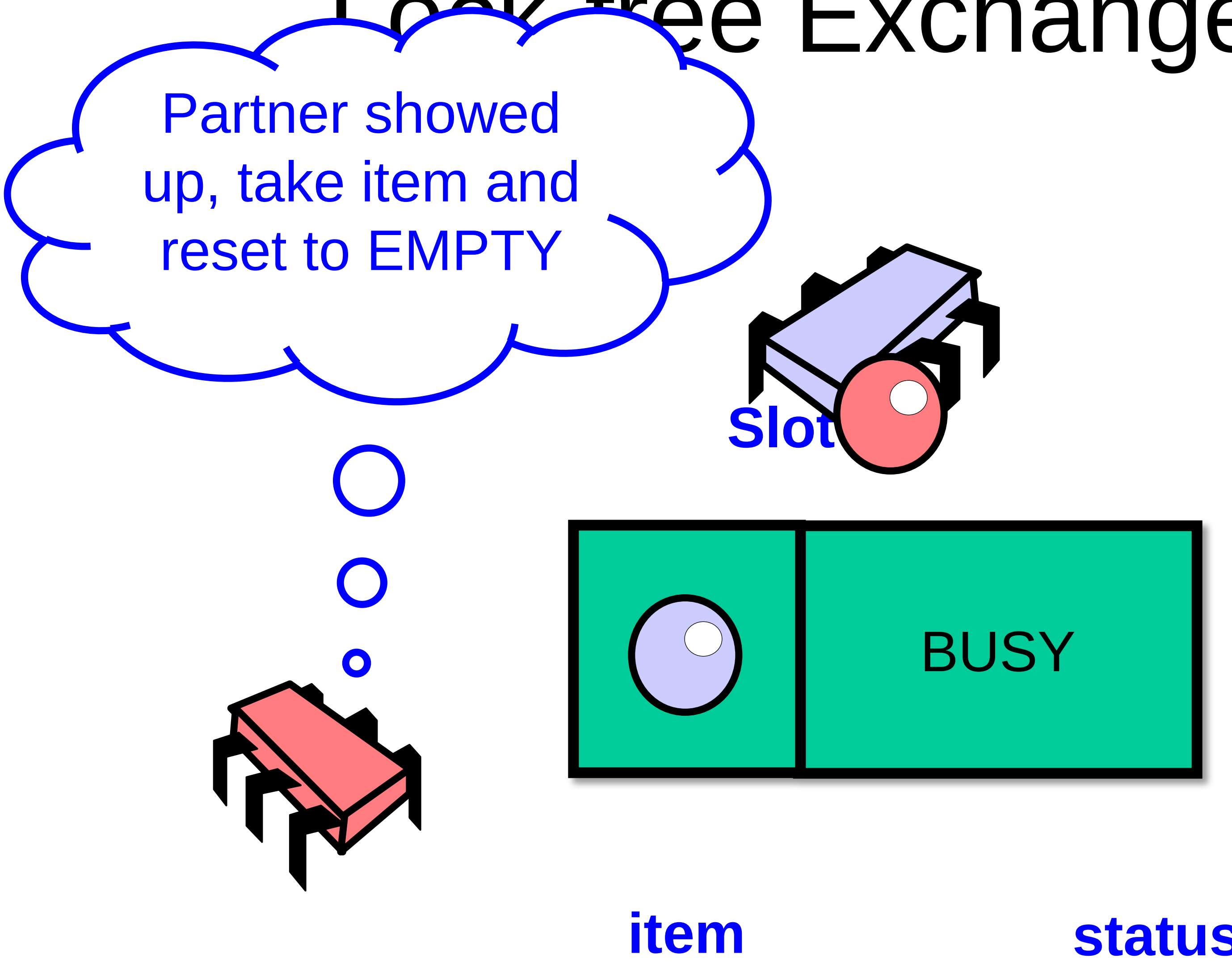
Lock-free Exchanger

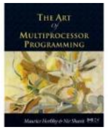


Lock-free Exc

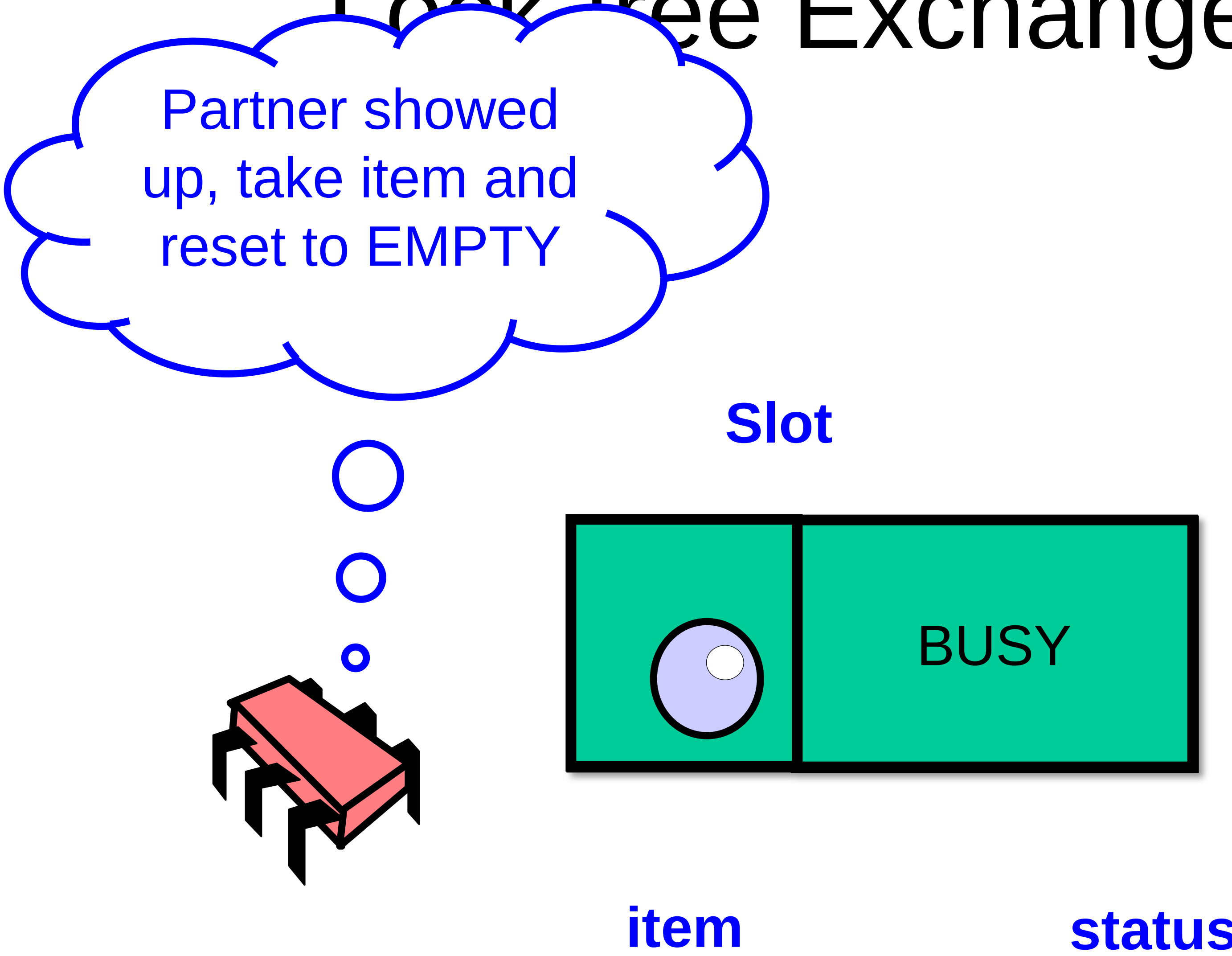


Lock-free Exchanger



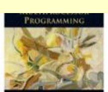


Lock-free Exchanger



Exchanger State EMPTY

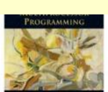
```
case EMPTY: // slot is free
  if (slot.CAS(herItem, myItem, EMPTY, WAITING)) {
   while (System.nanoTime() < timeBound){
     herItem = slot.get(stampHolder);
     if (stampHolder[0] == BUSY) {
       slot.set(null, EMPTY);
       return herItem;
     }}
   if (slot.CAS(myItem, null, WAITING, EMPTY)){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

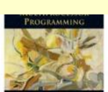
```
case EMPTY: // slot is free
  if (slot.CAS(herItem, myItem, EMPTY, WAITING)) {
    while (System.nanoTime() < timeBound){
      herItem = slot.get(stampHolder);
      if (stampHolder[0] == BUSY) {
        slot.set(null, EMPTY);
        return herItem;
      }}
    if (slot.CAS(myItem, null, WAITING,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

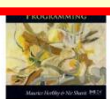
```
case EMPTY: // slot is free
  if (slot.CAS(herItem, myItem, EMPTY, WAITING)) {
   while (System.nanoTime() < timeBound){
     herItem = slot.get(stampHolder);
     if (stampHolder[0] == BUSY) {
       slot.set(null, EMPTY);
       retu
     }}
   if (slot.CAS(myItem, null, WAITING, EMPTY)){
    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

Clear slot and take that item

Exchanger State EMPTY

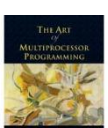
```
case EMPTY: // slot is free
  if (slot.CAS(herItem, myItem, EMPTY, WAITING)) {
   while (System.nanoTime() < timeBound){
     herItem = slot.get(stampHolder);
     if (stampHolder[0] == BUSY) {
       slot.set(null, EMPTY);
       return herItem;
     }}
   if (slot.CAS(myItem, null, WAITING, EMPTY)){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

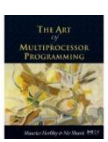
```
case WAITING:   // someone waiting for me
  if (slot.CAS(herItem, myItem, WAITING, BUSY))
    return herItem;
  break;
case BUSY:      // others in middle of exchanging
  break;
default:        // impossible
  break;
      }
    }
  }
}
```



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;
      }
    }
  }
}
```

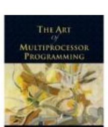
someone is waiting to exchange,
so try to CAS my item in
and change state to BUSY



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;
    }
   }
  }
}
```

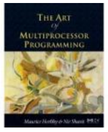
If successful, return other's item, otherwise someone else took it, so try again from start



States WAITING and BUSY

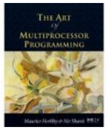
```
case WAITING:   // someone waiting for me
  if (slot.CAS(herItem, myItem, WAITING, BUSY))
    return herItem;
  break;
case BUSY:      // others in middle of exchanging
  break;
default:        // impossible
  break;
      }
    }
  }
}
```

If BUSY,
other threads exchanging,
so start again



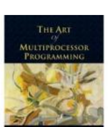
The Exchanger Slot

- 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

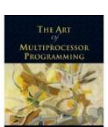
```
public class EliminationArray {
…
public T visit(T value, int range)
  throws TimeoutException {
    int slot = random.nextInt(range);
    int nanodur = convertToNanos(duration, timeUnit));
    return (exchanger[slot].exchange(value, nanodur)
}}
```



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)
}}
```

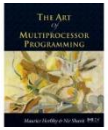
visit the elimination array with fixed value and range



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)
}}
```

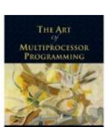
Pick a random array entry



Elimination Array

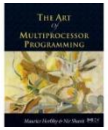
```
public class EliminationArray {
…
public T visit(T v
   throws TimeoutException {
     int slot = random.nextInt(range);
     int nanodur = convertToNanos(duration, timeUnit));
     return (exchanger[slot].exchange(value, nanodur)
}}
```

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

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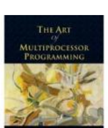
  if (tryPush(node)) {
    return;
  } else try {
      T otherValue =
      eliminationArray.visit(value,policy.range);
      if (otherValue == null) {
         return;
      }
}
```

First, try to push



Elimination Stack Push

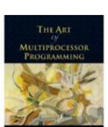
```
public void push(T value) {
...
 while (true) {
  if (tryPush(node)) {
    return;
  } else try {
      T otherValue =
      eliminationArray.visit(value,policy.range);
      if (otherValue == null) {
         return;
      }
}
```

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;
    }
}
```

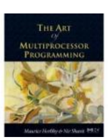
Value pushed and range to try



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



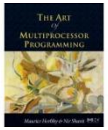
Elimination Stack Push

```
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

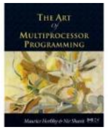
```
public T pop() {
 ...
 while (true) {
  if (tryPop()) {
   return returnNode.value;
   } else
      try {
        T otherValue =
        eliminationArray.visit(null,policy.range;
        if (otherValue != null) {
         return otherValue;
         }
      }
}}
```



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