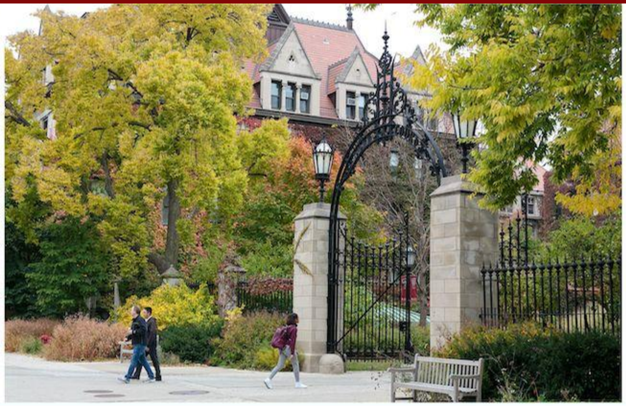
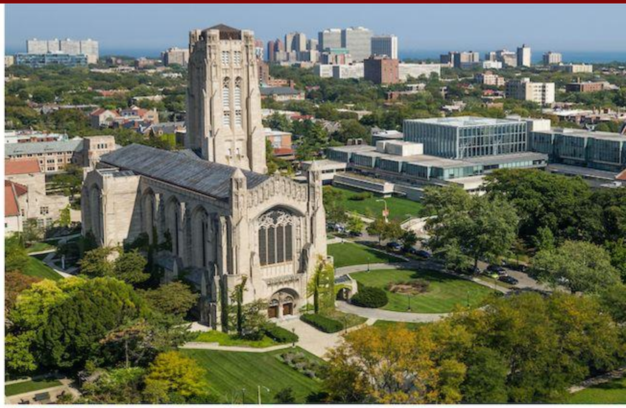
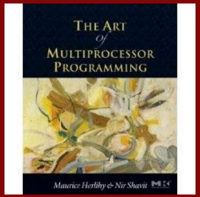
MPCS 52060 - Parallel Programming
M5: Concurrent Objects (Part 2)



Original slides from “The Art of Multiprocessor Programming by
Maurice Herlihy & Nir Shavit” With modifications by Lamont Samuels

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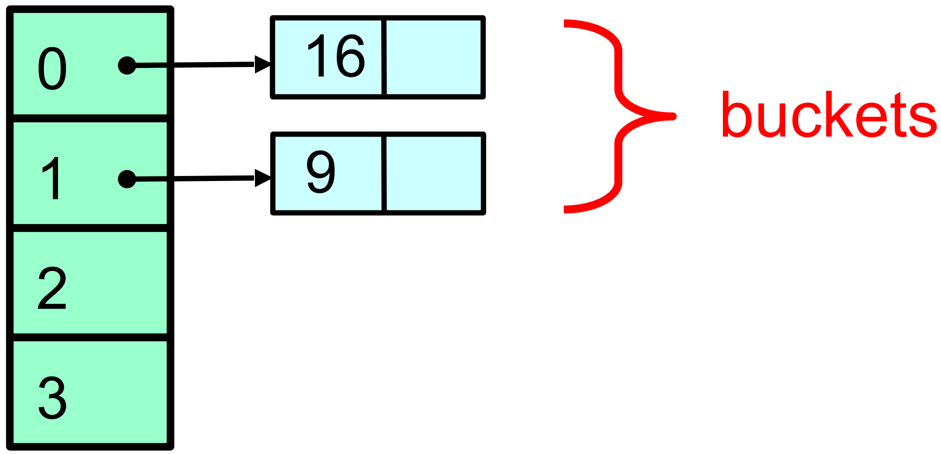
Hash tables

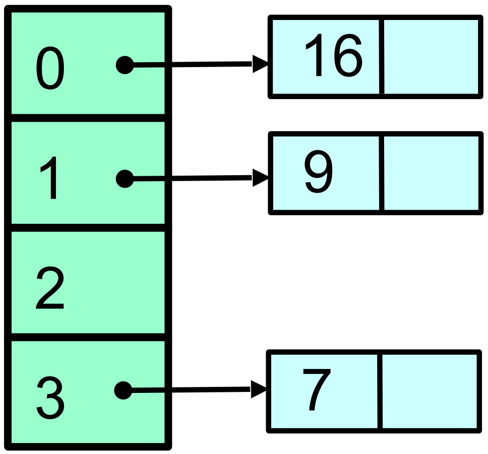
Sequential Closed Hash Map



2 Items

h(k) = k mod 4

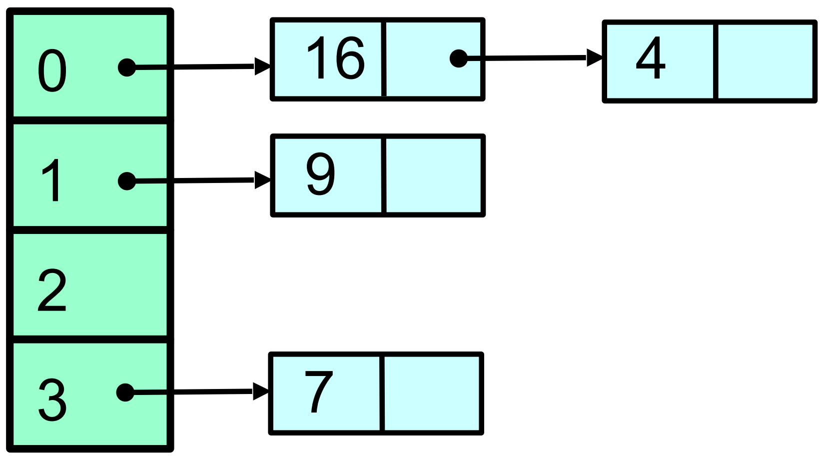
Add an Item



3 Items

h(k) = k mod 4

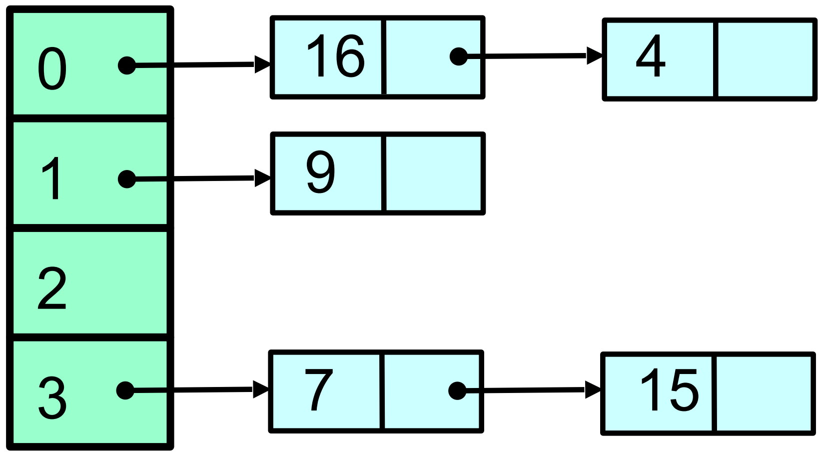
Add Another: Collision



4 Items

h(k) = k mod 4

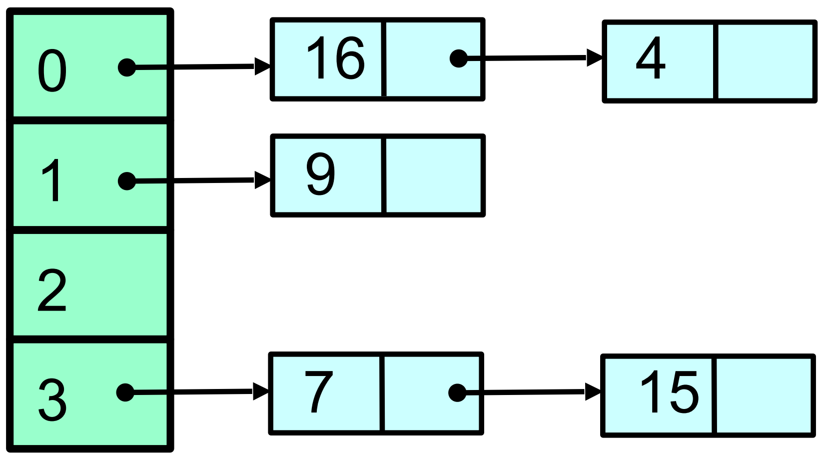
More Collisions



5 Items

h(k) = k mod 4

More Collisions

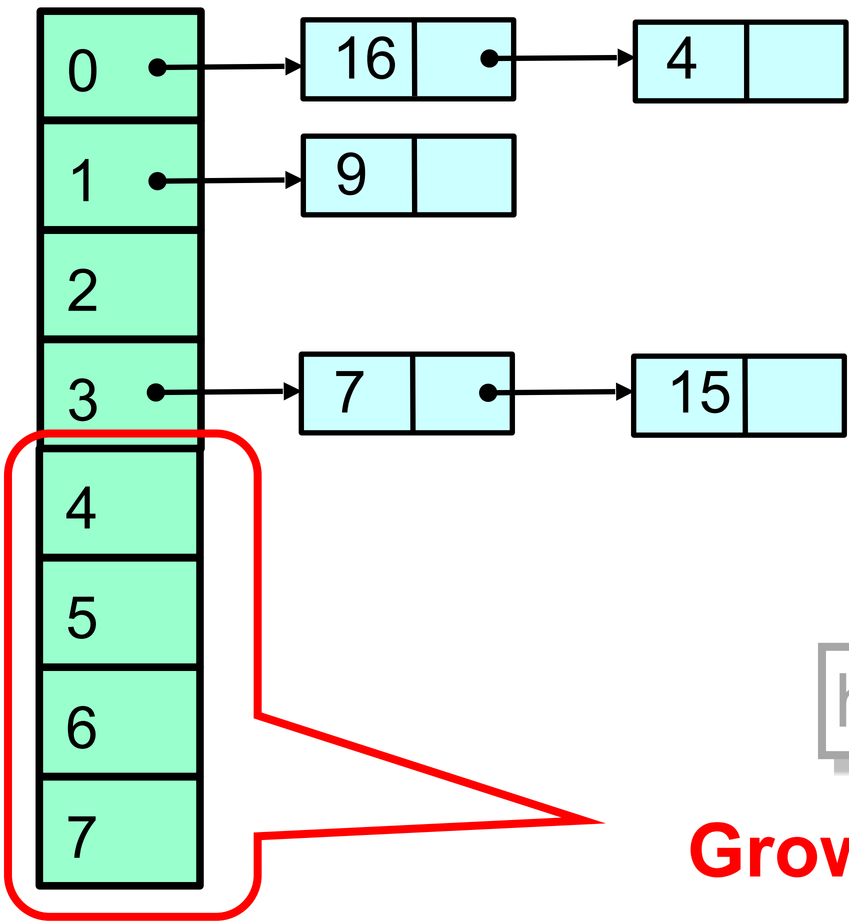


5 Items

$h(k) = k \bmod 4$

Problem:
buckets becoming too long

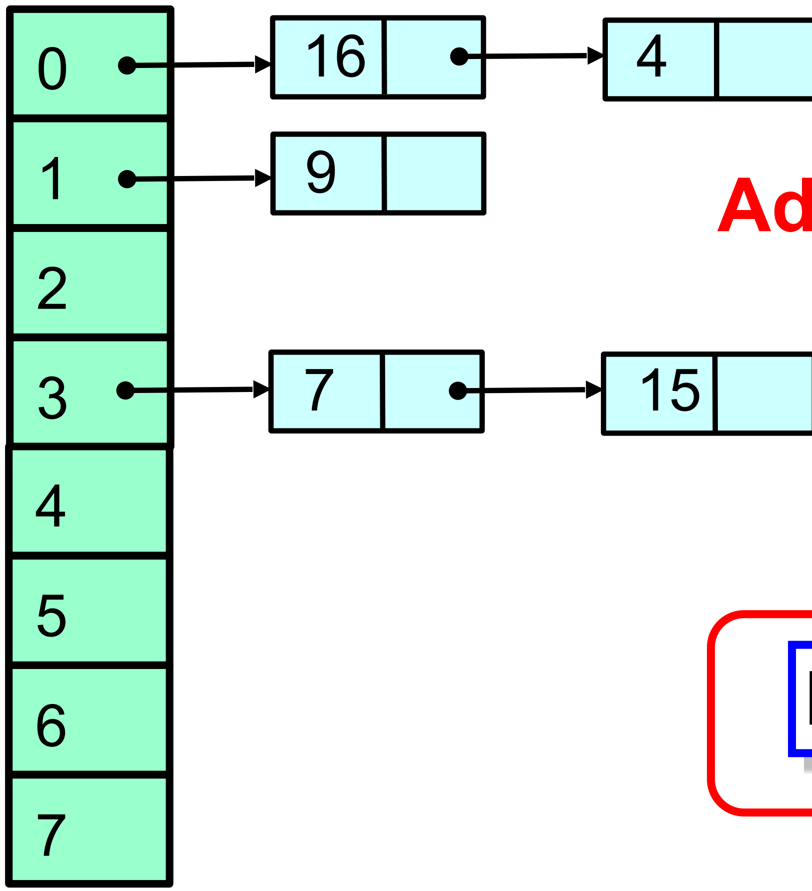
Resizing



5 Items

h(k) = k mod 4

Resizing

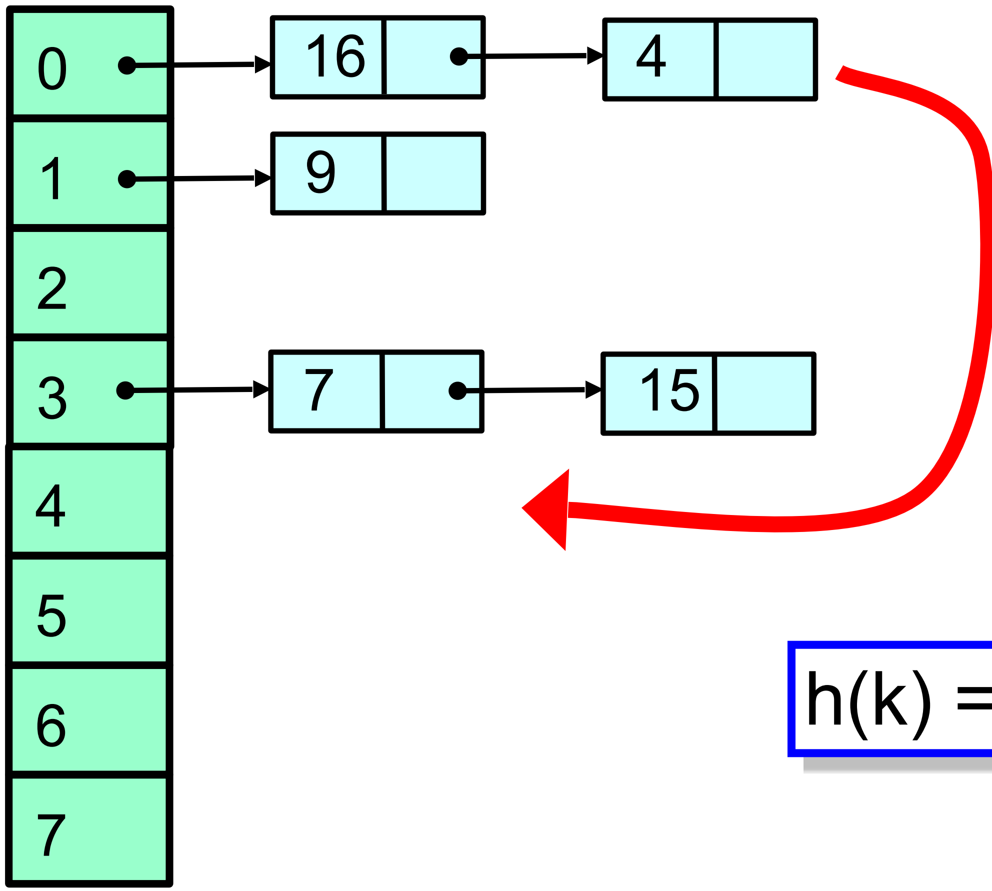


Adjust hash function

5 Items

h(k) = k mod 8

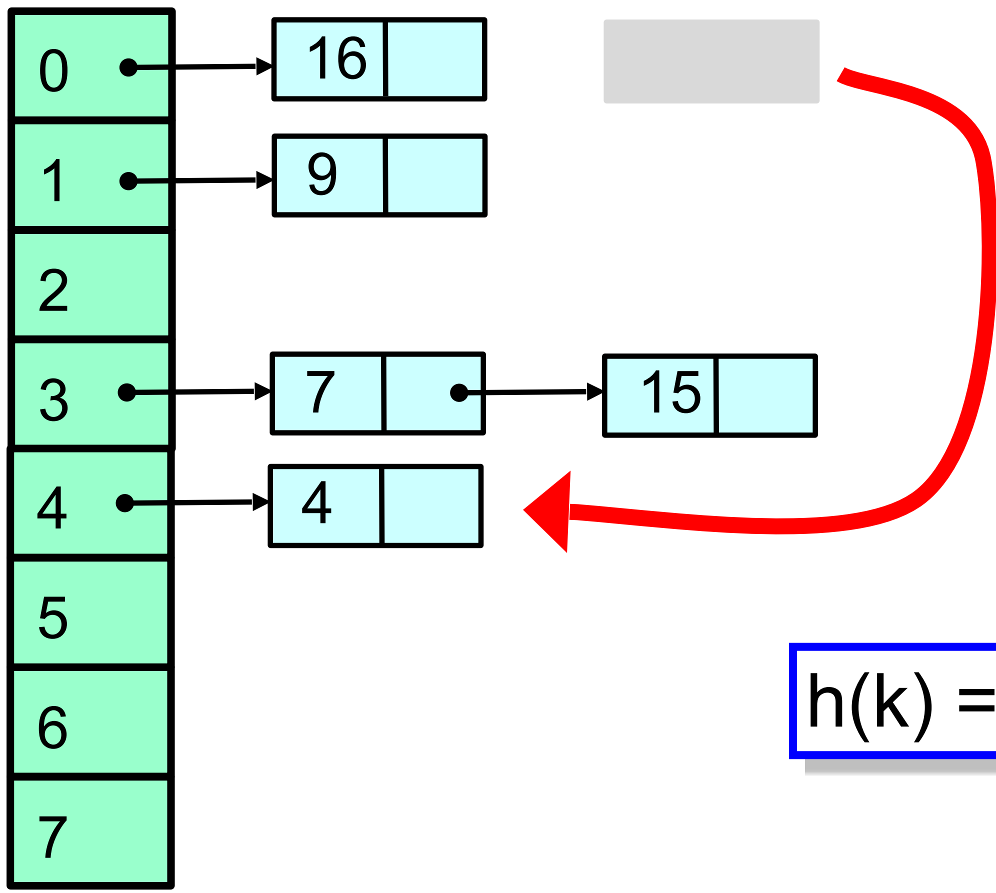
Resizing



h(4) = 4 mod 8

$\boxed{h(k) = k \bmod 8}$

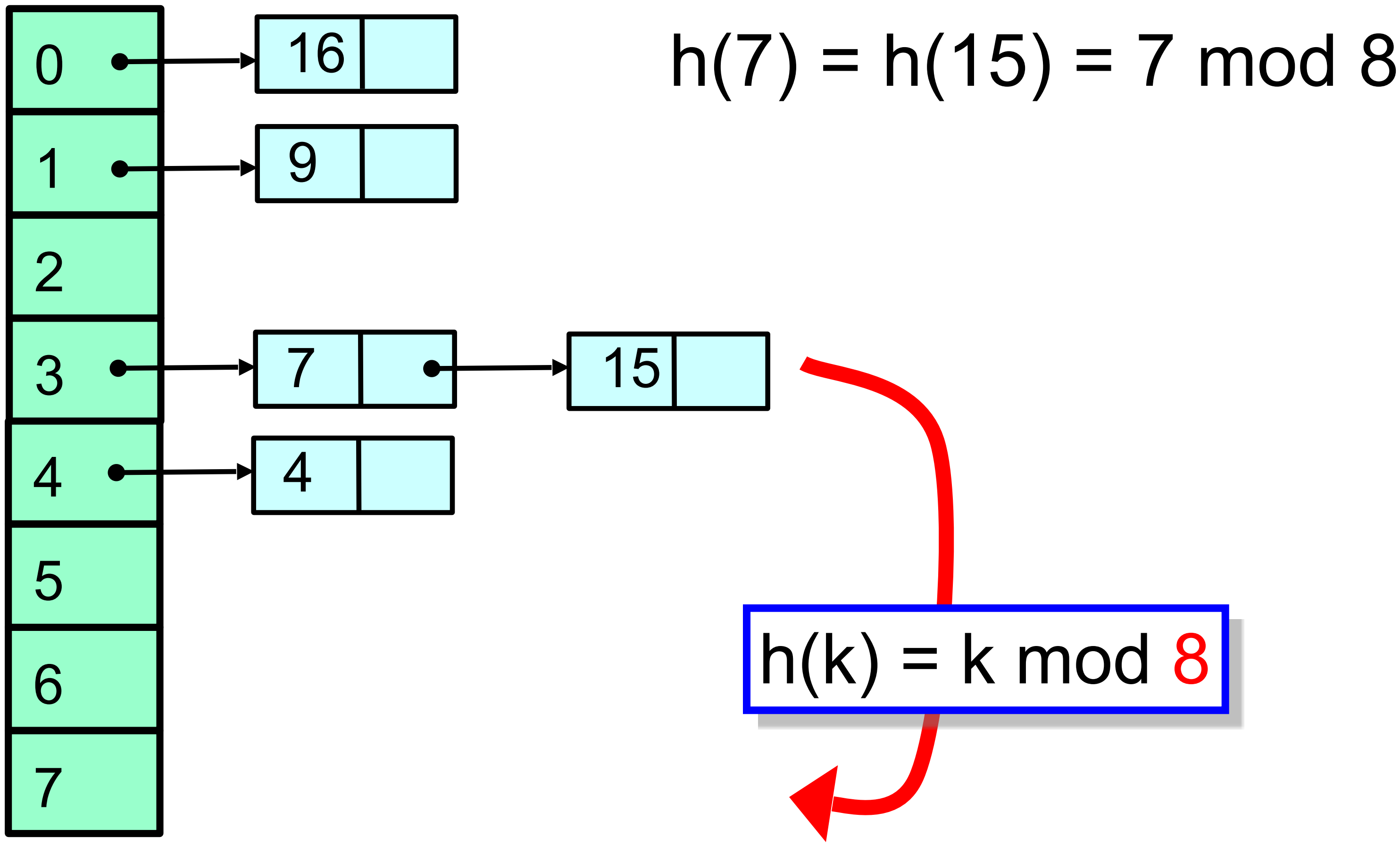
Resizing



$h(4) = 4 \bmod 8$

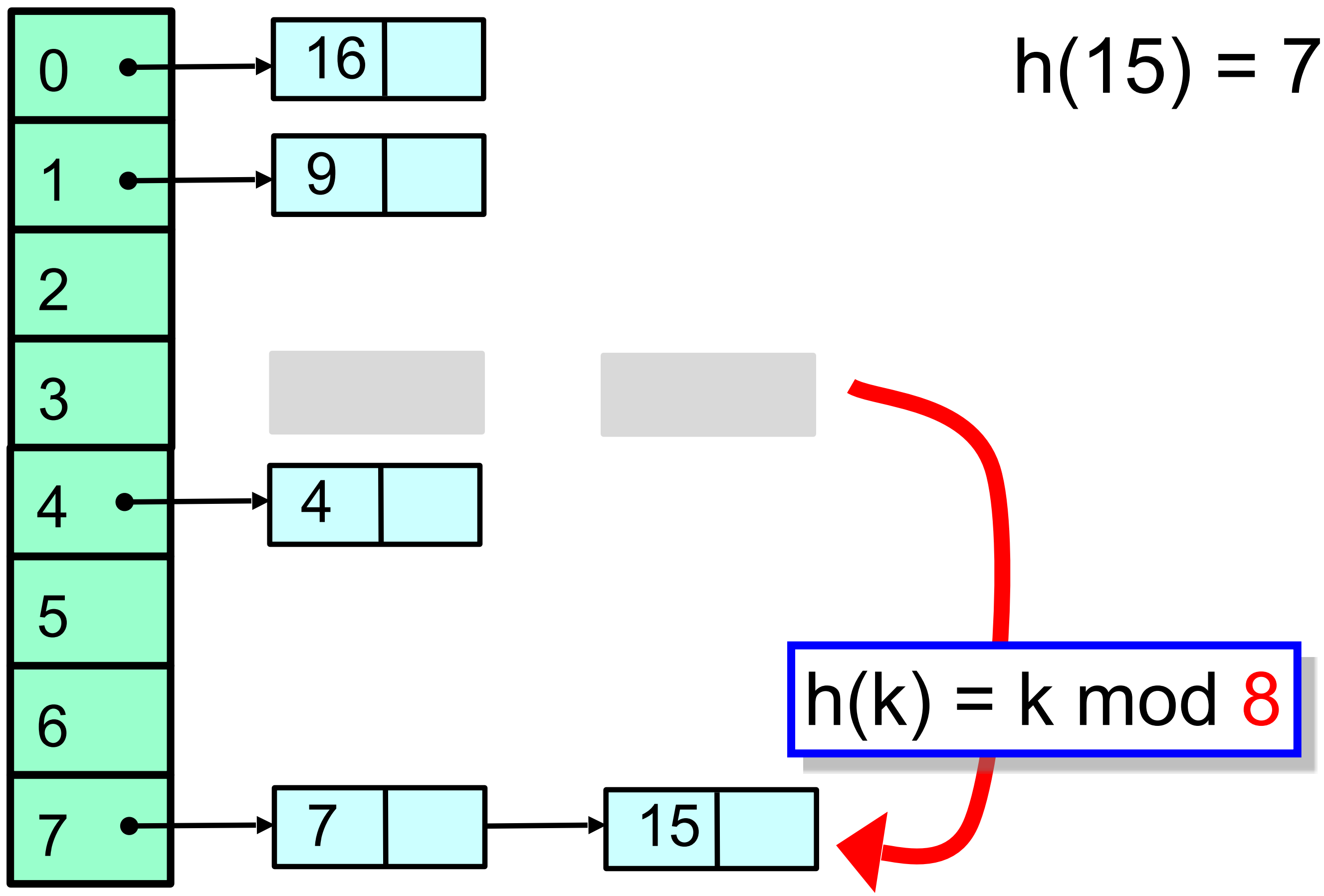
$\boxed{h(k) = k \bmod 8}$

Resizing



Resizing

$h(15) = 7 \bmod 8$



Fields

```
public class SimpleHashSet {
  protected LockFreeList[] table;

  public SimpleHashSet(int capacity) {
    table = new LockFreeList[capacity];
    for (int i = 0; i < capacity; i++)
      table[i] = new LockFreeList();
  }
…
```

Array of lock-free lists

Constructor

```
public class SimpleHashSet {
  protected LockFreeList[] table;

  public SimpleHashSet(int capacity) {
    table = new LockFreeList[capacity];
    for (int i = 0; i < capacity; i++)
      table[i] = new LockFreeList();
  }
…
```

Initial size

Constructor

```
public class SimpleHashSet {
  protected LockFreeList[] table;

  public SimpleHashSet(int capacity) {
    table = new LockFreeList[capacity];
    for (int i = 0; i < capacity; i++)
      table[i] = new LockFreeList();
  }
…
```

Allocate memory

Constructor

```
public class SimpleHashSet {
  protected LockFreeList[] table;

  public SimpleHashSet(int capacity) {
    table = new LockFreeList[capacity];
    for (int i = 0; i < capacity; i++)
      table[i] = new LockFreeList();
  }
…
```

Initialization

Add Method

```
public boolean add(Object key) {
 int hash =
  key.hashCode() % table.length;
 return table[hash].add(key);
}
```

Add Method

```
public boolean add(Object key) {
 int hash =
  key.hashCode() % table.length;
 return table[hash].add(key);
}
```

Use object hash code to pick a bucket

Add Method

```
public boolean add(Object key) {
 int hash =
  key.hashCode() % table.length;
 return table[hash].add(key);
}
```

Call bucket's add() method

No Brainer?

- We just saw a
  - Simple
  - Lock-free
  - Concurrent hash-based set implementation
- What's not to like?

No Brainer?

- We just saw a
  - Simple
  - Lock-free
  - Concurrent hash-based set implementation
- What's not to like?
- We don't know how to resize …

Is Resizing Necessary?

- Constant-time method calls require
  - Constant-length buckets
  - Table size proportional to set size
  - As set grows, must be able to resize

Set Method Mix

- Typical load
  - **90%** contains()
  - **9%** add ()
  - **1%** remove()
- Growing is important
- Shrinking not so much

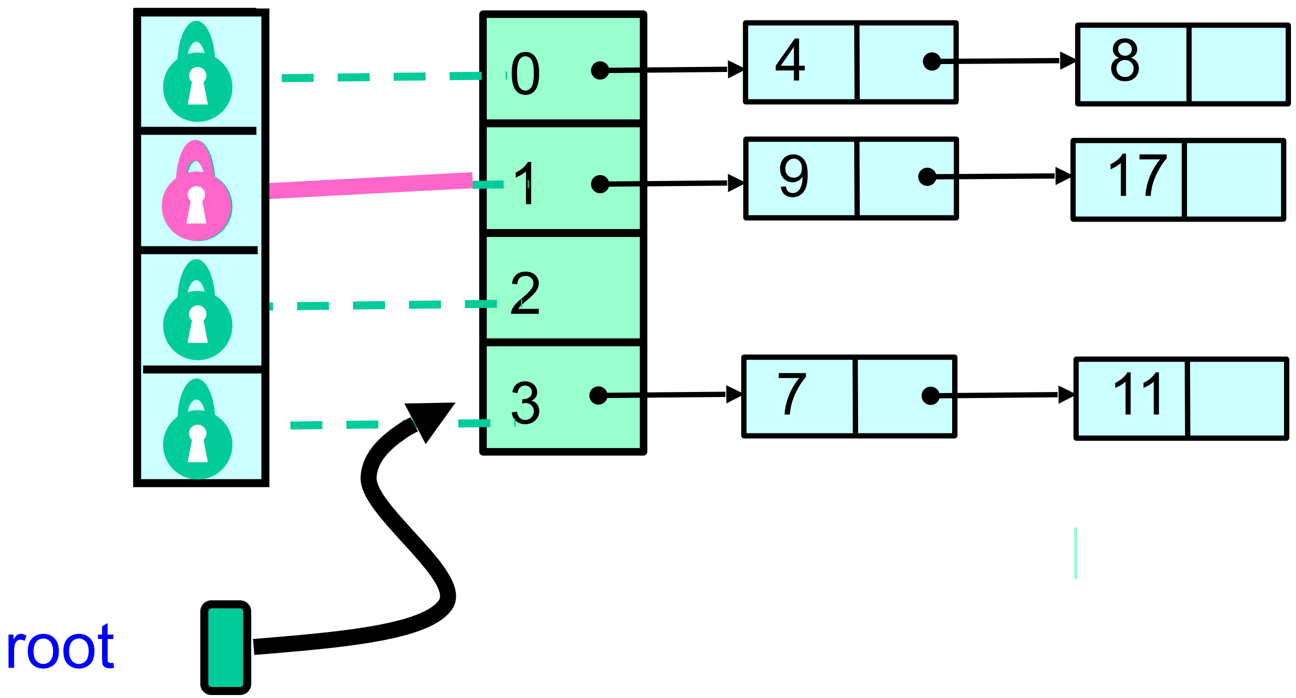
When to Resize?

- Many reasonable policies. Here's one.
- Pick a threshold on num of items in a bucket
- Global threshold
  - When ≥ ¼ buckets exceed this value
- Bucket threshold
  - When any bucket exceeds this value

Coarse-Grained Locking

- Good parts
  - Simple
  - Hard to mess up
- Bad parts
  - Sequential bottleneck

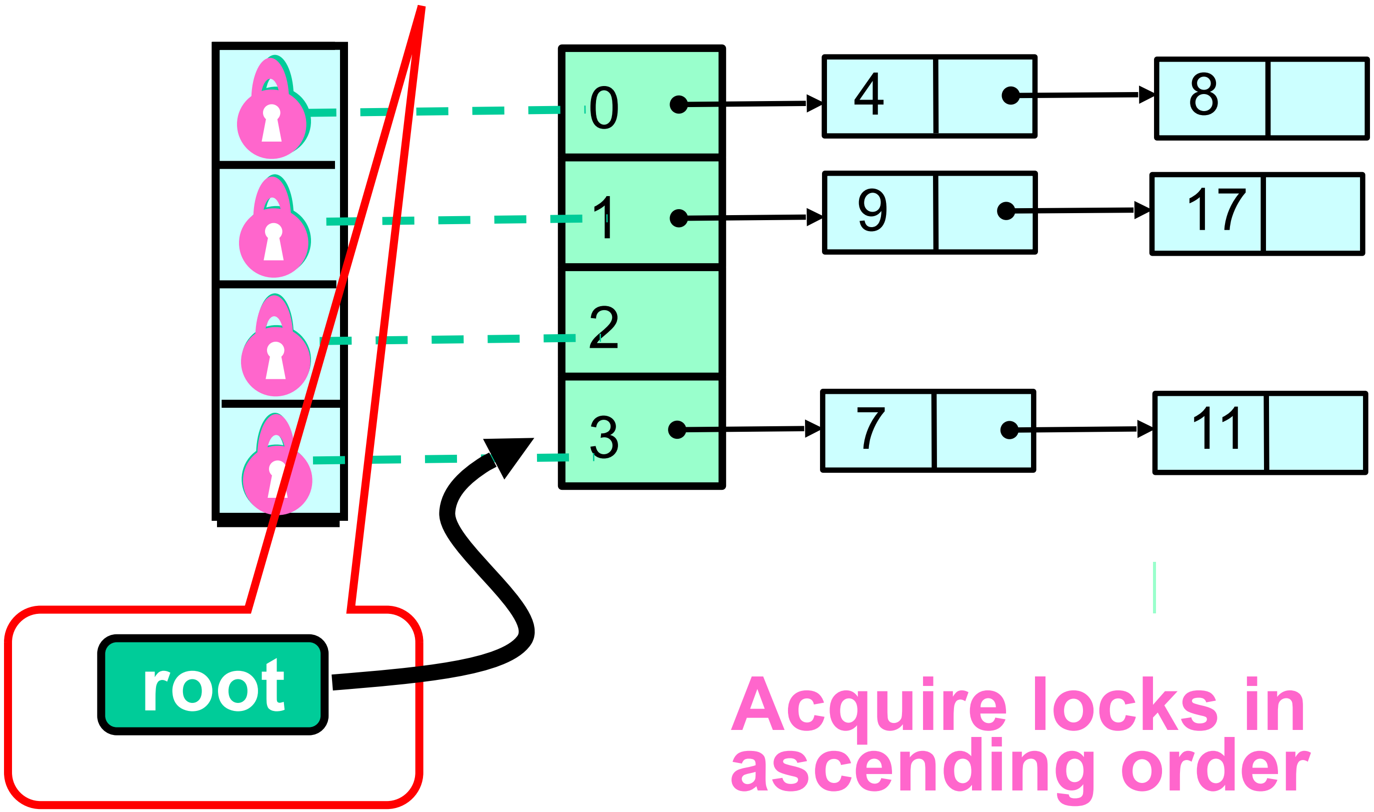
Fine-grained Locking



Each lock associated with one bucket

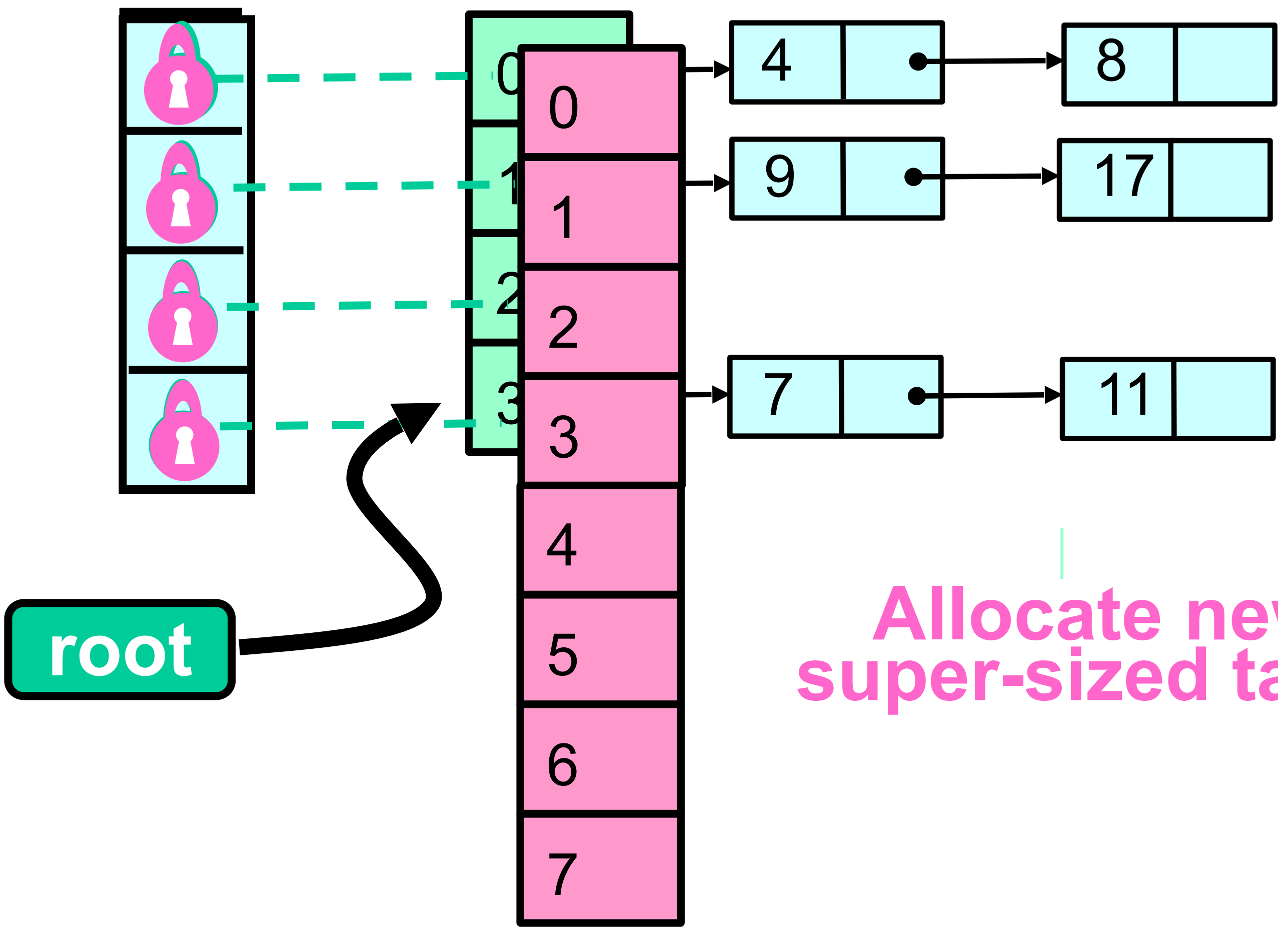
Resize This

Make sure root reference didn't change between resize decision and lock acquisition



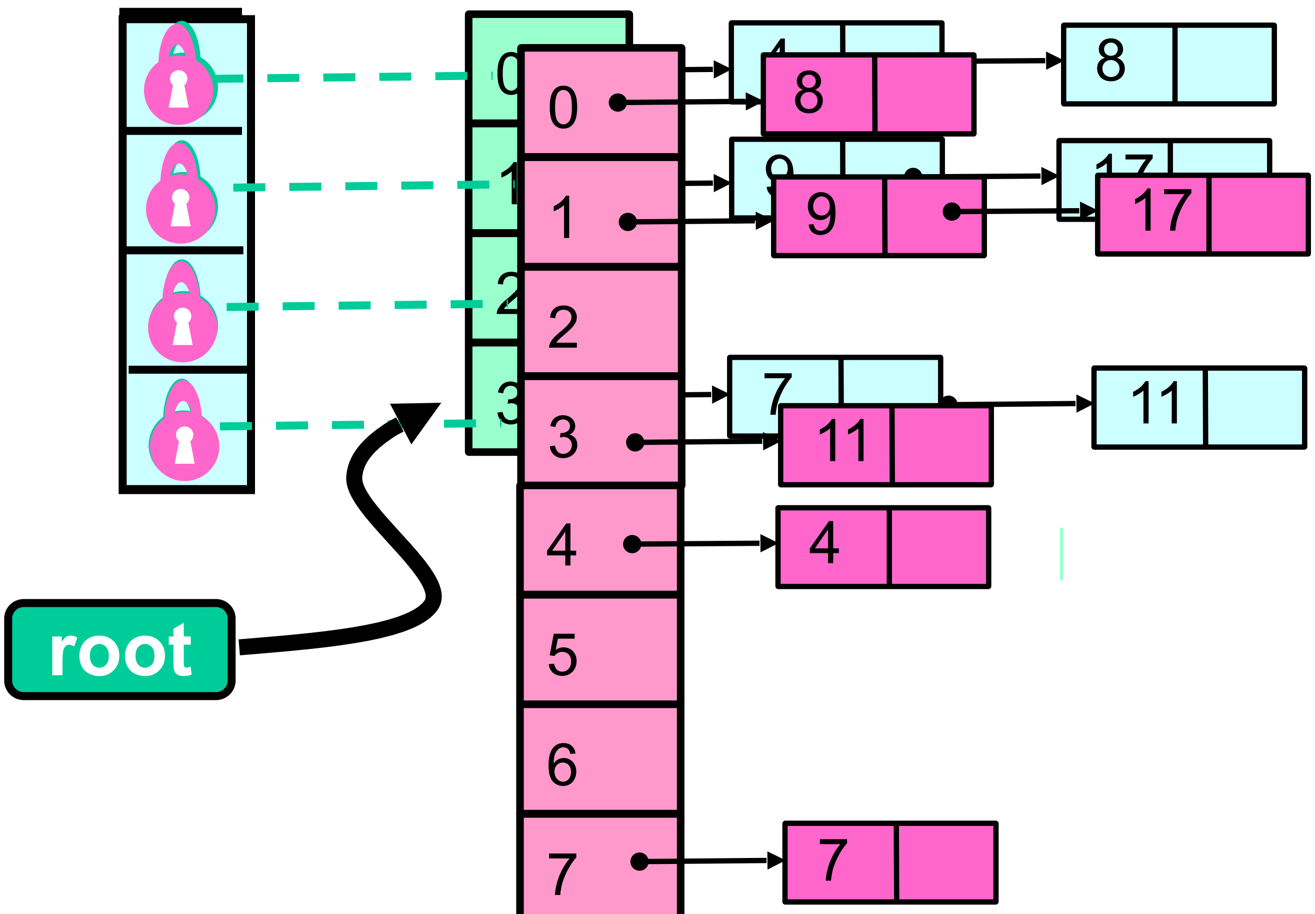
Acquire locks in ascending order

Resize This



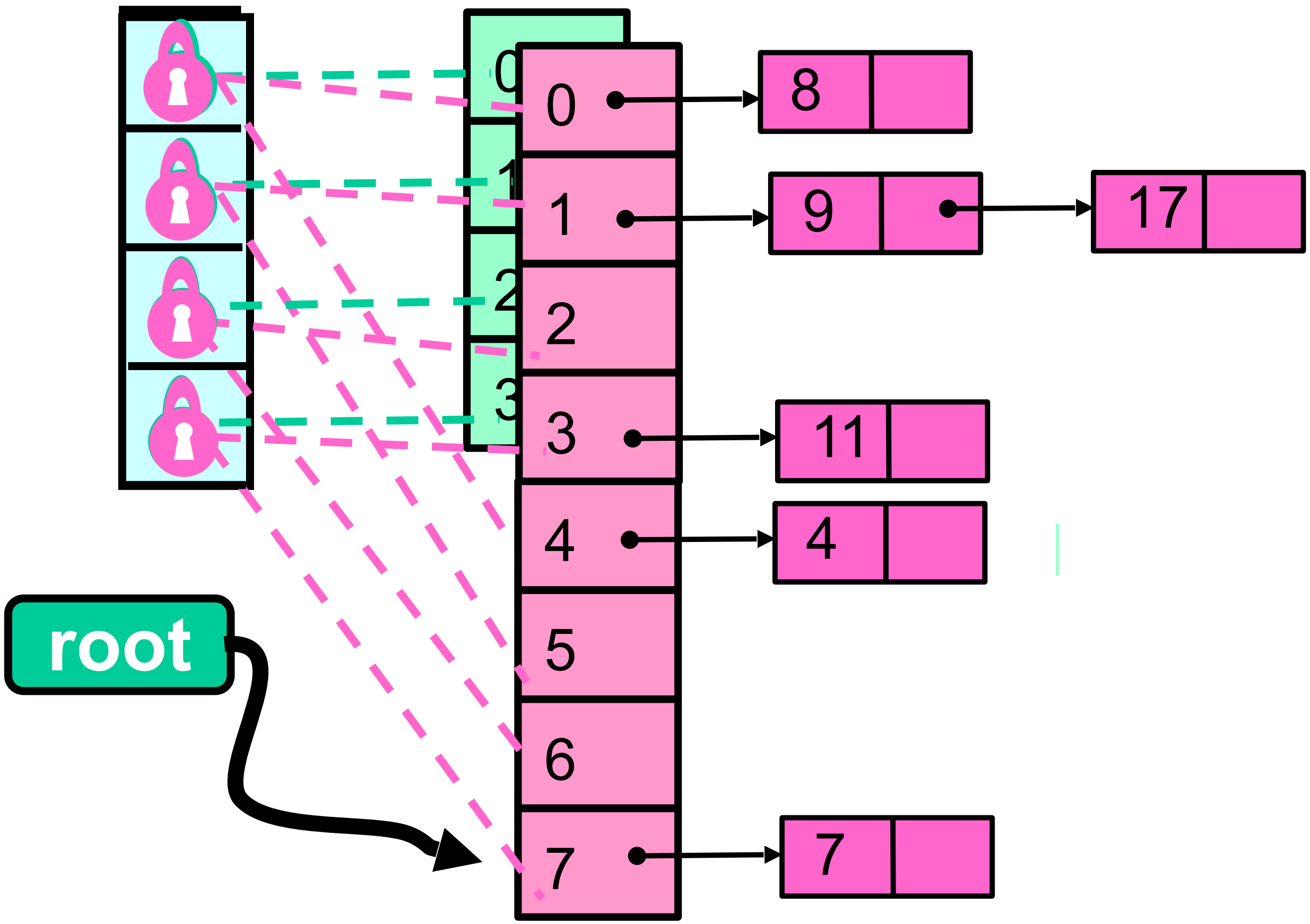
Allocate new super-sized table

Resize This



Striped Locks: each lock now associated with two buckets

Resize This



Observations

- We grow the table, but not locks
  - Resizing lock array is tricky …
- We use sequential lists
  - Not **LockFreeList** lists
  - If we're locking anyway, why pay?

Fine-Grained Hash Set

```
public class FGHashSet {
 protected RangeLock[] lock;
 protected List[] table;
 public FGHashSet(int capacity) {
  table = new List[capacity];
  lock = new RangeLock[capacity];
  for (int i = 0; i < capacity; i++) {
   lock[i] = new RangeLock();
   table[i] = new LinkedList();
  }} …
```

Fine-Grained Hash Set

```
public class FGHashSet {
 protected RangeLock[] lock;
 protected List[] table;
 public FGHashSet(int capacity) {
  table = new List[capacity];
  lock = new RangeLock[capacity];
  for (int i = 0; i < capacity; i++) {
   lock[i] = new RangeLock();
   table[i] = new LinkedList();
  }} …
```

Array of locks

Fine-Grained Hash Set

```
public class FGHashSet {
 protected RangeLock[] lock;
 protected List[] table;
 public FGHashSet(int capacity) {
  table = new List[capacity];
  lock = new RangeLock[capacity];
  for (int i = 0; i < capacity; i++) {
   lock[i] = new RangeLock();
   table[i] = new LinkedList();
  }} …
```

Array of buckets

Fine-Grained Hash Set

```
public class FGHashSet {
 protected RangeLock[] lock;
 protected List[] table;
 public FGHashSet(int capacity) {
  table = new List[capacity];
  lock = new RangeLock[capacity];
  for (int i = 0; i < capacity; i++) {
   lock[i] = new RangeLock();
   table[i] = new LinkedList();
  }} …
```

Initially *same* number of locks and buckets

The add() method

```
public boolean add(Object key) {
  int keyHash
   = key.hashCode() % lock.length;
  synchronized (lock[keyHash]) {
   int tabHash = key.hashCode() %
                          table.length;
   return table[tabHash].add(key);
  }
 }
```

Fine-Grained Locking

```
public boolean add(Object key) {
  int keyHash
   = key.hashCode() % lock.length;
  synchronized (lock[keyHash]) {
   int tabHash = key.hashCode() %
                        table.length;
   return table[tabHash].add(key);
  }
 }
```

Which lock?

The add() method

```
public boolean add(Object key) {
  int keyHash
   = key.hashCode() % lock.length;
  synchronized (lock[keyHash]) {
   int tabHash = key.hashCode() %
                            table.length;
   return table[tabHash].add(key);
  }
 }
```

Acquire the lock

Fine-Grained Locking

```
public boolean add(Object key) {
  int keyHash
   = key.hashCode() % lock.length;
  synchronized (lock[keyHash]) {
   int tabHash = key.hashCode() %
                          table.length;
   return table[tabHash].add(key);
  }
}
```

Which bucket?

The add() method

```
public boolean add(Object key) {
  int keyHash
   = key.hashCode() % locks.length;
  synchronized (lock[keyHash]) {
   int tabHash = key.hashCode() %
                       table.length;
   return table[tabHash].add(key);
  }
 }
```

Call that bucket's add() method

Resizing

```
private void resize(int depth,
                    List[] oldTab) {
 synchronized (lock[depth]) {
  if (oldTab == table){
   int next = depth + 1;
   if (next < lock.length)
    resize (next, oldTab);
   else
    sequentialResize();
 }}}
```

Fine-Grained Locking

```
private void resize(int depth,
                    List[] oldTab) {
 synchronized (lock[depth]) {
  if (oldTab == table){
   int next = depth + 1;
   if (next < lock.length)
    resize (next, oldTab);
   else
    sequentialResize();
}}}
```

resize() calls resize(0,table)

Resizing

```
private void resize(int depth,
                    List[] oldTab) {
 synchronized (lock[depth]) {
  if (oldTab == table){
   int next = depth + 1;
   if (next < lock.length)
    resize (next, oldTab);
   else
    sequentialResize();
 }}}
```

Acquire next lock

Resizing

```
private void resize(int depth,
                    List[] oldTab) {
 synchronized (lock[depth]) {
  if (oldTab == table) {
   int next = depth + 1;
   if (next < lock.length)
    resize (next, oldTab);
   else
    sequentialResize();
 }}}
```

Check that no one else has resized

Resizing

```
private void resize(int depth,
                    List[] oldTab) {
 synchronized (lock[depth]) {
  if (oldTab == table){
   int next = depth + 1;
   if (next < lock.length)
    resize (next, oldTab);
   else
    sequentialResize();
}}}
```

Recursively acquire next lock

Resizing

Locks acquired, do the work

```
private void resize(int depth,
                    List[] oldTab) {
 synchronized (lock[depth]) {
  if (oldTab == table){
   int next = depth + 1;
   if (next < lock.length)
    resize (next, oldTab);
   else
    sequentialResize();
}}}
```

Stop The World Resizing

- Resizing stops all concurrent operations
- What about an incremental resize?
- Must avoid locking the table
- A lock-free table + incremental resizing (see textbook)?

Closed (Chained) Hashing

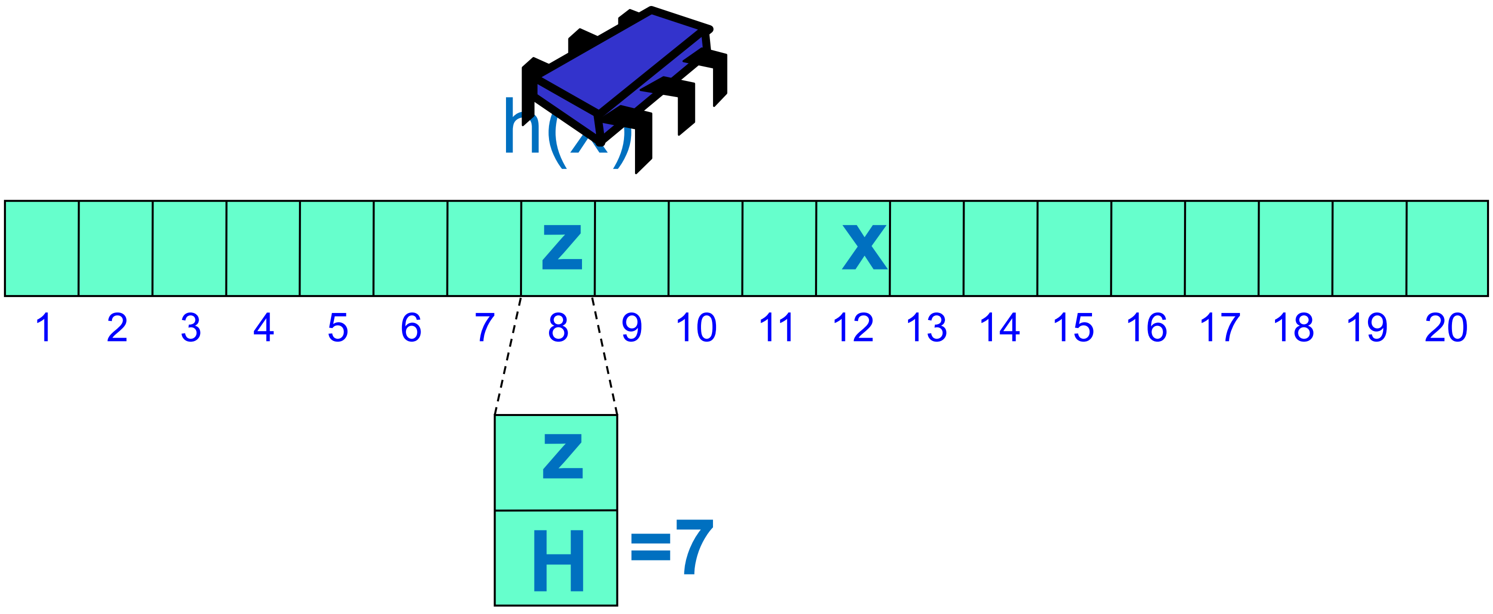
- Advantages:
  - with N buckets, M items, Uniform h
  - retains good performance as table density (M/N) increases → less resizing
- Disadvantages:
  - dynamic memory allocation
  - bad cache behavior (no locality)

Oh, did we mention that cache behavior matters on a multicore?

Open Addressed Hashing

- Keep all items in an array
- One per bucket
- If you have collisions, find an empty bucket and use it
- Must know how to find items if they are outside their bucket

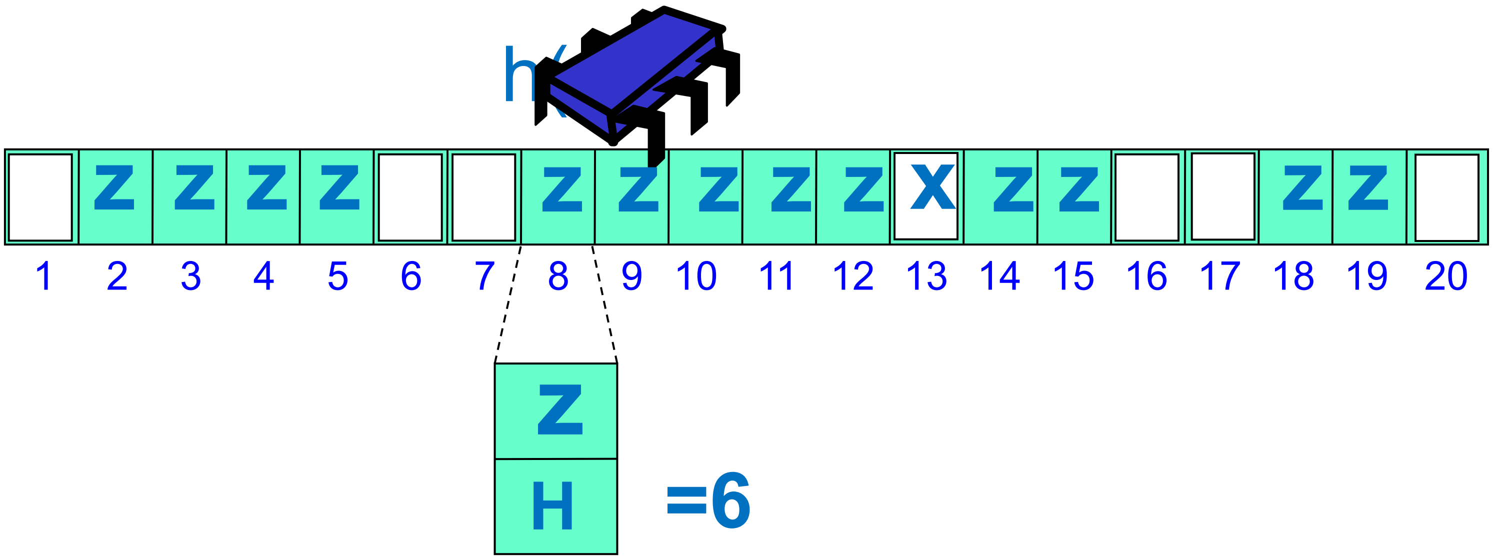
Linear Probing*



`contains(x)` – search linearly from h(x) to h(x) + H recorded in bucket.

*Attributed to Amdahl…

Linear Probing



`add(x)` – put in first empty bucket, and update H.

Linear Probing

- Expected items in bucket same as Chaining
- Expected distance till open slot:

$$\frac{1}{2}\left(1+\left(\frac{1}{1-M/N}\right)^2\right)$$

M/N = 0.5 ➔ *search 2.5 buckets*

M/N = 0.9 ➔ *search 50 buckets*

Linear Probing

- Advantages:
  - Good locality ➔ fewer cache misses
- Disadvantages:
  - As M/N increases more cache misses
    - searching 10s of unrelated buckets
    - “Clustering” of keys into neighboring buckets
  - As computation proceeds “Contamination” by deleted items ➔ more cache misses

Concurrent Open Address Hashing

- Need to either lock whole chain of displacements (see book)
- or have extra space to keep items as they are displaced step by step (Cuckoo hashing, see book).

Summary

- *Chained hash* with striped locking is simple and effective in many cases
- See Textbook: *Hopscotch (Concurrent Cuckoo Hashing)* with striped locking great cache behavior
- See Textbook: If incremental resizing needed go for *split-ordered*

Concurrent Pools

pool

- Data Structure similar to Set
  - Does not necessarily provide contains() method
  - Allows the same item to appear more than once
  - get() and set()

```
public interface Pool<T> {
  void put(T item);
  T get();
}
```

Queues & Stacks

- Both: pool of items
- Queue
  - enq() & deq()
  - First-in-first-out (FIFO) order
- Stack
  - push() & pop()
  - Last-in-first-out (LIFO) order

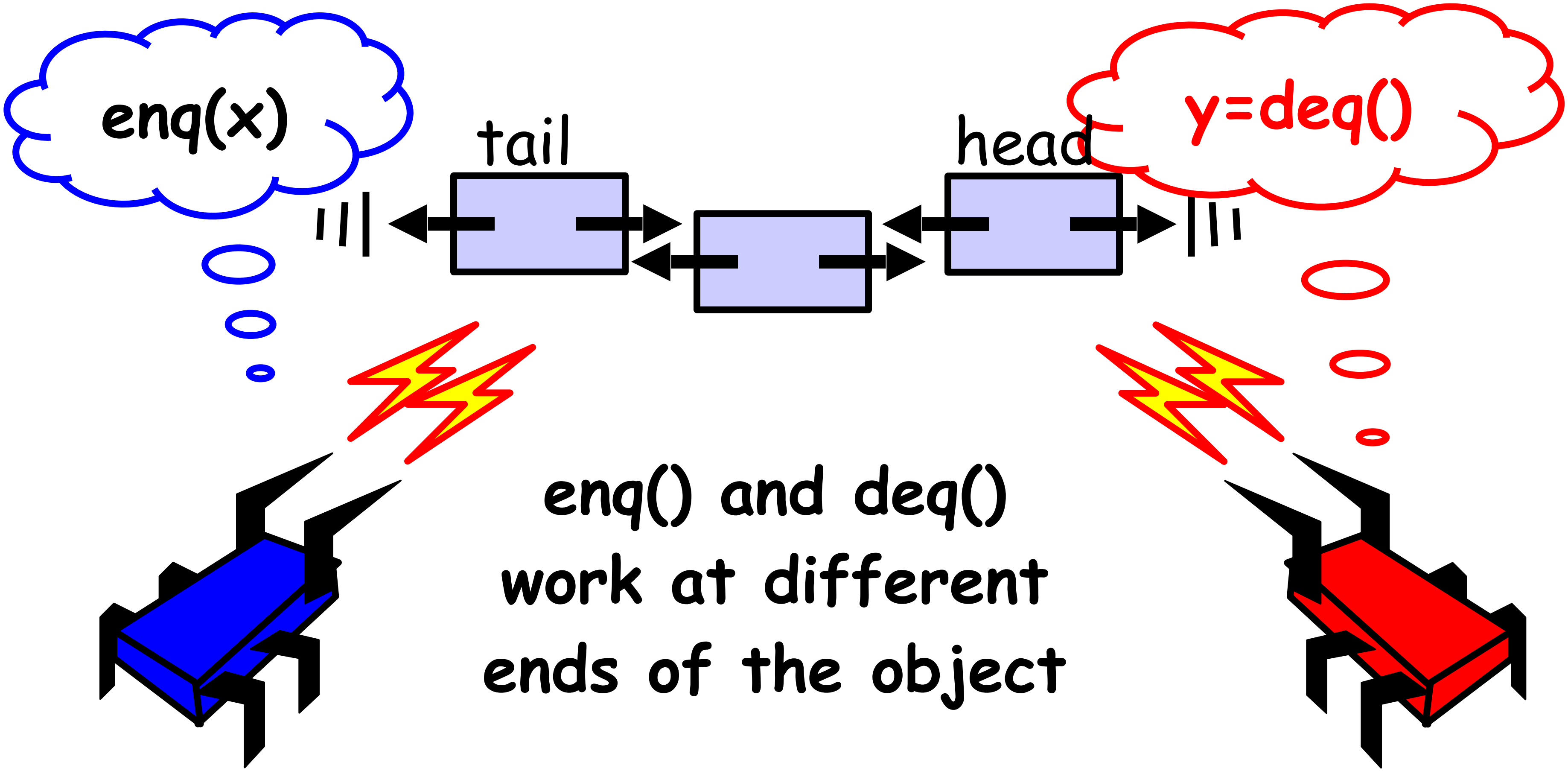
Bounded vs Unbounded

- Bounded
  - Fixed capacity
  - Good when resources an issue
- Unbounded
  - Holds any number of objects

Blocking vs Non-Blocking

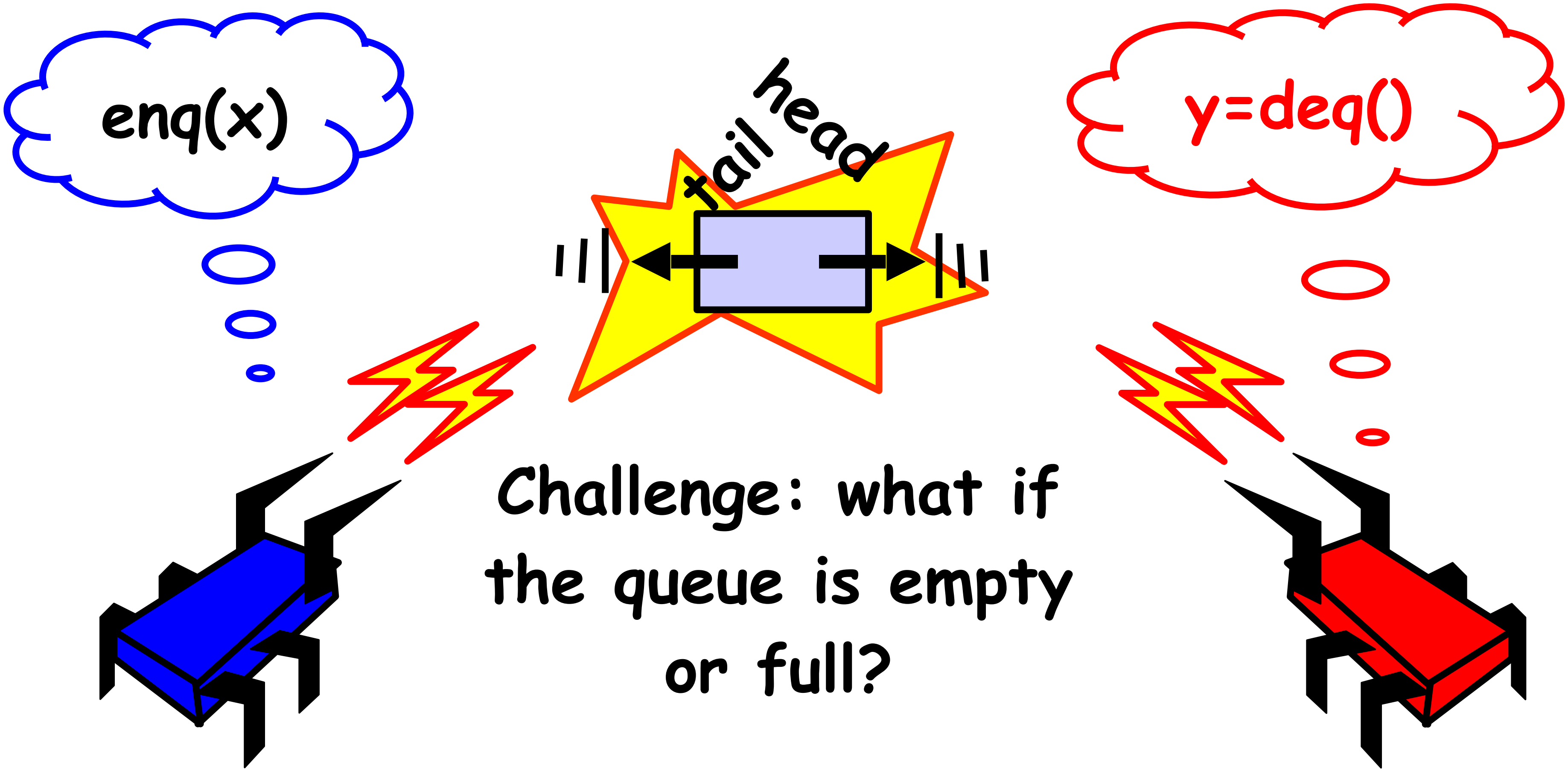
- Problem cases:
  - Removing from empty pool
  - Adding to full (bounded) pool
- Blocking
  - Caller waits until state changes
- Non-Blocking
  - Method throws exception or error

Queue: Concurrency



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

Concurrency



Challenge: what if the queue is empty or full?

lock

- enqLock/deqLock
  - At most one enqueuer/dequeuer at a time can manipulate the queue's fields
- Two locks
  - Enqueuer does not lock out dequeuer
  - vice versa
- Association
  - enqLock associated with notFullCondition
  - deqLock associated with notEmptyCondition

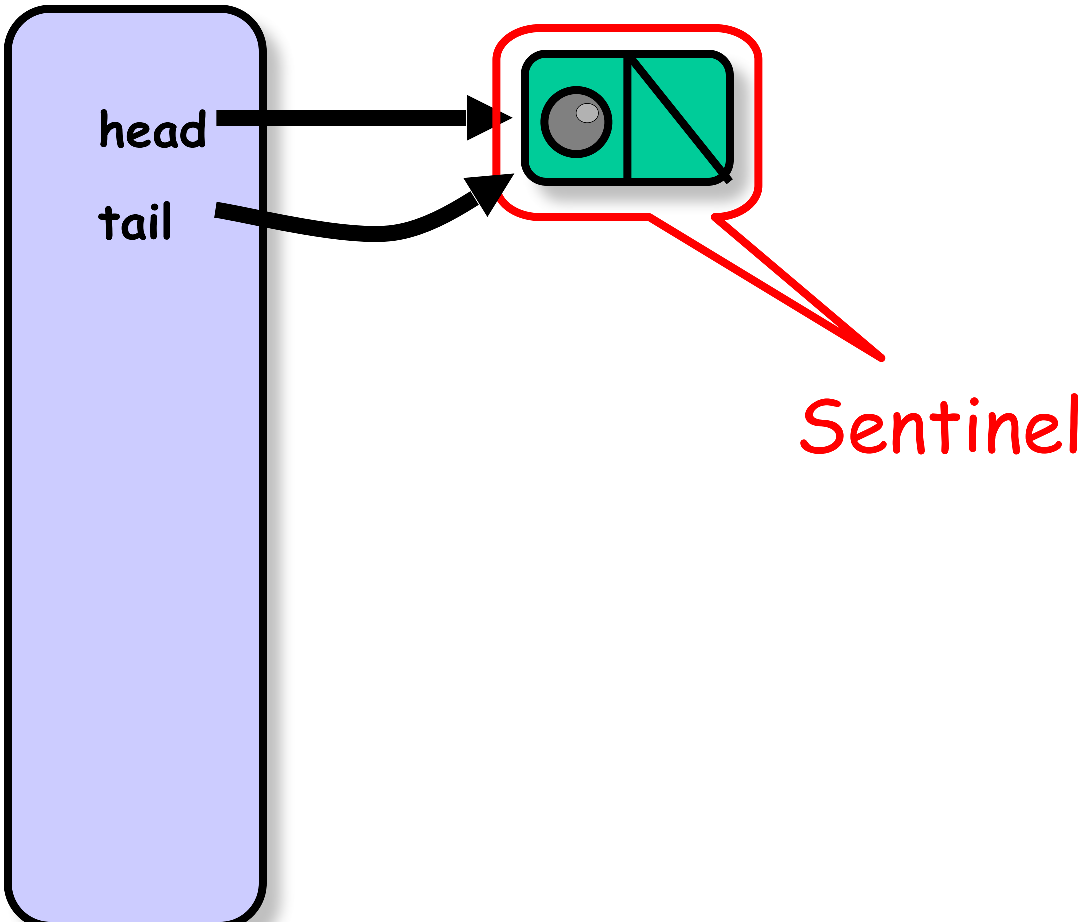
enqueue

1. Acquires enqLock
2. Reads the size field
3. If full, enqueuer must wait until dequeuer makes room
4. enqueuer waits on notFullCondition field, releasing enqLock temporarily, and blocking until that condition is signaled.
5. Each time the thread awakens, it checks whether there is a room, and if not, goes back to sleep
6. Insert new item into tail
7. Release enqLock
8. If queue was empty, notify/signal waiting dequeuers

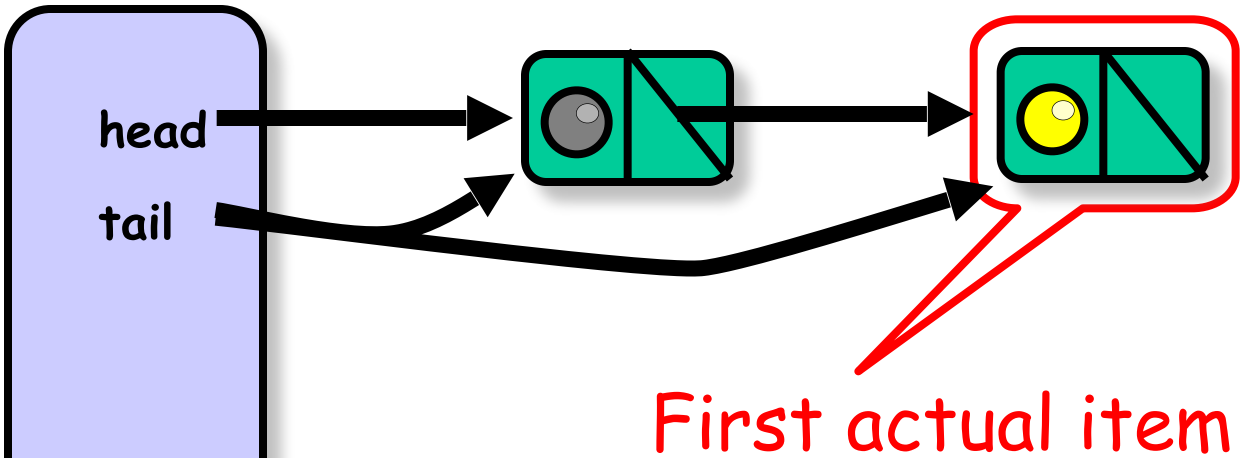
dequeue

1. Acquires deqLock
2. Reads the size field
3. If empty, dequeuer must wait until item is enqueued
4. dequeuer waits on notEmptyCondition field, releasing deqLock temporarily, and blocking until that condition is signaled.
5. Each time the thread awakens, it checks whether item was enqueued, and if not, goes back to sleep
6. Assigne the value of head's next node to "result" and reset head to head's next node
7. Release deqLock
8. If queue was full, notify/signal waiting enqueuers
9. Return "result"

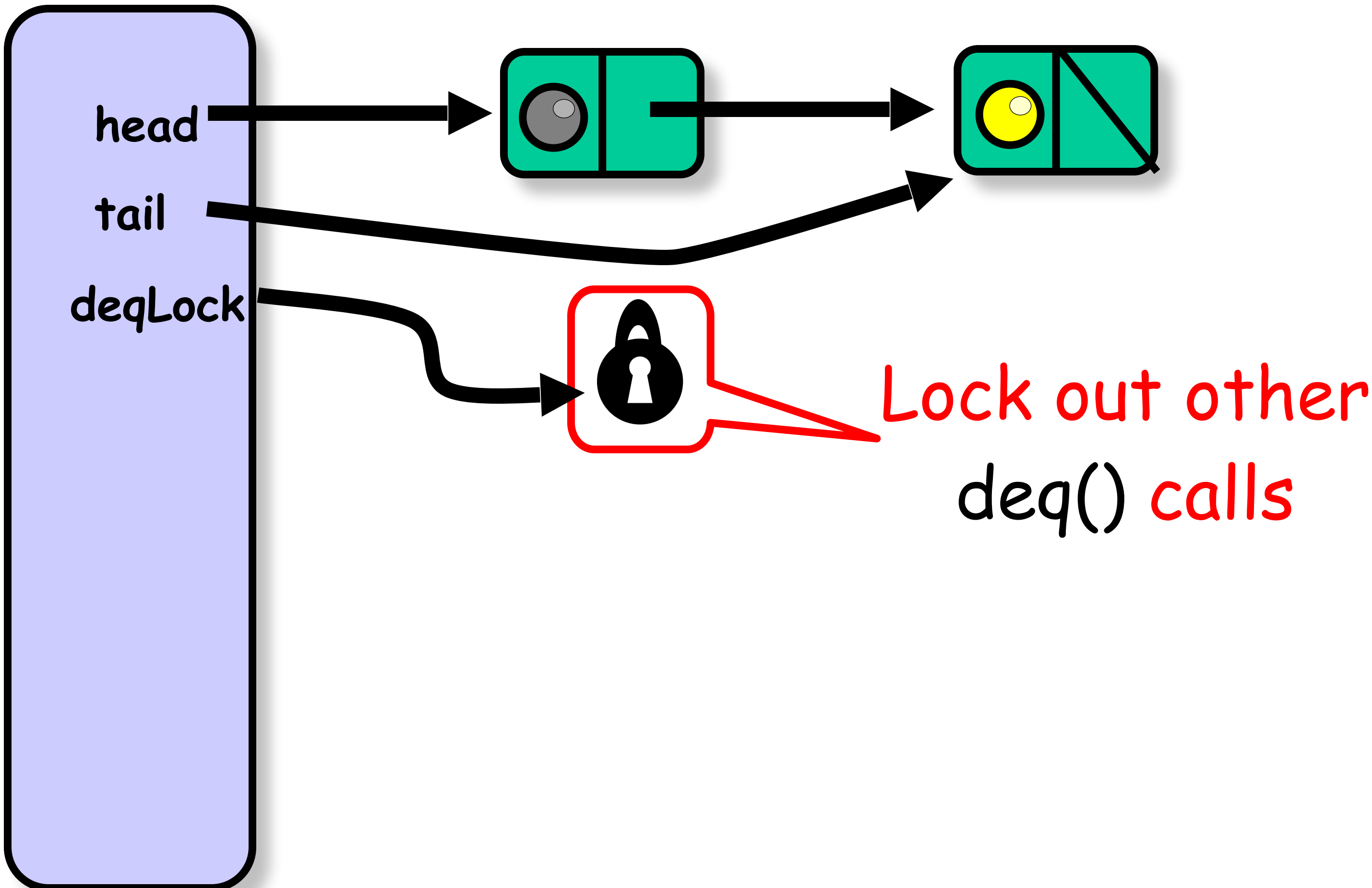
Bounded Queue



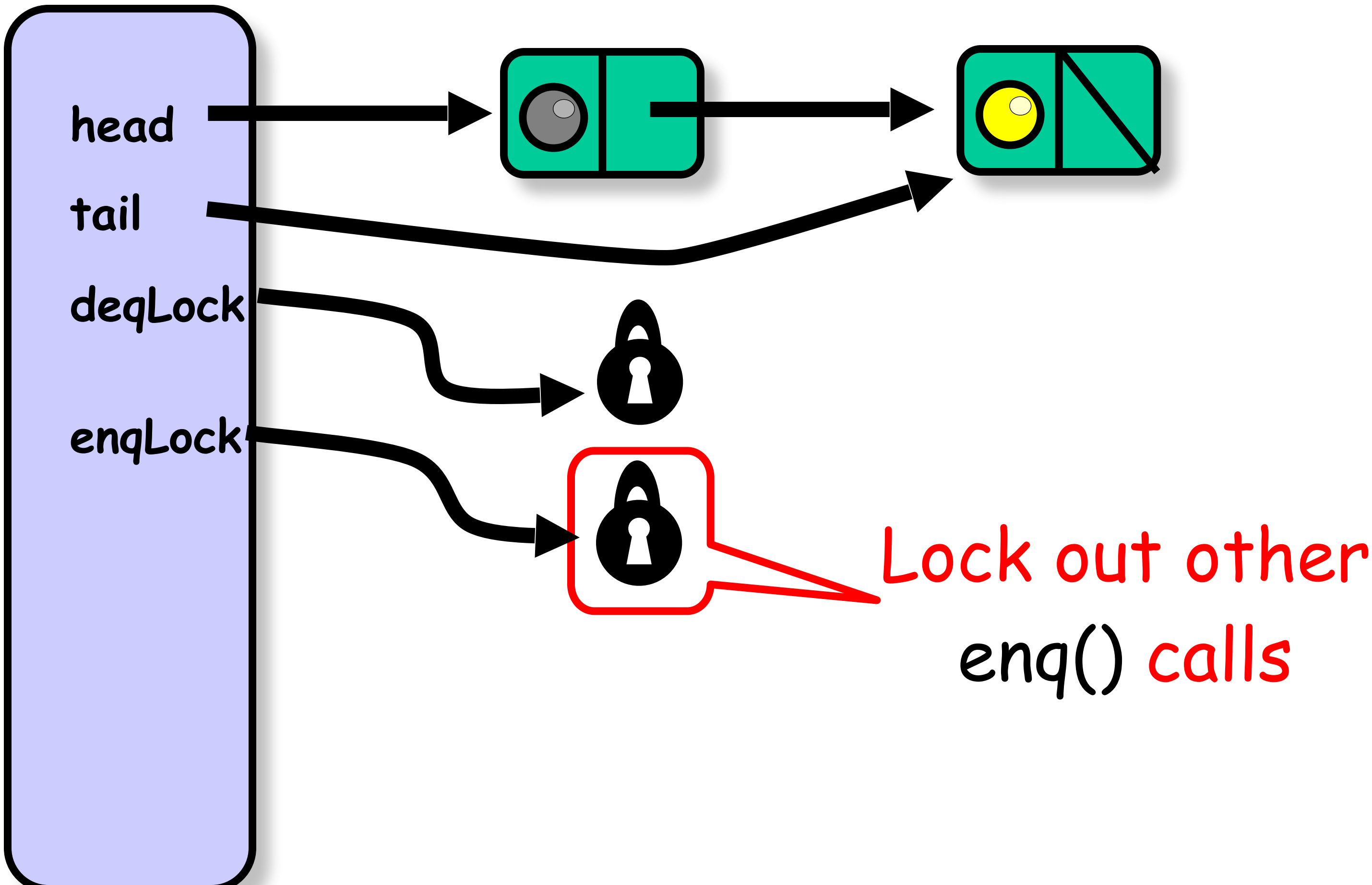
Bounded Queue



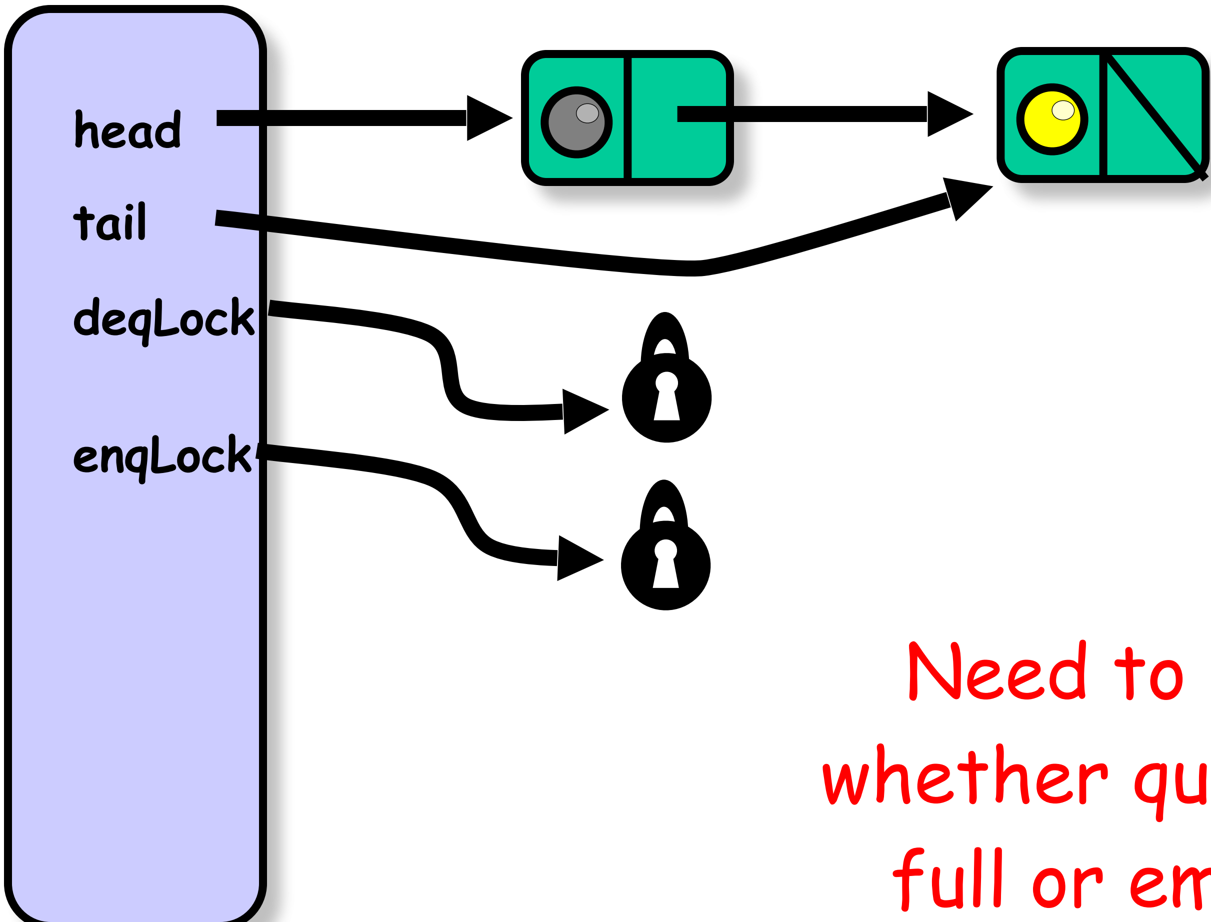
Bounded Queue



Bounded Queue

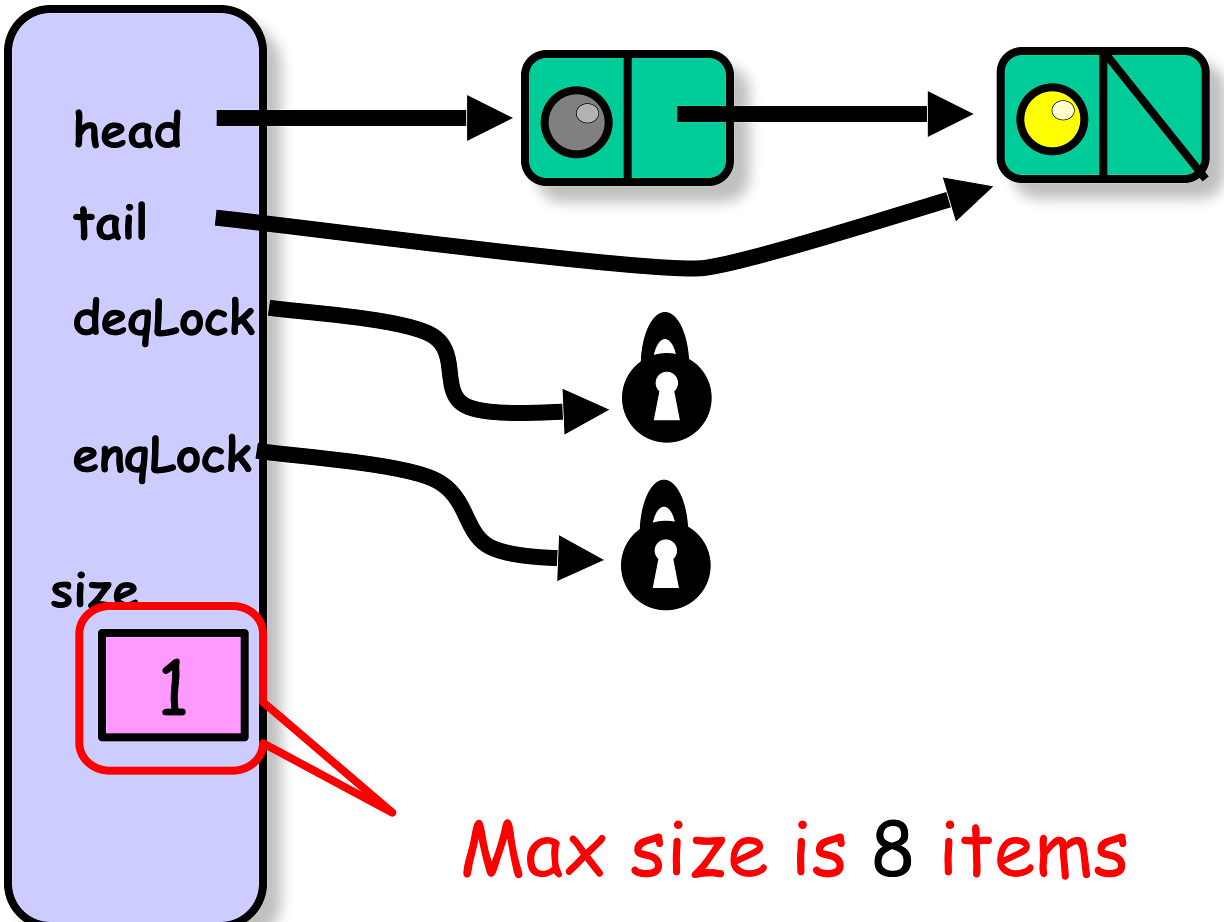


Not Done Yet

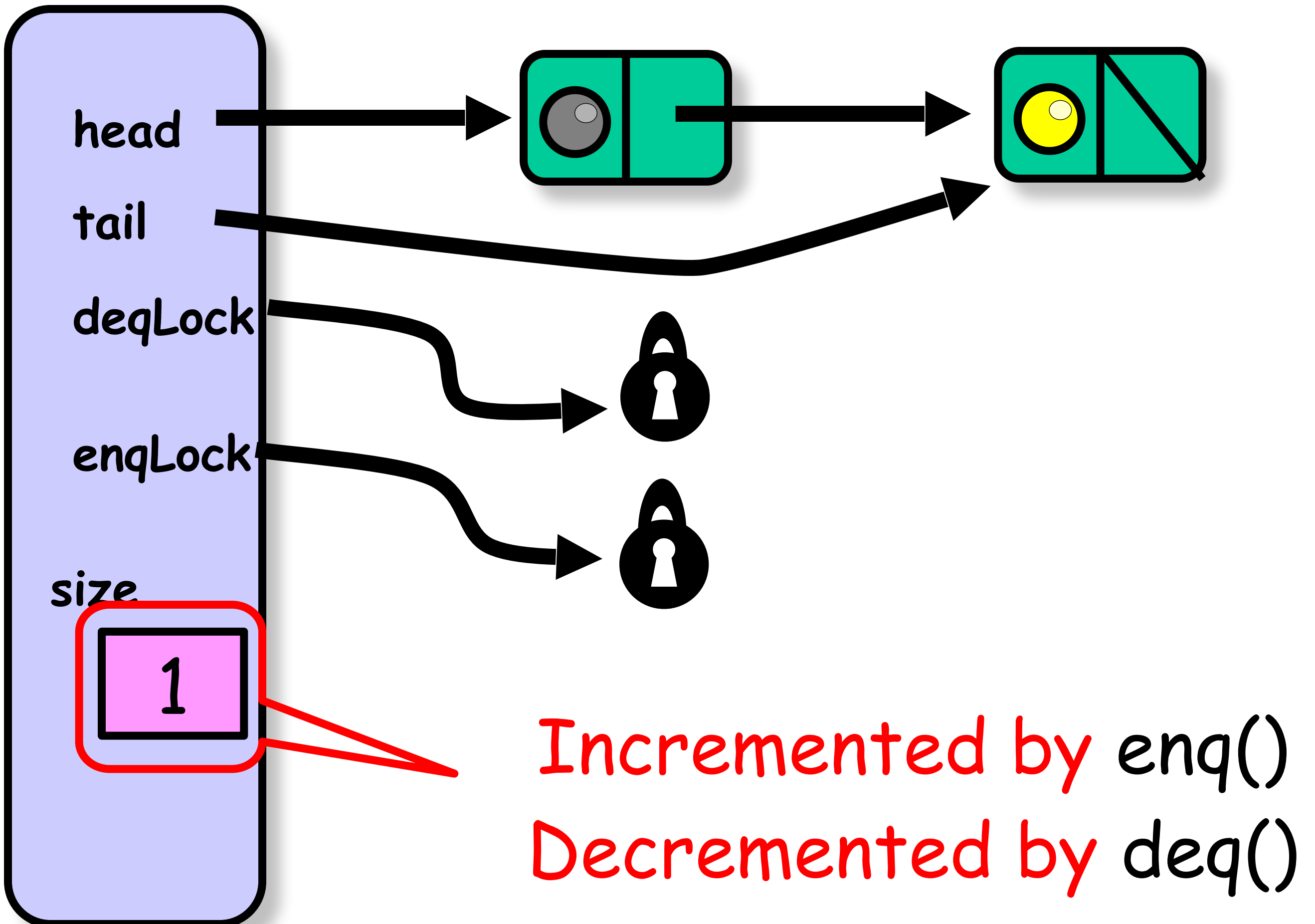


Need to tell whether queue is full or empty

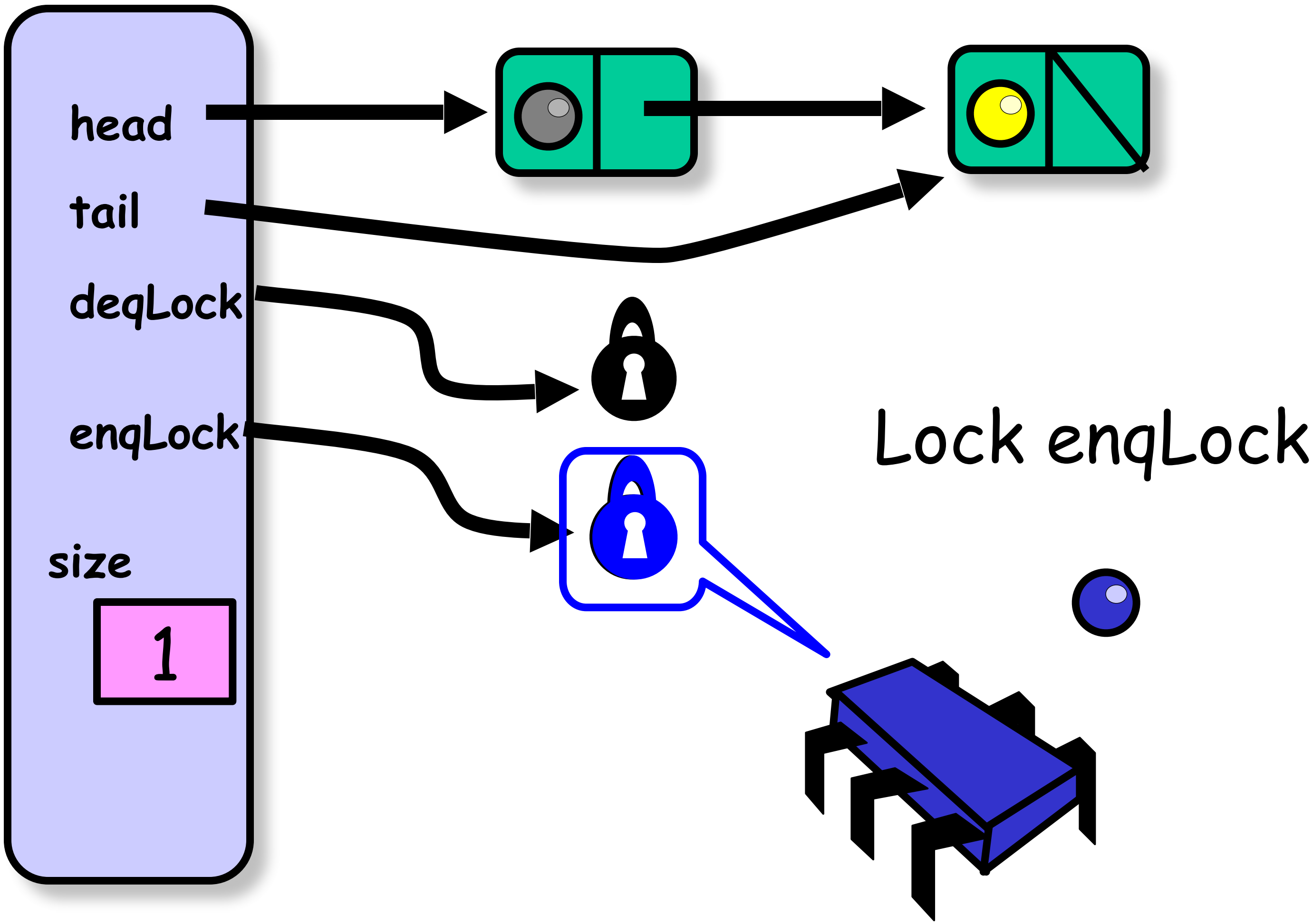
Not Done Yet



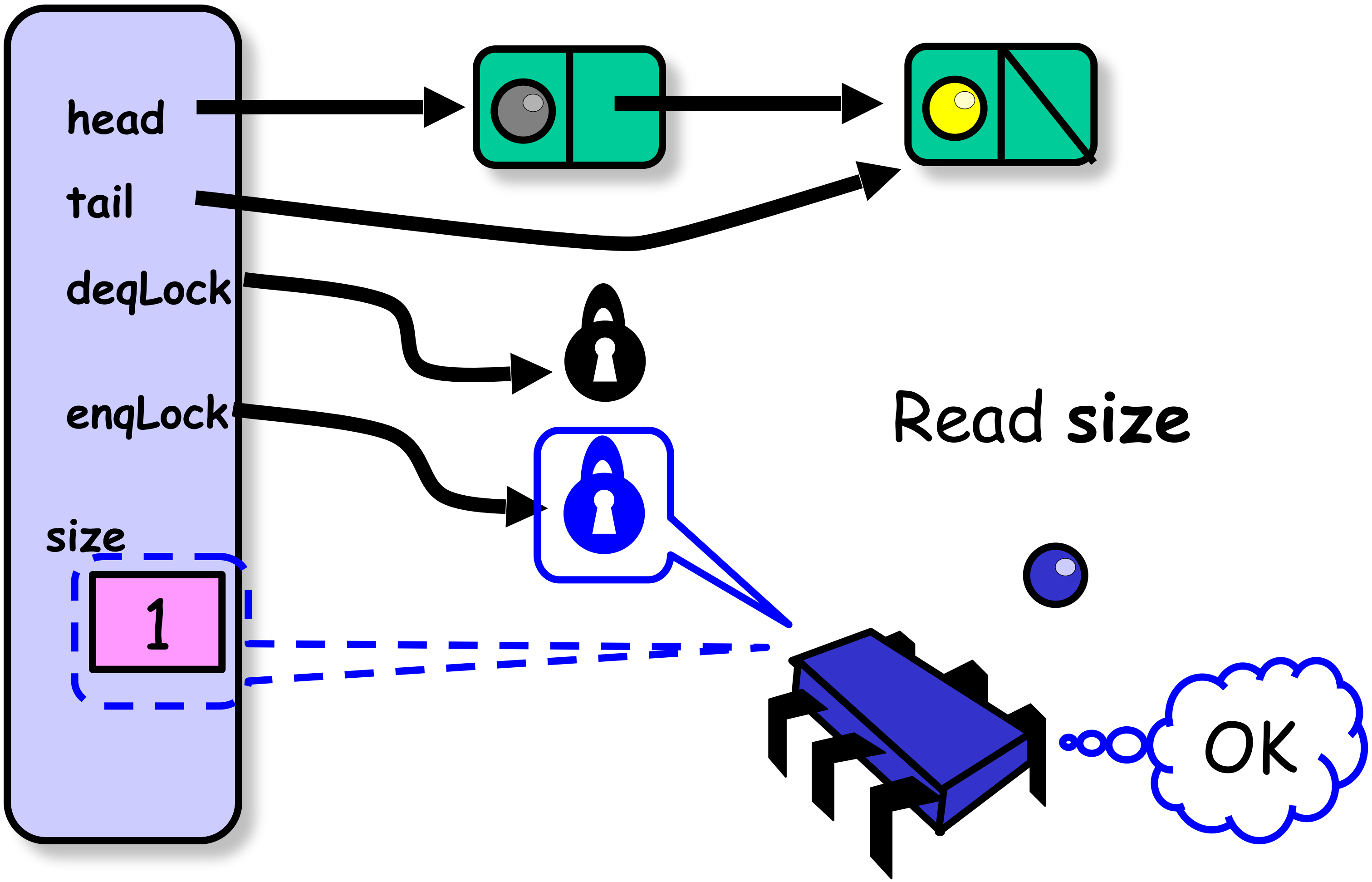
Not Done Yet


head
tail
deqLock
enqLock
size
1
Incremented by enq()
Decremented by deq()

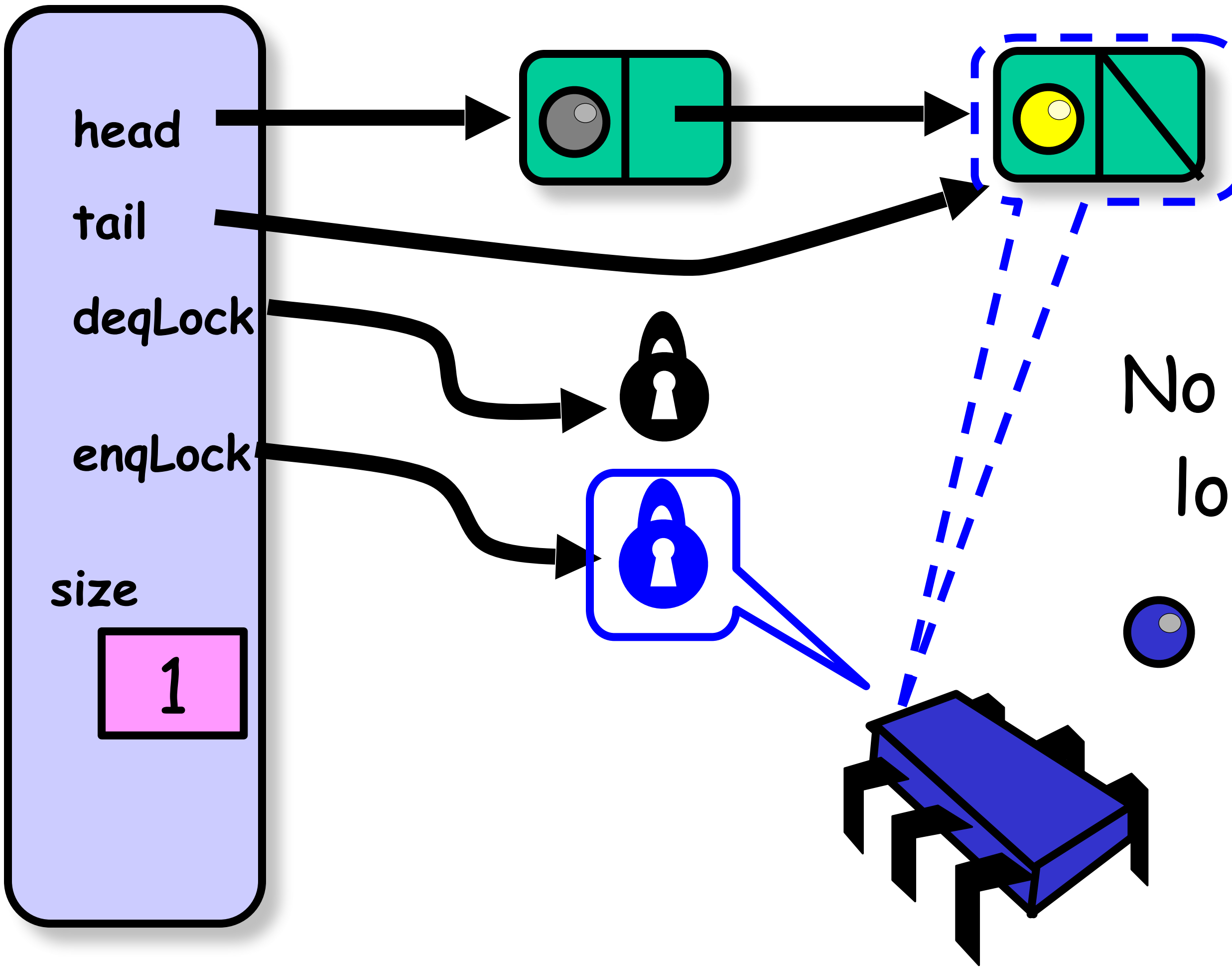
Enqueuer



Enqueuer

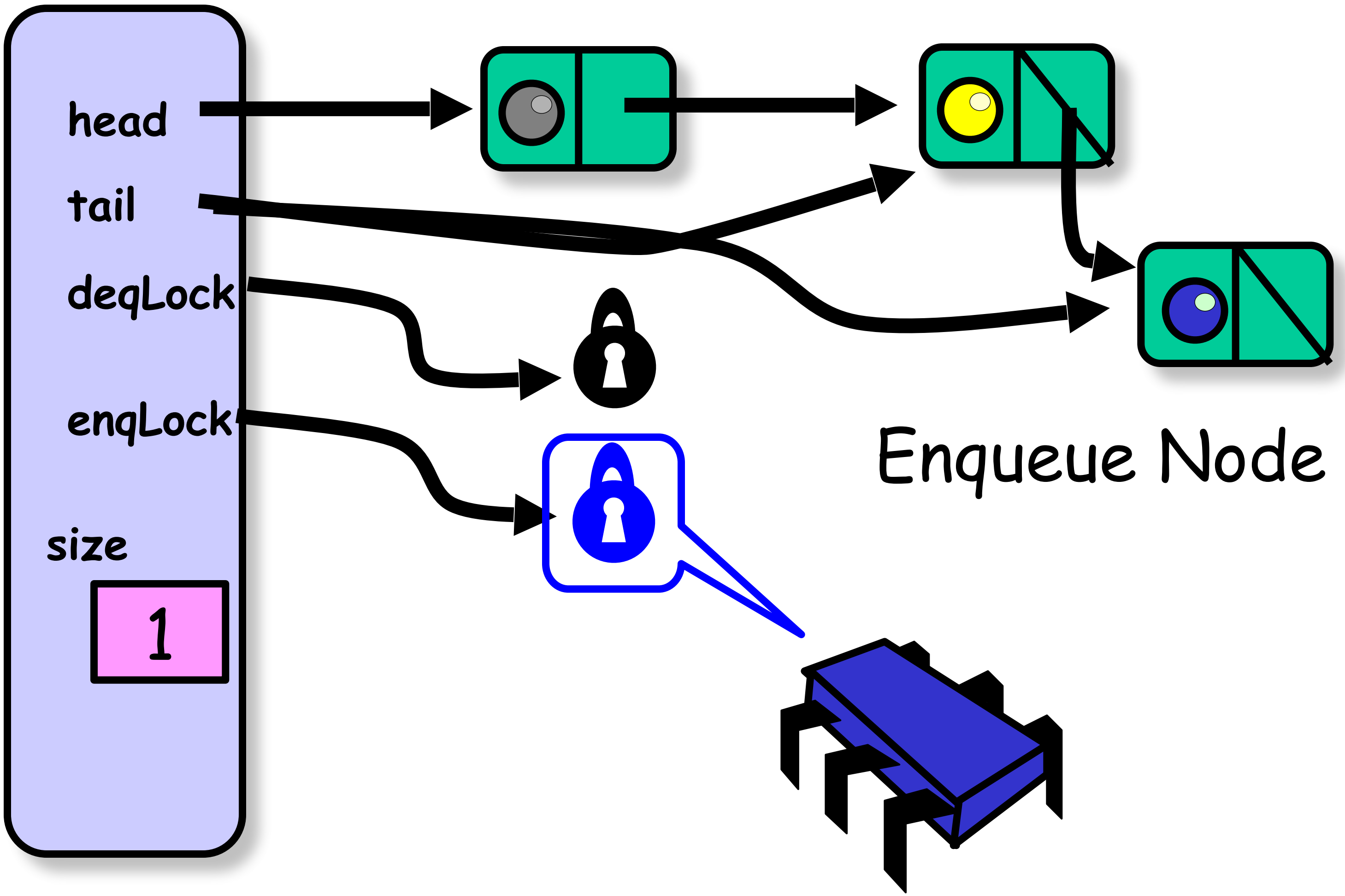


Enqueuer

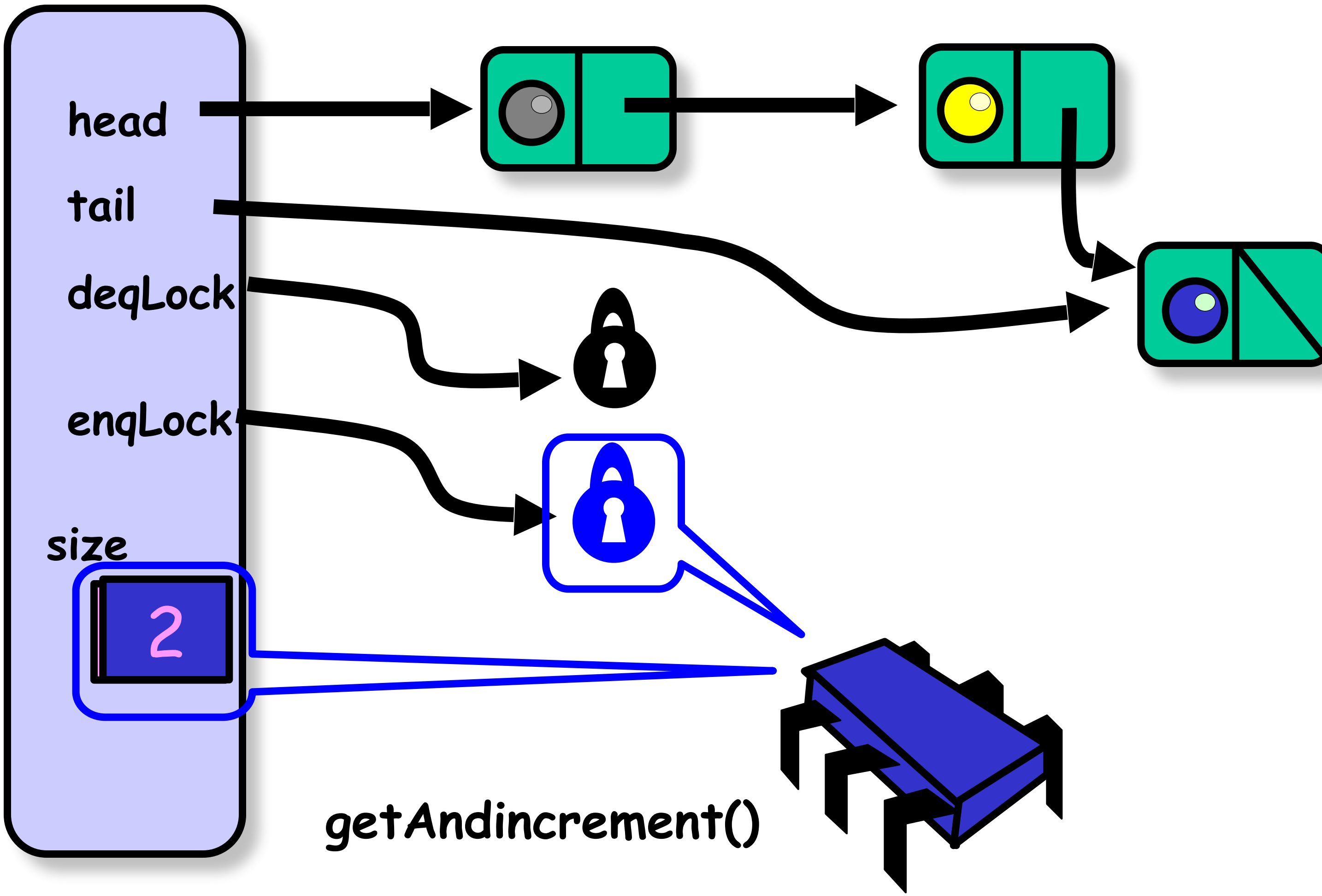


No need to lock **tail**

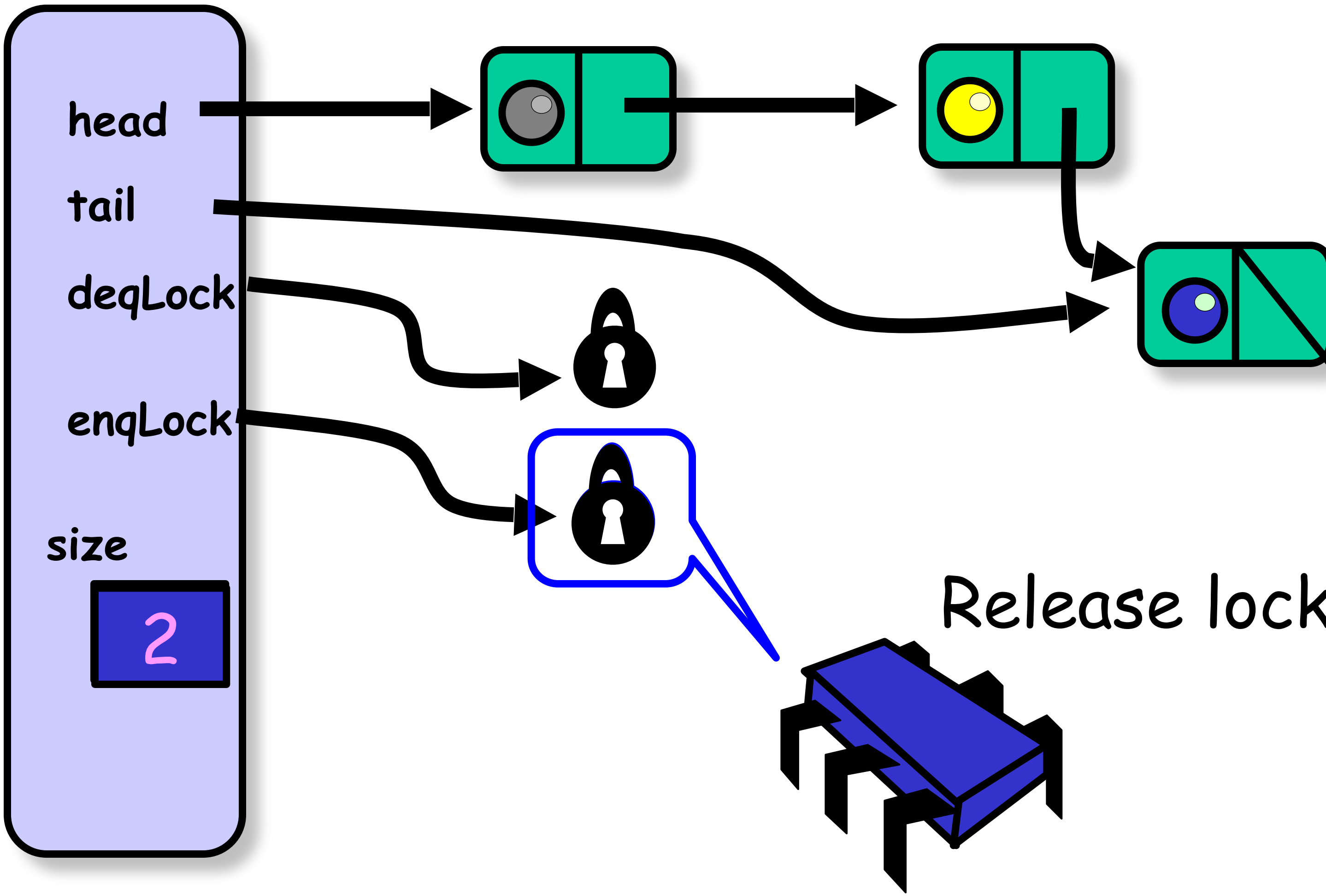
Enqueuer



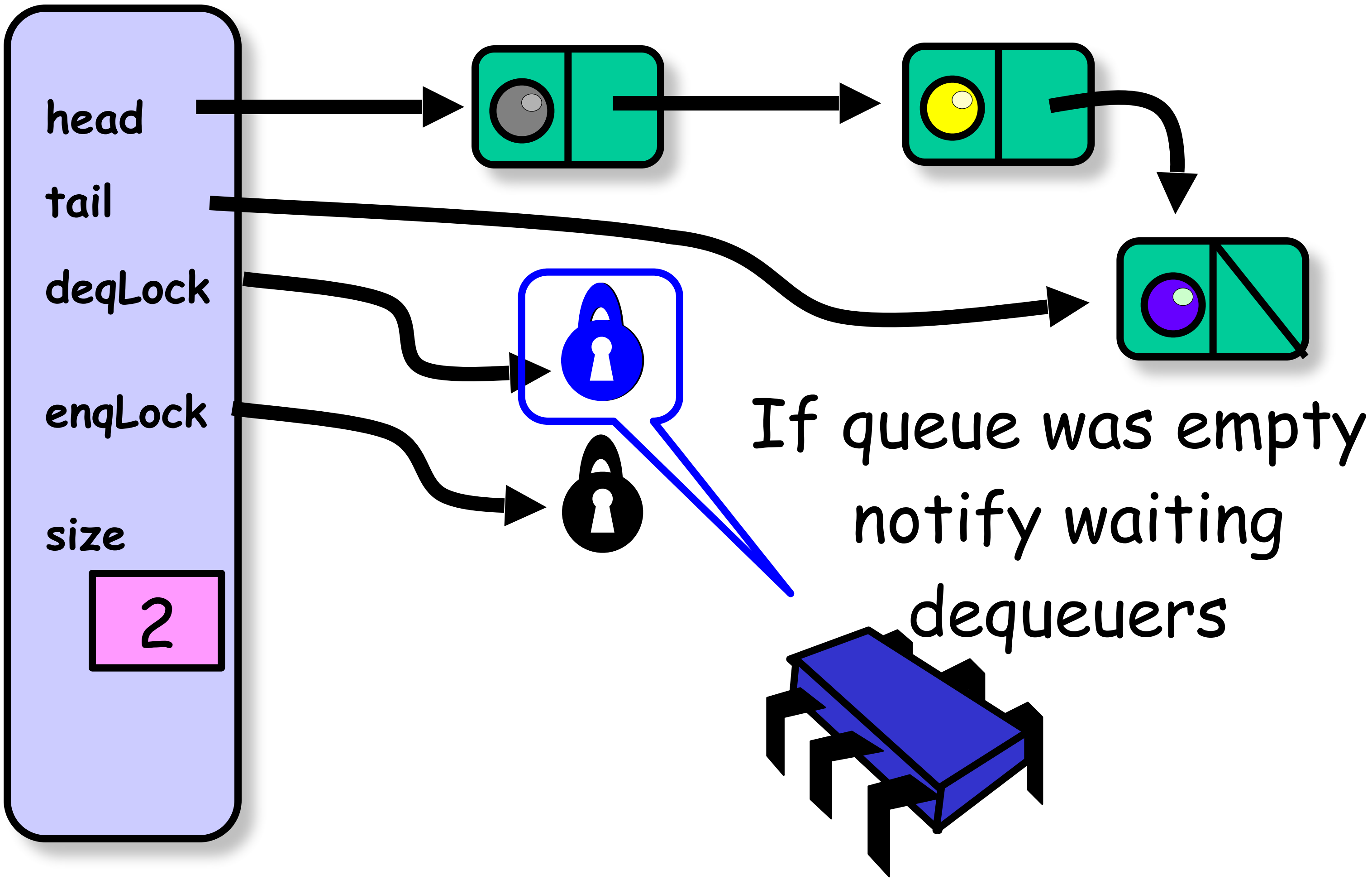
Enqueuer



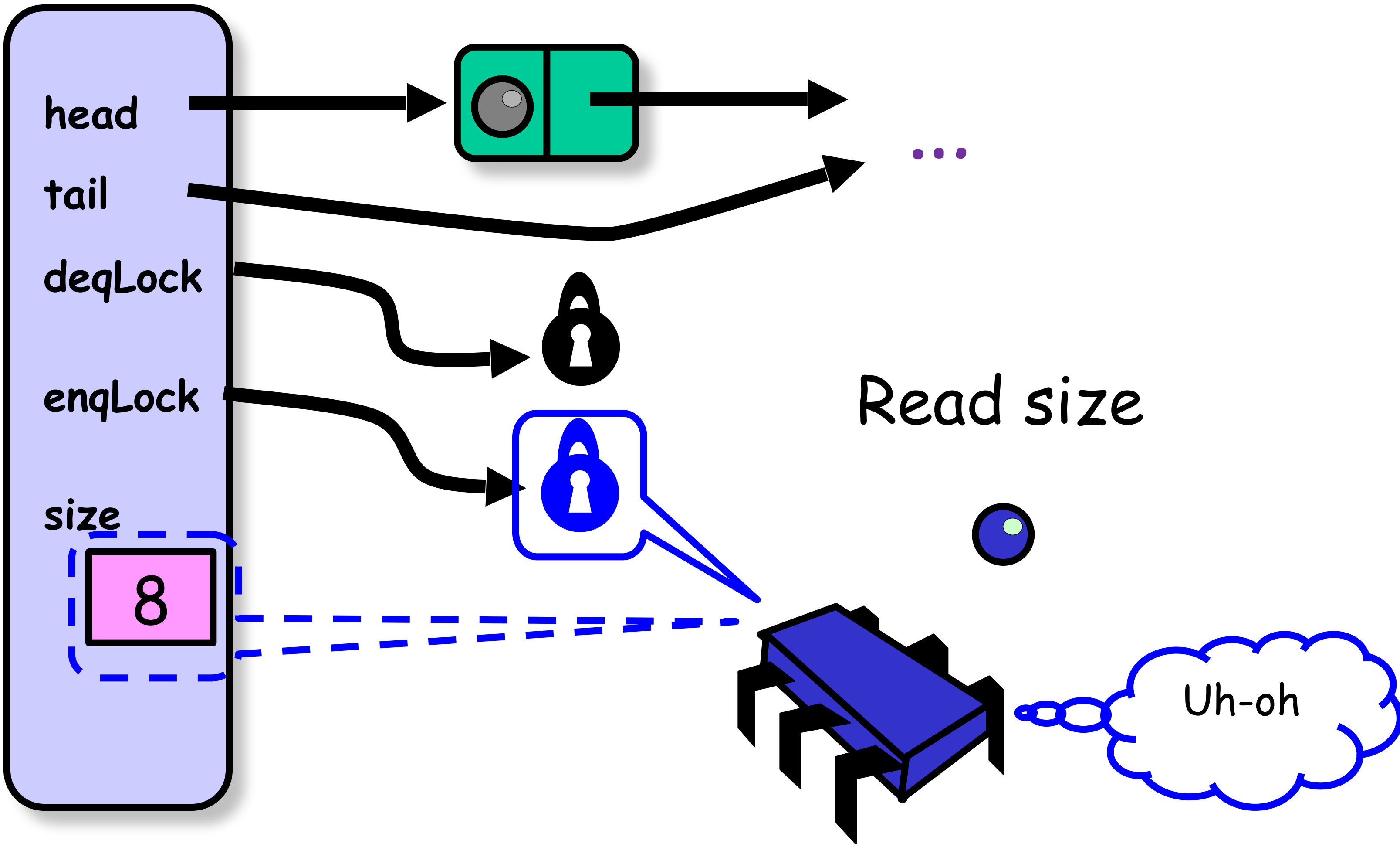
Enqueuer



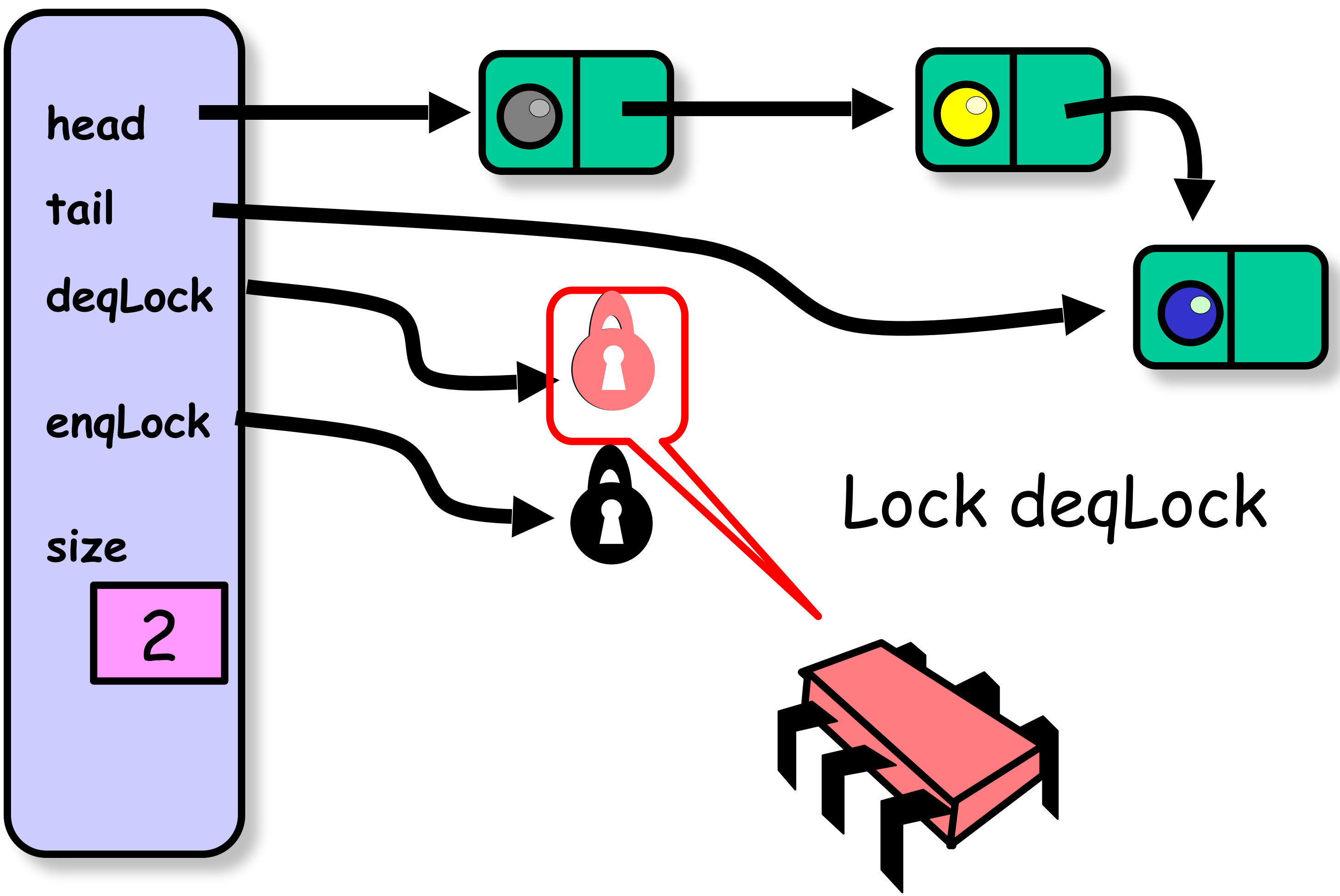
Enqueuer


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

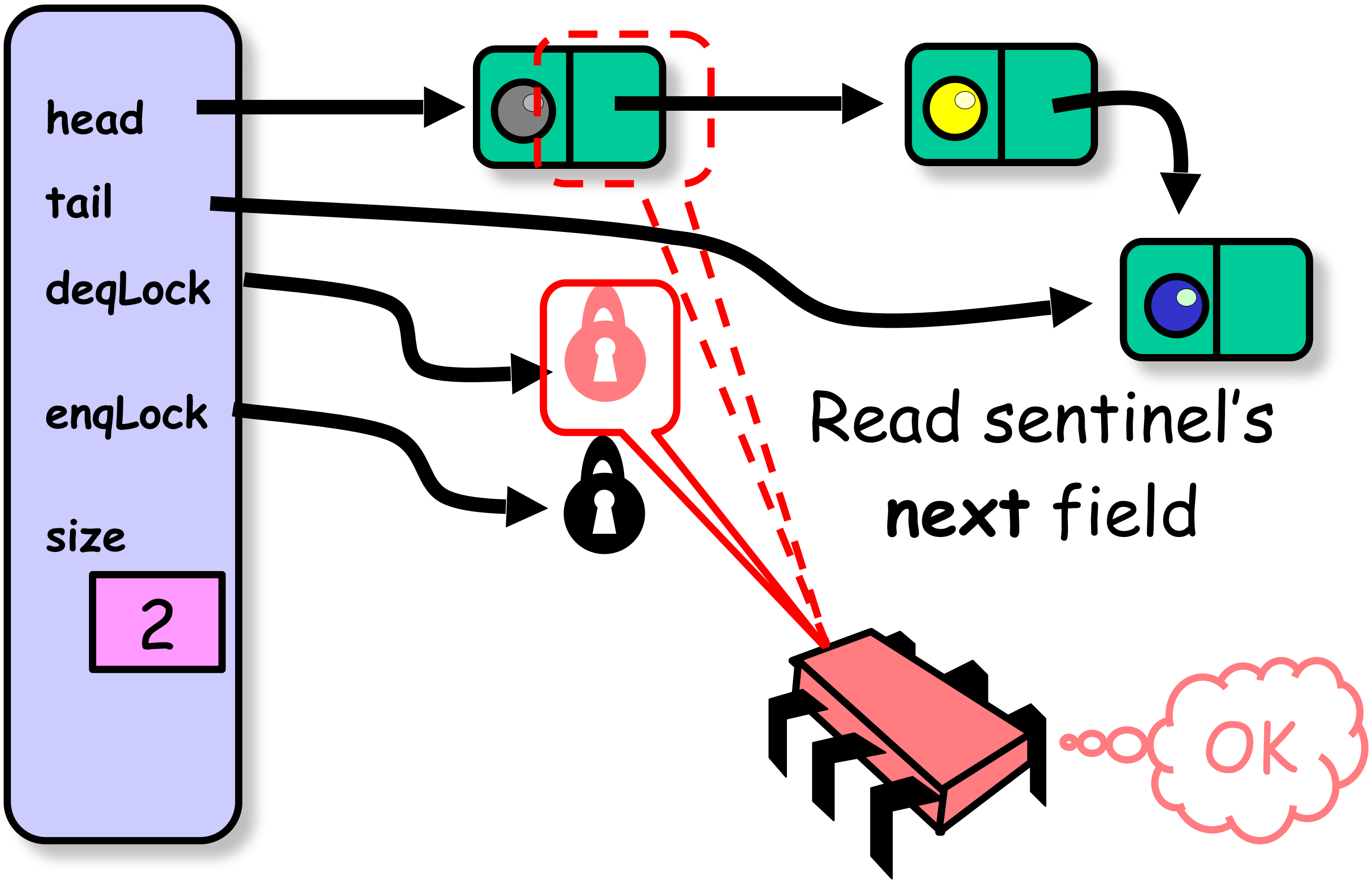
Unsuccesful Enqueuer



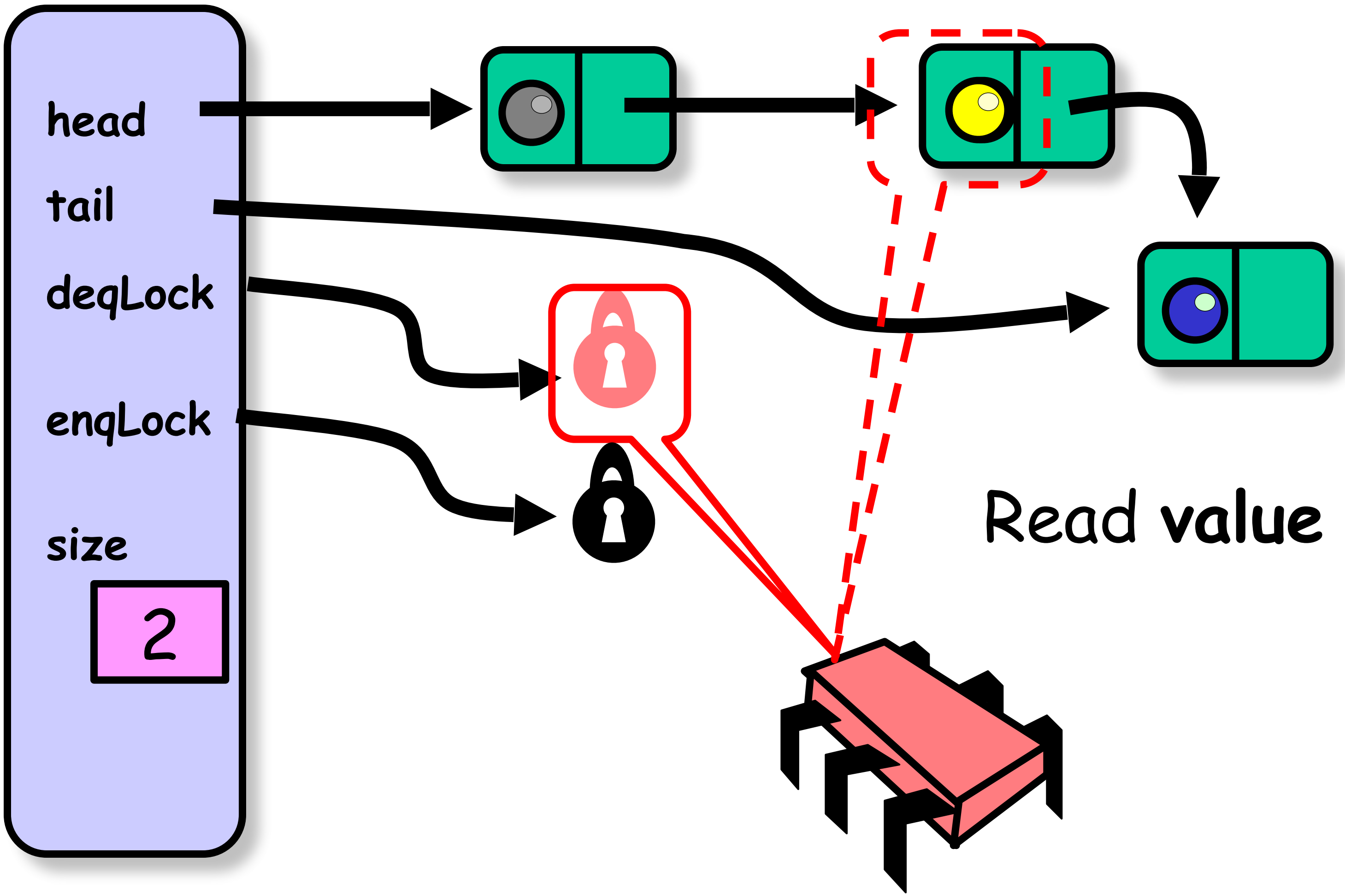
Dequeuer



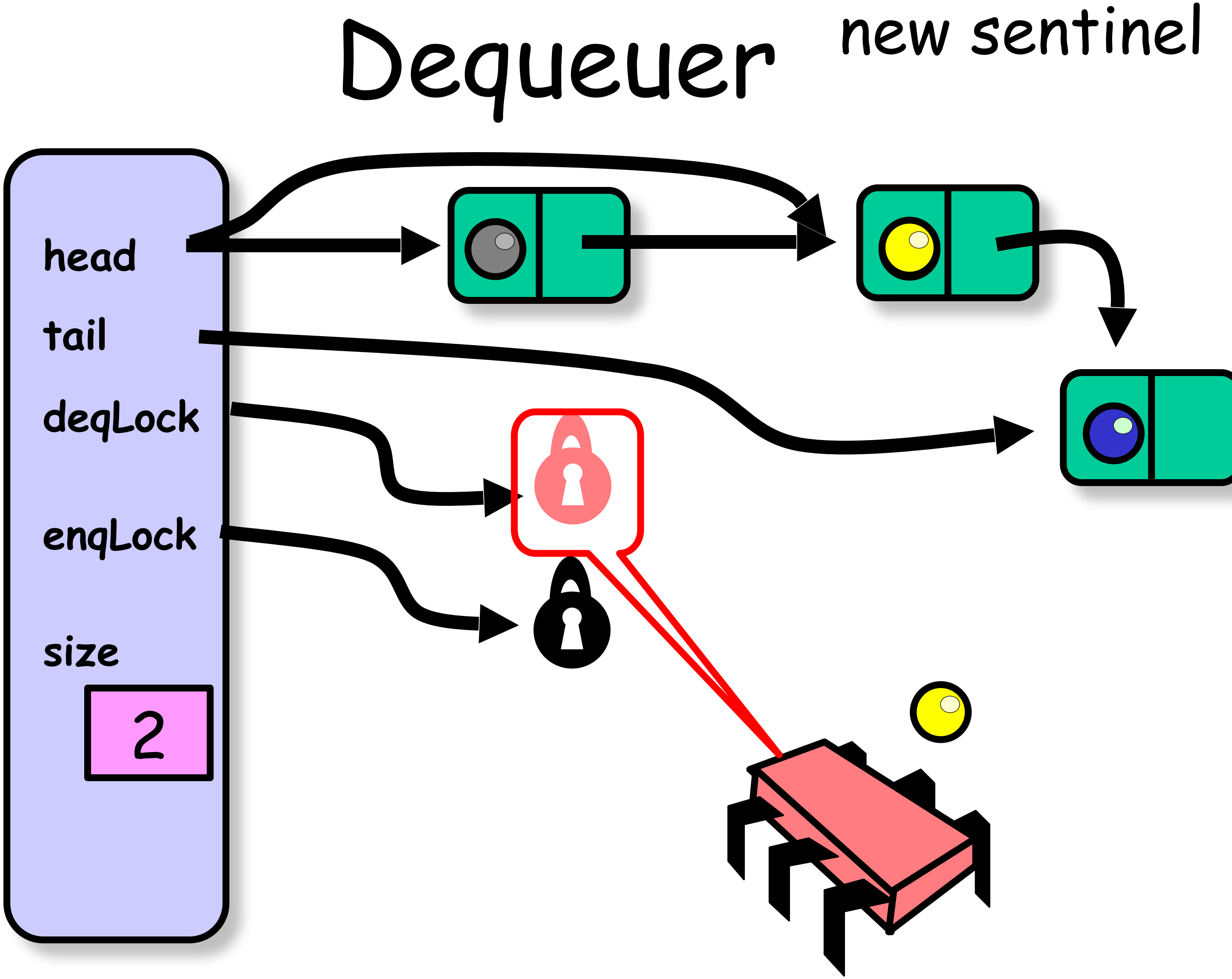
Dequeuer


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

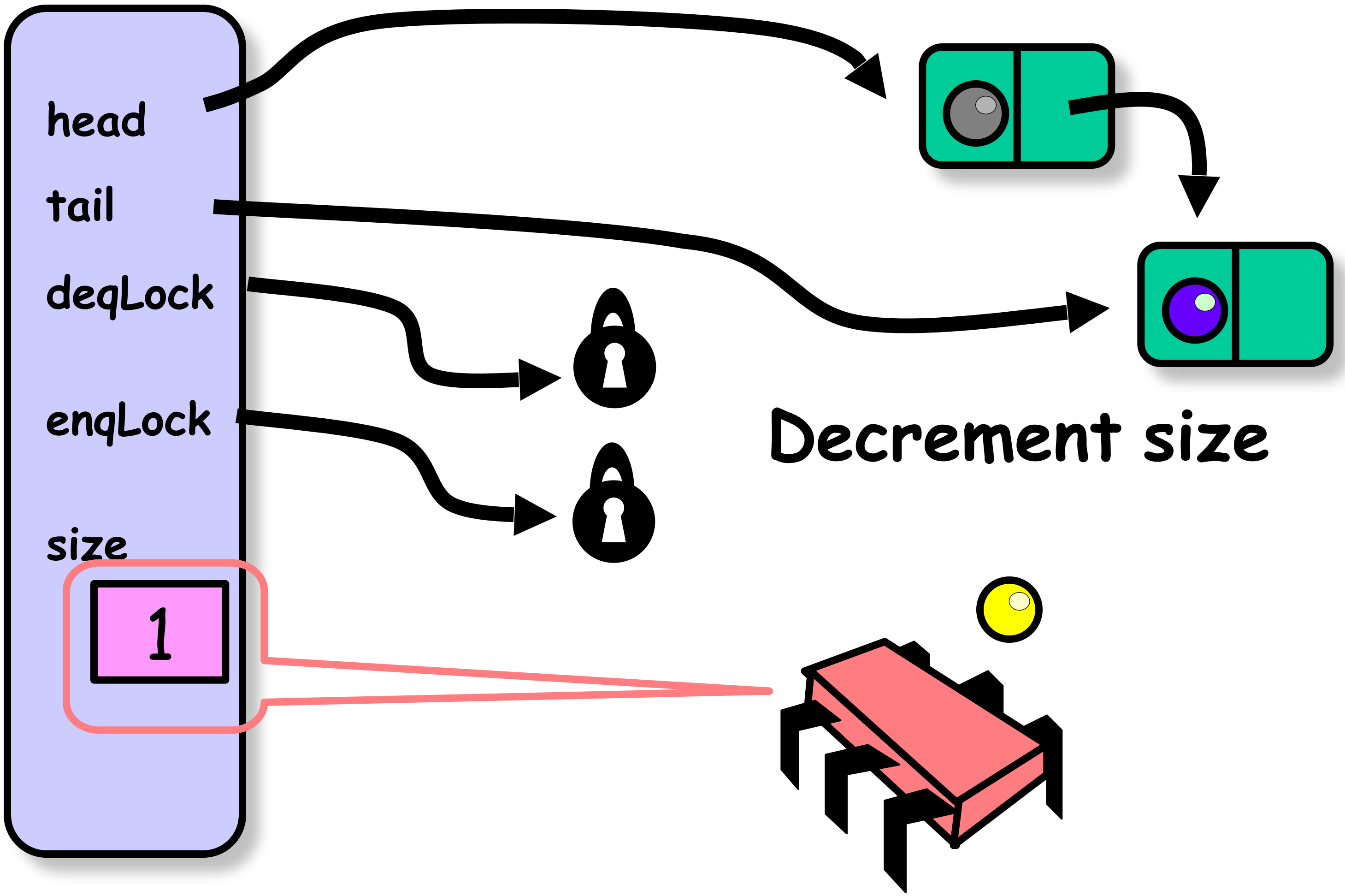
Dequeuer



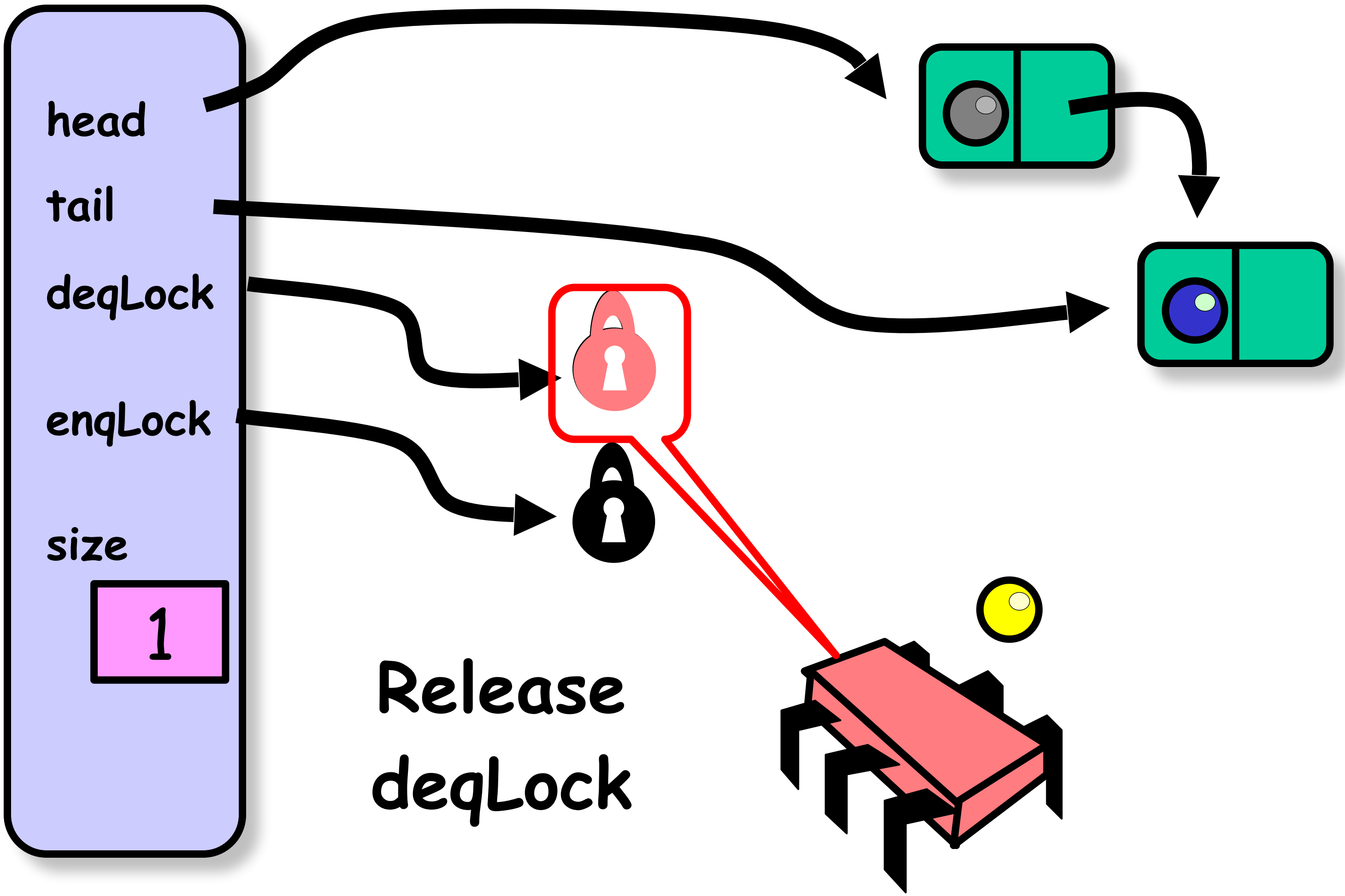
Make first Node new sentinel



Dequeuer



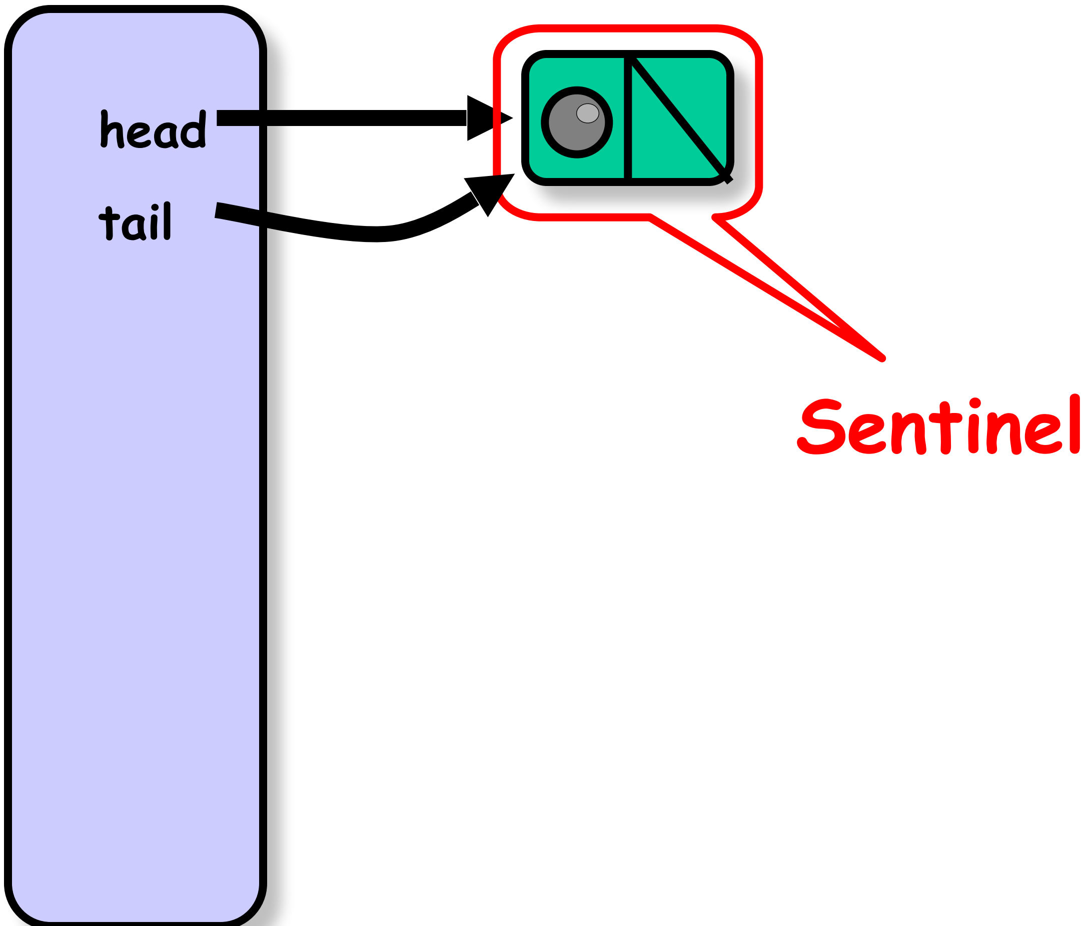
Dequeuer



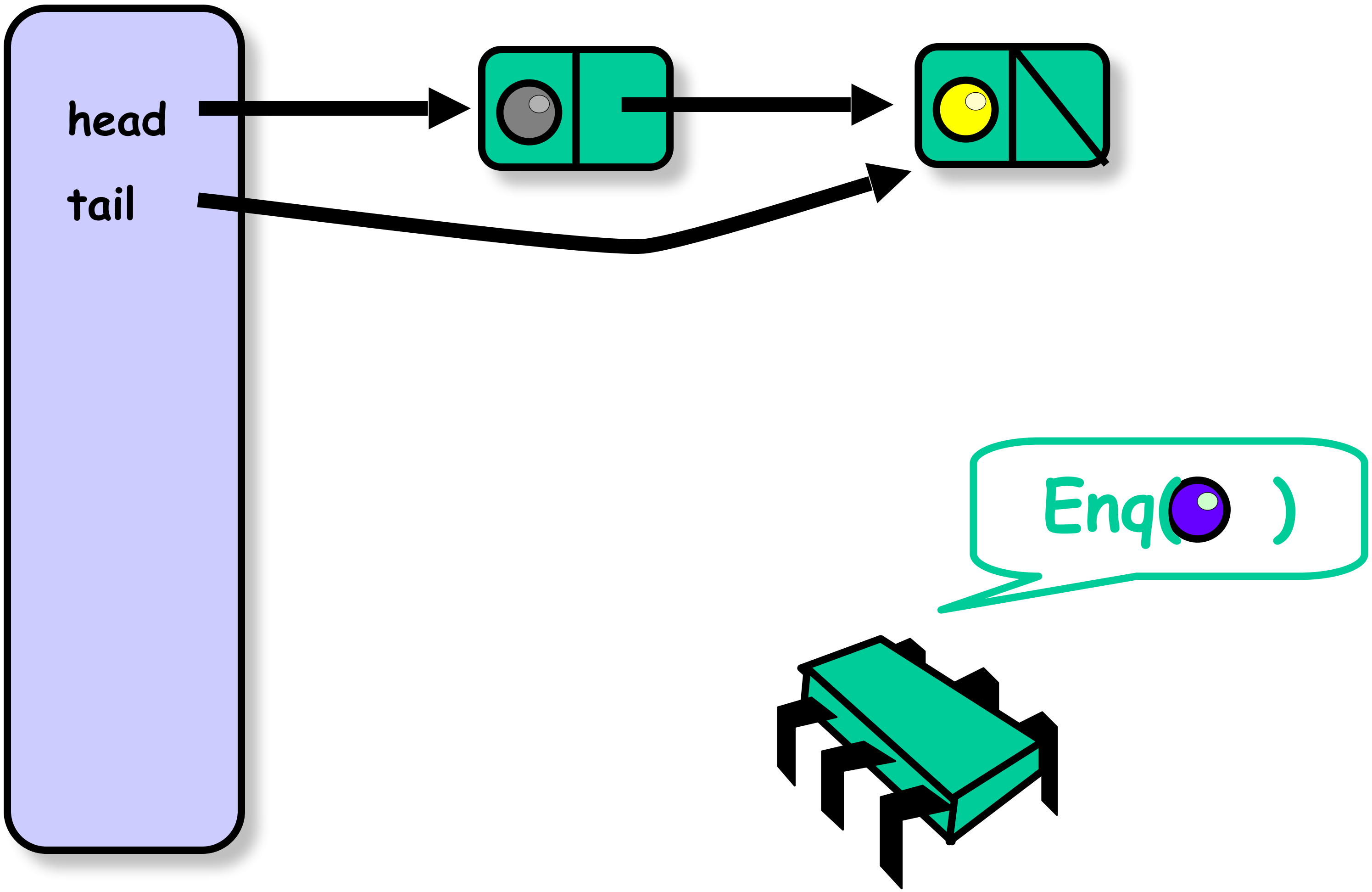
Unbounded Lock-Free Queue (Nonblocking)

- Unbounded
  - No need to count the number of items
- Lock-free
  - Use AtomicReference<V>
    - An object reference that may be updated atomically.
  - boolean compareAndSet(V expect, V update)
    - Atomically sets the value to the given updated value if the current value == the expected value.
- Nonblocking
  - No need to provide conditions on which to wait

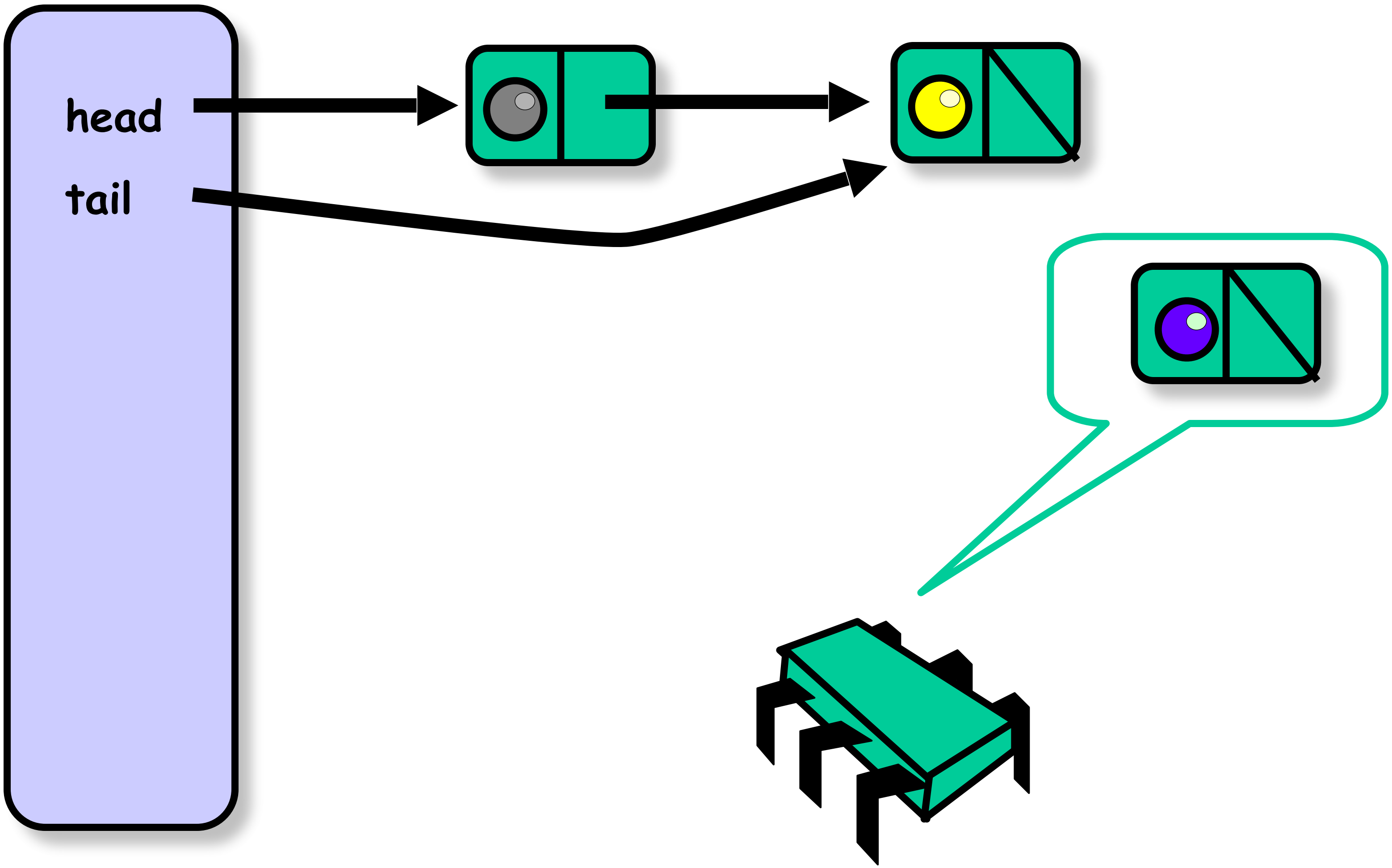
A Lock-Free Queue



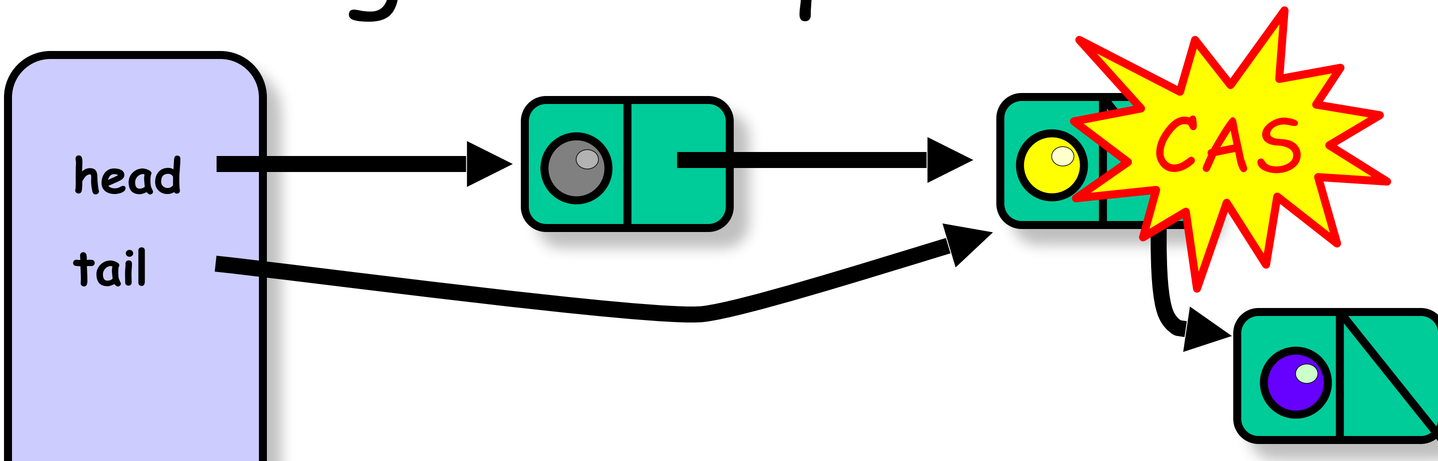
Enqueue

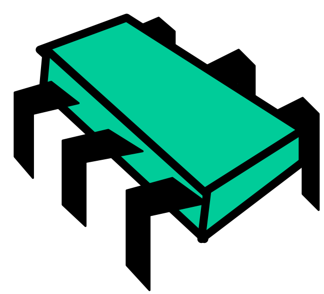


Enqueue

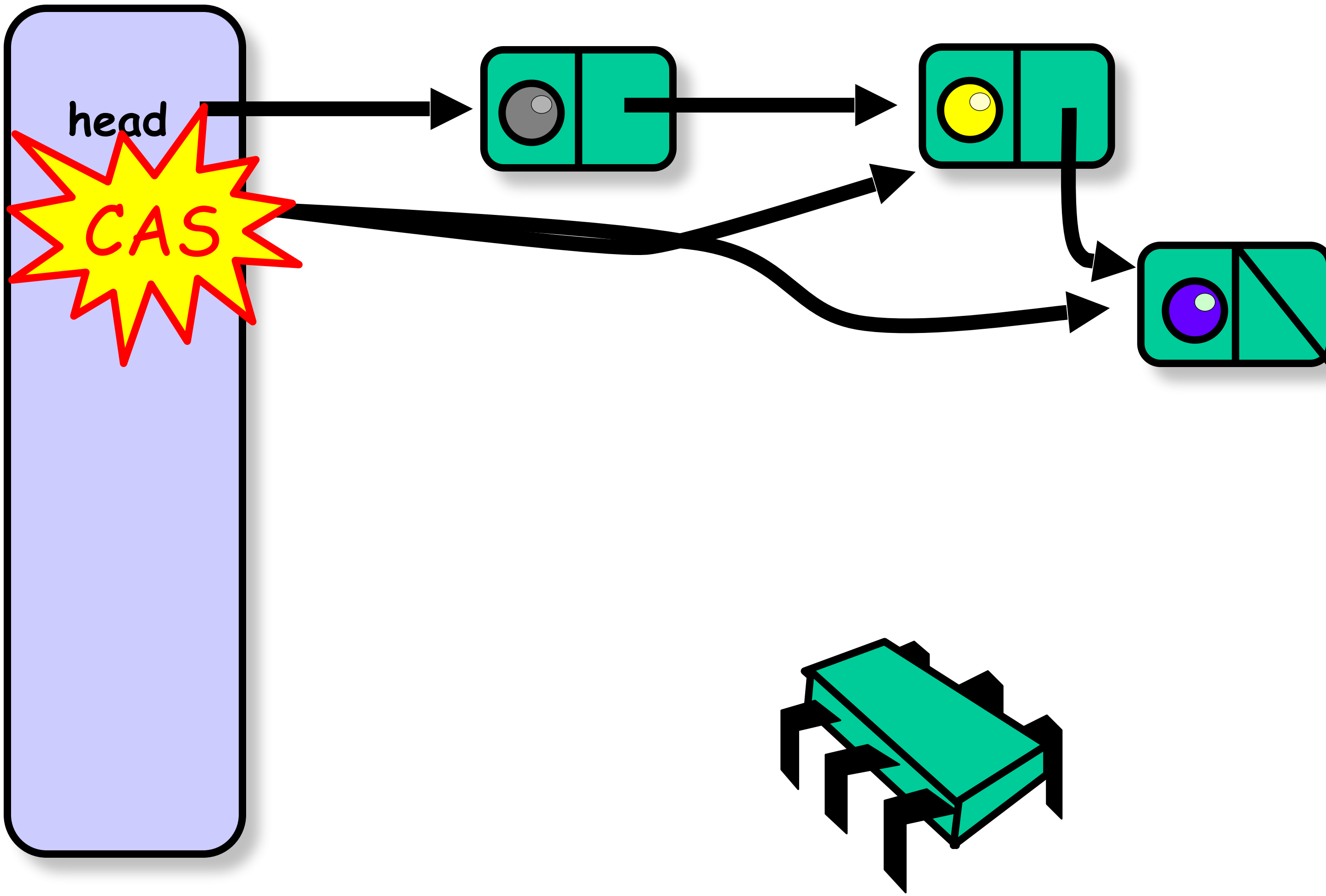


Logical Enqueue





Physical Enqueue



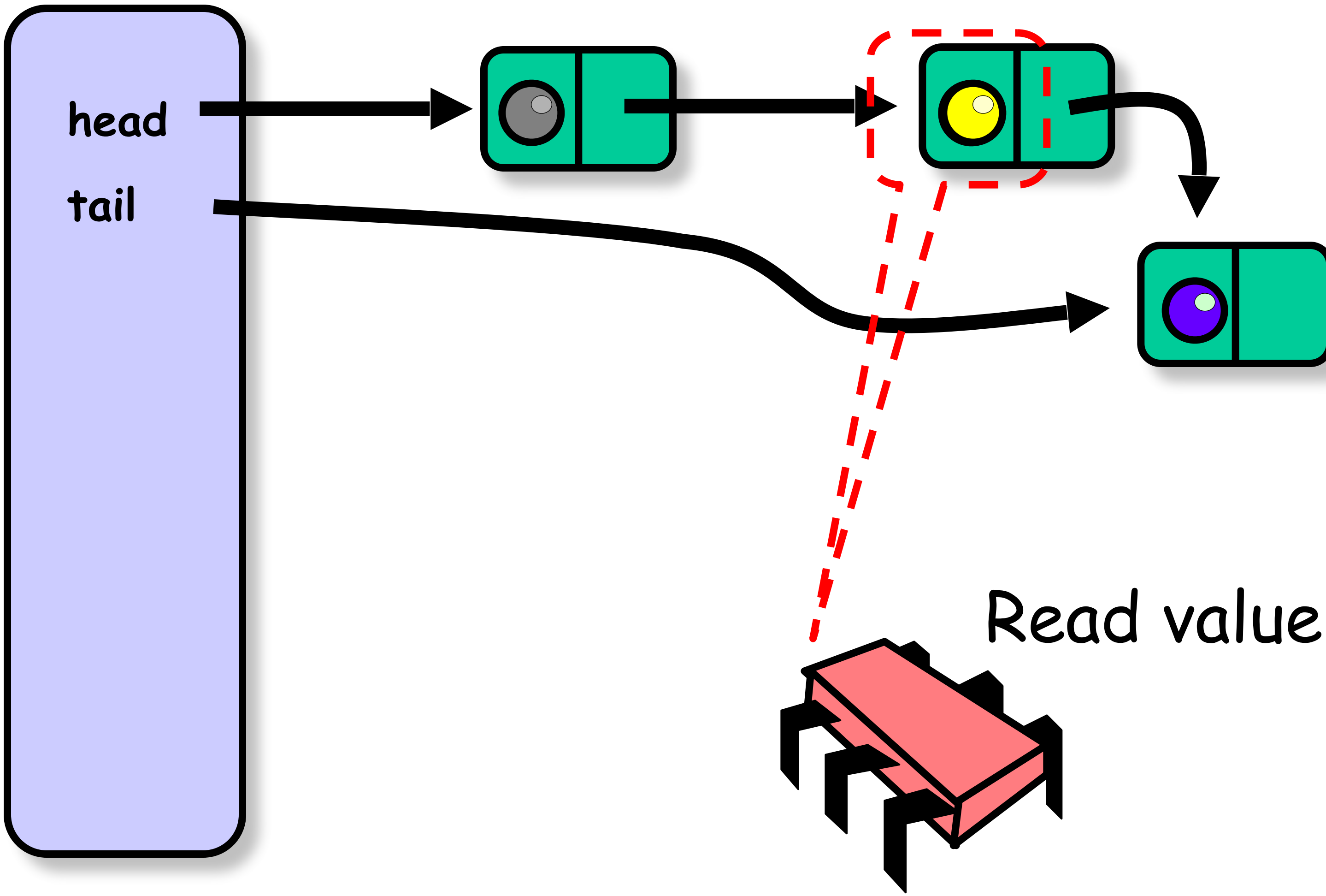
Enqueue

- These two steps are not atomic
- The tail field refers to either
  - Actual last Node (good)
  - Penultimate Node (not so good)
- Be prepared!
- (For you to think about) How could you fix that?

When CASs Fail

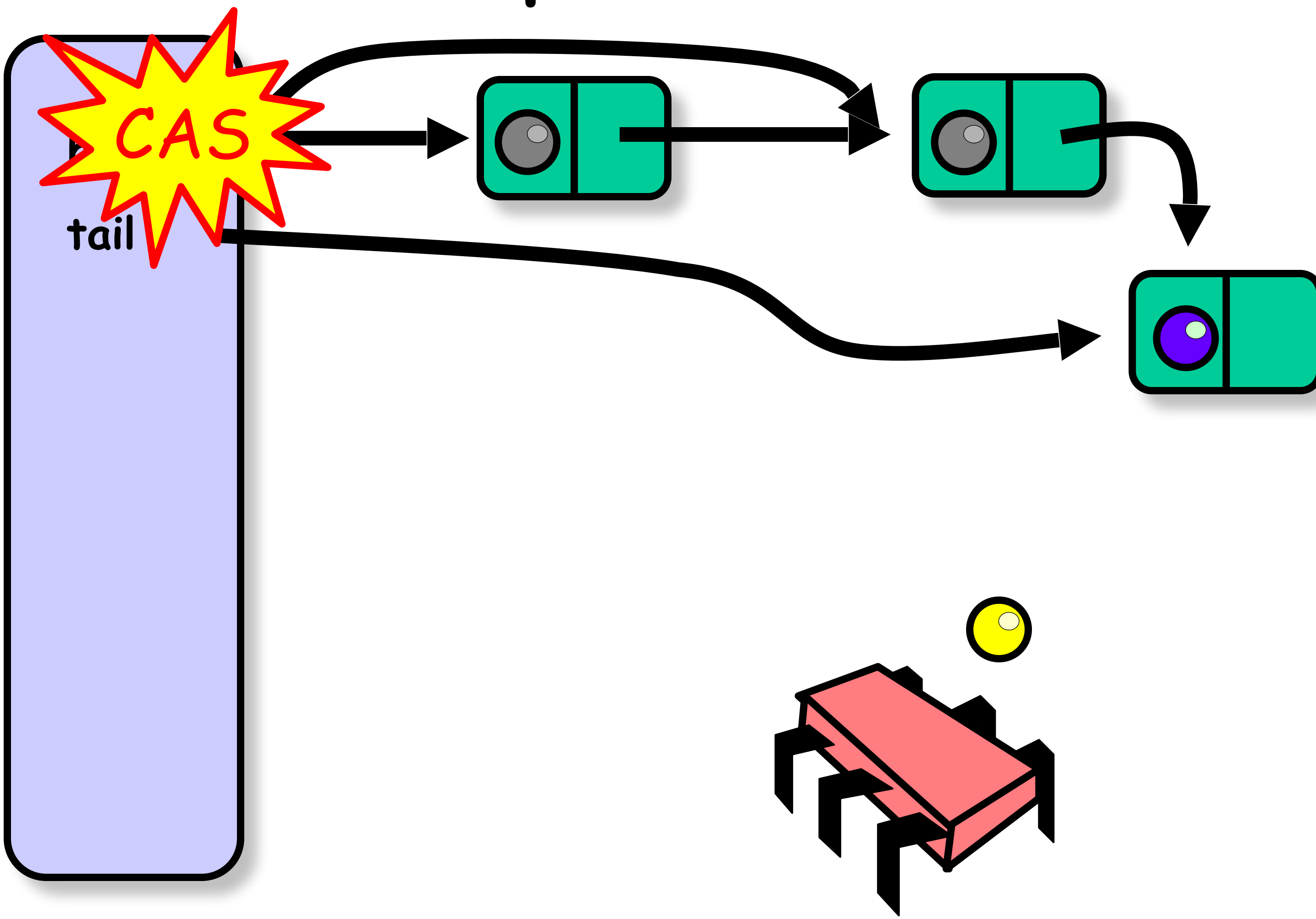
- During logical enqueue
  - Abandon hope, restart
  - Still lock-free (why?)
- During physical enqueue
  - Ignore it (why?)

Dequeuer



Make first Node new sentinel

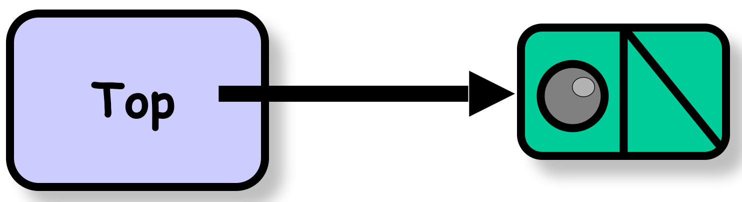
Dequeuer



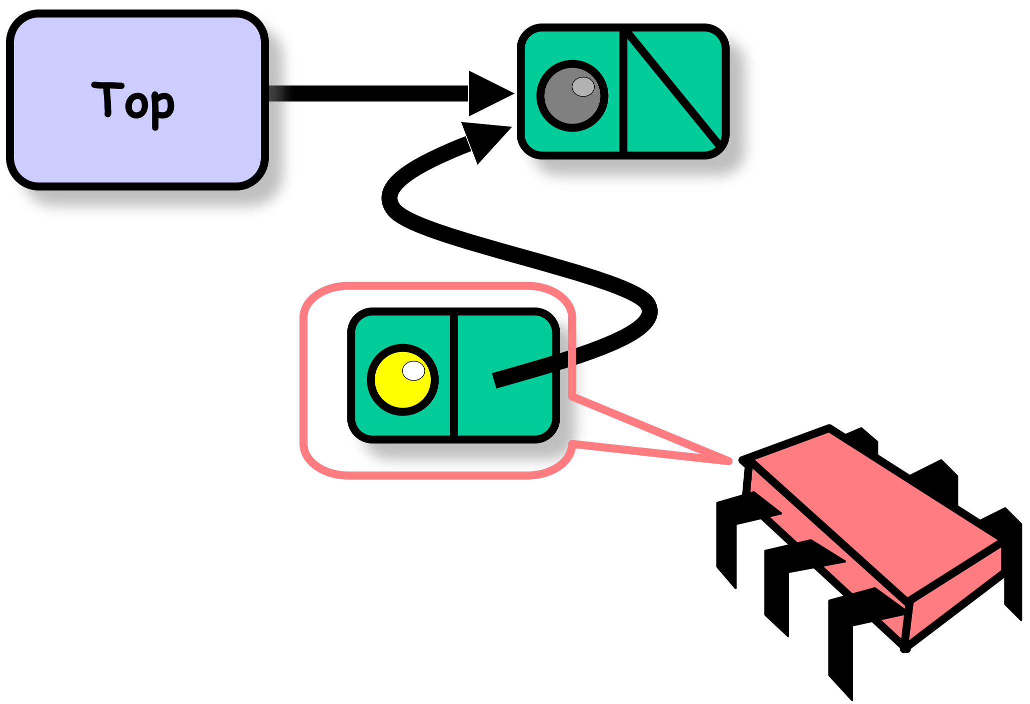
Concurrent Stack

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

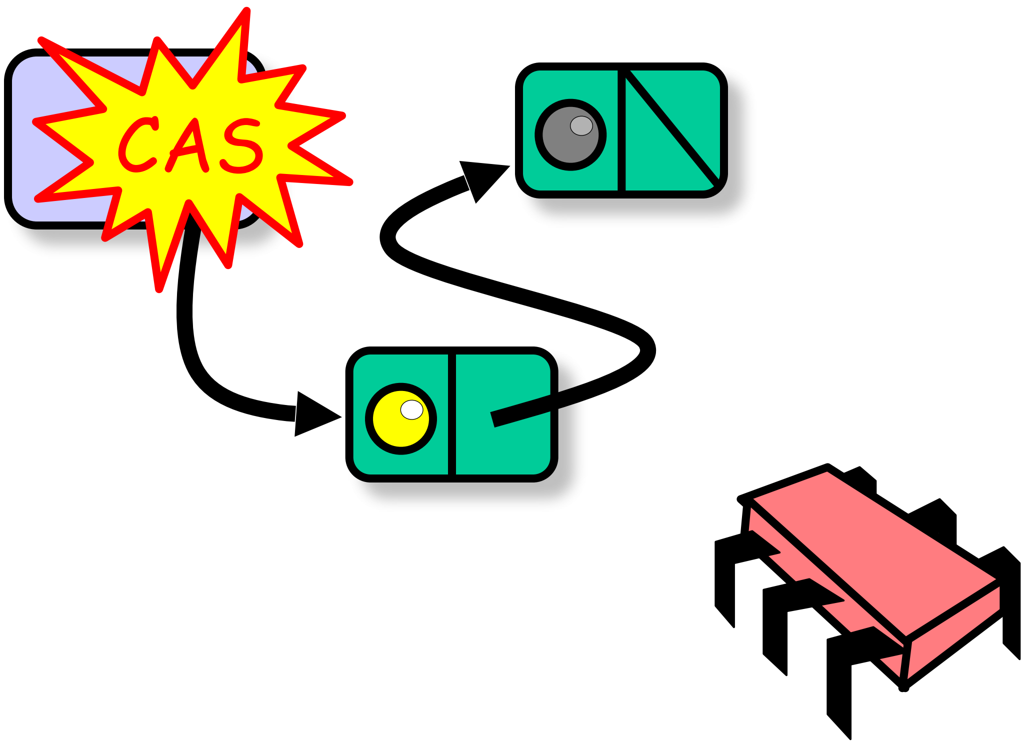
Empty Stack



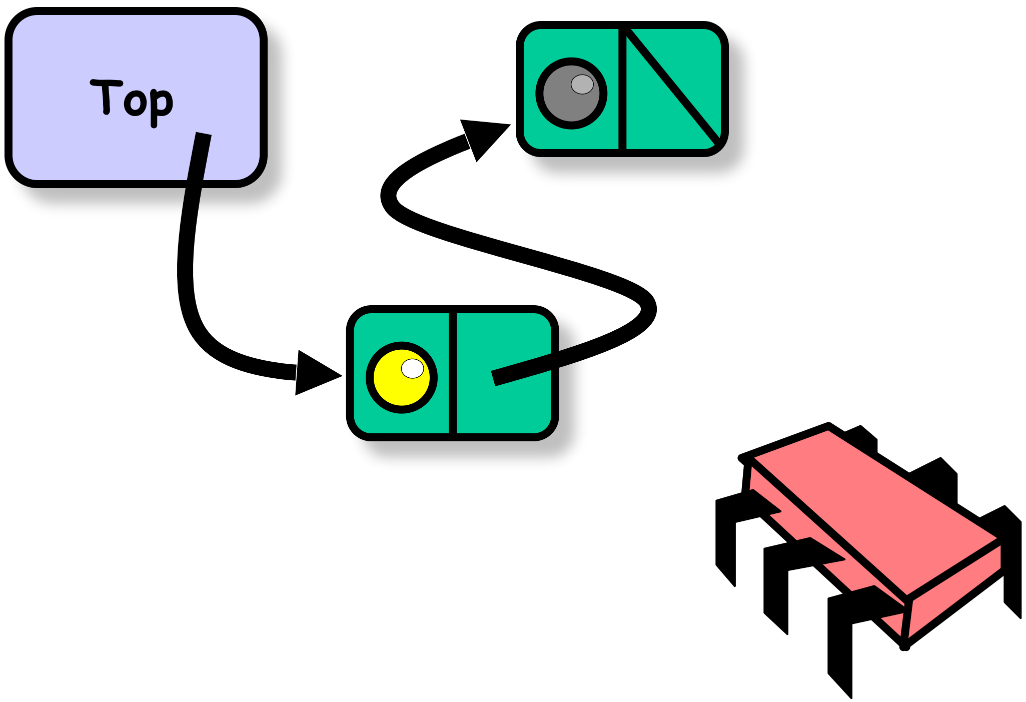
Push



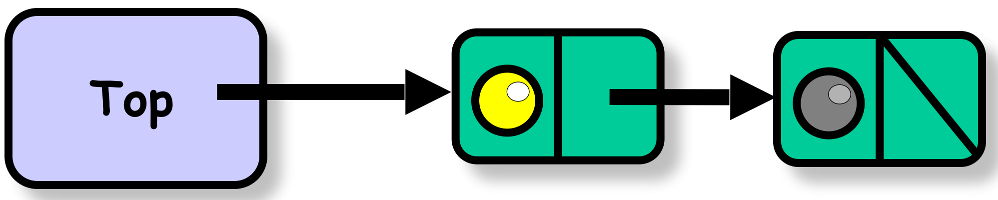
Push

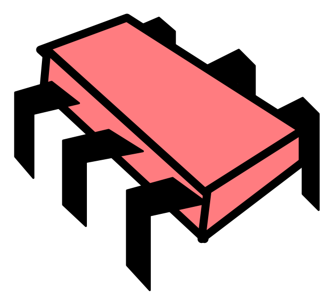


Push

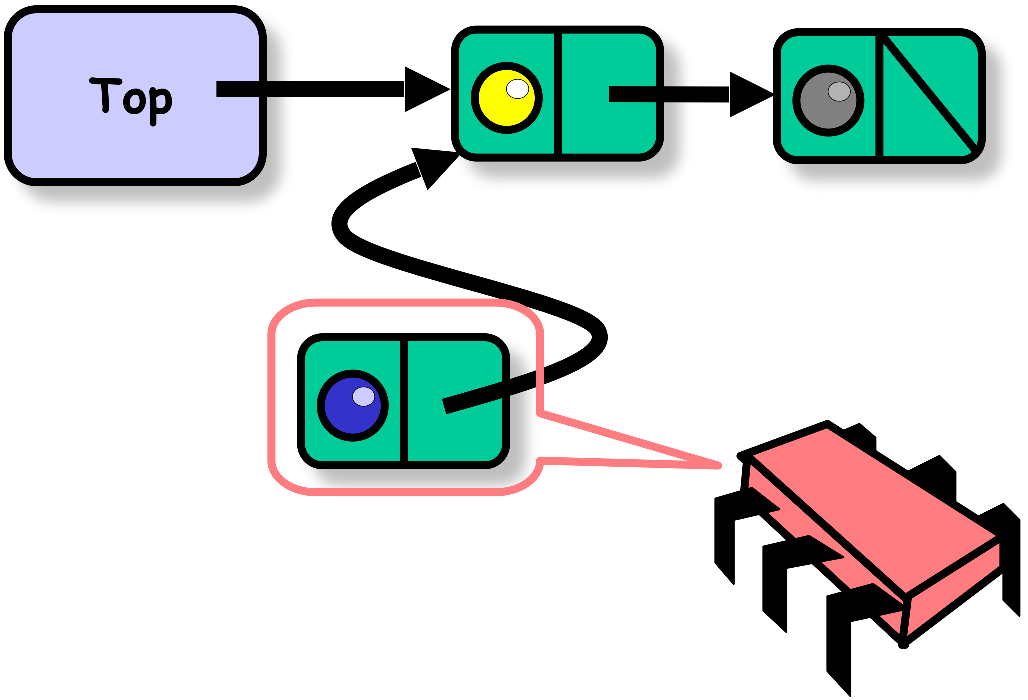


Push

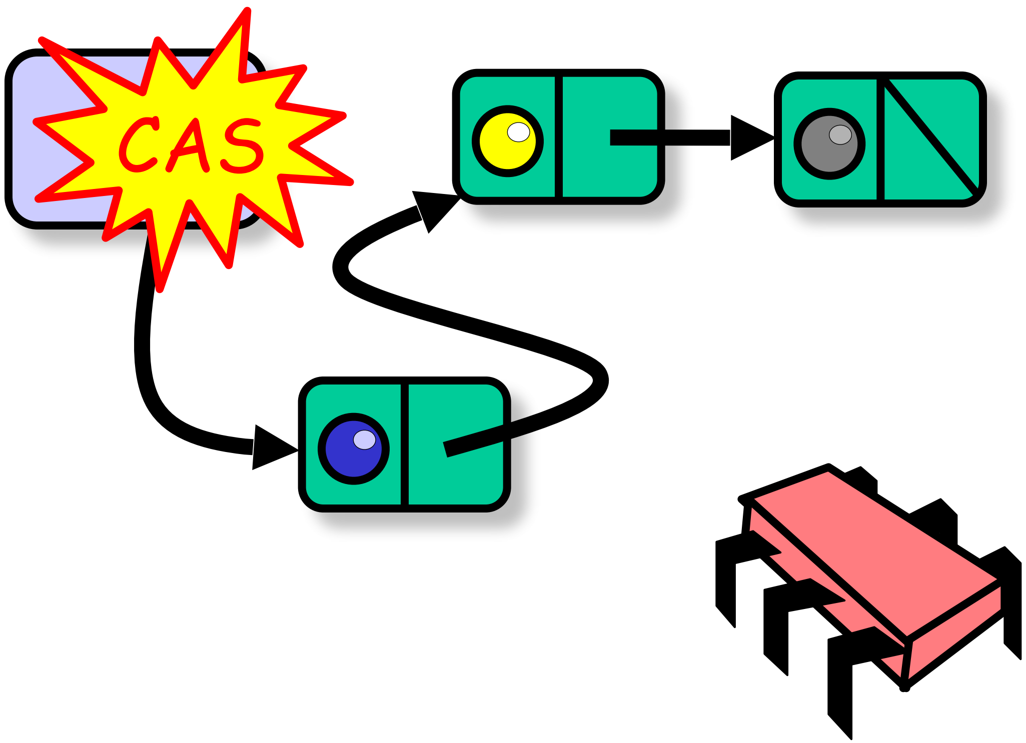




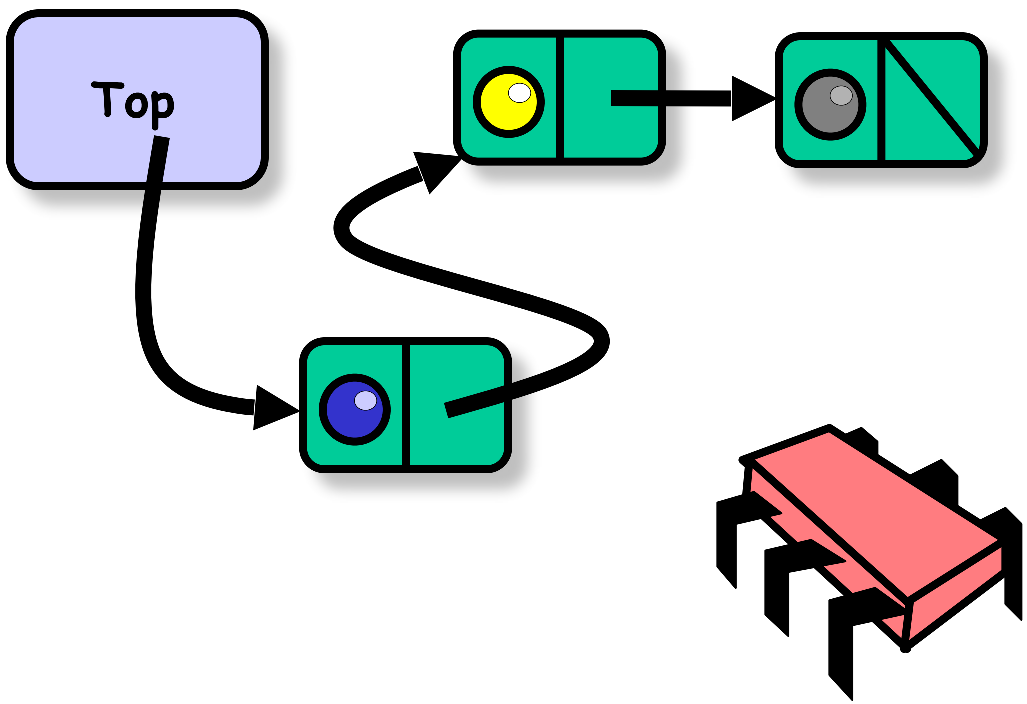
Push



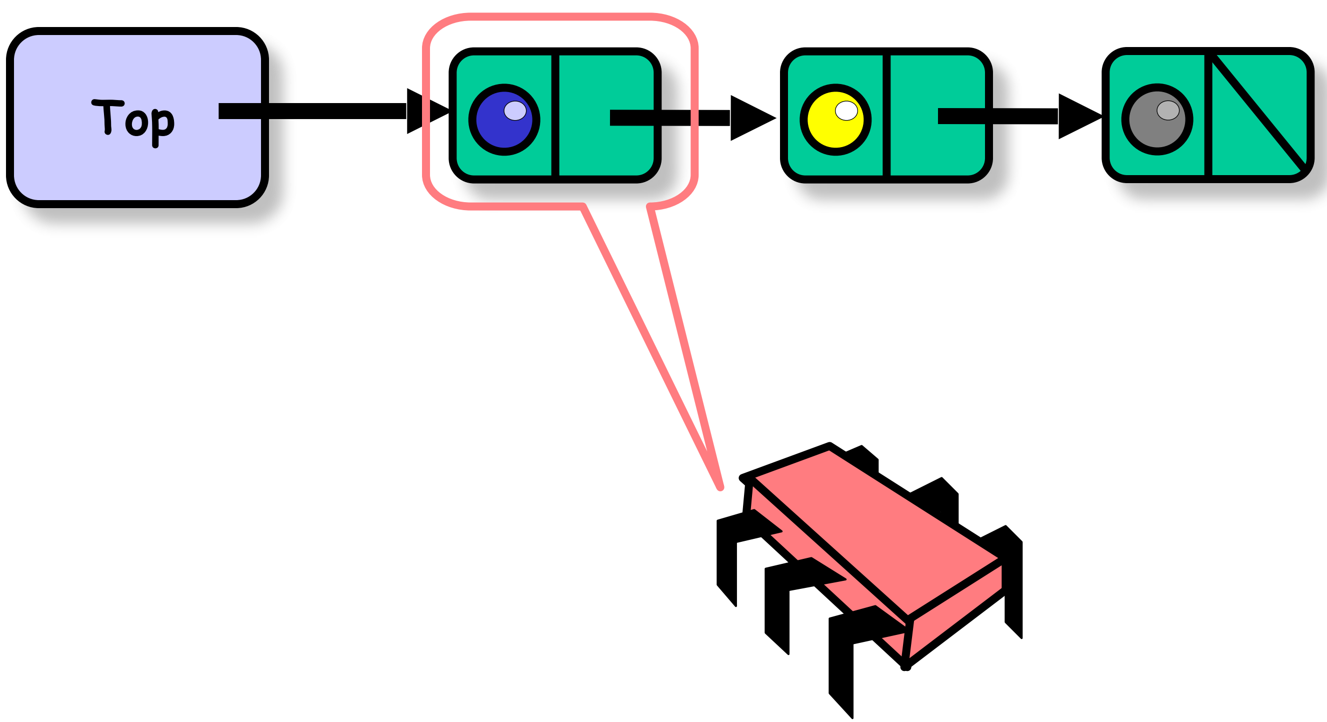
Push



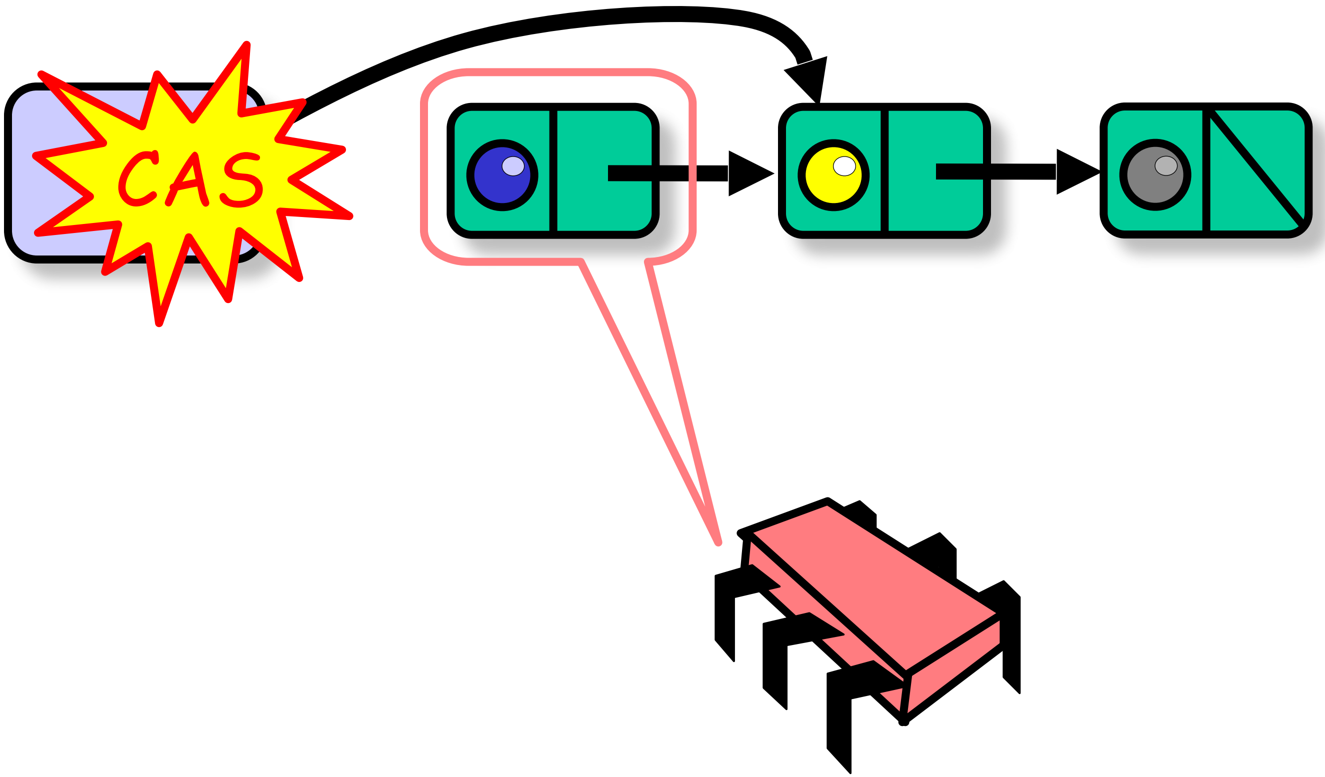
Push



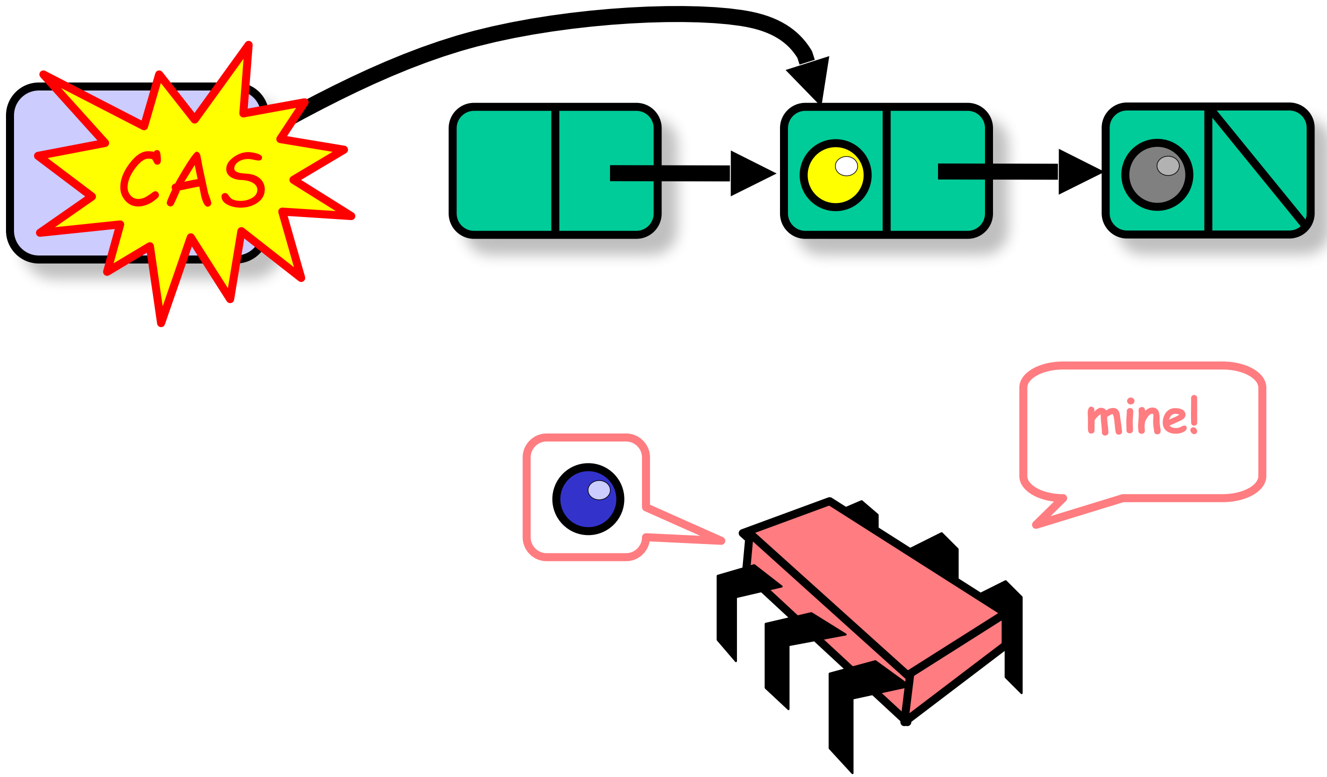
Pop



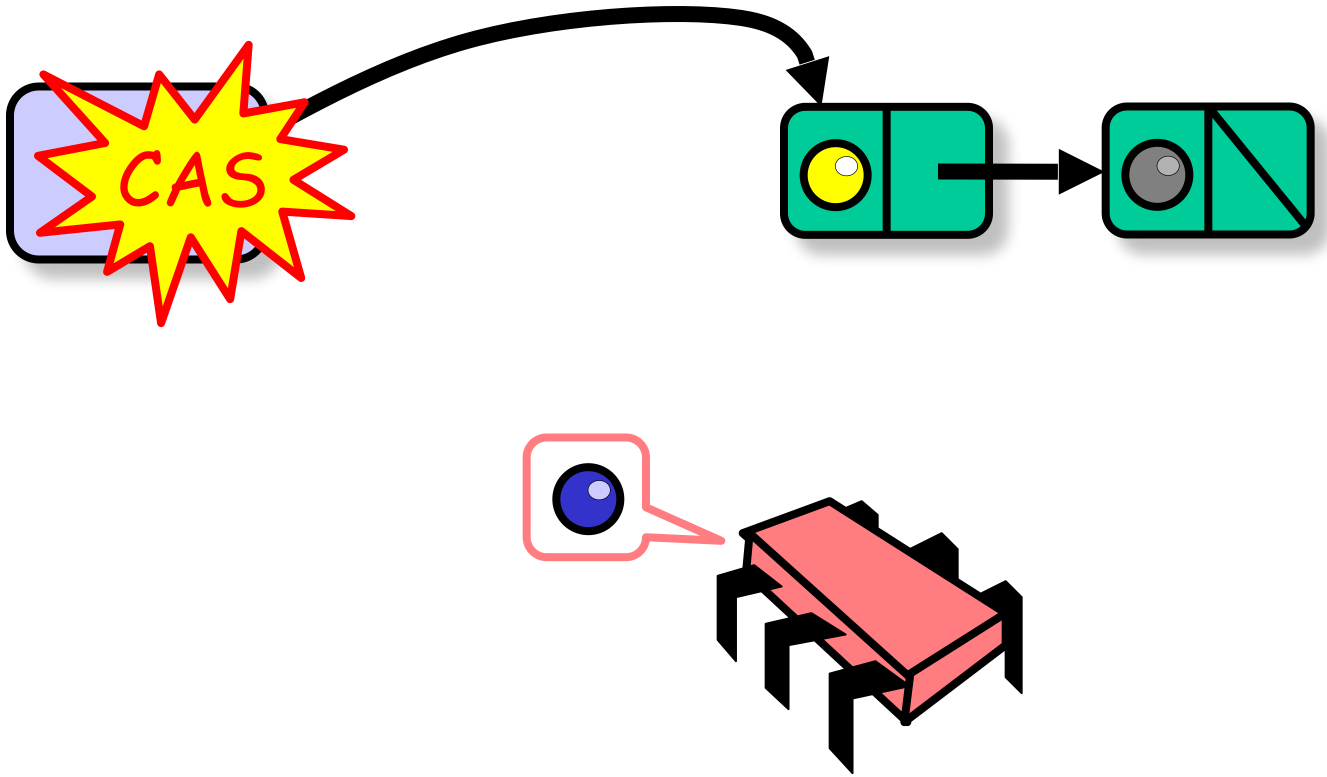
Pop



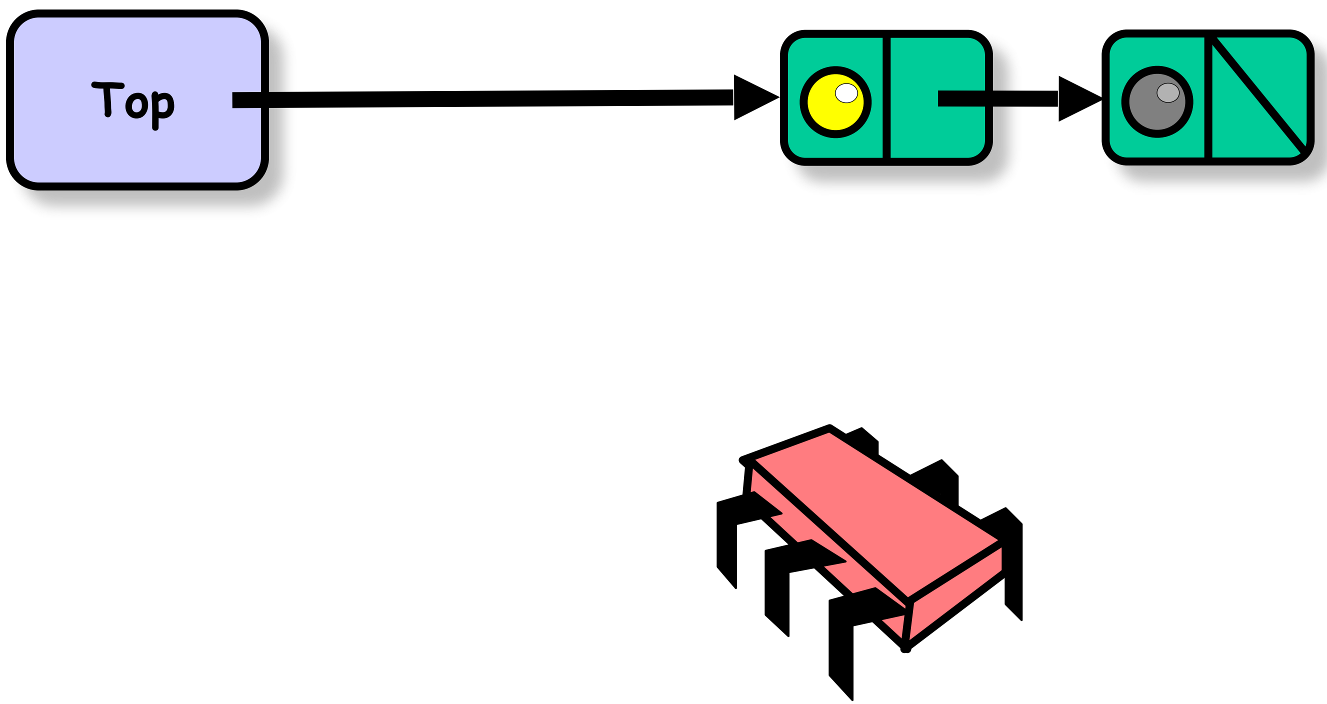
Pop



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;
      } else backoff.backoff()
}}
```

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;
      } else backoff.backoff()
}}
```

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

Unbounded Lock-Free Stack

```
protected 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( ); }
  }
}
```

```
protected Node tryPop( ) throws EmptyException
{
  Node oldTop = top.get();
  if ( oldTop == null ) {
    throw new EmptyException( );
  }
  Node newTop = oldTop.next;
  if ( top.compareAndSet( oldTop, newTop ) ) {
    return oldTop;
  } else { return null; }
}

public T pop() throws EmptyException {
  while (true) {
    Node returnNode = tryPop( );
    if ( returnNode != null ) {
      return returnNode.value;
    } else { backoff.backoff( ); }
  }
}
```

Lock-free Stack

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

Question

- Are stacks inherently sequential?
- Reasons why
  - Every **pop()** call fights for top item
- Reasons why not
  - Think about it!