# Concurrency and Correctness

CS 475, Spring 2019
Concurrent & Distributed Systems

GEORGE MASON UNIVERSITY

*With material from Herlihy & Shavit, Art of Multiprocessor Programming*

# Review: Interleavings

- Events of two or more threads
  - Interleaved
  - Not necessarily independent (why?)

# Review: Locks (Mutual Exclusion)

```
public interface Lock {

 public void lock();

 public void unlock();
}
```

# Review: Mutual Exclusion, Formally

- Let $CS_i^k$ ⟺ be thread i's k-th critical section execution
- And $CS_j^m$ ⟺ be thread j's m-th execution
- Then either
  - ⟺ ⟺ or ⟺ ⟺





**Aka: it is guaranteed that one critical section happens before the other**

# Review: Synchronized blocks in Java

- Can also use *any* object as that monitor

```
static Object someObject = new Object();
public static void increment()
{
    synchronized(someObject){
        i = i + 1;
    }
}
static Object someOtherObject = new Object();
public static void incrementOther()
{
    synchronized(someOtherObject){
        j = j + 1;
    }
}
```

Now, two different threads could call `increment()` and `incrementOther()` at the same time

# Review: Peterson's Alg: Mutual Exclusion

```
public void lock() {
  flag[i] = true;
  victim  = i;
  while (flag[j] && victim == i) {};
```

- If thread **1** in critical section,
  - flag[1]=true,
  - victim = 0
- If thread **0** in critical section,
  - flag[0]=true,
  - victim = 1

**Cannot both be true, hence yes: it is safe!**

# Review: Amdahl's Law

- Identifies performance gains from adding additional cores to an application that has both serial and parallel components
- S is serial portion
- N processing cores

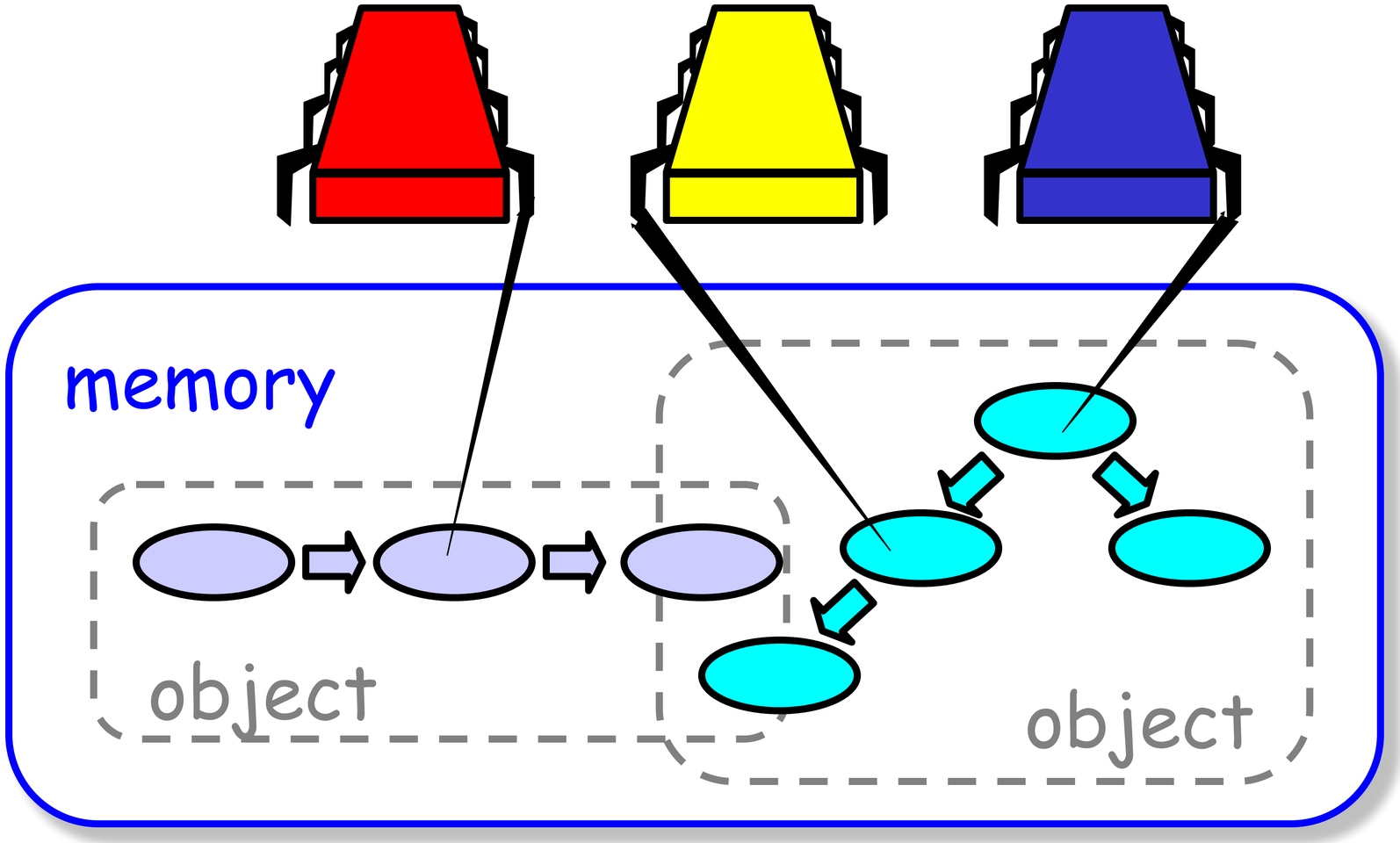
$$speedup \leq \frac{1}{S + \frac{(1-S)}{N}}$$

- That is, if application is 75% parallel / 25% serial, moving from 1 to 2 cores results in speedup of 1.6 times
- As N approaches infinity, speedup approaches 1 / S
- Serial portion of an application has disproportionate  effect on performance gained by adding additional cores

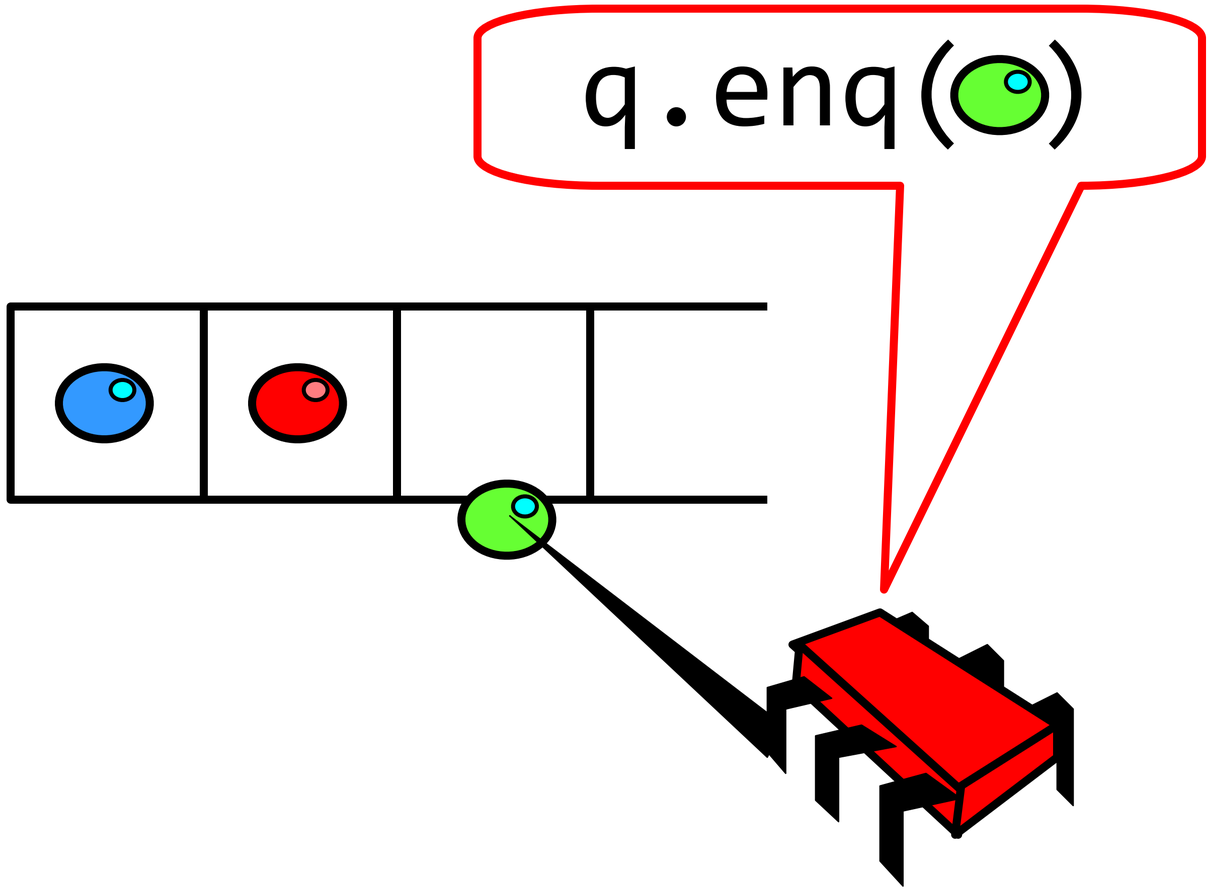
# Today

- Concurrent specifications
  - Linearizability
  - Reasoning about correctness
- Reading: H&S 2.1-2.3
- HW1 due soon! https://www.jonbell.net/gmu-cs-475-spring-2019/homework-1/

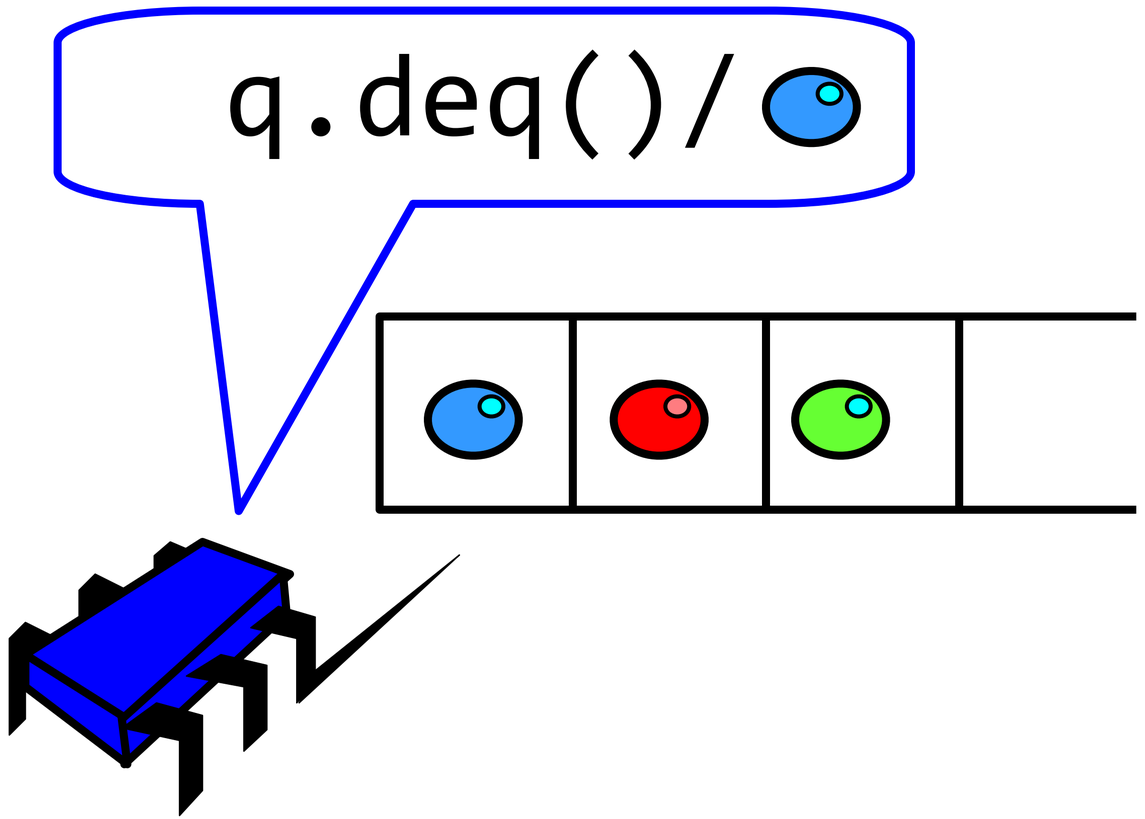
# Concurrent Computation



# FIFO Queue: Enqueue Method



# FIFO Queue: Dequeue Method



# A Lock-Based Queue

```
class LockBasedQueue<T> {
  int head, tail;
  T[] items;
  Lock lock;
  public LockBasedQueue(int capacity) {
    head = 0; tail = 0;
    lock = new ReentrantLock();
    items = (T[]) new Object[capacity];
}
```

# A Lock-Based Queue

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    items = (T[]) new Object[capacity];
}
```

**Queue fields protected by single shared lock**

# Implementation: Deq (Enq is similar)

```
public T deq() throws EmptyException {
  lock.lock();
  try {
    if (tail == head)
       throw new EmptyException();
    T x = items[head % items.length];
    head++;
    return x;
  } finally {
    lock.unlock();
  }
}
```

# Implementation: Deq

```
public T deq() throws EmptyException {
  lock.lock();
  try {
    if (tail == head)
       throw new EmptyException();
    T x = items[head % items.length];
    head++;
    return x;
  } finally {
    lock.unlock();
  }
}
```

Should be correct because modifications are mutually exclusive…

# Now consider the following implementation

- The same thing without mutual exclusion
  - Remember Amdahl's law?
- For simplicity, only two threads
  - One thread enq only
  - The other deq only

# Wait-free 2-Thread Queue

```
public class WaitFreeQueue {

  int head = 0, tail = 0;
  items = (T[]) new Object[capacity];

  public void enq(Item x) {
    while (tail-head == capacity); // busy-wait
    items[tail % capacity] = x; tail++;
  }
  public Item deq() {
     while (tail == head);      // busy-wait
     Item item = items[head % capacity]; head++;
     return item;
}}
```

# Wait-free 2-Thread Queue

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public class LockFreeQueue {

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# Lock-free 2-Thread Queue

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  public Item deq() {
     while (tail == head);     //
     Item item = items[head % capa
```

Queue is updated without a lock!

How do we define "correct" when modifications are not mutually exclusive?

# Wait-free 2-Thread Queue

**Argument for why this is OK (for now):**
**No two threads ever write the same variable**

```
public c
  i
  items = (T[]) new Object[capacity];

  public void enq(Item x) {
    while (tail-head == capacity); // busy-wait
    items[tail % capacity] = x; tail++;
  }
  public Item deq() {
     while (tail == head);      // busy-wait
     Item item = items[head % capacity]; head++;
     return item;
}}
```

Writes items, writes tail

Writes head

# Defining concurrent queue  implementations

- Need a way to specify a concurrent queue object
- Need a way to prove that an algorithm implements  the object's specification
- Lets talk about object specifications …

# Correctness and Progress

- In a concurrent setting, we need to specify both the safety and the liveness properties of an object
- Need a way to define
  - when an implementation is correct
  - the conditions under which it guarantees progress

**Lets begin with correctness**

# Sequential Objects

- Each object has a **state**
  - Usually given by a set of **fields**
  - Queue example: sequence of items
- Each object has a set of **methods**
  - Only way to manipulate state
  - Queue example: **enq** and **deq** methods

# Sequential Specifications

- If (precondition)
  - the object is in such-and-such a state
  - before you call the method,
- Then (postcondition)
  - the method will return a particular value
  - or throw a particular exception.
- and (postcondition, con't)
  - the object will be in some other state
  - when the method returns,

# Pre and PostConditions for Dequeue

- Precondition:
  - Queue is non-empty
- Postcondition:
  - Returns first item in queue
- Postcondition:
  - Removes first item in queue

# Pre and PostConditions for Dequeue

- Precondition:
  - Queue is empty
- Postcondition:
  - Throws Empty exception
- Postcondition:
  - Queue state unchanged

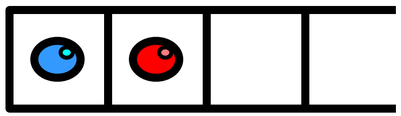
# Why Sequential Specifications Totally Rock

- Interactions among methods captured by side-effects on object state
  - State meaningful between method calls
- Documentation size linear in number of methods
  - Each method described in isolation
- Can add new methods
  - Without changing descriptions of old methods

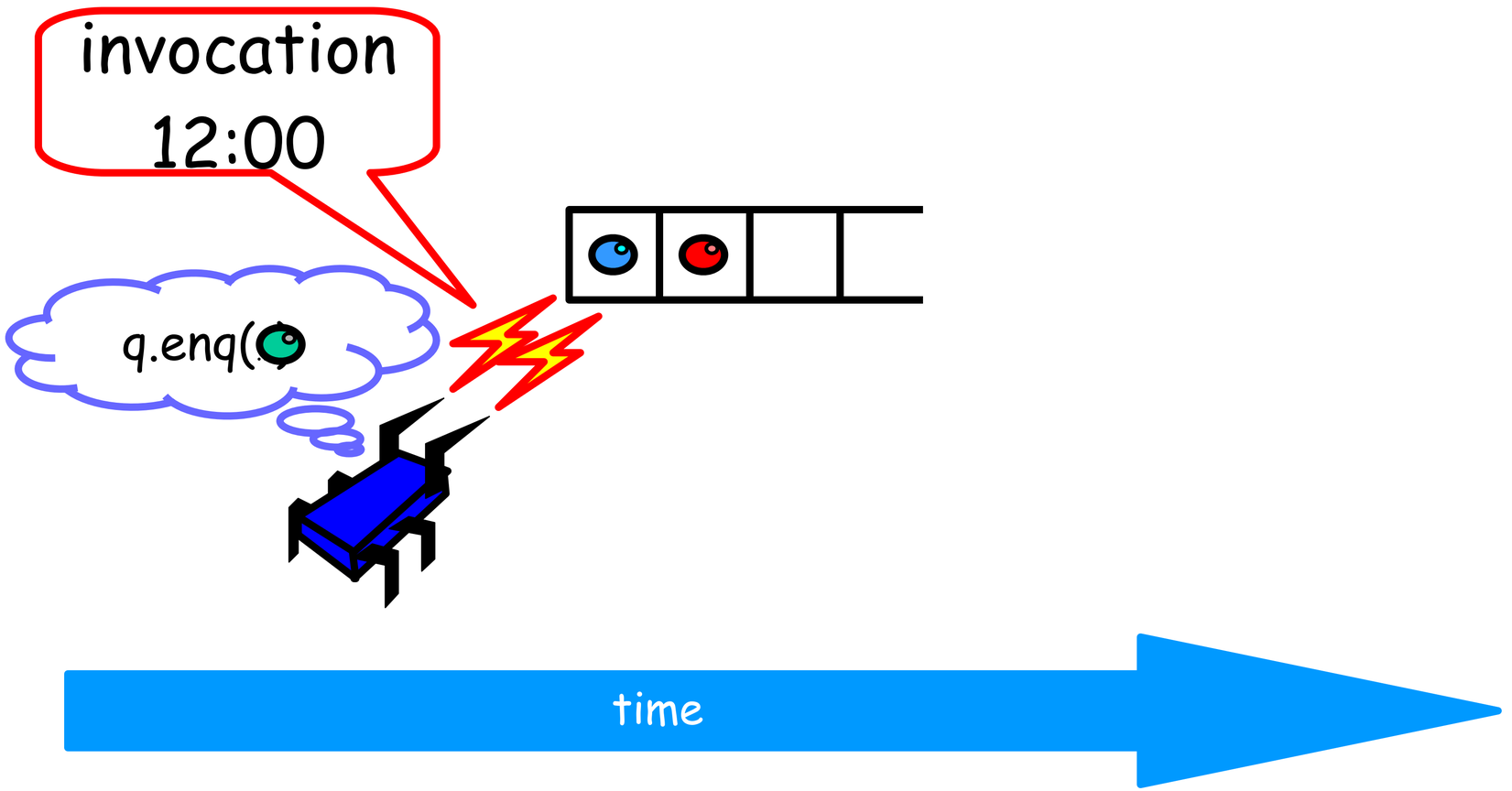
# What About Concurrent Specifications ?

- Methods?
- Documentation?
- Adding new methods?

# Methods Take Time



# Methods Take Time



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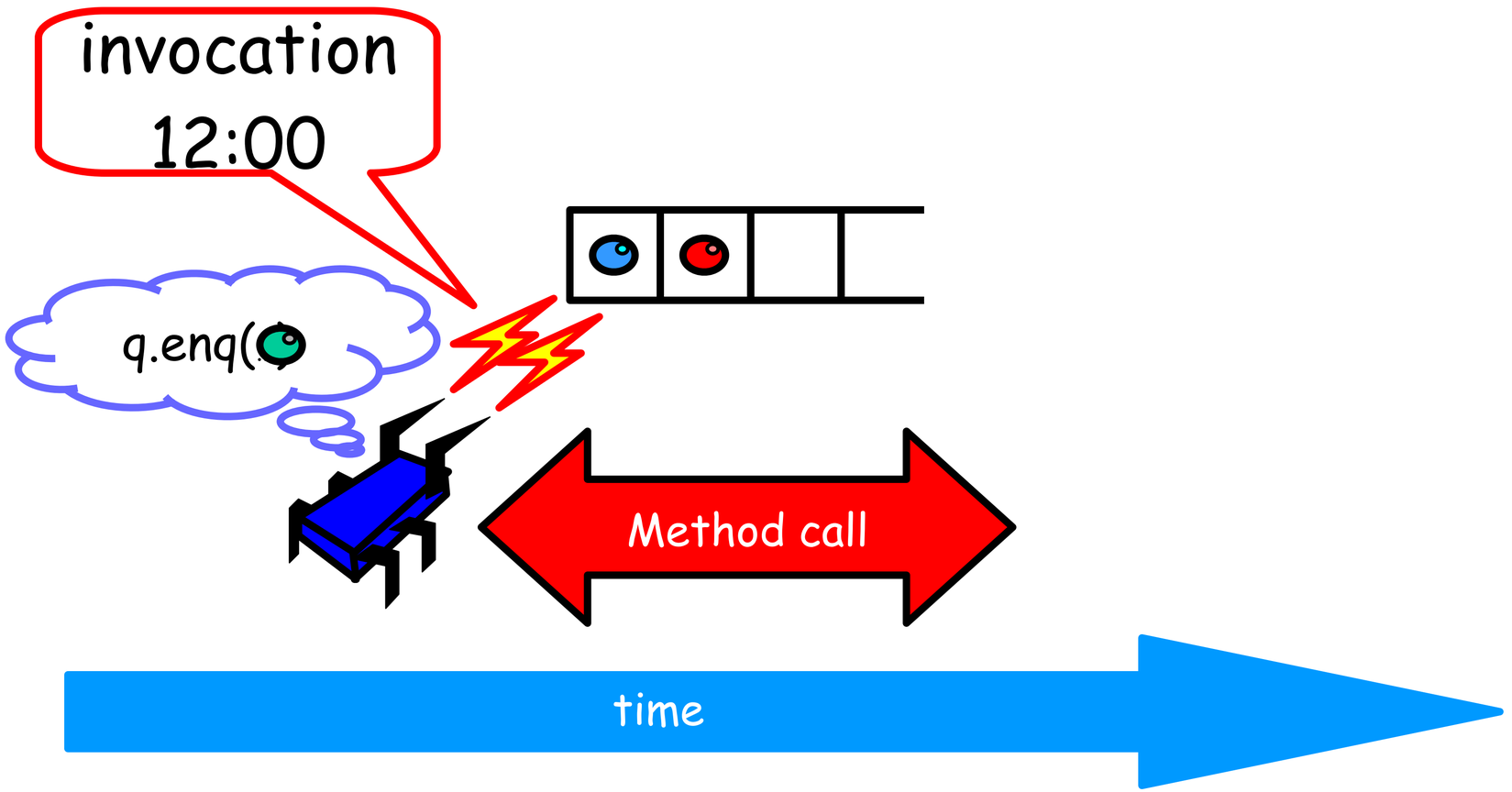

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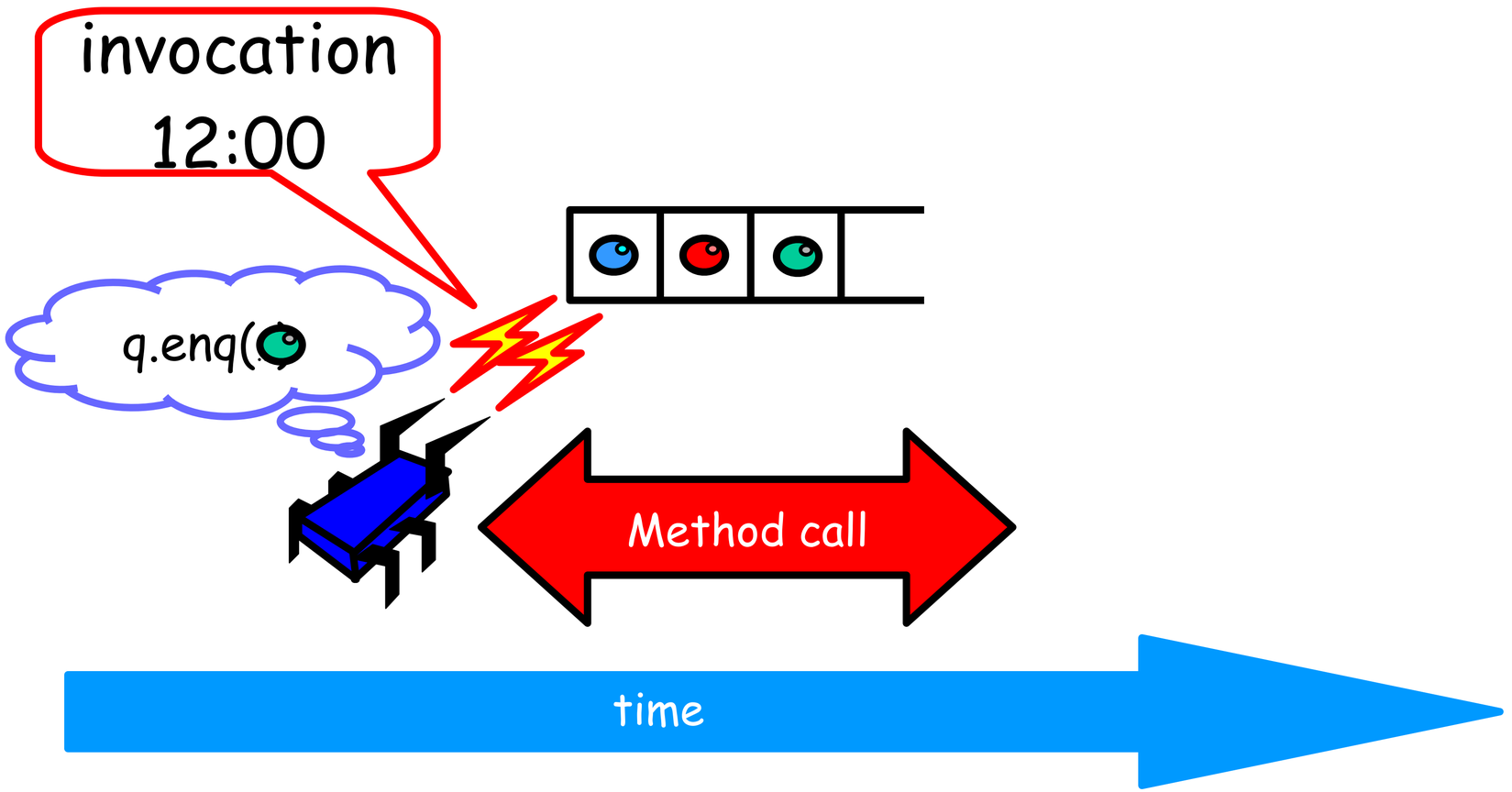

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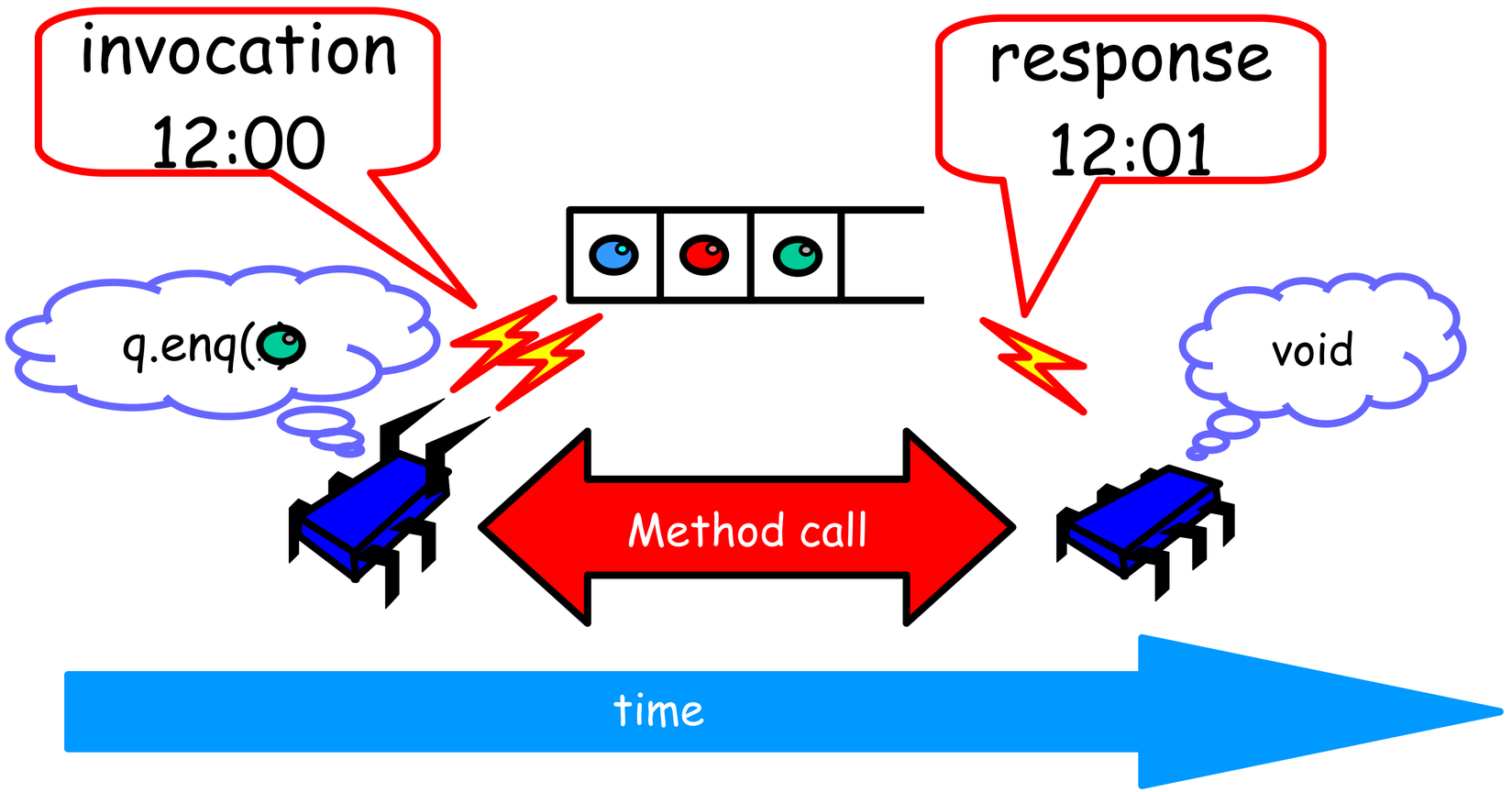
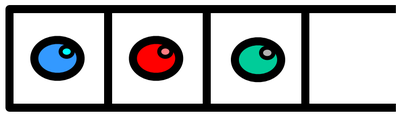


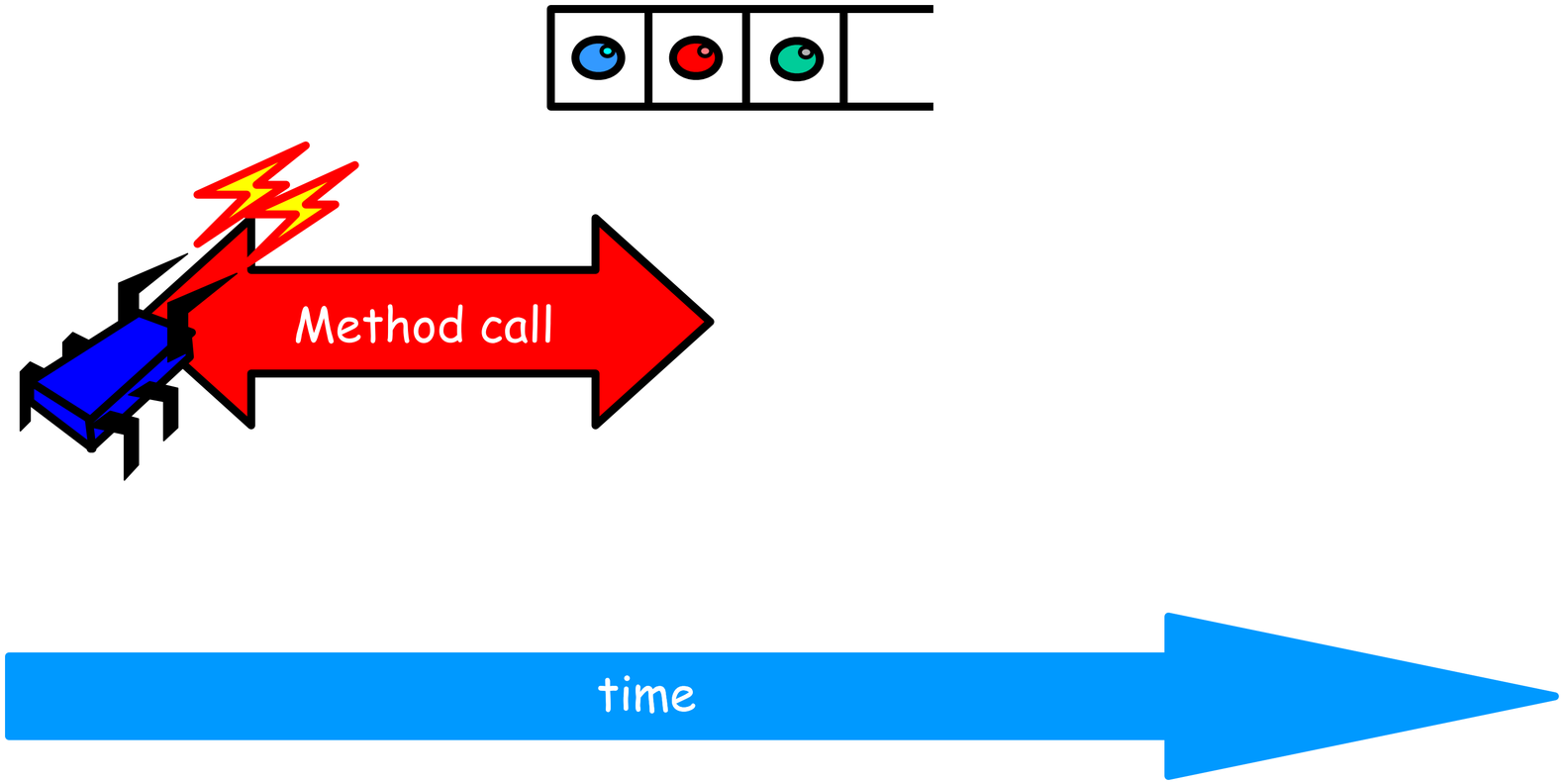
# Sequential vs Concurrent

- Sequential
  - Methods take time? Who knew?
- Concurrent
  - Method call is not an event
  - Method call is an interval.

# Concurrent Methods Take Overlapping Time



# Concurrent Methods Take Overlapping Time



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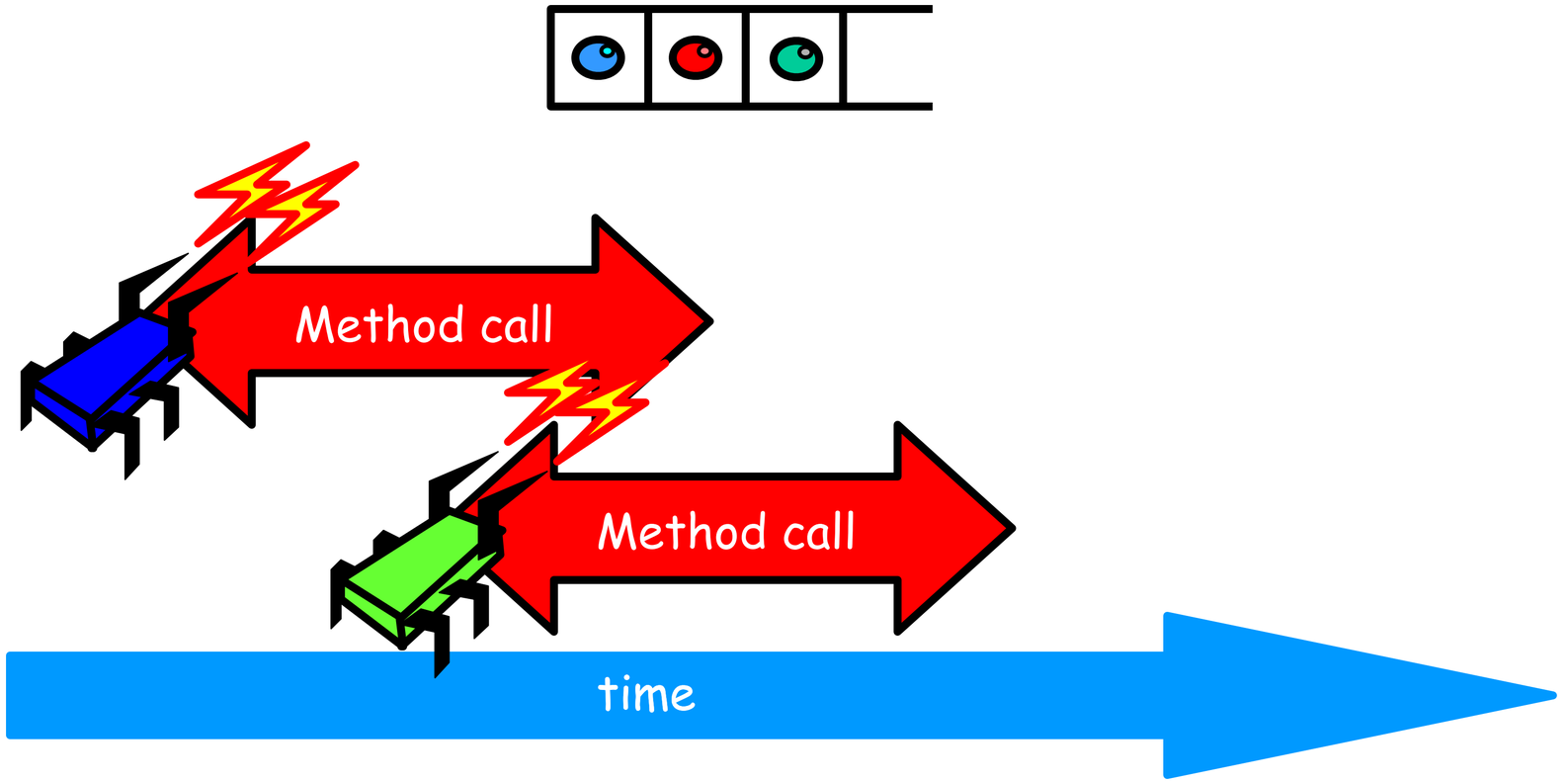
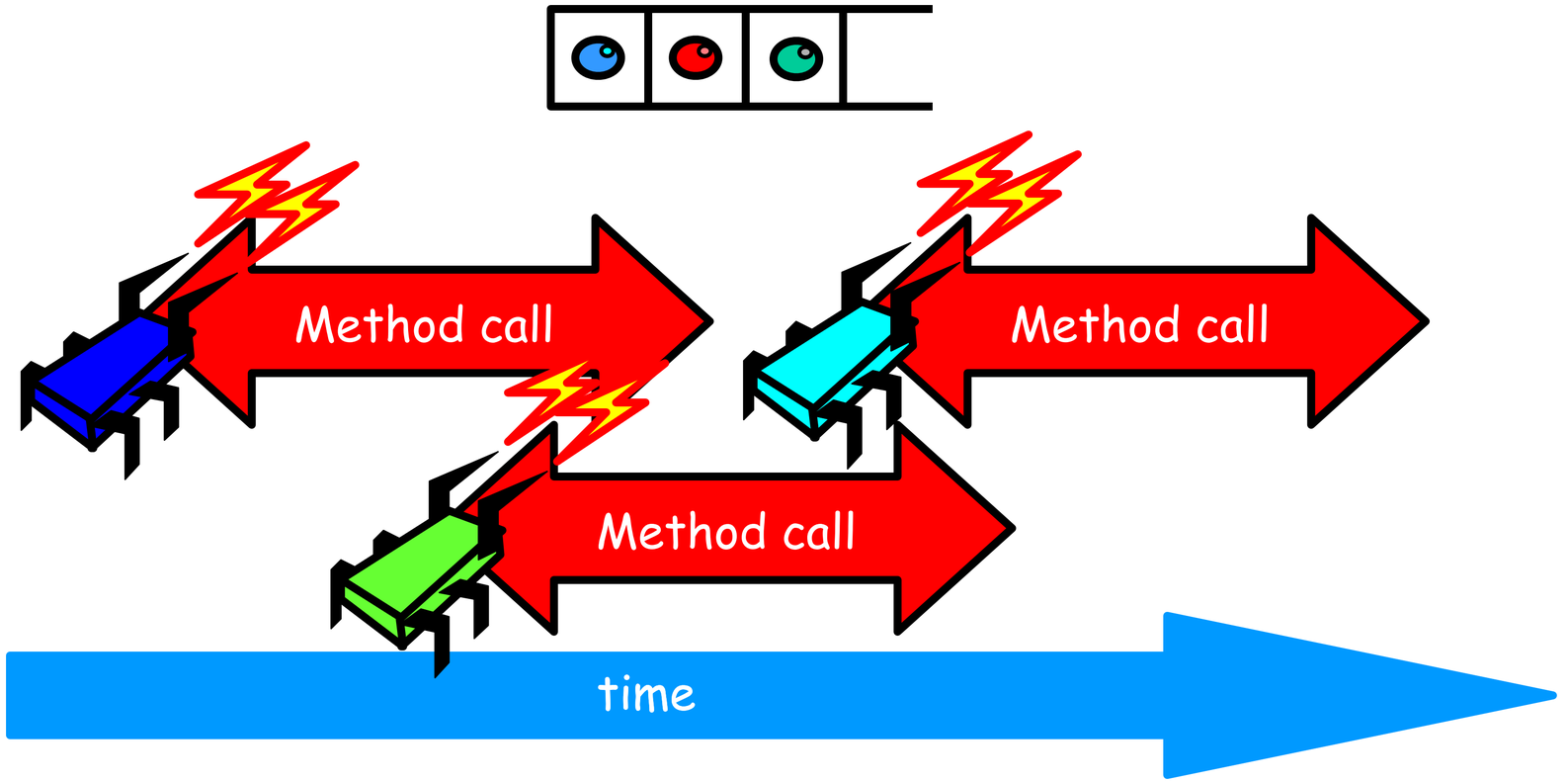


# Concurrent Methods Take Overlapping Time



# Sequential vs Concurrent

- Sequential:
  - Object needs meaningful state only between method calls
- Concurrent
  - Because method calls overlap, object might **never** be between method calls

# Sequential vs Concurrent

- Sequential:
  - Each method described in isolation
- Concurrent
  - Must characterize **all** possible interactions with concurrent calls
    - What if two **enq**s overlap?
    - Two **deq**s? **enq** and **deq**? …

# Sequential vs Concurrent

- Sequential:
  - Can add new methods without affecting older methods
- Concurrent:
  - Everything can potentially interact with everything else

# Sequential vs Concurrent

- Sequential:
  - Can add new methods without affecting older methods
- Concurrent:
  - Everything can potentially interact with everything else

# The Big Question

- What does it mean for a concurrent object to be correct?
  - What is a concurrent FIFO queue?
  - FIFO means strict temporal order
  - Concurrent means ambiguous temporal order

# Intuitively…

```
public T deq() throws EmptyException {
  lock.lock();
  try {
    if (tail == head)
       throw new EmptyException();
    T x = items[head % items.length];
    head++;
    return x;
  } finally {
    lock.unlock();
  }
}
```

# Intuitively…

```
public T deq() throws EmptyException {
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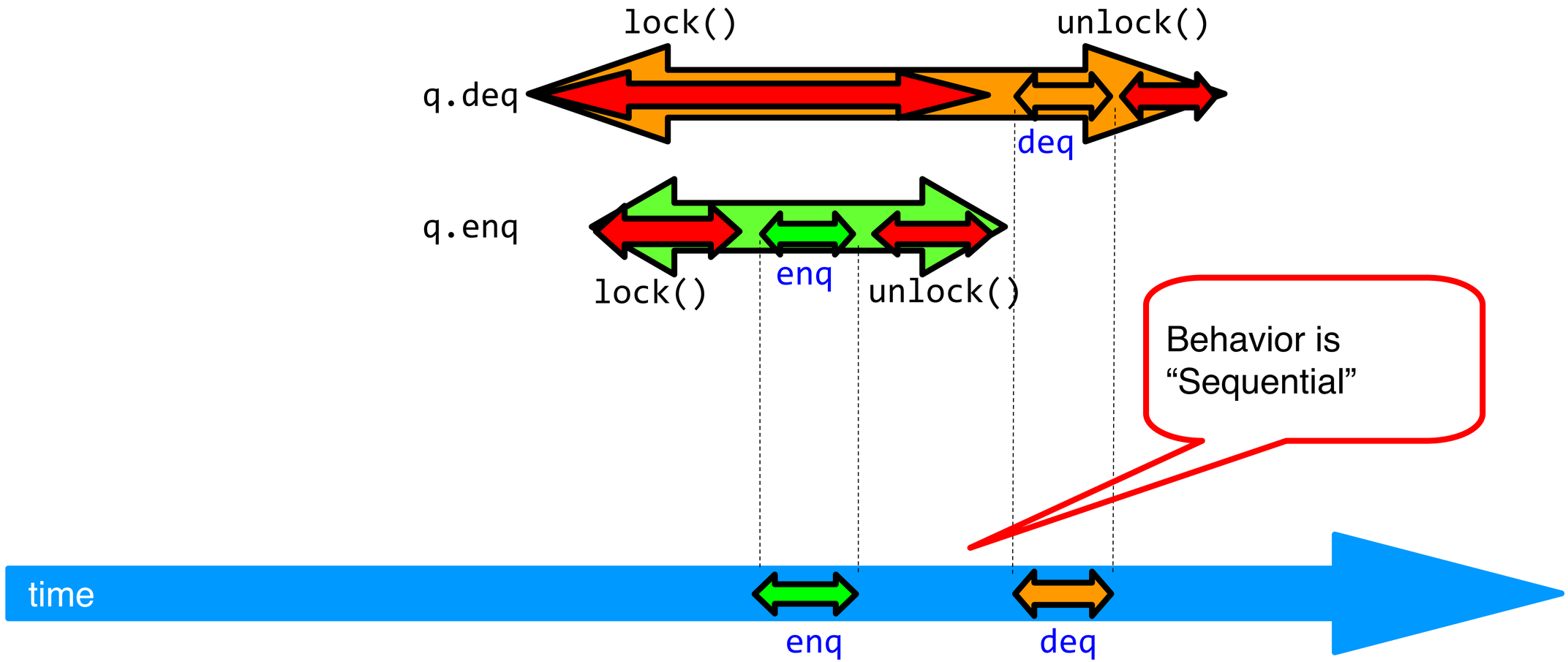
    return x;
  } finally {
    lock.unlock();
  }
}
```

**All modifications of queue are done mutually exclusive**

# Intuitively

**Lets capture the idea of describing the concurrent via the sequential model**



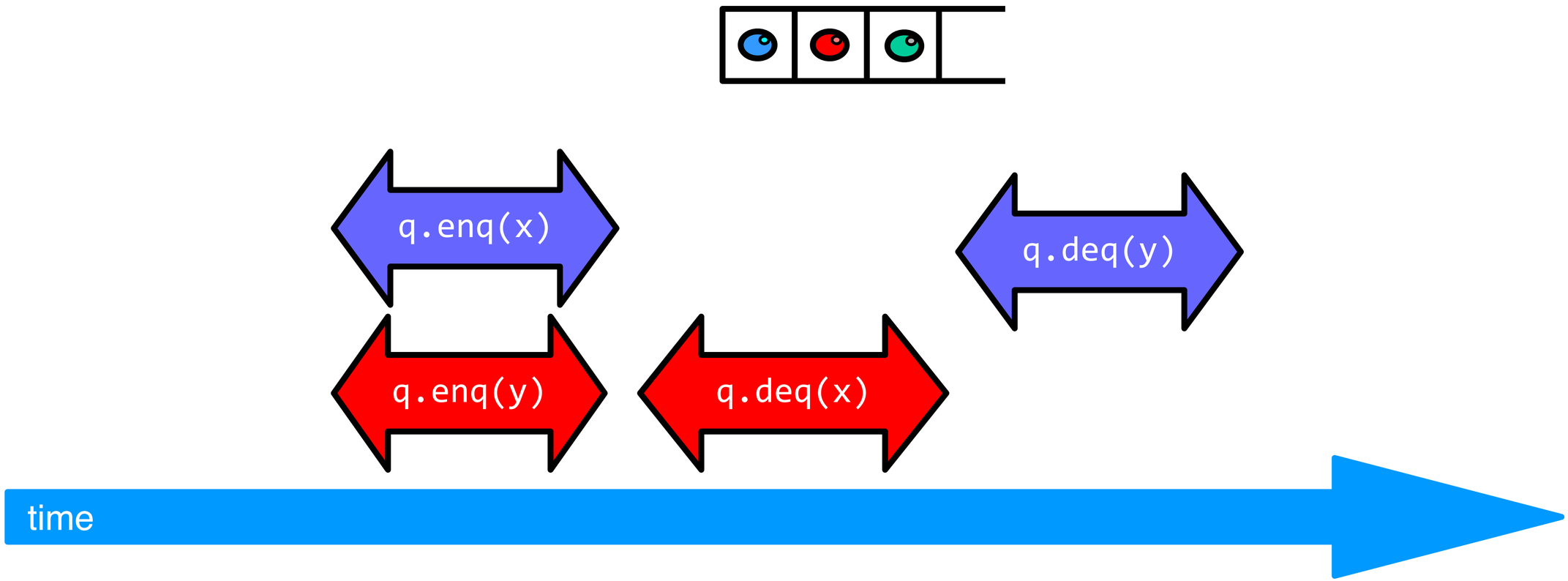
# Linearizability

- Each method should
  - “take effect”
  - Instantaneously
  - Between invocation and response events
- Object is correct if this “sequential” behavior is correct
- Any such concurrent object is *Linearizable*

# Is it really about the object?

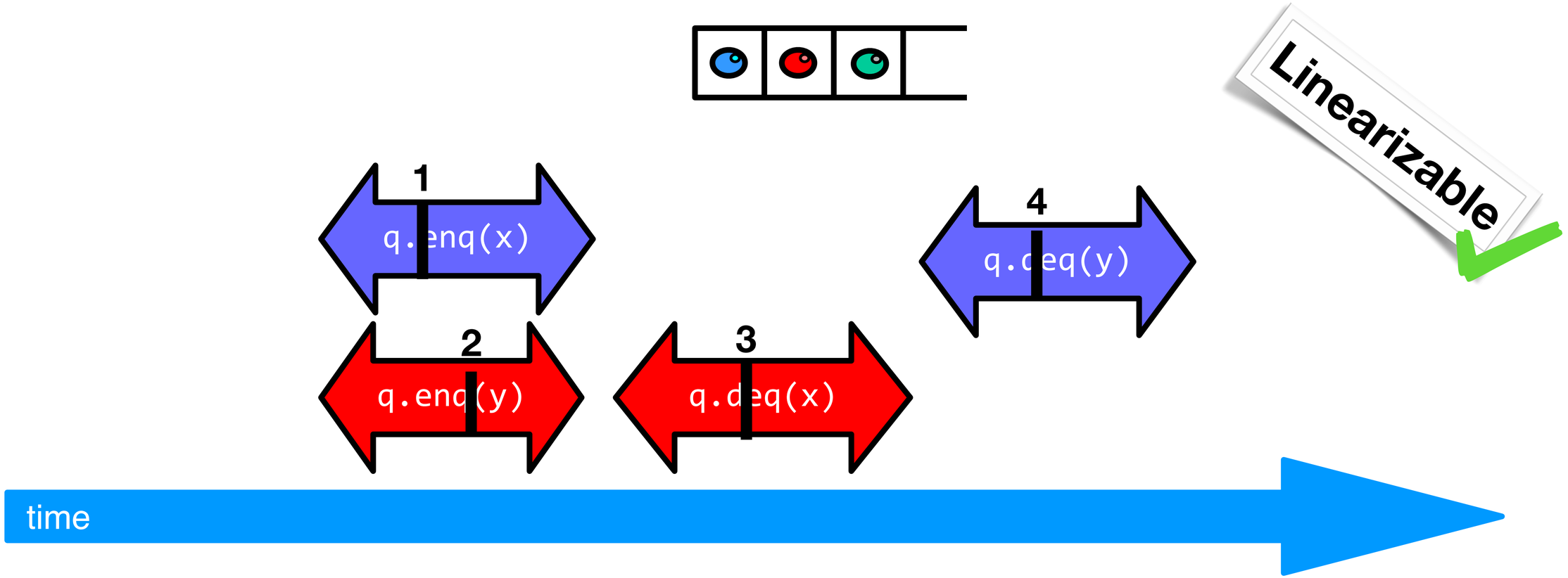
- Each method should
  - “take effect”
  - Instantaneously
  - Between invocation and response events
- Sounds like a property of an execution…
- A linearizable object: one all of whose possible executions are linearizable

# Example



# Example: Linearizable?

**Reminder: Linearizable means: each method takes effect instantaneously, sometime in its observed time window**



# Reasoning About  Lineraizability: Locking

```
public T deq() throws EmptyException {
  lock.lock();
  try {
    if (tail == head)
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    T x = items[head % items.length];
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  } finally {
    lock.unlock();
  }
}
```

# Reasoning About  Lineraizability: Locking

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    head++;
    return x;
  } finally {
    lock.unlock();
  }
}
```

Linearization points are when locks are released

# More Reasoning: Lock-free

```
public class LockFreeQueue {

  int head = 0, tail = 0;
  items = (T[]) new Object[capacity];

  public void enq(Item x) {
    while (tail-head == capacity); // busy-wait
    items[tail % capacity] = x; tail++;
  }
  public Item deq() {
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     Item item = items[head % capacity]; head++;
     return item;
}}
```

# More Reasoning

```
public class LockFreeQueue

  int hea      tail = 0;
  item       ew Object[

      d enq(Item x) {
      (tail-head == capacity); // busy-wait
    ms[tail % capacity] = x; tail++;
  }
  public Item deq() {
     while (tail == head);      // busy-wait
     Item item = items[head % capacity]; head++;
     return item;
}}
```

Remember that there is only one enqueuer and only one dequeuer

Linearization order is order head and tail fields modified

# What's next?

- Weds: One more consistency model: *sequential* (is included in reading for this lecture though, book covers it in a different order), plus more Java-specific implementation fun!
- Reminder for Monday: HW1 Due!!!

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