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 using linked lists
- Next: queues
- Next: stacks

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

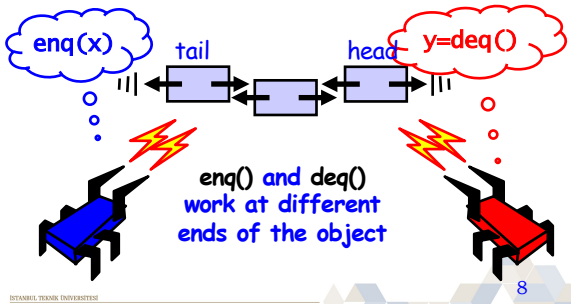
Blocking vs Non-Blocking

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

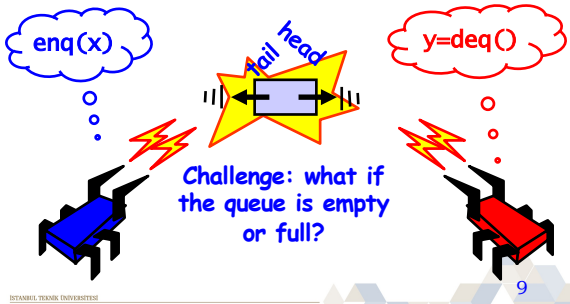
This Lecture

- Bounded, Blocking, Lock-based Queue
- Unbounded, Non-Blocking, Lock-free Queue
- Lost Wake-up problem
- Unbounded Non-Blocking Lock-free Stack
- Elimination-Backoff Stack

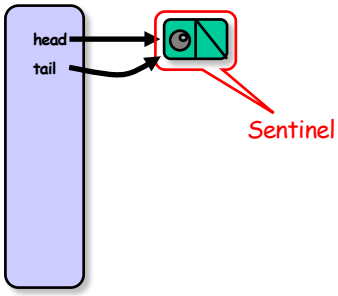
Queue: Concurrency



Concurrency



Bounded Queue



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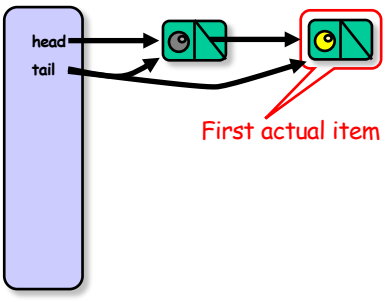
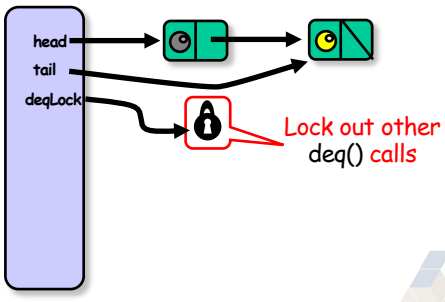
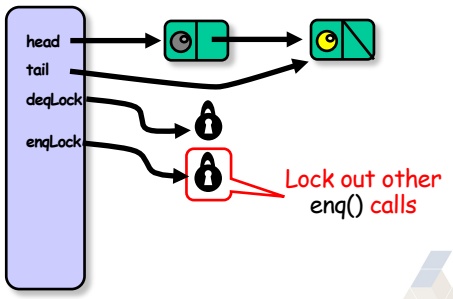


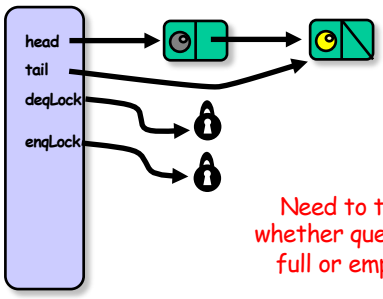
Bounded Queue



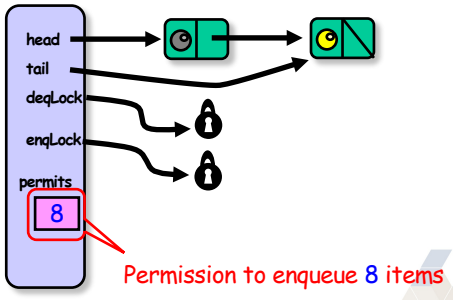
Bounded Queue



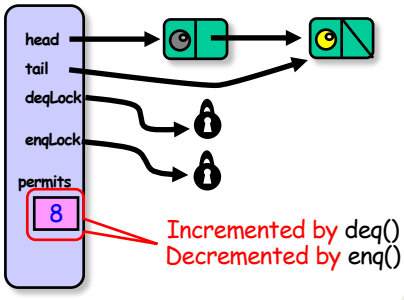
Not Done Yet



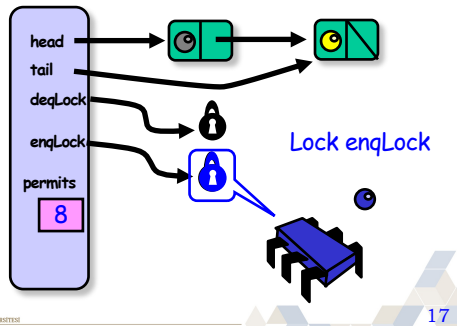
Not Done Yet



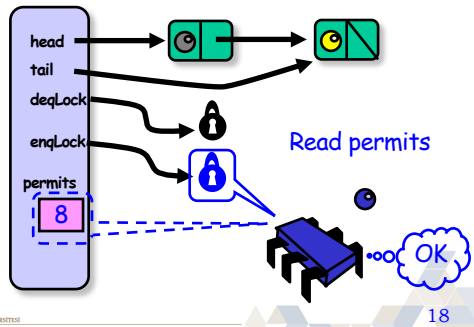
Not Done Yet



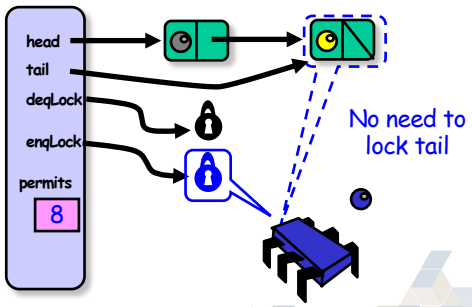
Enqueuer



Enqueuer



Enqueuer



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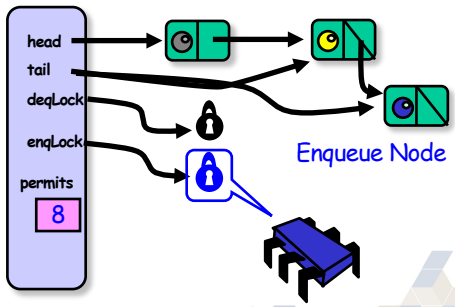

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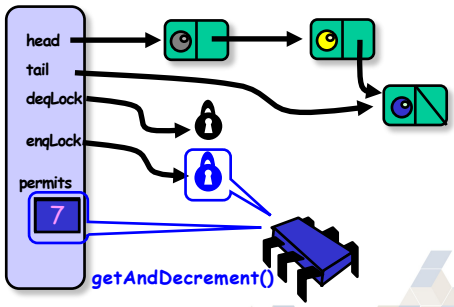
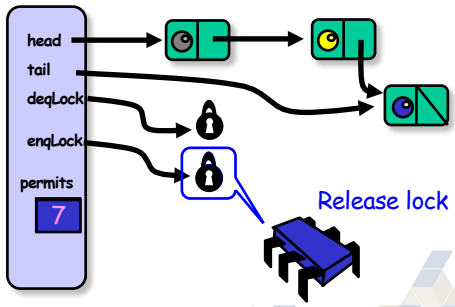
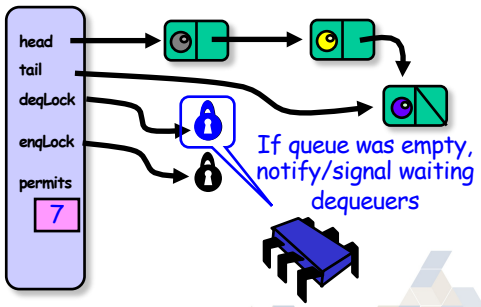


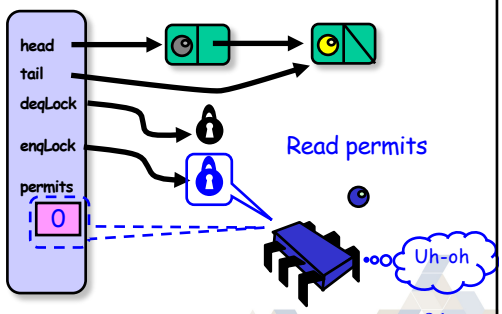
Enqueuer



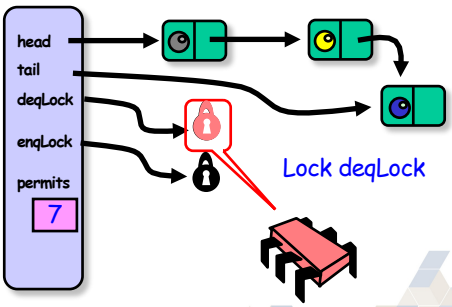
Enqueuer



Unsuccesful Enqueuer



Dequeuer



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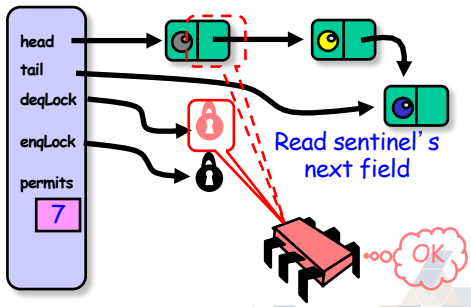
Dequeuer



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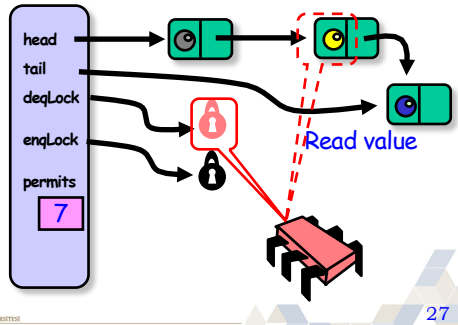
Dequeuer



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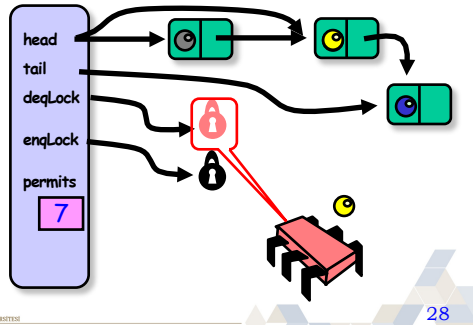
Dequeuer

Make first Node new sentinel



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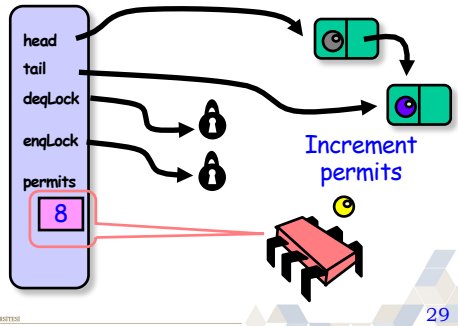
Dequeuer



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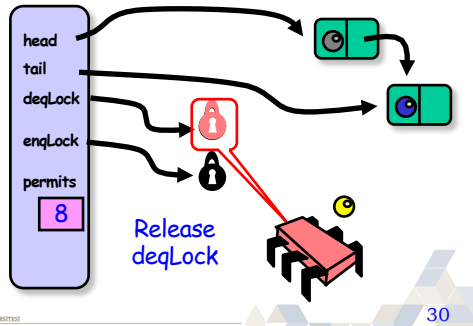
Dequeuer



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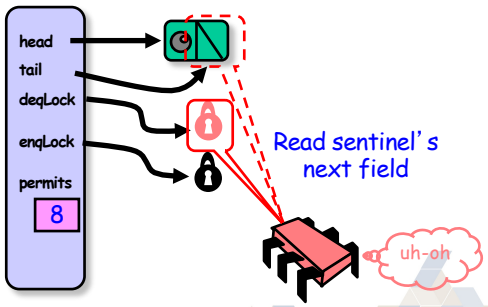
Unsuccesful Dequeuer



Bounded Queue

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

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  notEmptyCondition = deqLock.newCondition();
}
```

Enq & deq locks

Digression: Monitor Locks

- Java Synchronized objects and Java 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

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();
}
```

Release lock

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();
}
```

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

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();
}
```

Guess 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

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

```
q.await()
```


Signal

- Awakens one waiting thread
  - Which will reacquire lock

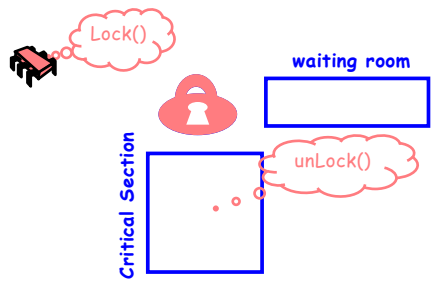
```
q.signal();
```


Signal All

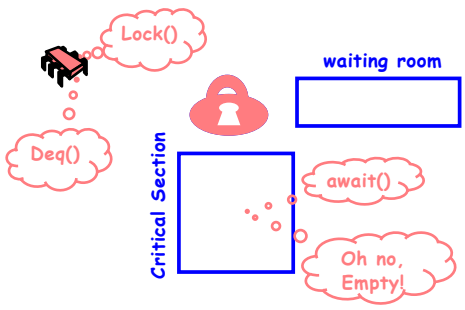
- Awakens all waiting threads
  - Which will each reacquire lock

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

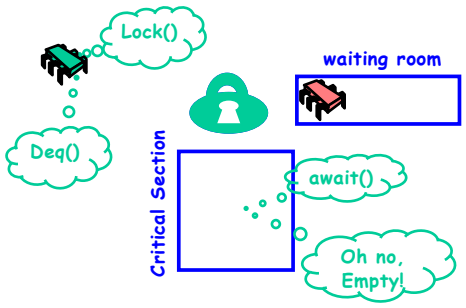

A Monitor Lock



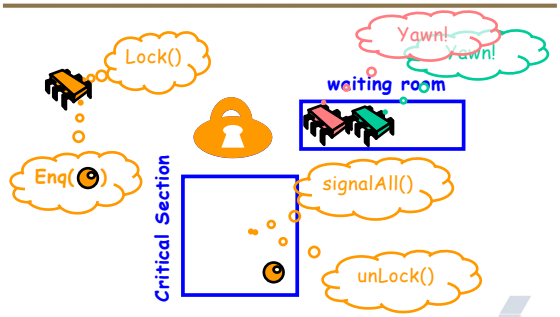
Unsuccessful Deq



Another One

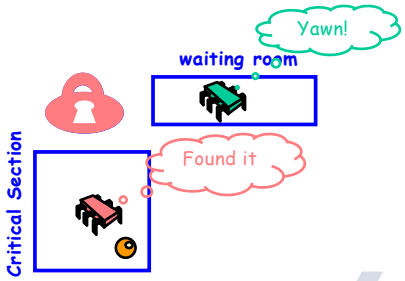


Enqueur to the Rescue



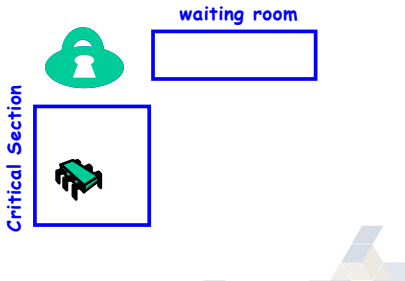
Monitor Signalling

Dequeurs Signalled

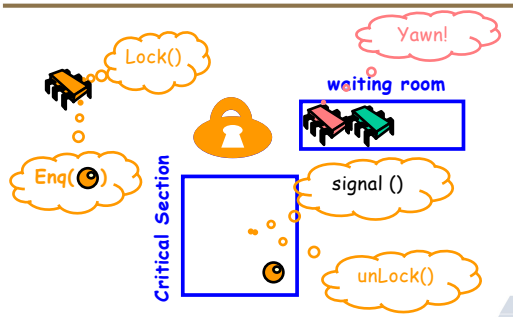


Dequeurs Signalled

Dollar Short + Day Late

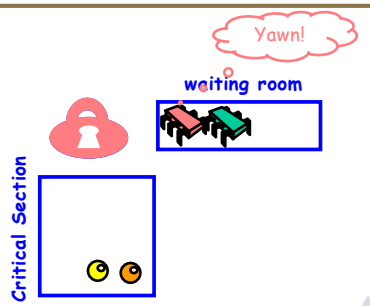


Lost Wake-Up

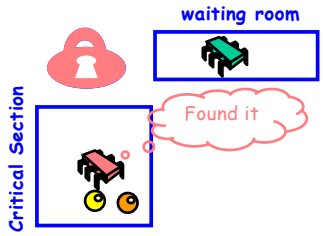


Lost Wake-Up

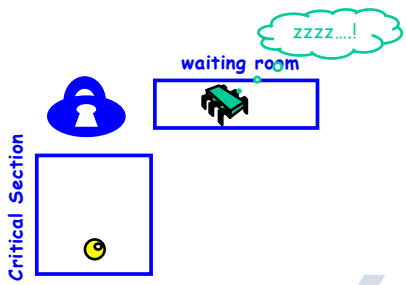
Lost Wake-Up



Lost Wake-Up



What's Wrong Here?



Solution to Lost Wakeup

- Always use signalAll and notifyAll
- Not signal and notify

Java Synchronized Methods

```
public class Queue<T> {

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

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


Java Synchronized Methods

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  …
}}
```

Each object has an implicit lock with an implicit condition

Java Synchronized Methods

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   return result;
  }
  …
}}
```

Lock on entry, unlock on return

Java Synchronized Methods

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  int head = 0, tail = 0;
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  public synchronized T deq() {
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   this.notifyAll();
   return result;
  }
  …
}}
```

Wait on implicit condition

Java Synchronized Methods

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public class Queue<T> {

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

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

Signal all threads waiting on condition

(Pop!) The Bounded Queue

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

Bounded Queue Fields

```
public class BoundedQueue<T> {
  ReentrantLock enqLock, deqLock;
  Condition notEmptyCondition, notFullCondition;
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Enq & deq locks

Bounded Queue Fields

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  notEmptyCondition = deqLock.newCondition();
}
```

Enq lock's associated condition

Bounded Queue Fields

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

Num permits: 0 to capacity

Bounded Queue Fields

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  notFullCondition = enqLock.newCondition();
  deqLock = new ReentrantLock();
  notEmptyCondition = deqLock.newCondition();
}
```

Head and Tail

Enq Method Part One

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


Enq Method Part One

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 } finally {
   enqLock.unlock();
 }
}
```

Lock and unlock enq lock

Enq Method Part One

```
public void enq(T x) {
 boolean mustWakeDequeuers = false;
 enqLock.lock();
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  Node e = new Node(x);
  tail.next = e;
  tail = e;
  if (permits.getAndDecrement() == capacity)
    mustWakeDequeuers = true;
 } finally {
    enqLock.unlock();
 }
 …
}
```

If queue is full, patiently await further instructions …

Be Afraid

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

How do we know the permits field won't change?

Enq Method Part One

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

Add new node

Enq Method Part One

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

If queue was empty, wake frustrated dequeuers

Enq Method Part Deux

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


Enq Method Part Deux

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

Are there dequeuers to be signaled?

Enq Method Part Deux

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

Lock and unlock deq lock

Enq Method Part Deux

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

Signal dequeuers that queue no longer empty

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?

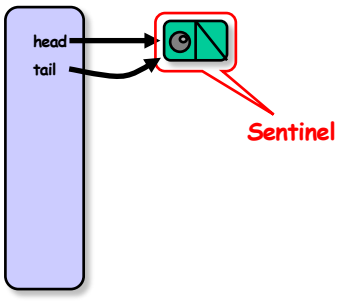
Split the Counter

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

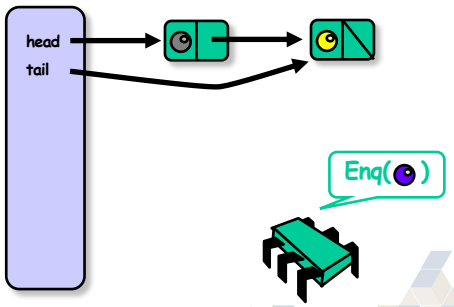
Split Counter

- Enqueuer decrements enqSidePermits
- Dequeuer increments deqSidePermits
- When enqueuer runs out
  - Locks deqLock
  - Transfers permits
- Intermittent synchronization
  - Not with each method call
  - Need both locks! (careful …)

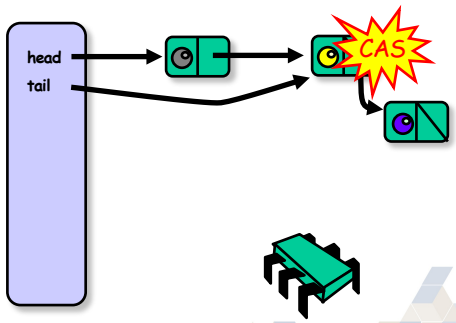
A Lock-Free Queue



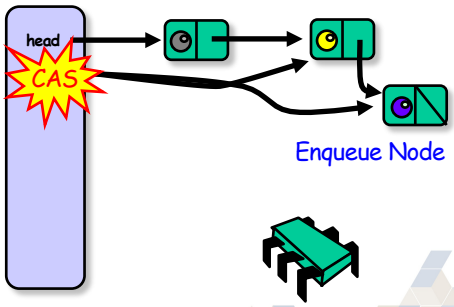
Enqueue



Logical Enqueue



Physical Enqueue



Enqueue

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

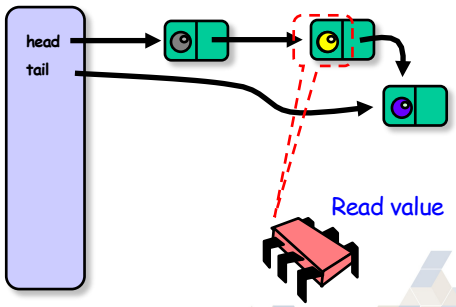
Enqueue

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

When CASs Fail

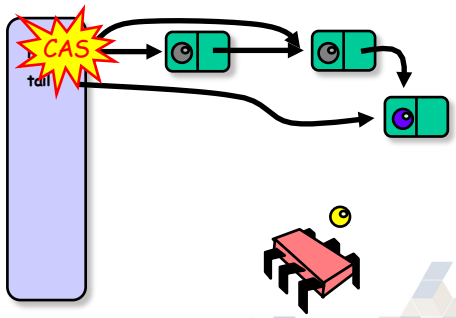
- During logical enqueue
  - Abandon hope, restart
  - Still lock-free
- During physical enqueue
  - Ignore it

Dequeuer



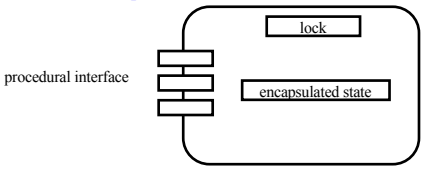
Dequeuer

Make first Node new sentinel



Monitors

- Communication and Synchronization
  - approaches broadly classified as shared-variable or message passing
  - many different models, a popular one is a monitor
  - a monitor can be considered as an object where each of its operation executes in mutual exclusion



Monitors

- Condition Synchronization
  - expresses a constraint on the ordering of execution of operations
  - e.g., data cannot be removed from a buffer until data has been placed in the buffer
- Monitors provide condition variables with two operations which can be called when the lock is held
  - wait: an unconditional suspension of the calling thread (the thread is placed on a queue associated with the condition variable)
  - notify: one thread is taken from the queue and re-scheduled for execution (it must reclaim the lock first)
  - notifyAll: all suspended threads are re-scheduled
  - **notify and notifyAll have no effect if no threads are suspended on the condition variable**

wait(), notify(), notifyAll()

wait() and notify() allows a thread to wait for an event

Instead of "busy wait" or sleep loop!

A call to notifyAll() allows all threads that are on wait() with the same lock to be released

A call to notify() allows one arbitrary thread that is on a wait() with the same lock to be released

wait(), notify(), notifyAll()

```
public class Drop {

  // Message sent from producer to consumer
  private String message;

  // A flag, True if consumer should wait for
  // producer to send message, False if producer
  // should wait for consumer to retrieve message
  private boolean empty = true;

  ...
```

Flag must be used, never count only on the notify

wait(), notify(), notifyAll()

```
public class Drop {
  ...
  public synchronized String take() {
    // Wait until message is available
    while (empty) {
      // we do nothing on InterruptedException
      // since the while condition is checked anyhow
      try { wait(); } catch (InterruptedException e) {}
    }
    // Toggle status and notify on the status change
    empty = true;
    notifyAll();
    return message;
  }
  ...
}
```


wait(), notify(), notifyAll()

```
public class Drop {
  ...
  public synchronized void put(String message) {
    // Wait until message has been retrieved
    while (!empty) {
      // we do nothing on InterruptedException
      // since the while condition is checked anyhow
      try { wait(); } catch (InterruptedException e) {}
    }
    // Toggle status, store message and notify consumer
    empty = false;
    this.message = message;
    notifyAll();
  }
  ...
}
```


The new `wait()` and `notify()`

- Remember **`Lock.newCondition();`** ?
- Condition factors out the Object monitor methods (**`wait`**, **`notify`** and **`notifyAll`**)
  - into distinct objects to give the effect of having multiple wait-sets per object
  - can combine them with the use of arbitrary **`Lock`** implementations.
- Where a **`Lock`** replaces the use of **`synchronized`** methods and statements, a **`Condition`** replaces the use of the Object monitor methods.

Conditions

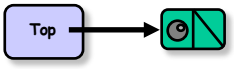
- Allows more than one wait condition per object
  - Even for built-in locks, via Locks utility class
- Allows much simpler implementation of

```
interface Condition {
  void await() throws IE;
  void awaitUninterruptibly();
  long awaitNanos(long nanos) throws IE;
  boolean awaitUntil(Date deadline) throws IE;
  void signal();
  void signalAll();
}
```

Concurrent Stack

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

Empty Stack



Push

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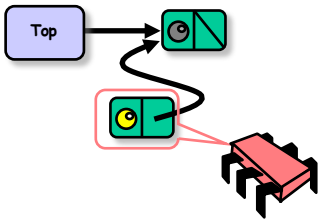

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Push

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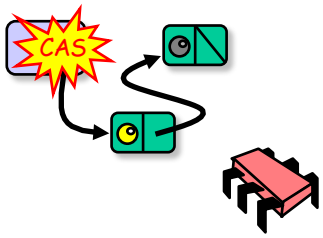

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Push

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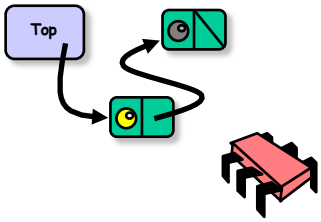

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Push

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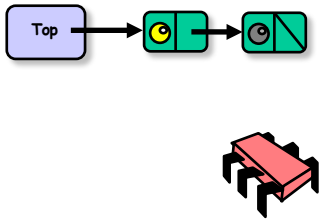

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Push

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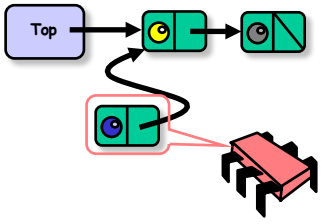

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Push

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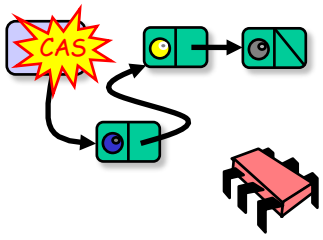

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Push

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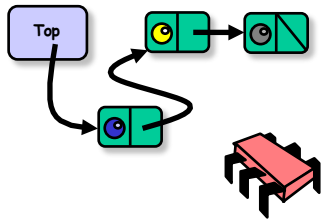

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Pop

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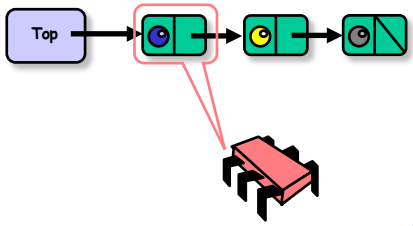

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Pop

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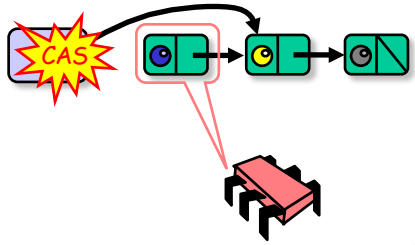

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Pop

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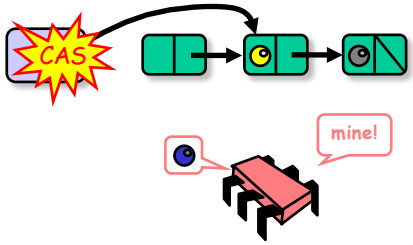

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Pop

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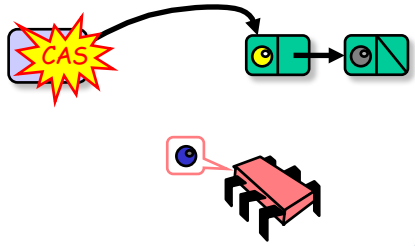

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Pop

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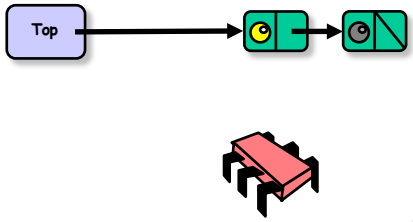

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Lock-free Stack

```
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

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

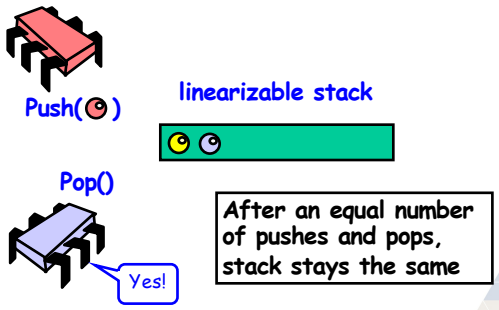
Big Question

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

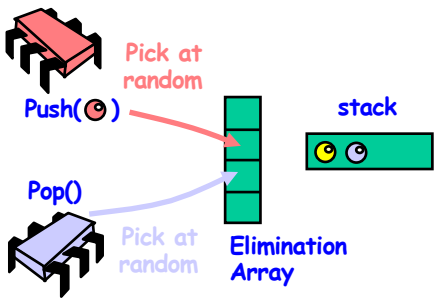
Elimination-Backoff Stack

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

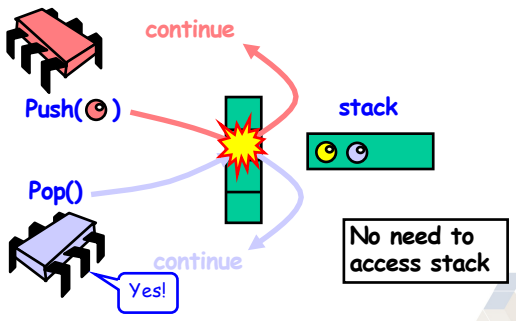
Observation



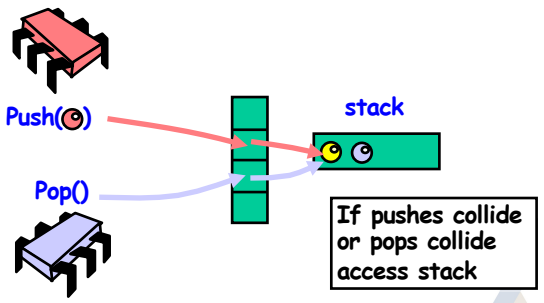
Idea: Elimination Array



Push Collides With Pop



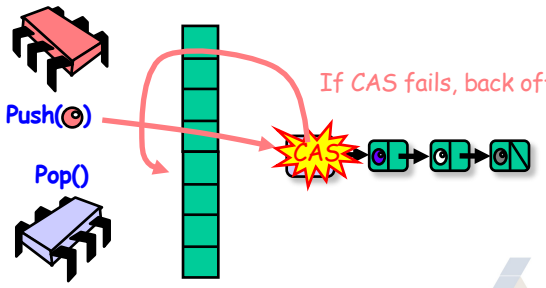
No Collision



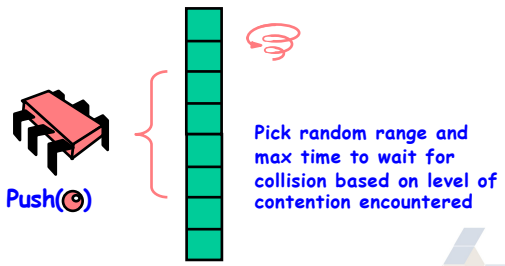
Elimination-Backoff Stack

- 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

Backoff Has Dual Effect

- Elimination introduces parallelism
- Backoff onto array cuts contention on lock-free stack
- Elimination in array cuts down total number of threads ever 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>();
  …
  }
  …
}
```


A Lock-Free Exchanger

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


Extracting Reference & Stamp

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

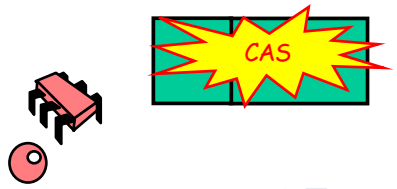

Exchanger Status

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

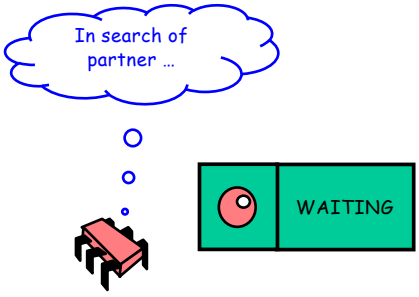

The Exchange

```
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
  }
 }
```

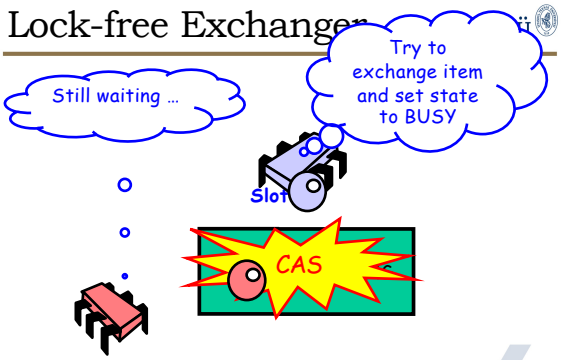
Lock-free Exchanger



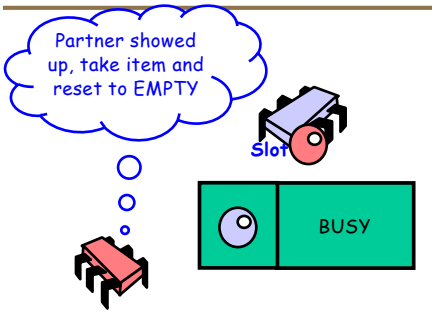
Lock-free Exchanger



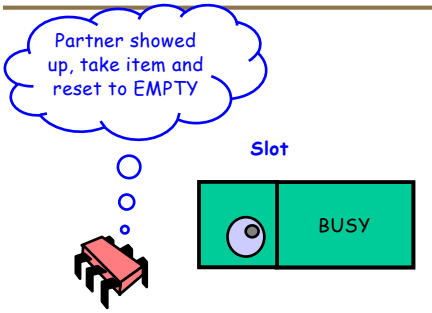
Lock-free Exchanger



Lock-free Exchanger



Lock-free Exchanger



Exchanger State EMPTY

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

States WAITING and BUSY

```
case WAITING:   // someone waiting for me
    if (slot.compareAndSet(herItem, myItem, WAITING, BUSY))
        return herItem;
break;

case BUSY:   // others in middle of exchanging
break;

default:  // impossible
break;

}}}}
```


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

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 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 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;
        }
      }
}}
```


Exchangers

- A synchronization point at which two threads can exchange objects
- Can be thought of as a CyclicBarrier with a count of two plus allowing an exchange of state at the barrier
- On calling the exchange() method the thread provides some object as input
- The exchange() methods returns the object entered as input by the second thread to the calling thread
- Useful for example in the case where one thread is filling a buffer (filler thread) and the other emptying (emptying thread)
- On calling exchange() the filler thread is passed an empty buffer
- The emptying thread obtain the newly full buffer from the filler thread

Concurrent Collections

The Concurrency framework provides implementation of several commonly used collections classes optimized for concurrent operations

`public interface Queue<E> extends Collection<E>:`

A collection class that hold elements prior to processing, generally orders element in a FIFO manner (however can also be LIFO etc).

Supports the following functionality

- Offer method inserts an element if possible else return false
- remove() and poll() return and remove the head of the queue
- element() and peek() return but do not remove the head of the queue

Concurrent Collections

The Concurrency framework queue implementations

- CopyOnWriteArrayList: A thread-safe variant of ArrayList
- ConcurrentLinkedQueue : An unbounded thread-safe queue based on linked nodes.
- *BlockingQueue : A Queue that additionally supports operations that wait for the queue to become non-empty when retrieving an element, and wait for space to become available in the queue when storing an element.*

Summary of BlockingQueue methods

	Throws exception	*Special value*	*Blocks*	*Times out*
Insert	`add(e)`	`offer(e)`	`put(e)`	`offer(e, time, unit)`
Remove	`remove()`	`poll()`	`take()`	`poll(time, unit)`
Examine	`element()`	`peek()`	*not applicable*	*not applicable*

Concurrent Collections

The Concurrency framework queue implementations

- *BlockingQueue*
  - ArrayBlockingQueue: A bounded blocking queue backed by an array.
  - DelayQueue: An element can only be taken when its delay has expired. Holds elements of *Delayed* instances.
  - LinkedBlockingDeque: An optionally-bounded blocking deque based on linked nodes.
  - LinkedTransferQueue: When transfer is used producing threads may wait until consumed.
  - PriorityBlockingQueue: An unbounded blocking queue that uses comparators for prioritizing.
  - SynchronousQueue: A blocking queue in which each insert operation must wait for a corresponding remove operation by another thread, and vice versa.

Concurrent Collections

`public interface ConcurrentMap<K,V> extends Map<K,V>:`

An extension to the Map interface that provides support for concurrency

- Supports concurrent putIfAbsent, remove and replace methods
- putIfAbsent(key, value): If the specifed key is not associated with a value associate it with a value. Performed atomically
- remove(key, value): Removes entry for a key if associated with value. Performed atomically
- remove(key, oldvalue, newvalue): Replaces entry for a key if associated with oldvalue with newvalue. Performed atomically

Concurrent Collections

The Concurrency framework queue implementations

- *ConcurrentMap*
  - ConcurrentHashMap: A hash table supporting full concurrency of retrievals and high expected concurrency for updates.
  - ConcurrentNavigableMap: A ConcurrentMap supporting NavigableMap operations, and recursively so for its navigable sub-maps
  - ConcurrentSkipListMap: A scalable concurrent ConcurrentNavigableMap implementation.

Concurrent Collections

```
public class Consumerthread implements Runnable{
   private static int capacity ;
   private BlockingQueue<Integer> intqueue;
   public consumerthread(BlockingQueue<Integer> queue, int cap){
       capacity = cap;
       this.intqueue = queue;
   }
   public void run(){
      int num;
      for(int i = 0; i<capacity; i++){
        try {
           num = intqueue.take();
           if(num == -1) break;
           System.out.println("Square of " + num + ":" + num*num);
        } catch (InterruptedException e) {
              e.printStackTrace();
         }
      }}}
```

Concurrent Collections

```
public class Producerthread implements Runnable {
private static int capacity ;
private BlockingQueue<Integer> intqueue;
public producerthread(BlockingQueue<Integer> queue, int cap){
   capacity = cap;
   this.intqueue = queue;
}
public void run(){
   for(int i = 0; i<capacity-1; i++){
      try {
       intqueue.put(i);
      } catch (InterruptedException e) {
       e.printStackTrace();}
   }
   try {
      intqueue.put(-1);
   } catch (InterruptedException e) {
      e.printStackTrace();}
}}
```

Concurrent Collections

```
public class Tester {
   public static void main(String [] args){
        BlockingQueue<Integer> queue = new
        ArrayBlockingQueue<Integer>(100);

        Consumerthread consumer = new Consumerthread(queue, 100);

        Producerthread producer = new Producerthread(queue, 100);

        new Thread(consumer).start();

        new Thread(producer).start();

   }
}
```

Concurrent Collections

That was an example of using blocking queues to implement producer consumer relationships

- The producer class fills in a queue of integers
- The consumer class pulls integers of this queue and finds the square
- If the queue is empty a take() blocks, if full a put() blocks
- We could extend this to use a thread pool for the producers

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
- ABA is a real problem, pay attention