Lecture 13: concurrent queues

queue as mutex, strong FIFO, per-producer FIFO, bounded/unbounded queue, SPSC, MPSC, SPMC, MPMC, total/partial/synchronous API, lock-free queue, ring buffer for bounded queues, concurrent dequeue, work stealing

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https://github.com/Svazars/parallel-programming/blob/main/slides/pdf/l13.pdf

In previous episodes

Threading models[1]

- 1:1 threading (user thread = OS thread, `ThreadFactory`)
- N:1 threading (event loop, `newSingleThreadExecutor`)
- N:M threading (coroutines, `newFixedThreadPool`)
- Lazy/on-demand thread creation (`newCachedThreadPool`)

Heavyweight OS threads affect programming style

- Task pools vs long-running tasks
- Task pools vs blocking methods
- Asynchronous I/O and callback-based programming

User-space scheduling:

- Stackless coroutines (CPS and suspend/resume coloring)
- Stackful coroutines (low-level: scheduling policy, context switch, preemption)

[1] https://en.wikipedia.org/wiki/Thread_(computing)#Threading_models

Lecture plan

1. Queues for mutual exclusion
2. Design space
3. Unbounded lock-free queue
4. Bounded array-based queues
   - SPSC
   - MPSC
   - SPMC
5. Concurrent DEQueue and work stealing
6. Summary

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Question time

Question: Name queue-based mutexes that you already know

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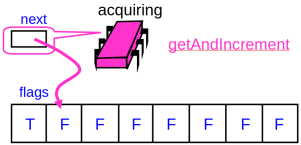

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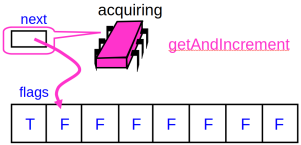
- LinkedList-based: CLH lock



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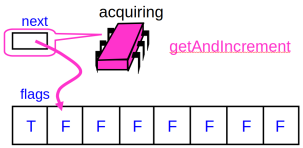

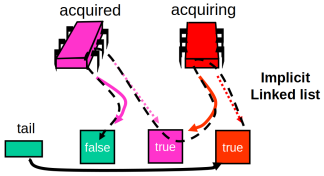

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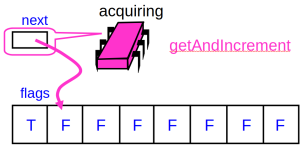

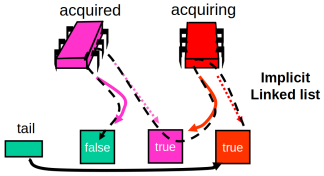

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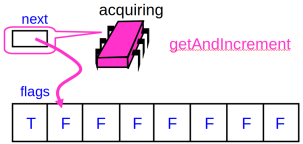

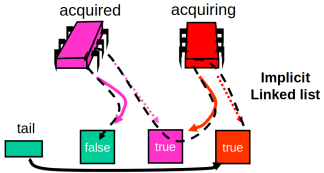

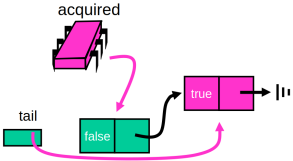

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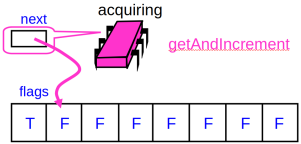

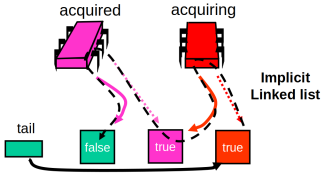

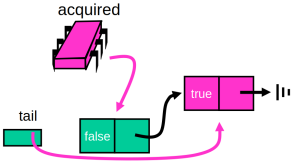

Idea: select container (LIFO, FIFO, priority queue) and use it to

- register competitors
- maintain admission policy

FIFO queue for mutual exclusion

```
class FIFOLock implements Lock {
  private Queue q = ...
  void lock() {
    myNode = new Node();
    q.enqueue(myNode);
    while (true) { if (q.peek() == myNode) return; /* it is my turn */ }
  }
  void unlock() {
    prevHead = q.dequeue(); // let other thread go
    assert prevHead == myNode; // could I delete myNode right now?
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Could be extended with spin-then-park and cancellation[2]

[2] https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/util/concurrent/locks/LockSupport.html

Question time

Question: How to implement mutex using lock-free LIFO stack?

Queues and mutexes: summary

Thread-safe FIFO container could be transformed into mutex

- admission policy control "out of the box"
- easy to associate data with every entering thread (e.g. thread-local memory for spinning)
- must maintain high level of concurrent consistency
  - Strong FIFO
  - Multiple enqueuers, Single dequeuer

Question time

Question: Name other usage scenarios for concurrent queues

Lecture plan

Queues: where to use

- Concurrency control

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What *precisely* do we need from thread-safe container?

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    - Message resent under some condition

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We will look at some points in this design space

Lecture plan

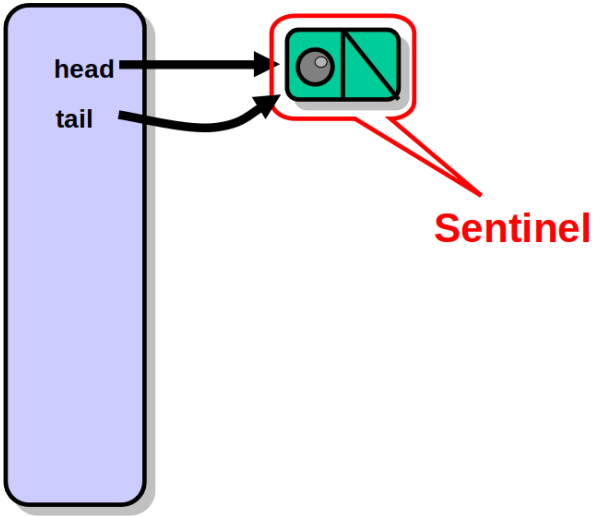
Unbounded MPMC linearizable total queue

- Strong FIFO
- MPMC
- Unbounded
- Total

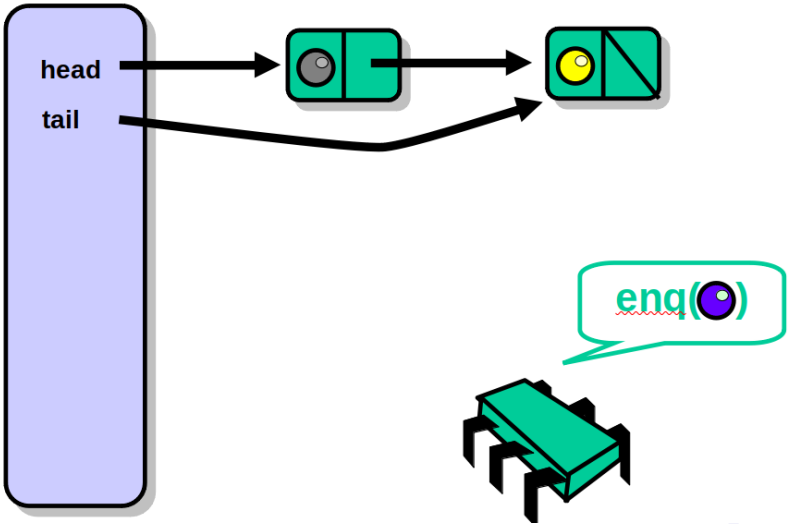
Unbounded MPMC linearizable total queue

- Strong FIFO
- MPMC
- Unbounded
- Total
- Lock-free

Lock-Free Queue



Enqueue



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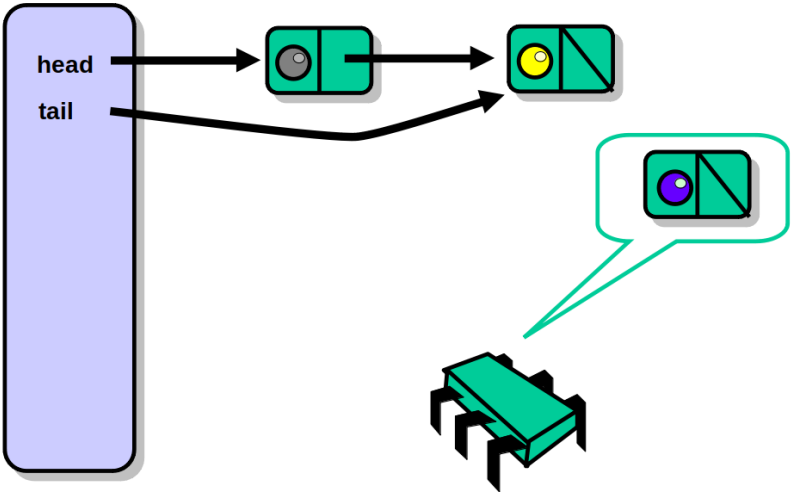
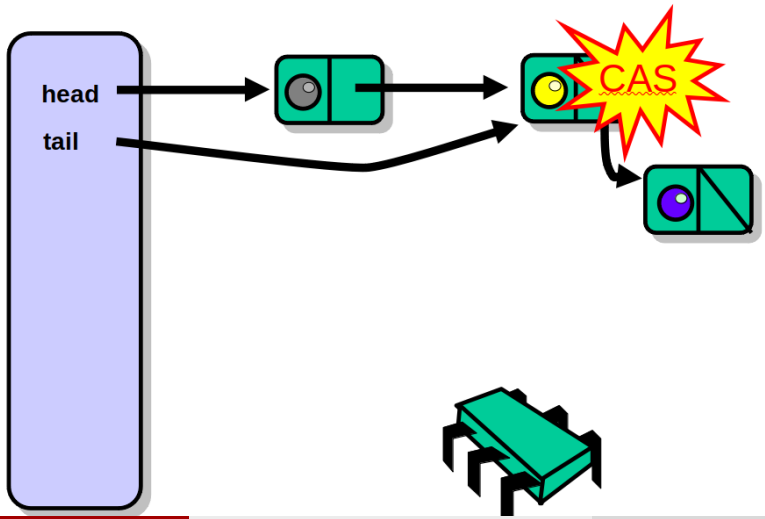
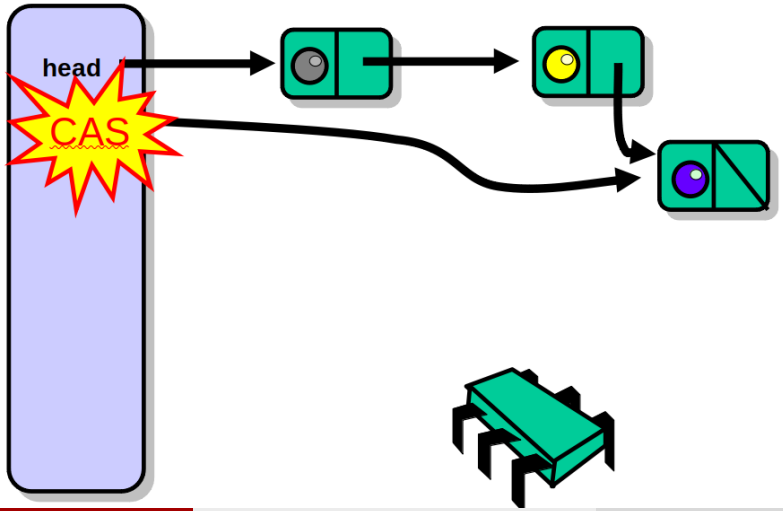


Logical enqueue



Physical enqueue



Enqueue

Logical enqueue and physical enqueue are separate steps

Enqueue

Logical enqueue and physical enqueue are separate steps

- `tail` fields refers to either

Enqueue

Logical enqueue and physical enqueue are separate steps

- `tail` fields refers to either
  - Actual last node (good)

Enqueue

Logical enqueue and physical enqueue are separate steps

- `tail` fields refers to either
  - Actual last node (good)
  - "Lagging" node (not so good)

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What should we do with "trailing tail"

Enqueue

Logical enqueue and physical enqueue are separate steps

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What should we do with "trailing tail"

- Stop and fix it before doing anything else

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- If `tail.next != null` then CAS `tail -> tail.next`

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- Logical `enqueue`
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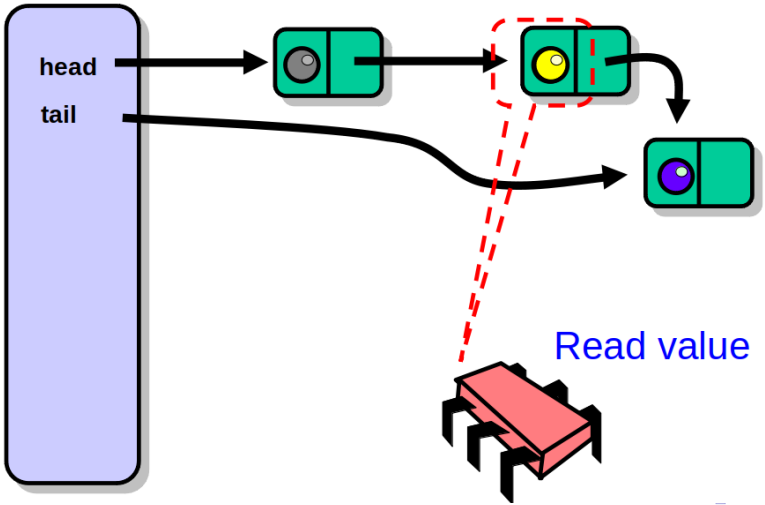
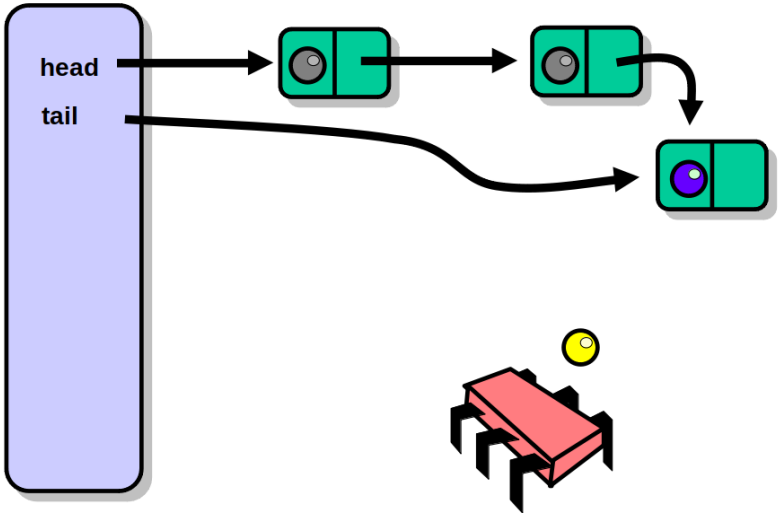
  - But still lock-free (why?)
- Physical `enqueue`
  - Failed CAS means other thread helped to fix invariants
- Inside `dequeue`
  - Actual `tail` lagging behind `head`
  - Swapping "sentinel" may delete actual data, make tail up-to-date before dequeue

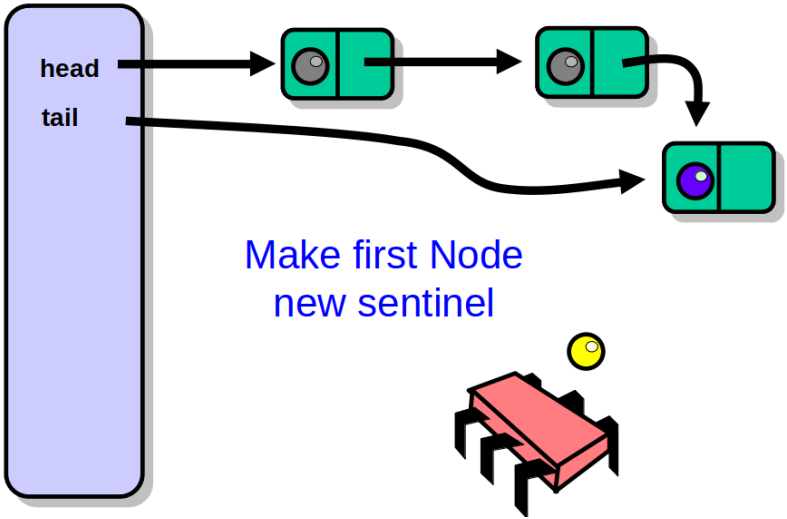
Dequeue



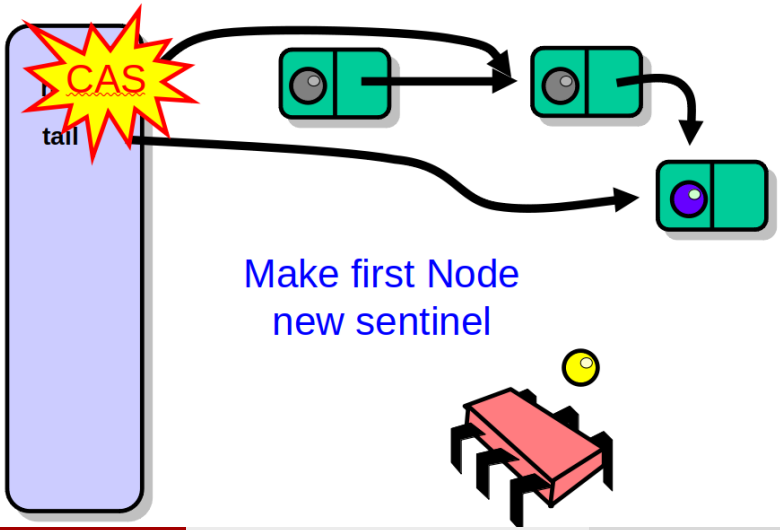
Dequeue



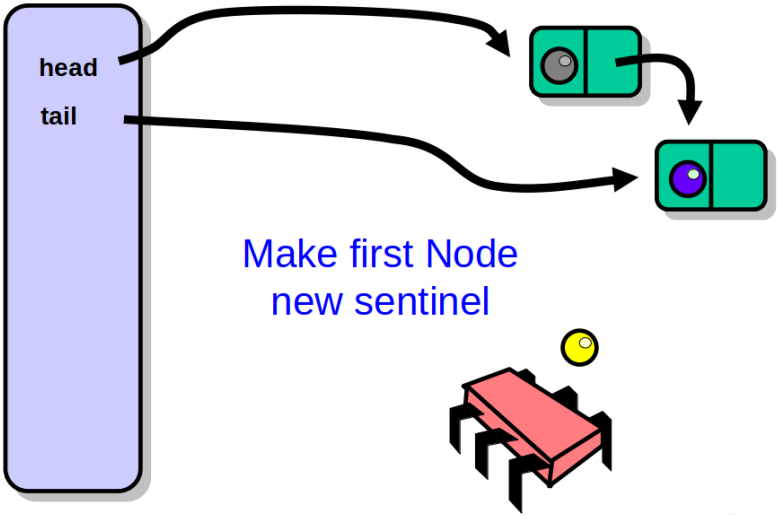
Dequeue



Dequeue



Dequeue



Enqueue: code

```
public void enqueue(T value) {
  Node node = new Node(value);
  while (true) {
    Node last = tail.get();
    Node next = last.next.get();
    if (last == tail.get()) {
      if (next == null) {
        if (last.next.compareAndSet(next, node)) { // logical
          tail.compareAndSet(last, node);          // physical
          return;
        }
      } else {
        tail.compareAndSet(last, next); // repair tail and repeat
      }
}}}
```

Dequeue: code

```
public T dequeue() {
  while (true) {
    Node first = head.get();
    Node last = tail.get();
    Node next = first.next.get();
    if (first == head.get()) {
      if (first == last) {
        if (next == null) throw new EmptyException();
        tail.compareAndSet(last, next); // repair tail and repeat
      } else {
        T value = next.value;
        if (head.compareAndSet(first, next)) return value;
}}}}
```

Unbounded MPMC linearizable total queue

- LinkedList-based
- Strong FIFO[4]
- Unbounded, needs Garbage Collection to avoid ABA
- Enqueue uses "helping hand" pattern to be lock-free
- Dequeue uses "helping hand" pattern to be correct

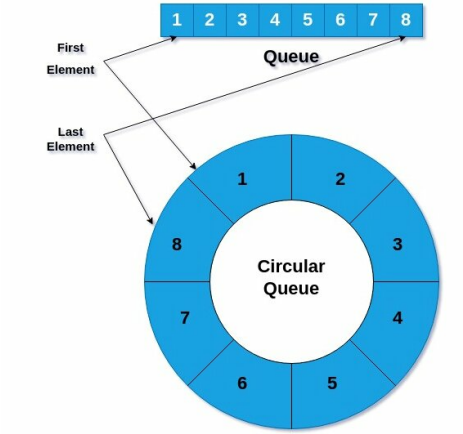
See Section 10.5 "An Unbounded Lock-Free Queue" in "The Art of Multiprocessor Programming" (pages 230 - 233).

[4] Homework: find linearization points

Lecture plan

1. Queues for mutual exclusion
2. Design space
3. Unbounded lock-free queue
4. Bounded array-based queues
   - SPSC
   - MPSC
   - SPMC
5. Concurrent DEQueue and work stealing
6. Summary

Bounded array-based queues



Lecture plan

SPSC

```
class SPSC_WaitFree_Queue<T> {
  volatile int head = 0, tail = 0; T[] items = (T[]) new Object[capacity];
  void enqueue(T x) {
    if (tail - head == items.length) throw new FullException();
    items[tail % items.length] = x;
    tail++; // not even getAndAdd
  }
  T dequeue() {
    if (tail - head == 0) throw new EmptyException();
    T x = items[head % items.length];
    head++; // not even getAndAdd
    return x;
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    head++; // not even getAndAdd
    return x;
}}
```

Could you find linearization points? Could you find memory barriers?

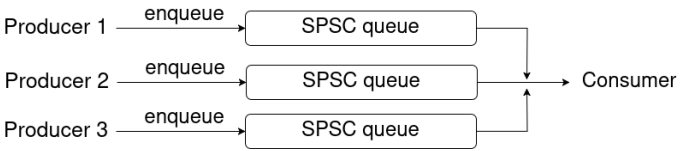
Lecture plan

MPSC

Question time

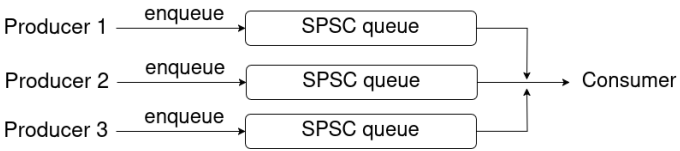
Question: How to create correct MPSC queue from **single** SPSC queue?

MPSC from N SPSC



MPSC from N SPSC

```
SPSC[] queues = ...
void enqueue(T x) {
  int id = ThreadID.get();
  queues[id].enqueue(x);
}
T dequeue() {
  for (q : queues) if (!q.isEmpty()) return q.dequeue();
  throw new EmptyException();
}
```



- Wait-free?

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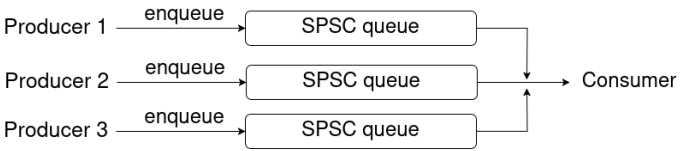

- Wait-free? Thanks to SPSC.

MPSC from N SPSC

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- Wait-free? Thanks to SPSC. But dequeue is O(T).

MPSC from N SPSC

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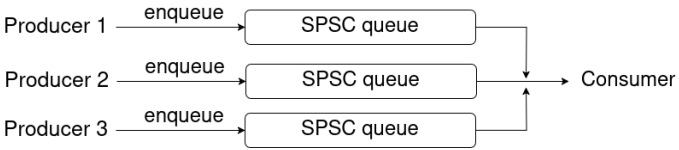

- Strong FIFO?

MPSC from N SPSC

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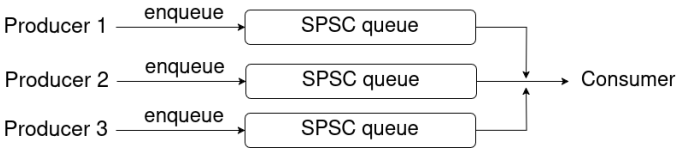

- Strong FIFO?
  - `t1:enq(x)` → `t2:enq(y)` **does not** imply `deq(x)` → `deq(y)`

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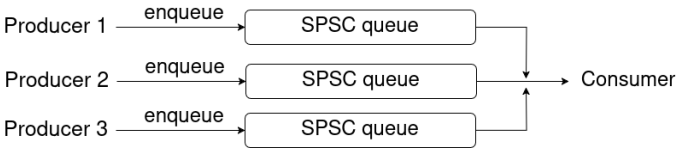

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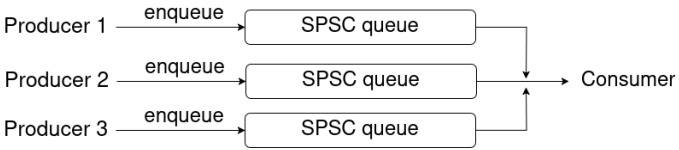

- Really empty?

MPSC from N SPSC

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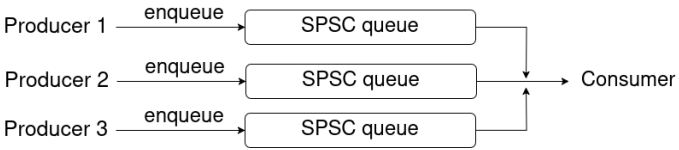

- Really empty? Homework: what is *empty* for this queue

MPSC from N SPSC

- Need to register threads in advance

MPSC from N SPSC

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- Weak ordering guarantees

MPSC from N SPSC

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- `isEmpty` takes O(T)

MPSC from N SPSC

- Need to register threads in advance
- Weak ordering guarantees
- But wait-free!
- `isEmpty` takes O(T)
- Use atomic counters for `size`?

MPSC from N SPSC

- Use atomic counters for O(1) size check

MPSC from N SPSC

- Use atomic counters for O(1) size check

```
void enqueue(T x) {
  size.getAndAdd(1);
  queues[ThreadID.get()].enqueue(x);
}
T dequeue() {
  if (size.get() == 0) throw new EmptyException();
  for (q : queues) if (!q.isEmpty()) {
    size.getAndAdd(-1);
    return q.dequeue();
  }
  assert false;
}
```

MPSC from N SPSC

- Use atomic counters for O(1) size check

```
void enqueue(T x) {
  size.getAndAdd(1);
  queues[ThreadID.get()].enqueue(x);
}
T dequeue() {
  if (size.get() == 0) throw new EmptyException();
  for (q : queues) if (!q.isEmpty()) {
    size.getAndAdd(-1);
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```

AssertionError!

MPSC from N SPSC

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MPSC from N SPSC

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}
```

Missing already available element?

MPSC from N SPSC

- Use atomic counters for O(1) size check

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  while (true) {
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MPSC from N SPSC

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- Wait-free?

MPSC from N SPSC

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}}
```

- Wait-free?
- Negative size?

Building queues from other queues: takeaways

Building distributed queue from more specialized parts:

Building queues from other queues: takeaways

Building distributed queue from more specialized parts:

- *Could* be scalability-friendly

Building queues from other queues: takeaways

Building distributed queue from more specialized parts:

- *Could* be scalability-friendly
- *Could* be *really* non-blocking

Building queues from other queues: takeaways

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Building queues from other queues: takeaways

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Building queues from other queues: takeaways

Building distributed queue from more specialized parts:

- *Could* be scalability-friendly
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Building queues from other queues: takeaways

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Building queues from other queues: takeaways

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Building queues from other queues: takeaways

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- *Definitely will be* error-prone
- Relaxing consistency requirements helps
- Useful to think in terms of linearization points
  - Operation takes effect **here**
  - Even if the whole API is not linearizable

Specialized lock-free single-queue algorithms exist:

- JCTools
  - `https://github.com/JCTools/JCTools`
  - `https://www.infoq.com/presentations/jctools-algorithms-optimization`
- 1024 cores
  - `https://www.1024cores.net/home/lock-free-algorithms/queues`

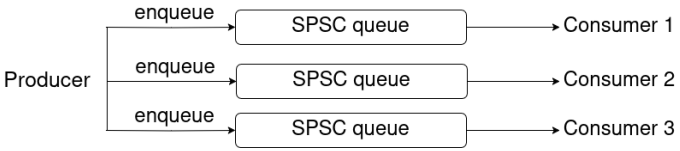
Lecture plan

SPMC

Question time

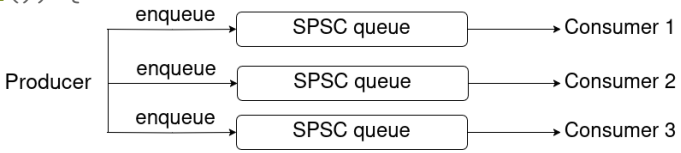
Question: How to build SPMC queue from **one** single-producer k-consumer queue?

SPMC from N SPSC



SPMC from N SPSC

```
SPSC[] queues = ...
void enqueue(T x) {
  for (q : queues) if (!q.isFull()) {
    q.enqueue(x); return;
  }
  throw new FullException();
}
T dequeue() {
  return queues[ThreadID.get()].dequeue();
}
```



SPMC from N SPSC

```
SPSC[] queues = ...
void enqueue(T x) {
  for (q : queues) if (!q.isFull()) {
    q.enqueue(x); return;
  }
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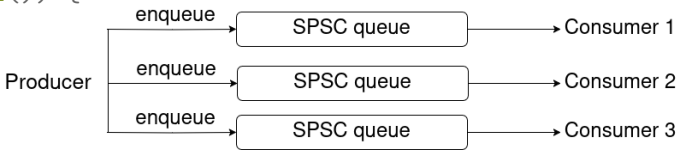
}
T dequeue() {
  return queues[ThreadID.get()].dequeue();
}
```



- What is empty queue?

SPMC from N SPSC

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SPSC[] queues = ...
void enqueue(T x) {
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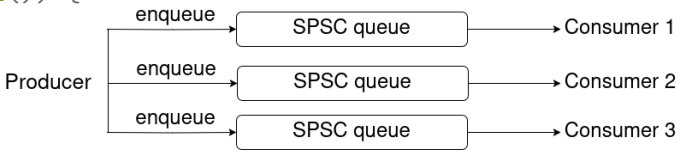

- What is empty queue?
  - Producer view: all consumer queues are empty

SPMC from N SPSC

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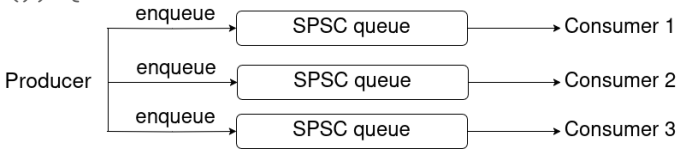

- What is empty queue?
  - Producer view: all consumer queues are empty
  - Consumer view: my queue is empty

SPMC from N SPSC

```
SPSC[] queues = ...
void enqueue(T x) {
  for (q : queues) if (!q.isFull()) {
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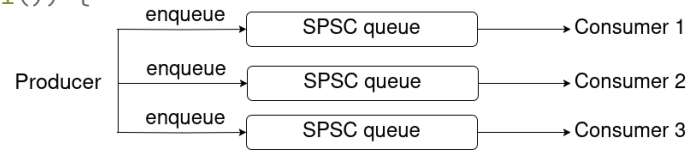

- Linearizability?

SPMC from N SPSC

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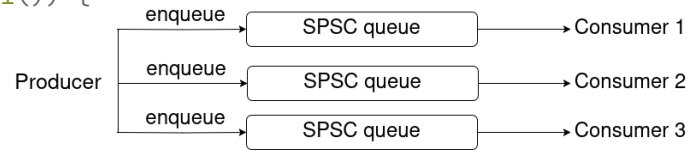

- Linearizability? No, but maybe OK

SPMC from N SPSC

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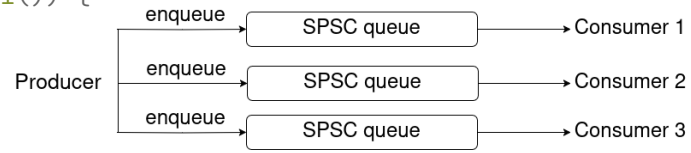

- Linearizability? No, but maybe OK
- Load balancing?

SPMC from N SPSC

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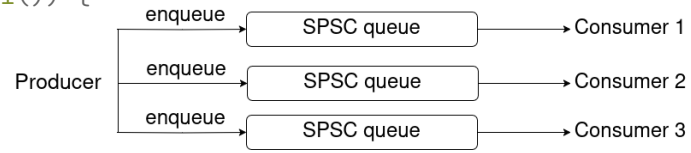
}
T dequeue() {
  return queues[ThreadID.get()].dequeue();
}
```



- Linearizability? No, but maybe OK
- Load balancing? No, definitely not OK

SPMC from N SPSC

- Naive work-stealing as load balancing strategy

SPMC from N SPSC

- Naive work-stealing as load balancing strategy

```
void enqueue(T x) {
  for (q : queues) synchronized(q) { if (!q.isFull()) {
    q.enqueue(x); return;
  }}
  throw new FullException();
}
T dequeue() {
  SPSC q = queues[ThreadID.get()];
  synchronized(q) { if (!q.isEmpty()) return q.dequeue(); }
  for(q : queues) synchronized(q) { if (!q.isEmpty()) return q.dequeue(x); }
}
```

SPMC from N SPSC

- Naive work-stealing as load balancing strategy

```
void enqueue(T x) {
  for (q : queues) synchronized(q) { if (!q.isFull()) {
    q.enqueue(x); return;
  }}
  throw new FullException();
}
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  synchronized(q) { if (!q.isEmpty()) return q.dequeue(); }
  for(q : queues) synchronized(q) { if (!q.isEmpty()) return q.dequeue(x); }
}
```

- Real-life algorithms: batch steal, lock-free steal

Consumer contention: takeaways

- Many producers/consumers – maybe strong FIFO is not that necessary

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Consumer contention: takeaways

- Many producers/consumers – maybe strong FIFO is not that necessary
- Many consumers – load balancing required
- Non-blocking work stealing looks like hard problem

Specialized lock-free single-queue algorithms exist:

- JCTools
  - `https://github.com/JCTools/JCTools`
  - `https://www.infoq.com/presentations/jctools-algorithms-optimization`
- 1024 cores
  - `https://www.1024cores.net/home/lock-free-algorithms/queues`

Lecture plan

1. Queues for mutual exclusion
2. Design space
3. Unbounded lock-free queue
4. Bounded array-based queues
   - SPSC
   - MPSC
   - SPMC
5. Concurrent DEQueue and work stealing
6. Summary

Lock-Free Work Stealing

Lock-Free Work Stealing

- Each thread has a pool of ready work

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- Each thread has a pool of ready work
- Remove work without synchronizing

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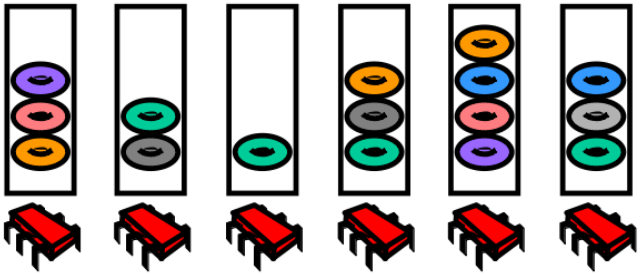
- Remove work without synchronizing
- If you run out of work, steal from someone

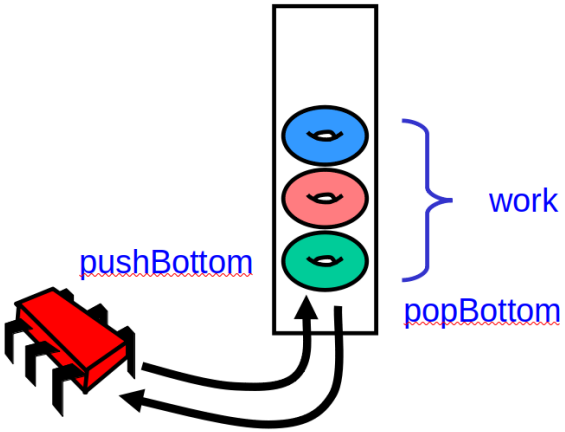
Lock-Free Work Stealing

- Each thread has a pool of ready work
- Remove work without synchronizing
- If you run out of work, steal from someone
- Choose victim at random

Local work pools

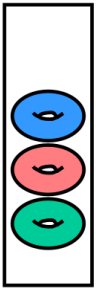


DoubleEndedQueue



Obtain work

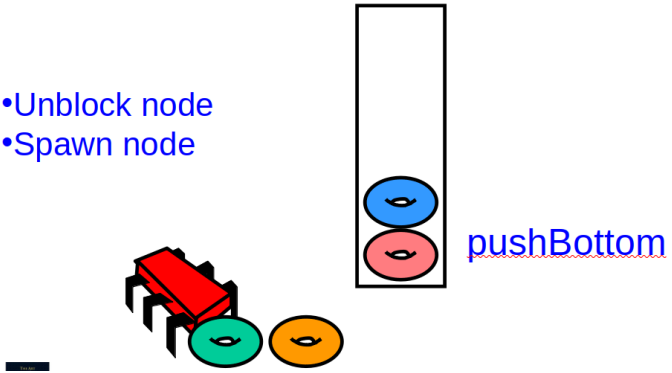
- Obtain work
- Run task until
- Blocks or terminates



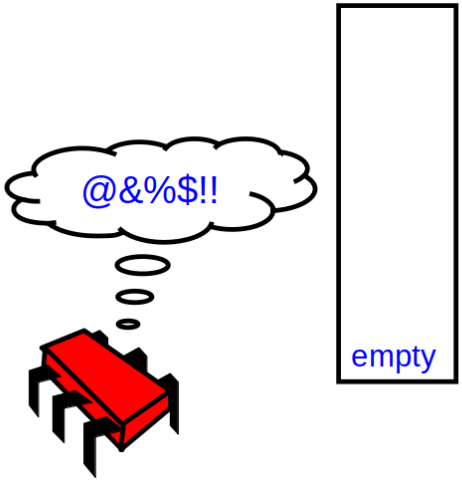
popBottom

New work

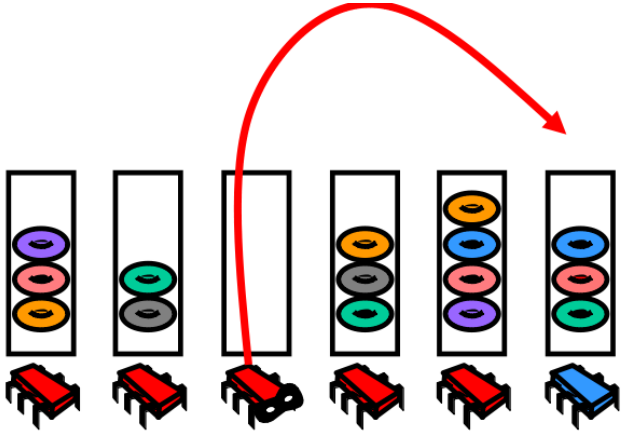
- Unblock node
- Spawn node



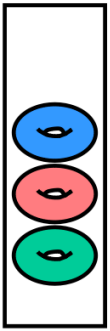
Out of work



Steal from others



Steal task



popTop

Task DEQueue

Methods:

- `pushBottom`, `popBottom`, `popTop`

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`pushBottom` and `popBottom` are never concurrent:

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Ideal requirements:

- Wait-Free, Linearizable, Constant time

Task DEQueue

Methods:

- `pushBottom`, `popBottom`, `popTop`

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Compromise:

Task DEQueue

Methods:

- `pushBottom`, `popBottom`, `popTop`

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- Wait-Free, Linearizable, Constant time

Compromise: method `popTop` may fail if

Task DEQueue

Methods:

- `pushBottom`, `popBottom`, `popTop`

`pushBottom` and `popBottom` are never concurrent:

- make them fast
- minimize use of CAS

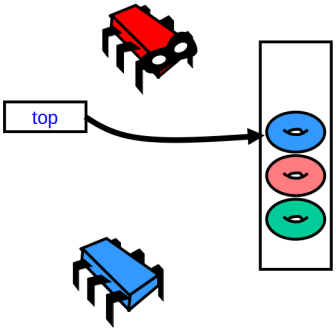
Ideal requirements:

- Wait-Free, Linearizable, Constant time

Compromise: method `popTop` may fail if

- Concurrent `popTop` succeeds or
- Concurrent `popBottom` takes last task

ABA problem



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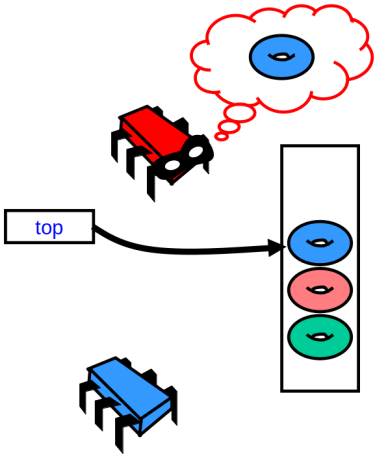

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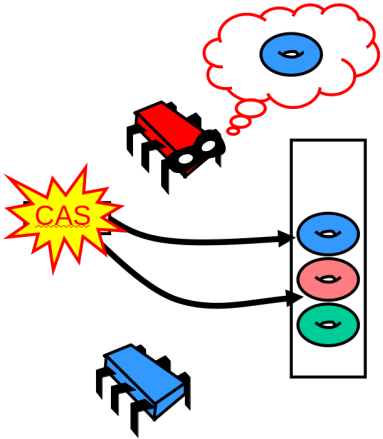

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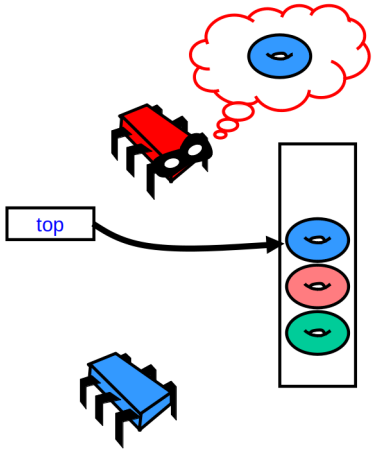

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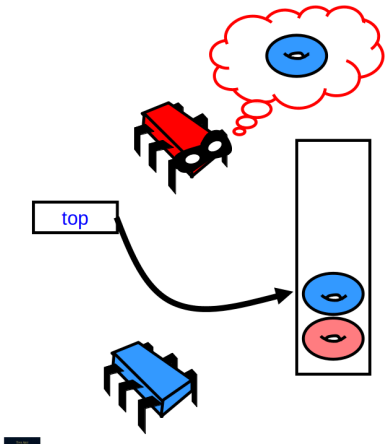

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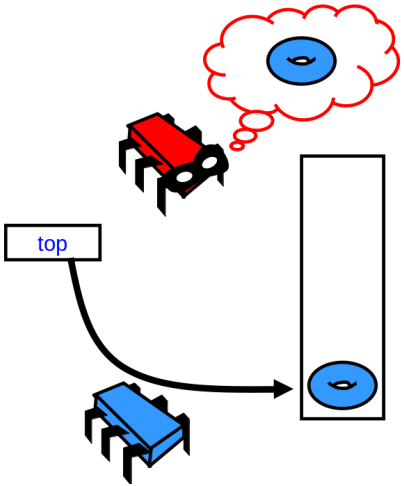

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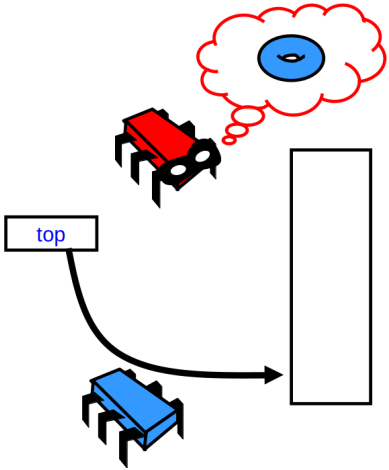

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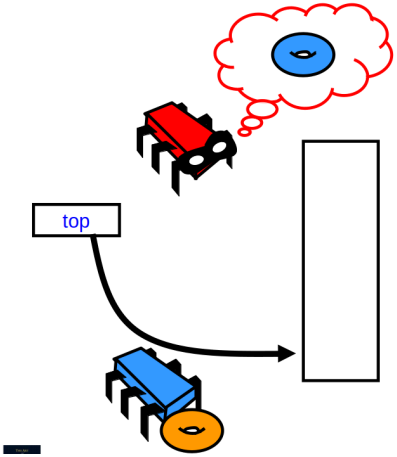

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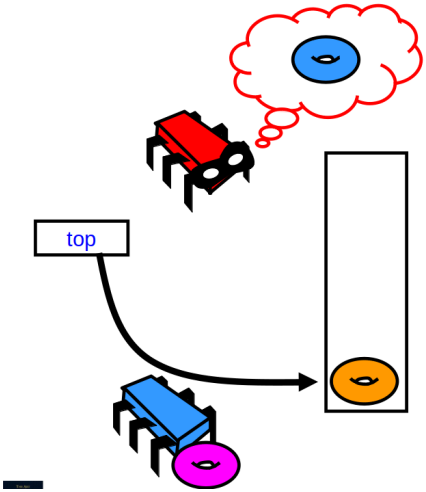

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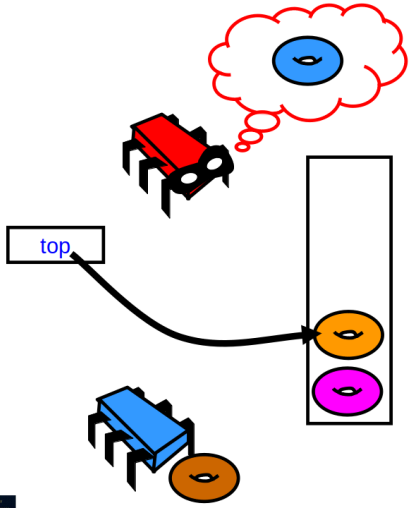

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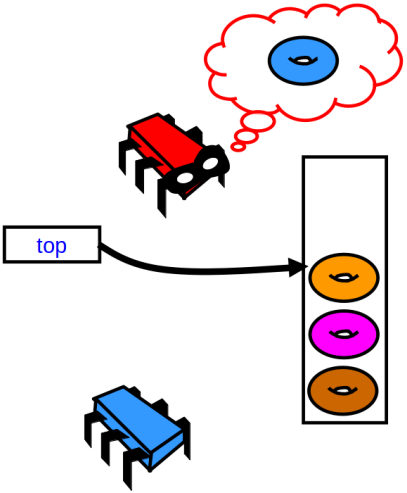

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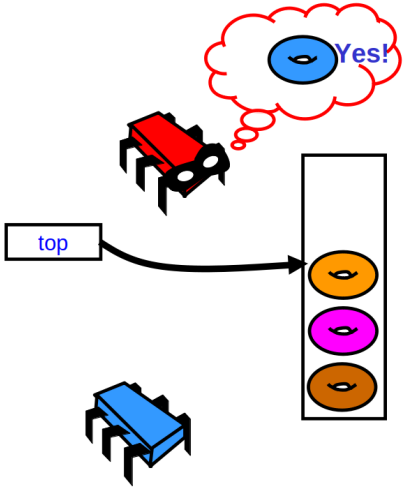

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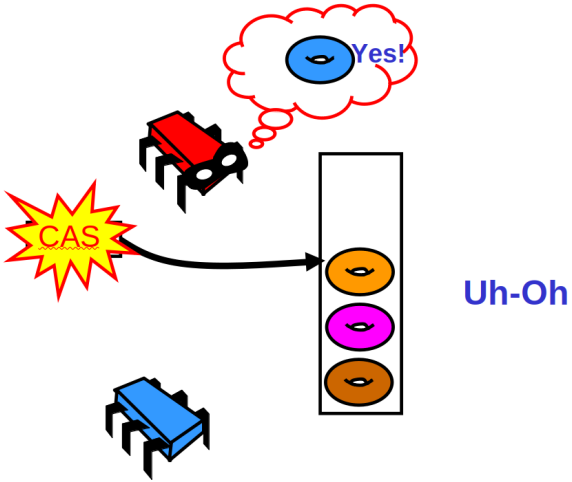
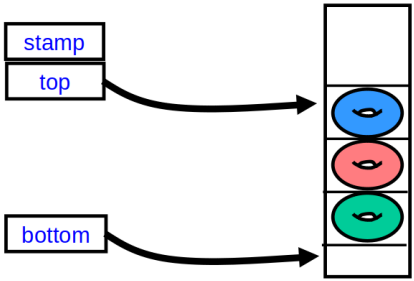


Fix for ABA problem



Bounded DEQueue

```
public class BDEQueue {
 AtomicStampedReference<Integer> top;
 volatile int bottom;
 Runnable[] tasks;
 …
}
```

Bounded DEQueue

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 AtomicStampedReference<Integer> top;
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 …
}
```
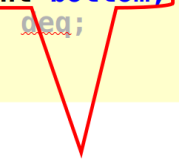

Index & Stamp
(synchronized)

Bounded DEQueue

```
public class BDEQueue {
 AtomicStampedReference<Integer> top;
 volatile int bottom;
 Runnable[] deq;
 …
}
```



index of bottom task
no need to synchronize
memory barrier needed

Bounded DEQueue

```
public class BDEQueue {
 AtomicStampedReference<Integer> top;
 volatile int bottom;
 Runnable[] tasks;
 …
}
```

Array holding tasks

pushBottom

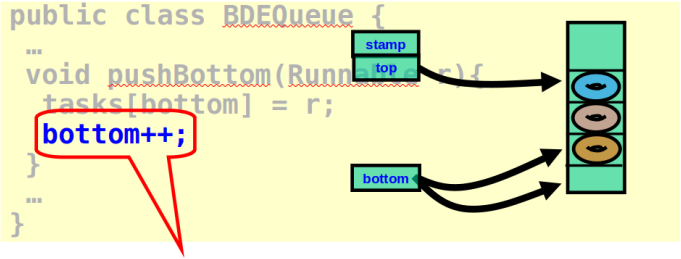
```
public class BDEQueue {
 …
 void pushBottom(Runnable r){
  tasks[bottom] = r;
  bottom++;
 }
 …
}
```

pushBottom

```
public class BDEQueue {
 …
 void pushBottom(Runnable r){
  tasks[bottom] = r;
  bottom++;
 }
 …
}
```

Bottom is the index to store the new task in the array

pushBottom


public class BDEQueue {
…
void pushBottom(Runnable r){
tasks[bottom] = r;
bottom++;
}
…
}
stamp
top
bottom
Adjust the bottom index

Steal work

```
public Runnable popTop() {
 int[] stamp = new int[1];
 int oldTop = top.get(stamp), newTop = oldTop + 1;
 int oldStamp = stamp[0], newStamp = oldStamp + 1;
 if (bottom <= oldTop)
   return null;
 Runnable r = tasks[oldTop];
 if (top.CAS(oldTop, newTop, oldStamp, newStamp))
  return r;
 return null;
 }
```

Steal work

```
public Runnable popTop() {
 int[] stamp = new int[1];
 int oldTop = top.get(stamp), newTop = oldTop + 1;
 int oldStamp = stamp[0], newStamp = oldStamp + 1;
 if (bottom <= oldTop)
   return null;
 Runnable r = tasks[oldTop];
 if (top.CAS(oldTop, newTop, oldStamp, newStamp))
  return r;
 return null;
 }
```

Read top (value & stamp)

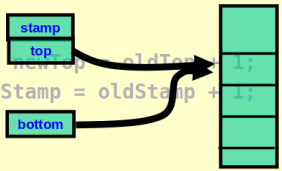
Steal work

```
public Runnable popTop() {
 int[] stamp = new int[1];
 int oldTop = top.get(stamp), newTop = oldTop + 1;
 int oldStamp = stamp[0], newStamp = oldStamp + 1;
 if (bottom <= oldTop)
   return null;
 Runnable r = tasks[oldTop];
 if (top.CAS(oldTop, newTop, oldStamp, newStamp))
  return r;
 return null;
 }
```

Compute new value & stamp

Steal work

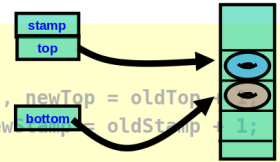
```
public Runnable popTop() {
 int[] stamp = new int[1];
 int oldTop = top.get(stamp), newTop = oldTop + 1;
 int oldStamp = stamp[0], newStamp = oldStamp + 1;
if (bottom <= oldTop)
  return null;
 Runnable r = tasks[oldTop];
 if (top.CAS(oldTop, newTop, oldStamp, newStamp))
  return r;
 return null;
 }
```



Quit if queue is empty

Steal work

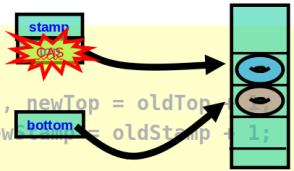
```
public Runnable popTop() {
 int[] stamp = new int[1];
 int oldTop = top.get(stamp), newTop = oldTop + 1;
 int oldStamp = stamp[0], newStamp = oldStamp + 1;
 if (bottom <= oldTop)
   return null;
 Runnable r = tasks[oldTop];
 if (top.CAS(oldTop, newTop, oldStamp, newStamp))
   return r;
 return null;
 }
```



Try to steal the task

Steal work

```
public Runnable popTop() {
 int[] stamp = new int[1];
 int oldTop = top.get(stamp), newTop = oldTop + 1;
 int oldStamp = stamp[0], newStamp = oldStamp + 1;
 if (bottom <= oldTop)
   return null;
 Runnable r = tasks[oldTop];
 if (top.CAS(oldTop, newTop, oldStamp, newStamp))
  return r;
 return null;
 }
```



Try to steal the task

Steal work


public Runnable popTop() {
int[] stamp = new int[1];
int oldTop = top.get(stamp), newTop = oldTop + 1;
int oldStamp = stamp[0], newStamp = oldStamp + 1;
if (bottom <= oldTop)
return null;
Runnable r = tasks[oldTop];
if (top.CAS(oldTop, newTop, oldStamp, newStamp))
return r;
return null;
}
stamp
CAS
bottom
Try to steal the task

Steal work

```
public Runnable popTop() {
 int[] stamp = new int[1];
 int oldTop = top.get(stamp), newTop = oldTop + 1;
 int oldStamp = stamp[0], newStamp = oldStamp + 1;
 if (bottom <= oldTop)
   return null;
 Runnable r = tasks[oldTop];
 if (top.CAS(oldTop, newTop, oldStamp, newStamp))
   return r;
return null;
}
```

Give up if conflict occurs

Take work

```
Runnable popBottom() {
 if (bottom == 0) return null;
 bottom--;
 Runnable r = tasks[bottom];
 int[] stamp = new int[1];
 int oldTop = top.get(stamp), newTop = 0;
 int oldStamp = stamp[0], newStamp = oldStamp + 1;
 if (bottom > oldTop) return r;
 if (bottom == oldTop){
   bottom = 0;
   if (top.CAS(oldTop, newTop, oldStamp, newStamp))
     return r;
   }
 top.set(newTop,newStamp); return null;
 bottom = 0; }
```

Take work

```
Runnable popBottom() {
if (bottom == 0) return null;
bottom--;
Runnable r = tasks[bottom];
int[] stamp = new int[1];
int oldTop = top.get(stamp), newTop = 0;
int oldStamp = stamp[0], newStamp = oldStamp + 1;
if (bottom > oldTop) return r;
if (bottom == oldTop){
  bottom = 0;
  if (top.CAS(oldTop, newTop, oldStamp, newStamp))
    return r;
  }
top.set(newTop,newStamp); return null;
bottom = 0; }
```

Make sure queue is non-empty

Take work

```
Runnable popBottom() {
 if (bottom == 0) return null;
 bottom--;
 Runnable r = tasks[bottom];
 int[] stamp = new int[1];
 int oldTop = top.get(stamp), newTop = 0;
 int oldStamp = stamp[0], newStamp = oldStamp + 1;
 if (bottom > oldTop) return r;
 if (bottom == oldTop){
   bottom = 0;
   if (top.CAS(oldTop, newTop, oldStamp, newStamp))
     return r;
   }
 top.set(newTop,newStamp); return null;
 bottom = 0; }
```

Prepare to grab bottom task

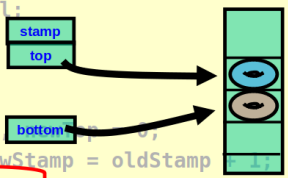
Take work

```
Runnable popBottom() {
 if (bottom == 0) return null;
 bottom--;
 Runnable r = tasks[bottom];
 int[] stamp = new int[1];
 int oldTop = top.get(stamp), newTop = 0;
 int oldStamp = stamp[0], newStamp = oldStamp + 1;
 if (bottom > oldTop) return r;
 if (bottom == oldTop){
   bottom = 0;
   if (top.CAS(oldTop, newTop, oldStamp, newStamp))
     return r;
   }
 top.set(newTop,newStamp); return null;
 bottom = 0; }
```

Read top, & prepare new values

Take work

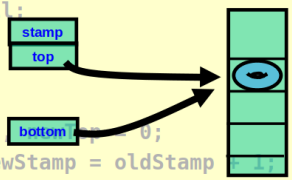
```
Runnable popBottom() {
 if (bottom == 0) return null;
 bottom--;
 Runnable r = tasks[bottom];
 int[] stamp = new int[1];
 int oldTop = top.get(stamp)
 int oldStamp = stamp[0], newStamp = oldStamp
if (bottom > oldTop) return r;
 if (bottom == oldTop){
   bottom = 0;
   if (top.CAS(oldTop, newTop, oldStamp, newStamp))
top.set(newTop,ne                    null;
 bottom = 0;}
```



If top & bottom one or more apart, no conflict

Take work

```
Runnable popBottom() {
 if (bottom == 0) return null;
 bottom--;
 Runnable r = tasks[bottom];
 int[] stamp = new int[1];
 int oldTop = top.get(stamp);
 int oldStamp = stamp[0], newStamp = oldStamp + 1;
 if (bottom > oldTop) return r;
 if (bottom == oldTop){
   bottom = 0;
   if (top.CAS(oldTop, newTop, oldStamp, newStamp))
     return r;
   }
 top.set(newTop,newStamp); return null;
 bottom = 0;}
```



At most one item left

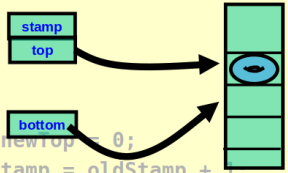
Take work

Try to steal last task.
Reset `bottom` because the DEQueue will be empty even if unsuccessful (why?)

```
int oldStamp = stamp[0], newStamp = oldStamp + 1;
if (bottom > oldTop) return r;
if (bottom == oldTop){
  bottom = 0;
  if (top.CAS(oldTop, newTop, oldStamp, newStamp))
    return r;
  }
top.set(newTop,newStamp); return null;
bottom = 0;}
```

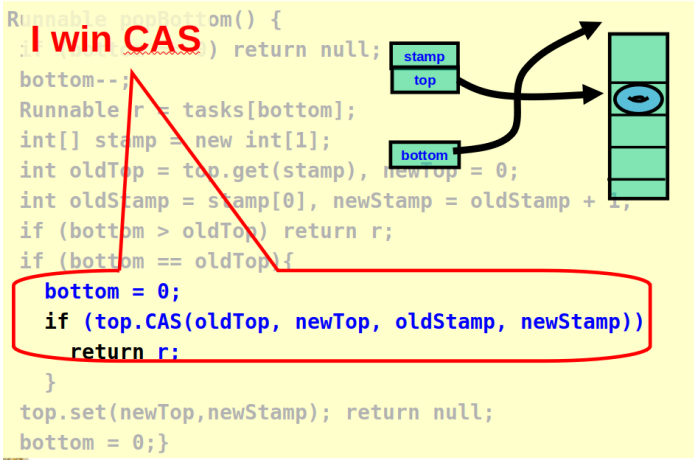
Take work

I win CAS

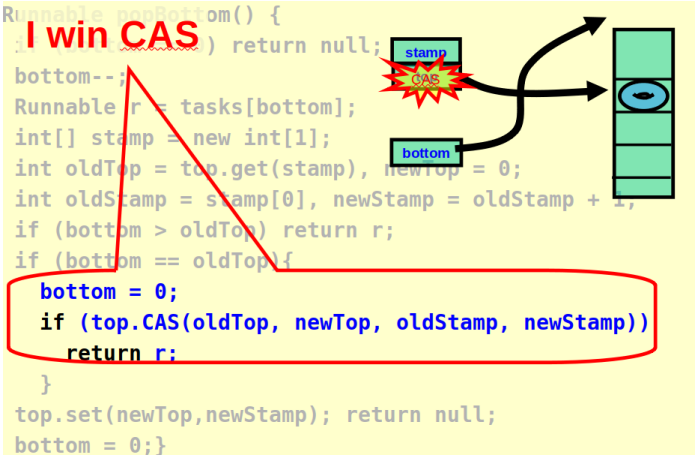



```
Runnable popBottom() {
  if (bottom == 0) return null;
  bottom--;
  Runnable r = tasks[bottom];
  int[] stamp = new int[1];
  int oldTop = top.get(stamp), newTop = 0;
  int oldStamp = stamp[0], newStamp = oldStamp + 1;
  if (bottom > oldTop) return r;
  if (bottom == oldTop){
    bottom = 0;
    if (top.CAS(oldTop, newTop, oldStamp, newStamp))
      return r;
    }
  top.set(newTop,newStamp); return null;
  bottom = 0;}
```

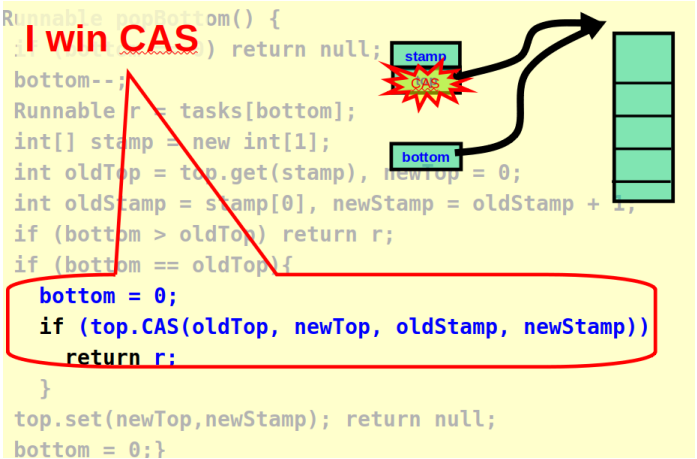
Take work


I win CAS
stamp
top
bottom
Runnable popBottom() {
) return null;
bottom--;
Runnable r = tasks[bottom];
int[] stamp = new int[1];
int oldTop = top.get(stamp), newTop = 0;
int oldStamp = stamp[0], newStamp = oldStamp + 1;
if (bottom > oldTop) return r;
if (bottom == oldTop){
bottom = 0;
if (top.CAS(oldTop, newTop, oldStamp, newStamp))
return r;
}
top.set(newTop,newStamp); return null;
bottom = 0;}

Take work

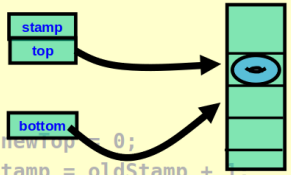

I win CAS
stamp
CAS
bottom
Runnable popBottom() {
if (bottom == 0) return null;
bottom--;
Runnable r = tasks[bottom];
int[] stamp = new int[1];
int oldTop = top.get(stamp), newTop = 0;
int oldStamp = stamp[0], newStamp = oldStamp + 1;
if (bottom > oldTop) return r;
if (bottom == oldTop){
bottom = 0;
if (top.CAS(oldTop, newTop, oldStamp, newStamp))
return r;
}
top.set(newTop,newStamp); return null;
bottom = 0;}

Take work


I win CAS
stamp
CAS
bottom
Runnable popBottom() {
) return null;
bottom--;
Runnable r = tasks[bottom];
int[] stamp = new int[1];
int oldTop = top.get(stamp), newTop = 0;
int oldStamp = stamp[0], newStamp = oldStamp + 1;
if (bottom > oldTop) return r;
if (bottom == oldTop){
bottom = 0;
if (top.CAS(oldTop, newTop, oldStamp, newStamp))
return r;
}
top.set(newTop,newStamp); return null;
bottom = 0;}

Take work

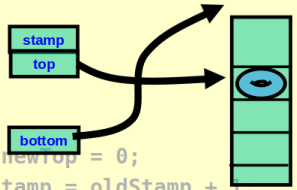
If I lose CAS, thief must have won…




```
Runnable popBottom() {
                                          ull;
 Runnable r = tasks[bottom];
 int[] stamp = new int[1];
 int oldTop = top.get(stamp), newTop = 0;
 int oldStamp = stamp[0], newStamp = oldStamp + 1;
 if (bottom > oldTop) return r;
 if (bottom == oldTop){
   bottom = 0;
   if (top.CAS(oldTop, newTop, oldStamp, newStamp))
     return r;
   }
 top.set(newTop,newStamp); return null;
 bottom = 0;}
```

Take work

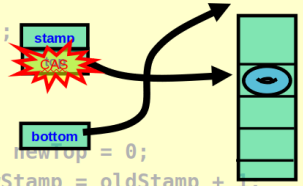
If I lose CAS, thief must have won…




```
Runnable popBottom() {
                                          ull;
 Runnable r = tasks[bottom];
 int[] stamp = new int[1];
 int oldTop = top.get(stamp), newTop = 0;
 int oldStamp = stamp[0], newStamp = oldStamp + 1;
 if (bottom > oldTop) return r;
 if (bottom == oldTop){
   bottom = 0;
   if (top.CAS(oldTop, newTop, oldStamp, newStamp))
     return r;
   }
 top.set(newTop,newStamp); return null;
 bottom = 0;}
```

Take work

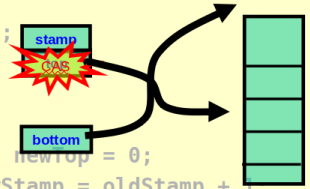
If I lose CAS, thief must have won…




```
Runnable popBottom() {
  Runnable r = tasks[bottom];
  int[] stamp = new int[1];
  int oldTop = top.get(stamp), newTop = 0;
  int oldStamp = stamp[0], newStamp = oldStamp + 1;
  if (bottom > oldTop) return r;
  if (bottom == oldTop){
    bottom = 0;
    if (top.CAS(oldTop, newTop, oldStamp, newStamp))
      return r;
    }
  top.set(newTop,newStamp); return null;
  bottom = 0;}
```

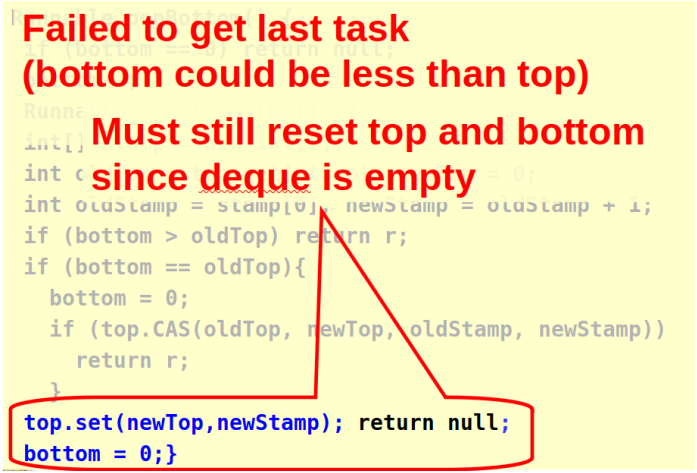
Take work

If I lose CAS, thief must have won…




```
Runnable popBottom() {
if (bottom-oldTop) return null;
Runnable r = tasks[bottom];
int[] stamp = new int[1];
int oldTop = top.get(stamp), newTop = 0;
int oldStamp = stamp[0], newStamp = oldStamp + 1;
if (bottom > oldTop) return r;
if (bottom == oldTop){
  bottom = 0;
  if (top.CAS(oldTop, newTop, oldStamp, newStamp))
    return r;
  }
top.set(newTop,newStamp); return null;
bottom = 0;}
```

Take work


Failed to get last task
(bottom could be less than top)
Must still reset top and bottom
since deque is empty
int oldStamp = stamp[0]; newStamp = oldStamp + 1;
if (bottom > oldTop) return r;
if (bottom == oldTop){
bottom = 0;
if (top.CAS(oldTop, newTop, oldStamp, newStamp))
return r;
top.set(newTop,newStamp); return null;
bottom = 0;}

Work stealing and balancing

- Trade-offs: fast-path/slow-path, FIFO/LIFO, lock-free/obstruction-free, steal size

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Work stealing and balancing

- Trade-offs: fast-path/slow-path, FIFO/LIFO, lock-free/obstruction-free, steal size
- Clean separation between app and scheduling layer
- Works well when number of processors fluctuates
- Works on "black-box" operating systems

Summary

Queues are quite universal construct:

- Concurrency control (mutex, latch, semaphore)
- Data transfer
- Load balancing

Design space:

- Strong FIFO, per-producer FIFO, best-effort FIFO
- SPSC, MPSC, SPMC, MPMC
- Bounded, unbounded
- Total, partial, synchronous methods
- Wait-free/lock-free/blocking enqueuers/dequeuers

Load balancing using DoubleEndedQueue

- bottom-oriented LIFO for local tasks
- top-oriented work-stealing