Lock-Free Programming: Pro Tips

Jean-Philippe BEMPEL
Performance Architect

@jpbempel
http://jpbempel.blogspot.com

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CONNECT. TRADE.

Agenda

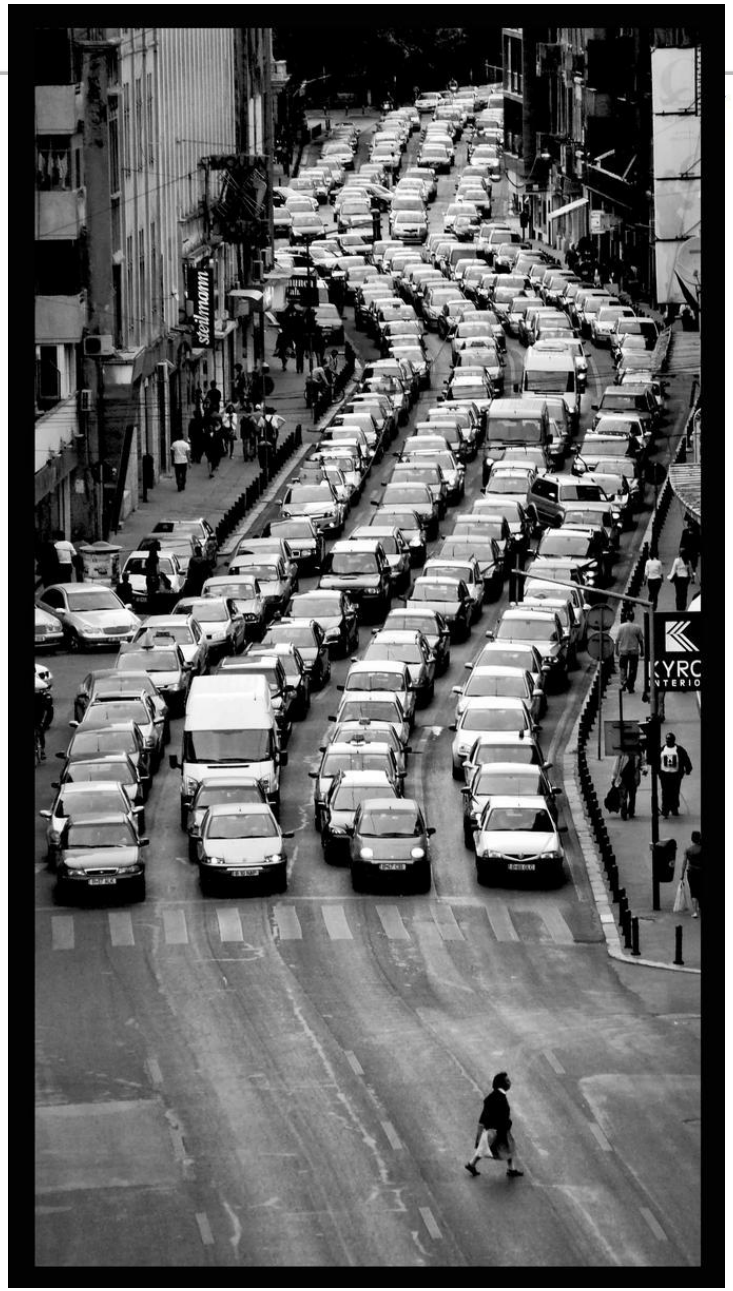
- Measuring Contention
- Lock Striping
- Compare-And-Swap
- Introduction to Java Memory Model
- Disruptor & RingBuffer
- Spinning
- Ticketing: OrderedScheduler

Immutability

Contention

Contention

- Two or more thread competing to acquire a lock
- Thread parked when waiting for a lock
- Number one reason we want to avoid lock



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Measure, don’t guess!

Kirk Pepperdine & Jack Shirazi

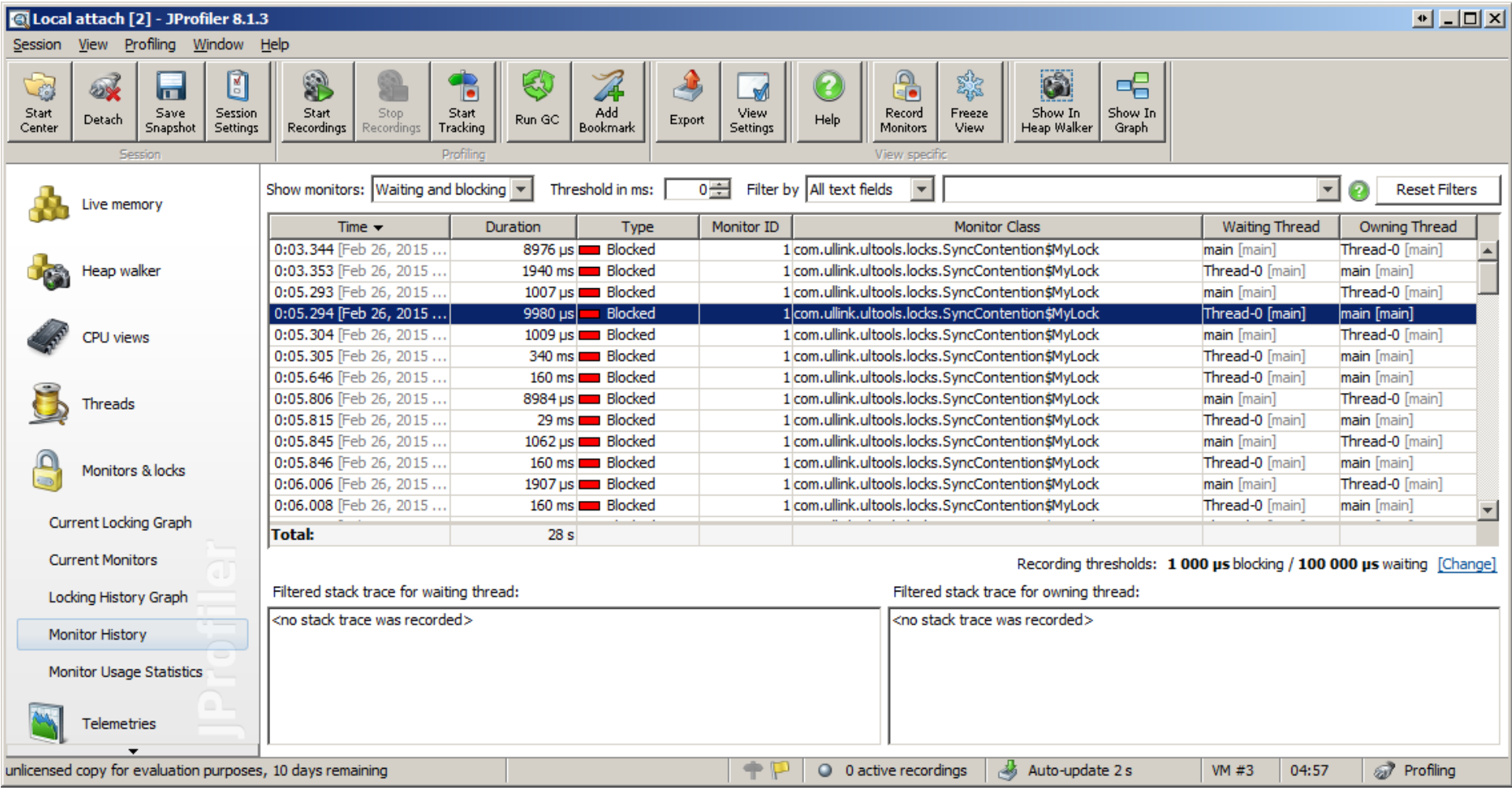
Measure, don’t premature!

Measuring Contention

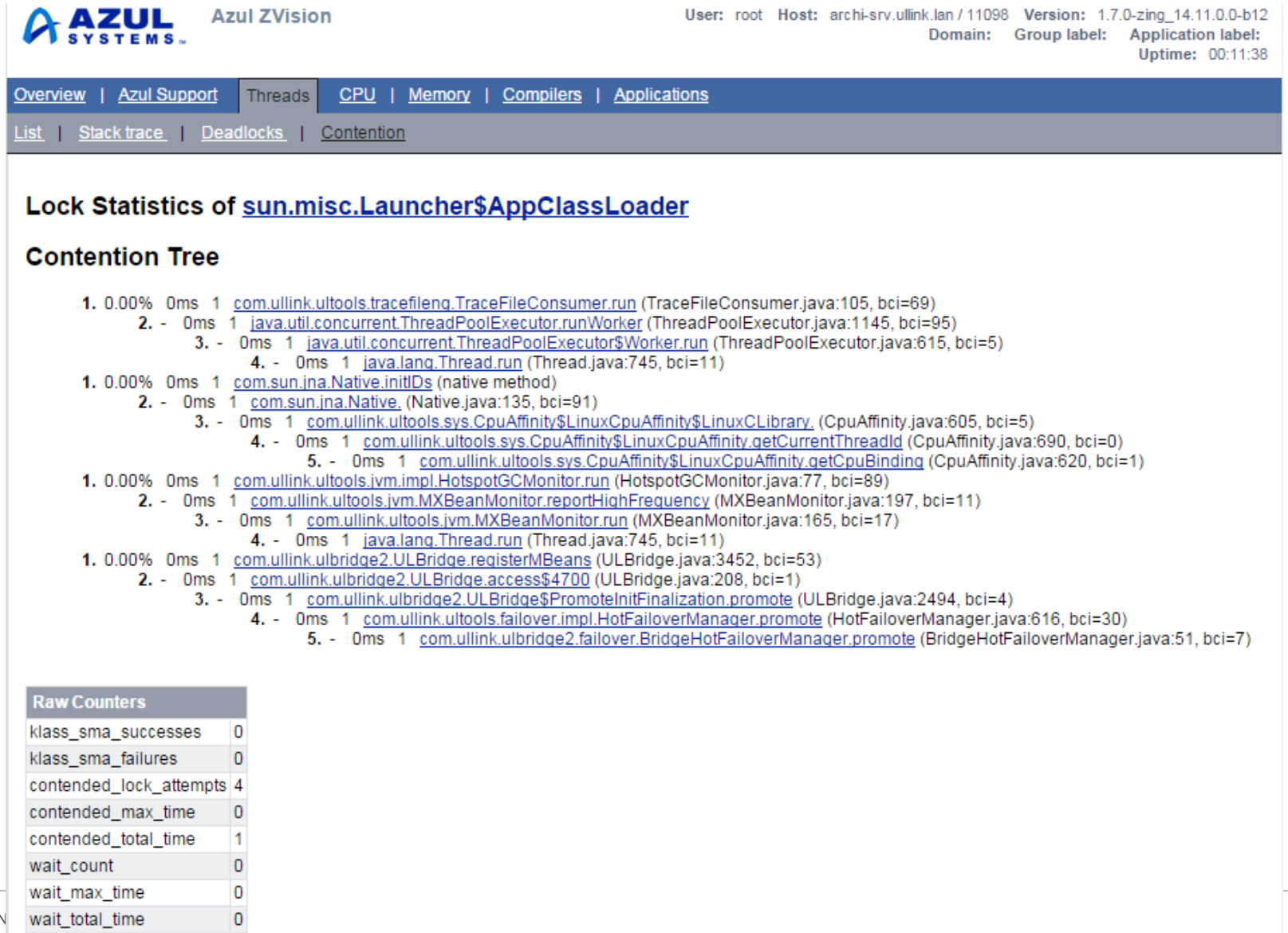
Synchronized blocks:

- Profilers (YourKit, JProfiler, ZVision)
- JVMTI native agent
- Results may be difficult to exploit

Measuring Contention: JProfiler



Measuring Contention: ZVision

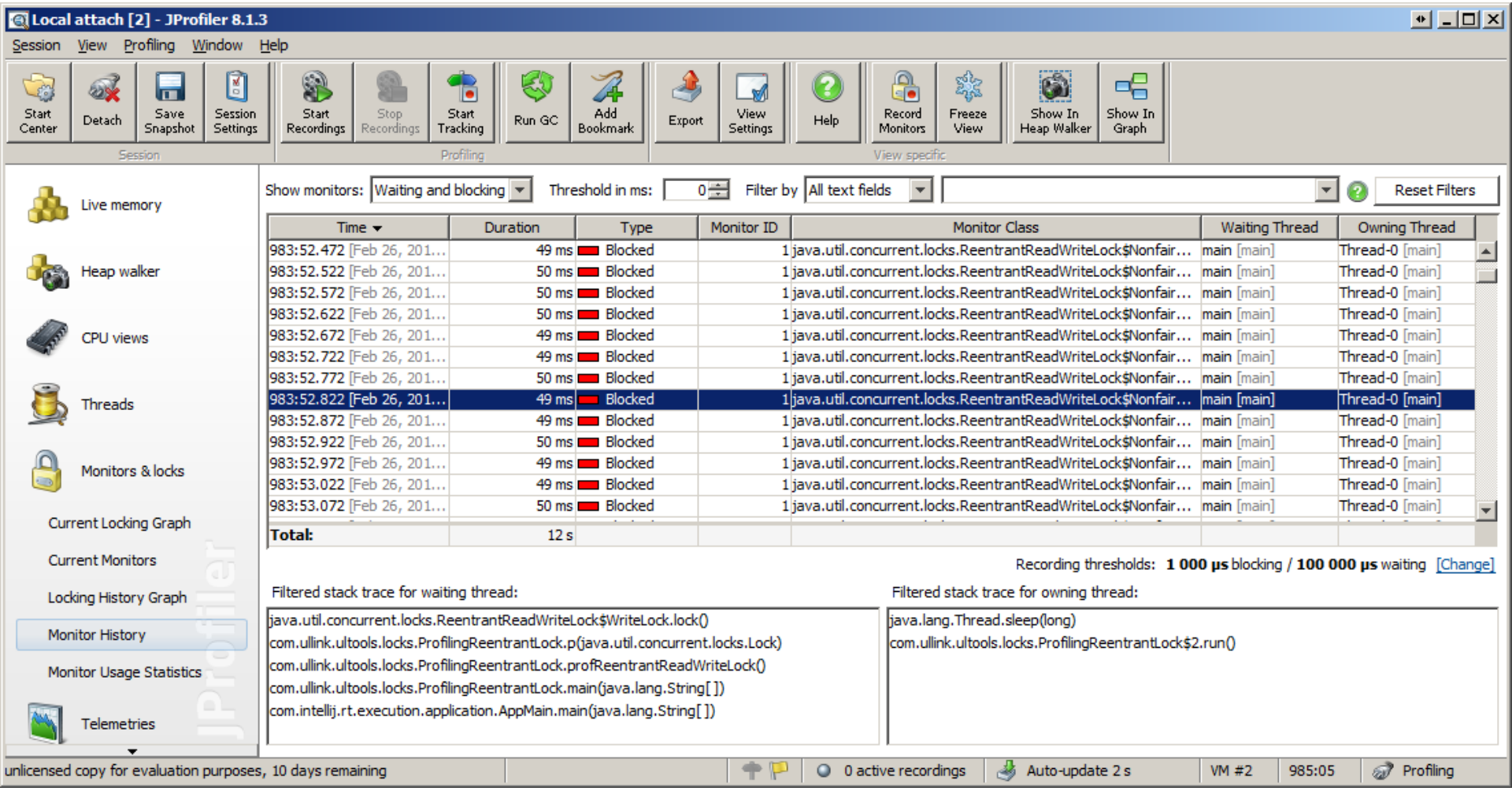


Measuring Contention

java.util.concurrent.Lock:

- JVM cannot helps us here
- JDK classes (lib), regular code
- JProfiler can measure them
- j.u.c classes modification + bootclasspath (jucprofiler)

Measuring Contention: JProfiler



Measuring Contention

- Insertion of contention counters
  - Identify place where lock fail to be acquired
  - increment counter
- Identify Locks
  - Call stacks at construction
  - Logging counter status
- How to measure existing locks in your code
  - Modify JDK classes
  - Reintroduce in bootclasspath

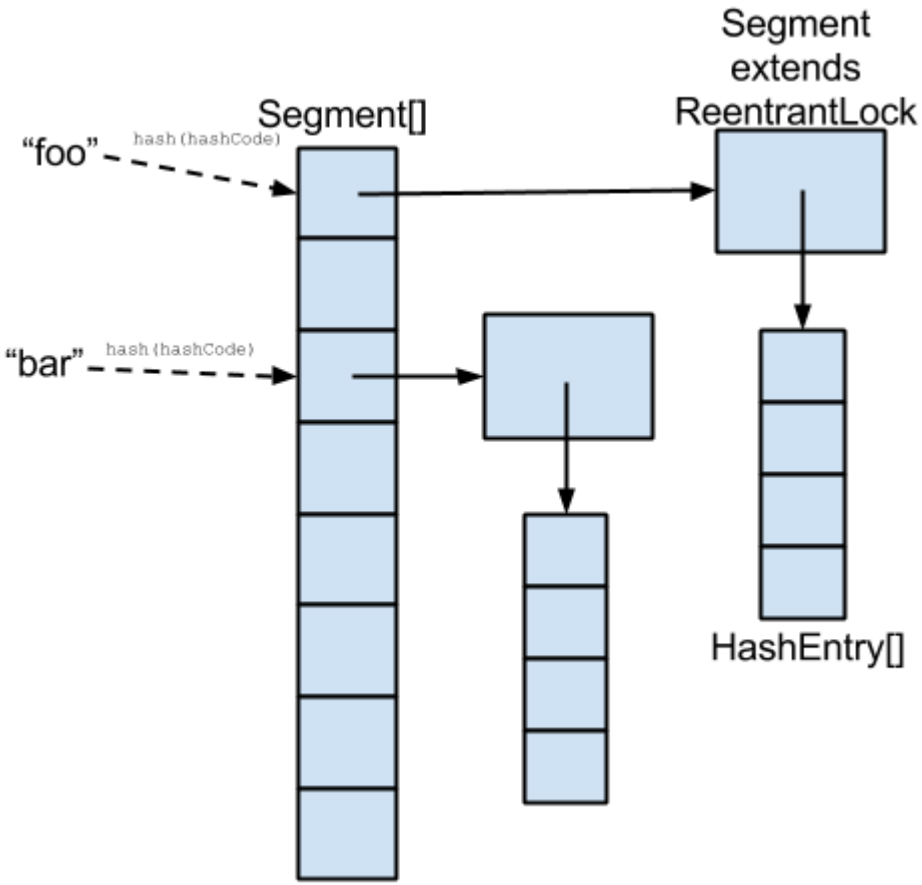
Lock striping

Lock striping

- Reduce contention by distributing it
- Not remove locks, instead adding more
- Good partitioning is key to be effective (like HashMap)

Lock striping

Best example in JDK: ConcurrentHashMap



Lock striping

- Relatively easy to implement
- Can be very effective as long as good partitioning
- Can be tuned (number of partition) regarding the contention/concurrency level

Compare-And-Swap

Compare-And-Swap

- Basic primitive for any lock-free algorithm
- Used to implement any locks or synchronization primitives
- Handled directly by the CPU (instructions)

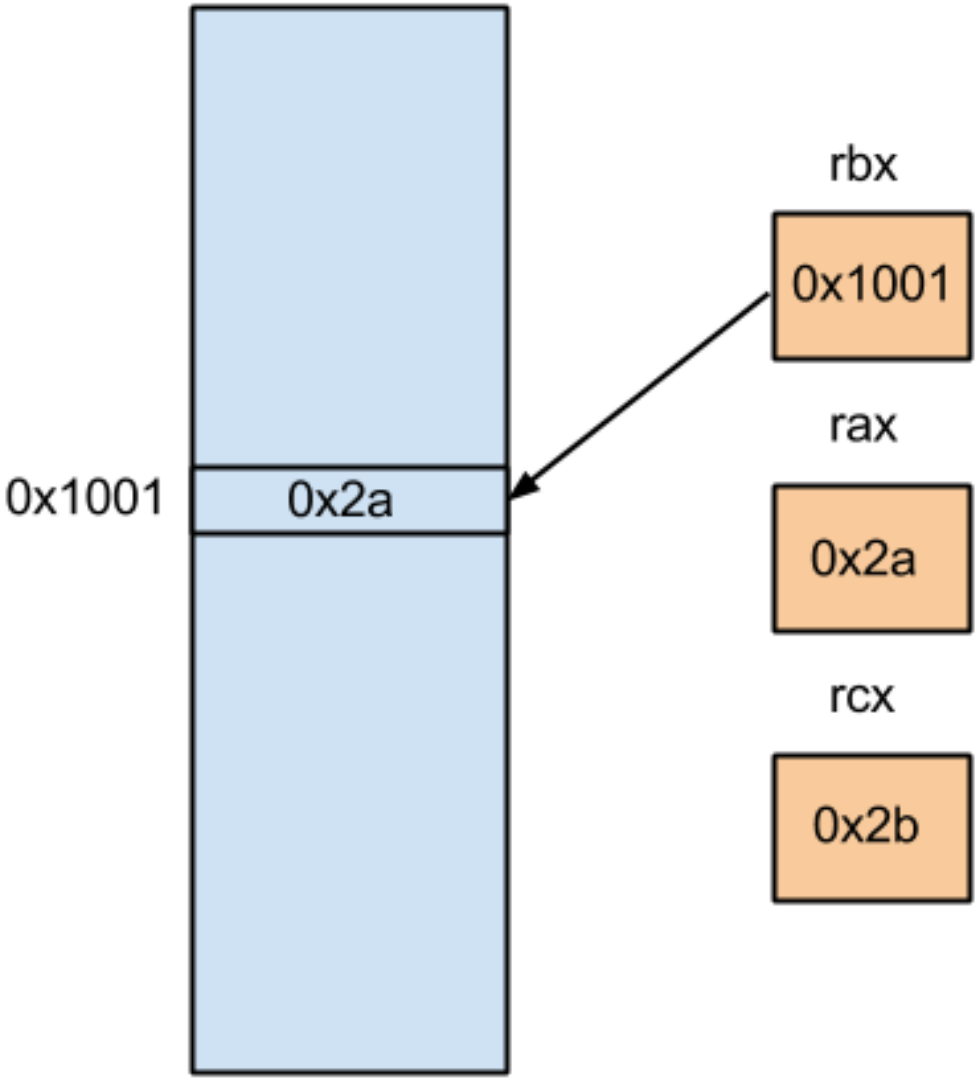
Compare-And-Swap

- Update atomically a memory location by another value if the previous value is the expected one

- instruction with 3 arguments:
  - memory address (rbx)
  - expected value (rax)
  - new value (rcx)

```
movabs rax,0x2a
movabs rcx,0x2b
lock cmpxchg QWORD PTR [rbx],rcx
```

Compare-And-Swap



Compare-And-Swap

- In Java for AtomicXXX classes:

  ```
  boolean compareAndSet(long expect, long update)
  ```

- Memory address is the internal `value` field of the class

Compare-And-Swap: AtomicLong

- Atomic increment with CAS
  [JDK7] getAndIncrement():

```
while (true) {
    long current = get();
    long next = current + 1;
    if (compareAndSet(current, next))
        return current;
}
```

  [JDK8] getAndIncrement():

```
return unsafe.getAndAddLong(this, valueOffset, 1L);
```

  intrinsified to:

```
movabs rsi,0x1
lock xadd QWORD PTR [rdx+0x10],rsi
```

Compare-And-Swap: Lock implementation

ReentrantLock is implemented with a CAS:

```
volatile int state;

lock()
  compareAndSet(0, 1);
```

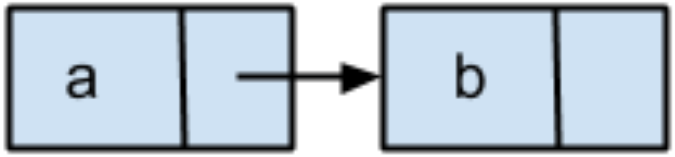
if CAS fails => lock already acquired

```
unlock()
  setState(0)
```

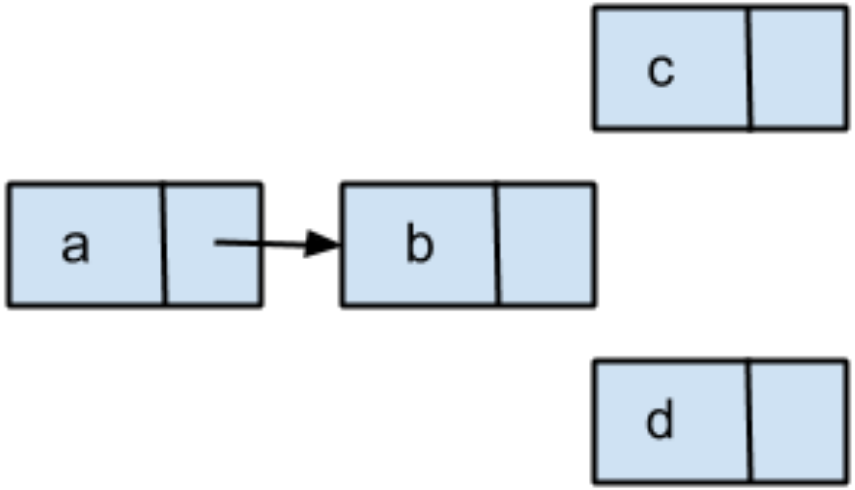
Compare-And-Swap: ConcurrentLinkedQueue

- Simplest lock-free algorithm
- Use CAS to update the next pointer into a linked list
- if CAS fails, means concurrent update happened
- Read new value, go to next item and retry CAS

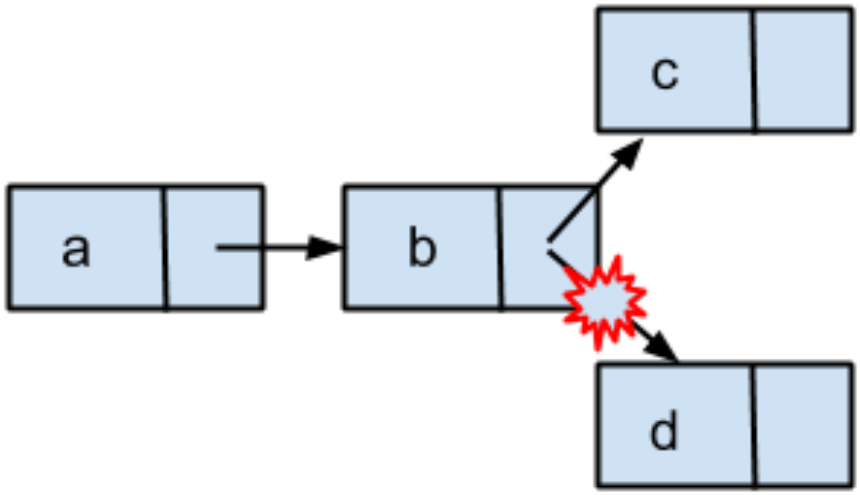
Compare-And-Swap: ConcurrentLinkedQueue



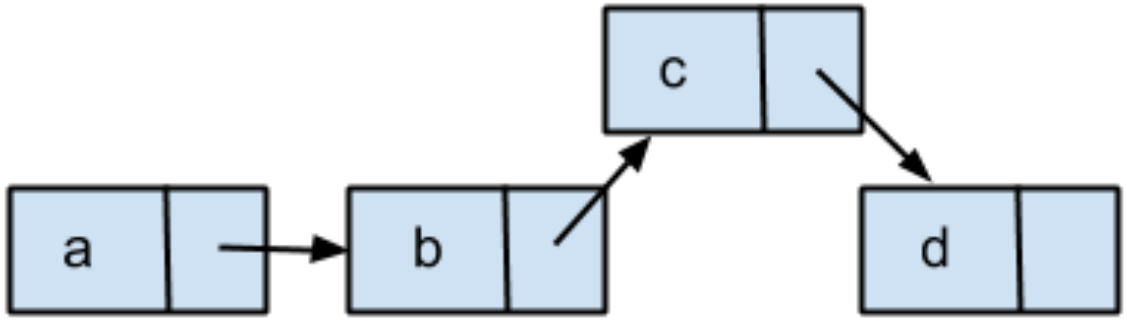
Compare-And-Swap: ConcurrentLinkedQueue



Compare-And-Swap: ConcurrentLinkedQueue



Compare-And-Swap: ConcurrentLinkedQueue



Java Memory Model (introduction)

Memory Model

- First language having a well defined memory model:
  Java JDK 5 (2004) with JSR 133
- C++ get a standard Memory Model in 2011 (C++11)
- Before that, some constructions may have undefined/different behavior on different platform (Double Check Locking)

Memory ordering

```
int a;
int b;
boolean enabled;
```

```
{
    a = 21;
    b = a * 2;
    enabled = true;
}
```

JIT Compiler

```
{
    enabled = true;
    a = 21;
    b = a * 2;
}
```

Memory ordering

```
int a;
int b;
boolean enabled;
```

Thread 1

```
{
    a = 21;
    b = a * 2;
    enabled = true;
}
```

Thread 2

```
{
    if (enabled)
    {
        int answer = b
        process(answer);
    }
}
```

Memory ordering

```
int a;
int b;
volatile boolean enabled;
```

Thread 1

```
{
    a = 21;
    b = a * 2;
    enabled = true;
}
```

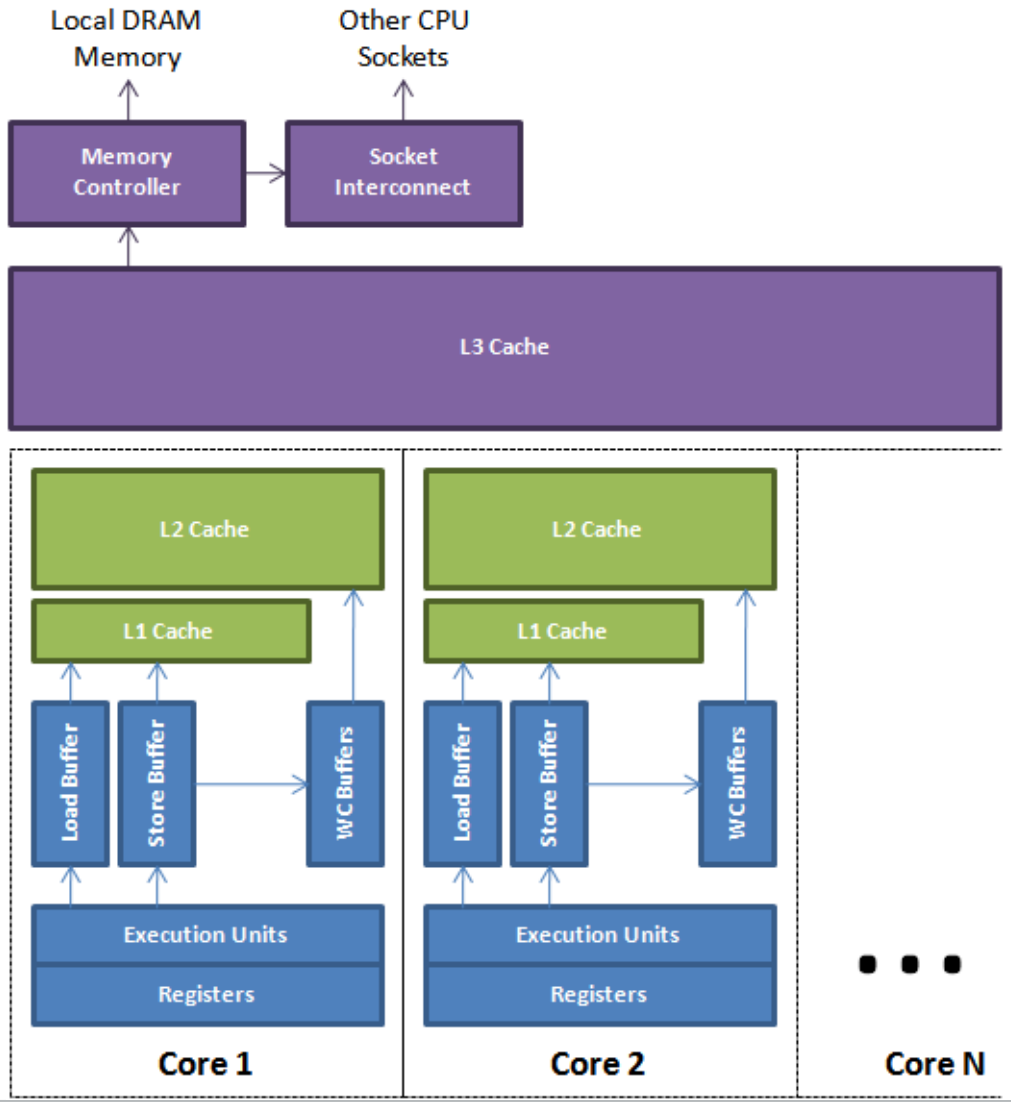
Thread 2

```
{
    if (enabled)
    {
        int answer = b
        process(answer);
    }
}
```

Memory barriers

- Can be at 2 levels: Compiler & Hardware
- Depending on CPU architecture, barrier is not required
- on x86: Strong model, limited reordering

Memory barriers



Memory barriers: volatile

- volatile field implies memory barrier
- Compiler barrier: prevent reordering
- Hardware barrier: Ensure drain of the memory buffers
- on X86, only store barrier emits an hardware one

```
lock add DWORD PTR [rsp],0x0
```

Memory barriers: CAS

- CAS is also a memory barrier
- Compiler: recognized by JIT to prevent reordering
- Hardware: all lock instructions is a memory barrier

Memory barriers: synchronized

- Synchronized blocks have implicit memory barriers
- Entering block: Load memory barrier
- Exiting block: store memory barrier

Memory barriers: synchronized

```
synchronized (this)
{
    enabled = true;
    b = 21;
    a = b * 2;
}
```

Memory barriers: lazySet

- method from AtomicXXX classes
- Compiler only memory barrier
- Does not emit hardware store barrier
- Still guarantee non reordering (most important) but not immediate effect for other thread

Disruptor & Ring Buffer

Disruptor

- LMAX library (incl. Martin Thompson)
- Not a new idea, circular buffers in Linux Kernel, Lamport
- Ported to Java

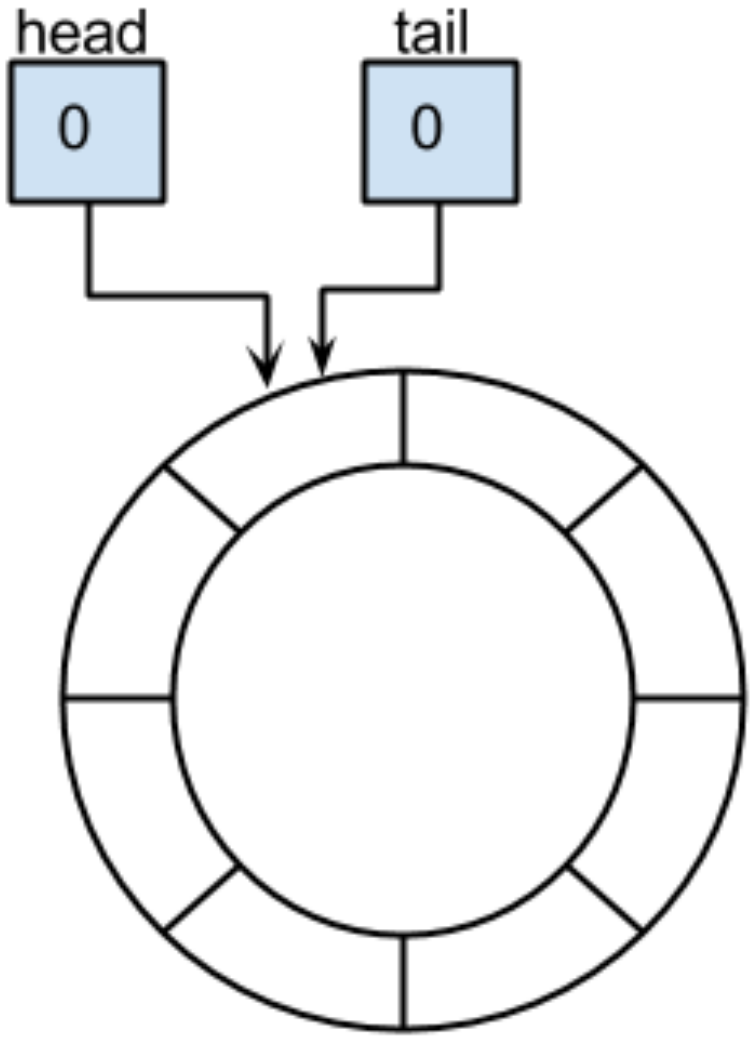
Disruptor

Why not used CLQ which is lock(wait)-free?

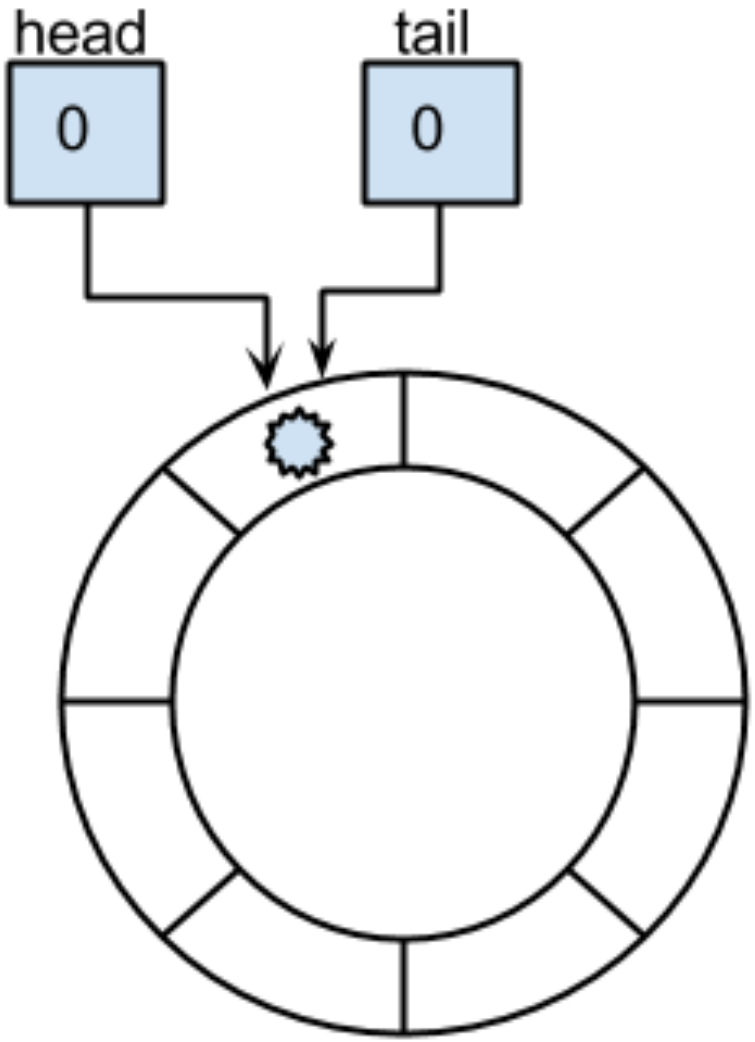
- Queue unbounded et non blocking
- Allocate a node at each insertion
- Not CPU cache friendly
- MultiProducer and MultiConsumer

Array/LinkedBlockingQueue: Not lock-free

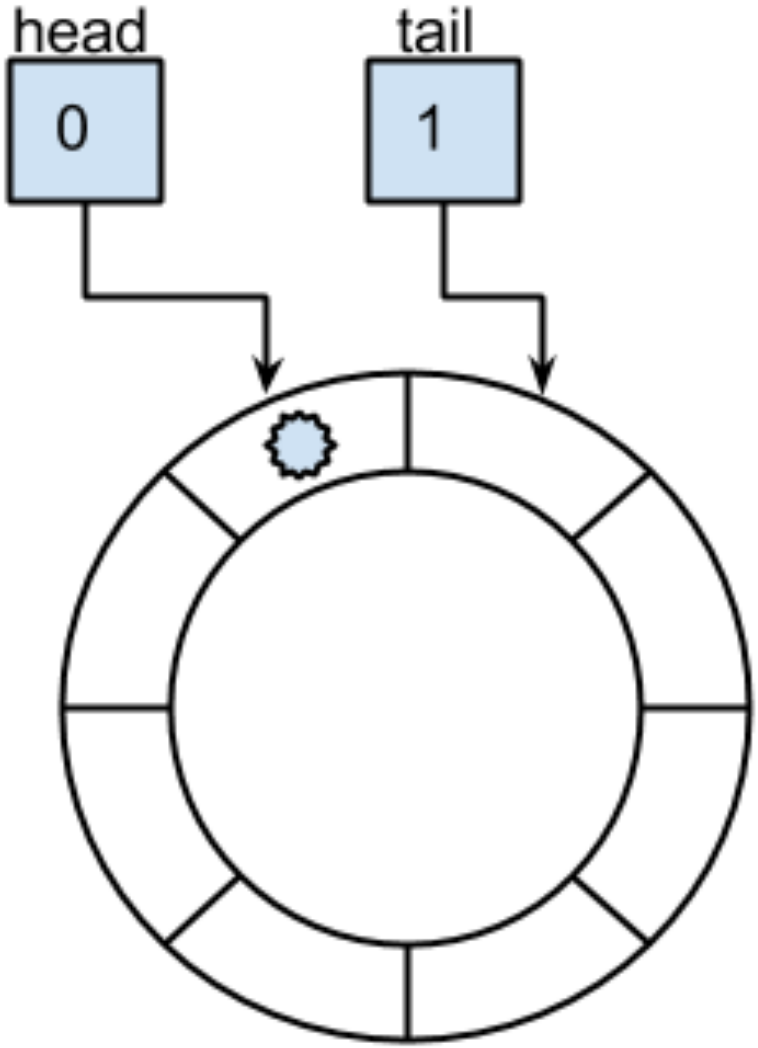
Ring Buffer: 1P 1C



Ring Buffer: 1P 1C



Ring Buffer: 1P 1C



Ring Buffer: 1P 1C

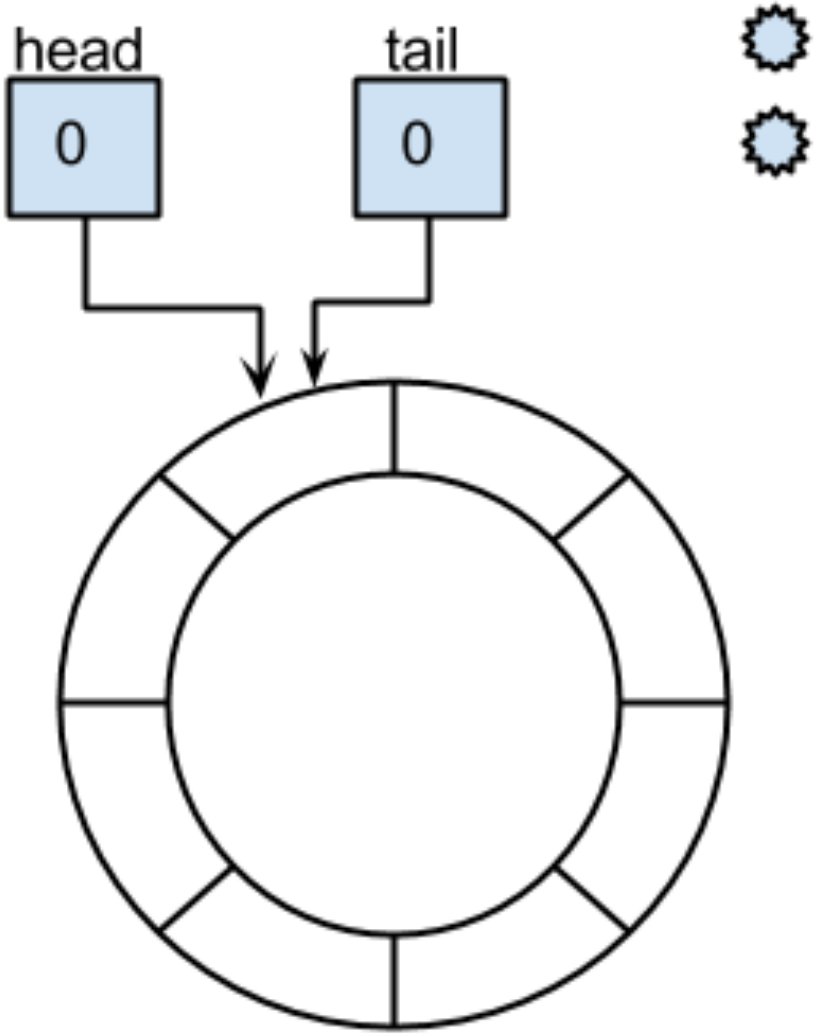
```
Object[] ringBuffer;
volatile int head;
volatile int tail;

public boolean offer(E e) {
    if (tail - head == ringBuffer.length)
        return false;
    ringBuffer[tail % ringBuffer.length] = e;
    tail++; // volatile write
    return true;
}
```

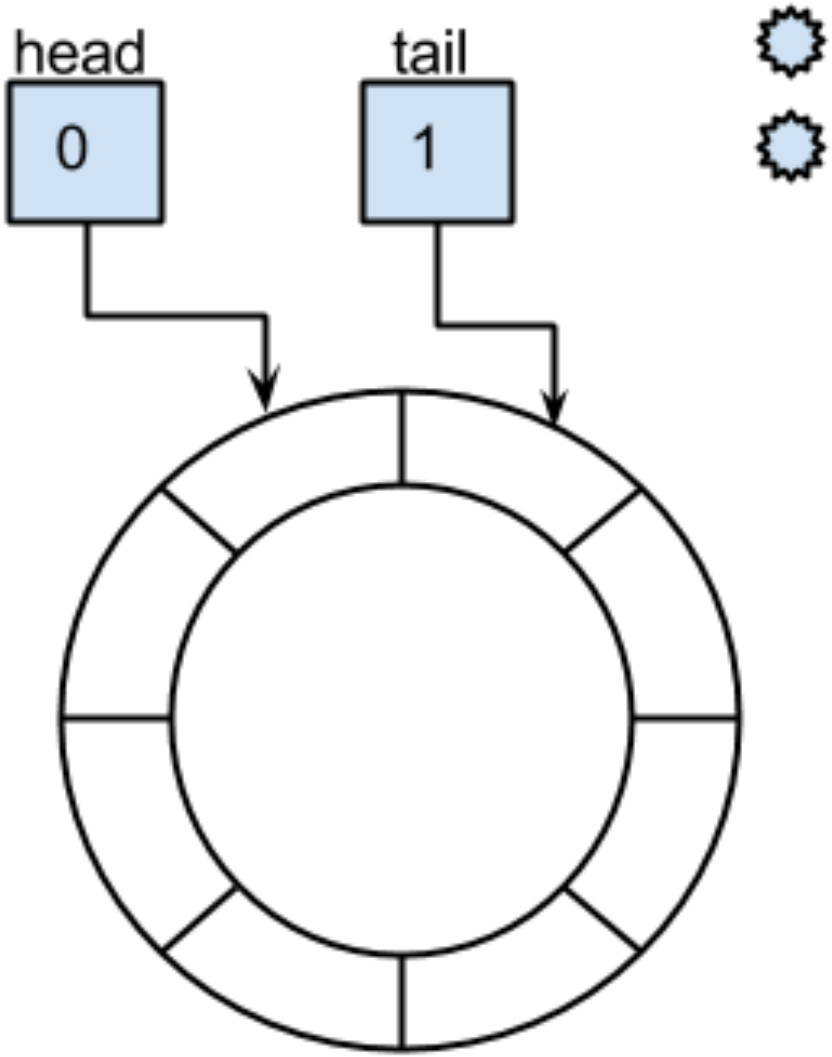
Ring Buffer: 1P 1C

```
public E poll() {
    if (tail == head)
        return null;
    int idx = head % ringBuffer.length
    E element = ringBuffer[idx];
    ringBuffer[idx] = null;
    head++; // volatile write
    return element;
}
```

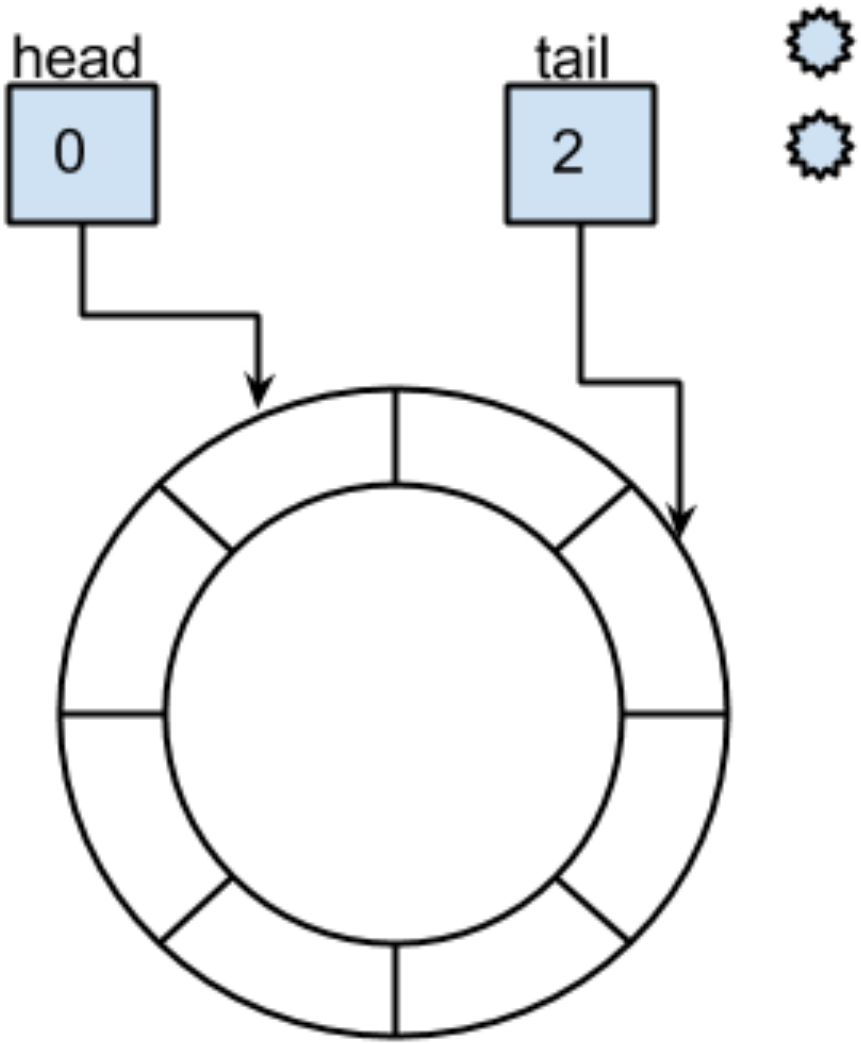
Ring Buffer: nP 1C



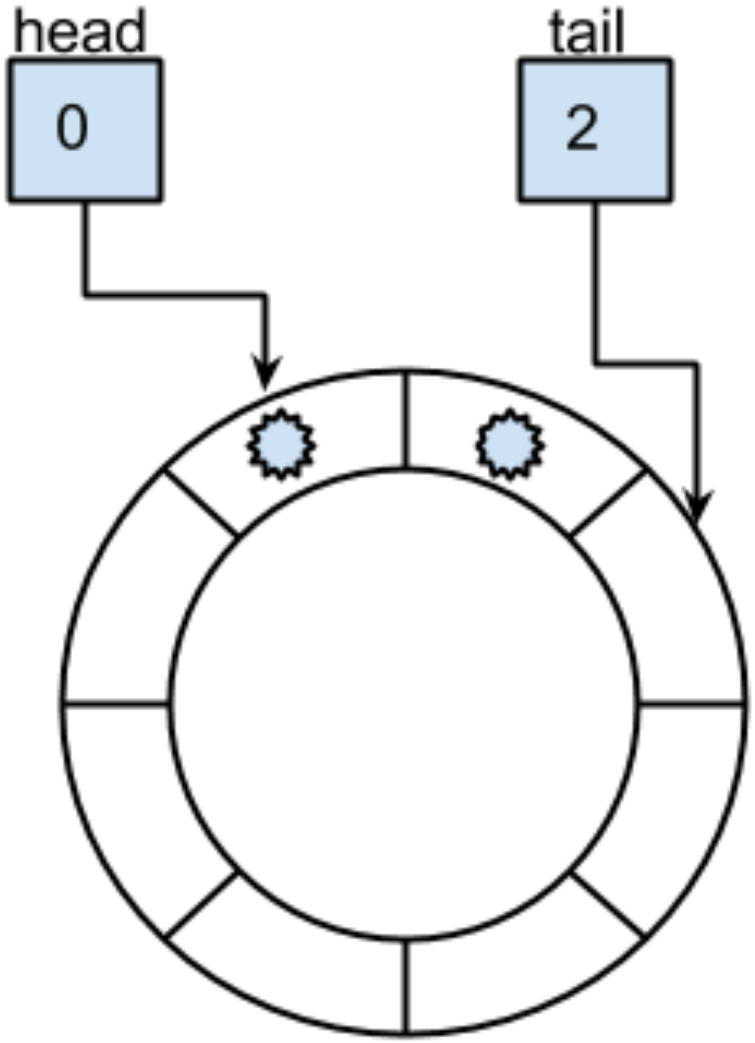
Ring Buffer: nP 1C



Ring Buffer: nP 1C



Ring Buffer: nP 1C



Ring Buffer: nP 1C

```
AtomicReferenceArray ringBuffer;
volatile long head;
AtomicLong tail;
```

Ring Buffer: nP 1C

```
public boolean offer(E e) {
    long curTail;
    do {
        curTail = tail.get();
        if (curTail - head == ringBuffer.length())
            return false;
    } while (!tail.compareAndSet(curTail, curTail+1));
    int idx = curTail % ringBuffer.length();
    ringBuffer.set(idx, e); // volatile write
    return true;
}
```

Ring Buffer: nP 1C

```
public E poll() {
    int index = head % ringBuffer.length();
    E element = ringBuffer.get(index);
    if (element == null)
        return null;
    ringBuffer.set(index, null);
    head++; // volatile write
    return element;
}
```

Disruptor

- Very flexible for different usages (strategies)
- Very good performance
- Data transfer from one thread to another (Queue)

Spinning

spinning

- Active wait
- very good for consumer reactivity
- Burns a cpu permanently

spinning

- Some locks are implemented with spinning (spinLock)
- Synchronized blocks spin a little bit on contention
- use of the pause instruction (x86)

spinning

How to avoid burning a core ?

Backoff strategies:

- Thread.yield()
- LockSupport.parkNanos(1)
- Object.wait()/Condition.await()/LockSupport.park()

Ticketing: OrderedScheduler

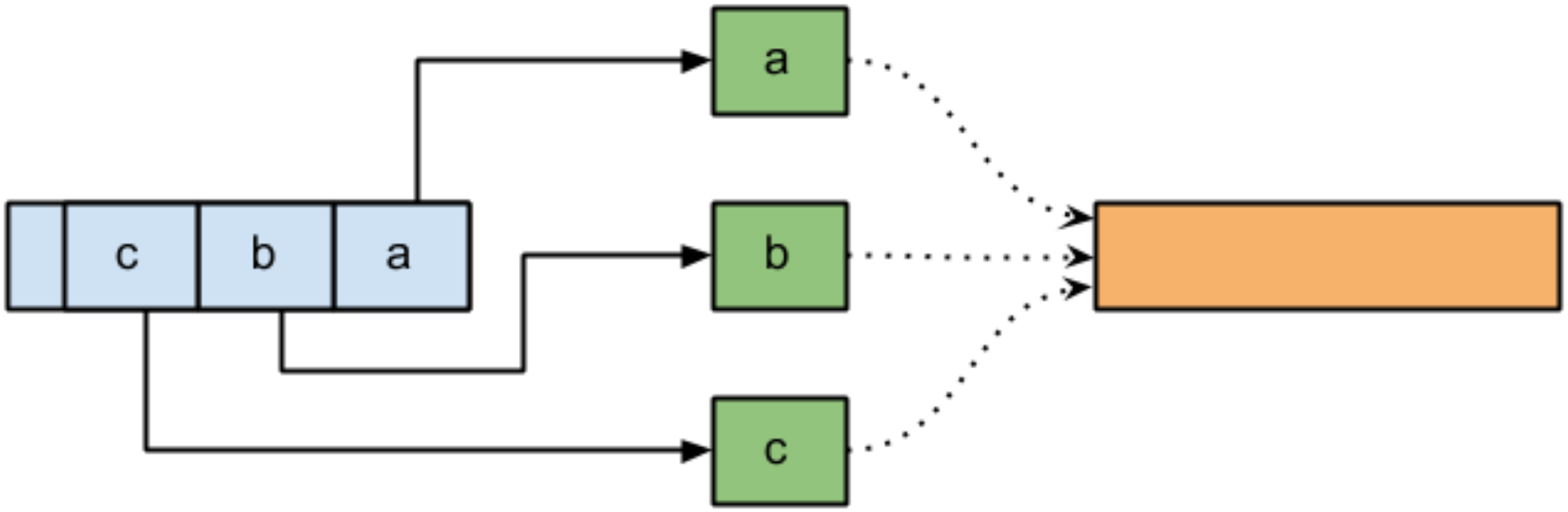
Ticketing

How to parallelize tasks while keeping ordering ?

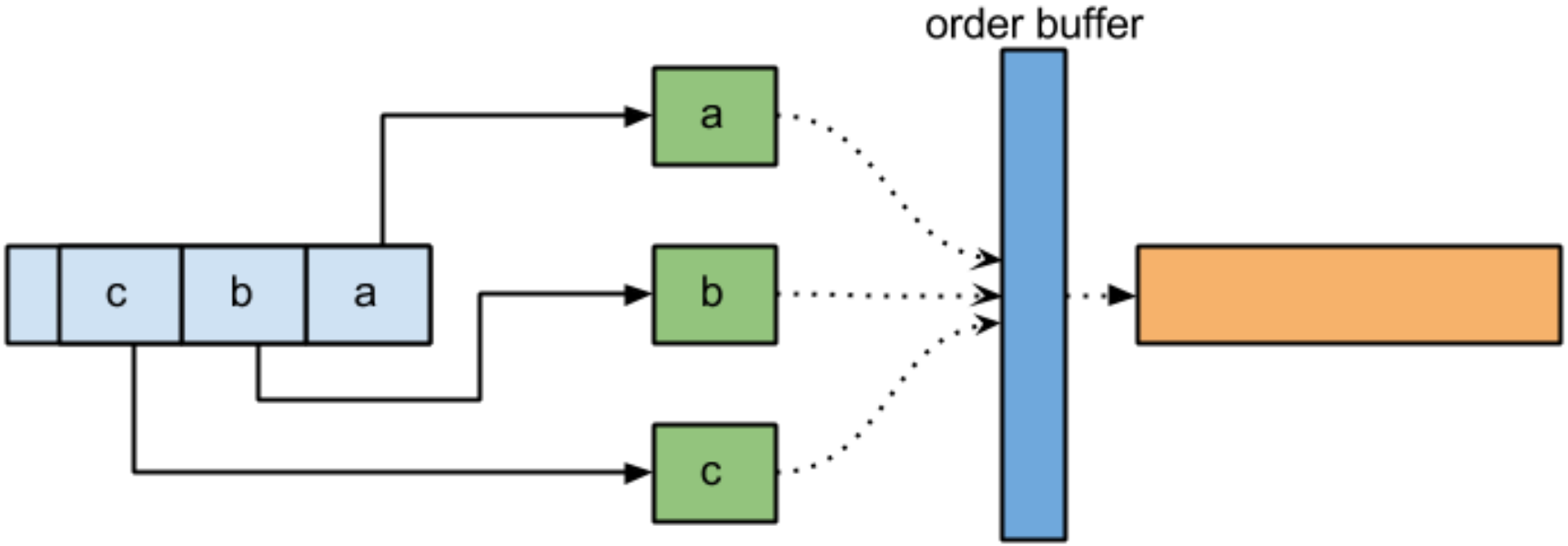
Example: Video stream processing

- read frame from the stream
- processing of the frame (parallelisable)
- writing into the output (in order)

Ticketing



Ticketing



Ticketing

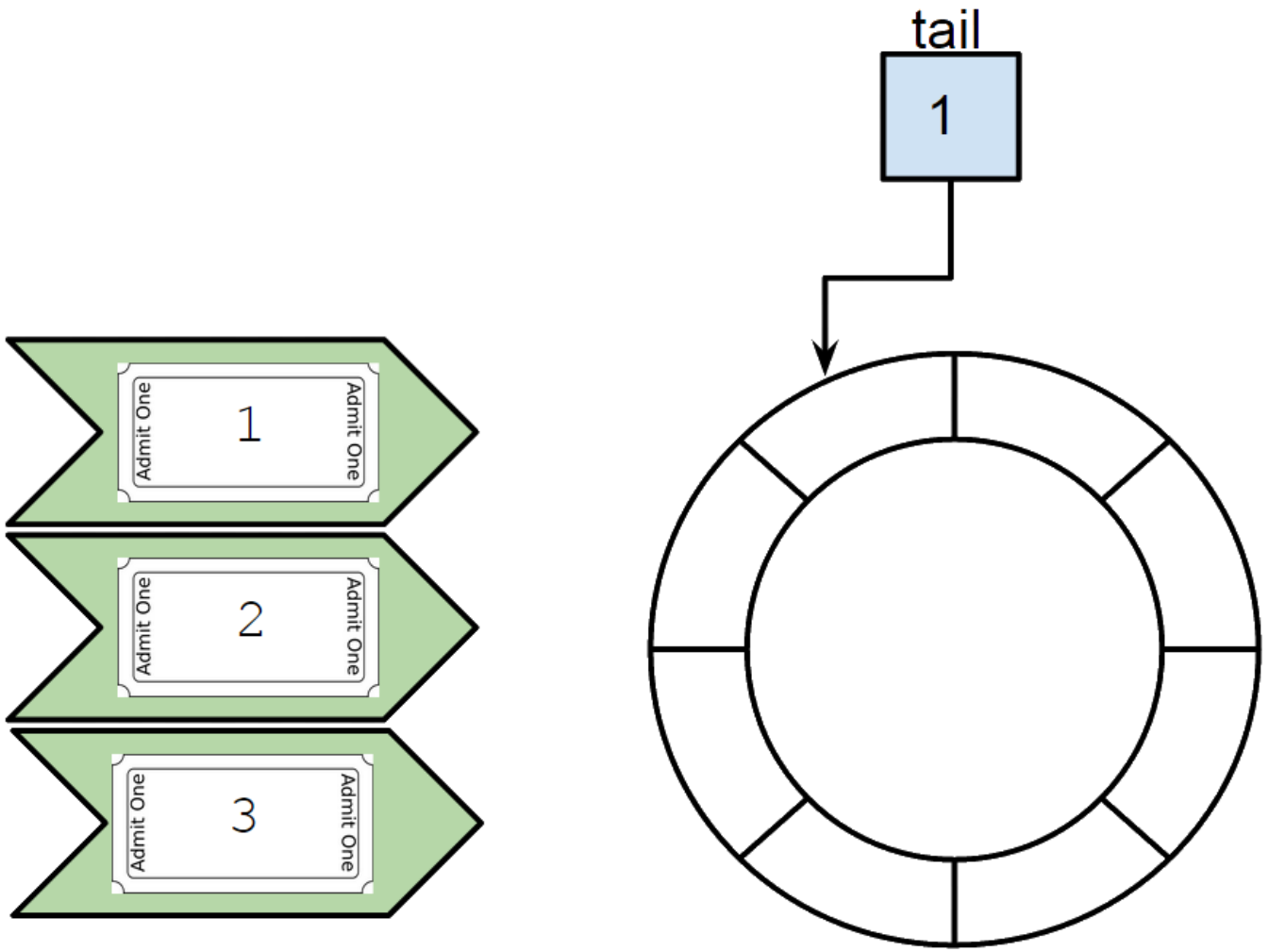
Can do this with Disruptor, but with a consumer thread

OrderedScheduler can do the same but:

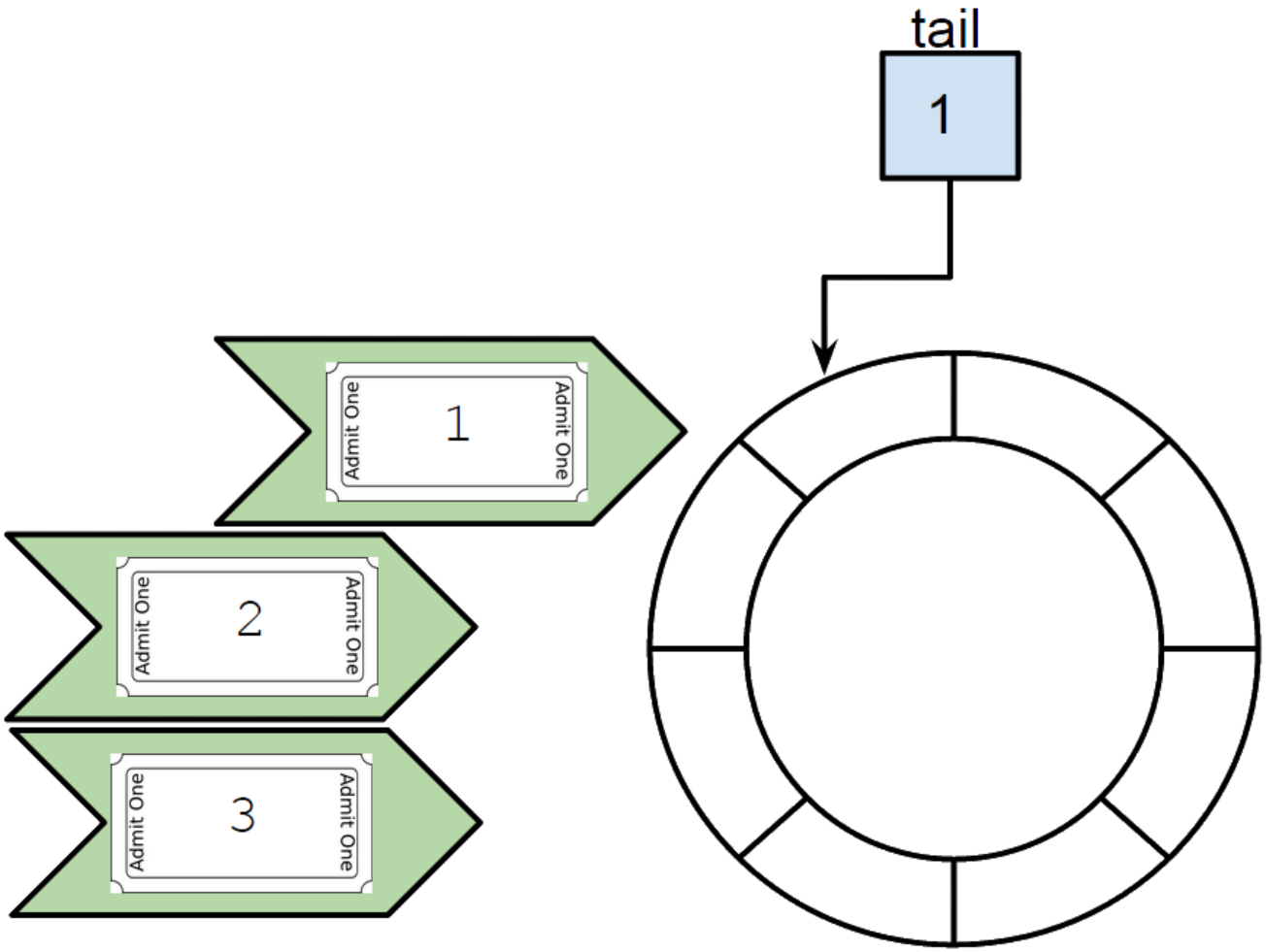
- no inter-thread communication overhead
- no additional thread
- no wait strategy

Take a ticket...

OrderedScheduler



OrderedScheduler



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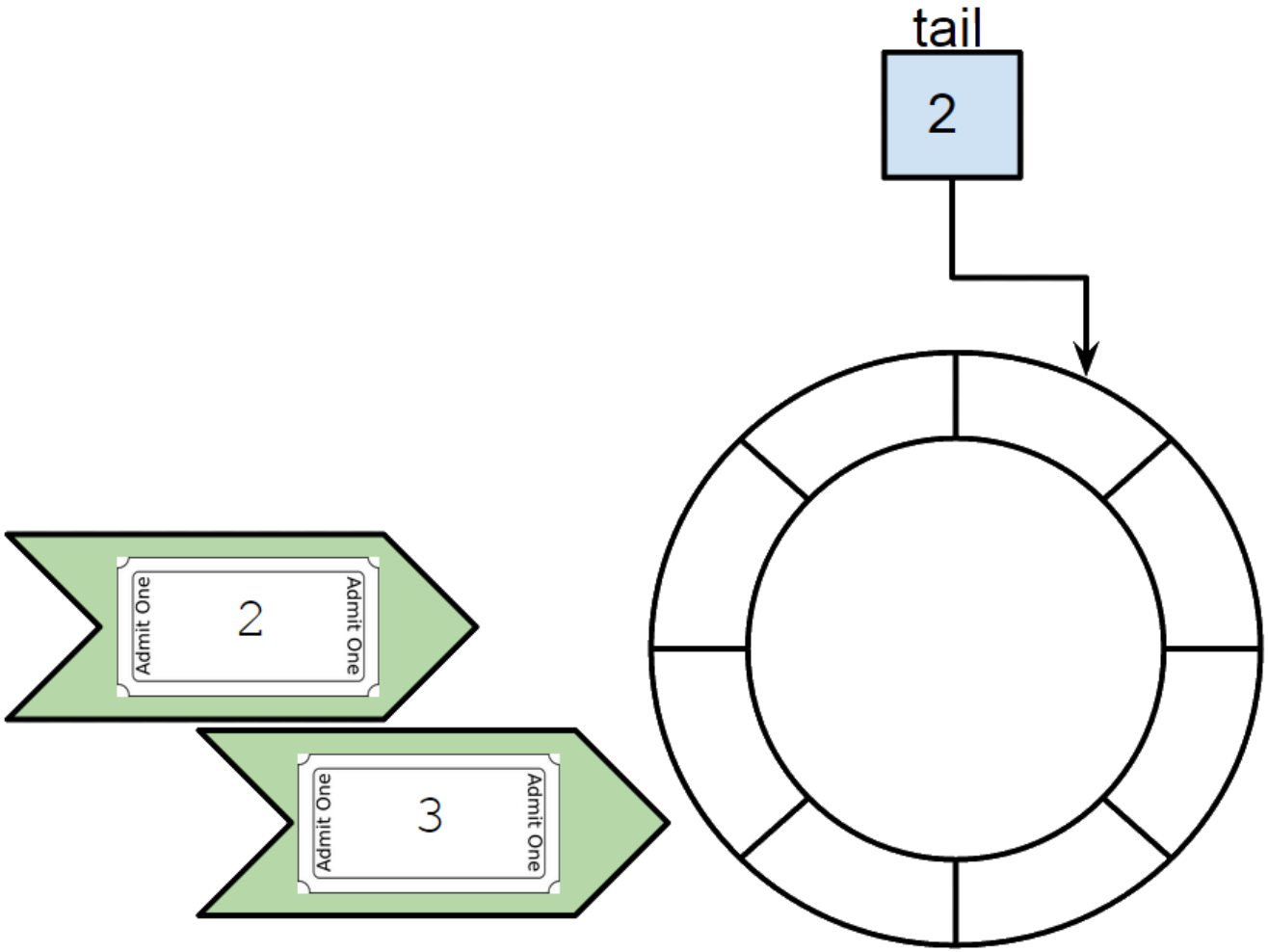
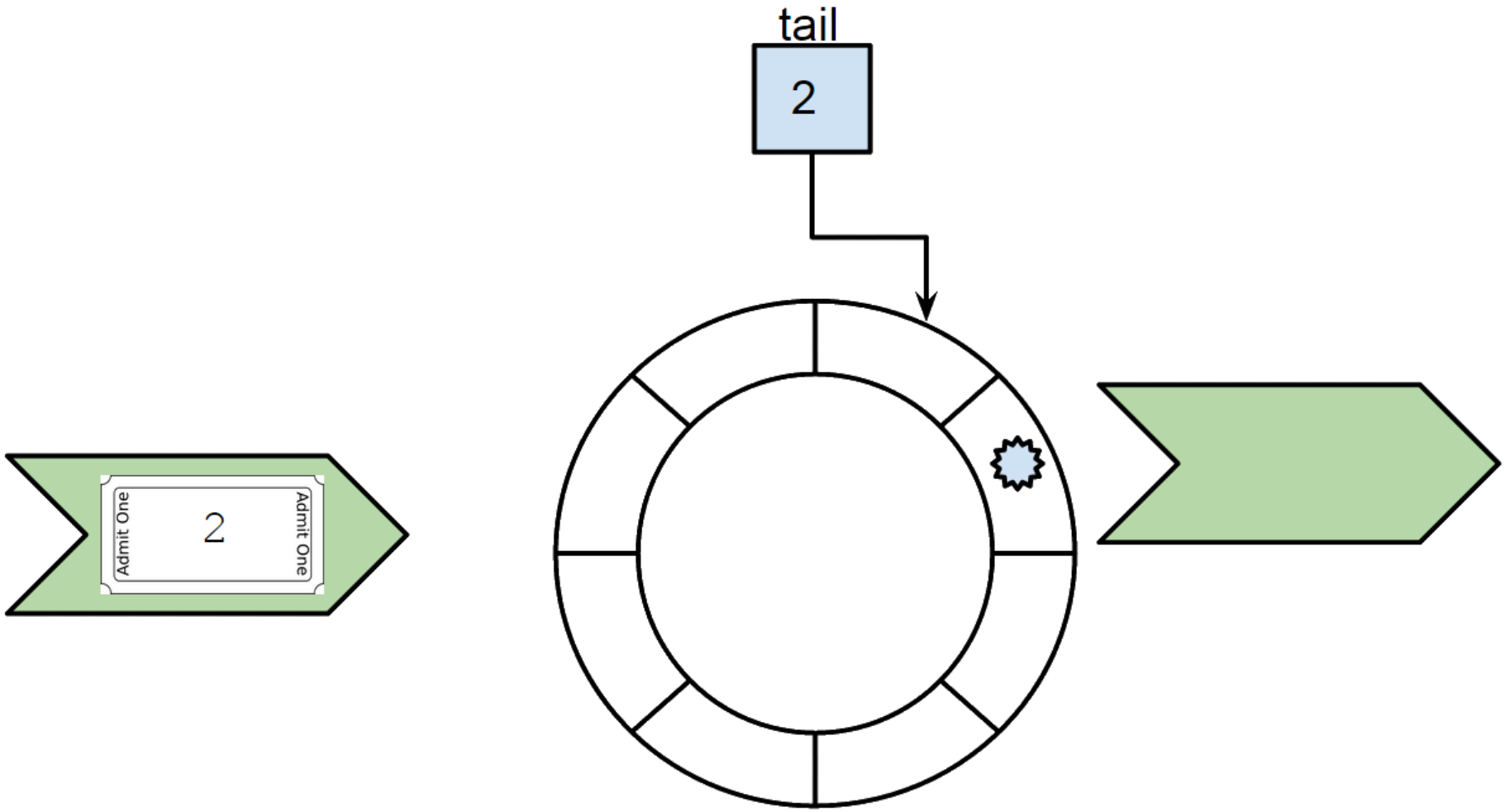


OrderedScheduler



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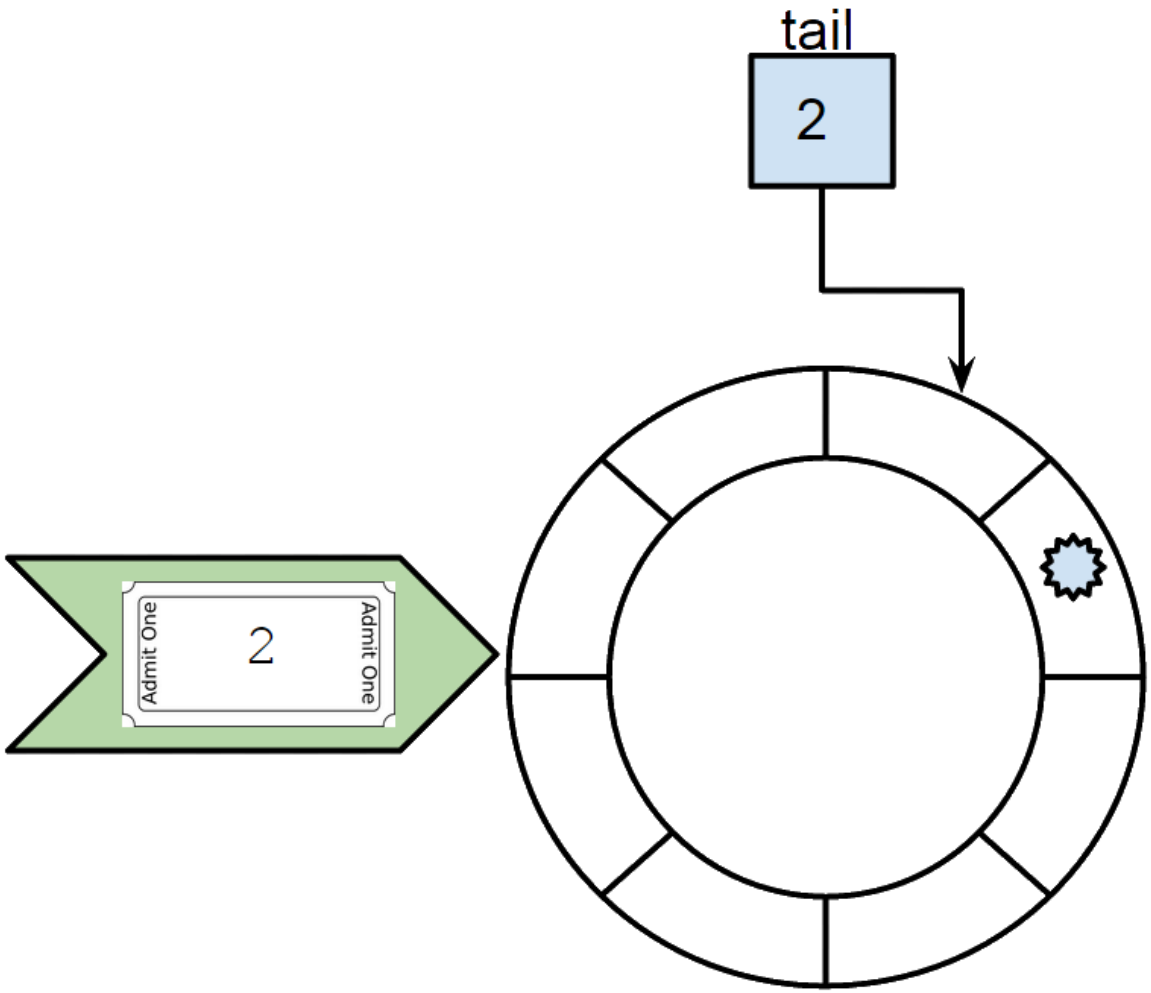

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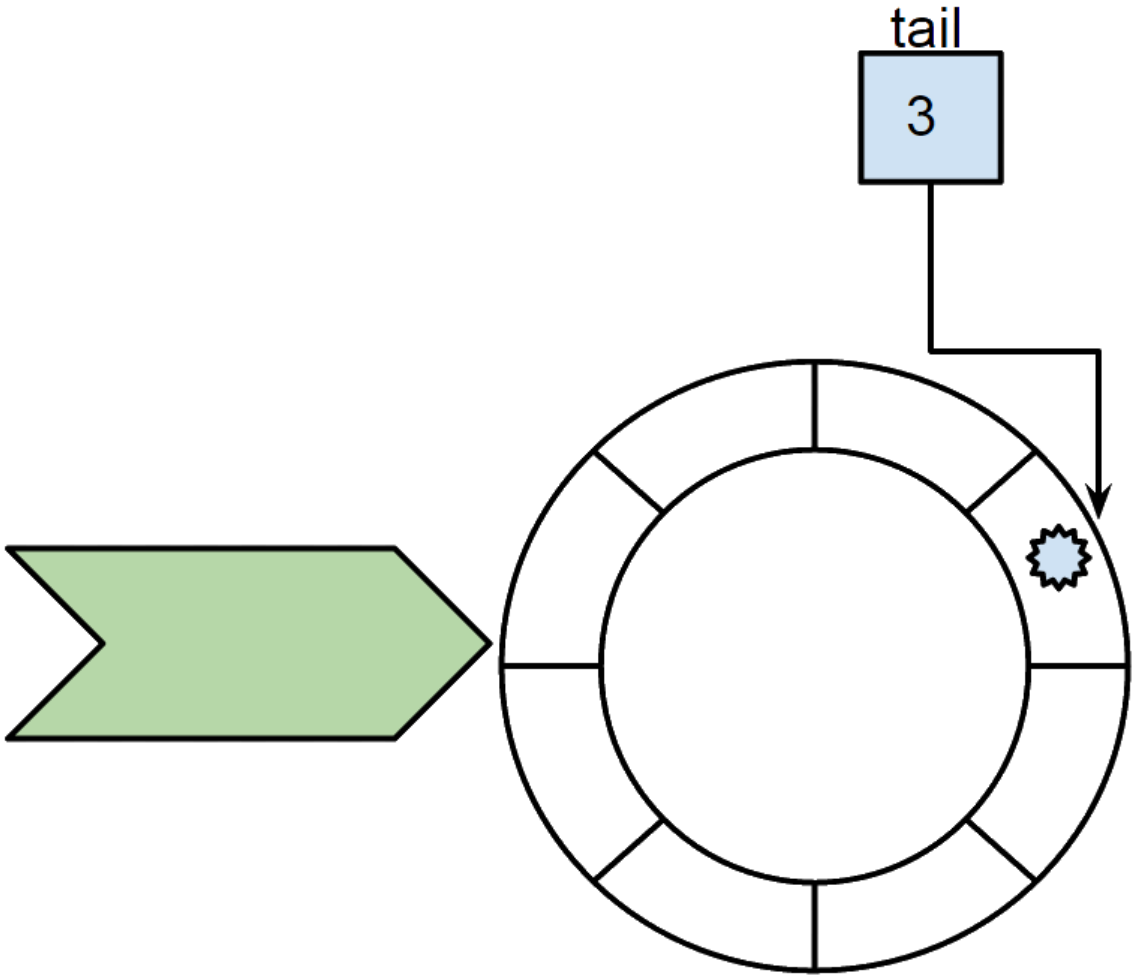
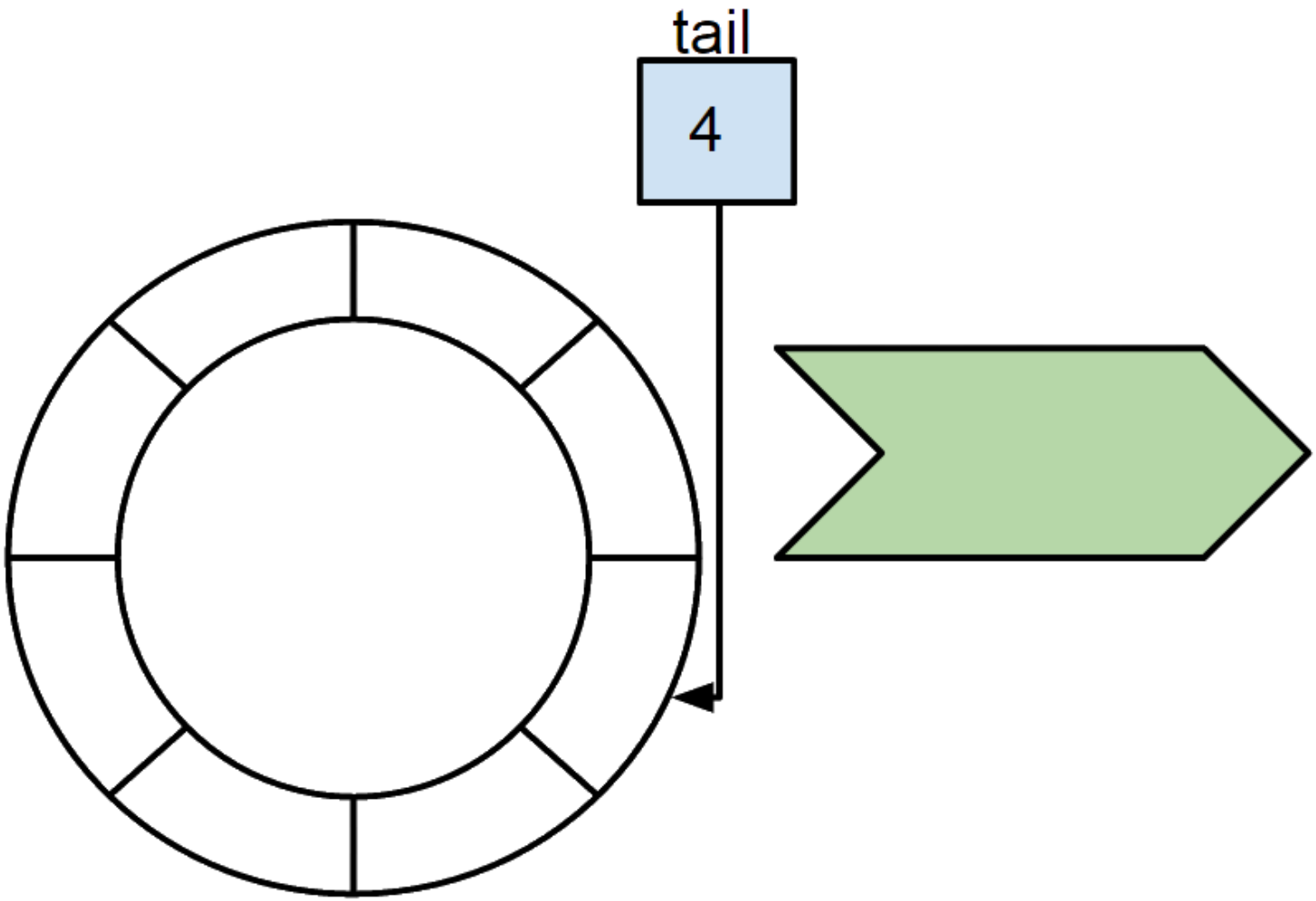


OrderedScheduler



OrderedScheduler

```
public void execute() {
    synchronized (this) {
        FooInput input = read();
        BarOutput output = process(input);
        write(output);
    }
}
```

OrderedScheduler

```
OrderedScheduler scheduler = new OrderedScheduler();

public void execute() {
    FooInput input;
    long ticket;
    synchronized (this) {
        input = read();
        ticket = scheduler.getNextTicket();
    }
[...]
```

OrderedScheduler

```
public void execute(){
[...]
    BarOutput output;
    try {
        output = process(intput);
    }
    catch (Exception ex) {
        scheduler.trash(ticket);
        throw new RuntimeException(ex);
    }
    scheduler.run(ticket, { () => write(output); });
}
```

Ticketing

- Open sourced on GitHub
- Opened to PR & discussion on the design
- Used internally

Takeaways

Takeaways

- Measure
- Distribute
- Atomically update
- Order
- RingBuffer: easy lock-free
- Ordered without consumer thread

References

- jucProfiler: http://www.infoq.com/articles/jucprofiler
- Java Memory Model Pragmatics: http://shipilev.net/blog/2014/jmm-pragmatics/
- Memory Barriers and JVM Concurrency: http://www.infoq.com/articles/memory_barriers_jvm_concurrency
- JSR 133 (FAQ): http://www.cs.umd.edu/~pugh/java/memoryModel/jsr-133-faq.html
- CPU cache flushing fallacy: http://mechanical-sympathy.blogspot.fr/2013/02/cpu-cache-flushing-fallacy.html
- atomic<> Weapons: http://channel9.msdn.com/Shows/Going+Deep/Cpp-and-Beyond-2012-Herb-Sutter-atomic-Weapons-1-of-2

References

- circular buffers: http://lwn.net/Articles/378262/
- Mr T queues: https://github.com/mjpt777/examples/tree/master/src/java/uk/co/real_logic/queues
- Lock-free algorithms by Mr T: http://www.infoq.com/presentations/Lock-free-Algorithms
- Futex are tricky U. Drepper: http://www.akkadia.org/drepper/futex.pdf
- JCTools: https://github.com/JCTools/JCTools
- Nitsan Wakart blog: http://psy-lob-saw.blogspot.com

References

- Exploiting data parallelism in ordered data streams: https://software.intel.com/en-us/articles/exploiting-data-parallelism-in-ordered-data-streams
- OrderedScheduler: https://github.com/Ullink/ordered-scheduler
- Concurrency Freaks: http://concurrencyfreaks.blogspot.com
- Preshing on programming: http://preshing.com/
- Is Parallel Programming Hard, And If So, What Can You Do About It? https://kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook.2015.01.31a.pdf

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connect@ullink.com