Practical Concurrent and Parallel Programming 11

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Plan for today

- **Michael and Scott unbounded queue 1996**
- Progress concepts
  - Wait-free, lock-free, obstruction-free
- Union-find data structure
- Work-stealing dequeues
  - Chase-Lev dequeue 2005

Based on slides by
Peter Sestoft

Bonus: More on volatile and CAS speed

TestTimeCas.java

- Int field increment:

```
data.x = data.x + 1;
```

  - Single thread; and non-volatile or volatile
- AtomicInteger "incr":

```
int old = data.get();
data.compareAndSet(old, old+1);
```

  - Single thread
  - Single thread, one other interfering thread
  - Single thread, one other non-interfering thread
- Results

Activity	Time/ns
Non-volatile field `x`	0.9
Volatile field `x`	8.8
CAS alone	11.4
CAS with interfering thread	74.5
CAS with non-interfering thread	11.7

Lock-based queue with sentinel

Q 1

TestMSqueue.java

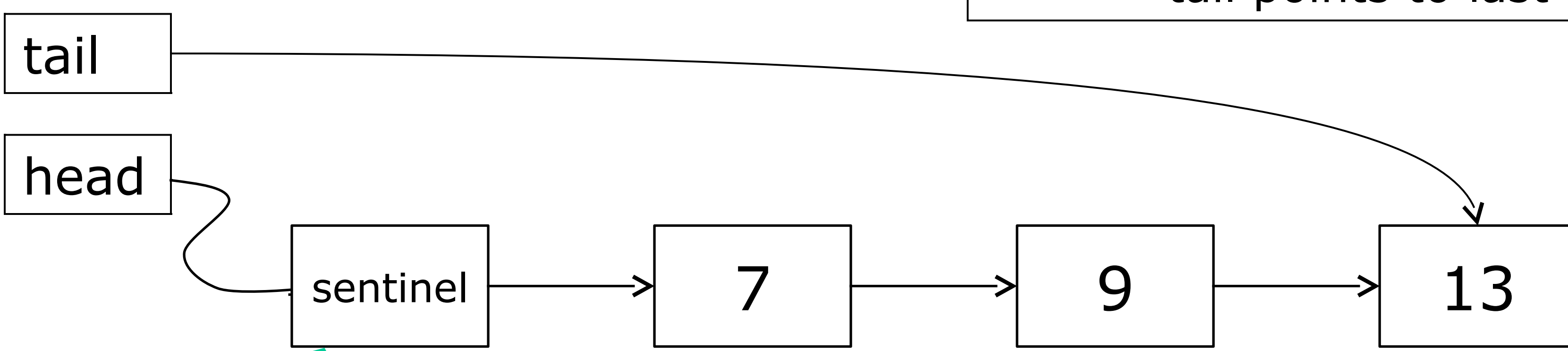
```
class LockingQueue<T> implements UnboundedQueue<T> {
  private Node<T> head, tail;

  public LockingQueue() {
    head = tail = new Node<T>(null, null);
  }
  ...
}
```

Make sentinel node

```
private static class Node<T> {
   final T item;
   Node<T> next;
 }
```

Invariants:
head≠null
tail.next=null
If empty, head=tail
If non-empty: head≠tail,
head.next is first item,
tail points to last item



Purpose: Avoid special case for empty queue

Lock-based queue operations

```
public synchronized void enqueue(T item) {
  Node<T> node = new Node<T>(item, null);
  tail.next = node;
  tail = node;
}
```

Enqueue at tail

Atomic

```
public synchronized T dequeue() {
  if (head.next == null)
    return null;
  Node<T> first = head;
  head = first.next;
  return head.item;
}
```

Atomic

Dequeue from second node, second becomes new sentinel

TestMSqueue.java

- Important property:
  - Enqueue (**put**) updates **tail** but not **head**
  - Dequeue (**take**) updates **head** but not **tail**

Michael-Scott lock-free queue, CAS

```
private static class Node<T> {
  final T item;
  final AtomicReference<Node<T>> next;
}
```

Michael and Scott: Simple, Fast, and Practical Non-Blocking and Blocking Concurrent Queue Algorithms, 1996

```
class MSQueue<T> implements UnboundedQueue<T> {
  private final AtomicReference<Node<T>> head, tail;

  public MSQueue() {
    Node<T> dummy = new Node<T>(null, null);
    head = new AtomicReference<Node<T>>(dummy);
    tail = new AtomicReference<Node<T>>(dummy);
  }
}
```

Make sentinel node

TestMSQueue.java

- If non-empty:
  - As before, **`head.next`** is first item
  - But **`tail`** points to last item ("quiescent state") **or** second-last item ("intermediate state")

Intermediate state and "help"

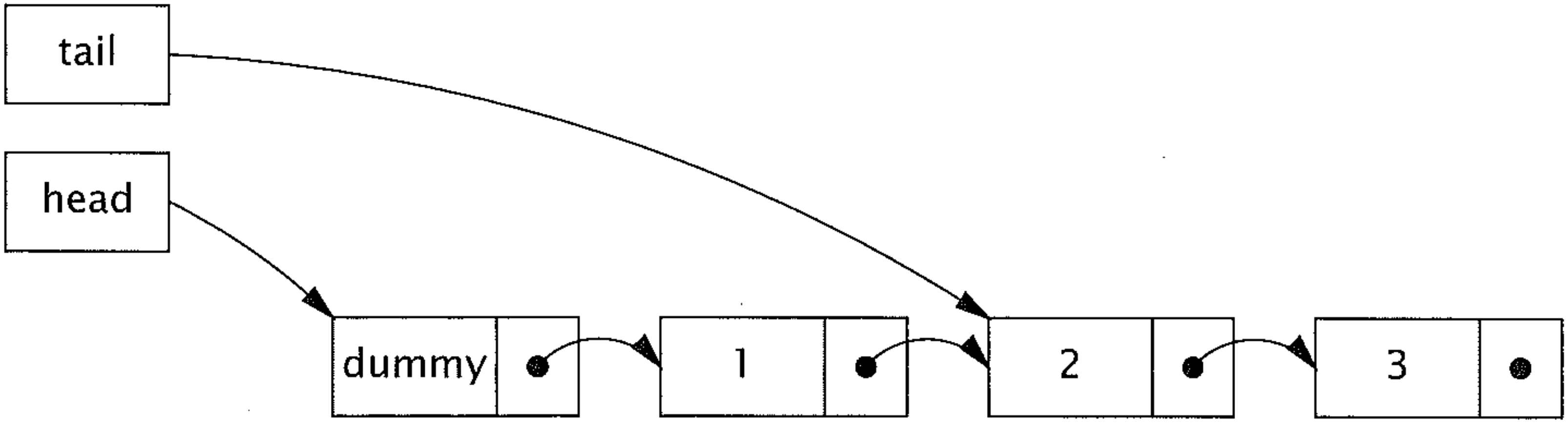


FIGURE 15.4. Queue in intermediate state during insertion.

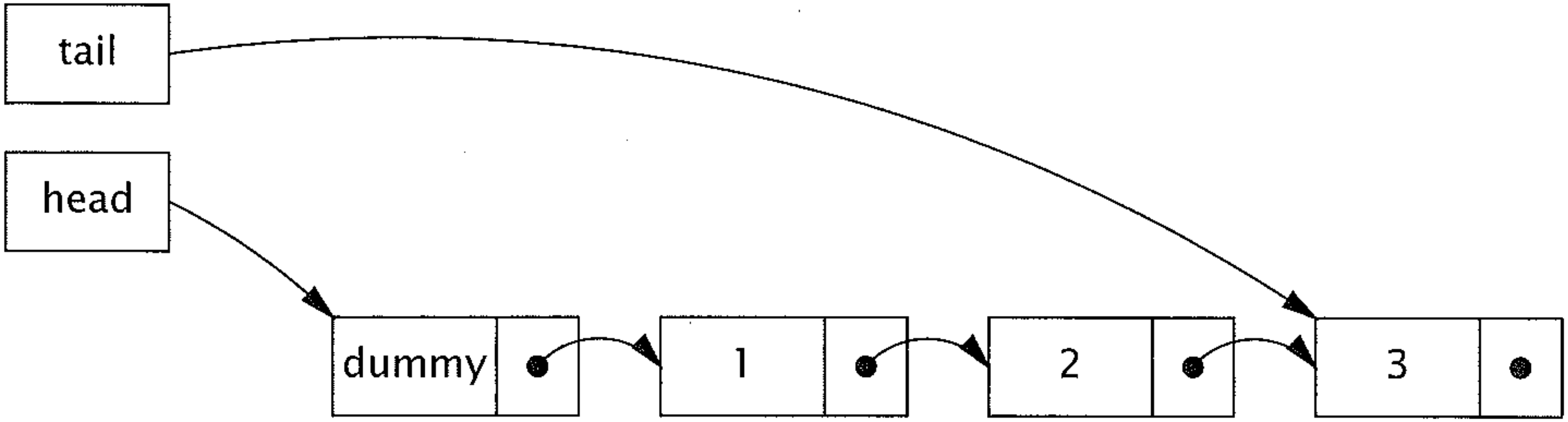
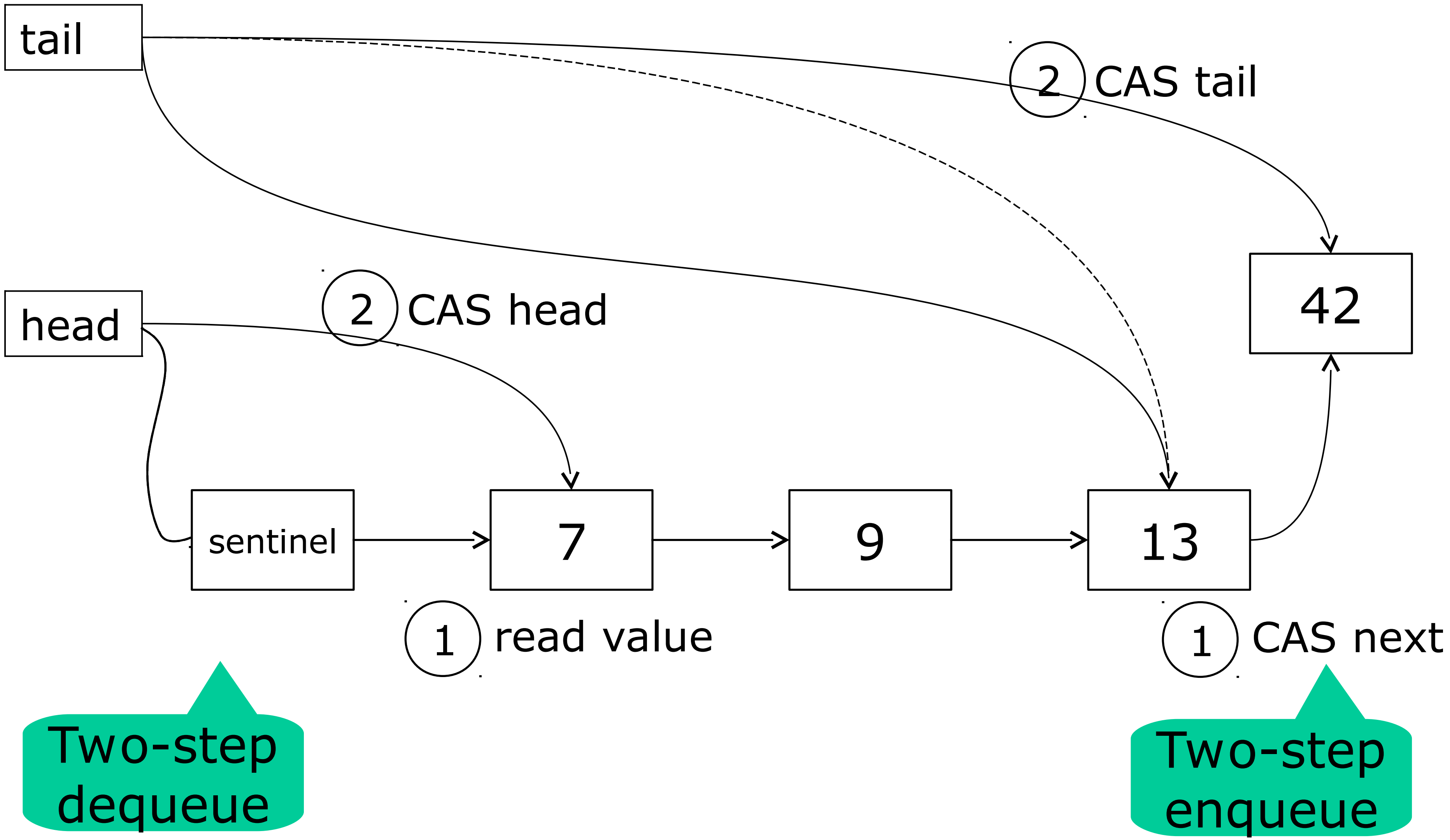


FIGURE 15.5. Queue again in quiescent state after insertion is complete.

Goetz p. 333

Michael & Scott queue operations



After Herlihy & Shavit p. 232

Q 2

Michael-Scott dequeue (take)

TestMSqueue.java

```
public T dequeue() {
  while (true) {
    Node<T> first = head.get(),
            last = tail.get(),
            next = first.next.get();
    if (first == head.get()) {
      if (first == last) {
        if (next == null)
          return null;
        else
          tail.compareAndSet(last, next);
      } else {
        T result = next.item;
        if (head.compareAndSet(first, next)) {
          return result;
        }
      }
    }
  }
}
```

Needed? (on `if (first == head.get())`)

May be empty (on `if (first == last)`)

Is empty (on `return null;`)

Intermediate, try move tail (on `tail.compareAndSet(last, next);`)

Try move head (on `if (head.compareAndSet(first, next))`)

Michael-Scott enqueue (put)

```
public void enqueue(T item) { // at tail
  Node<T> node = new Node<T>(item, null);
  while (true) {
    Node<T> last = tail.get(),
            next = last.next.get();
    if (last == tail.get()) {
      if (next == null)  {
        if (last.next.compareAndSet(next, node)) {
          tail.compareAndSet(last, node);
          return;
        }
      } else {
        tail.compareAndSet(last, next);
      }
    }
  }
}
```

Needed?

Quiescent, try add

Success, try move tail

Intermediate, try move tail

"help another enqueuer"

TestMSqueue.java

Why must dequeue mess with the tail?

Q 2

```
public T dequeue() {
  ...
  if (first == last) {
    if (next == null)
      return null;
    else
      tail.compareAndSet(last, next);
  } else ...
}
```

Intermediate, try move tail

TestMSqueue.java

Scenario without it:
If queue empty, head==tail

A: enqueue(7)

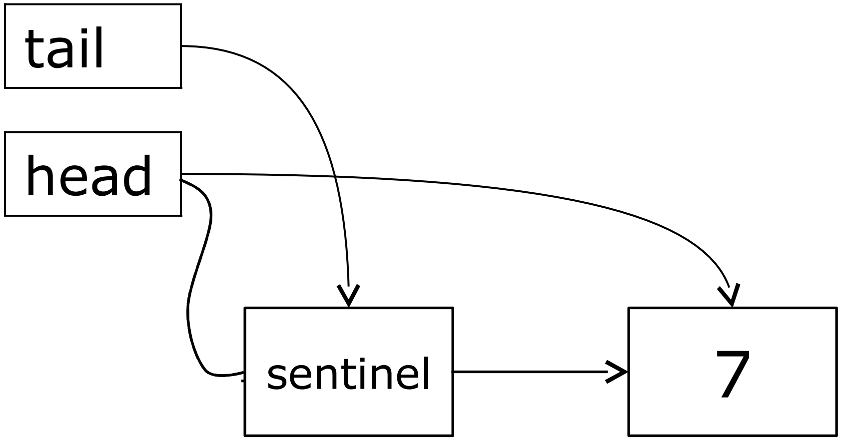
A: update a.next

B: dequeue()

B: update head

Now tail lags behind head, not good

So B: dequeue() must move tail before moving head



After Herlihy & Shavit p. 233

Understanding Michael-Scott queue

- Linearization point: where method takes effect
- Linearizable, with linearization points:
  - enqueue: successful CAS at E9
  - dequeue returning null: D3
  - dequeue returning item: successful CAS at D13

```
public T dequeue() { // from head
  while (true) {
    Node<T> first = head.get(),
            last = tail.get(),
            next = first.next.get();
    if (first == head.get()) { // D5
      if (first == last) {
        if (next == null)
          return null;
        else
          tail.compareAndSet(last, next);
      } else {
        T result = next.item;
        if (head.compareAndSet(first, next))
          return result;
      }
    }
  }
}
```

D3

D13

```
public void enqueue(T item) { // at tail
  Node<T> node = new Node<T>(item, null);
  while (true) {
    Node<T> last = tail.get(),
            next = last.next.get();
    if (last == tail.get()) { // E7
      if (next == null)  {
        if (last.next.compareAndSet(next, node)) {
          tail.compareAndSet(last, node);
          return;
        }
      } else
        tail.compareAndSet(last, next);
    }
  }
}
```

E9

Groves: Verifying Michael and Scott's Lock-Free Queue Algorithm using Trace Reduction, 2008

Nice, but ... needs a lot of AtomicReference objects

```
private static class Node<T> {
  final T item;
  final AtomicReference<Node<T>> next;

  public Node(T item, Node<T> next) {
    this.item = item;
    this.next = new AtomicReference<Node<T>>(next);
  }
}
```

Must be CAS'able

One AR per Node

Q 2

```
private static class Node<T> {
  final T item;
  volatile Node<T> next;
  ...
}
```

Q 3

Better, no AtomicReference object needed

Instead, make an "updater"

A la Goetz p. 335

```
private final AtomicReferenceFieldUpdater<Node<T>, Node<T>> nextUpdater
  = AtomicReferenceFieldUpdater.newUpdater((Class<Node<T>>)(Class<?>)(Node.class),
                                           (Class<Node<T>>)(Class<?>)(Node.class),
                                           "next");
```

Michael-Scott enqueue, using the "updater" for `last.next`

Q 3

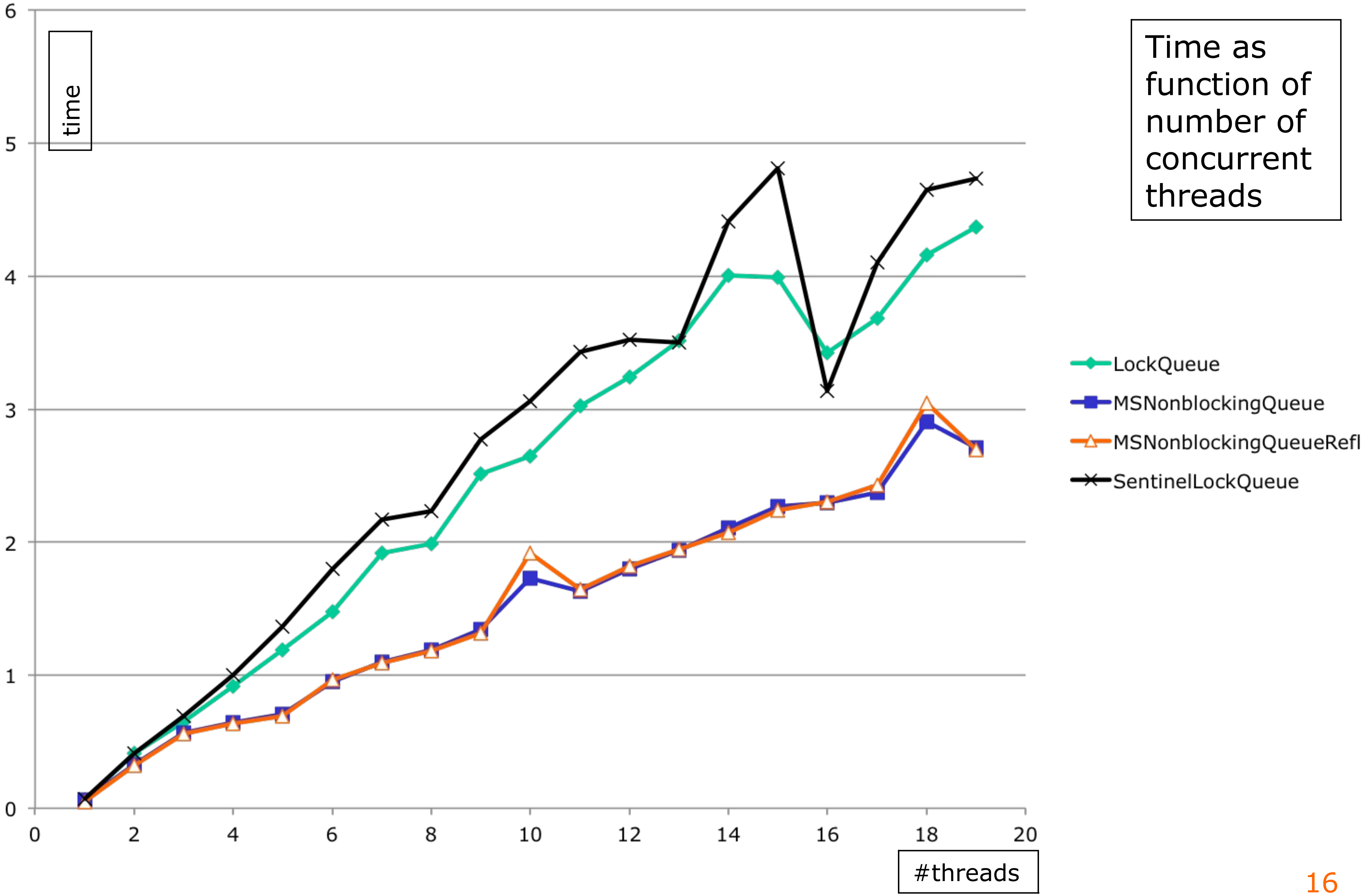
```
public void enqueue(T item) { // at tail
  Node<T> node = new Node<T>(item, null);
  while (true) {
    Node<T> last = tail.get(), next = last.next;
    if (last == tail.get()) {
      if (next == null)  {
        if (nextUpdater.compareAndSet(last, next, node)) {
          tail.compareAndSet(last, node);
          return;
        }
      } else {
        tail.compareAndSet(last, next);
      }
    }
  }
}
```

If "next" field of **`last`** equals **`next`**, set to **`node`**

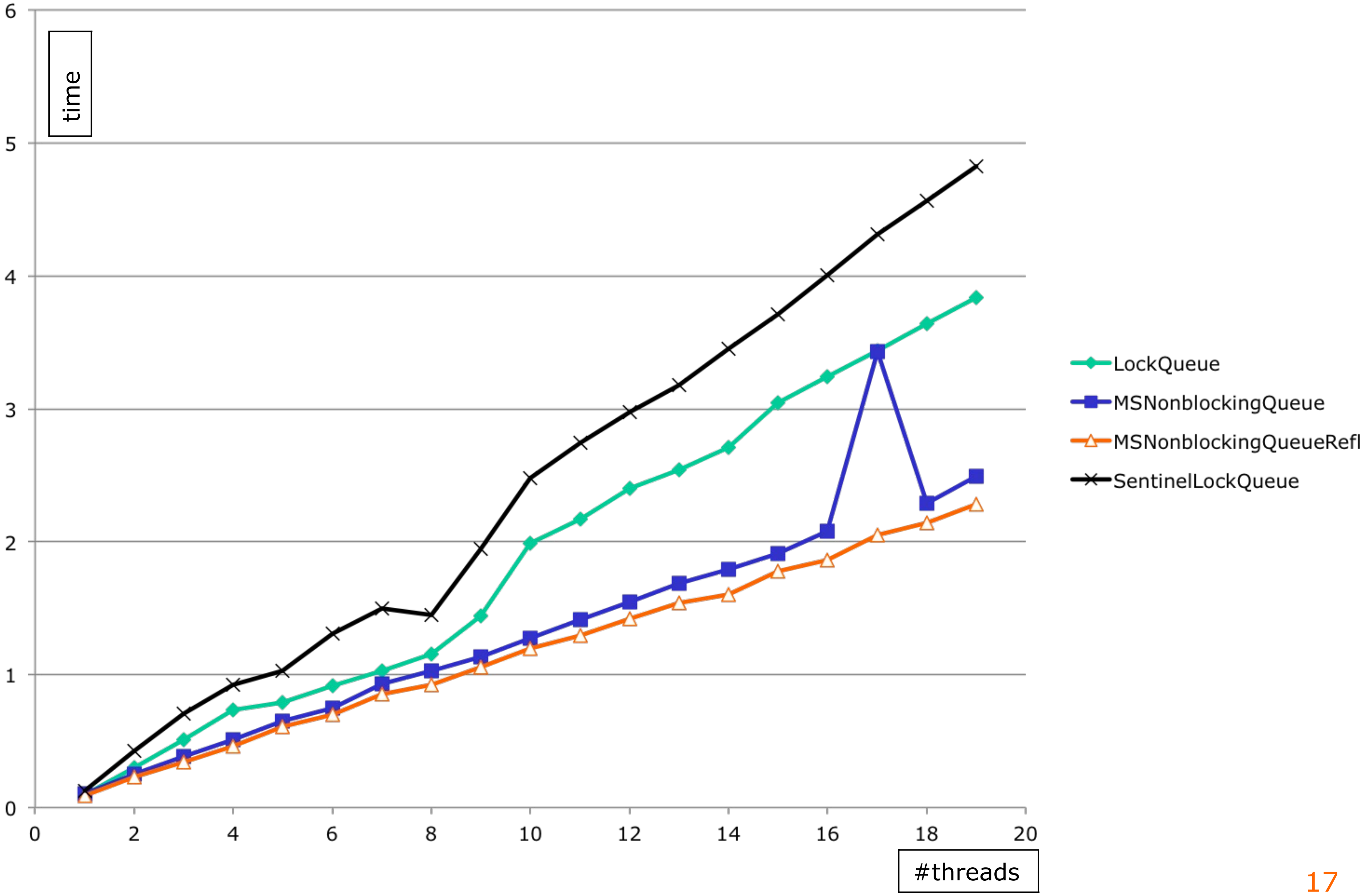
Queue benchmarks

- Queue implementations
  - Lock-based
  - Lock-based, sentinel node
  - Lock-free, sentinel node, AtomicReference
  - Lock-free, sentinel node, AtomicReferenceFieldUpdater
- Platforms
  - Hotspot 64 bit Java 1.7.0_b147, Windows 7, Xeon W3505, 2.53GHz, 2 cores, 2009Q1
  - Hotspot 64 bit Java 1.6.0_37, MacOS, Core 2 Duo, 2.66GHz, 2 cores, 2008Q1
  - Icedtea Java 1.7.0_b21, Linux, Xeon E5320, 1.86GHz, 4/8 cores, 2006Q4
  - Hotspot 64 bit Java 1.7.0_25-b15, Linux, AMD Opteron 6386 SE, 32 cores, 2012Q4
- Measurements probably flawed: the client threads do no useful work, only en/dequeue
- Nevertheless, **big** differences between machines

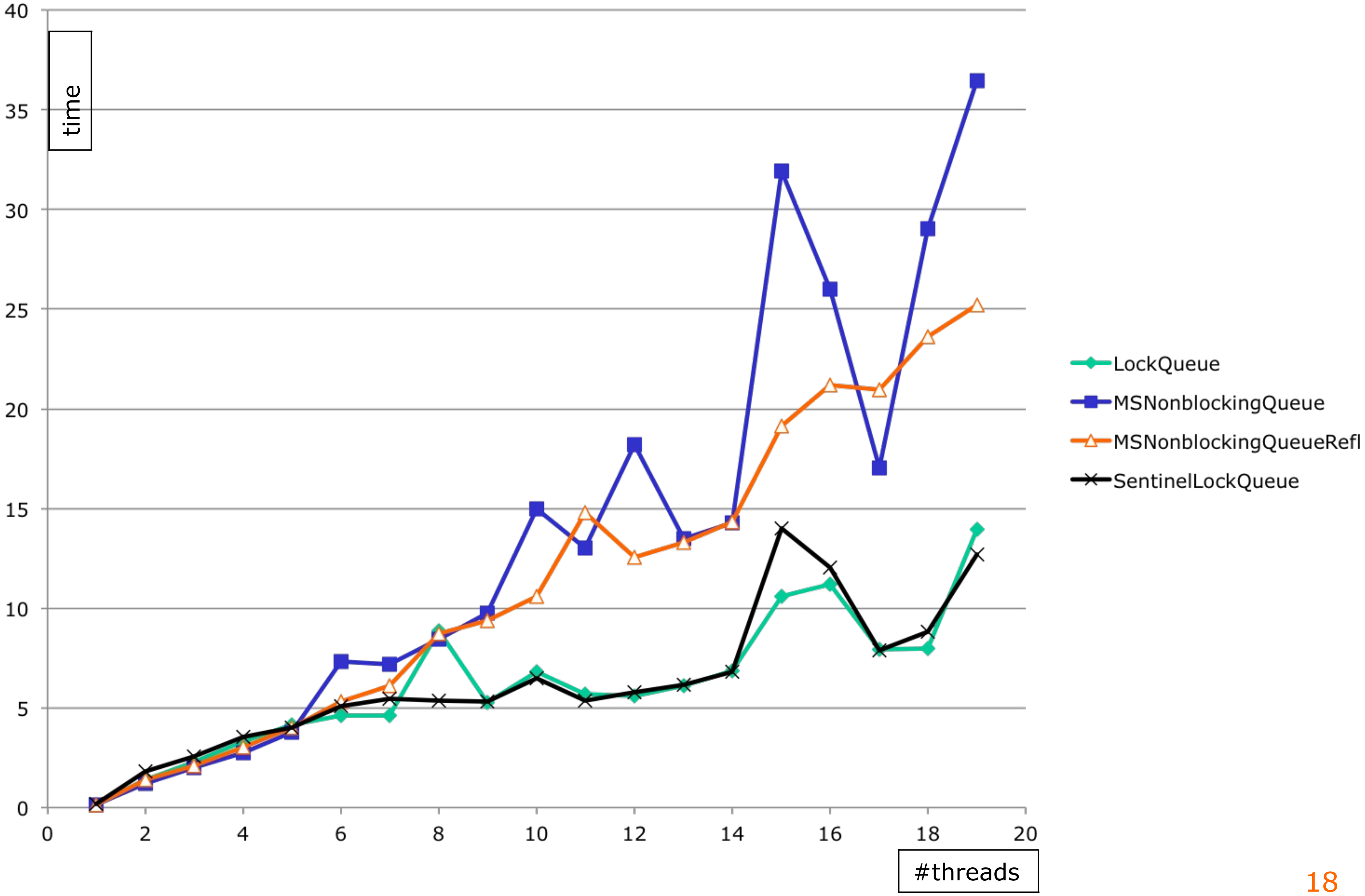
Java 1.7, Xeon W3505, 2 cores



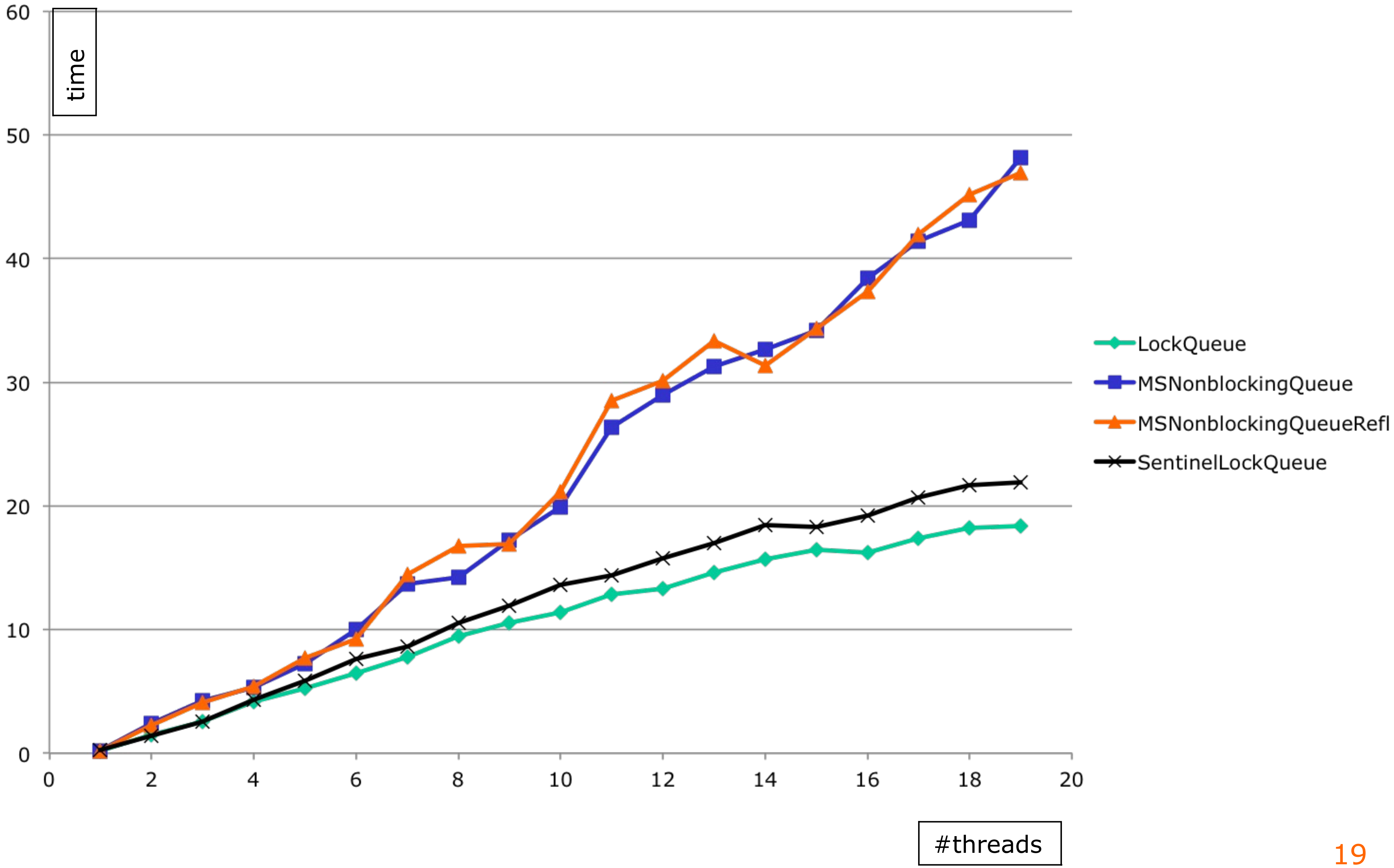
Java 1.6, Core 2 Duo, 2 cores



Java 1.7, Xeon E5320, 4x2 cores



Java 1.7, AMD Opteron, 32 cores



Plan for today

- Michael and Scott unbounded queue 1996
- **Progress concepts**
  - **Wait-free, lock-free, obstruction-free**
- Work-stealing dequeues
  - Chase-Lev dequeue 2005
- Union-find data structure

Progress concepts

- *Non-blocking*: A call by thread A cannot prevent a call by thread B from completing
  - Not true for lock-based queue: A holds lock to **`put()`**, gets descheduled or crashes, while B wants to **`take()`** but cannot get lock
- *Wait-free*: Every call finishes in finite time
  - True for SimpleTryLock's **`tryLock`**
  - Not true for AtomicInteger's **`getAndAdd`**
- *Bounded wait-free*: Every … in bounded time
- *Lock-free*: Some call finishes in finite time
  - True for AtomicInteger's **`getAndAdd`**
  - Any wait-free method is also lock-free
  - Lock-free is good enough in practice

Not same as lock-less

Shavit et al, CACM November 2014, p. 13-15

Goetz §15.4 and Herlihy & Shavit §3.7

Obstruction freedom

- *Obstruction-free*: If a method call executes alone, it finishes in finite time
  - Lock-based data structures are not obstruction-free
  - A *lock-free* method is also obstruction-free
  - Obstruction-free sounds rather weak, but in combination with back-off it ensures progress
  - Some people even think it too strong:

> ... we argue that obstruction-freedom is not an important property for software transactional memory, and demonstrate that, if we are prepared to drop the goal of obstruction-freedom, software transactional memory can be made significantly faster

Ennals 2006: STM should not be obstruction-free

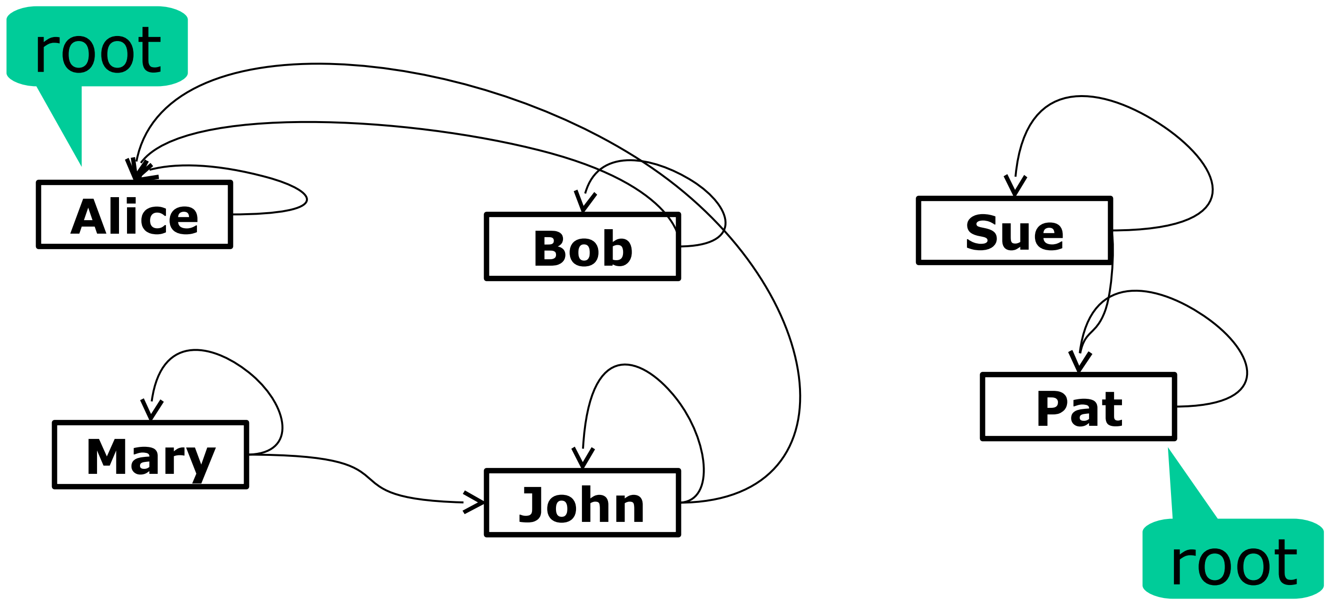
Plan for today

- Michael and Scott unbounded queue 1996
- Progress concepts
  - Wait-free, lock-free, obstruction-free
- **Union-find data structure**
- Work-stealing dequeues
  - Chase-Lev dequeue 2005

The union-find data structure

- Efficient way to maintain equivalence classes
- Used in
  - type inference in compilers: F#, Scala, C# ...
  - image segmentation
  - network analysis: chips, WWW, Facebook friends ...
- Example: family relations, who are related?

Tarjan: Data structures and network algorithms, 1983



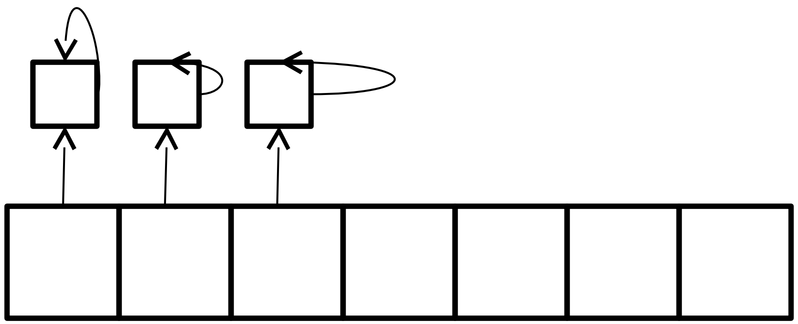
Sue is Pat's sister
Alice is Bob's sister
Mary is John's mother
Mary is Bob's mother

Are Sue and Mary related?

Three union-find implementations

- A: Coarse-locking = Synchronized methods
- B: Fine-locking = Lock on each set partition
- C: Wait-free = Optimistic, CAS-based

```
interface UnionFind {
  int find(int x);
  void union(int x, int y);
  boolean sameSet(int x, int y);
}
```



```
class Node {
  volatile int
    next, rank;
}
```

```
class CoarseUnionFind implements UnionFind {
  private final Node[] nodes;

  public CoarseUnionFind(int count) {
    this.nodes = new Node[count];
    for (int x=0; x<count; x++)
      nodes[x] = new Node(x);
  }
```

TestUnionFind.java

Coarse-locking union-find

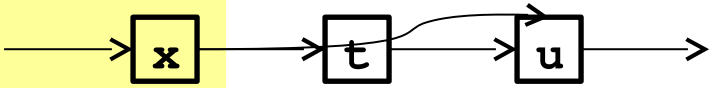
```
class CoarseUnionFind implements UnionFind {
  private final Node[] nodes;
  public synchronized int find(int x) {
    while (nodes[x].next != x) {
      final int t = nodes[x].next, u = nodes[t].next;
      nodes[x].next = u;
      x = u;
    }
    return x;
  }
  public synchronized void union(int x, int y) {
    int rx = find(x), ry = find(y);
    if (rx == ry)
      return;
    if (nodes[rx].rank > nodes[ry].rank) {
      int tmp = rx; rx = ry; ry = tmp;
    }
    nodes[rx].next = ry;
    if (nodes[rx].rank == nodes[ry].rank)
      nodes[ry].rank++;
  }
}
```

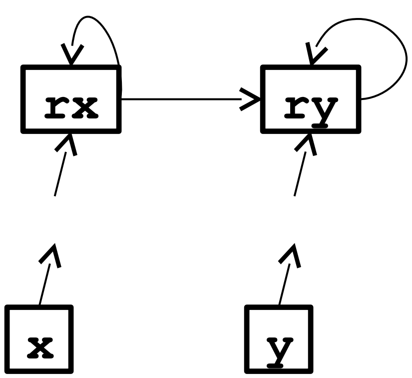
Path halving

Find roots

Union by rank

TestUnionFind.java





Fine-locking union-find

- No locking in find
  - Do path compression separately
  - Ensure visibility by **`volatile next, rank`** in Node

```
class FineUnionFind implements UnionFind {
  public int find(int x) {
    while (nodes[x].next != x)
      x = nodes[x].next;
    return x;
  }

  // Assumes lock is held on nodes[root]
  private void compress(int x, final int root) {
    while (nodes[x].next != x) {
      int next = nodes[x].next;
      nodes[x].next = root;
      x = next;
    }
  }
}
```

No path halving

Path compression

TestUnionFind.java

Fine-locking union-find

```
public void union(final int x, final int y) {
  while (true) {
    int rx = find(x), ry = find(y);
    if (rx == ry)
      return;
    else if (rx > ry) {
      int tmp = rx; rx = ry; ry = tmp;
    }
    synchronized (nodes[rx]) {
      synchronized (nodes[ry]) {
        if (nodes[rx].next != rx || nodes[ry].next != ry)
          continue;
        if (nodes[rx].rank > nodes[ry].rank) {
          int tmp = rx; rx = ry; ry = tmp;
        }
        nodes[rx].next = ry;
        if (nodes[rx].rank == nodes[ry].rank)
          nodes[ry].rank++;
        compress(x, ry);
        compress(y, ry);
    } }
} }
```

Consistent lock order

Restart if updated

Union by rank and path compression

TestUnionFind.java

Wait-free union-find with CAS

Anderson and Woll: Wait-free parallel algorithms for the union-find problem, 1991

```
class Node {
  private final AtomicInteger next;
  private final int rank;
}
```

```
public int find(int x) {
  while (nodes.get(x).next.get() != x) {
    final int t = nodes.get(x).next.get(),
              u = nodes.get(t).next.get();
    nodes.get(x).next.compareAndSet(t, u);
    x = u;
  }
  return x;
}
```

Path halving with CAS

TestUnionFind.java

Atomic update of root **nodes[x]** to point to fresh **Node(y,newRank)**

```
boolean updateRoot(int x, int oldRank, int y, int newRank) {
  final Node oldNode = nodes.get(x);
  if (oldNode.next.get() != x || oldNode.rank != oldRank)
    return false;
  Node newNode = new Node(y, newRank);
  return nodes.compareAndSet(x, oldNode, newNode);
}
```

Wait-free union-find: union

```
public void union(int x, int y) {
  int xr, yr;
  do {
    x = find(x);
    y = find(y);
    if (x == y)
      return;
    xr = nodes.get(x).rank;
    yr = nodes.get(y).rank;
    if (xr > yr || xr == yr && x > y) {
      { int tmp = x; x = y; y = tmp; }
      { int tmp = xr; xr = yr; yr = tmp; }
    }
  } while (!updateRoot(x, xr, y, xr));
  if (xr == yr)
    updateRoot(y, yr, y, yr+1);
  setRoot(x);
}
```

Union-by-rank, deterministic

Restart if updated

TestUnionFind.java

Plan for today

- Michael and Scott unbounded queue 1996
- Progress concepts
  - Wait-free, lock-free, obstruction-free
- Union-find data structure
- **Work-stealing dequeues**
  - **Chase-Lev dequeue 2005**

Perspective: Work-stealing dequeues

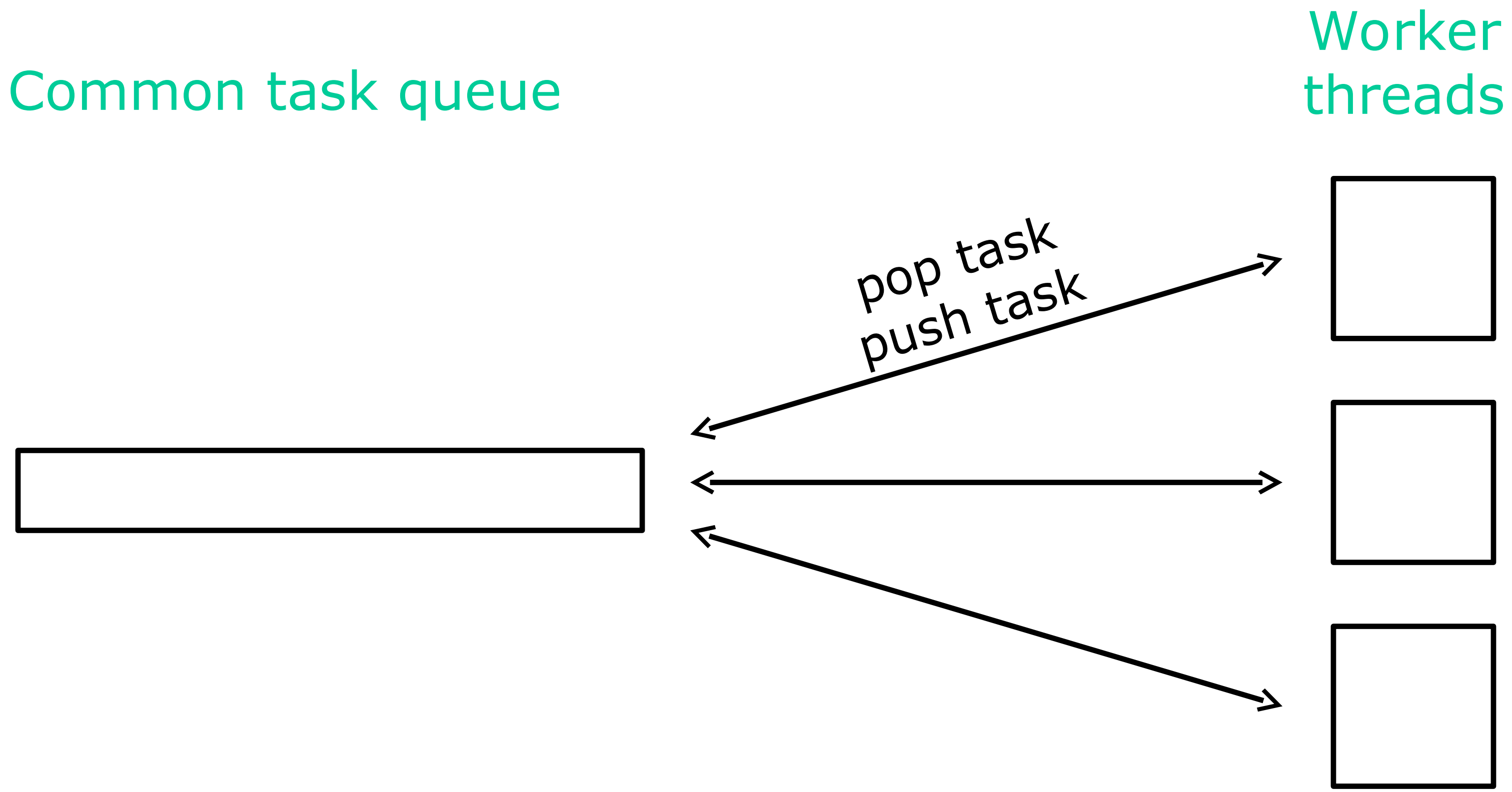
- Double-ended concurrent queues
- Used to implement
  - Java 7's Fork-Join framework, and Akka (wk 13-14)
  - Java 8's newWorkStealingPool executor
  - .NET 4.0 Task Parallel Library
- Chase and Lev: *Dynamic circular work-stealing queue*, SPAA 2005
- Michael, Vechev, Saraswat: *Idem-potent work stealing*, PPoPP 2009
- Leijen, Schulte, Burckhardt: *The design of a task parallel library*, OOPSLA 2009

PCPP exam Jan 2015

Java 8 source

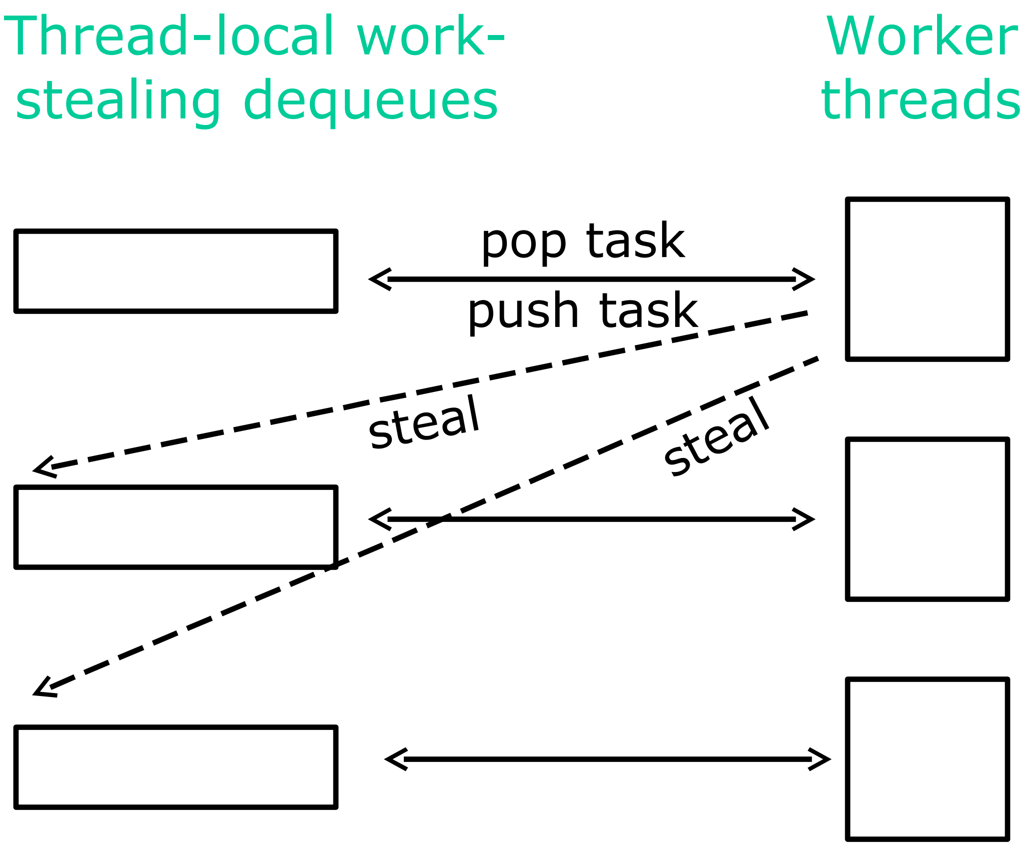
.NET TPL

A worker/task framework



- Worker threads pop and push tasks on queue
- **Not scalable** because single queue is used by many threads

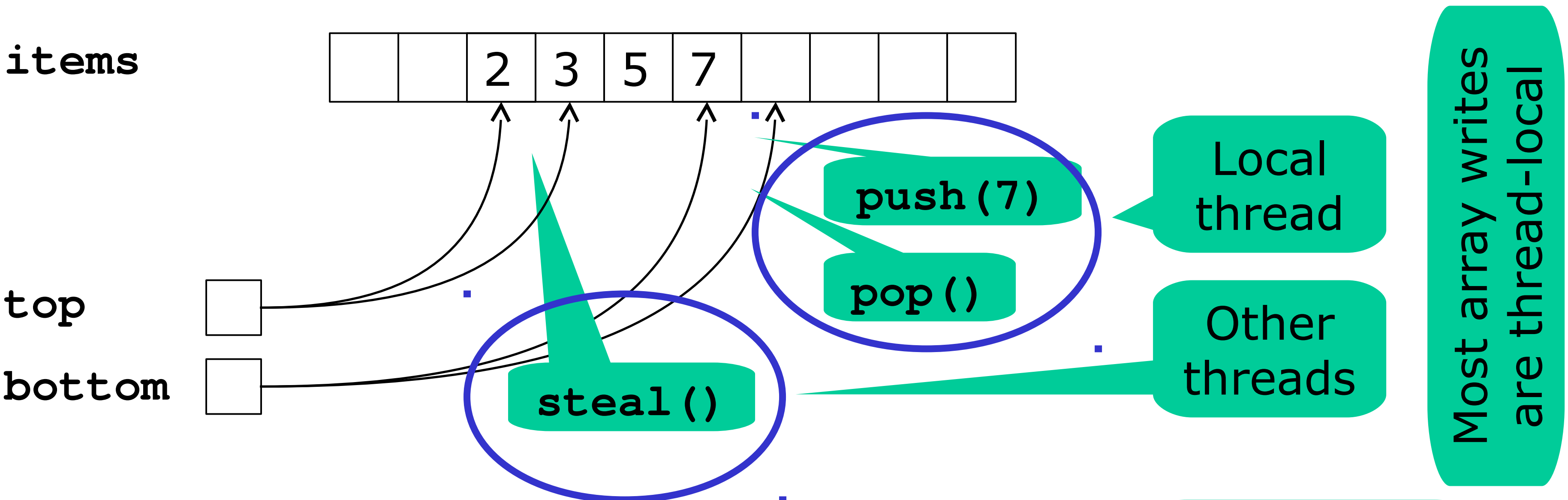
Better worker/task framework




```
interface WSDeque<T> {
  void push(T item);
  T pop();
  T steal();
}
```

- Fewer memory write conflicts:
  - Most queue accesses are from local thread only
  - Pop from bottom, steal from top, conflicts are rare
- **Much better scalability**

Chase-Lev workstealing queue (2005)




```
class ChaseLevDeque<T> {
  final T[] items;
  volatile long bottom = 0;
  final AtomicLong top = new AtomicLong();
  ...
}
```

Fixed size, for simplicity

Only the local thread writes

- **push** and **pop** at bottom: stack for local thread
- **steal** at top: queue for other threads

Chase-Lev push at bottom

```
public void push(T item) {
  final long b = bottom, t = top.get(), size = b - t;
  if (size == items.length)
    throw new RuntimeException("queue overflow");
  items[index(b, items.length)] = item;
  bottom = b+1;
}
```

TestChaseLevQueue.java

- This is thread-safe, even without locks or CAS
  - Only one thread calls **`push`**
  - So only one thread *updates* the **`bottom`** field
  - Other threads *read* it, so it must be volatile

Chase-Lev steal at top

```
public T steal() {
  final long t = top.get(), b = bottom, size = b - t;
  if (size <= 0)
    return null;
  else {
    T result = items[index(t, items.length)];
    if (top.compareAndSet(t, t+1))
      return result;
    else
      return null;
  }
}
```

Empty before call

Somebody else stole top item

TestChaseLevQueue.java

- Several threads may call **steal**
  - And try to increment **top**, hence an AtomicLong
  - So **steal** may fail (with null) due to interference
    - even if queue is non-empty
  - OK because callers keep stealing until success

Chase-Lev pop at bottom

```
public T pop() {
  final long b = bottom - 1;
  bottom = b;
  final long t = top.get(), afterSize = b - t;
  if (afterSize < 0) {
    bottom = t;
    return null;
  } else {
    T result = items[index(b, items.length)];
    if (afterSize > 0)
      return result;
    else {
      if (!top.compareAndSet(t, t+1))
        result = null;
      bottom = t+1;
      return result;
    }
  }
}
```

Empty before call

Non-empty after call

Became empty

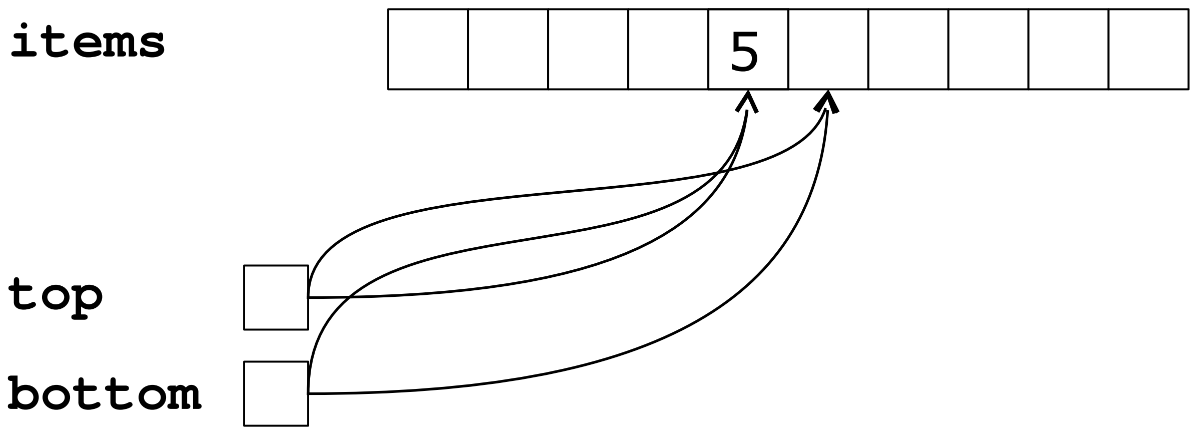
… so write **top** then set **bottom**

Oops, somebody stole last item

TestChaseLevQueue.java

Why does pop update top?

- If **pop** takes the last item, it may clash with a concurrent **steal** operation
  - Because then **size == 0** and so **bottom == top**



- Hence **pop** must
  - check **top** is unchanged (nobody stole item yet)
  - if so, update **top** so stealers know item is taken
  - both done by **top.compareAndSet(t, t+1)**
  - no ABA problem because **top** always increases

Linearization points

- When does **`steal`** take effect?
- When does **`push`** take effect?
- When does **`pop`** take effect?

This week

- Reading
  - Michael & Scott 1996: *Simple, fast, and practical non-blocking and blocking concurrent queue ...*
  - Chase & Lev 2005: *Dynamic circular work-stealing deque*, sections 1, 2, 5
- Exercises
  - Test and experiment with the lock-free Michael & Scott queue
  - Test and experiment with the Chase-Lev work-stealing dequeue
- Read before next week – Claus lectures!
  - Armstrong, Virding, Williams: *Concurrent programming in Erlang*, chapters 1, 2, 5, 11.1