Lecture 11: advanced locking

Anderson Queue Lock, CLH, MCS, check-then-act, spin-then-park

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https://github.com/Svazars/parallel-programming/blob/main/slides/pdf/l11.pdf

In previous episodes

Hardware optimizations

- Store buffering, Load buffering, Invalidate Queues, Interconnect topology

Compiler optimizations

- reorder/invent/delete memory operations, prevent it via compiler barriers

Abstractions and algorithms

- Events, Precedence, Consistency
- Mutual exclusion: Peterson‘s algorithm, FilterLock
- Progress conditions: wait-free, lock-free, obstruction-free, starvation-free, deadlock-free
- Read-Modify-Write operations: lock-free stack

Language memory model – bridge between

- chaos of hardware, anarchy of compiler optimizations
- consistency requirements for high-level concurrent algorithms

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- Read-Modify-Write operations: lock-free stack

Language memory model – bridge between

- chaos of hardware, anarchy of compiler optimizations
- consistency requirements for high-level concurrent algorithms

It is time to approach fundamental problems yet again, but using advanced techniques

Lecture plan

1. Locking revisited
2. Array-based locks: Anderson Queue Lock
3. Queue-based locks: CLH
4. Queue-based locks: MCS
5. Challenges: interrupt/timeout
6. Challenges: memory management
7. Spin-then-park
8. Summary

Lecture plan

Question time

Question: Name 3 key properties of concurrent algorithm that we are studying in this course

Locking revisited

Safety
Progress
Performance

Locking revisited

Safety

- Mutual exclusion

Progress
Performance

Locking revisited

Safety

- Mutual exclusion

Lecture 6:

Mutual exclusion:

- Critical sections of different threads do not overlap. $\forall A, B, k, j\ CS_A^k \rightarrow CS_B^j$ or $CS_B^j \rightarrow CS_A^k$

Progress

Performance

Locking revisited

Safety

- Mutual exclusion
- Deadlock-freedom

Progress
Performance

Locking revisited

Safety

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Lecture 6:
Freedom from deadlock:

- If some thread attempts to acquire the lock, then some thread will succeed in acquiring the lock. If thread `A` calls `lock()` but never acquires the lock, then other threads must be completing an infinite number of critical sections.

Progress
Performance

Locking revisited

Safety

- Mutual exclusion
- Deadlock-freedom
- Visibility

Progress
Performance

Locking revisited

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- Mutual exclusion
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Lecture 10:

- Compiler barriers
- Memory barriers
- Consistency guarantees from language memory model

Progress

Performance

Locking revisited

Safety

- Mutual exclusion, Deadlock-freedom, Visibility

Progress

Performance

Locking revisited

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Progress

- Starvation-freedom

Performance

Locking revisited

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- Mutual exclusion, Deadlock-freedom, Visibility

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Lecture 6:

Freedom from starvation (lockout freedom):

- Every thread that attempts to acquire the lock eventually succeeds. Every call to `lock()` eventually returns.

Performance

Locking revisited

Safety

- Mutual exclusion, Deadlock-freedom, Visibility

Progress

- Starvation-freedom
- Fairness

Locking revisited

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Lecture 2: admission policy

Competing threads	How to manage EnterSet?	How to manage ArriveSet?
• **owner**	• LIFO	• try-lock-then-wait (ArriveSet > EnterSet)
• **waiters** (EnterSet)	• FIFO	• if-busy-then-wait (ArriveSet < EnterSet)
• **arriving threads** (ArriveSet)	• priority/random	• random or heuristic

Locking revisited

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Locking revisited

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Performance

- Memory overhead

Locking revisited

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- Mutual exclusion, Deadlock-freedom, Visibility

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- Memory overhead

Lecture 6

Theorem

Mutual exclusion for N threads requires read-write of at least N distinct locations

Lecture 8

Theorem

`compareAndSet` has ∞ consensus number

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Safety

- Mutual exclusion, Deadlock-freedom, Visibility

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- Starvation-freedom, Fairness

Performance

- Memory overhead
- Throughput in uncontended mode (fast path)

Locking revisited

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- Memory overhead
- Throughput in uncontended mode (fast path)
- Efficiency in contended mode

Question time

Question: What is lock convoy?

Question time

Question: What is thundering herd problem?

Locking revisited

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- Mutual exclusion, Deadlock-freedom, Visibility

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Performance

- Memory overhead
- Throughput in uncontended mode (fast path)
- Efficiency in contended mode
- Scalability

Question time

Question: Mutex guarantees only one thread will execute critical section at any moment of time. What do you mean under "scalability" of mutex?

Question time

Question: What is invalidation storm?

Locking revisited

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- Backoff policy

Question time

Question: What is backoff strategy and which trade-offs it implies?

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Simplest non-reenterable mutex on `AtomicBoolean`?

TATAS lock

```
class TATASlock {
  private static final boolean LOCKED = true, UNLOCKED = false;
  private final AtomicBoolean state = new AtomicBoolean(UNLOCKED);
  private boolean tryLock() { return state.getAndSet(LOCKED) == UNLOCKED; }
  void lock() {
    while (true) {
      while (state.get() == LOCKED) {} // do not write if mutex is busy
      if (tryLock()) return;
  }}
  void unlock() { state.set(UNLOCKED); }
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Safety: Mutual exclusion

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Safety: Deadlock-freedom

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Safety: Visibility

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Progress: Starvation-freedom

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Progress: Fairness

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Performance: Backoff policy

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Performance: Efficiency in contended mode

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Performance: Efficiency in contended mode
Hint: invalidation storm and quiescence time (Lecture 8)

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```

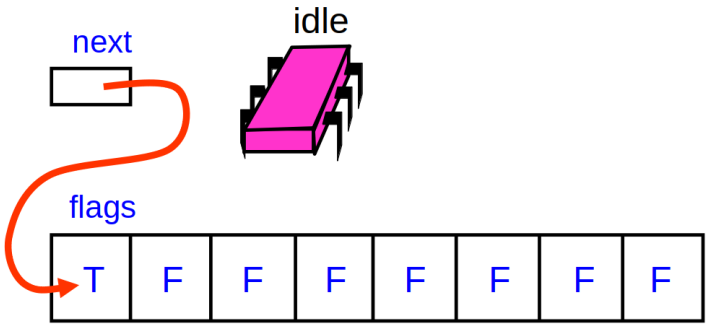
Idea: independent threads should spin on independent memory locations

Lecture plan

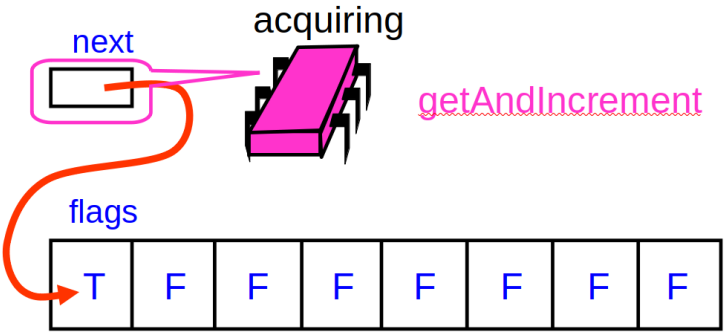
Anderson Queue Lock

- Avoid useless invalidations
  - By keeping a queue of threads
- Each thread
  - Notifies next in line
  - Without bothering the others

Anderson Queue Lock



Anderson Queue Lock



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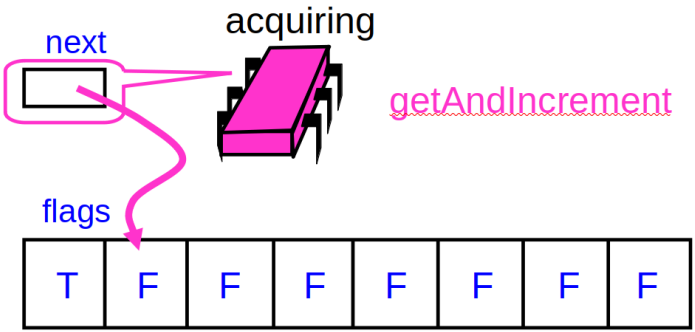

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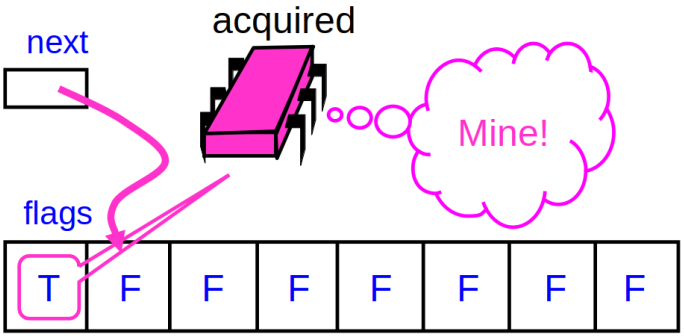

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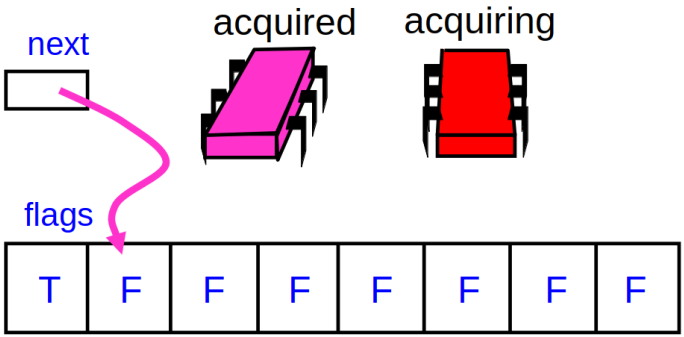

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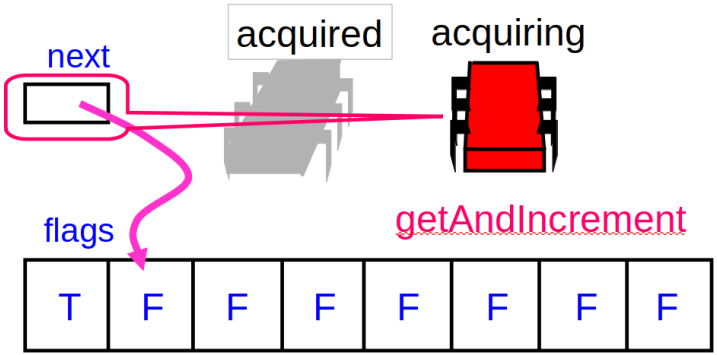

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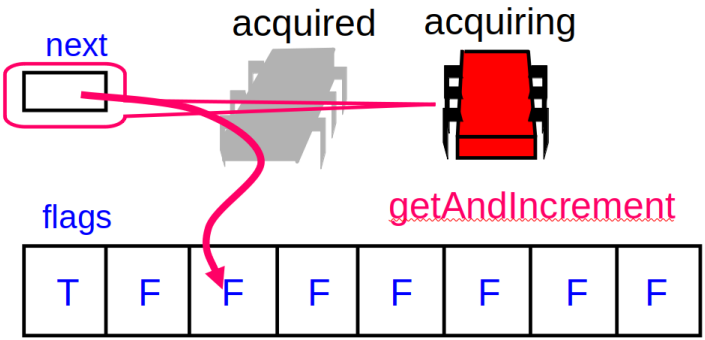

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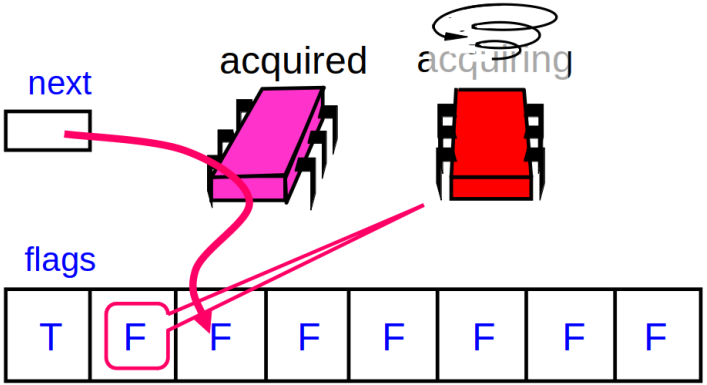

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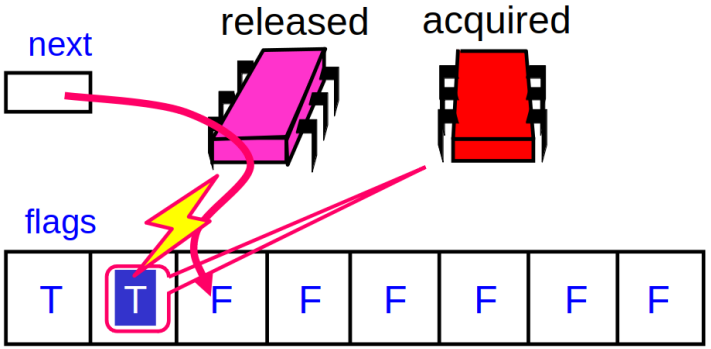
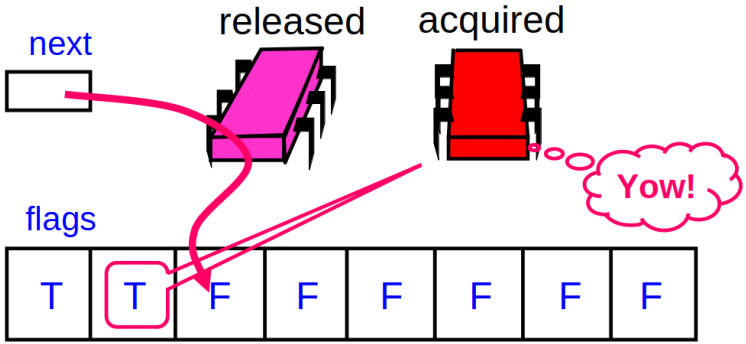


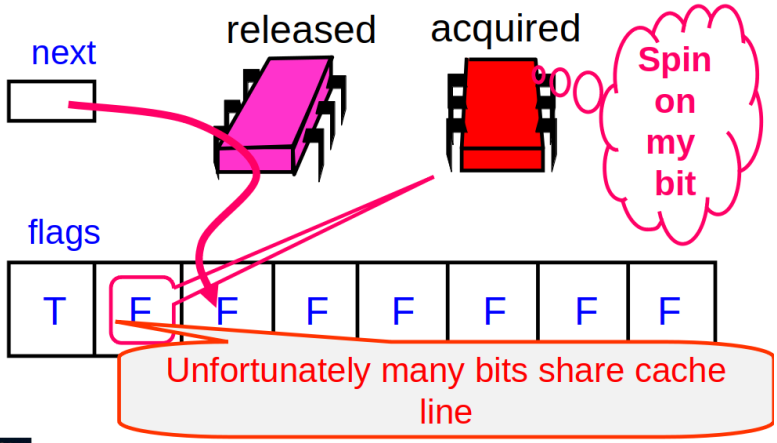
Anderson Queue Lock



Anderson Queue Lock

```
class ALock implements Lock {
  boolean[] flags = {true,false, ...,false}; // one flag per thread
  AtomicInteger next = new AtomicInteger(0); // next flag to use
  ThreadLocal<Integer> mySlot;               // thread-local variable
  public lock() {
    mySlot = next.getAndIncrement();         // take next slot
    while (flags[mySlot % n] == false) {};   // await
    flags[mySlot % n] = false;               // prepare slot for re-use
  }
  public unlock() {
    flags[(mySlot + 1) % n] = true;          // tell next thread to go
  }
```

False sharing



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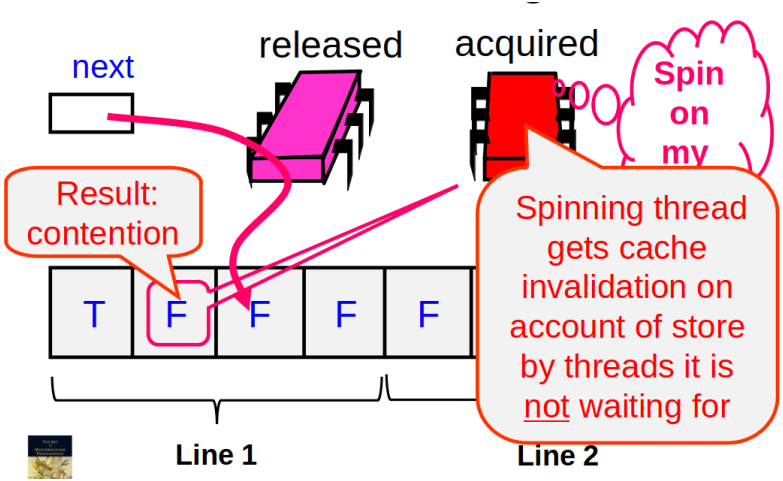
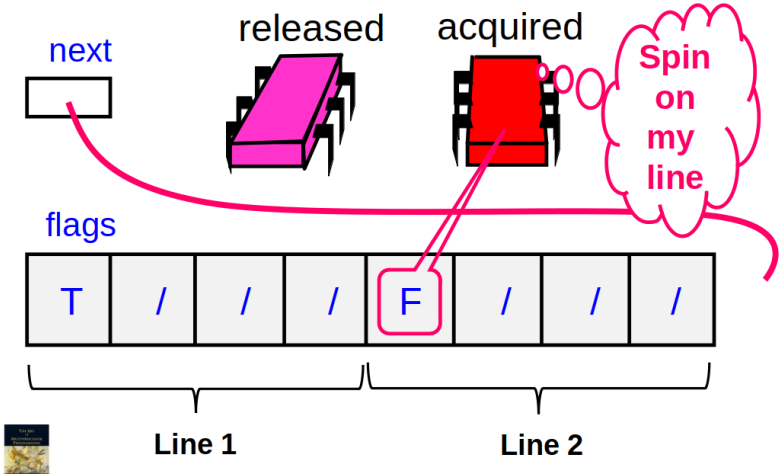


Solution: padding



Anderson Queue Lock

Safety

- Mutual exclusion, Deadlock-freedom, Visibility

Progress

- Starvation-freedom, **Fairness** (FIFO)

Performance

- Memory overhead
  - cache line per competitor
  - $O(LN)$ where L = number of locks, N = number of threads
  - what if number of threads is unknown?
- Efficiency in contended mode, Scalability
  - First "truly scalable" lock in our course
- Backoff policy
  - Spin me right round, baby, right round

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Idea: use O(1) thread-local memory to decrease memory overhead

Lecture plan

CLH lock

- CLH – Craig, Landin, Hagersten
- FIFO
- every thread has thread-private node to be used as a part of a queue

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We are discussing simplified implementation in Garbage-collected language (Java) to avoid manual memory management in concurrent environment

CLH lock

- CLH – Craig, Landin, Hagersten
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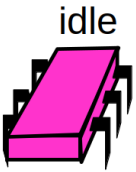
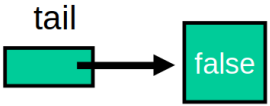
- every thread has thread-private node to be used as a part of a queue

We are discussing simplified implementation in Garbage-collected language (Java) to avoid manual memory management in concurrent environment
Reminder: in Lecture 8 we broke lock-free stack by using node pooling (ABA problem)

CLH lock: initialization





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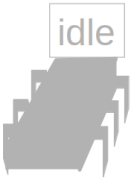

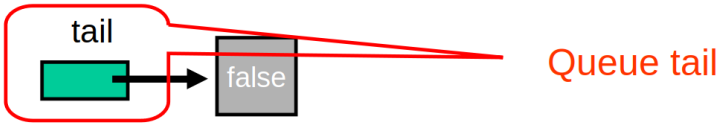

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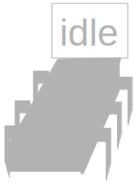

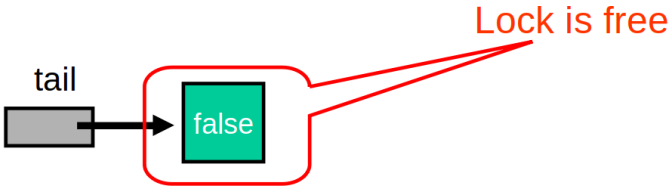

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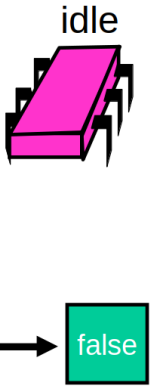
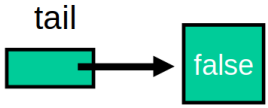


Purple Wants the Lock



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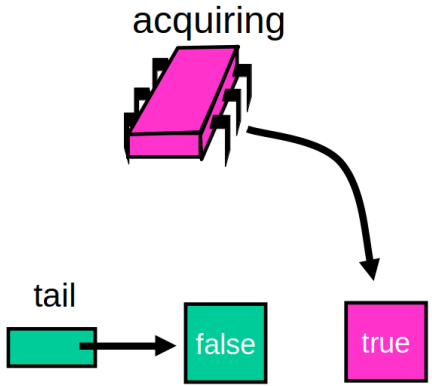

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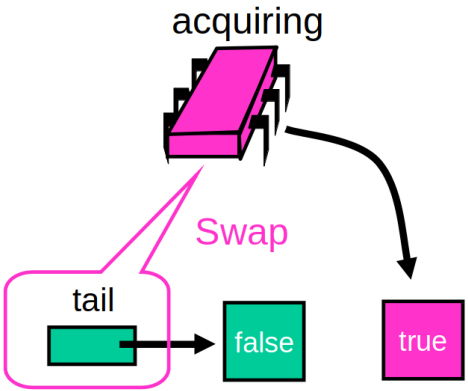
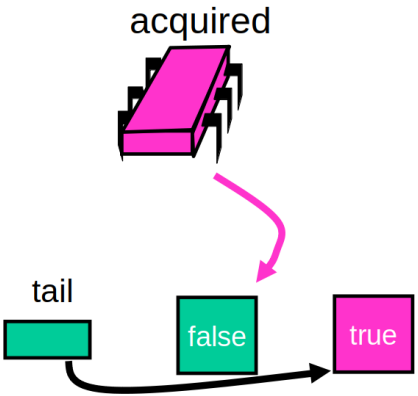
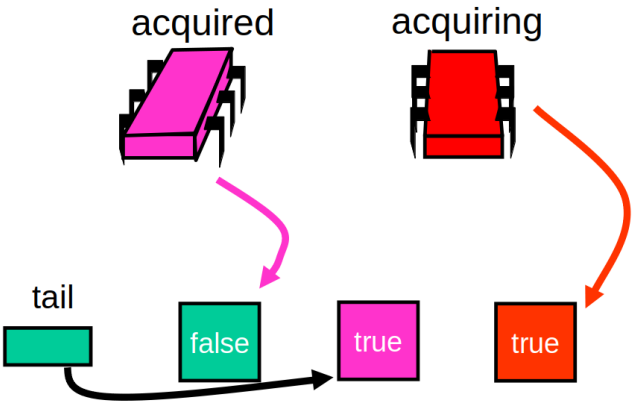


Purple Has the Lock



Red Wants the Lock



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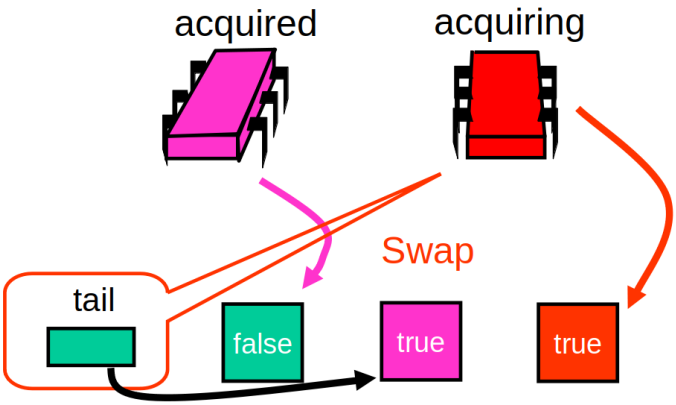

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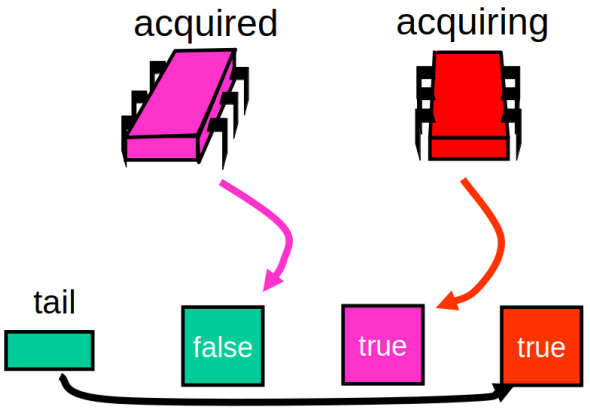

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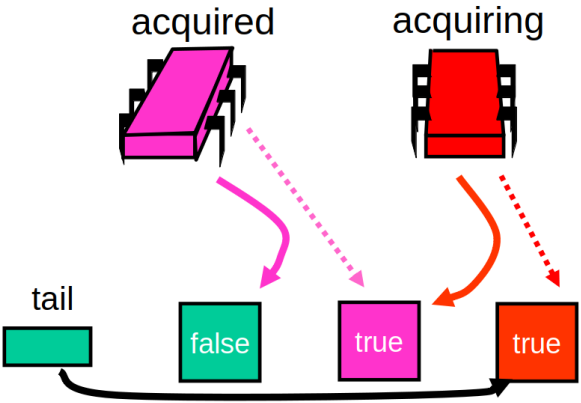

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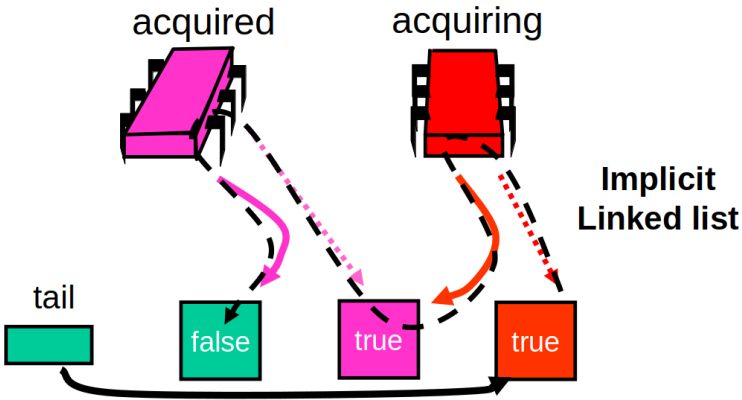

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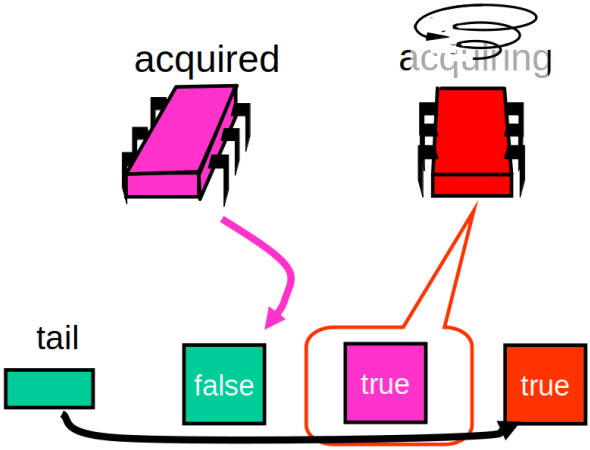

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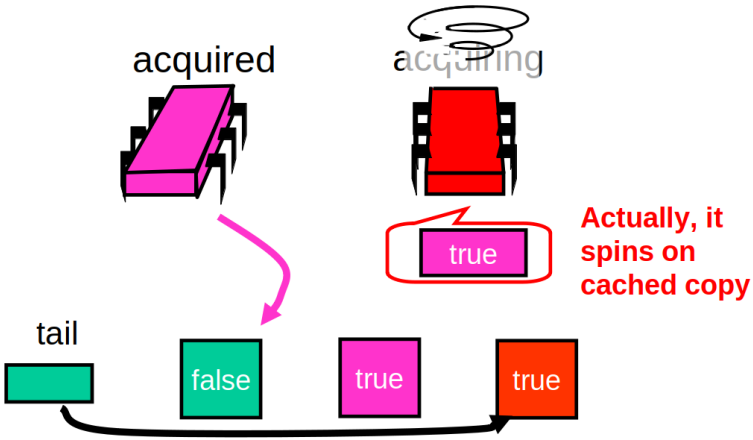
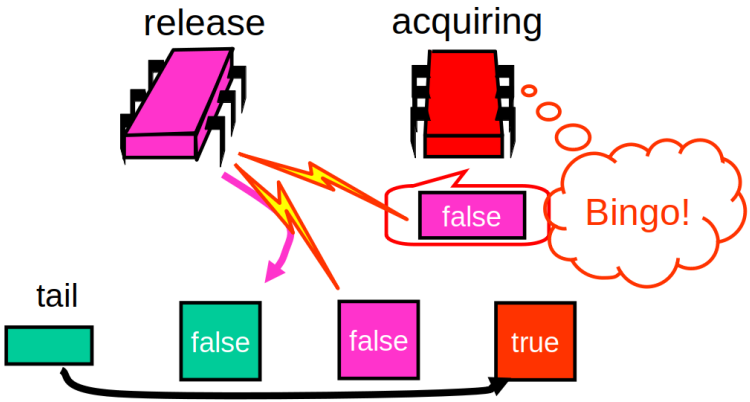
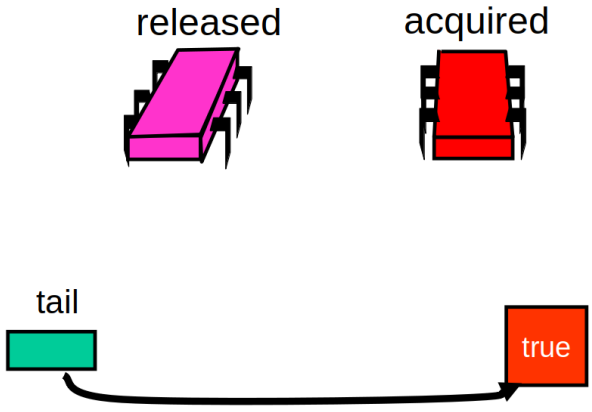


Purple Releases



Purple Releases



CLH

```
class Qnode { AtomicBoolean locked = new AtomicBoolean(); }
class CLHLock implements Lock {
  AtomicReference<Qnode> tail = new AtomicReference(new Qnode(false));
  ThreadLocal<Qnode> node;      // thread-local variable
  public void lock() {
    node.set(new Qnode(true)); // allocate my node as not released
    Qnode pred = tail.getAndSet(node.get()); // swap in my node
    while (pred.locked.get()) {} // spin until predecessor releases lock
  }
  public void unlock() {
    node.get().locked.set(false); // notify successor
    node.set(null);               // node is not needed by current thread
                                  // but could still be read by other threads
                                  // cannot `free` it
  }
```

CLH: summary

Safety

- Mutual exclusion, Deadlock-freedom, Visibility

Progress

- Starvation-freedom, **Fairness** (FIFO)

Performance

- Memory overhead
  - fixed-size node per competitor
  - $O(L + N)$ where L = number of locks, N = number of threads
- Efficiency in contended mode, Scalability
  - Second "truly scalable" lock in our course
  - Spins on random **remote** memory location
- Backoff policy
  - Spin me right round, baby, right round

CLH: locality

Contender of CLH lock spins on random **remote** memory location

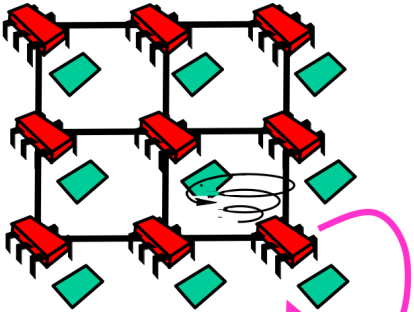
CLH: locality

Contender of CLH lock spins on random **remote** memory location
NUMA Architectures:

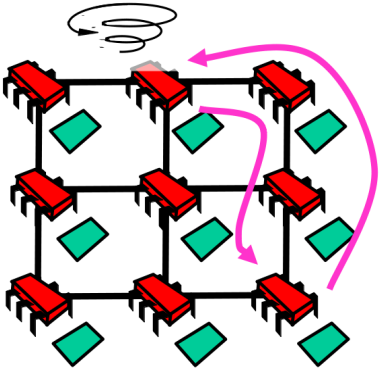
- **N**on-**U**niform **M**emory **A**rchitecture
- Illusion: flat shared memory
- Truth:
  - No caches (sometimes)
  - Some memory regions faster than others

NUMA and locking

Contender of CLH lock spins on random **remote** memory location



Spinning on local memory is fast

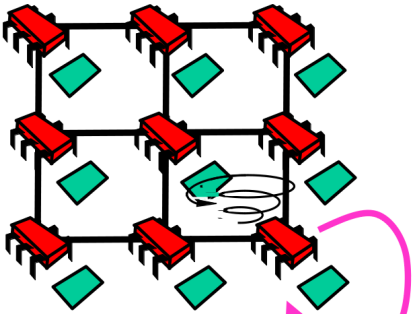


Spinning on remote memory is slow

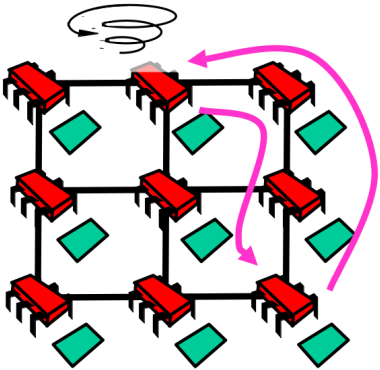
NUMA and locking

Contender of CLH lock spins on random **remote** memory location

Idea: spin on thread-private memory



Spinning on local memory is fast



Spinning on remote memory is slow

Lecture plan

MCS

- MCS – Mellor-Crummey and Scott
- FIFO
- every thread has thread-private node to be used as a part of a queue
- thread spins on this thread-local memory

MCS

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We are discussing simplified implementation in Garbage-collected language (Java) to avoid manual memory management in concurrent environment

MCS

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- FIFO
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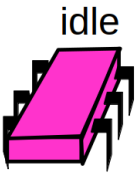
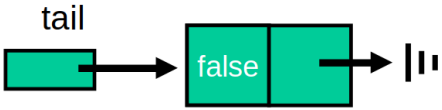
- thread spins on this thread-local memory

We are discussing simplified implementation in Garbage-collected language (Java) to avoid manual memory management in concurrent environment

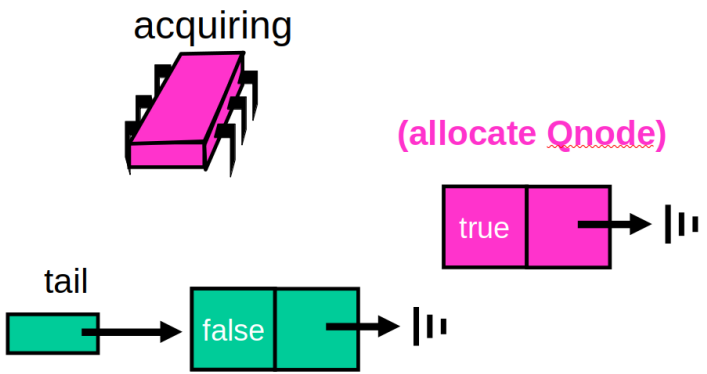
Reminder: in Lecture 8 we broke lock-free stack by using node pooling (ABA problem)

MCS lock: initialization





Acquiring



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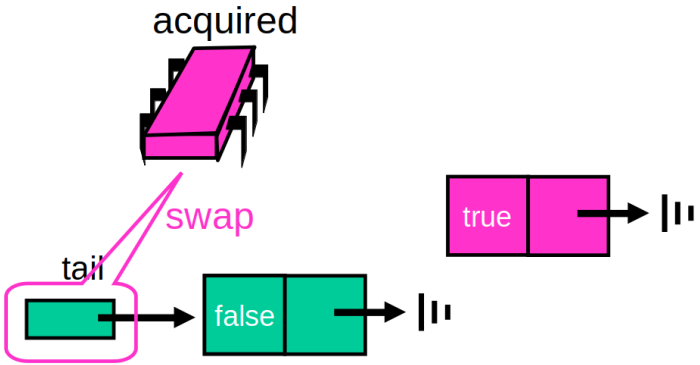

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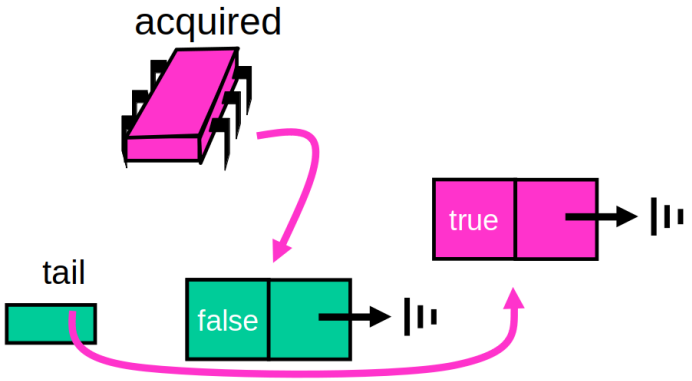

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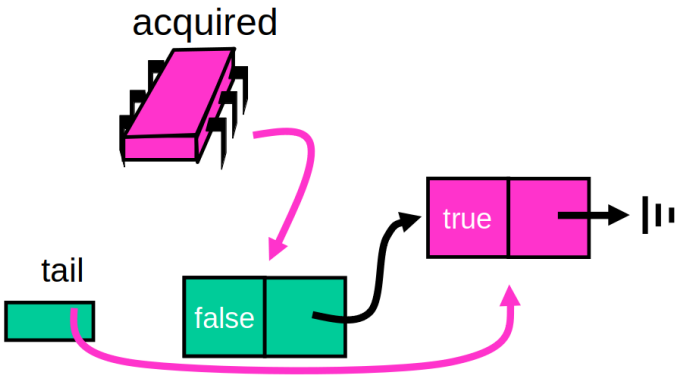

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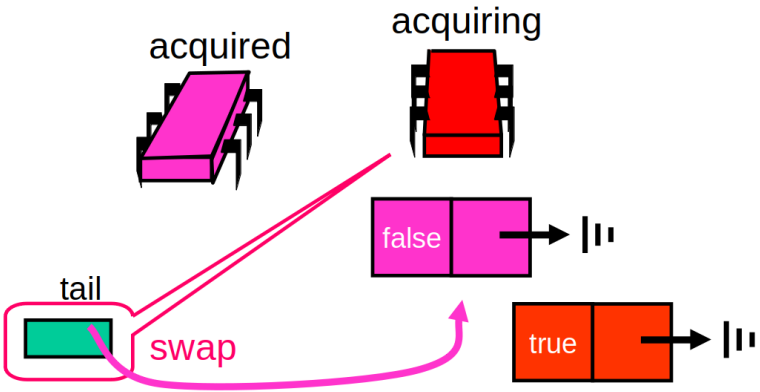

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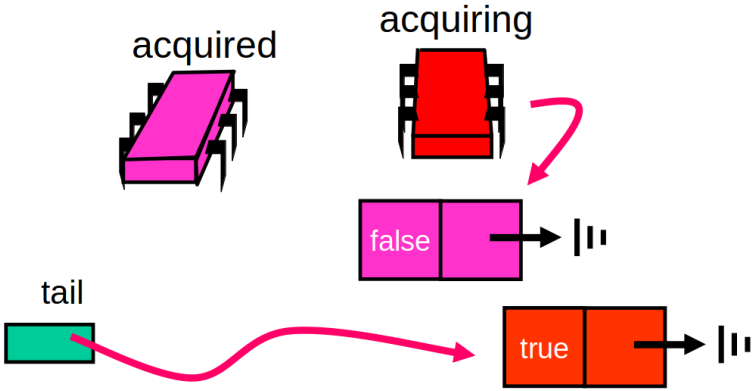

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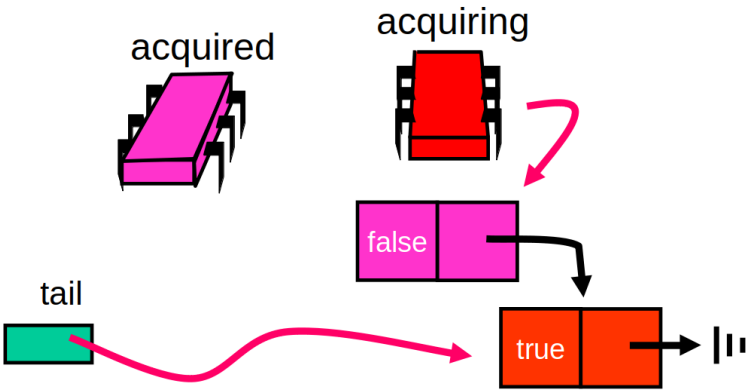

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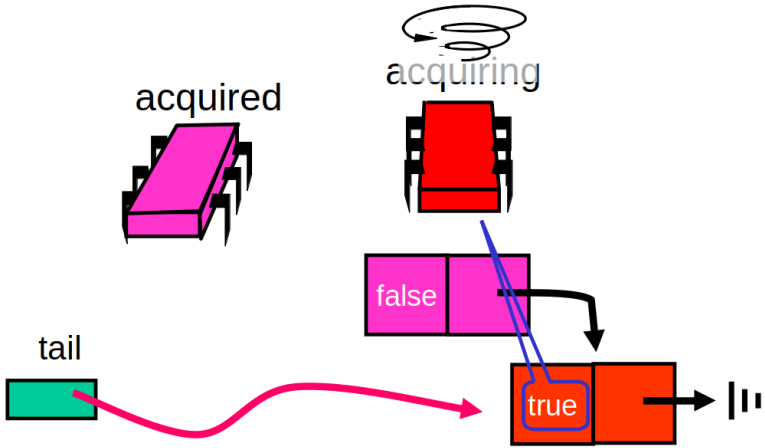

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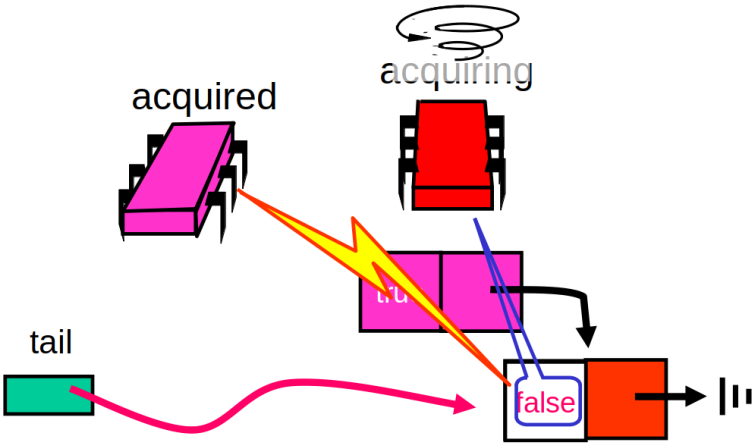

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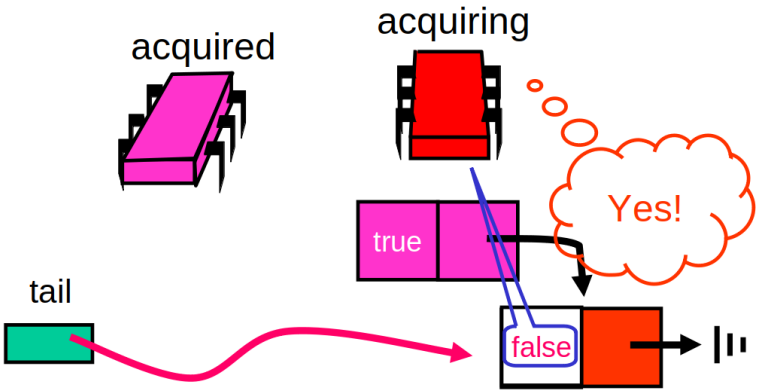


MCS: definitions

```
class Qnode {
  AtomicBoolean locked = new AtomicBoolean(false);
  AtomicReference<Qnode> next = new AtomicReference<Qnode>(null);
}
Qnode qnode, pred;
// shortcut: boolean assignment
  qnode.locked = true;    // pseudocode
  qnode.locked.set(true) // java code
// shortcut: reference assignment
  pred.next = qnode;      // pseudocode
  pred.next.set(qnode)    // java code
```

MCS: definitions

```
class Qnode {  var locked = new AtomicBoolean(false);
               var next = new AtomicReference<Qnode>(null); }
ThreadLocal<Qnode> node = ...
Qnode qnode, pred;
// shortcut: init thread locals
  node = new Qnode(...);     // pseudocode
  node.set(new Qnode(...)); // java code
// shortcut: use thread locals
  pred.next = node;           // pseudocode
  pred.next.set(node.get()); // java code
```

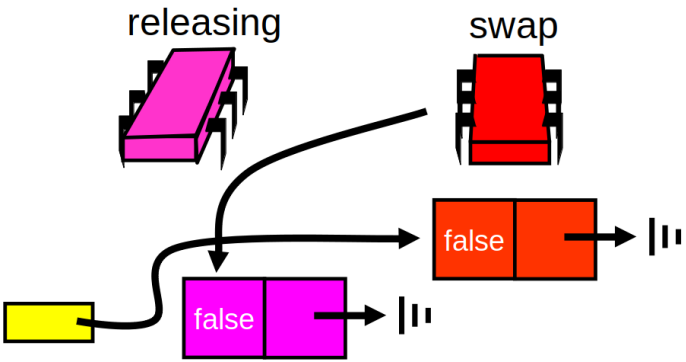
MCS: lock

```
class MCSLock implements Lock {
  AtomicReference<Qnode> tail = new AtomicReference<>(null);
  ThreadLocal<Qnode> node; // thread-local variable
  public void lock() {
    node = new Qnode(locked = false, next = null);
    Qnode pred = tail.getAndSet(node); // swap in my node
    if (pred != null) { // fix if queue was non-empty
      node.locked = true;
      pred.next = node; // now other thread could see my node
      while (node.locked) {} // wait until unlocked
    }
  }
}
```

MCS: unlock

```
class MCSLock implements Lock {
  AtomicReference<Qnode> tail = new AtomicReference<>(null);
  ThreadLocal<Qnode> node; // thread-local variable
  public void unlock() {
    if (node.next == null) { // missing successor?
      if (tail.CAS(node, null)) return; // if really no successor, return
      while (node.next == null) {} // otherwise wait for successor to catch up
    }
    node.next.locked = false; // pass lock to successor
    node.set(null); // not needed by current thread
                    // but could be read by others
  }
}
```

Purple release



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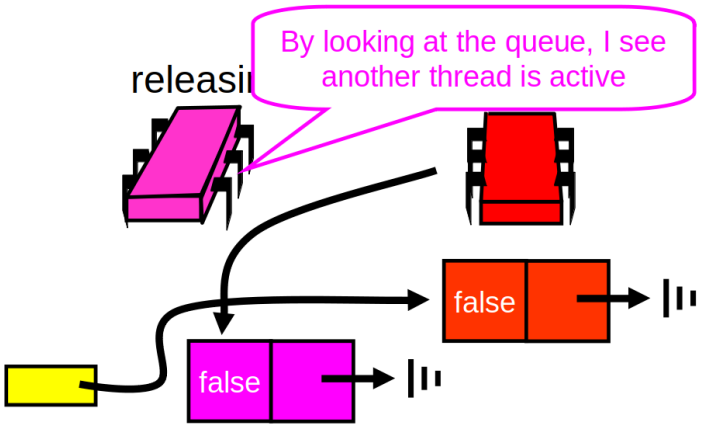

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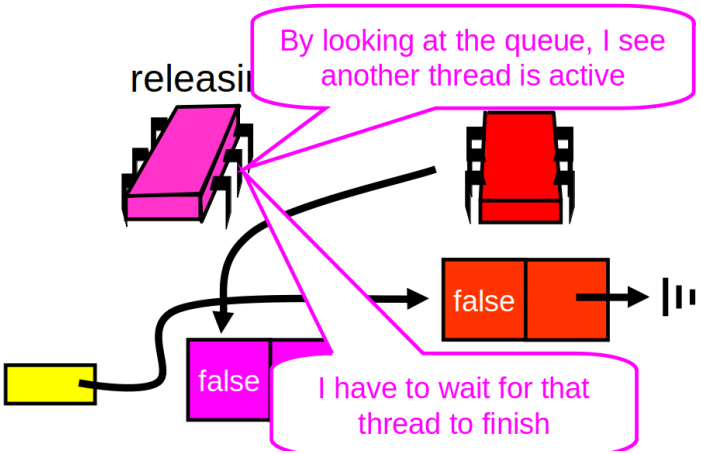

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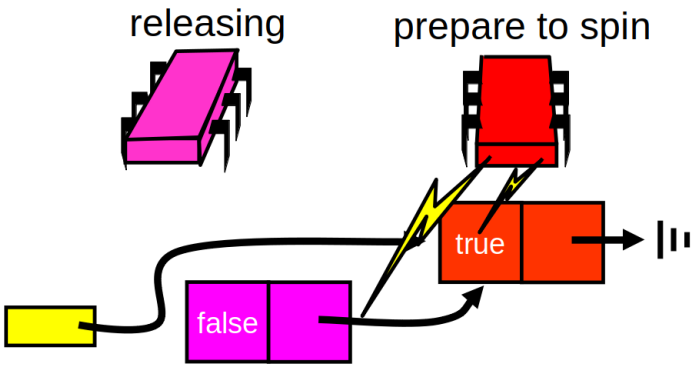

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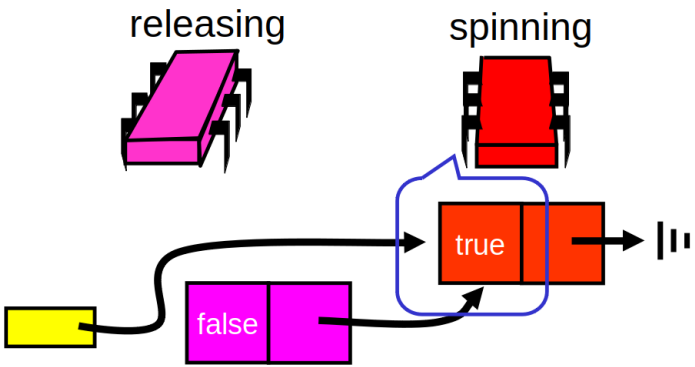

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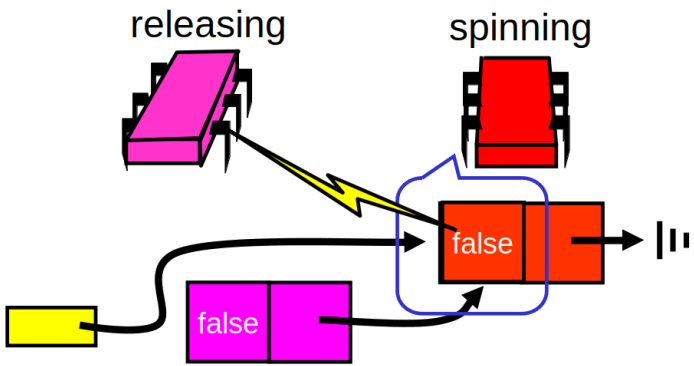

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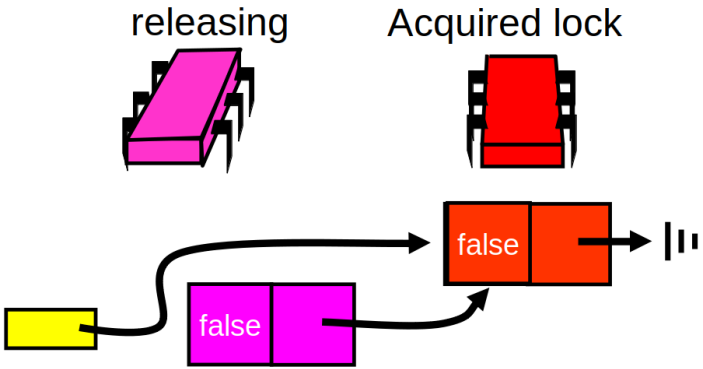

MCS: summary

Safety

- Mutual exclusion, Deadlock-freedom, Visibility

Progress

- Starvation-freedom, **Fairness** (FIFO)

Performance

- Memory overhead
  - fixed-size node per competitor
  - $O(L + N)$ where L = number of locks, N = number of threads
- Efficiency in contended mode, Scalability
  - Third "truly scalable" lock in our course
  - Spins on **local** memory location
- Backoff policy
  - Spin me right round, baby, right round

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The best lock ever?

Lecture plan

Abortable locks

What if you want to give up waiting for a lock?

- Timeout
- Database transaction aborted by user
- Task of current thread was cancelled

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- Task of current thread was cancelled
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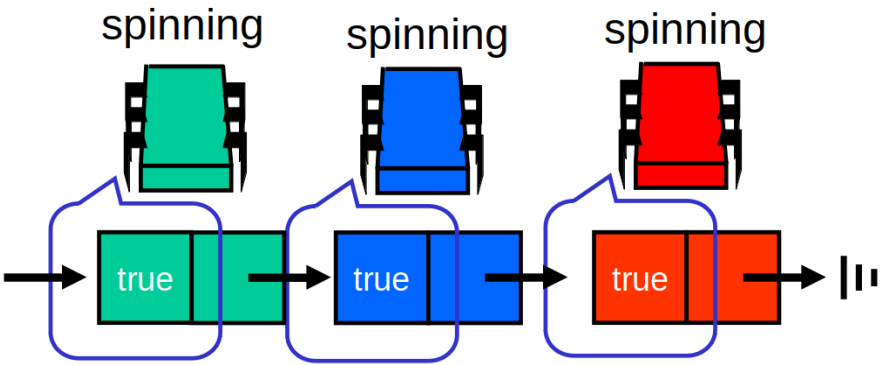
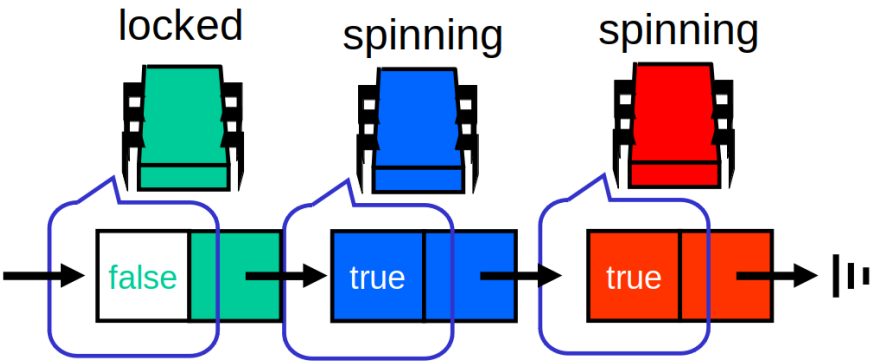
TATAS: just return, no problem
Queue-based locks: can't just quit

- Thread in line behind will starve
- Need a graceful way out

Abortable queue locks: problem



Abortable queue locks: problem



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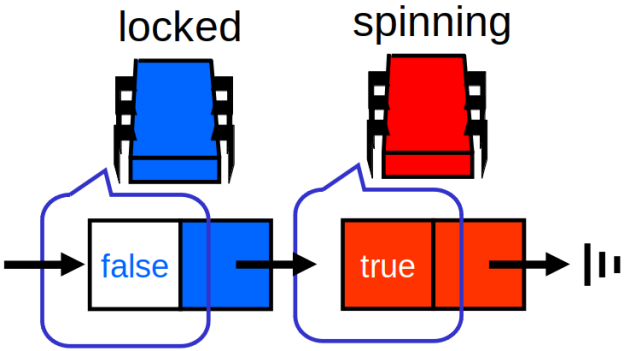

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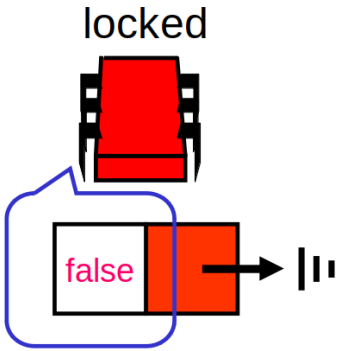

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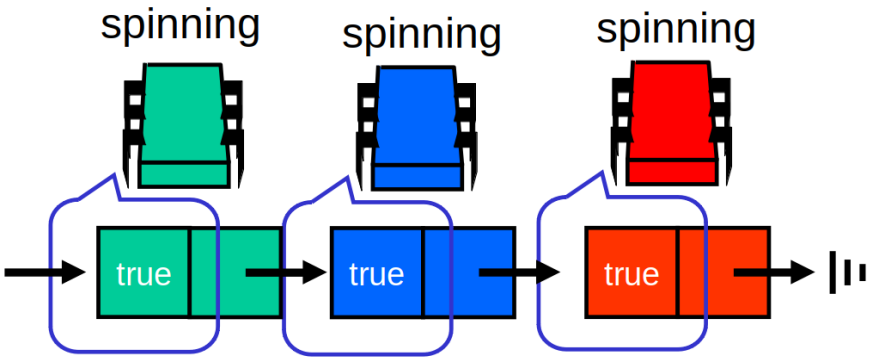

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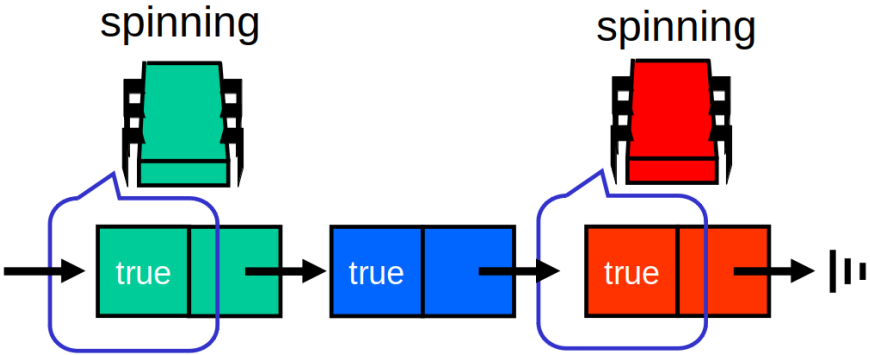
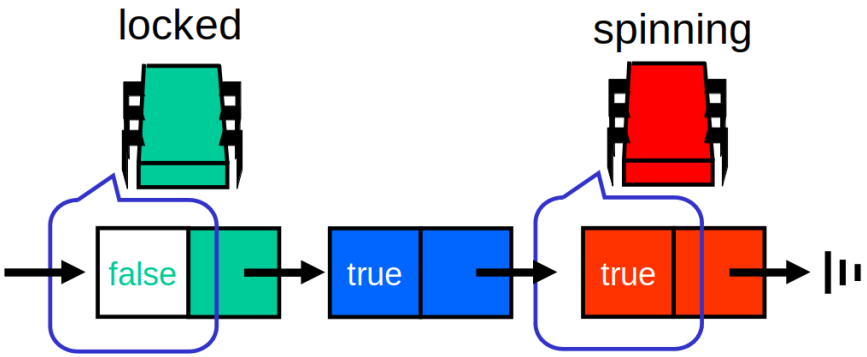


Abortable queue locks: problem



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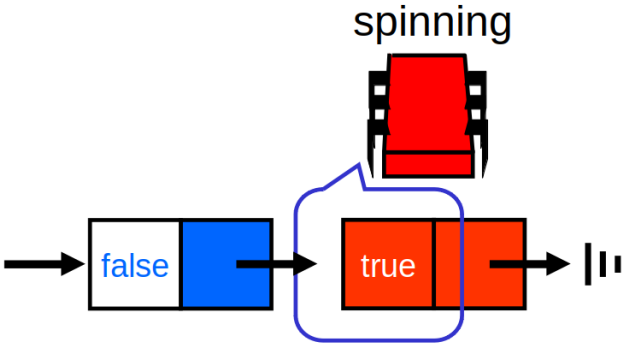

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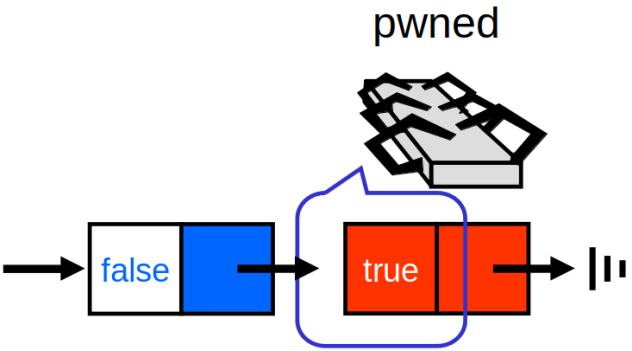

Abortable queue locks: solutions

Abortable queue locks: solutions

- Exist

Abortable queue locks: solutions

- Exist for some algorithms

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- Exist for some algorithms
- Have advantages and disadvantages

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See Section 7.6 "A Queue Lock with Timeouts" in "The Art of Multiprocessor Programming"

Abortable queue locks: solutions

- Exist for some algorithms
- Have advantages and disadvantages
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See Section 7.6 "A Queue Lock with Timeouts" in "The Art of Multiprocessor Programming"
We will highly appreciate if you will not do THIS in your 3rd critical task

Lecture plan

Reusing node from queue-based lock

Common problems with memory management in concurrent environments

Reusing node from queue-based lock

Common problems with memory management in concurrent environments

- ABA problem

Reusing node from queue-based lock

Common problems with memory management in concurrent environments

- ABA problem
  - reused node makes some `CAS` operation to succeed

Reusing node from queue-based lock

Common problems with memory management in concurrent environments

- ABA problem
  - reused node makes some `CAS` operation to succeed
  - which is incorrect, "identity" of node changed (it is "other" node)

Reusing node from queue-based lock

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- Inconsistent state (pending write)

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- ABA problem
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  - Thread A observed node as "previous" in queue

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    - plan to write `node.locked = false`

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    - context switch

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  - Thread B advanced queue, marked node as removed

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  - Thread C reused node: `node.locked = true`

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    - plan to write `node.locked = false`
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  - Thread B advanced queue, marked node as removed
  - Thread C reused node: `node.locked = true`
  - Thread A wake-ups and "spoils" node

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Reusing node from queue-based lock

Common problems with memory management in concurrent environments

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Reusing node from queue-based lock

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  - Thread A published thread-local node

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  - Thread A published thread-local node
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  - Thread A published thread-local node
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  - Thread A published thread-local node
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  - Thread A published thread-local node
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    - saved to local variable
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    - context switch
  - Thread A entered lock
  - Thread A released lock
  - Thread A finished

Reusing node from queue-based lock

Common problems with memory management in concurrent environments

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- Inconsistent state (pending write)
- Use-after-free
  - Thread A published thread-local node
  - Thread B observed node as "previous" in queue
    - saved to local variable
    - plan to read
    - context switch
  - Thread A entered lock
  - Thread A released lock
  - Thread A finished
  - Thread B reads from already freed memory

Reusing node from queue-based lock

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- Inconsistent state (pending write)
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Reusing node from queue-based lock

Common problems with memory management in concurrent environments

- ABA problem
- Inconsistent state (pending write)
- Use-after-free
- Many more...

Reusing node from queue-based lock

Common problems with memory management in concurrent environments

- ABA problem, Inconsistent state (pending write), Use-after-free, ...

Reusing node from queue-based lock

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Automatic memory management tremendously simplify development of concurrent algorithms

Reusing node from queue-based lock

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- There are implementations of CLH/MCS with node reuse[1]

[1] Chapter 7 in "The Art of Multiprocessor Programming"

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- Developing custom algorithms is hard

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Automatic memory management tremendously simplify development of concurrent algorithms

- There are implementations of CLH/MCS with node reuse[1]
- Developing custom algorithms is hard see KSUH story
  - Hydraconf "Java Path Finder: going to Mars without bugs and deadlocks"[2]
  - Heisenbug "Java Path Finder: летим на Марс без багов и дедлоков"[3]

[1] Chapter 7 in "The Art of Multiprocessor Programming"

[2] https://youtu.be/dgHbSL_aDsO?si=vi81xieQ4zKRECQG

[3] https://youtu.be/sQSwShW_IlI?si=ZMlKKLQxMZYhk1T7

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- "Atomic weapons" from Herb Sutter is a good way to dive in[4]

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- "Atomic weapons" from Herb Sutter is a good way to dive in[4]
- Using `std::shared_ptr` everywhere could be a bad idea[5]

[4] https://youtu.be/A8eCGOqgvH4

[5] https://pvs-studio.ru/ru/blog/posts/cpp/1174/#ID1DE383AA76

Lecture plan

Backoff policy revisited

```
class TATAS_Exponential_Backoff {
  void lock() {
    int delay = MIN_DELAY;
    while (true) {
      while (state.get() == LOCKED) {} // read-only polling
      if (lock.getAndSet(LOCKED) == UNLOCKED) return; // return on success
      sleep(random() % delay); // delay next write request on failure
      delay = Math.min(delay * 2, MAX_DELAY); // keep delay within bounds
    }}
  void unlock() { state.set(UNLOCKED); }
}
```

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Trade-off: time-to-react (latency) vs throughput (CPU)

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Trade-off: time-to-react (latency) vs throughput (CPU)

Idea: wake-up as soon as lock ready but not earlier

Question time

Question: Which concurrent primitive helps one thread to inform other thread that some event has happened?

Spin-then-park: idea

`LockSupport.park`, `LockSupport.unpark`[6]

```
boolean tryLock() { return lock.getAndSet(LOCKED) == UNLOCKED; }
void lock() {
  try { while (true) {
    for (int i = 0; i < SPIN; i++) { if (tryLock()) return; }
    enterSet.registerWaiter(currentThread()); // "wake-up me on unlock"
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  }} finally { enterSet.removeIfPresent(currentThread()); }}
void unlock() {
  state.set(UNLOCKED);
  enterSet.unparkAllWaiters(); } // wake-up all registered threads
```

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

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```

Do you see thundering herd problem here?

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

Spin-then-park: idea

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void unlock() {
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  enterSet.unparkOneWaiter(); } // wake-up one of registered threads
```

Do you see race condition here?

Check-then-act race condition

Race condition:

- Thread A sees occupied lock (`check`), decides to park
- Thread B releases lock, notifies all pending threads (e.g. nobody)
- Thread A sleeps on condition variable (act)

Question time

Question: Concurrent protocol "fires" message in inappropriate time (when `EnterSet` is empty). How do we call it?

Check-then-act

One of the most common high-level errors in concurrent algorithms

Check-then-act

One of the most common high-level errors in concurrent algorithms

- Thread A observes system state (`check`)

Check-then-act

One of the most common high-level errors in concurrent algorithms

- Thread A observes system state (`check`)
- Thread B changes system state

Check-then-act

One of the most common high-level errors in concurrent algorithms

- Thread A observes system state (`check`)
- Thread B changes system state
- Thread A does something (`act`) which is incorrect for new system state

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Solutions:

Check-then-act

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Solutions:

- atomic transaction (check-then-act under lock)

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  - "missed signal is not a problem"

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  - "missed signal is not a problem"
- rework protocol

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- algorithm tolerates "inconsistent actions"
  - "missed signal is not a problem"
- rework protocol
  - "never miss signal"

Spin-then-park with timeouts

"Missed signal is not a problem"

```
void lock() {
  try { while (true) {
    for (int i = 0; i < SPIN; i++) { if (tryLock()) return; }
    enterSet.registerWaiter(currentThread()); // "wake-up me on unlock"
    currentThread().park(1_000); // fixed time sleep
  }} finally { enterSet.removeIfPresent(currentThread()); }}
void unlock() {
  state.set(UNLOCKED);
  enterSet.unparkOneWaiter(); } // wake-up one of registered threads
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void unlock() {
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```

Problem: many waiting threads will repeatedly wake-up and sleep

Spin-then-park with double check

"Never miss signal"

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    if (tryLock()) return;  // maybe unlock happened before register?
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```

Requires intricate reasoning for all possible interleavings of

- `tryLock`, `registerWaiter`, `park`, `unparkOneWaiter`

and assumes all of them are linearizable

Summary

Advanced alternatives for single-location TATAS

- Array-based lock: Anderson Queue Lock (spin on cache line indexed by `AtomicInteger`)
- Queue-based lock: CLH (spin on remote location, implicit linked list)
- Queue-based lock: MCS (spin on local location, explicit linked list)

Challenges with advanced locks

- cancellation/timeout support
- manual memory management

Spin-then-park optimization

- Better utilization of CPU and scheduling quantum
- Check-then-act race conditions should be avoided in implementation