Replication and Consistency

08 Spin Locking and Contention

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Thank you!

These slides are based on companion material of the following books:

- **The Art of Multiprocessor Programming** by Maurice Herlihy and Nir Shavit
- **Synchronization Algorithms and Concurrent Programming** by Gadi Taubenfeld

Previously on Replication and Consistency

- Models
  - Accurate (we never lied to you)
  - But idealized (we forgot to mention a few things)
- Protocols
  - Elegant
  - Essential
  - But naive

New Focus: Performance in Real Systems

- Models
  - More complicated (more details)
  - Still focus on principles (not soon to become obsolete)
- Protocols
  - Elegant (in their fashion)
  - Important (why else would we discuss them)
  - And realistic (more optimizations will be possible, though)

Mutual Exclusion, revisited

- Think of **performance**, not just correctness and progress
- Begin to understand how performance depends on our software properly utilizing the **multiprocessor machine's hardware**
- And get to know a collection of **locking algorithms**

If a processor doesn't get a lock . . .

Question

What can the processor do?

If a processor doesn't get a lock . . .

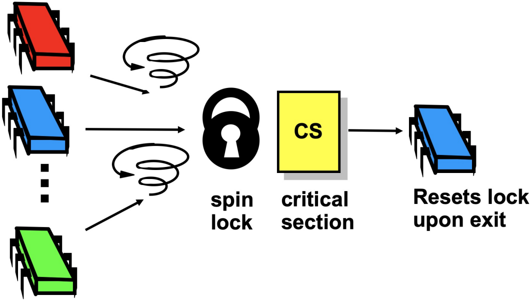
Question

What can the processor do?

- Keep trying
  - “spin” or “busy-wait” as with Filter and Bakery algorithm
  - Useful on multi-processors if expected delays are short
- Suspend and allow scheduler to schedule other processes
  - “blocking' ' as with Java's monitors
  - Good if delays are long
  - Always good on uniprocessors
- In practise, often mix of both strategies
  - Spin for a short time
  - Then, suspend

Basic Spin-Lock

- **Contention:** Multiple threads try to acquire lock at the same time
- Hoch can we avoid or alleviate contention?



Test-and-Set (TAS) revisited

- Machine-instruction on one word (*here:* for boolean values)
- Atomically, swap new value with prior value and return prior value
- Swapping in **`true`** is called Test-And-Set
- Aka `getAndSet()` in Java

```
\\ Package java.utitl.concurrent.atomic

public class AtomicBoolean {
  boolean value;

  // implemented as one hardware instruction
  public synchronized boolean getAndSet(boolean newValue) {
    boolean prior = value;
    value = newValue;
    return prior;
  }
}
```

Task: Design a lock using Test-and-Set (TAS)!

```java
class TASLock implements Lock{

  // if false, lock is free
  // if true, lock is taken
  AtomicBoolean state = new AtomicBoolean(false);

  void lock() {
    // TODO
  }

  void unlock() {
    // TODO
  }
}
```

Test-and-Set Lock

```
class TASLock {

  AtomicBoolean state = new AtomicBoolean(false);

  void lock() {
    while (state.getAndSet(true)) {}
  }

  void unlock() {
    state.set(false);
  }
}
```

Space Complexity

- TAS spin-lock has small “footprint”
  - N thread spin-lock uses $O(1)$ space
  - As opposed to $O(N)$ Peterson/Bakery

Question

How did we overcome the $\Omega(N)$ lower bound?

Space Complexity

- TAS spin-lock has small "footprint"
  - N thread spin-lock uses $O(1)$ space
  - As opposed to $O(N)$ Peterson/Bakery

Question

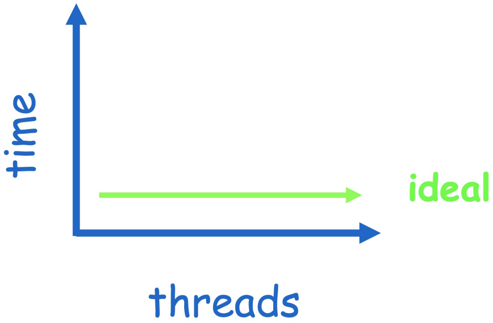
How did we overcome the $\Omega(N)$ lower bound?
⇒ Use an object with higher consensus number!

Performance Evaluation

- Experiment
  - Spawn N threads
  - Increment shared counter 1 million times
  - Work is split between the threads, i.e. each thread does $10^6/N$ increments
  - Each thread takes lock, increments a counter, releases lock
- How long should it take?
- How long does it take?

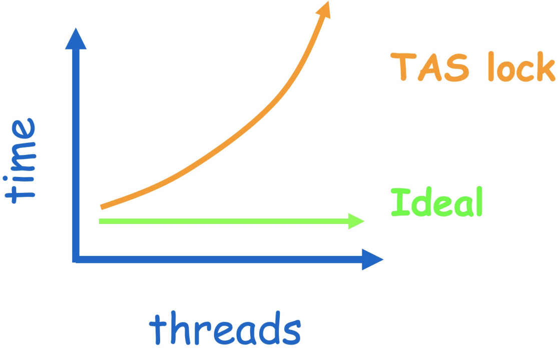
Hypothesis

- No speedup because lock is sequential bottleneck (Amadahl's law!)



Mystery 1

A typical evaluation looks like this:



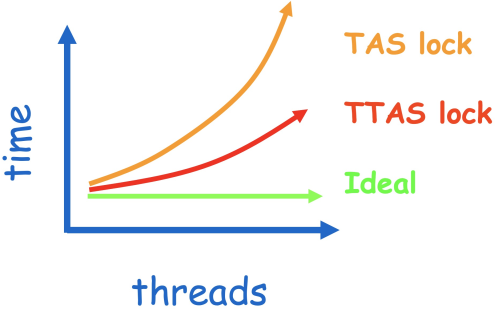
New approach: Test-and-Test-and-Set Locks

- Lurking stage
    - Wait until lock seems to be free
    - Spin while read returns true (lock taken)
- Pouncing state
    - As soon as lock seems to be available
    - Read returns false (lock free)
    - Call TAS to acquire lock
    - If TAS loses, back to lurking

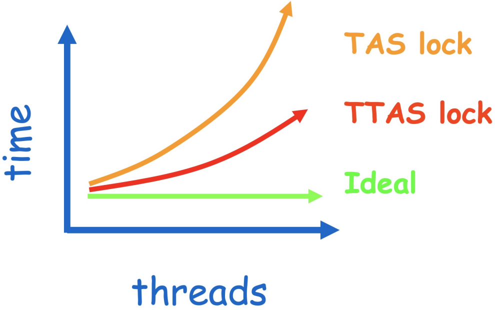
Test-and-Test-and-Set Locks

```
class TTASLock extends TASLock{
  void lock() {
    while (true) {
      while (state.get()) {} // Lurk
      if (!state.getAndSet(true)) // Pounce
        return;
  }
}
```

Mystery 2



Mystery 2



- Both TAS and TTAS do the same thing in our model
- But TTAS performs much better in actual evaluations
- Neither approach is ideal

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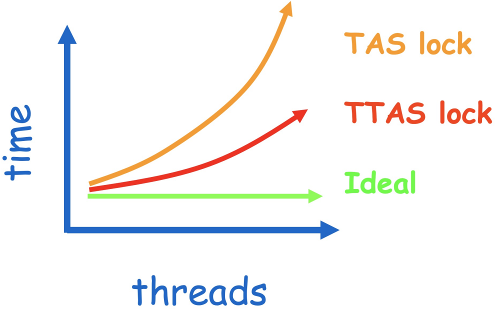
Mystery 2



- Both TAS and TTAS do the same thing in our model
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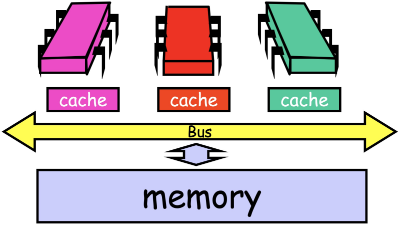
Our memory abstraction is broken! We need a more detailed model!

Bus-Based Architectures



- Random Access Memory (access time: 10s of cycles)
- Shared Bus as broadcast medium
  - One broadcaster at a time
  - Other processors and memory can passively listen
- Per-Processor Caches (access time: 1-2 cycles)

Cache Coherence

- We have lots of copies of data
  - Original copy in memory
  - Cached copies at processors
- If some processor modifies its own copy:
  - What do we do with the others?
  - How to avoid confusion about actual value?

Cache Coherence

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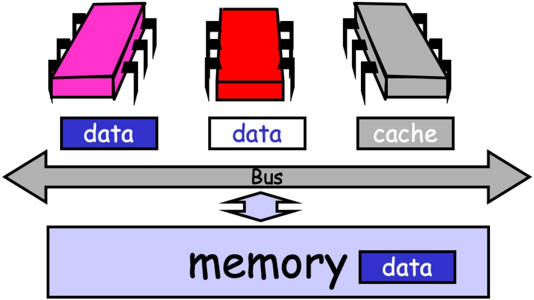
Cache coherence protocol!

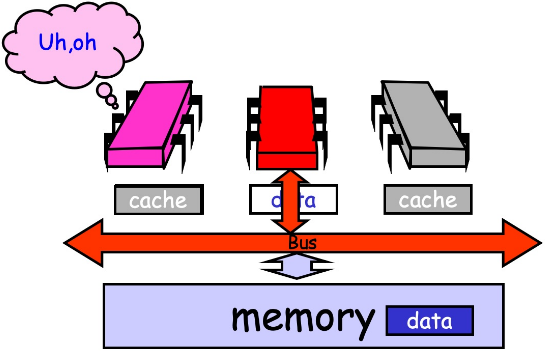
Write-Back Caches

- **Idea:** Accumulate changes in cache and write back when needed
  - Because we need cache for something else
  - Or because another processor wants to read the changed value
- On first modification, invalidate all other entries
- Cache entry can be marked as **dirty** (i.e. it must be eventually written back to main memory)

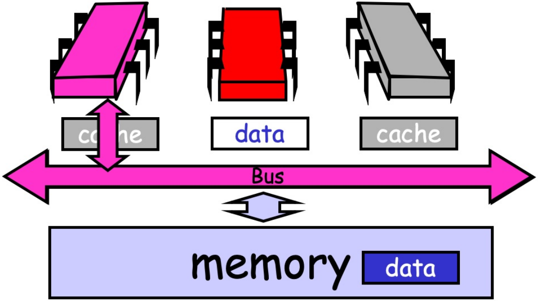
When a thread modifies its cache value, . . .



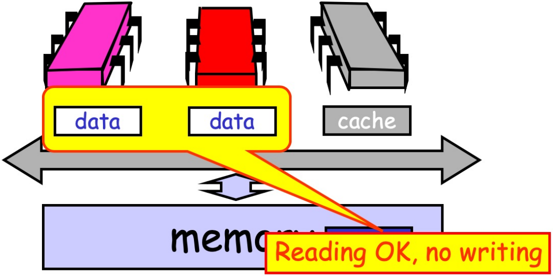
. . . it invalidates all other caches



When another thread want to read, . . .



. . . the owner responds



Mystery Explained!

TAS-Lock

- Spinning threads invalidate cache line with TAS, keeps bus busy
- Threads wanting to release lock is delayed behind spinners

TTAS-Lock

- Threads spin on local cache
- No bus use while lock is taken
- *Problem:* When lock is released, reads are satisfied sequentially on bus
- Eventually system **quiesces** after lock has been acquired

→ quiescence time linear in number of threads for bus architecture

Solution: Introduce Delay

“If the lock looks free, but I fail to get it, there must be lots of contention!”

$\Rightarrow$ Better to back off than to collide again

Solution: Introduce Delay

"If the lock looks free, but I fail to get it, there must be lots of contention!"

⇒ Better to back off than to collide again

Example: Exponential Backoff

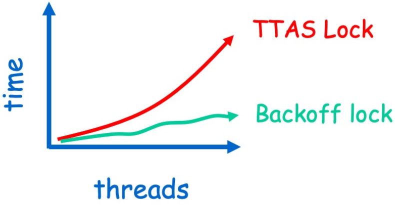
If I fail to get lock

- Wait random duration before retry
- Each subsequent failure doubles expected wait (up to fixed maximum)

Exponential Backoff Lock

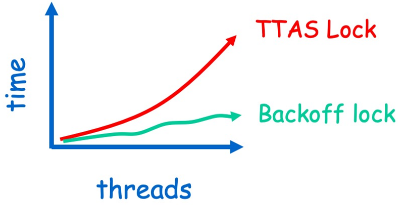
```
class Backoff extends TTASLock {

  void lock() {
    int delay = MIN_DELAY;
    while (true) {
        while (state.get()) {}
        if (!lock.getAndSet(true))
            return;
        // if not successful, we wait
        sleep(random() % delay);
        if (delay < MAX_DELAY)
            delay = 2 * delay;
    }
  }
}
```

Exponential Backoff Lock



- Easy to implement
- But must choose parameters carefully
- Not portable across platforms

Exponential Backoff Lock

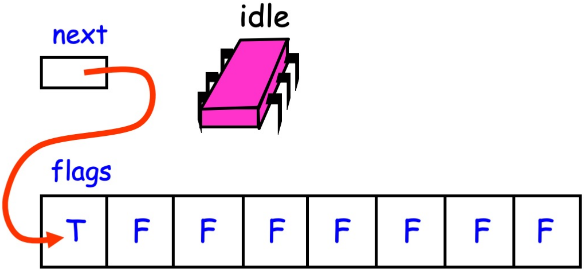


- Easy to implement
- But must choose parameters carefully
- Not portable across platforms

Idea

- Avoid useless invalidations by keeping a queue of threads
- Each thread notifies next in line without bothering the others

Anderson Queue Lock



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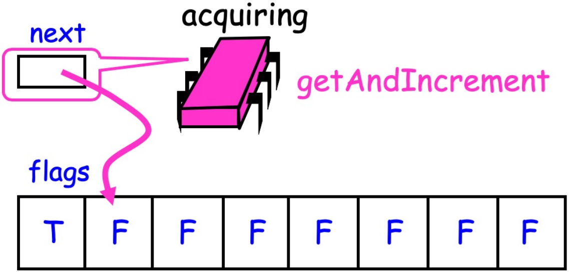

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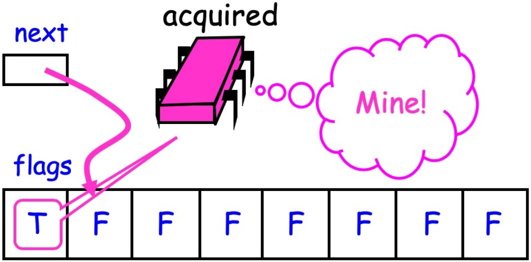

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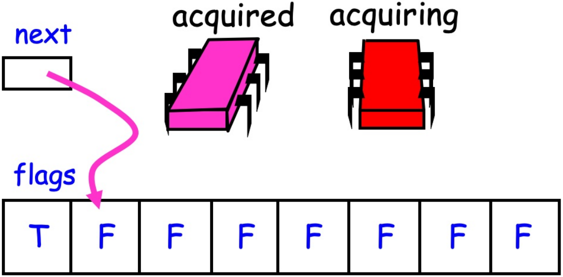

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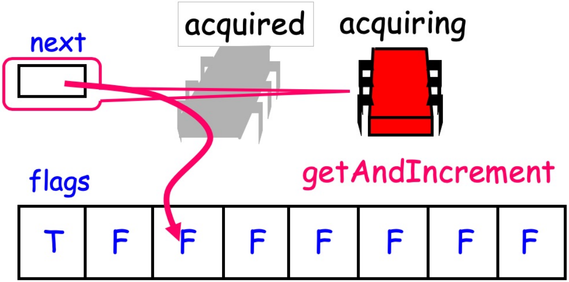

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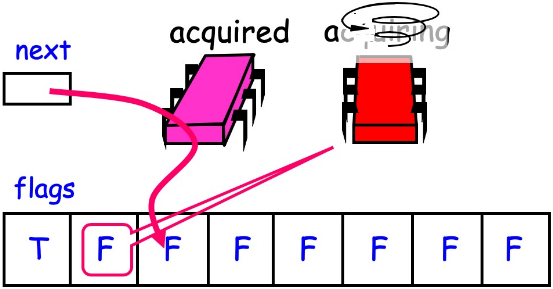

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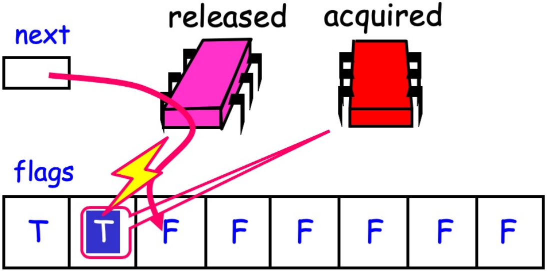
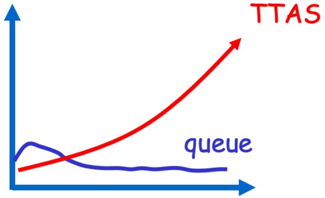


Anderson Queue Lock

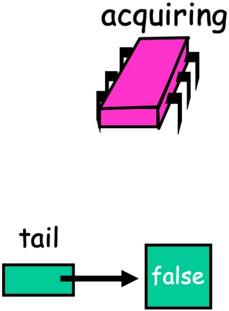
```
class ALock implements Lock {
  boolean[] flags = {true,false,...,false}; // one per thread
  AtomicInteger next = new AtomicInteger(0);
  ThreadLocal<Integer> mySlot;  // thread-local per thread

  void lock() {
    mySlot = next.getAndIncrement();
    while (!flags[mySlot % n]) {}; //spin
    flags[mySlot % n] = false;  // prepare for re-use (wrong in
    Figure!)
  }

  void unlock() {
    flags[(mySlot+1) % n] = true; // tell next thread
  }
}
```

Anderson Lock

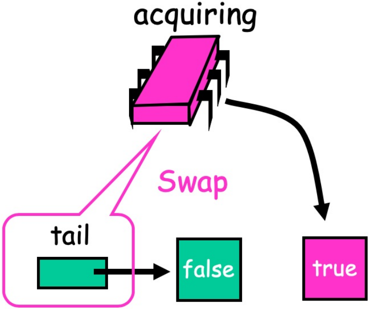


- FIFO fairness, no lockout
- Scalable performance
  - Threads spin on locally cached copy of single array location
  - But beware of *false sharing* of items on the same cache line!
  - Invalidations always per cache line
  - *Trick:* Use padding to avoid sharing
- Not space-efficient
- Requires knowledge about number of threads

CLH Lock (by Craig, Landin, Hagersten)



CLH Lock: Acquiring a lock



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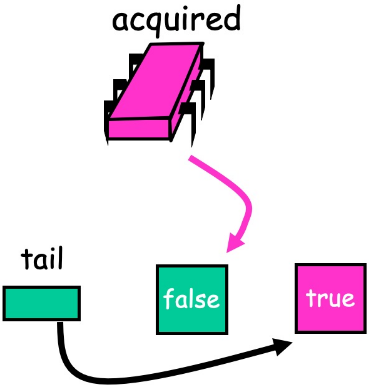
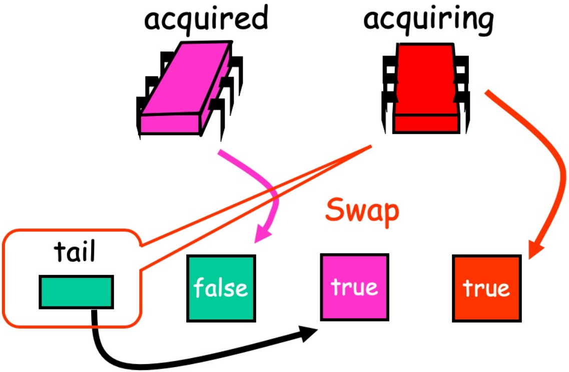
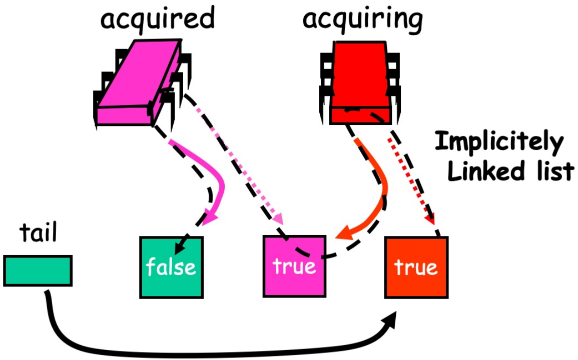


CLH Lock: It's a Queue!



CLH Lock: Releasing a lock



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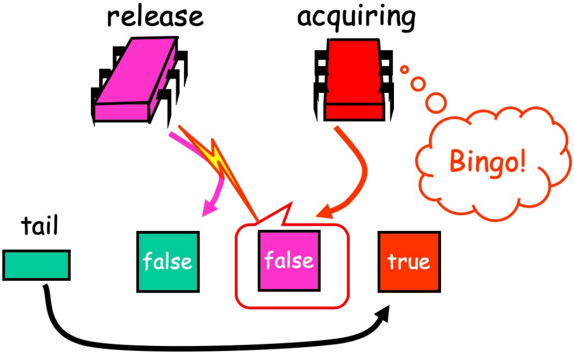


Remarks

- Threads spin on cached copy (efficient)
- Lock can reuse predecessor's node for future lock accesses

CLH Lock

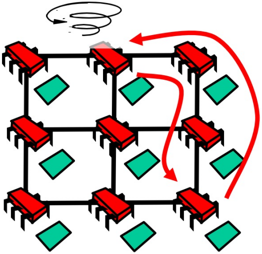
```
class Qnode {
  AtomicBoolean locked = new AtomicBoolean(true);
}

class CLHLock implements Lock {

  AtomicReference<Qnode> tail = new AtomicReference<Qnode>(null);
  ThreadLocal<Qnode> myNode = new Qnode(); // per thread

  void lock() {
    qnolde.locked = true;
    Qnode pred = tail.getAndSet(myNode); // swap my node into
    queue
    while (pred.locked) {} // spin
  }

  void unlock() {
    myNode.locked = false;
    myNode = pred; // "reuse" predecessor's qnode (see book)
  }
}
```

CLH Lock

- Lock release affects only successor
- Does not depend on prior knowledge about number of threads
- FIFO Fairness
- But doesn't work (efficiently) for uncached NUMA architectures

NUMA Architectures

- **N** on-**U** niform-**M** emomory-**A** rchitecture
- Model: Flat shared memory, no caches (in most variants)
- Some memory regions faster accessible than others
- Spinning on remote memory is slow



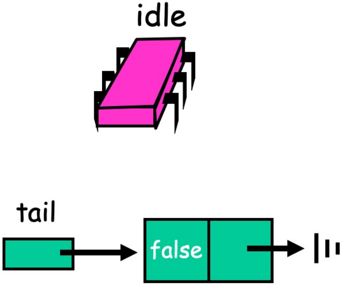
MCS Lock (by Mellor-Crummey and Scott)

- FIFO order
- Spin on local memory only
- Small, constant-size overhead

Idea:

- To acquire lock, place own Qnode at tail of list
- If it has a predecessor, modify predecessor's node to refer to own Qnode

MCS Lock



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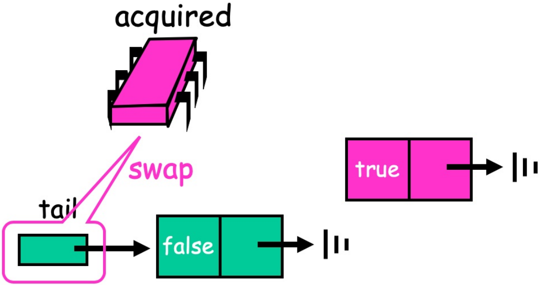

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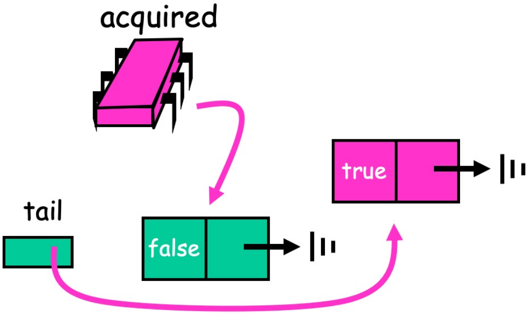

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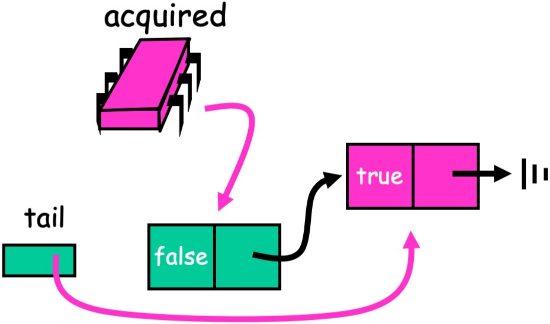

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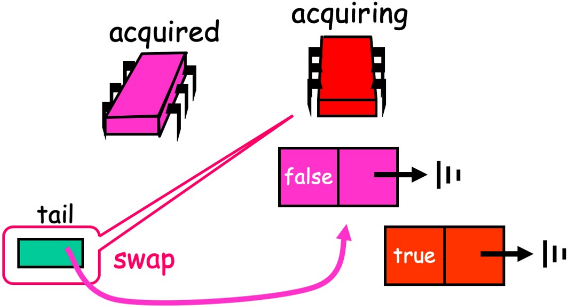

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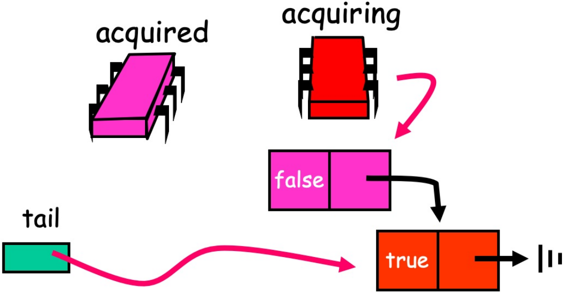
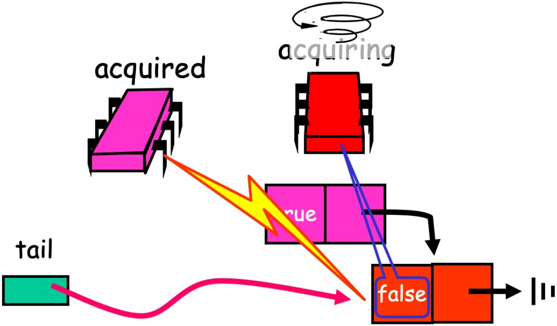


MCS Lock: Releasing a lock



MCS Lock

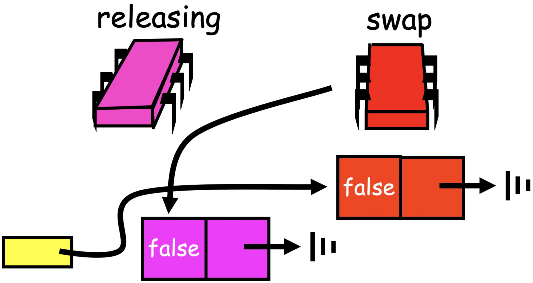
```
class Qnode {
  boolean locked = false;  // only reads/writes required
  Qnode   next   = null;
}
```

MCS Lock

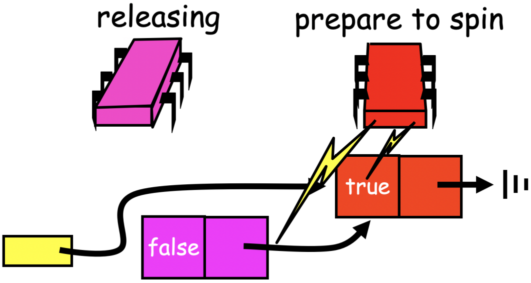
```
class MCSLock implements Lock {

  AtomicReference tail;
  ThreadLocal<Qnode> qnode = new Qnode();

  void lock() {
    // reset for reuse
    qnode.next = null;
    qnode.locked = false;

    // swap my node in
    Qnode pred = tail.getAndSet(qnode);

    if (pred != null) {
      // lock is taken, so set my status to wait
      qnode.locked = true;
      // tell predecessor where to find me
      pred.next = qnode;
      // spin on my node
      while (qnode.locked) {}
    }
  } ...
```

MCS Lock: Releasing

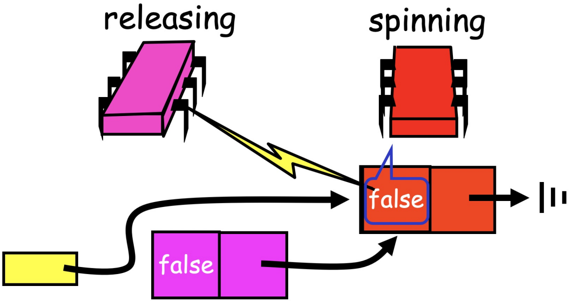
- Status of `qnode.next` indicates that other thread is active
- Need to wait for it to finish and start spinning



MCS Lock: Releasing



MCS Lock: Releasing



MCS Lock

```
  void unlock() {
    if (qnode.next == null) {
      // if really no thread waiting
      if (tail.compareAndSet(qnode, null)
        return;
      // otherwise, wait for successor to finish
      while (qnode.next == null) {}
    }
    // tell successor that it can start
    qnode.next.locked = false;
  }
}
```

Abortable Locks

- What if you want to give up waiting for a lock?
  - For example: timeout, transaction aborted by user, ...
- Simple for Backoff-Lock
  - Just return from `lock()` call
  - No cleanup, wait-free, immediate
- Problematic for Queue Locks
  - Can't just quit
  - Thread in line behind will starve

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- Problematic for Queue Locks
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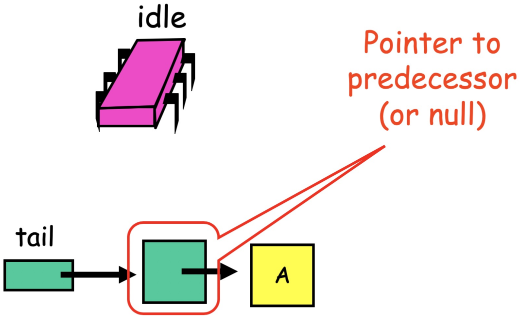
Idea: Let successor deal with the problem!

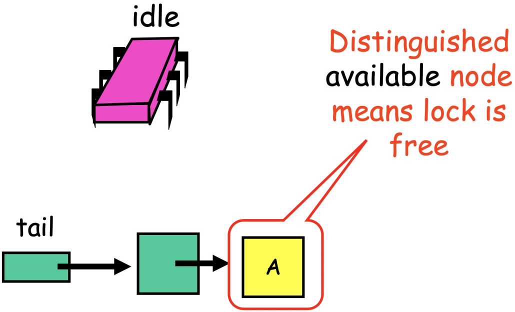
⇒ Abortable CLH Lock

Timeout Lock



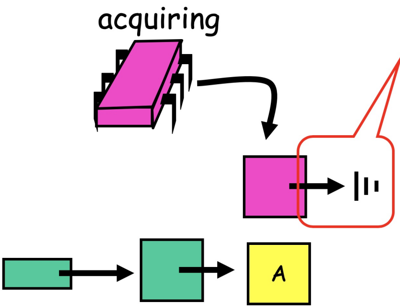
Pointer to predecessor (or null)

Timeout Lock: Acquire



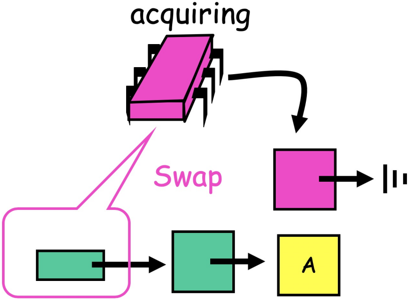
Distinguished available node means lock is free

Timeout Lock: Acquire

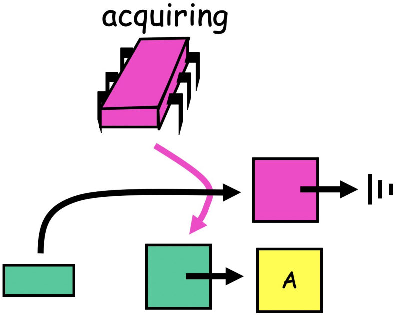


Null predecessor means lock not released or aborted

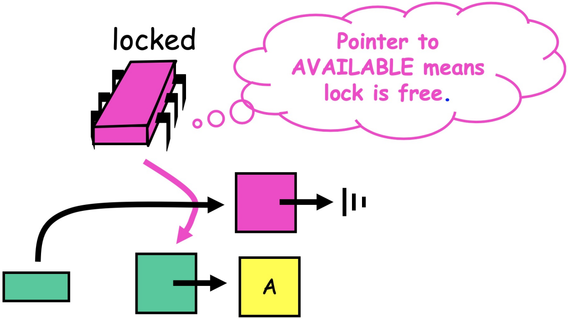
Timeout Lock: Acquire



Timeout Lock: Acquire



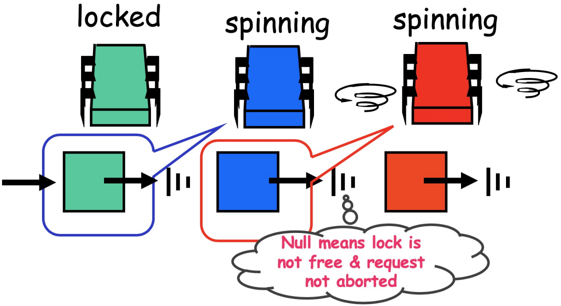
Timeout Lock: Acquire



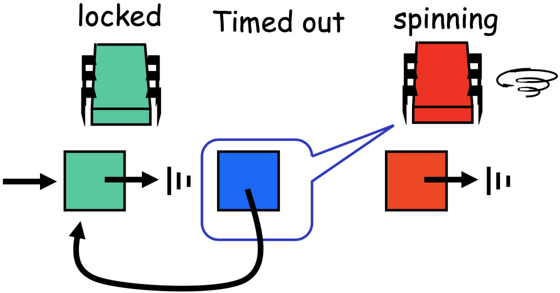
locked

Pointer to AVAILABLE means lock is free.

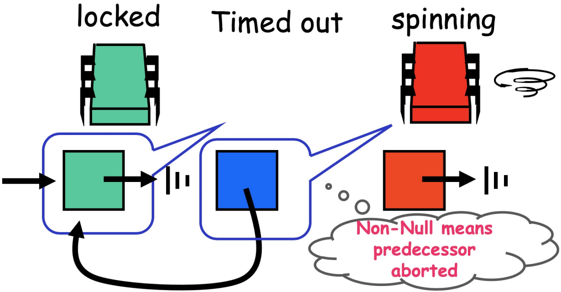
Timeout Lock: While waiting, ...



Timeout Lock: Thread times out



Timeout Lock: Thread times out



Timeout Locks: Implementation

```
class TOLock {
  static Qnode AVAILABLE = new Qnode(); // signifies free lock
  AtomicReference<Qnode> tail;
  ThreadLocal<Qnode> myNode; // per thread

  // Return value indicates success
  boolean lock(long timeout) {
    // Initialize node
    Qnode qnode = new Qnode();
    myNode = qnode;
    qnode.prev = null;

    // swap with tail
    Qnode myPred = tail.getAndSet(qnode);

    // if predecessor absent or released, we are done
    if (myPred == null || myPred.prev == AVAILABLE) {
      return true;
   }
...
```

Timeout Locks

```
...
  // Keep trying for a while
  long start = now();
  while (now()- start < timeout) {
    // Spin on predecessor's prev field
    Qnode predPred = myPred.prev;
    if (predPred == AVAILABLE) {
      // predecessor released lock
      return true;
    } else if (predPred != null) {
      // predecessor aborted, we advance in queue
      myPred = predPred;
    }
  }
...
```

Timeout Locks

```
...
// In case timeout happened, we waited long enough
if (!tail.compareAndSet(qnode, myPred)){
  // If CAS fails, tell successor about my predecessor
    qnode.prev = myPred;
  }
  // If CAS succeeds, no successor, nothing to do
  return false;
}
```

Timeout Locks

```
void unlock() {
  Qnode qnode = myNode.get();
  if (!tail.compareAndSet(qnode, null)) {
    // If CAS failed: there is successor
    // Notify successor that it can enter
    qnode.prev = AVAILABLE;
  }
  // If CAS succeeds: no successor waiting
  // Set tail to null, no clean up
}
```

Summary: One Lock To Rule Them All?

- TTAS+Backoff, CLH, MCS, ToLock ...
- Each one better than others in some way
- There is no *one* solution
- Decision really depends on:
  - the application
  - the hardware
  - which properties are important