Locks

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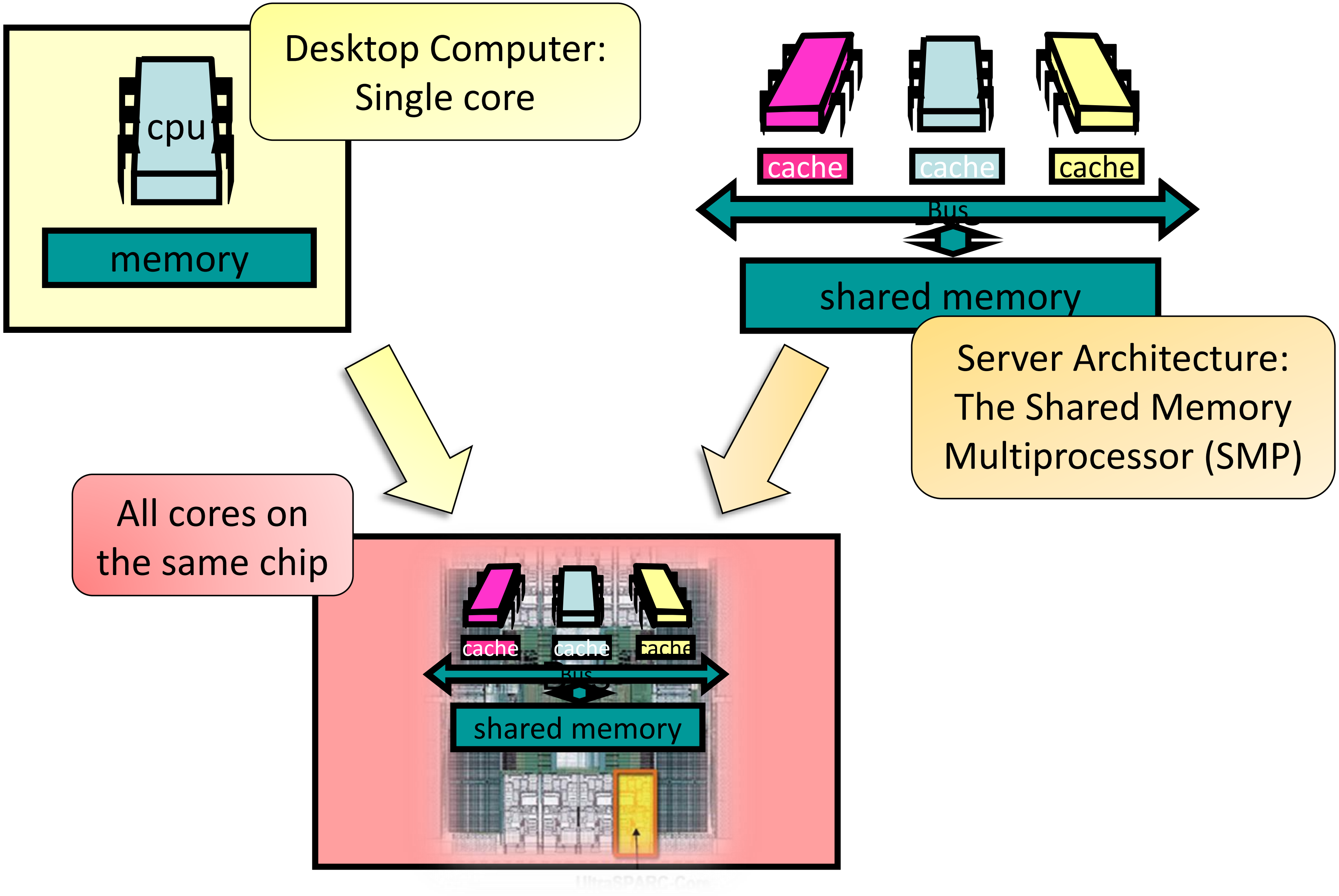
Overview

- Introduction
- Spin Locks
  - Test-and-Set & Test-and-Test-and-Set
  - Backoff lock
- Queue locks

Introduction: From Single-Core to Multi-Core Computers

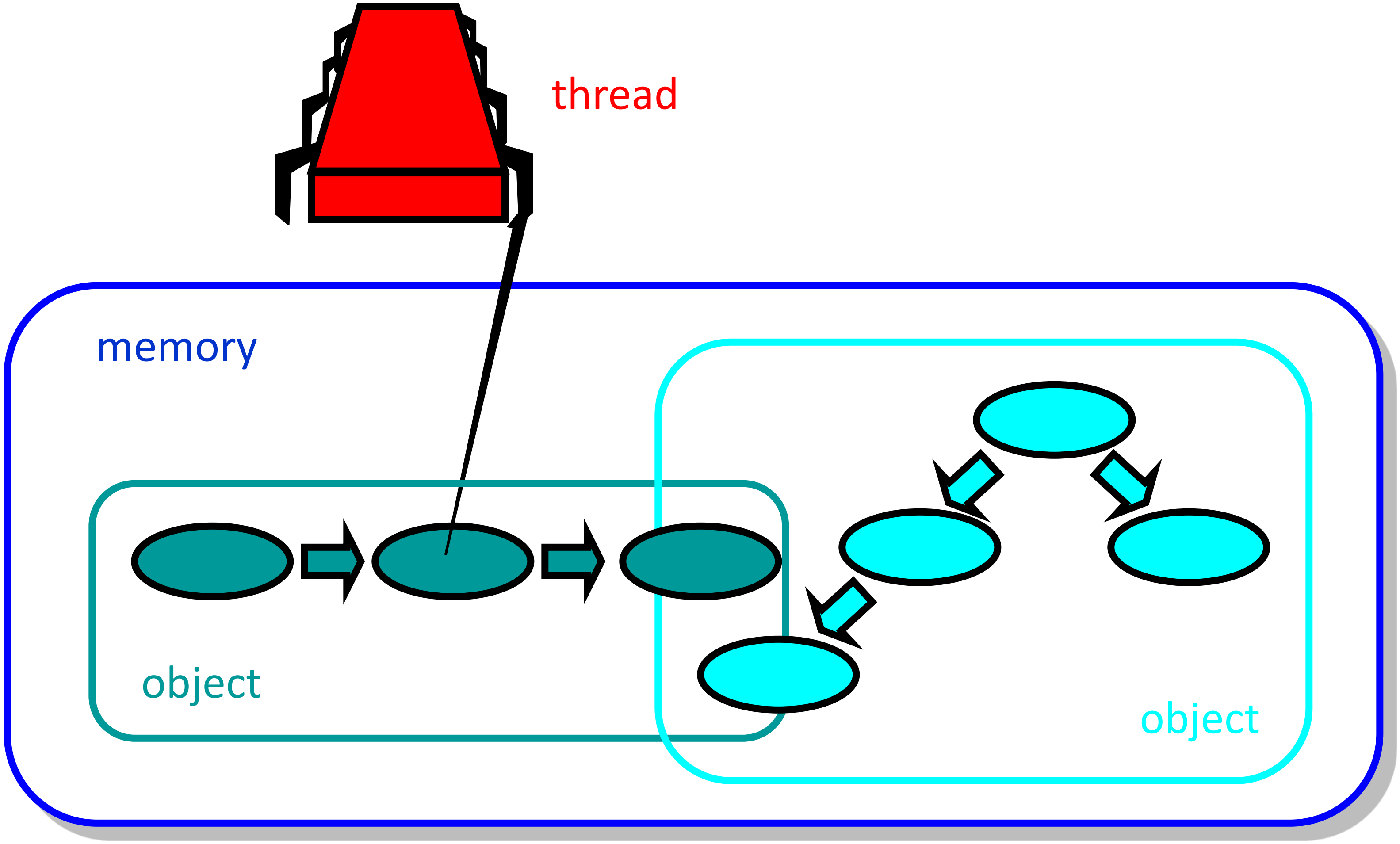


Desktop Computer:
Single core

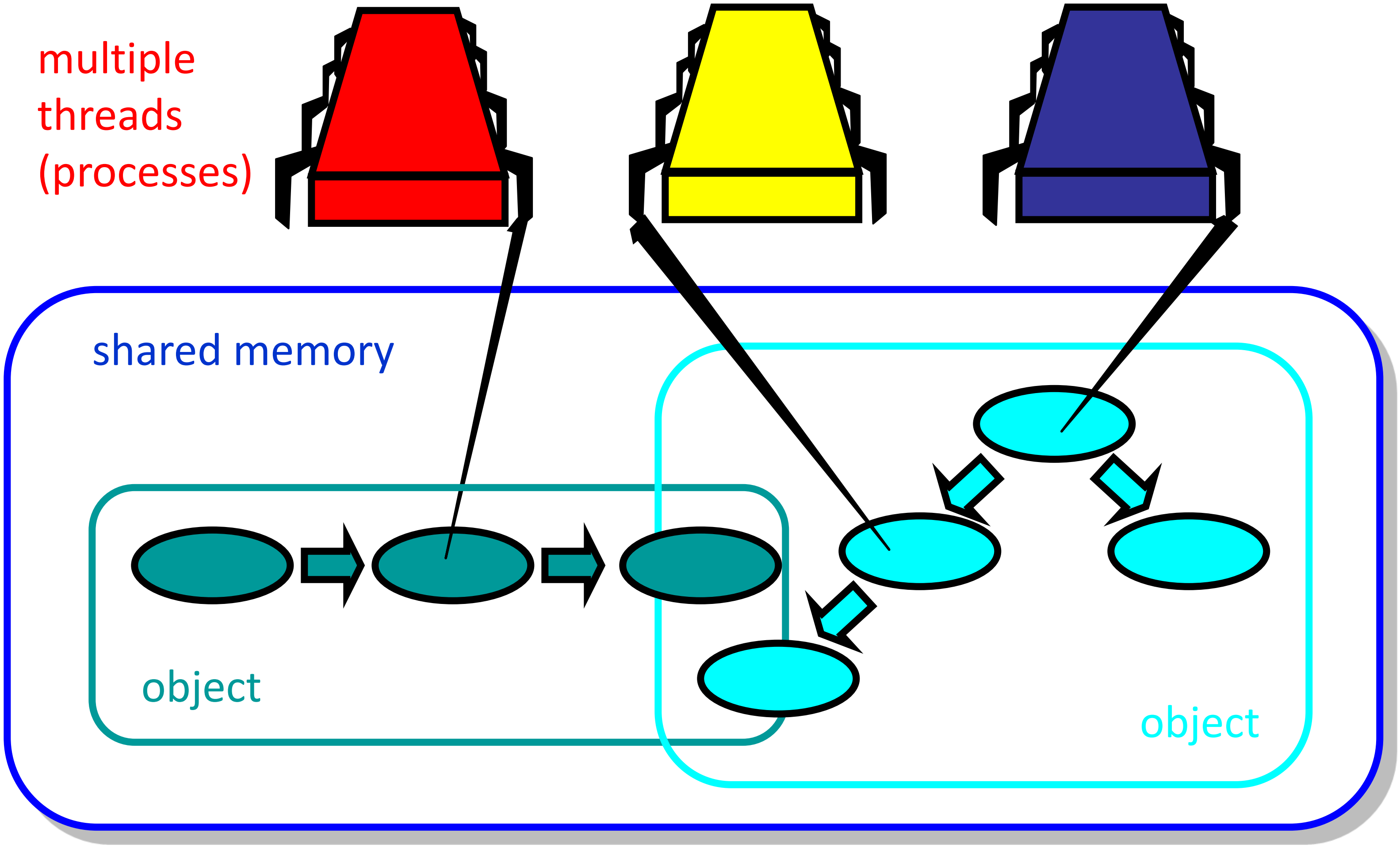
Server Architecture:
The Shared Memory
Multiprocessor (SMP)

All cores on
the same chip

Sequential Computation



Concurrent Computation



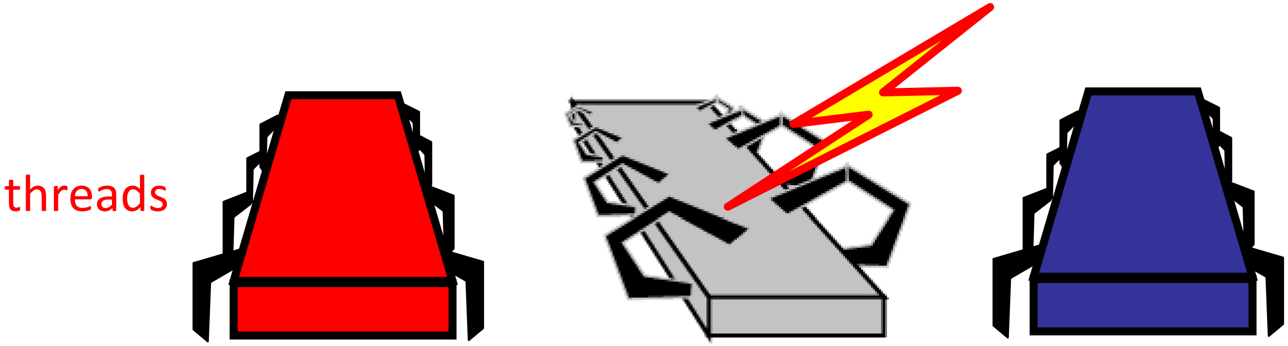
multiple threads (processes)

shared memory

object

object

Fault Tolerance & Asynchrony



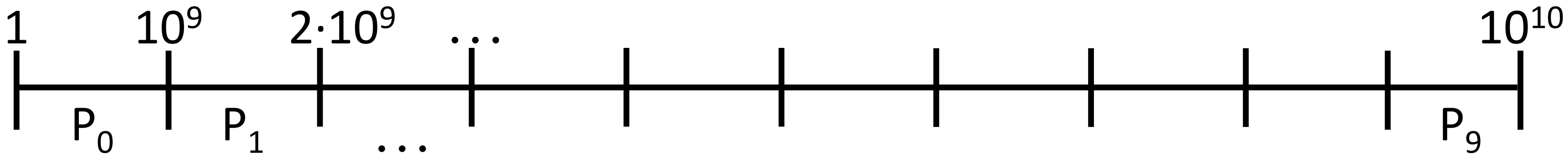
- Why fault tolerance?
  - Even if processes do not die, there are “near-death experiences”
- Sudden unpredictable delays:
  - Cache misses (short)
  - Page faults (long)
  - Scheduling quantum used up (really long)

Example: Parallel Primality Testing

- Challenge
  - Print all primes from 1 to 10^{10}
- Given
  - Ten-core multiprocessor
  - One thread per processor
- Goal
  - Get ten-fold speedup (or close)

- Naïve Approach
  - Split the work evenly
  - Each thread tests range of 10^9

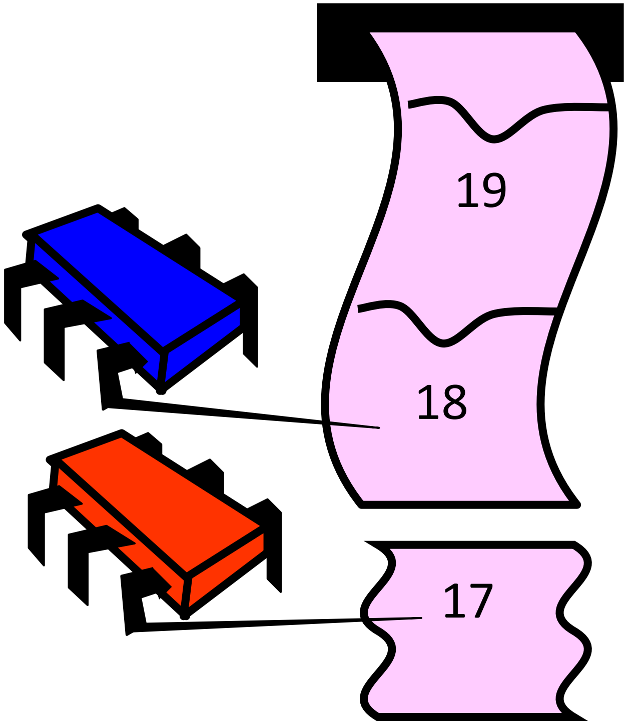
Problems with this approach?



Issues

- Higher ranges have fewer primes
- Yet larger numbers are harder to test
- Thread workloads
  - Uneven
  - Hard to predict
- Need dynamic load balancing

- Better approach
  - Shared counter!
  - Each thread takes a number



Procedure Executed at each Thread

```
Counter counter = new Counter();

void primePrint() {
  long j = 0;
  while (j < 10^10) {
    j = counter.getAndIncrement();
    if (isPrime(j))
      print(j);
  }
}
```

Shared counter object

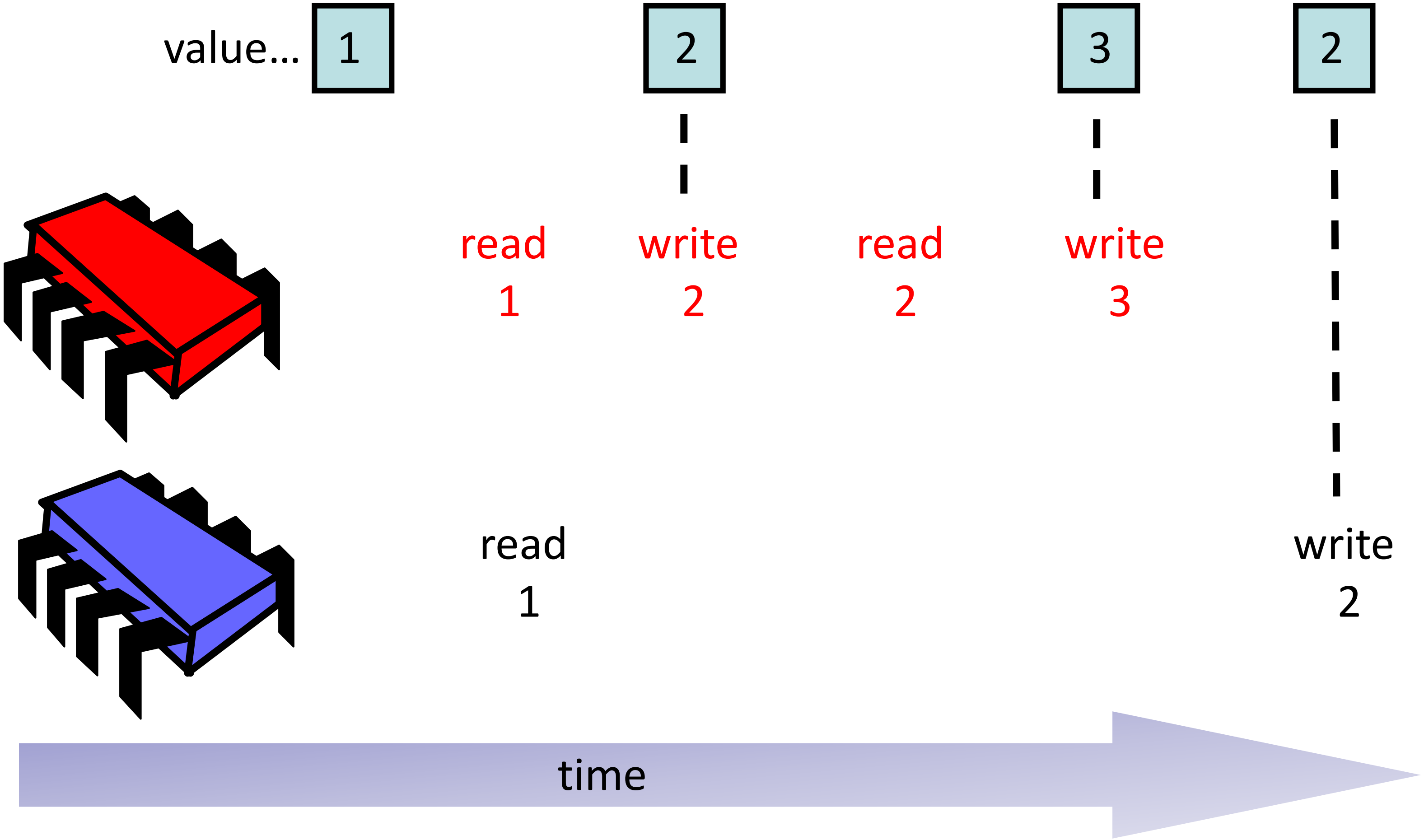
Increment counter & test if return value is prime

Counter Implementation

```
class Counter {
  private long value = 1;

  public long getAndIncrement() {
    return value++;
  }
}
```

What's the problem with this implementation?

Problem



value… 1 2 3 2

read 1

write 2

read 2

write 3

read 1

write 2

time

Counter Implementation

```
class Counter {
  private long value = 1;

  public long getAndIncrement() {
    long temp = value;
    value = temp + 1;
    return temp;
  }
}
```

These steps must be atomic!

We have to guarantee **mutual exclusion!**

We could use **Read-Modify-Write (RMW)** instructions.

Common RMW Instructions

```
int value;
```

```
synchronized int testAndSet() {
  int prior = value;
  value = 1;
  return prior;
}
```

```
synchronized int getAndIncrement() {
  int prior = value;
  value = value + 1;
  return prior;
}
```

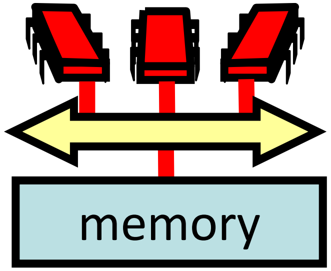
```
synchronized int compareAndSwap(int old, int new) {
  int prior = value;
  if (value == old)
    value = new;
  return prior;
}
```

Model

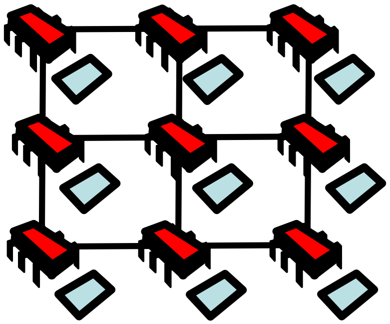
- The Architecture of Multiprocessor Systems
  - Theory vs. Practice

I.e., multiprocessors

- In Theory
  - Multiple instruction multiple data (MIMD) architecture
  - Each thread/process has its own code and local variables
  - Shared memory feels the same for all threads/processes



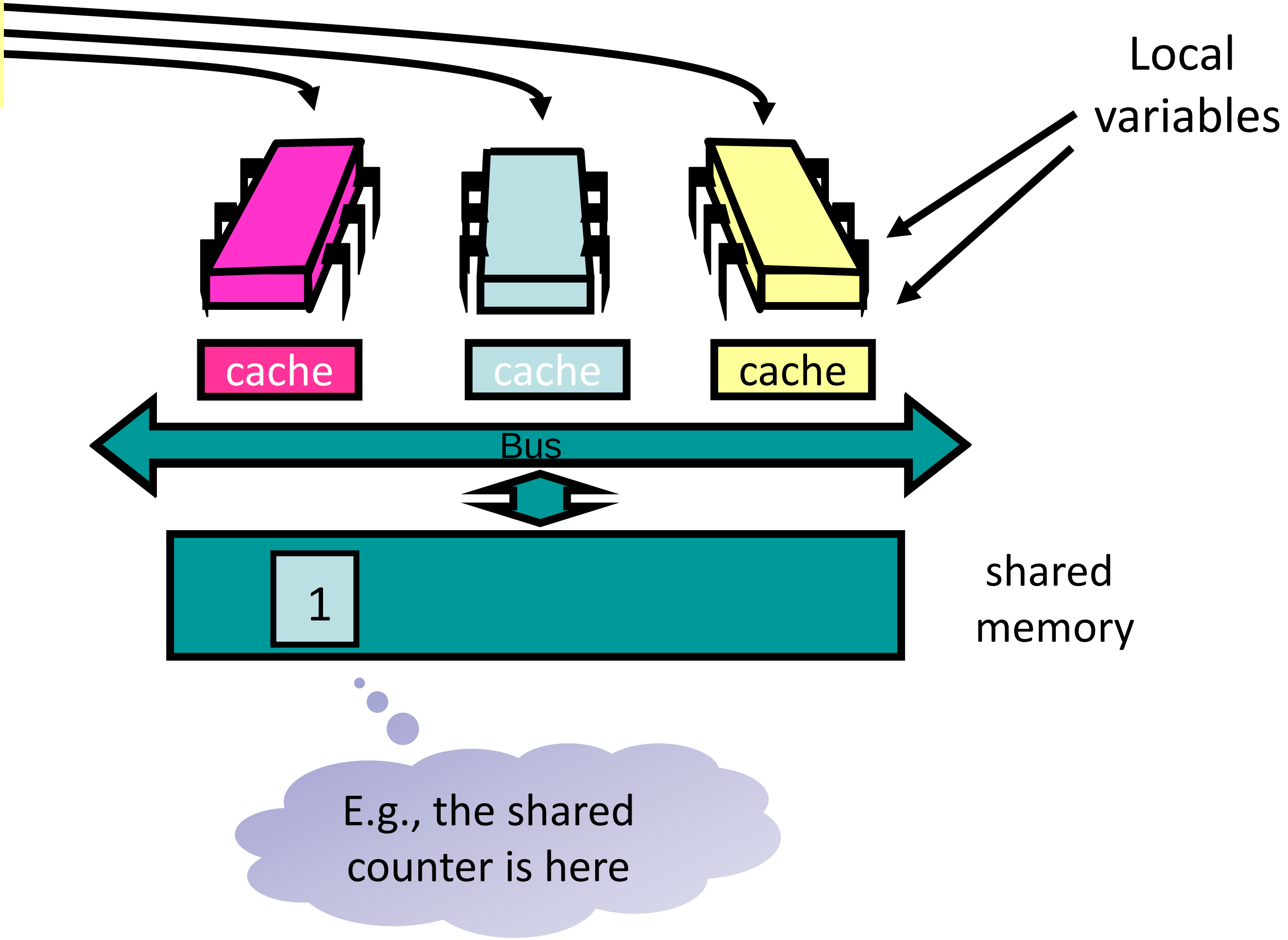
- In Practice
  - There is a shared memory that all threads can access
  - Typically, communication runs over a shared bus (alternatively, there may be several channels)
  - Communication contention
  - Communication latency
  - Each thread has a local cache



Model: Where Things Reside

```
Counter counter = new Counter();

void primePrint() {
  long j = 0;
  while (j < 10¹⁰) {
    j = counter.getAndIncrement();
    if (isPrime(j))
      print(j);
  }
}
```

Code



Local variables

cache

cache

cache

Bus

1

shared memory

E.g., the shared counter is here

Mutual Exclusion

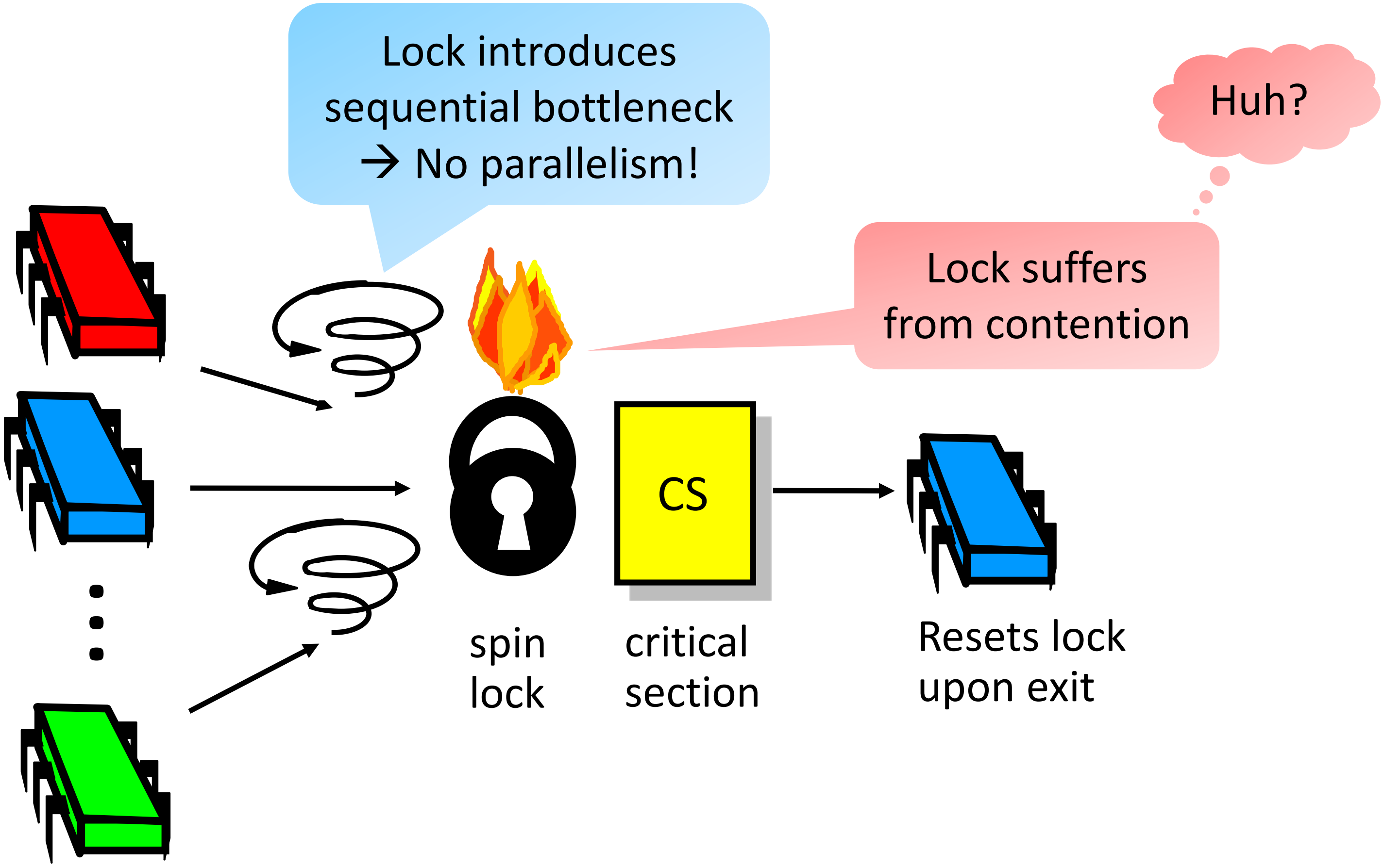
- We need mutual exclusion for our counter
- We are now going to study mutual exclusion from a different angle
  - Focus on performance, not just correctness and progress
- We will begin to understand how performance depends on our software properly utilizing the multiprocessor machine’s hardware,
  and get to know a collection of locking algorithms!

- What should you do if you can’t get a lock?
- Keep trying
  - “spin” or “busy-wait”
  - Good if delays are short

Our focus

- Give up the processor
  - Good if delays are long
  - Always good on uniprocessor

Basic Spin-Lock



Lock introduces sequential bottleneck
→ No parallelism!

Huh?

Lock suffers from contention

CS

spin lock

critical section

Resets lock upon exit

Test&Set

- Boolean value
- Test-and-set (TAS)
  - Swap **true** with current value
  - Return value tells if prior value was **true** or **false**
- Can reset just by writing **false**
- Also known as “getAndSet”

Test&Set in Java

java.util.concurrent.atomic

```
class AtomicBoolean {
  private boolean value;

  public synchronized boolean getAndSet() {
    boolean prior = this.value;
    this.value = true;
    return prior;
  }

  ...

}
```

Get current value and set value to true

Test&Set Locks

- Locking
  - Lock is free: value is false
  - Lock is taken: value is true
- Acquire lock by calling TAS
  - If result is false, you win
  - If result is true, you lose
- Release lock by writing false

Test&Set Lock

```
class TASLock implements Lock {
  AtomicBoolean state = new AtomicBoolean(false);

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

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

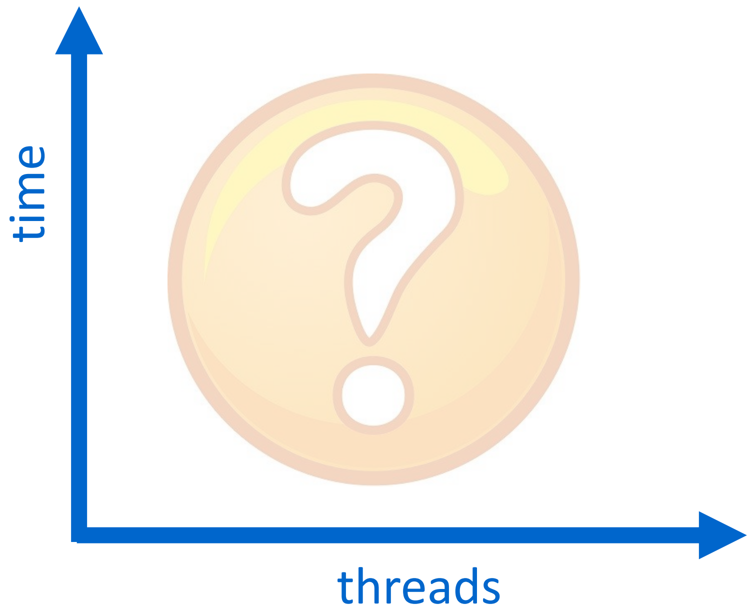
Lock state is AtomicBoolean

Keep trying until lock acquired

Release lock by resetting state to false

Performance

- Experiment
  - *n* threads
  - Increment shared counter 1 million times (without computing primes)
- How long should it take?
- How long does it take?



Test&Test&Set Locks

- How can we improve TAS?
- A crazy idea: Test before you test and set!

- Lurking stage
  - Wait until lock “looks” free
  - Spin while read returns true (i.e., the lock is taken)
- Pouncing state
  - As soon as lock “looks” available
  - Read returns false (i.e., the lock is free)
  - Call TAS to acquire the lock
  - If TAS loses, go back to lurking

Test&Test&Set Lock

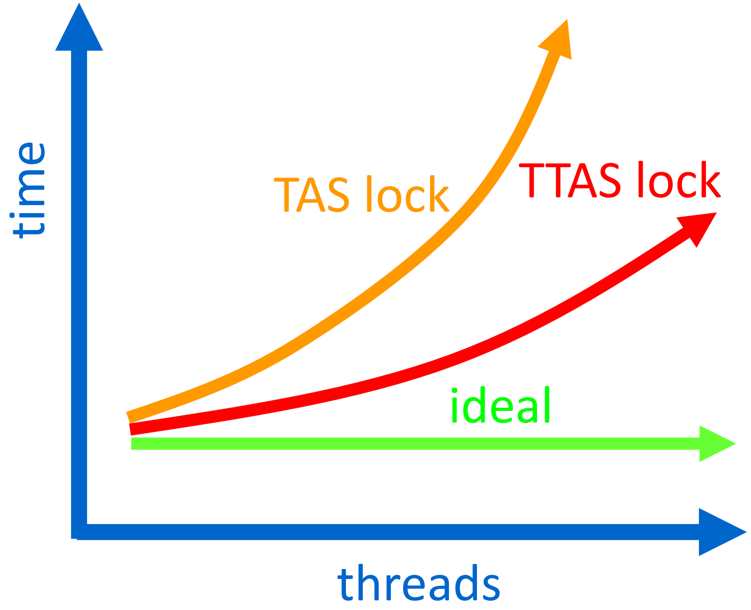
```
class TTASLock implements Lock {
  AtomicBoolean state = new AtomicBoolean(false);

  public void lock() {
    while (true) {
      while (state.get()) {}
      if (!state.getAndSet())
        return;
    }
  }

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

Wait until lock looks free

Then try to acquire it

Performance

- Both TAS and TTAS do the same thing (semantically)
- So, we would expect basically the same results



- Why is TTAS so much better than TAS? Why are both far from ideal?

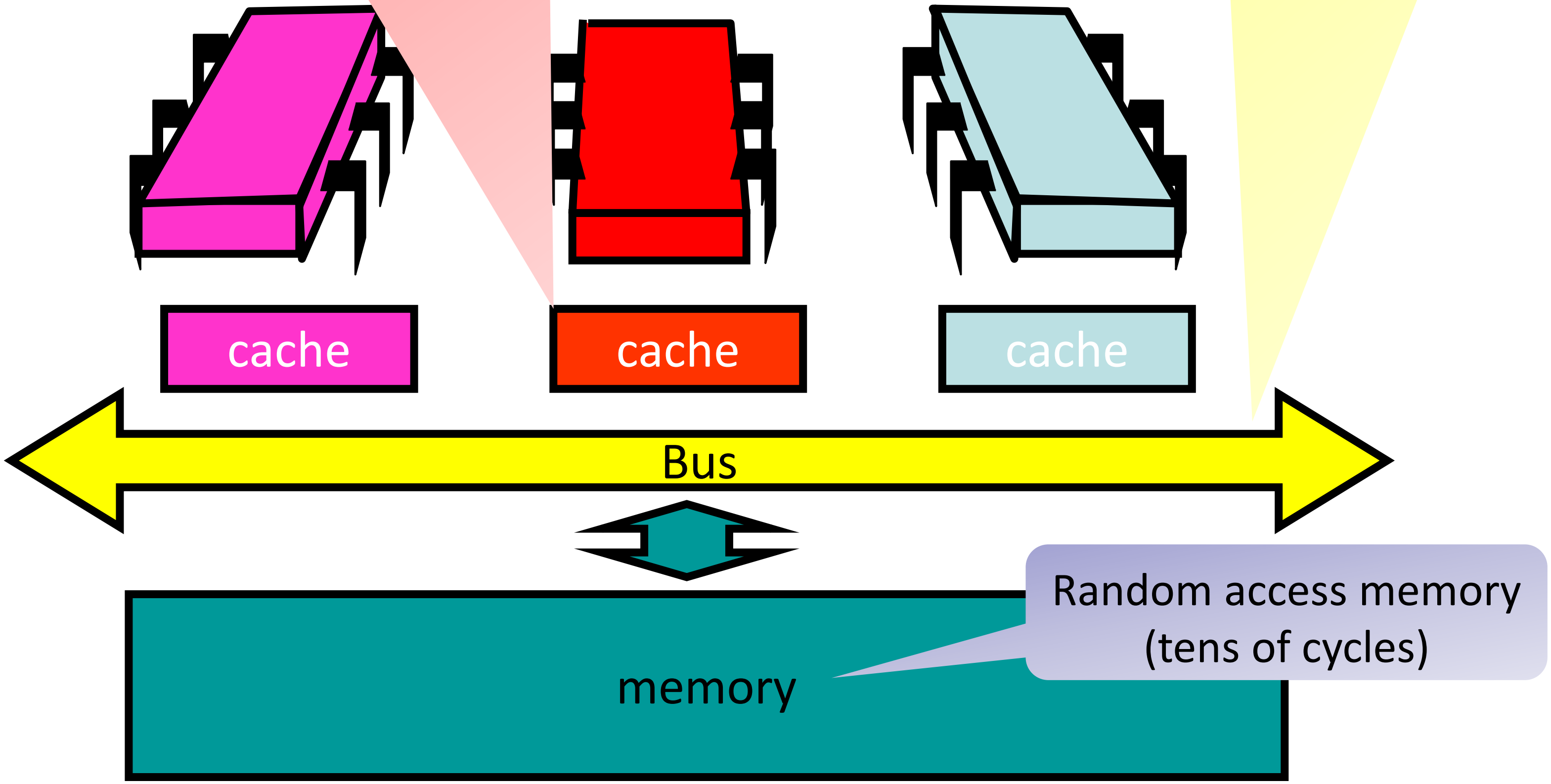
Opinion

- TAS & TTAS locks
  - are provably the same (in theory)
  - except they aren’t (in reality)
- Obviously, it must have something to do with the model…
- Let’s take a closer look at our new model and try to find a reasonable explanation!

Bus-Based Architectures

Per-processor caches
- Small
- Fast: 1 or 2 cycles
- Address and state information

Shared bus
- Broadcast medium
- One broadcaster at a time
- Processors (and memory) “snoop”



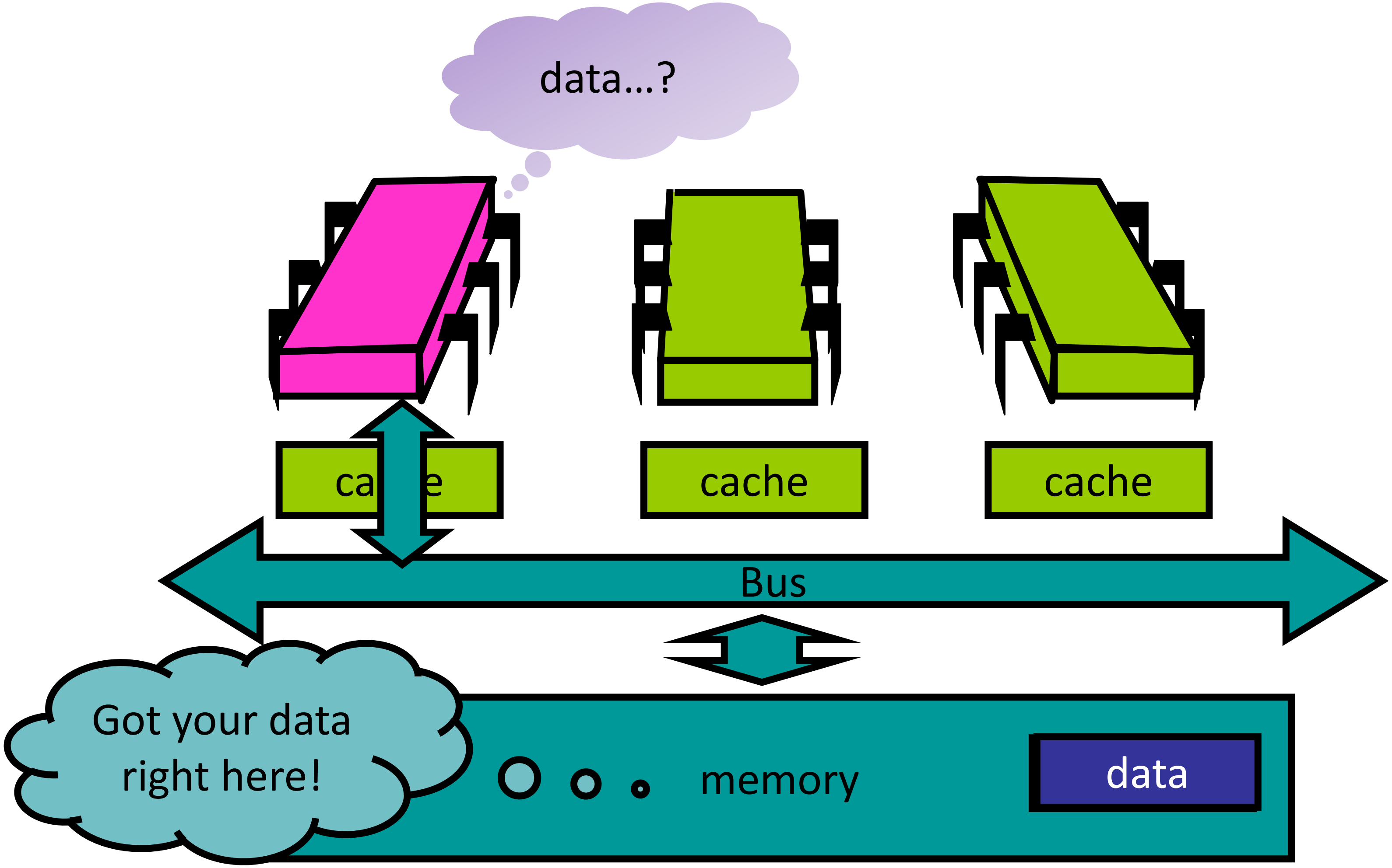
Random access memory
(tens of cycles)

Jargon Watch

- Load request
  - When a thread wants to access data, it issues a load request
- Cache hit
  - The thread found the data in its own cache
- Cache miss
  - The data is not found in the cache
  - The thread has to get the data from memory

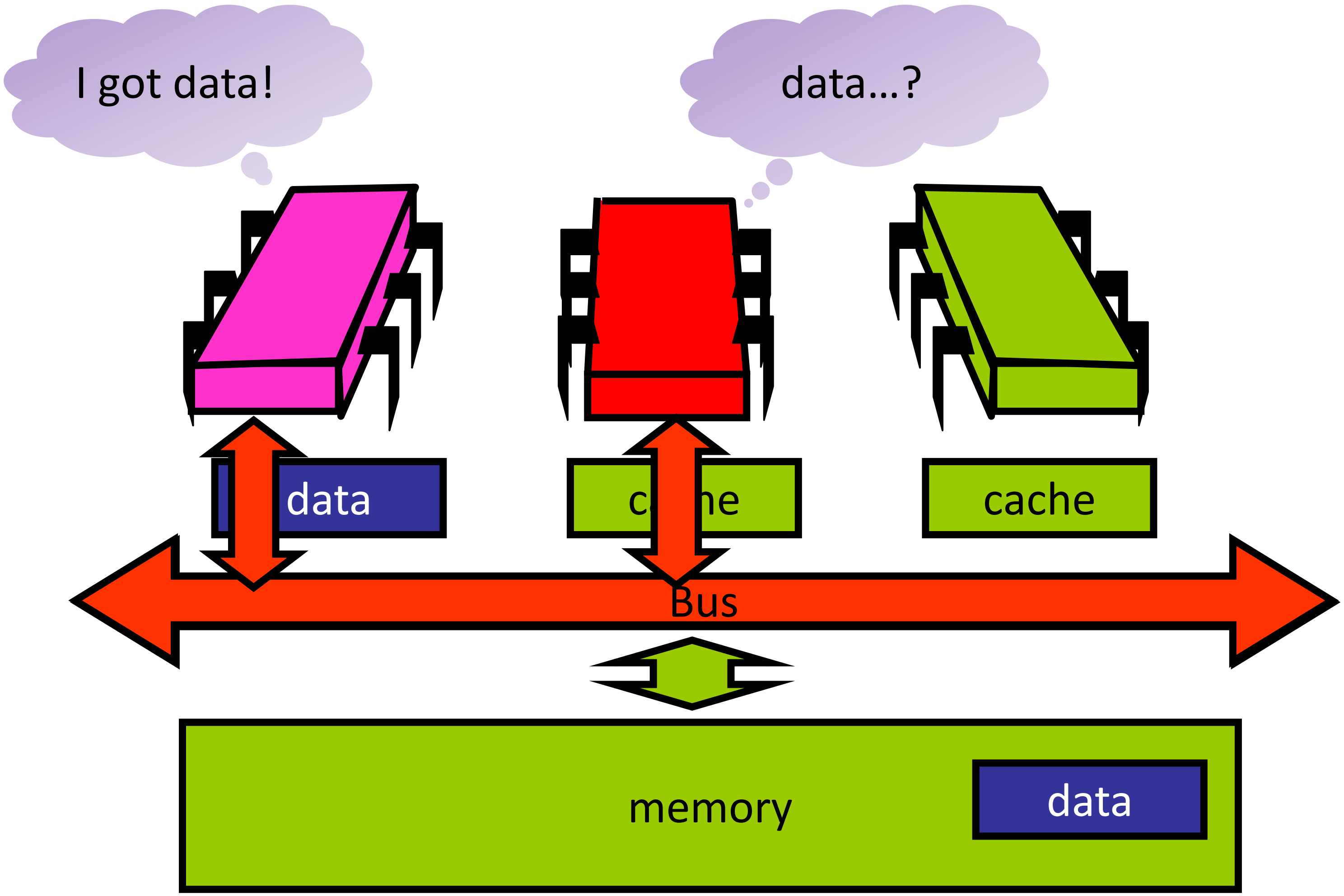
Load Request

- Thread issues load request and memory responds



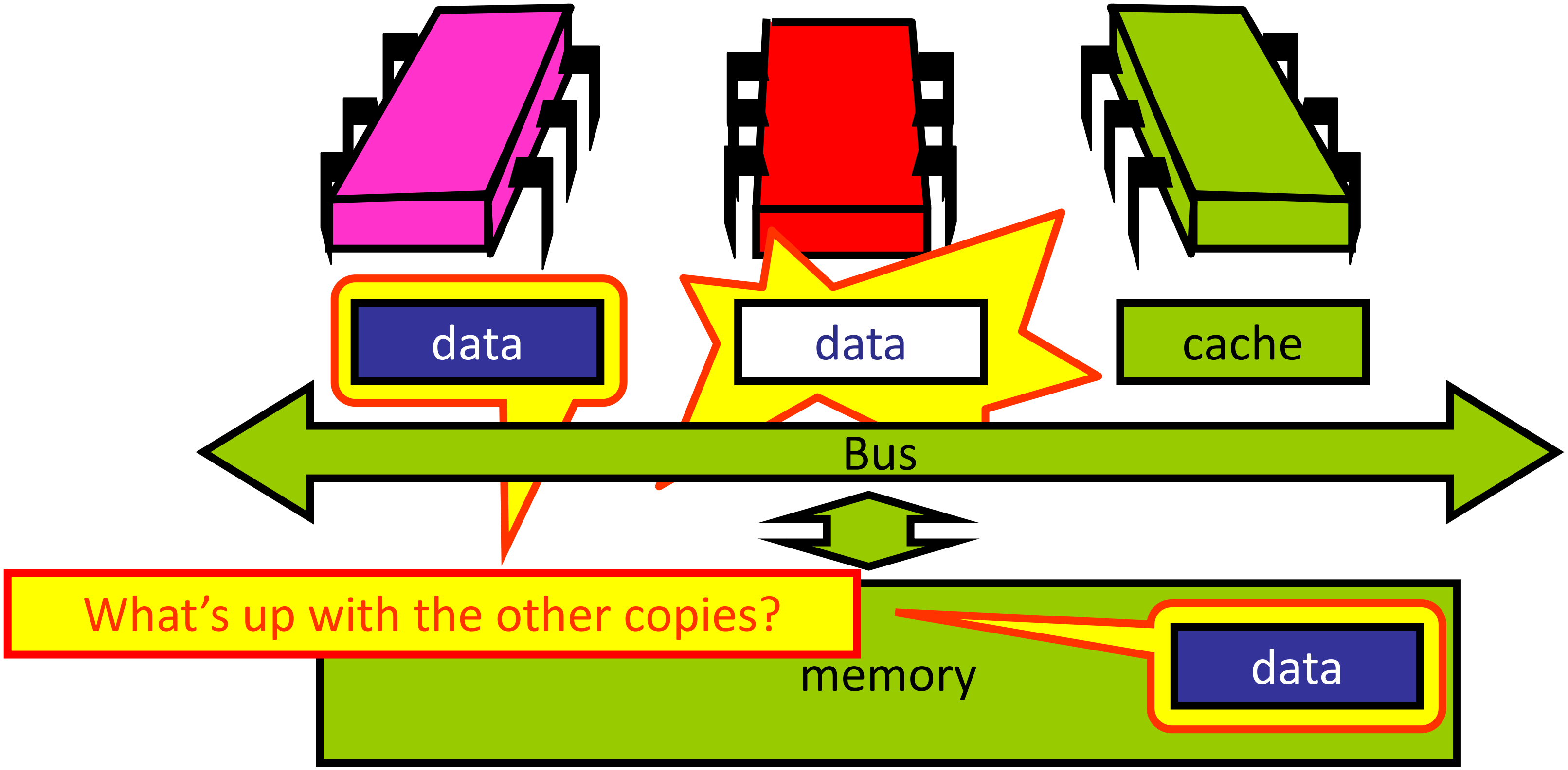
Another Load Request

- Another thread wants to access the same data. Get a copy from the cache!



Modify Cached Data

- Both threads now have the data in their cache
- What happens if the red thread now modifies the data…?



What's up with the other copies?

Cache Coherence

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

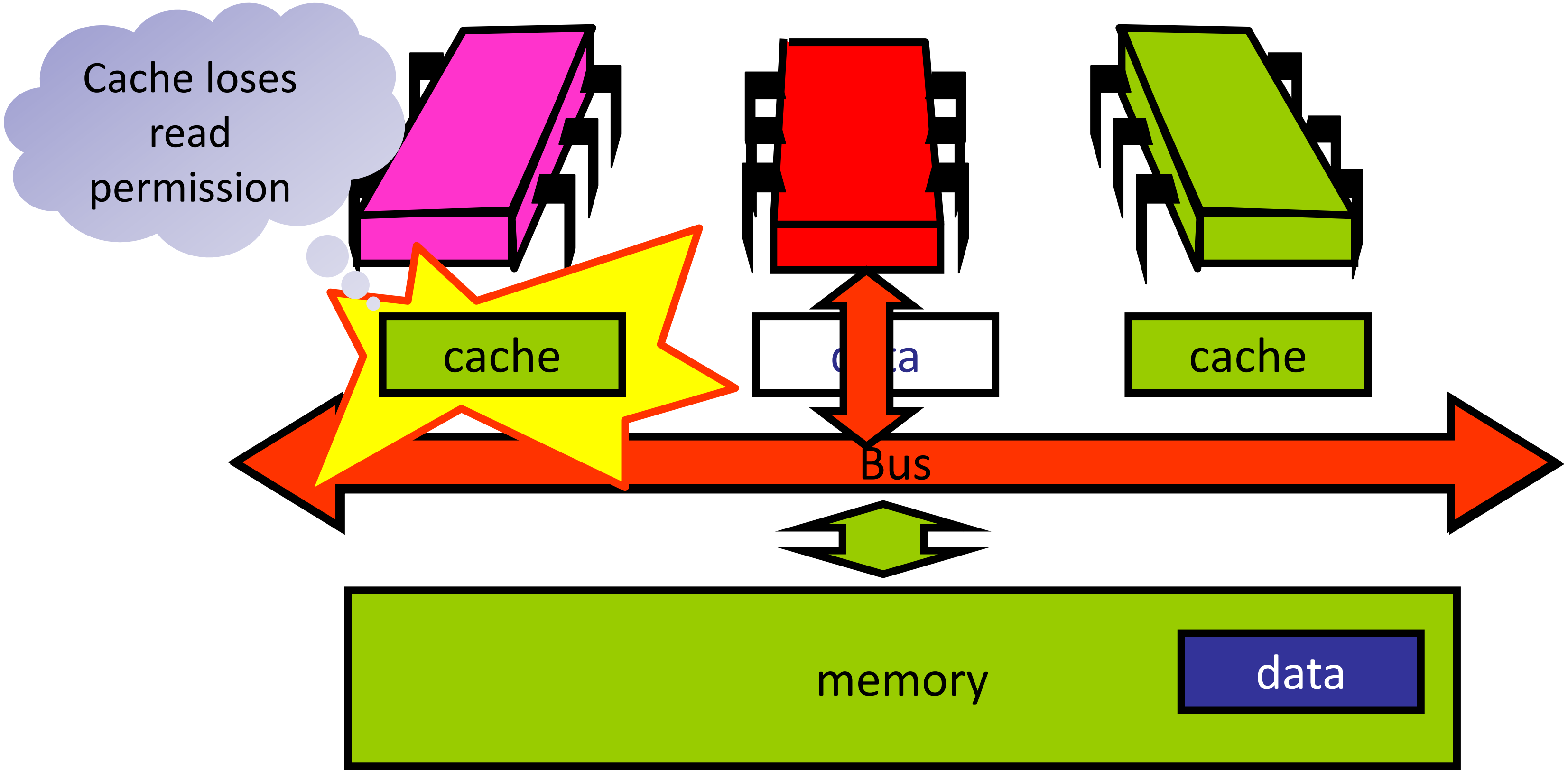
Write-Back Caches

- Accumulate changes in cache
- Write back when needed
  - Need the cache for something else
  - Another processor wants it
- On first modification
  - Invalidate other entries
  - Requires non-trivial protocol …

- Cache entry has three states:
  - Invalid: contains raw bits
  - Valid: I can read but I can’t write
  - Dirty: Data has been modified
    - Intercept other load requests
    - Write back to memory before reusing cache

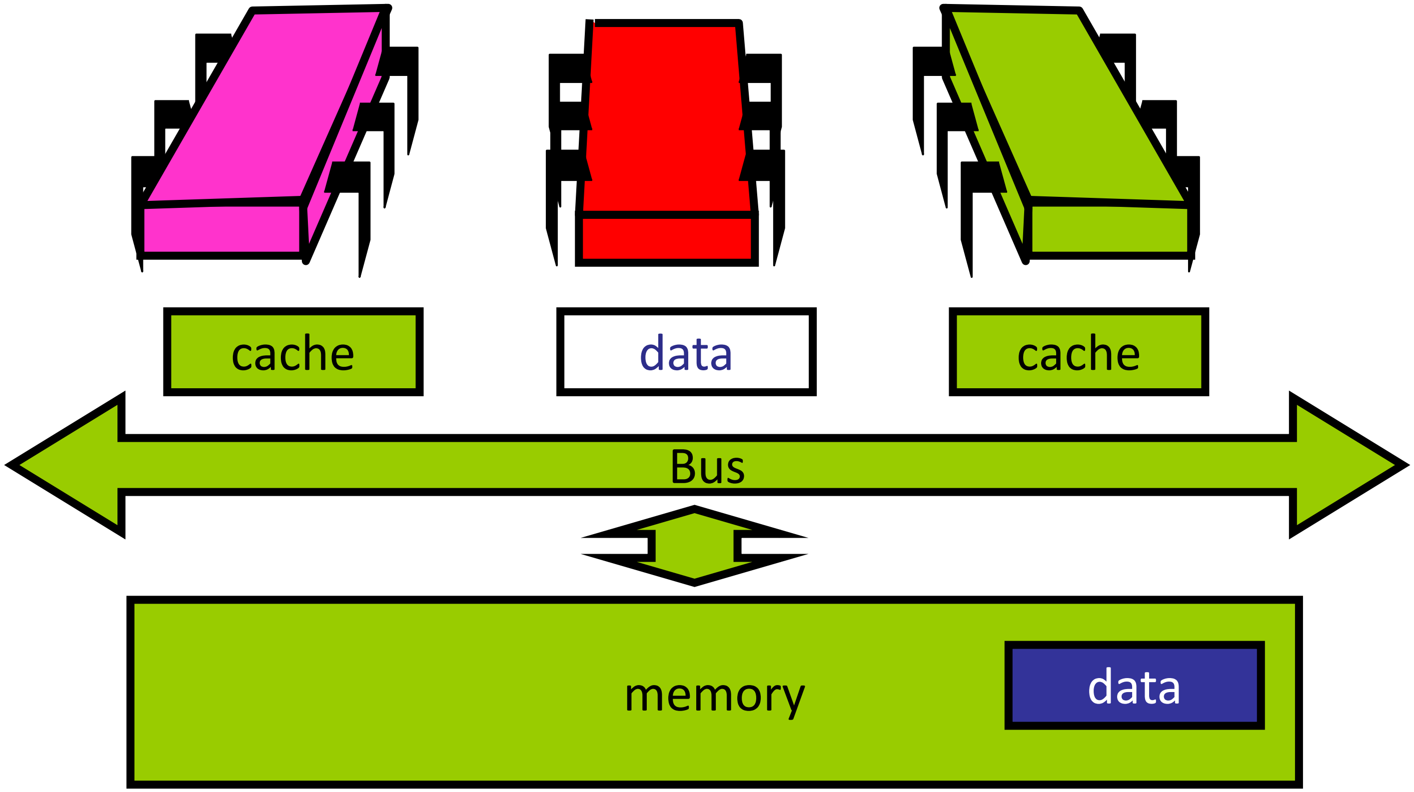
Invalidate

- Let’s rewind back to the moment when the red processor updates its cached data
- It broadcasts an invalidation message → Other processor invalidates its cache!



Invalidate

- Memory provides data only if not present in any cache, so there is no need to change it now (this is an expensive operation!)
- Reading is not a problem → The threads get the data from the red process



Mutual Exclusion

- What do we want to optimize?
  1. Minimize the bus bandwidth that the spinning threads use
  2. Minimize the lock acquire/release latency
  3. Minimize the latency to acquire the lock if the lock is idle

TAS vs. TTAS

- TAS invalidates cache lines
- Spinners
  - Always go to bus
- Thread wants to release lock
  - delayed behind spinners!!!

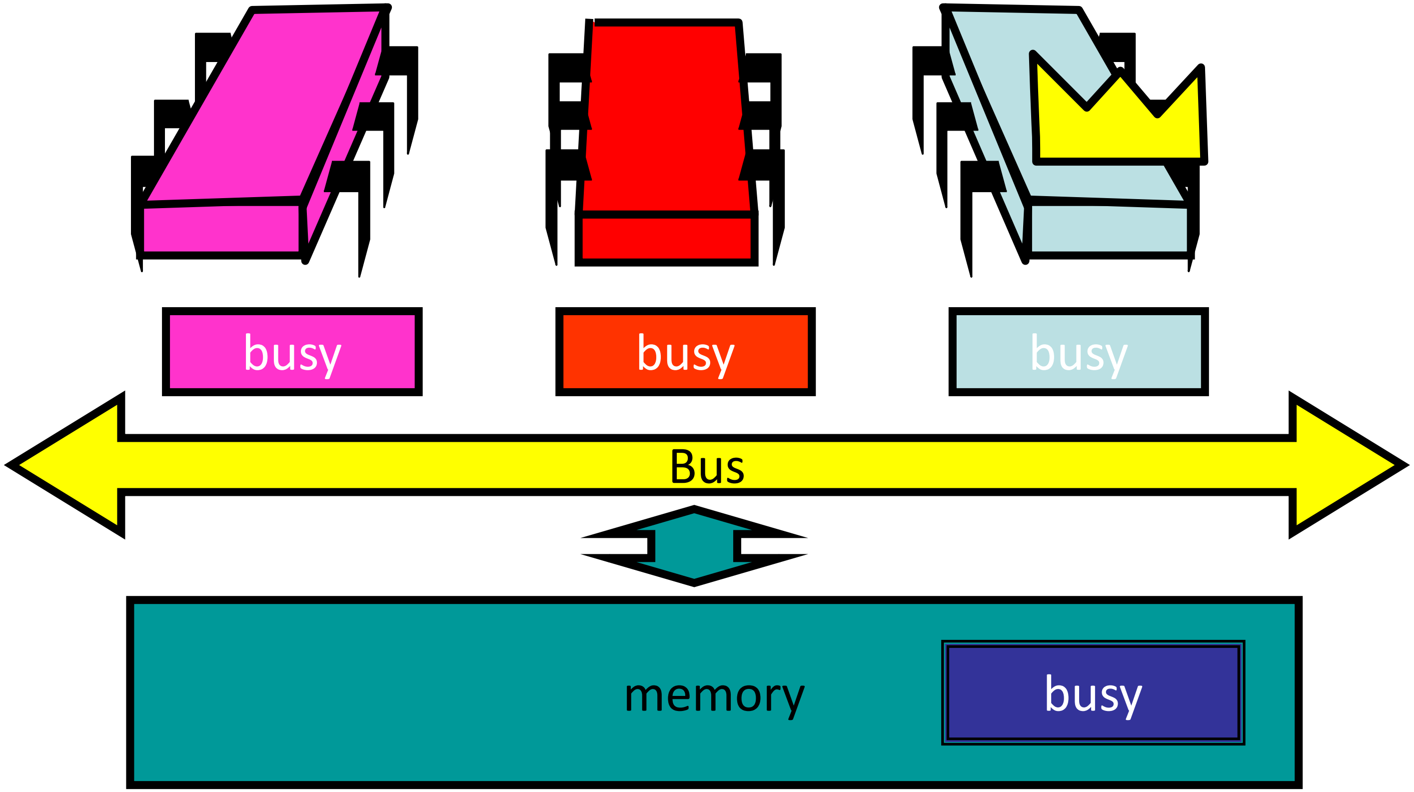
- TTAS waits until lock “looks” free
  - Spin on local cache
  - No bus use while lock busy
- Problem: when lock is released
  - Invalidation storm …

This is why TAS performs so poorly…

Huh?

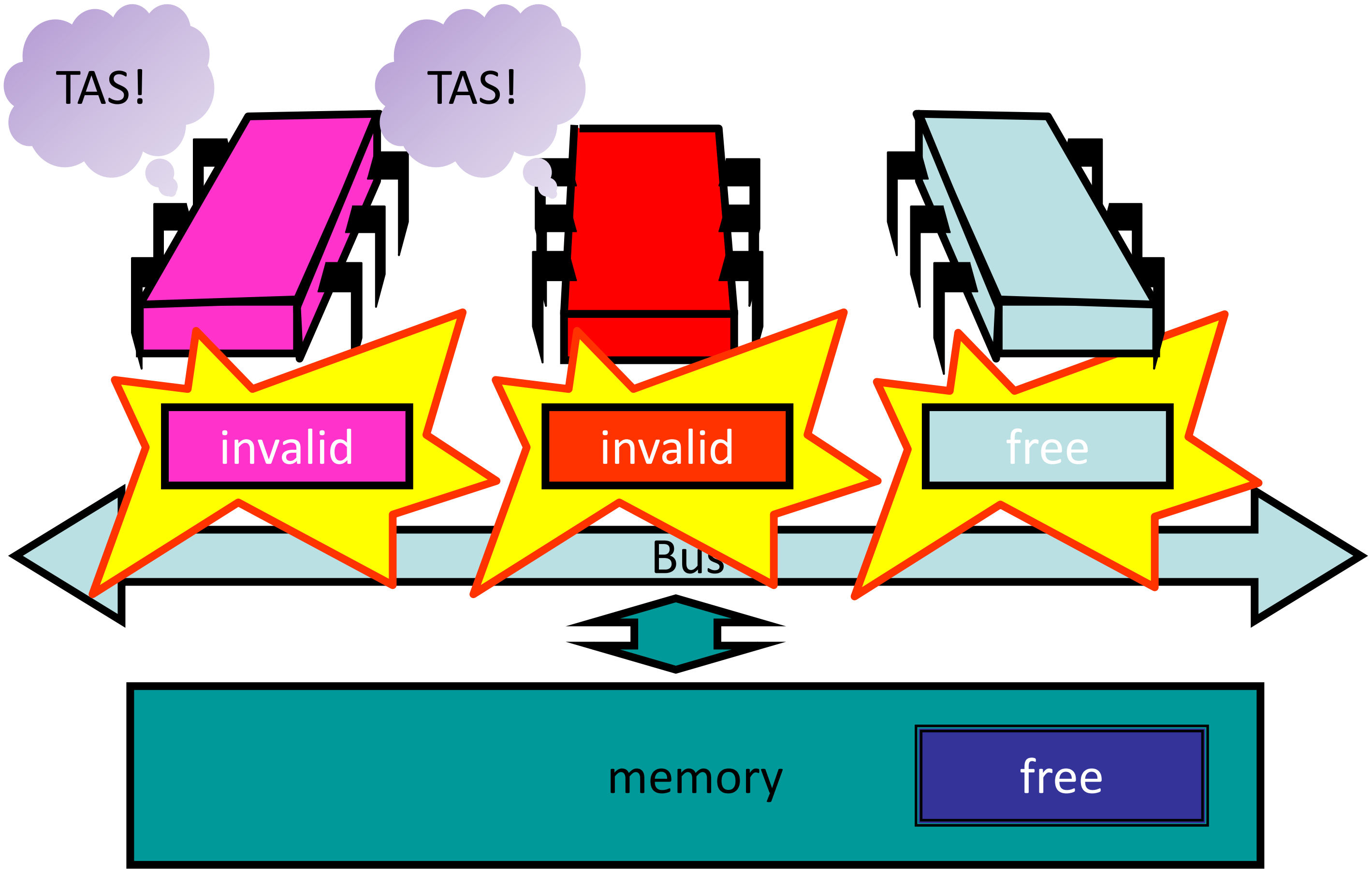
Local Spinning while Lock is Busy

- While the lock is held, all contenders spin in their caches, rereading cached data without causing any bus traffic



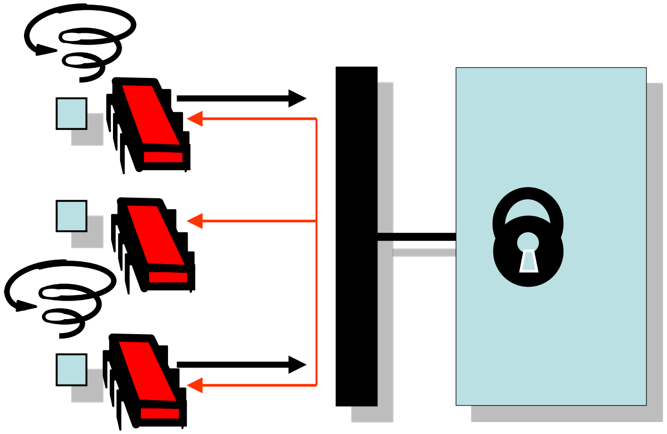
On Release

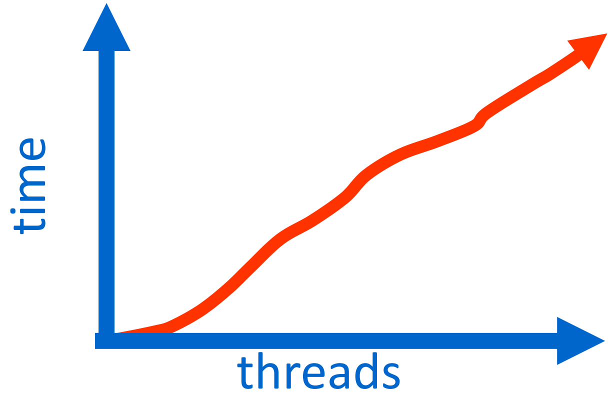
- The lock is released. All spinners take a cache miss and call Test&Set!



Time to Quiescence

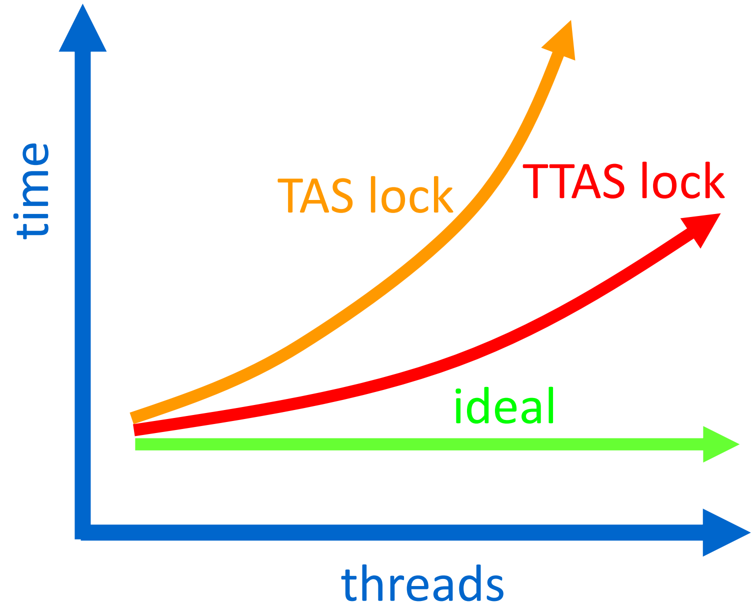
- Every process experiences a cache miss
  - All state.get() satisfied sequentially
- Every process does TAS
  - Caches of other processes are invalidated
- Eventual quiescence ("silence") after acquiring the lock
- The time to quiescence increases linearly with the number of processors for a bus architecture!





Mystery Explained

- Now we understand why the TTAS lock performs much better than the TAS lock, but still much worse than an ideal lock!

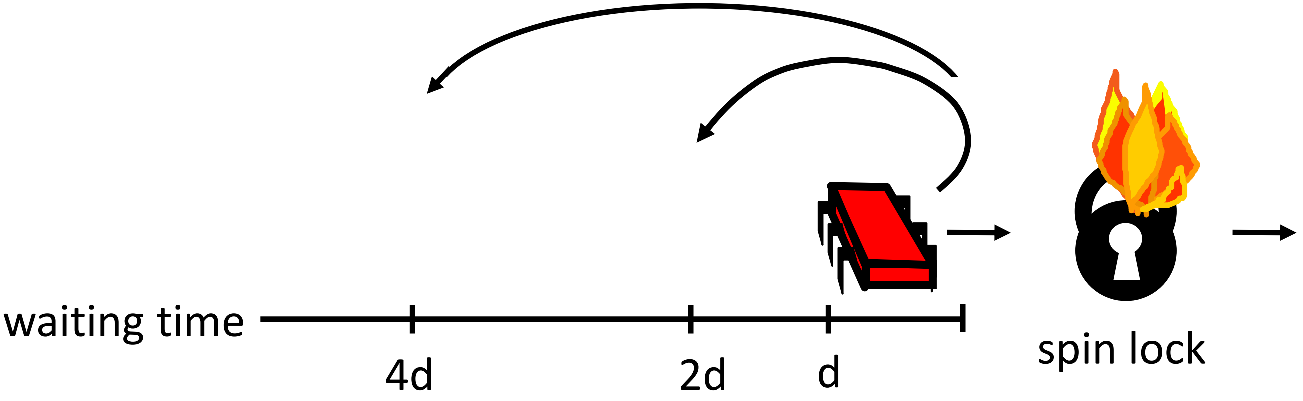


- How can we do better?

Introduce Delay

- If the lock looks free, but I fail to get it, there must be lots of contention
- It’s better to back off than to collide again!

- Example: Exponential Backoff
- Each subsequent failure doubles expected waiting time



Exponential Backoff Lock

```
class Backoff implements Lock {
  AtomicBoolean state = new AtomicBoolean(false);

  public void lock() {
    int delay = MIN_DELAY;
    while (true) {
      while(state.get()) {}
      if (!state.getAndSet())
        return;
      “sleep”(random() % delay);
      if (delay < MAX_DELAY)
        delay = 2 * delay;
    }
  }

  // unlock() remains the same

}
```

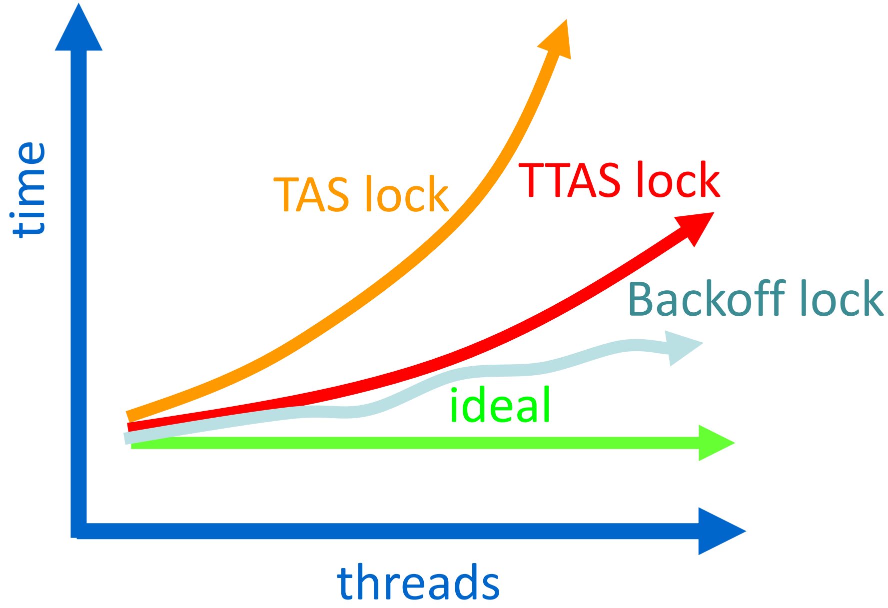
Fix minimum delay

Back off for random duration, but don’t swap out

Double maximum delay until an upper bound is reached

Backoff Lock: Performance

- The backoff lock outperforms the TTAS lock!
- But it is still not ideal…



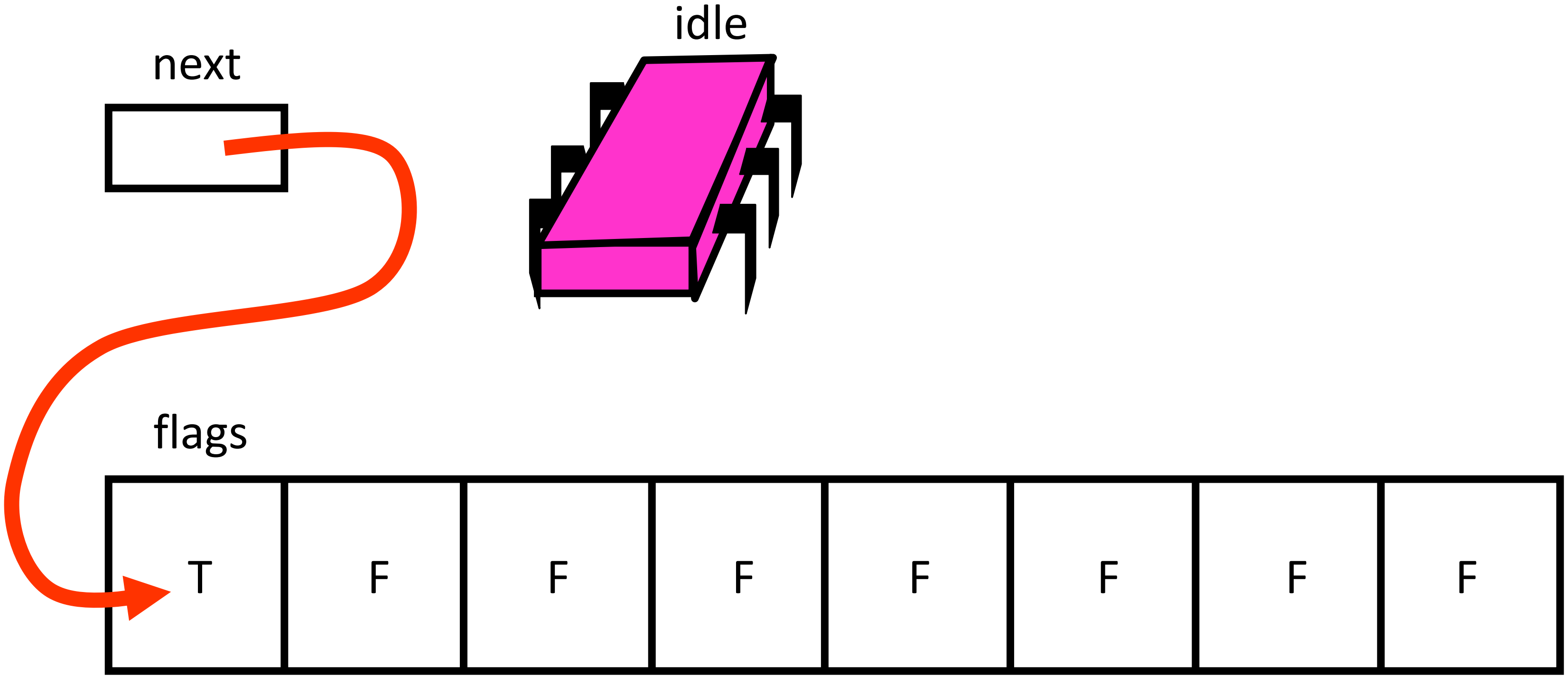
Backoff Lock: Evaluation

- Good
  - Easy to implement
  - Beats TTAS lock
- Bad
  - Must choose parameters carefully
  - Not portable across platforms

- How can we do better?
- Avoid useless invalidations
  - By keeping a queue of threads
- Each thread
  - Notifies next in line
  - Without bothering the others

ALock: Initially

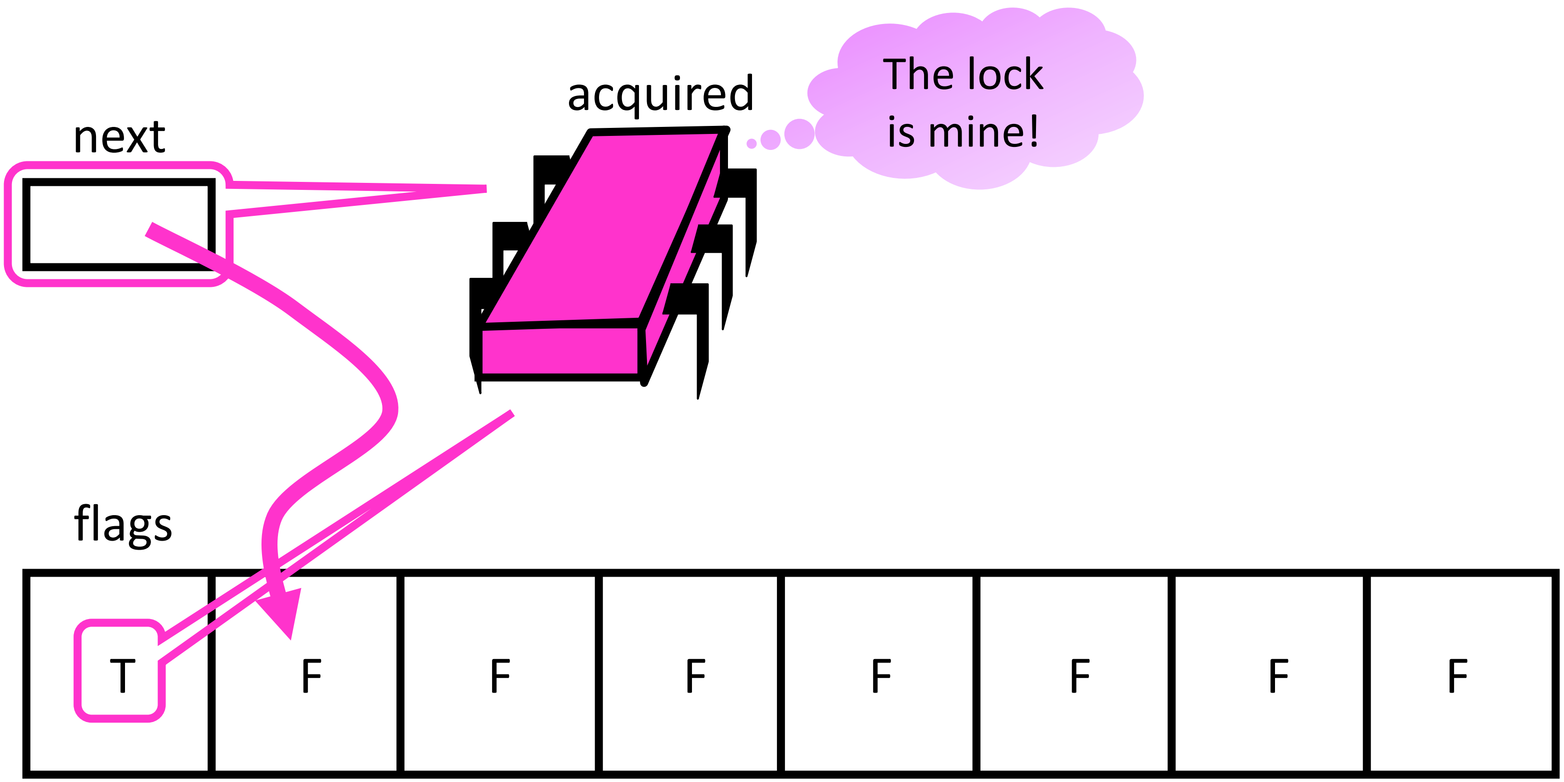
- The Anderson queue lock (ALock) is an array-based queue lock
- Threads share an atomic tail field (called next)



T	F	F	F	F	F	F	F

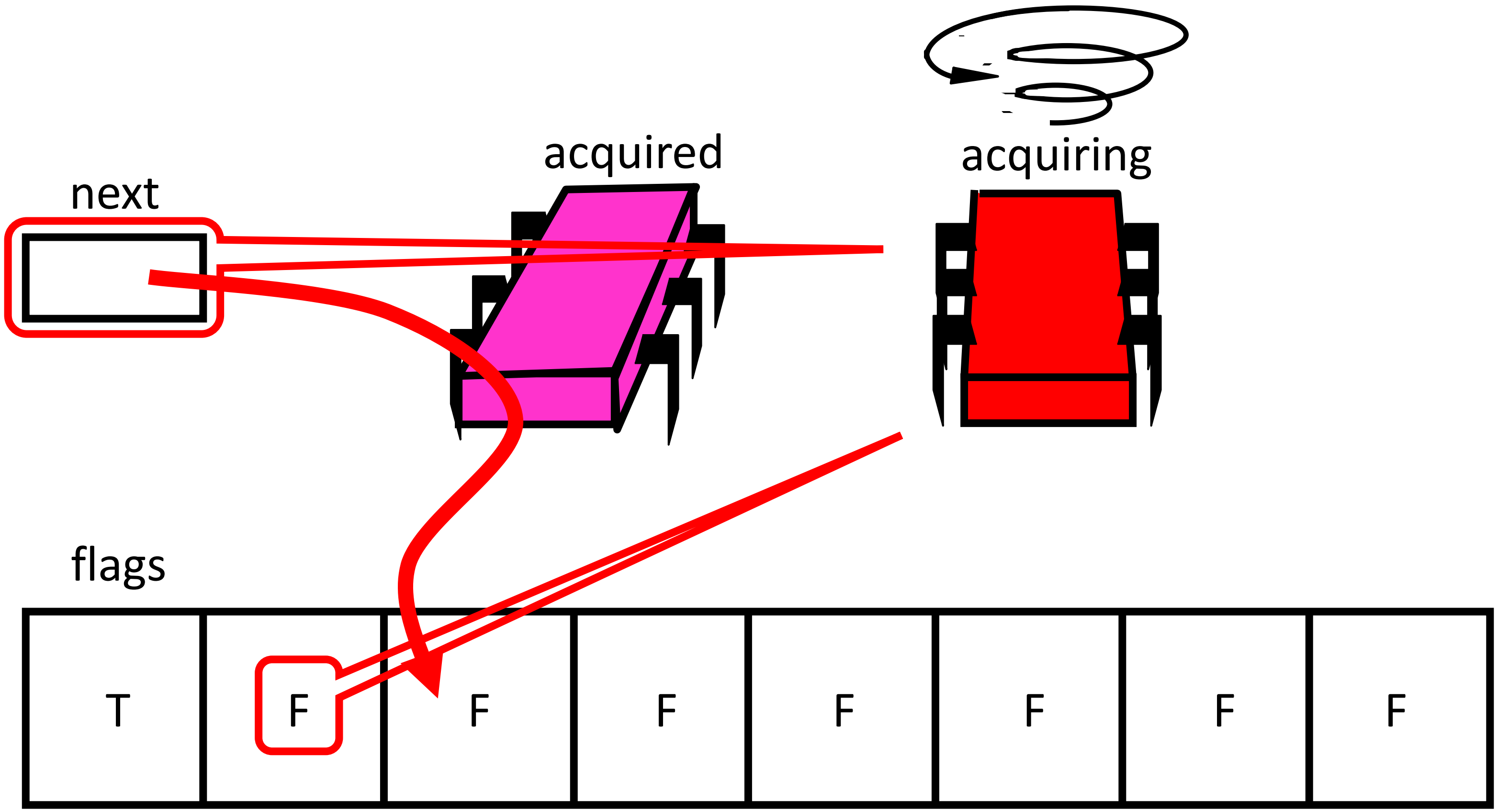
ALock: Acquiring the Lock

- To acquire the lock, each thread atomically increments the tail field
- If the flag is true, the lock is acquired
- Otherwise, spin until the flag is true



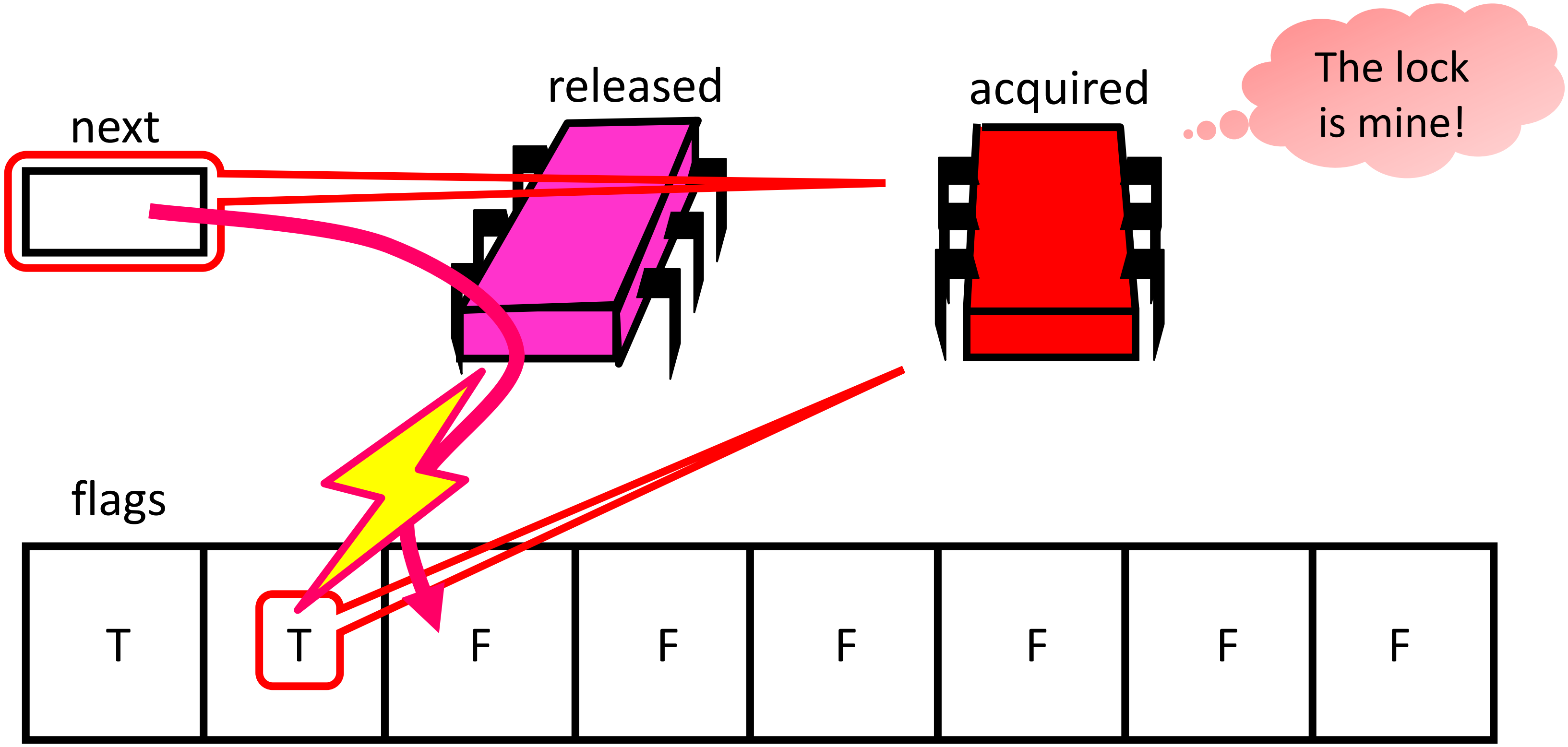
ALock: Contention

- If another thread wants to acquire the lock, it applies get&increment
- The thread spins because the flag is false



ALock: Releasing the Lock

- The first thread releases the lock by setting the next slot to true
- The second thread notices the change and gets the lock



ALock

```
class Alock implements Lock {
  boolean[] flags = {true,false,...,false};
  AtomicInteger next = new AtomicInteger(0);
  ThreadLocal<Integer> mySlot;

  public void lock() {
    mySlot = next.getAndIncrement();
    while (!flags[mySlot % n]) {}
    flags[mySlot % n] = false;
  }

  public void unlock() {
    flags[(mySlot+1) % n] = true;
  }
}
```

One flag per thread

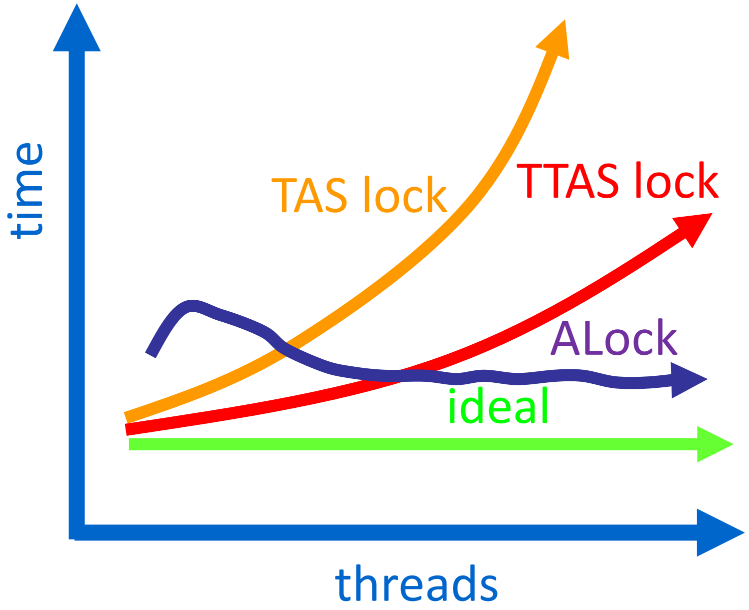
Thread-local variable

Take the next slot

Tell next thread to go

ALock: Performance

- Shorter handover than backoff
- Curve is practically flat
- Scalable performance
- FIFO fairness

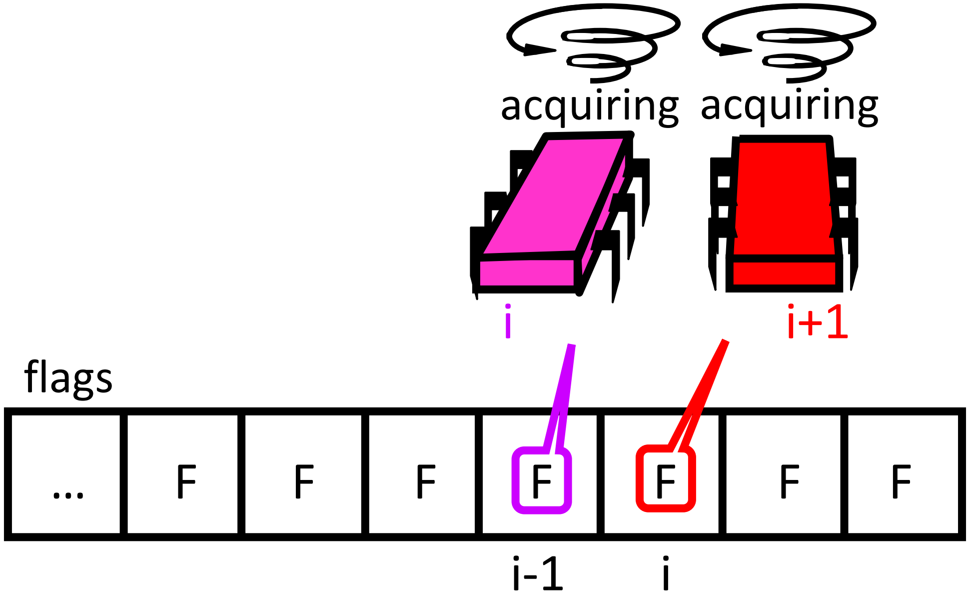


ALock: Evaluation

- Good
  - First truly scalable lock
  - Simple, easy to implement
- Bad
  - One bit per thread
  - Unknown number of threads?

ALock: Alternative Technique

- The threads could update own flag and spin on their predecessor's flag



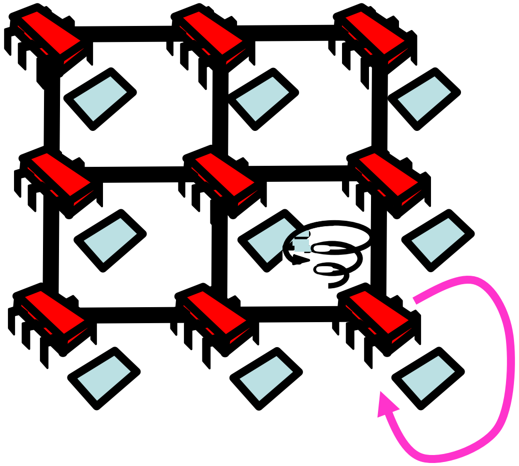
- This is basically what the CLH lock does, but using a linked list instead of an array
- Is this a good idea?

Not discussed
in this lecture

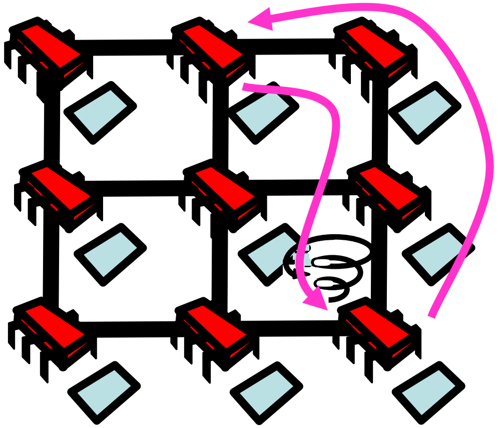
NUMA Architectures

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

Spinning on local memory is fast:



Spinning on remote memory is slow:



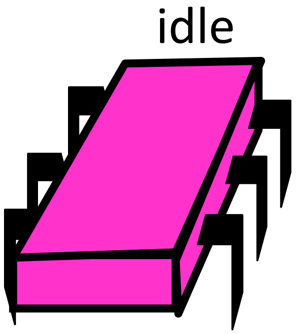
MCS Lock

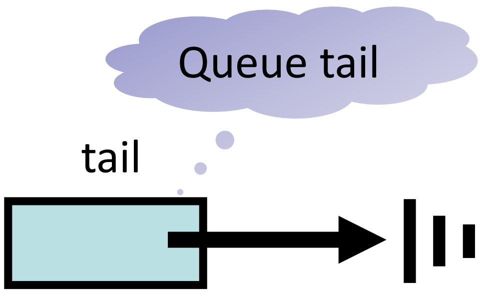
- Idea
  - Use a linked list instead of an array → small, constant-sized space
  - Spin on own flag, just like the Anderson queue lock

- The space usage
  - L = number of locks
  - N = number of threads
- of the Anderson lock is O(LN)
- of the MCS lock is O(L+N)

MCS Lock: Initially

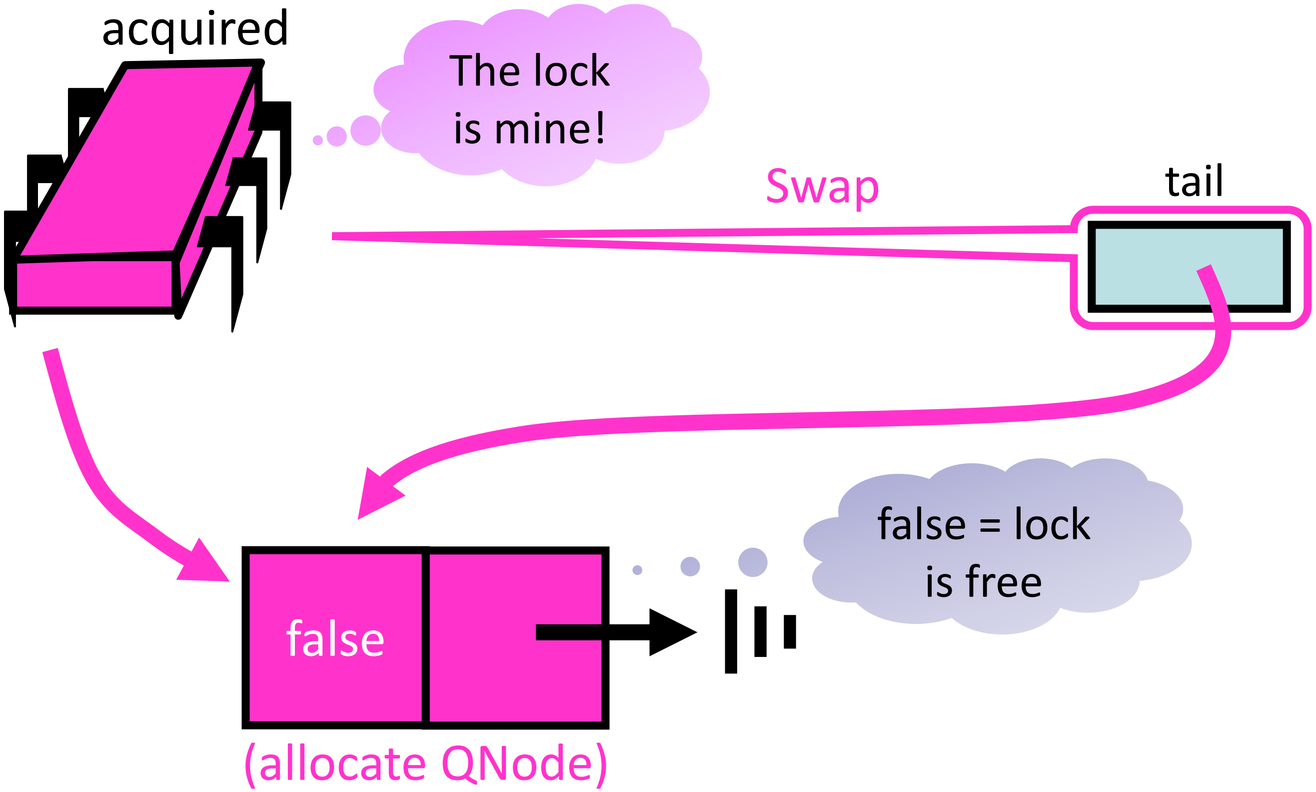
- The lock is represented as a linked list of QNodes, one per thread
- The tail of the queue is shared among all threads





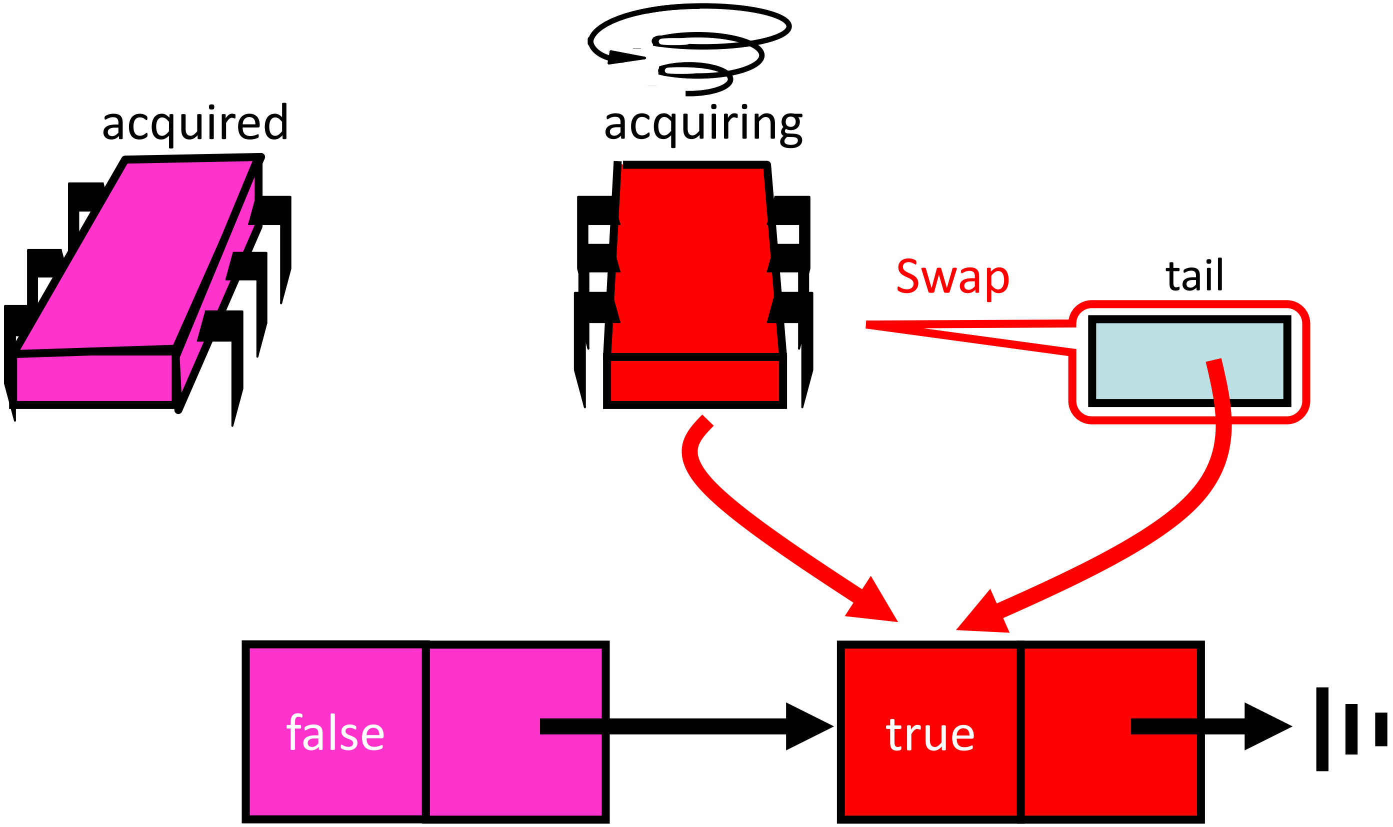
MCS Lock: Acquiring the Lock

- To acquire the lock, the thread places its QNode at the tail of the list by swapping the tail to its QNode
- If there is no predecessor, the thread acquires the lock



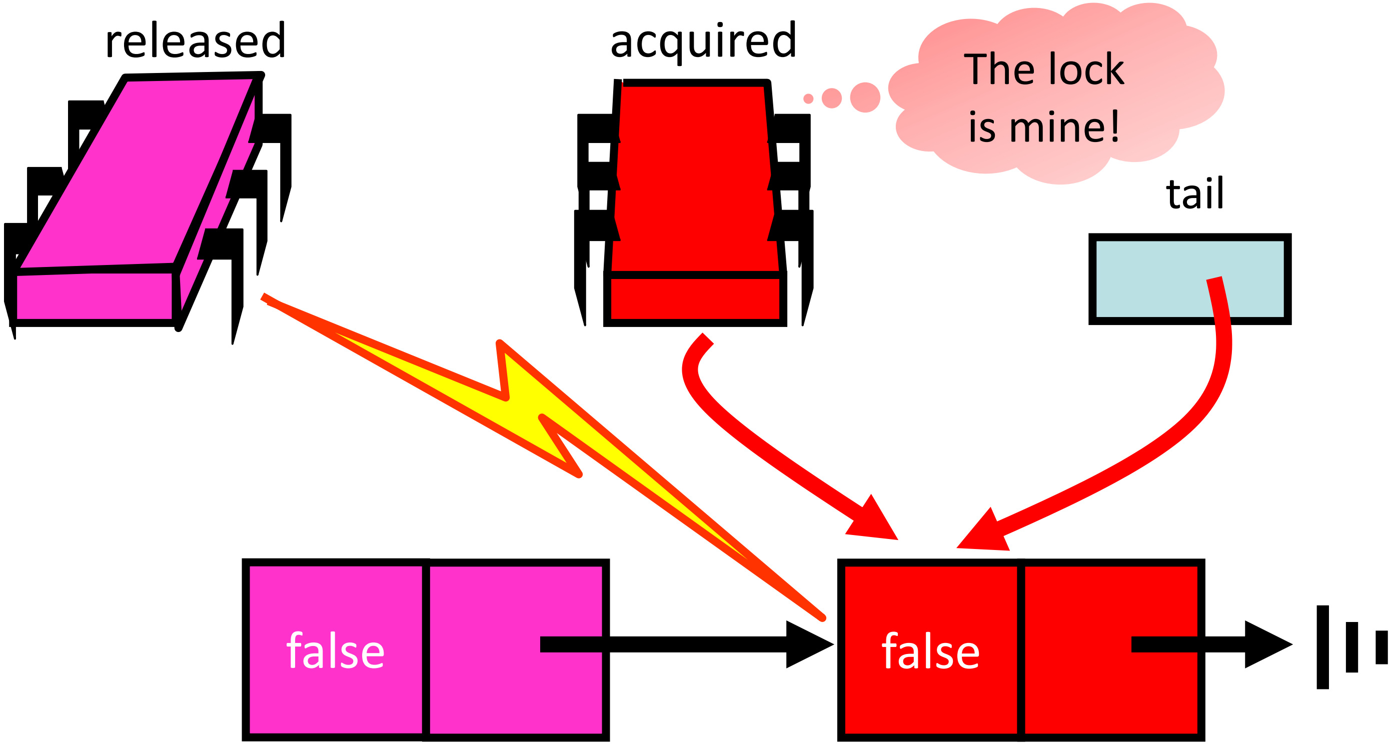
MCS Lock: Contention

- If another thread wants to acquire the lock, it again applies swap
- The thread spins on its own QNode because there is a predecessor



MCS Lock: Releasing the Lock

- The first thread releases the lock by setting its successor’s QNode to false



MCS Queue Lock

```
class QNode {
  boolean locked = false;
  QNode next = null;
}
```

MCS Queue Lock

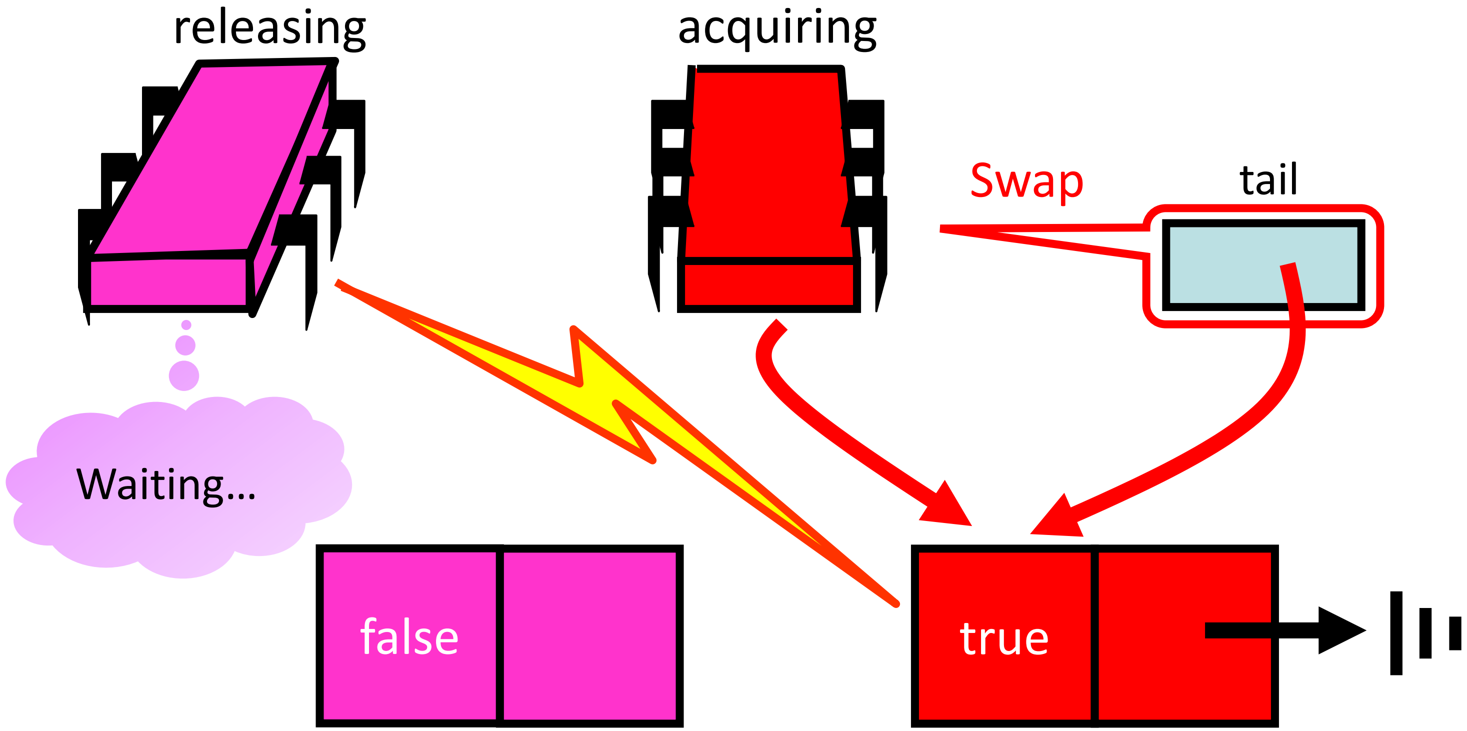
```
class MCSLock implements Lock {
  AtomicReference tail;

  public void lock() {
    QNode qnode = new QNode();
    QNode pred = tail.getAndSet(qnode);
    if (pred != null) {
      qnode.locked = true;
      pred.next = qnode;
      while (qnode.locked) {}
    }
  }

  ...
```

Add my node to the tail

Fix if queue was non-empty

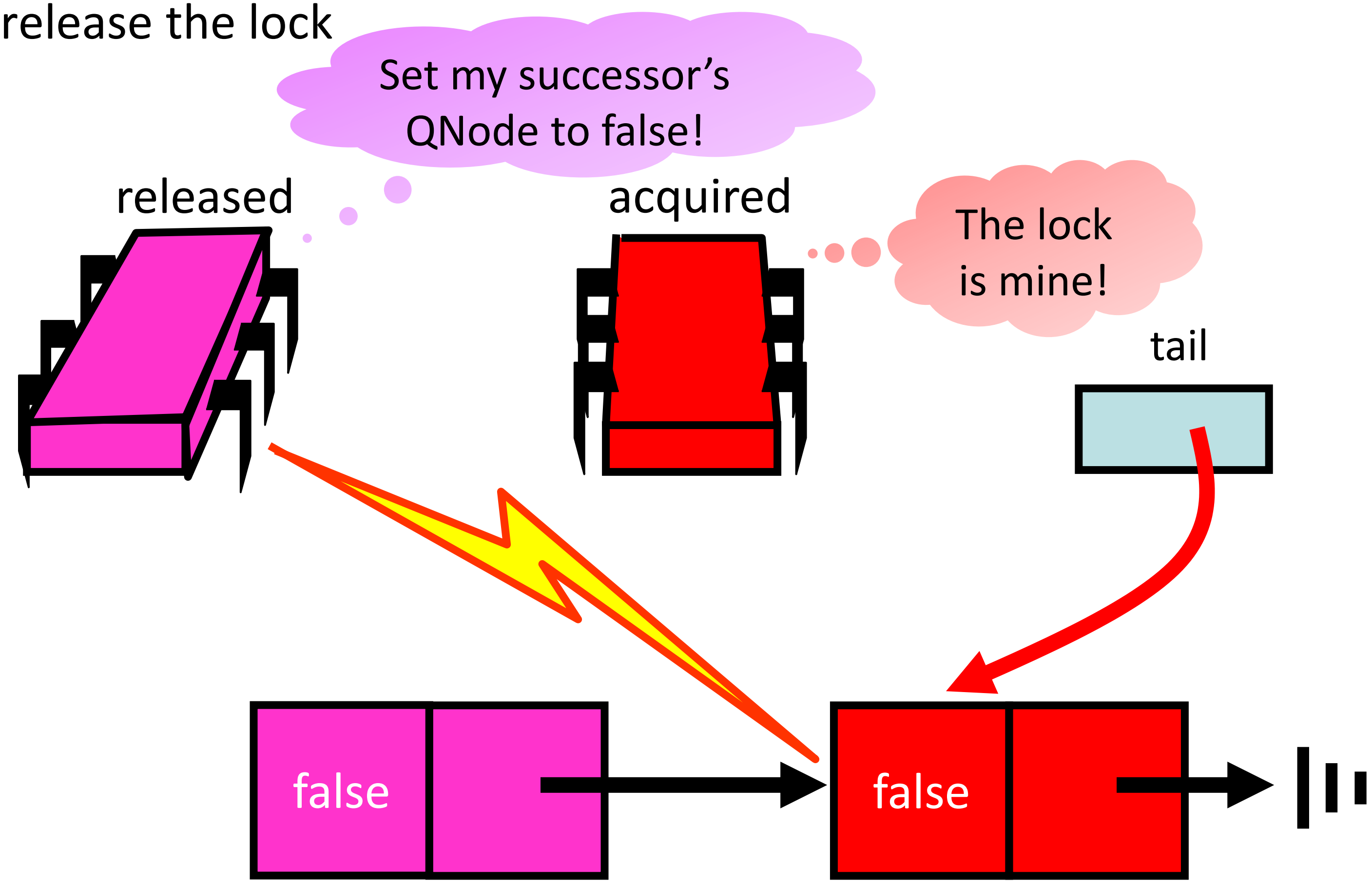
MCS Lock: Unlocking

- If there is a successor, unlock it. But, be cautious!
- Even though a QNode does not have a successor, the purple thread knows that another thread is active because tail does not point to its QNode!



MCS Lock: Unlocking Explained

- As soon as the pointer to the successor is set, the purple thread can release the lock



MCS Queue Lock

```
 ...

 public void unlock() {
  if (qnode.next == null) {
   if (tail.CAS(qnode, null))
    return;
   while (qnode.next == null) {}
  }
  qnode.next.locked = false;
 }
}
```

Missing successor?

If really no successor, tail = null

Otherwise, wait for successor to catch up

Pass lock to successor

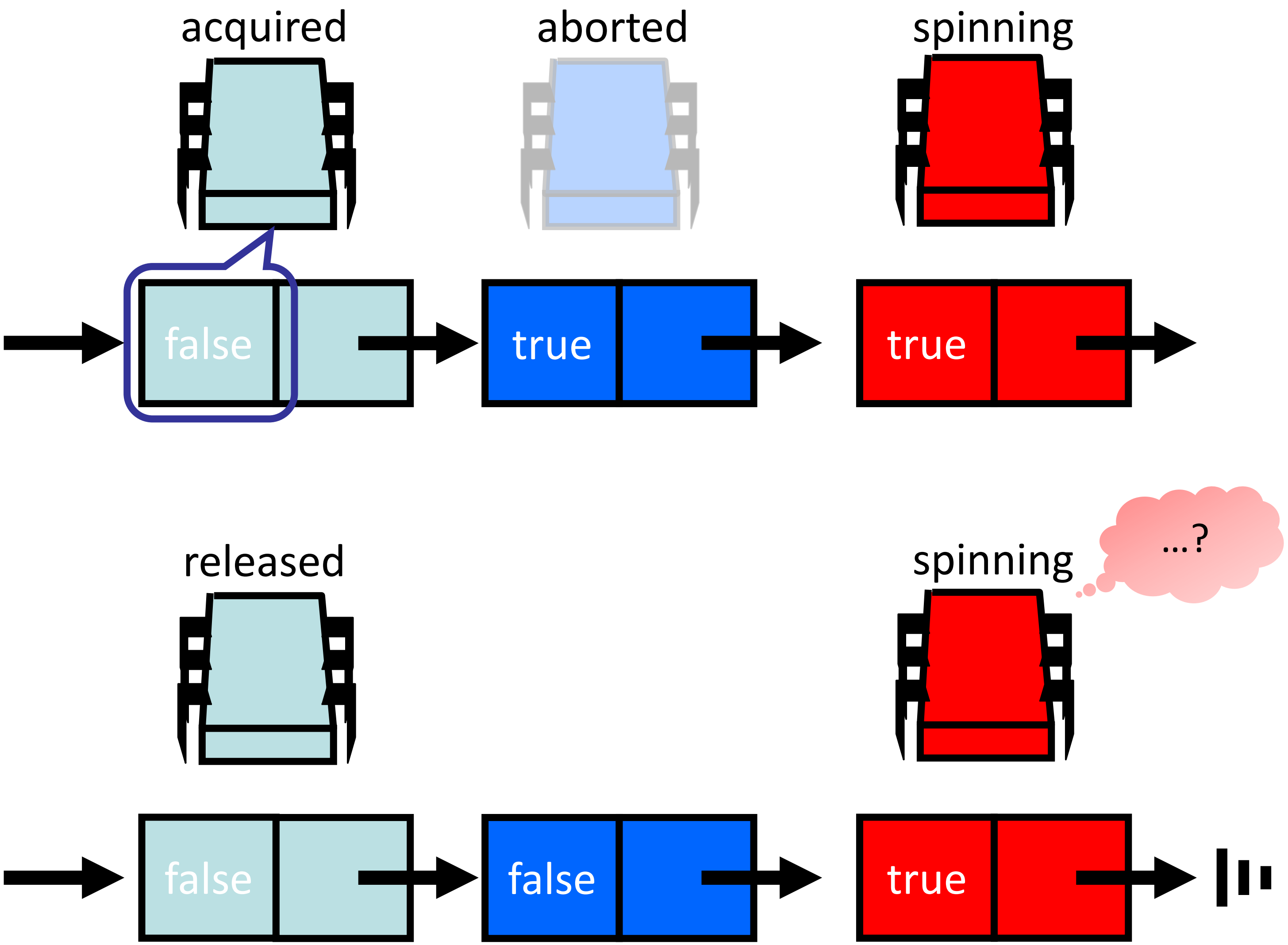
Abortable Locks

- What if you want to give up waiting for a lock?
- For example
  - Time-out
  - Database transaction aborted by user

- Back-off Lock
  - Aborting is trivial: Just return from lock() call!
  - Extra benefit: No cleaning up, wait-free, immediate return

- Queue Locks
  - Can’t just quit: Thread in line behind will starve
  - Need a graceful way out…

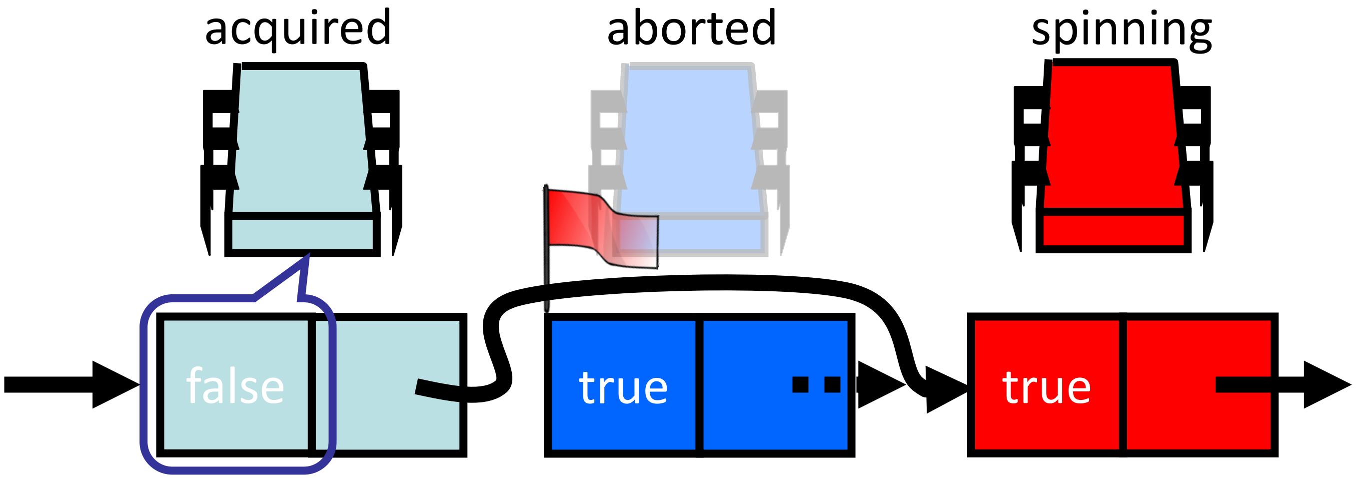
Problem with Queue Locks



Abortable MCS Lock

- A mechanism is required to recognize and remove aborted threads
  - A thread can set a flag indicating that it aborted
  - The predecessor can test if the flag is set
  - If the flag is set, its new successor is the successor's successor
  - How can we handle concurrent aborts? This is not discussed in this lecture

Spinning on remote object...?!



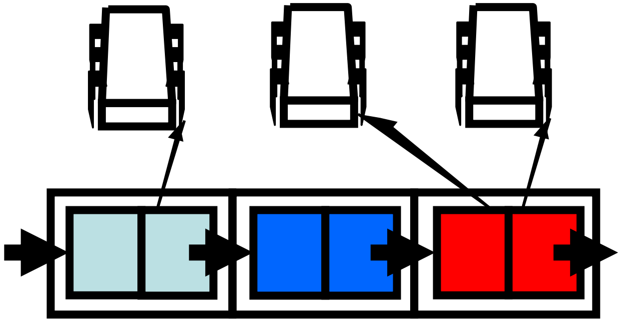
Composite Locks

- Queue locks have many advantages
  - FIFO fairness, fast lock release, low contention

  but require non-trivial protocols to handle aborts (and recycling of nodes)
- Backoff locks support trivial time-out protocols

  but are not scalable and may have slow lock release times

- A composite lock combines the best of both approaches!
- Short fixed-sized array of lock nodes
- Threads randomly pick a node and try to acquire it
- Use backoff mechanism to acquire a node
- Nodes build a queue
- Use a queue lock mechanism to acquire the lock



One Lock To Rule Them All?

- TTAS+Backoff, MCS, Abortable MCS…
- Each better than others in some way
- There is not a single best solution
- Lock we pick really depends on
  - the application
  - the hardware
  - which properties are important

Handling Multiple Threads

- Adding threads should not lower the throughput
  - Contention effects can mostly be fixed by Queue locks

- Adding threads should increase throughput
  - Not possible if the code is inherently sequential
  - Surprising things are parallelizable!

- How can we guarantee consistency if there are many threads?

Coarse-Grained Synchronization

- Each method locks the object
  - Avoid contention using queue locks
  - Mostly easy to reason about
  - This is the standard Java model (**synchronized** blocks and methods)

- Problem: Sequential bottleneck
  - Threads “stand in line”
  - Adding more threads does not improve throughput
  - We even struggle to keep it from getting worse…

- So why do we even use a multiprocessor?
  - Well, some applications are inherently parallel…
  - We focus on exploiting non-trivial parallelism

Credits

- The TTAS lock is due to Kruskal, Rudolph, and Snir, 1988.
- Tom Anderson invented the ALock, 1990.
- The MCS lock is due to Mellor-Crummey and Scott, 1991.

That’s all!

Questions & Comments?

Roger Wattenhofer