

YSC4231: Parallel, Concurrent and Distributed Programming

Spin Locks and Contention

Focus so far: Correctness and Progress

- Models
 - Accurate (we never lied to you)
 - But idealized (so we forgot to mention a few things)
- Protocols
 - Elegant
 - Important
 - But naïve

New Focus: Performance

- Models
 - More complicated (not the same as complex!)
 - Still focus on principles (not soon obsolete)
- Protocols
 - Elegant (in their fashion)
 - Important (why else would we pay attention)
 - And realistic (your mileage may vary)

Today: Revisit Mutual Exclusion

- Performance, not just correctness
- Proper use of multiprocessor architectures
- A collection of locking algorithms...

What Should you do if you can't get a lock?

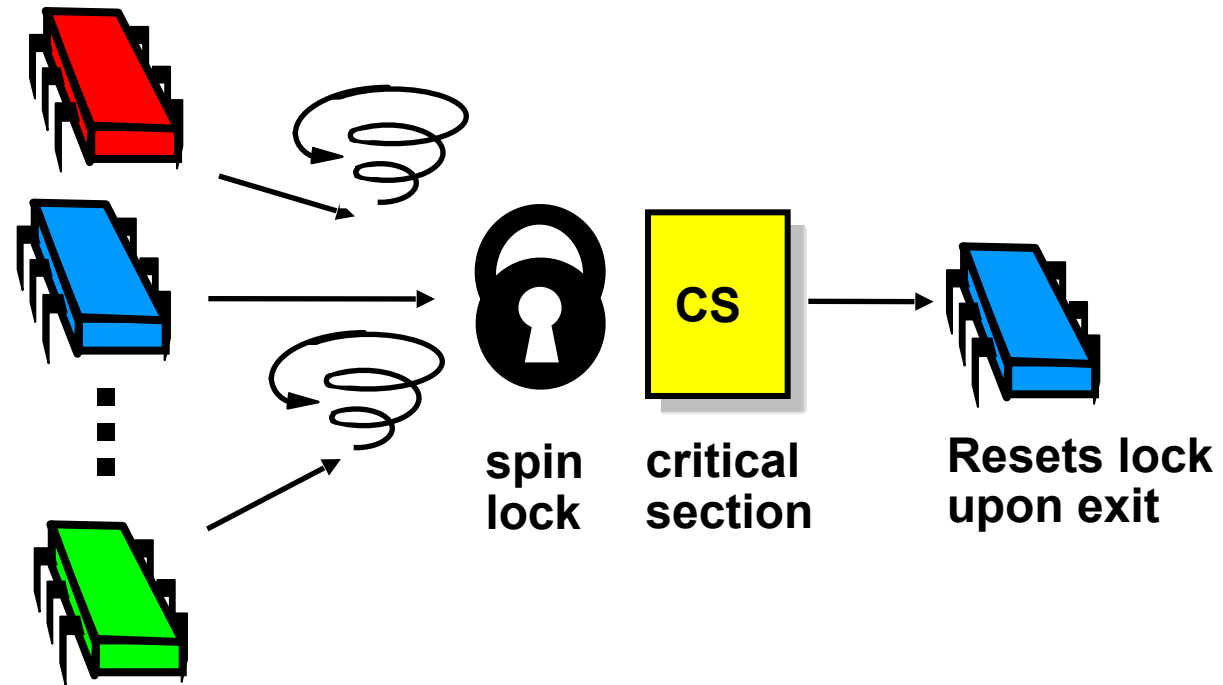
- Keep trying
 - “spin” or “busy-wait”
 - Good if delays are short
- Give up the processor
 - Good if delays are long
 - Always good on uniprocessor

What Should you do if you can't get a lock?

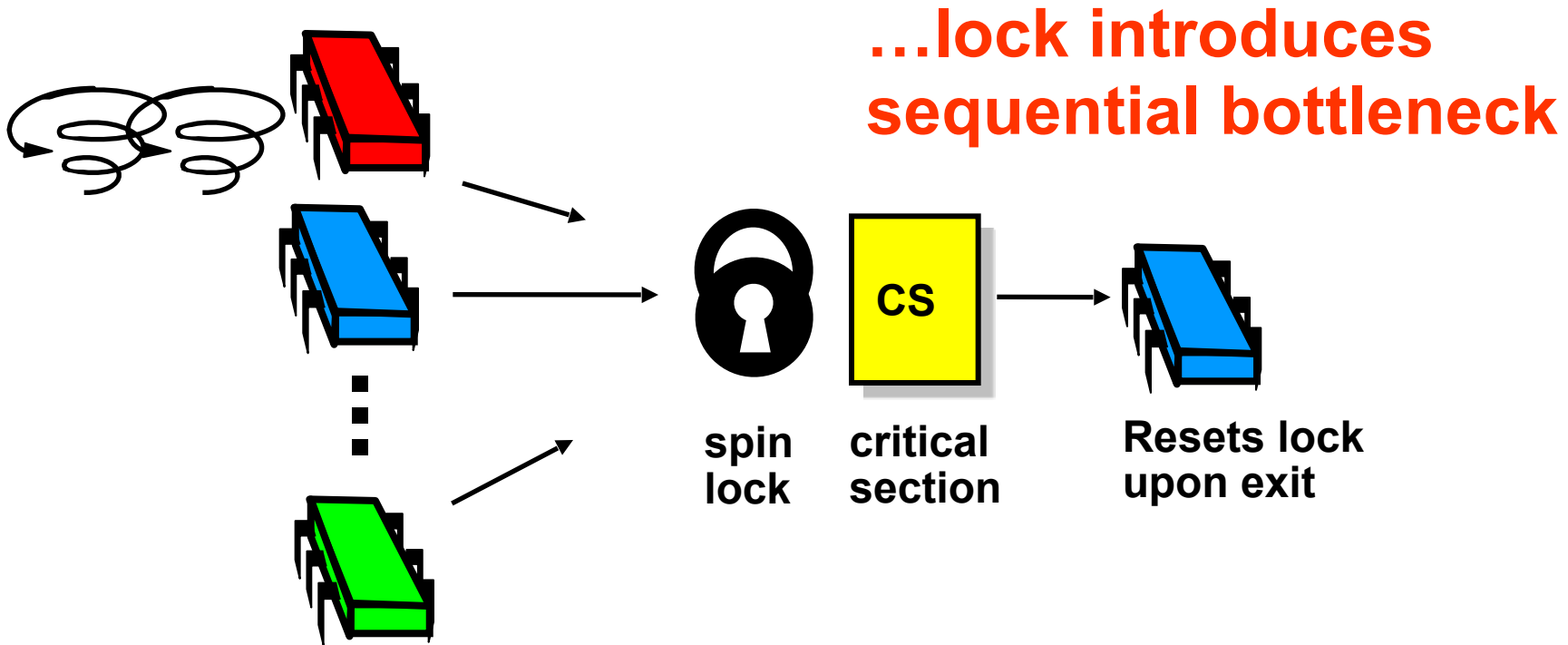
- Keep trying
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our focus now

Basic Spin-Lock

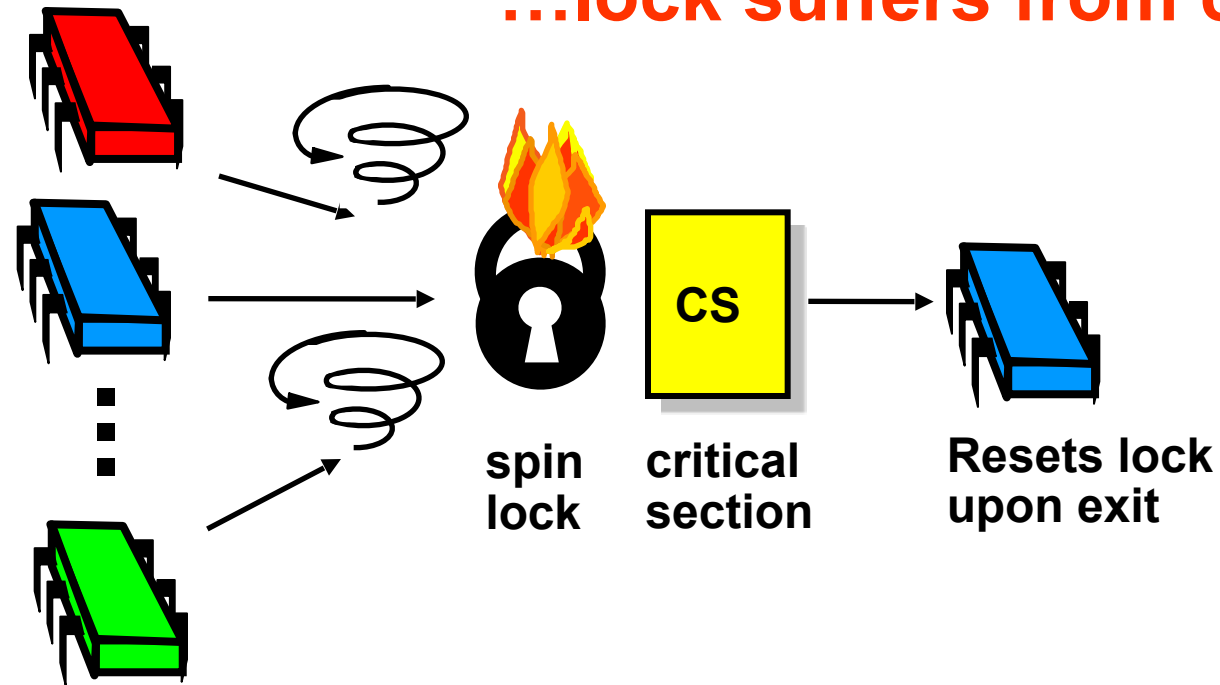


Basic Spin-Lock



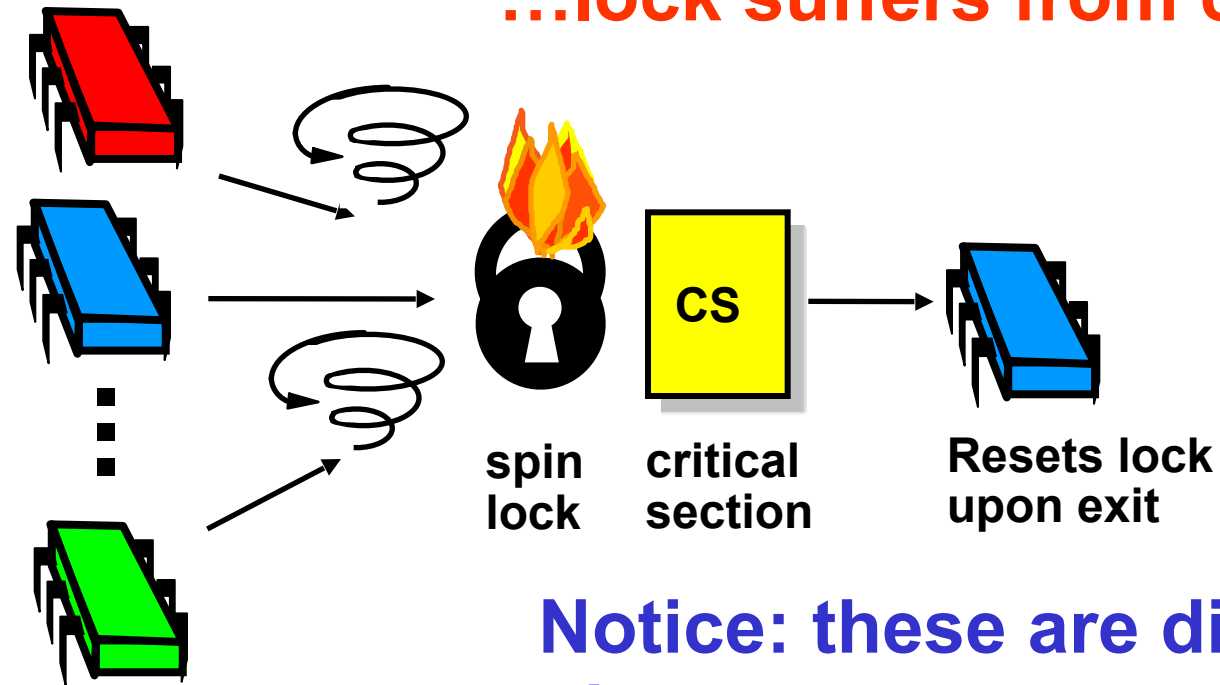
Basic Spin-Lock

...lock suffers from contention



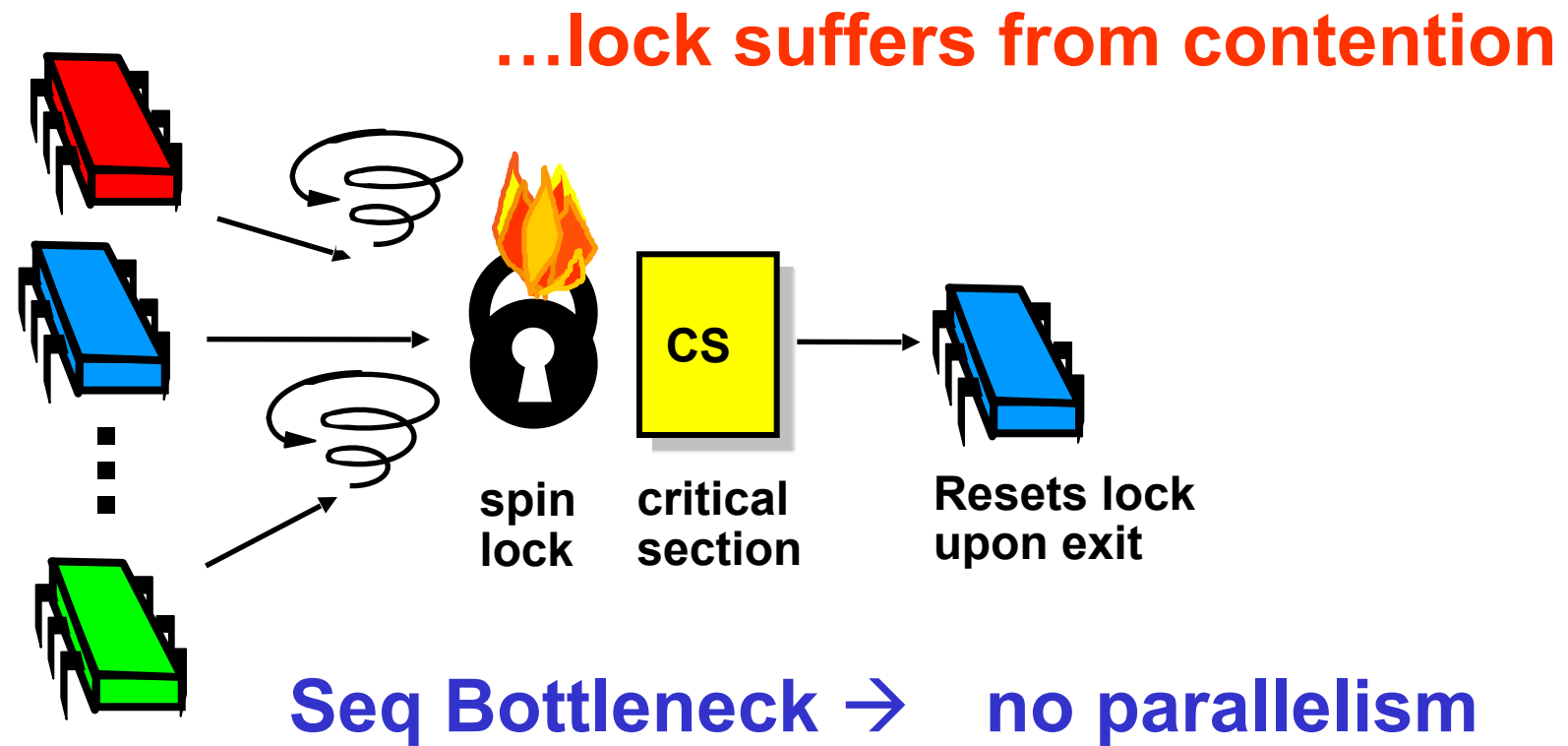
Basic Spin-Lock

...lock suffers from contention

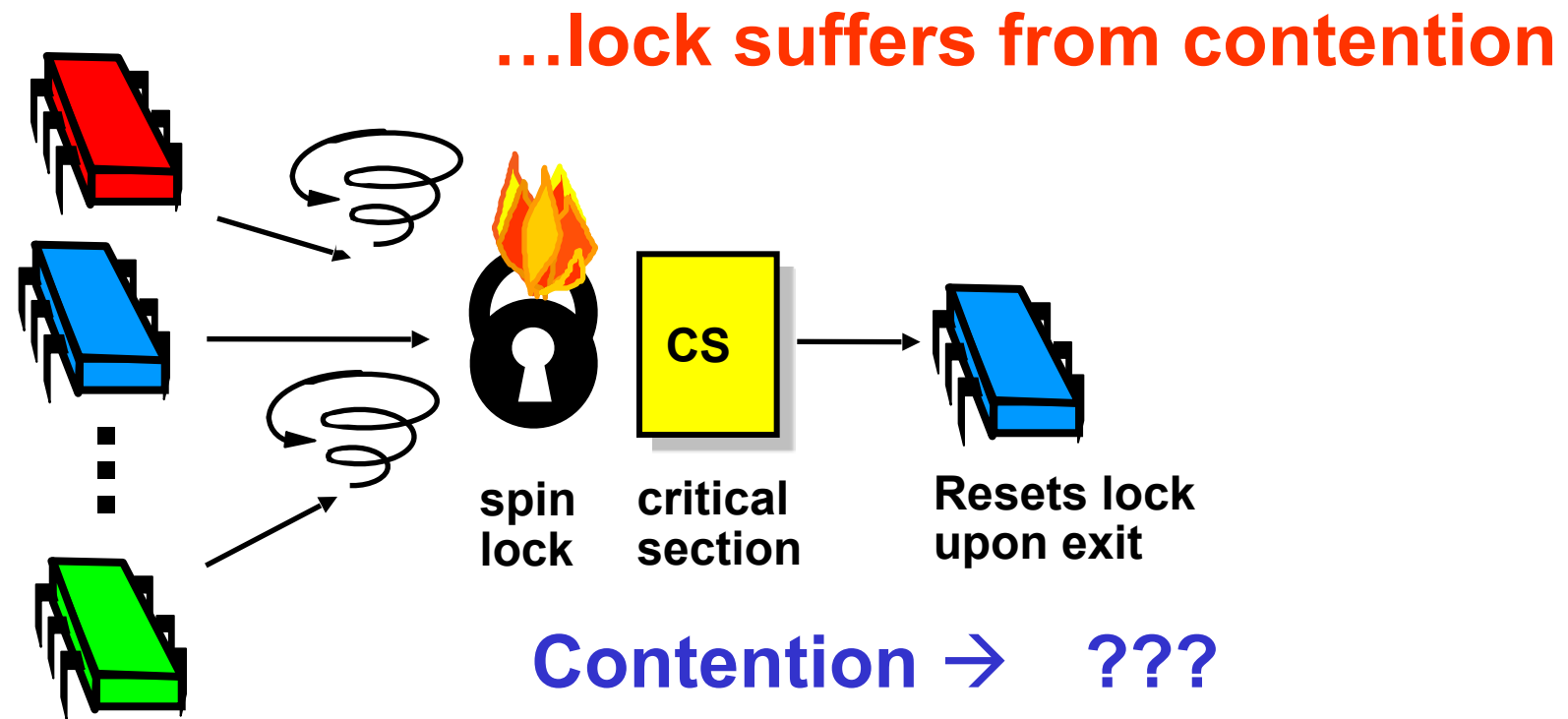


Notice: these are distinct phenomena

Basic Spin-Lock



Basic Spin-Lock





Review: Test-and-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**
- TAS aka “getAndSet” in Scala/Java

Review: Test-and-Set

```
class AtomicBoolean {  
    var value: Boolean  
  
    def getAndSet(newValue: Boolean) =  
        this.synchronized {  
            val prior = value  
            value = newValue  
            prior  
        }  
}
```

Review: Test-and-Set

```
class AtomicBoolean {  
    var value: Boolean  
  
    def getAndSet(newValue: Boolean) =  
        this.synchronized {  
            val prior = value  
            value = newValue  
            prior  
        }  
}
```

Package

java.util.concurrent.atomic

Review: Test-and-Set

```
class AtomicBoolean {  
    var value: Boolean  
  
    def getAndSet(newValue: Boolean) =  
        this.synchronized {  
            val prior = value  
            value = newValue  
            prior  
        }  
}
```

**Swap old and new
values**

Review: Test-and-Set

```
val lock = new AtomicBoolean(false)  
...  
val prior = lock.getAndSet(true)
```

Review: Test-and-Set

```
val lock = new AtomicBoolean(false)  
...  
val prior = lock.getAndSet(true)
```

**Swapping in `true` is called
“test-and-set” or TAS**

Test-and-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-and-set Lock

```
class TASLock extends SpinLock {  
    val state = new AtomicBoolean(false)  
  
    override def lock() = {  
        while(state.getAndSet(true)) {  
            // spin  
        }  
    }  
  
    override def unlock() = {  
        state.set(false)  
    }  
}
```

Test-and-set Lock

```
class TASLock extends SpinLock {  
    val state = new AtomicBoolean(false)  
  
    override def lock() = {  
        while (state.getAndSet(true)) {  
            // spin  
        }  
    }  
  
    override def Lock state is AtomicBoolean  
        state.set(false)  
    }  
}
```

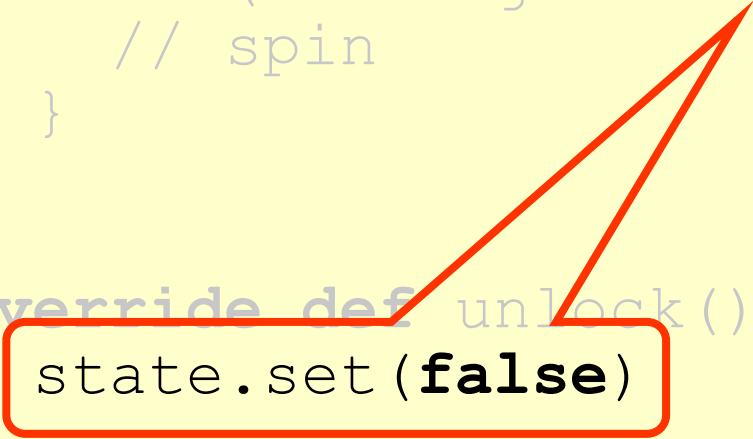
Test-and-set Lock

```
class TASLock extends SpinLock {  
  val state = new AtomicBoolean(false)  
  
  override def lock() = {  
    while (state.getAndSet(true)) {  
      // spin  
    }  
  }  
  
  override def unlock() = {  
    state.set(false)  
  }  
}
```

Keep trying until lock acquired

Test-and-set Lock

```
class TASLock extends SpinLock {  
  val st  
  Release lock by resetting  
  state to false  
  override while (state.getAndSet(true)) {  
    // spin  
  }  
  override def 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
- How did we overcome the $\Omega(n)$ lower bound?
- We used a RMW operation...

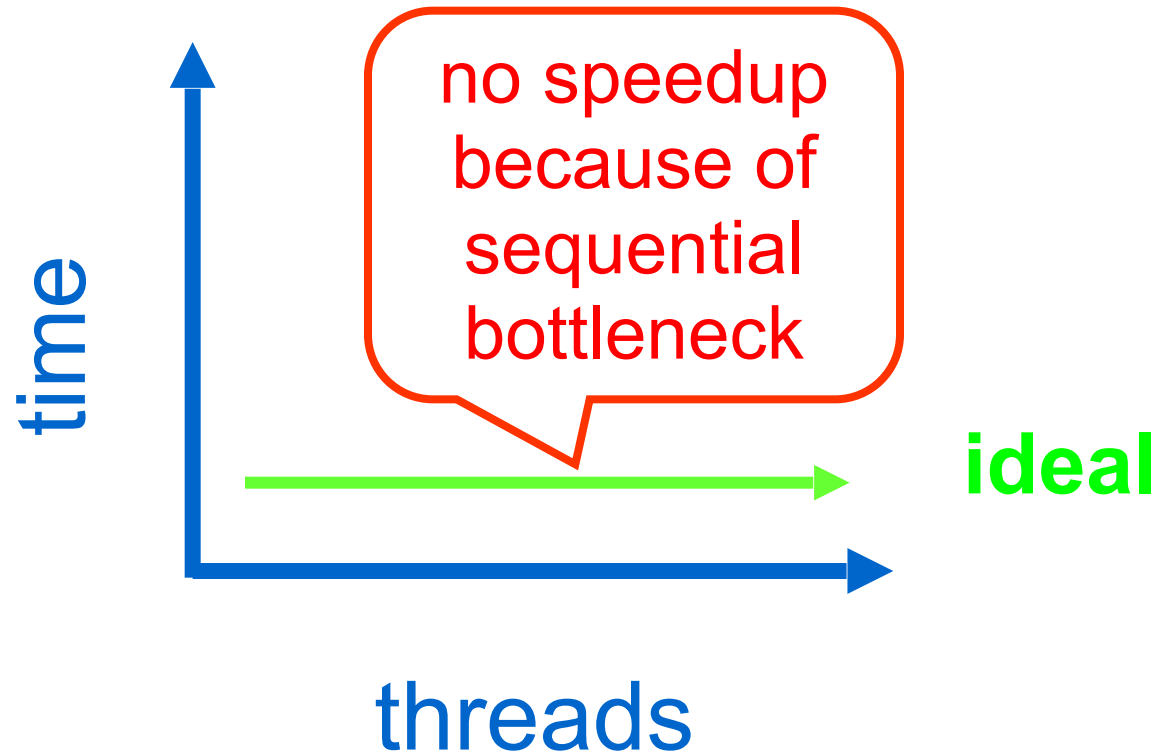
Performance

- Experiment
 - n threads
 - Increment shared counter 1 million times
 - Demo: *SpinLockBenchmark* and *TASLockRunner*

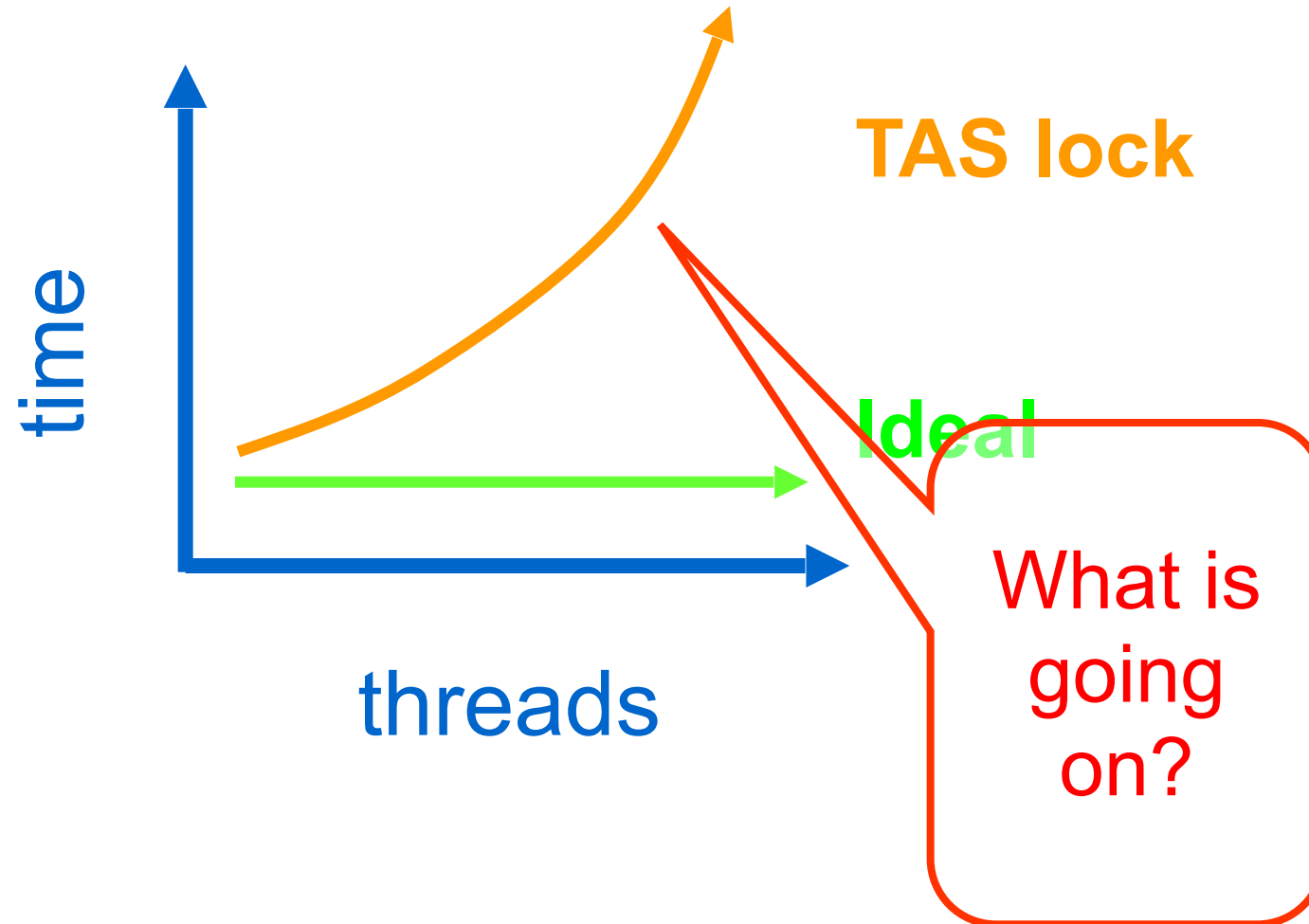
Performance

- Experiment
 - n threads
 - Increment shared counter 1 million times
 - Demo: *SpinLockBenchmark* and *TASLockRunner*
- How long should it take?
- How long does it take?

Graph



Mystery #1



Test-and-Test-and-Set Locks

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

Test-and-test-and-set Lock

```
class TTASLock extends SpinLock {  
    val state = new AtomicBoolean(false)  
  
    override def lock(): Unit = {  
        while (true) {  
            while (state.get()) {}  
            if (!state.getAndSet(true)) {  
                return  
            }  
        }  
    }  
    ...  
}
```

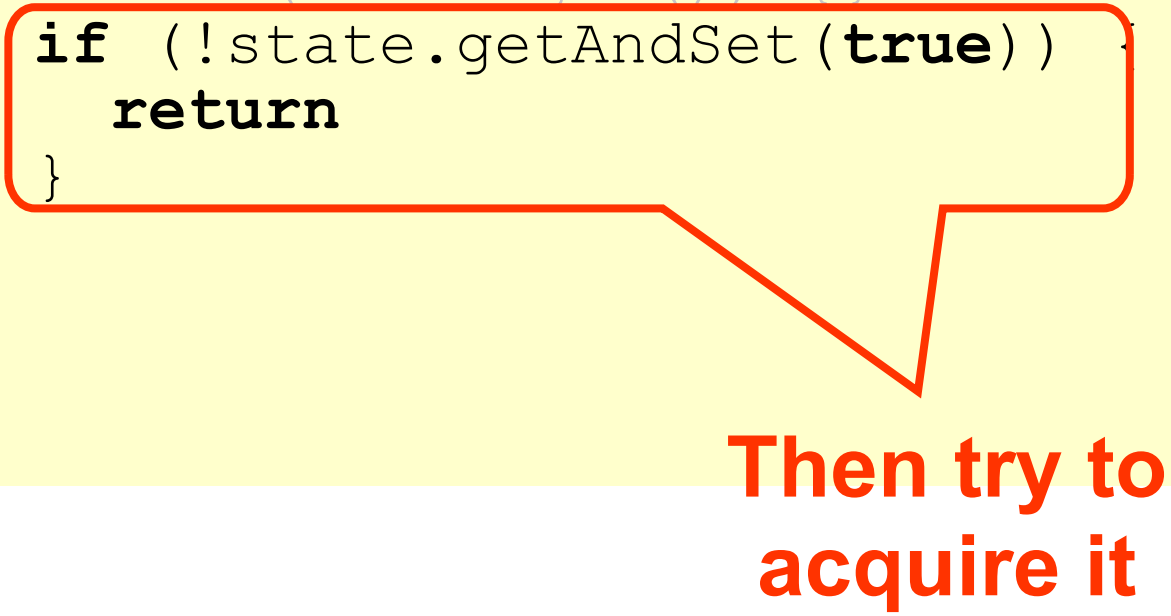
Test-and-test-and-set Lock

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      }  
    }  
  }  
  ...  
}
```

Wait until lock looks free

Test-and-test-and-set Lock

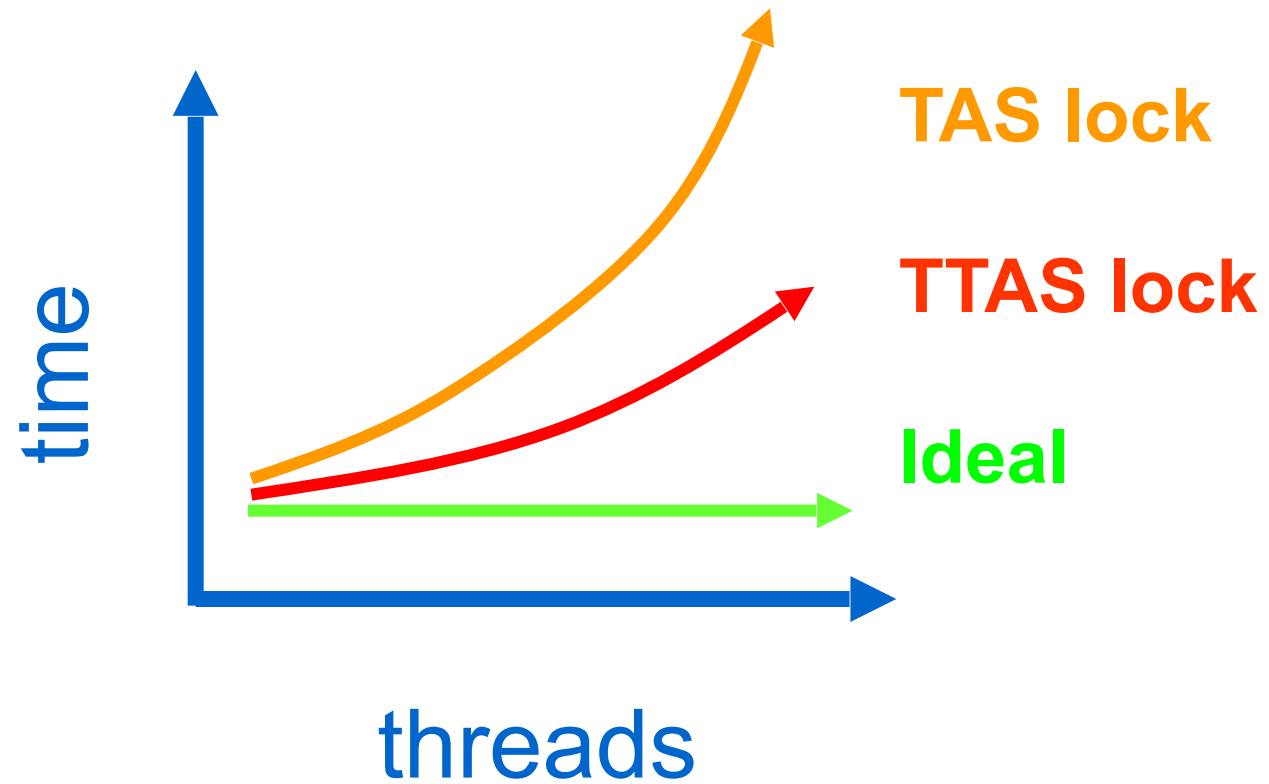
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    }  
  }  
  ...  
}
```



**Then try to
acquire it**

Demo

Mystery #2



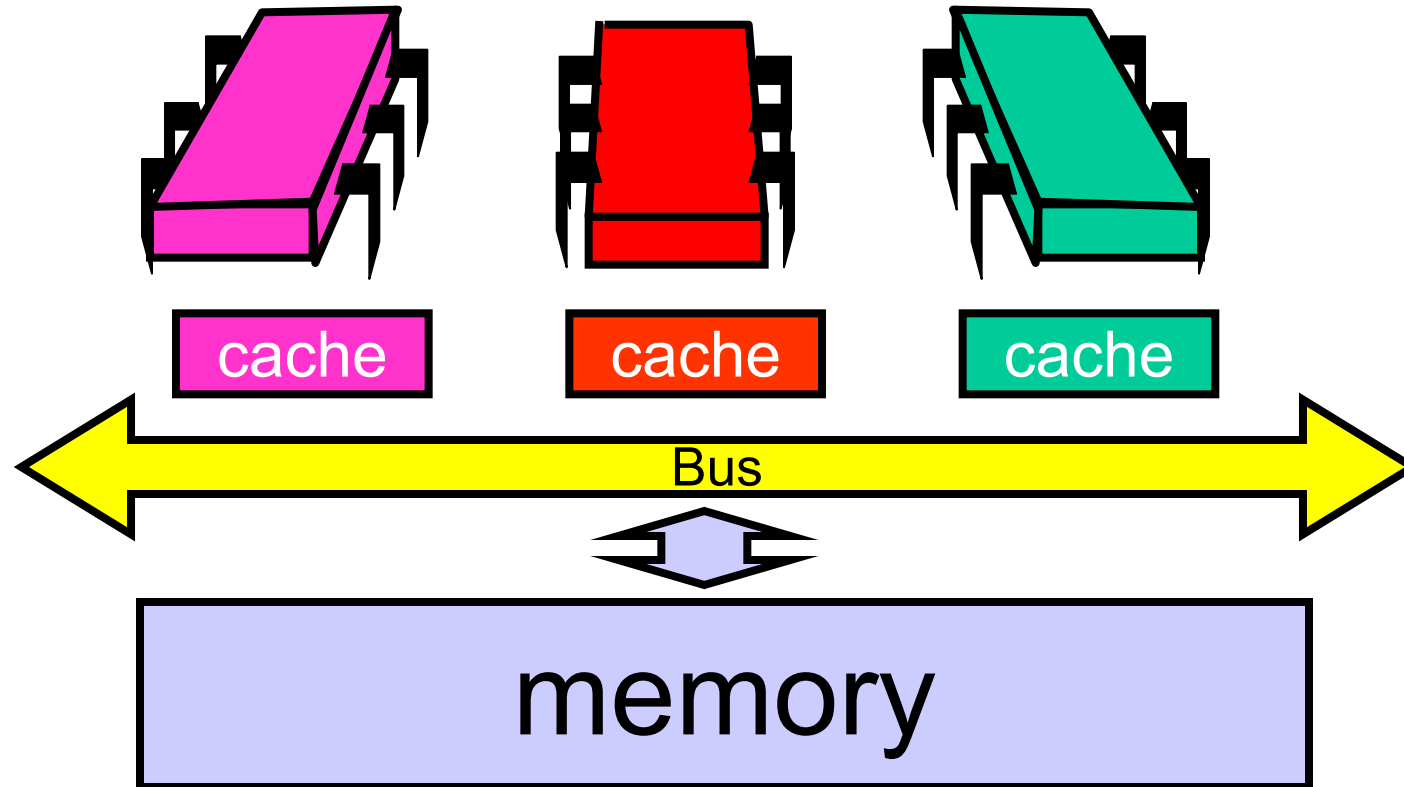
Mystery

- Both
 - TAS and TTAS
 - Do the same thing (in our model)
- Except that
 - TTAS performs better than TAS
 - Neither approaches ideal

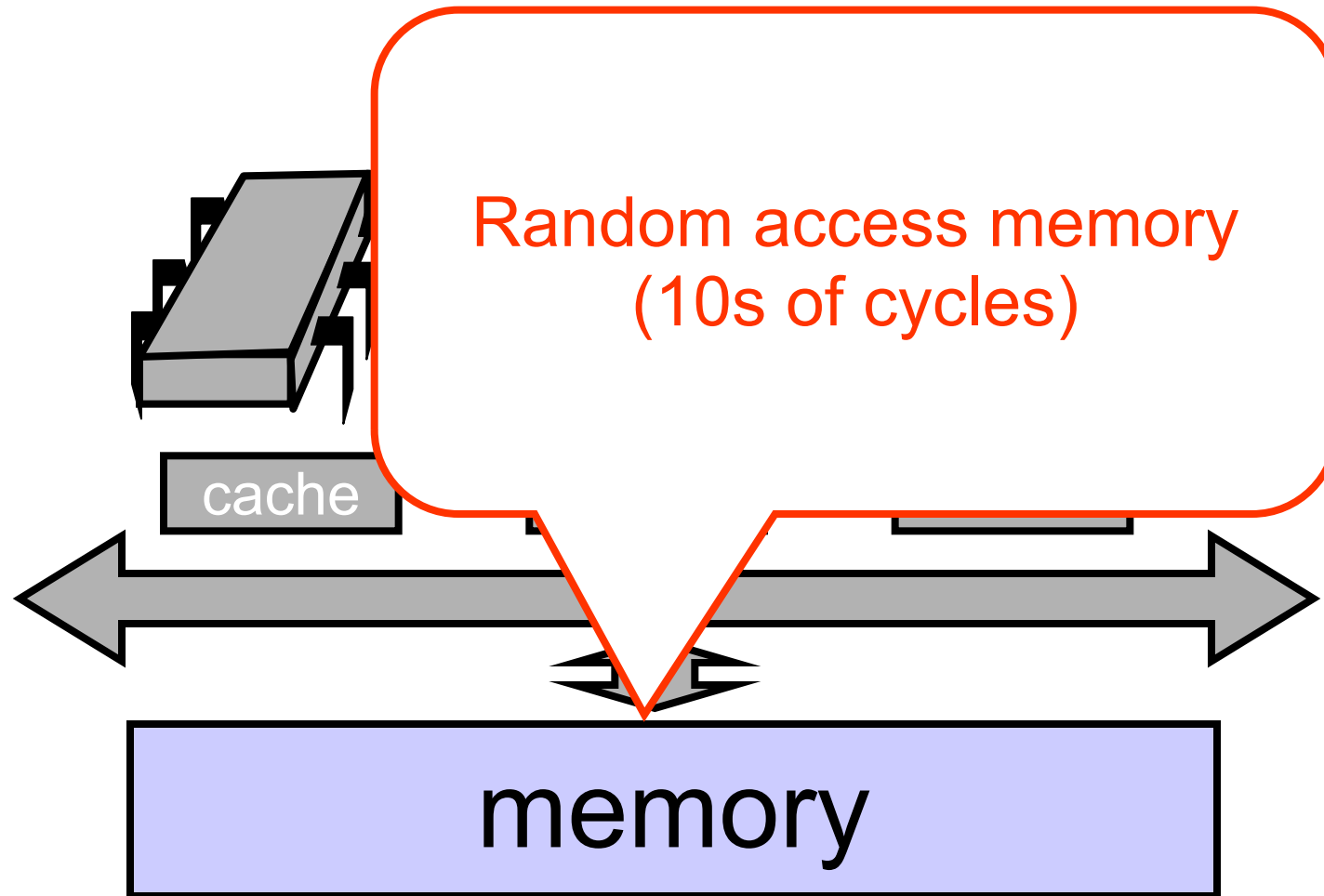
Opinion

- Our memory abstraction is broken
- TAS & TTAS methods
 - Are provably the same (in our model)
 - Except they aren't (in field tests)
- Need a more detailed model ...

Bus-Based Architectures



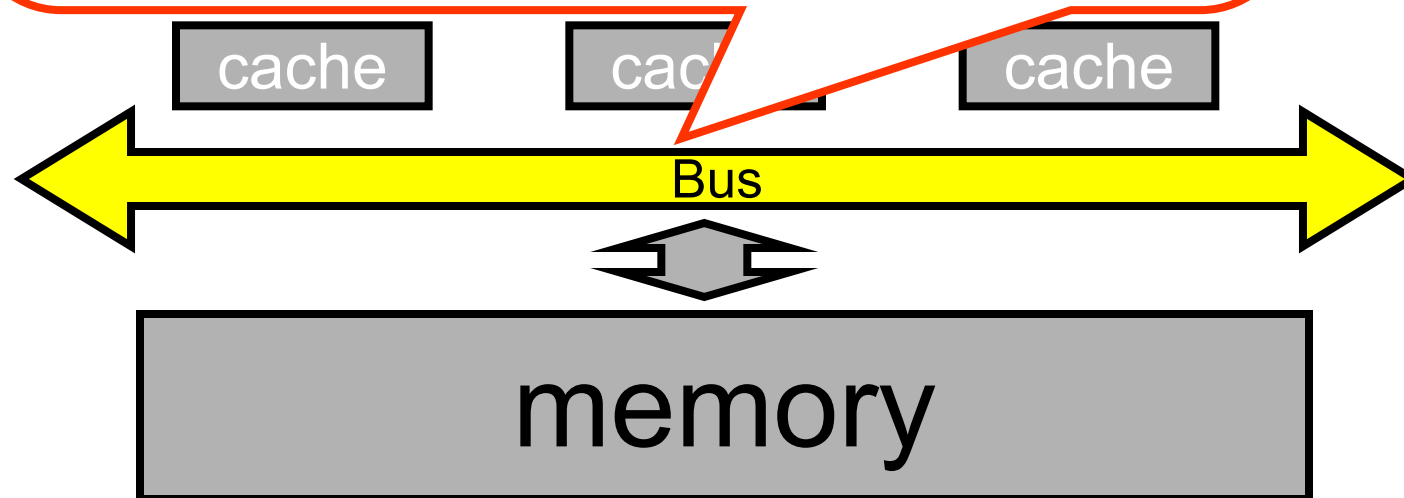
Bus-Based Architectures



Bus-Based Architectures

Shared Bus

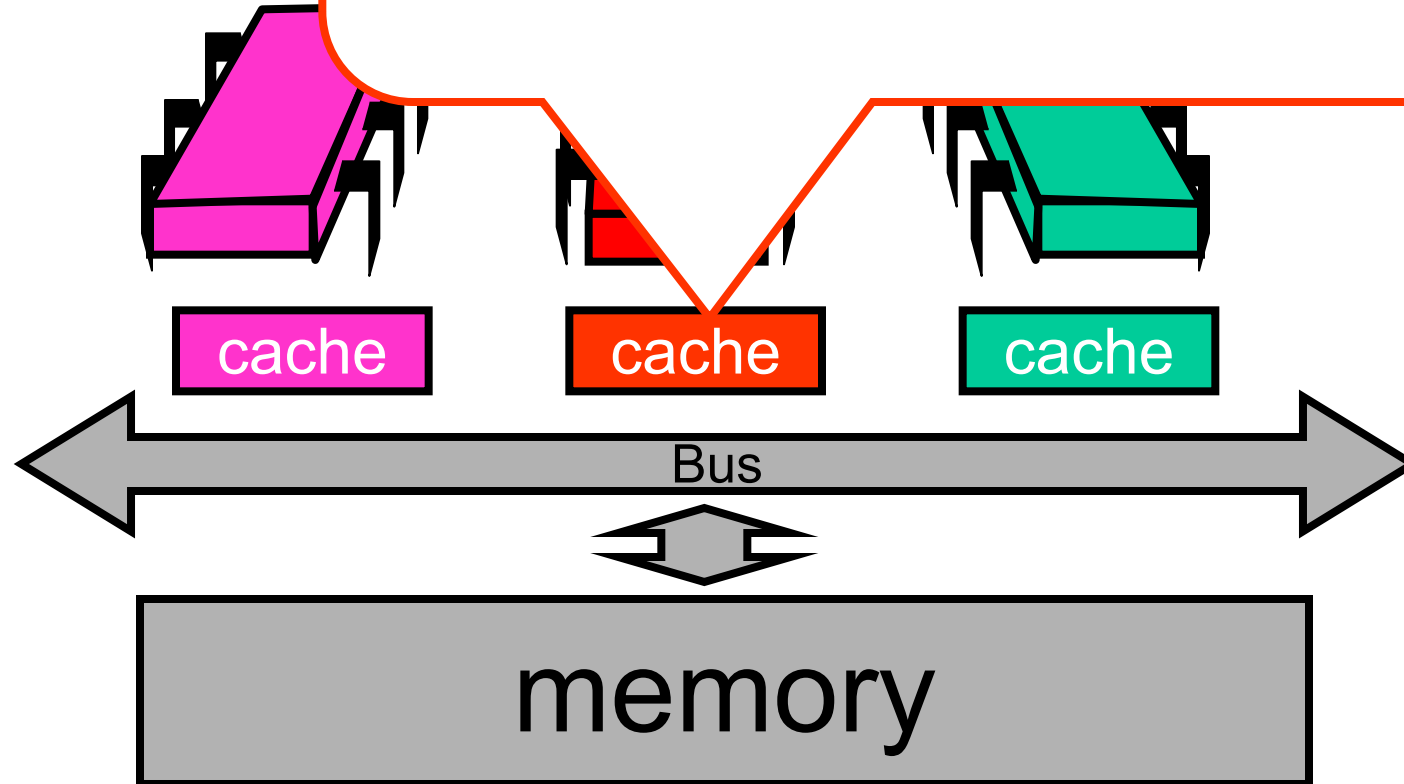
- Broadcast medium
- One broadcaster at a time
- Processors and memory all “snoop”



Bus-

Per-Processor Caches

- Small
- Fast: 1 or 2 cycles
- Address & state information



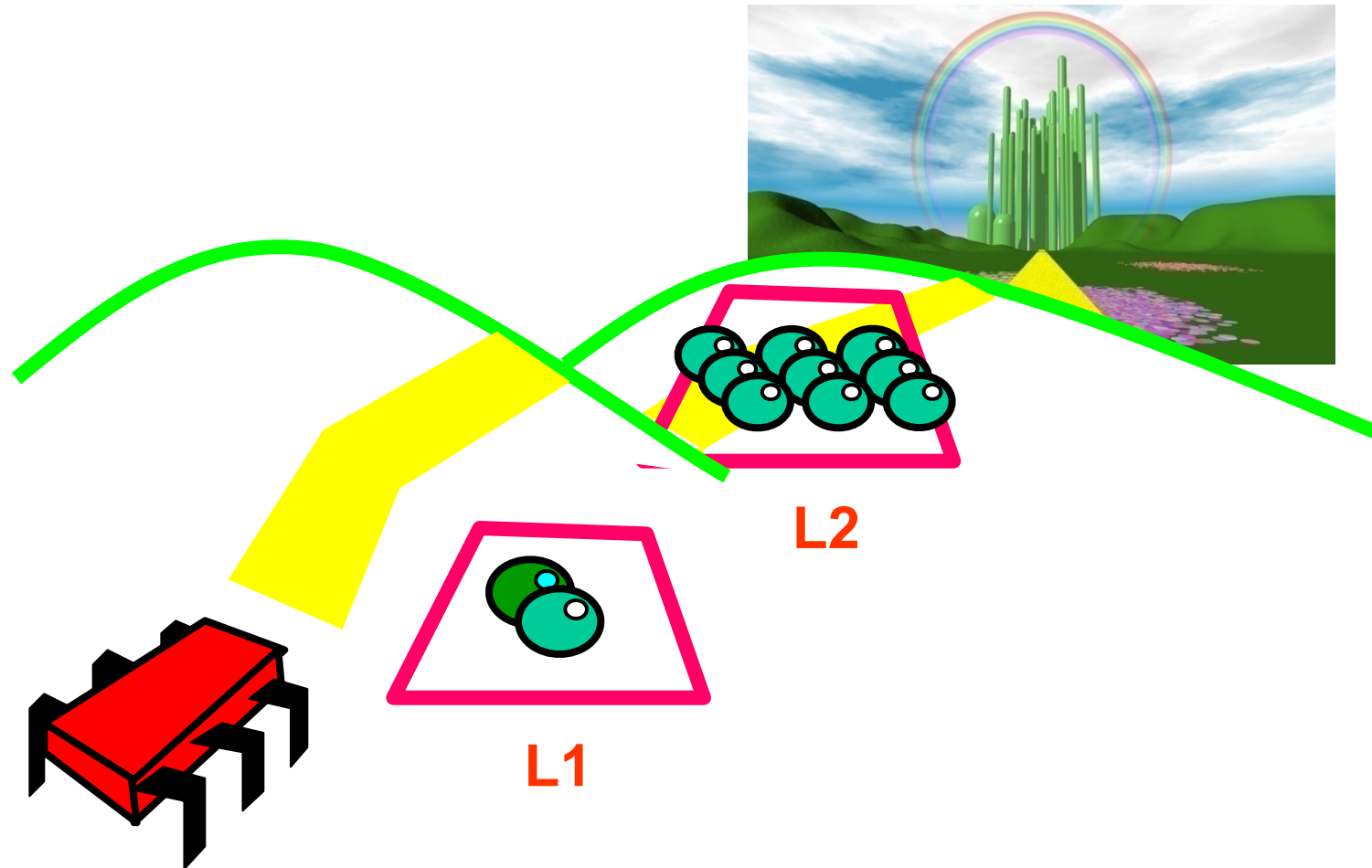
Granularity

- Caches operate at a larger granularity than a word (32 or 64 bits)
- Cache line: fixed-size block containing of neighbouring words (today 64 or 128 bytes)

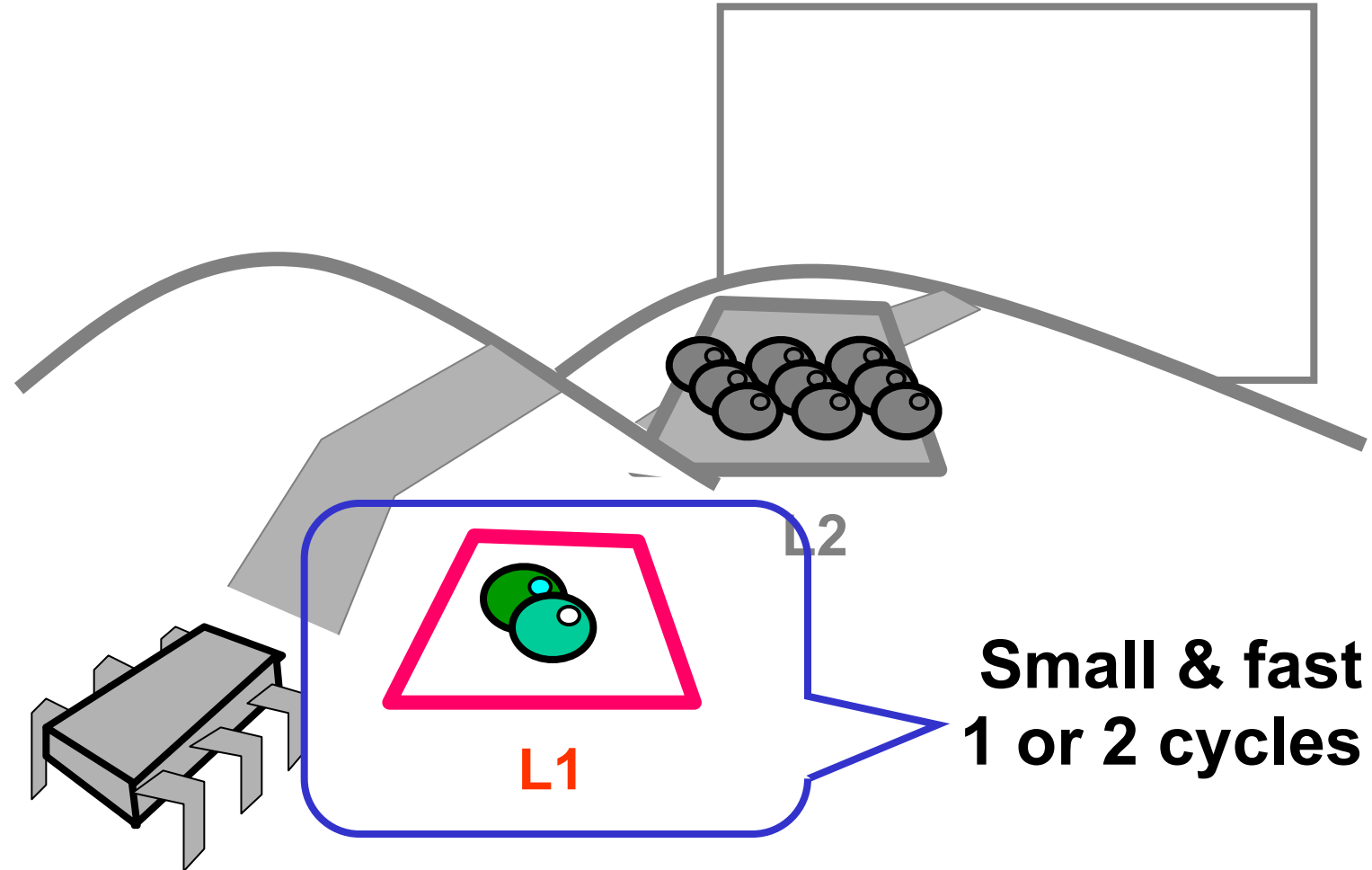
Locality

- If you use an address now, you will probably use it again soon
 - Fetch from cache, not memory
- If you use an address now, you will probably use a nearby address soon
 - In the same cache line

L1 and L2 Caches

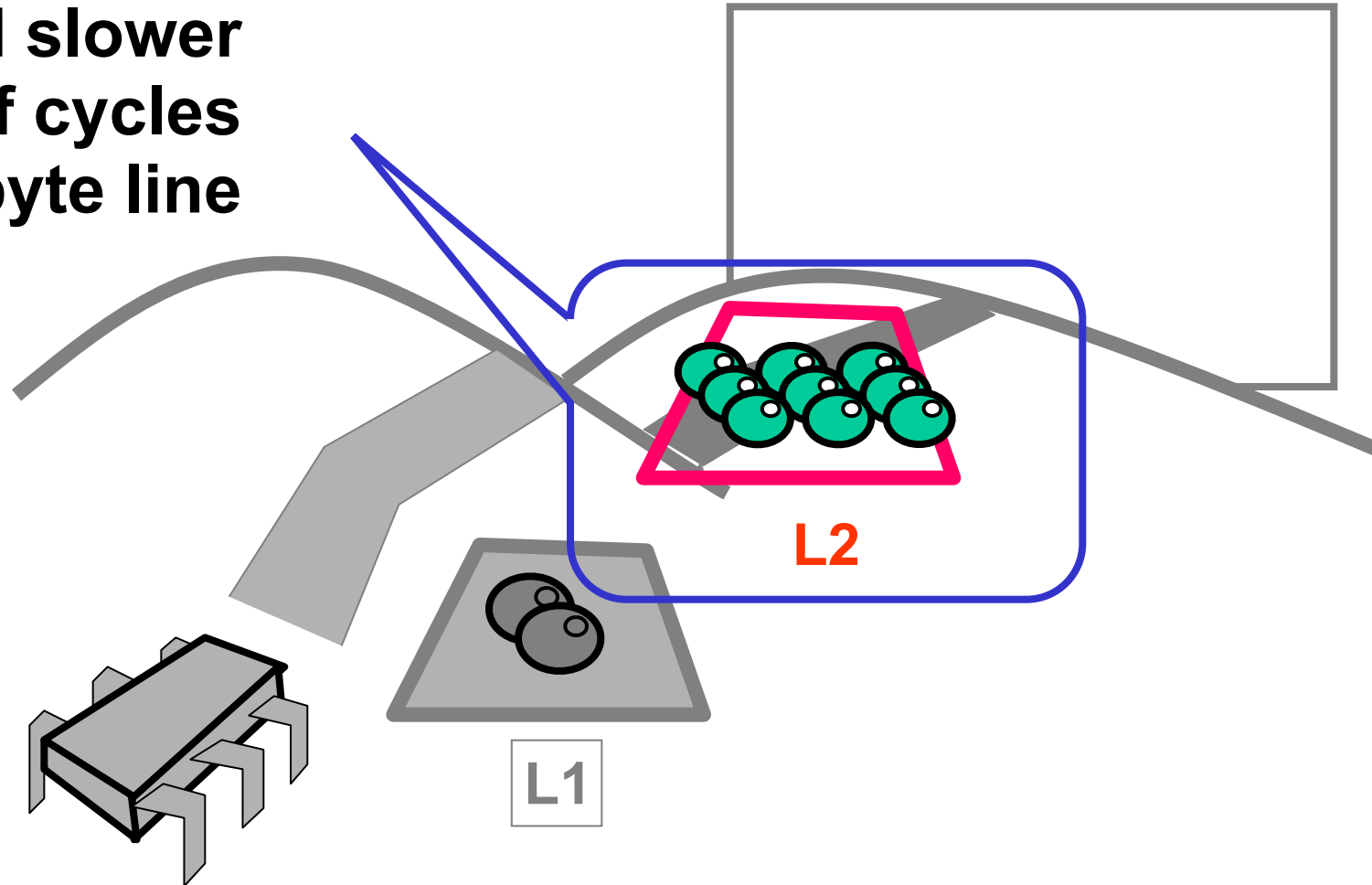


L1 and L2 Caches



L1 and L2 Caches

Larger and slower
10s of cycles
~128 byte line



Jargon Watch

- Cache hit
 - “I found what I wanted in my cache”
 - Good Thing™
- Cache miss
 - “I had to shlep all the way to memory for that data”
 - Bad Thing™

Cave Canem

- This model is **still** a simplification
 - But not in any essential way
 - Illustrates basic principles
- Will discuss complexities later

When a Cache Becomes Full...

- Need to make room for new entry
- By evicting an existing entry
- Need a replacement policy
 - Usually some kind of least recently used heuristic

Cache Coherence

- A and B both cache address x
- A writes to x
 - Updates cache
- How does B find out?
- Many cache coherence protocols in literature

MESI

- Modified
 - Have modified cached data, must write back to memory

MESI

- Modified
 - Have modified cached data, must write back to memory
- Exclusive
 - Not modified, I have only copy

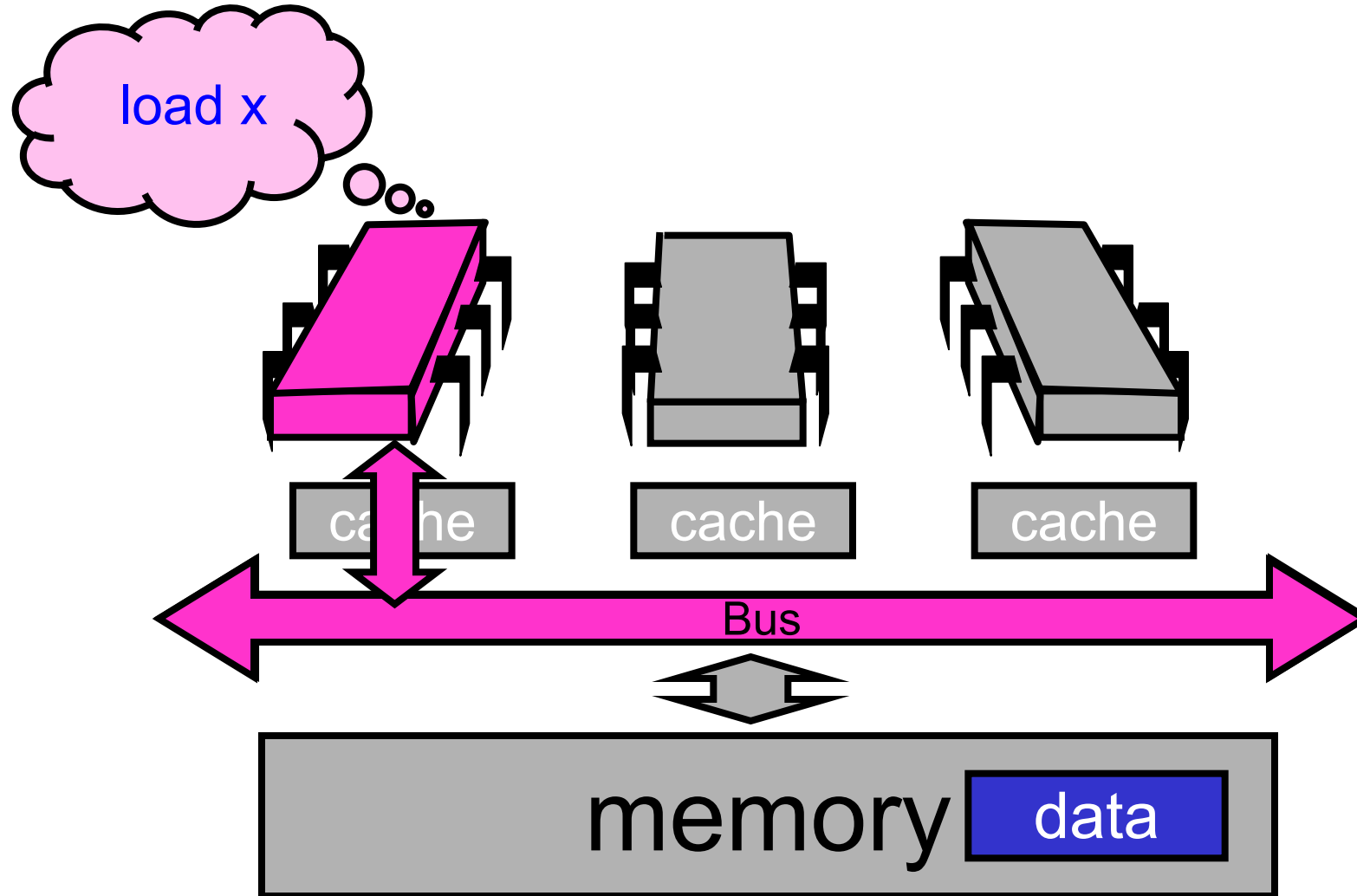
MESI

- Modified
 - Have modified cached data, must write back to memory
- Exclusive
 - Not modified, I have only copy
- Shared
 - Not modified, may be cached elsewhere

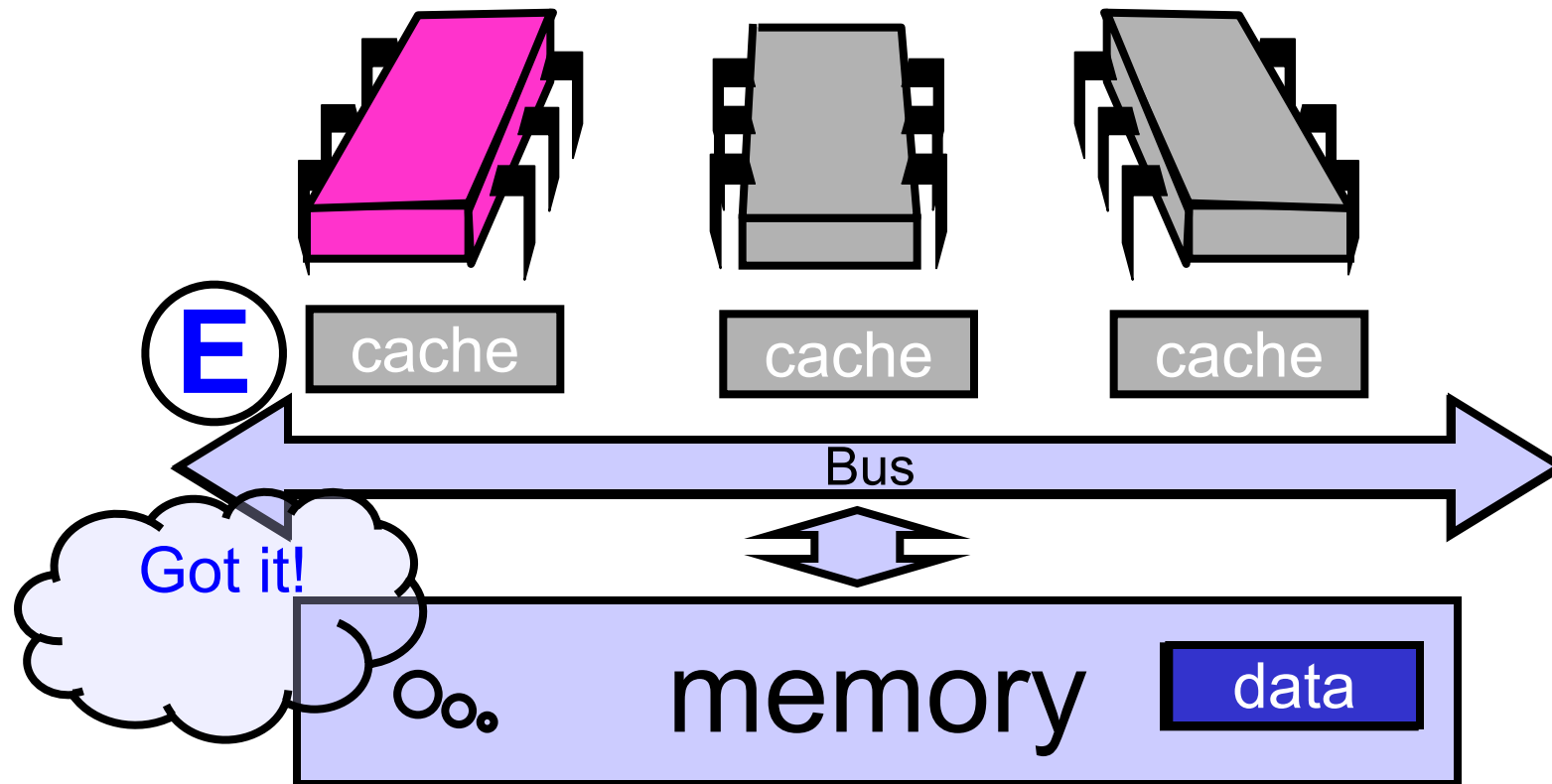
MESI

- **Modified**
 - Have modified cached data, must write back to memory
- **Exclusive**
 - Not modified, I have only copy
- **Shared**
 - Not modified, may be cached elsewhere
- **Invalid**
 - Cache contents not meaningful

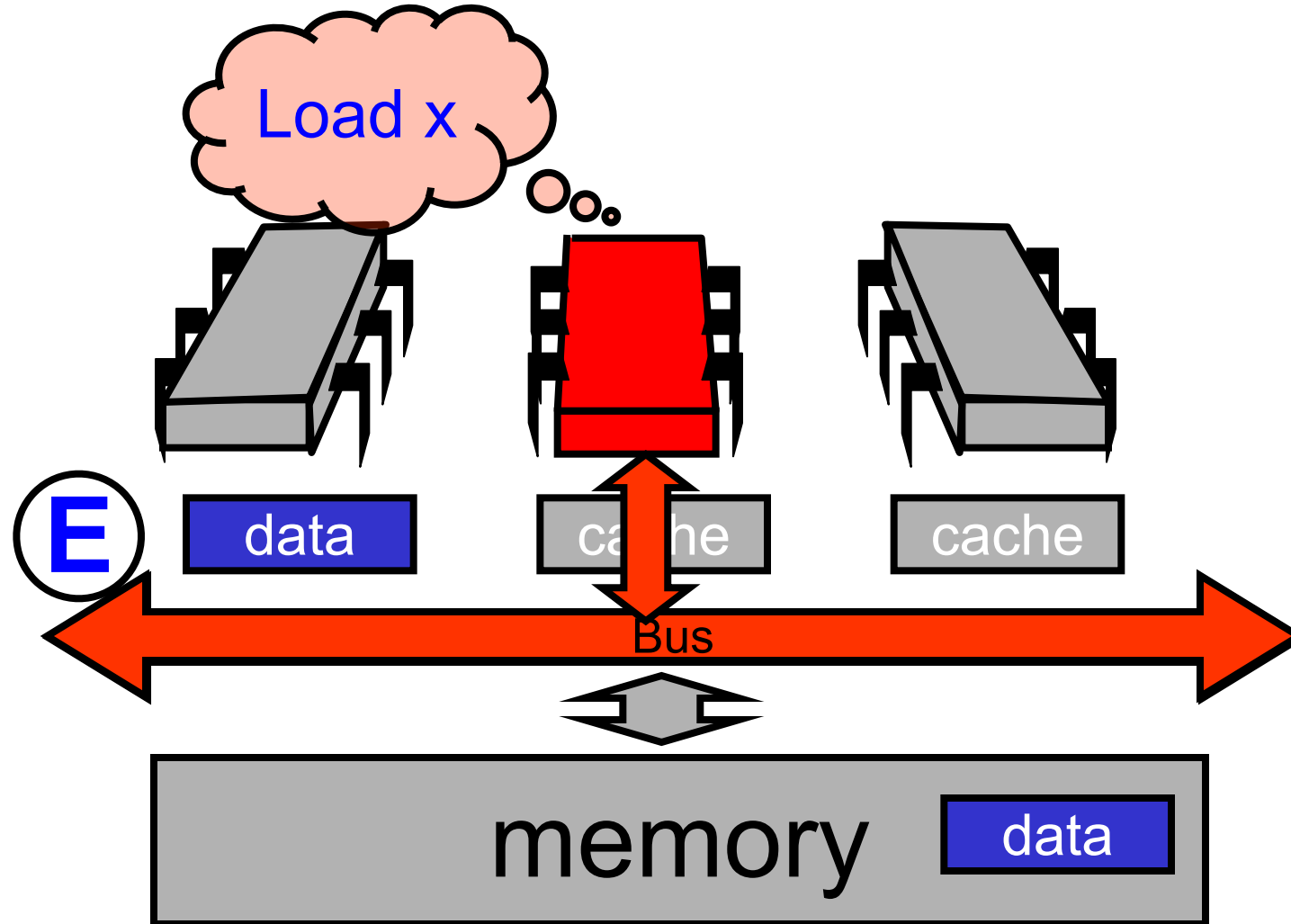
Processor Issues Load Request



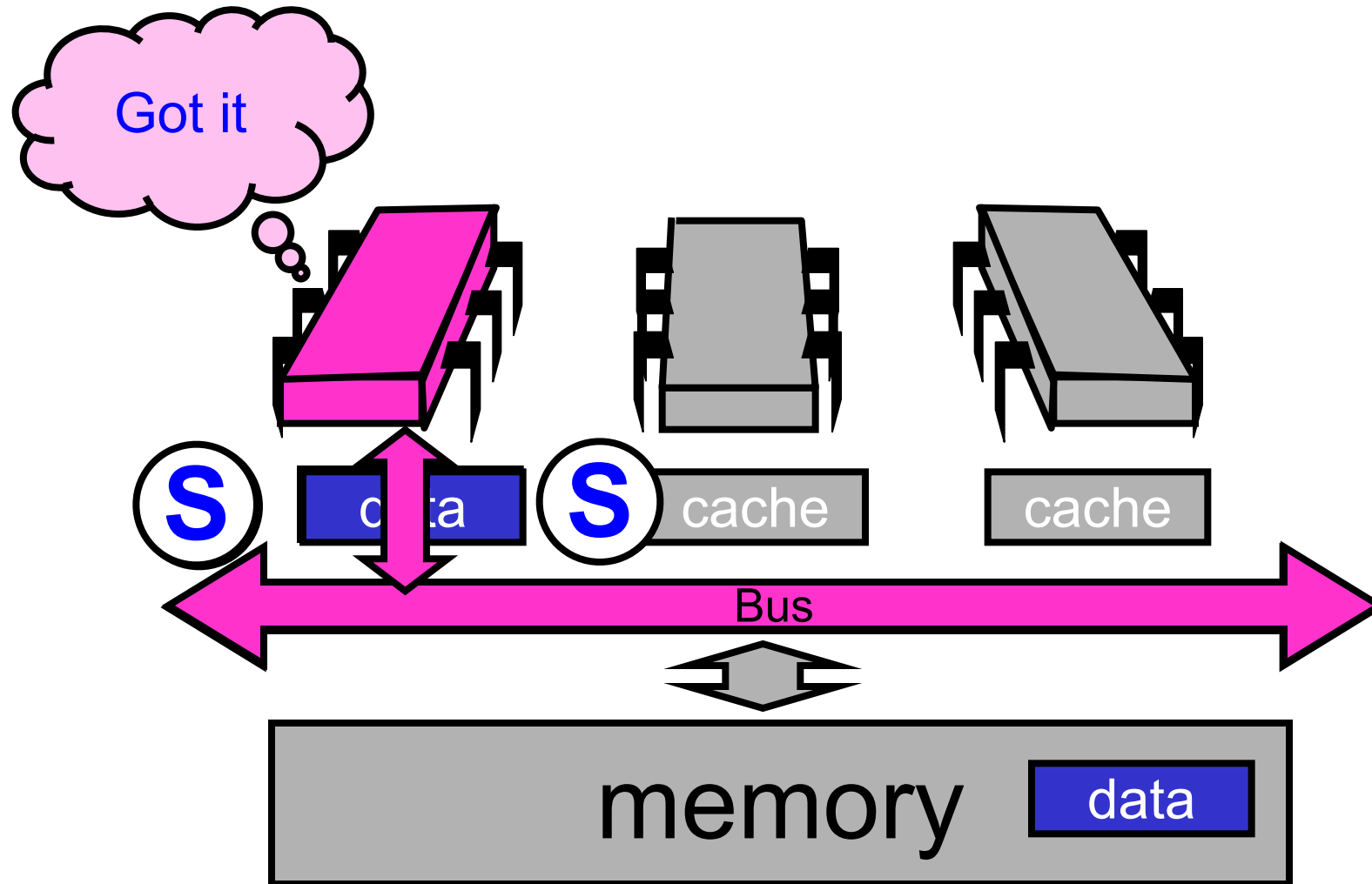
Memory Responds



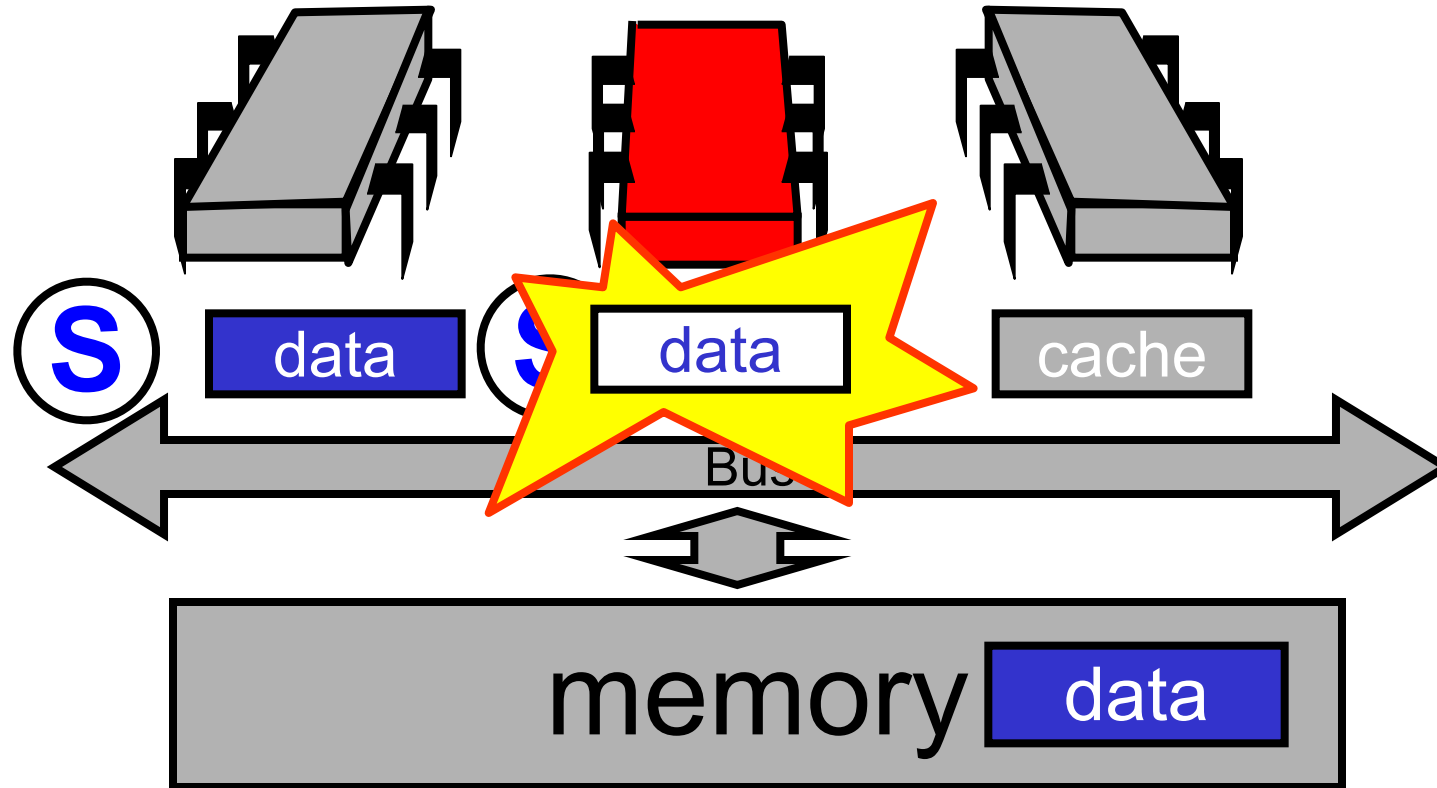
Processor Issues Load Request



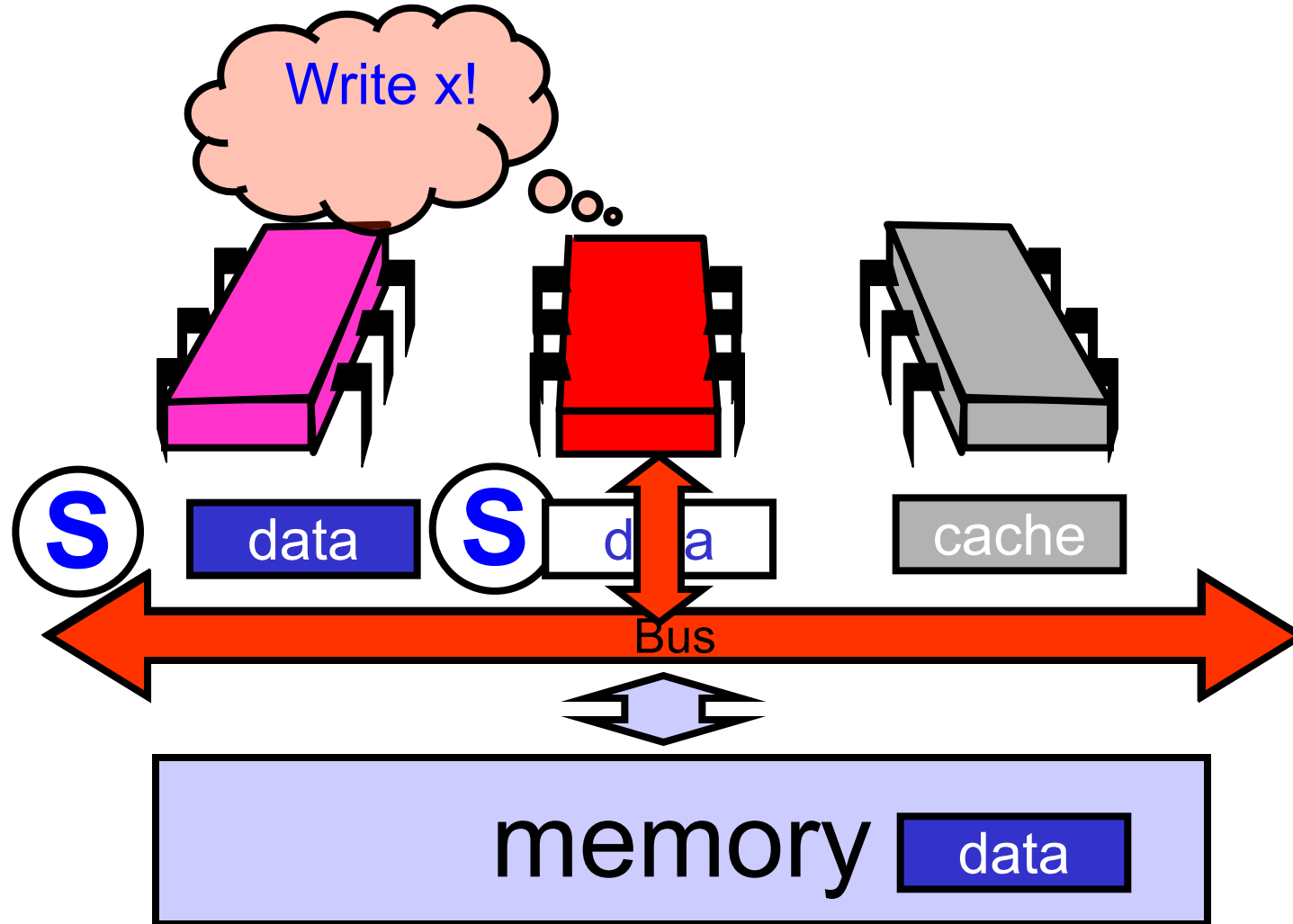
Other Processor Responds



Modify Cached Data



Write-Through Cache



Write-Through Caches

- Immediately broadcast changes
- Good
 - Memory, caches always agree
 - More read hits, maybe
- Bad
 - Bus traffic on all writes
 - Most writes to unshared data
 - For example, loop indexes ...

Write-Through Caches

- Immediately broadcast changes

- Good

- Memory, caches always agree
 - More read hits, maybe

“show stoppers”

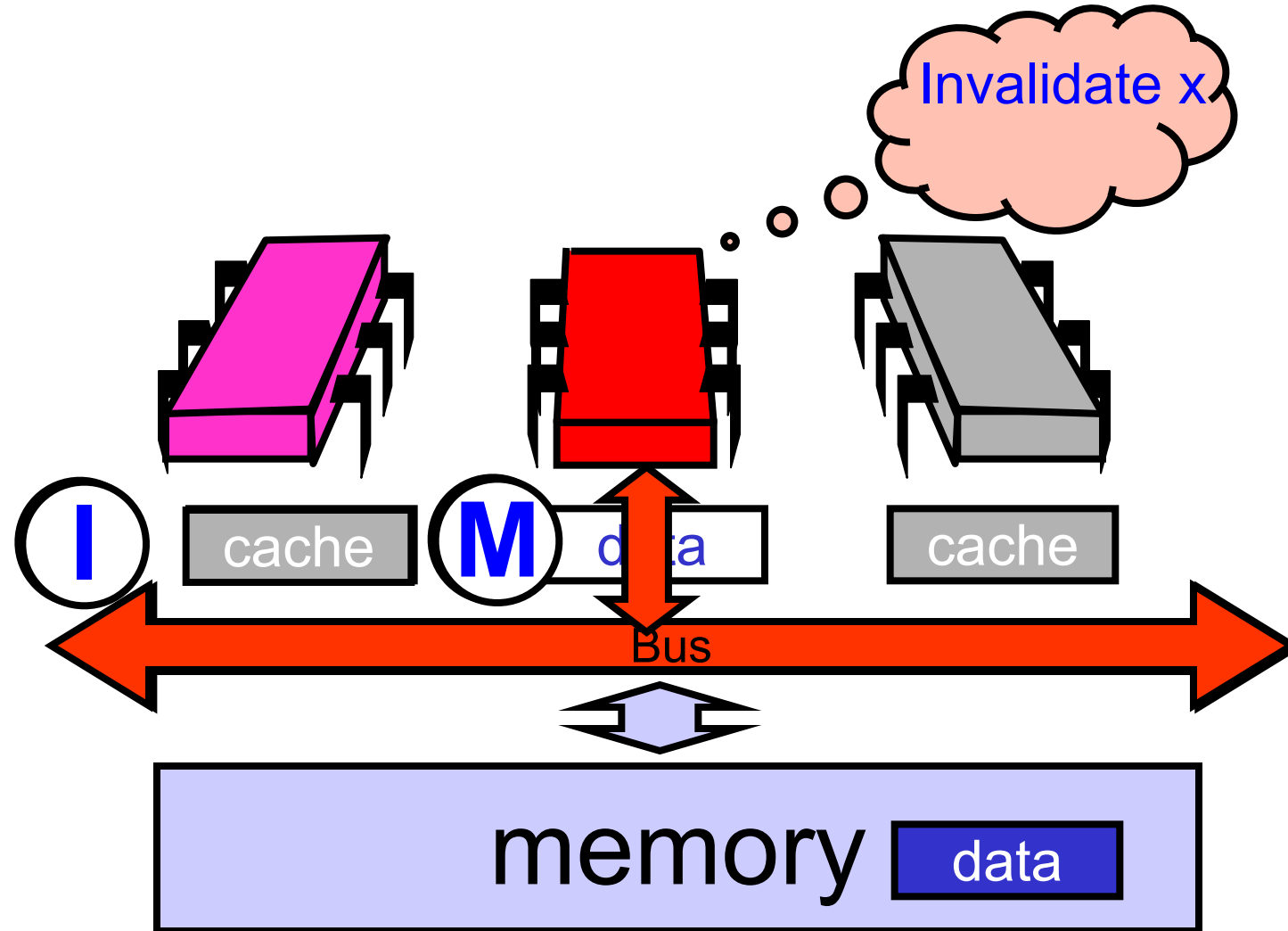
- Bad

- Bus traffic on all writes
 - Most writes to unshared data
 - For example, loop indexes ...

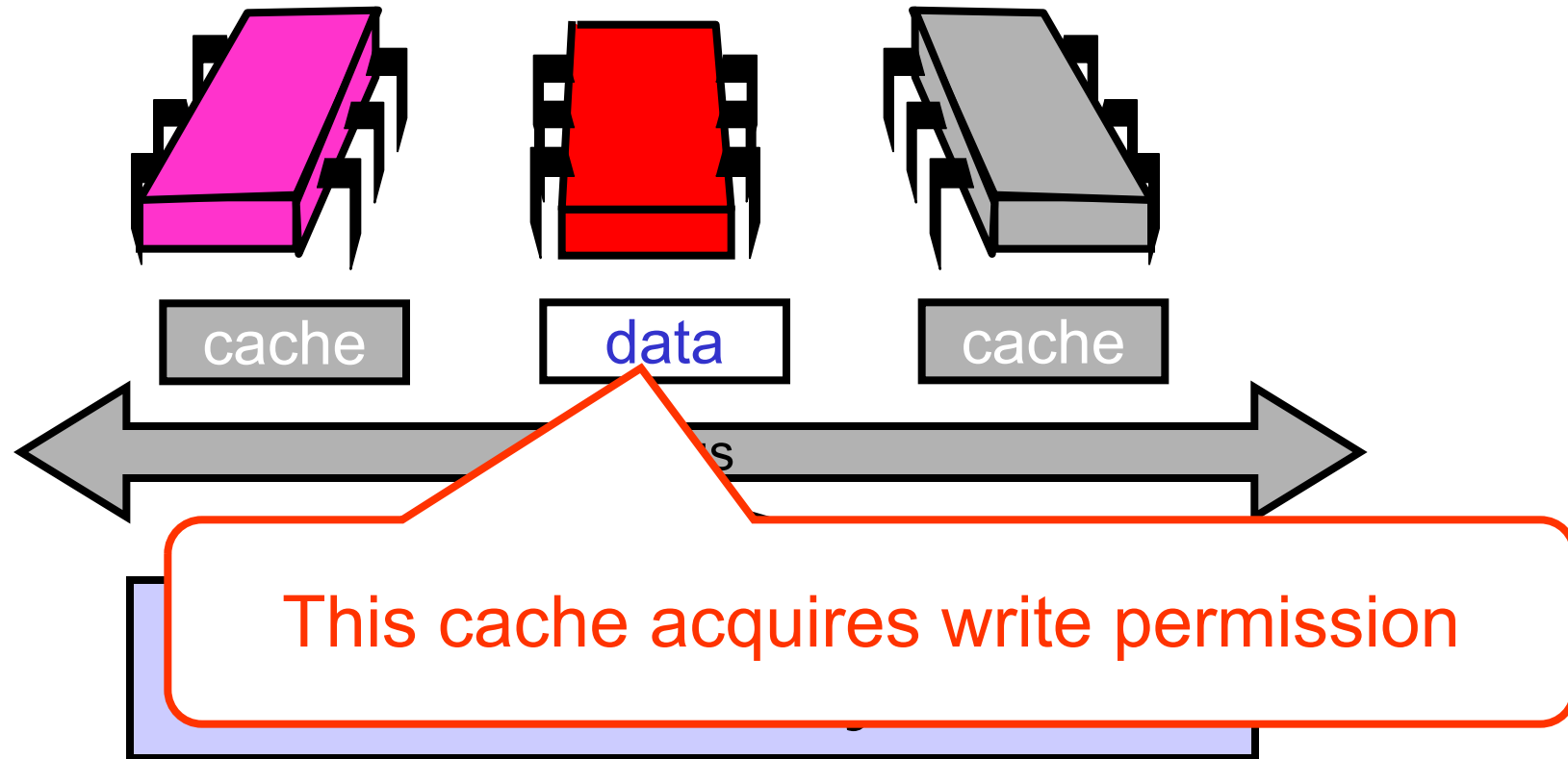
Write-Back Caches

- Accumulate changes in cache
- Write back when line evicted
 - Need the cache for something else
 - Another processor wants it

Invalidate

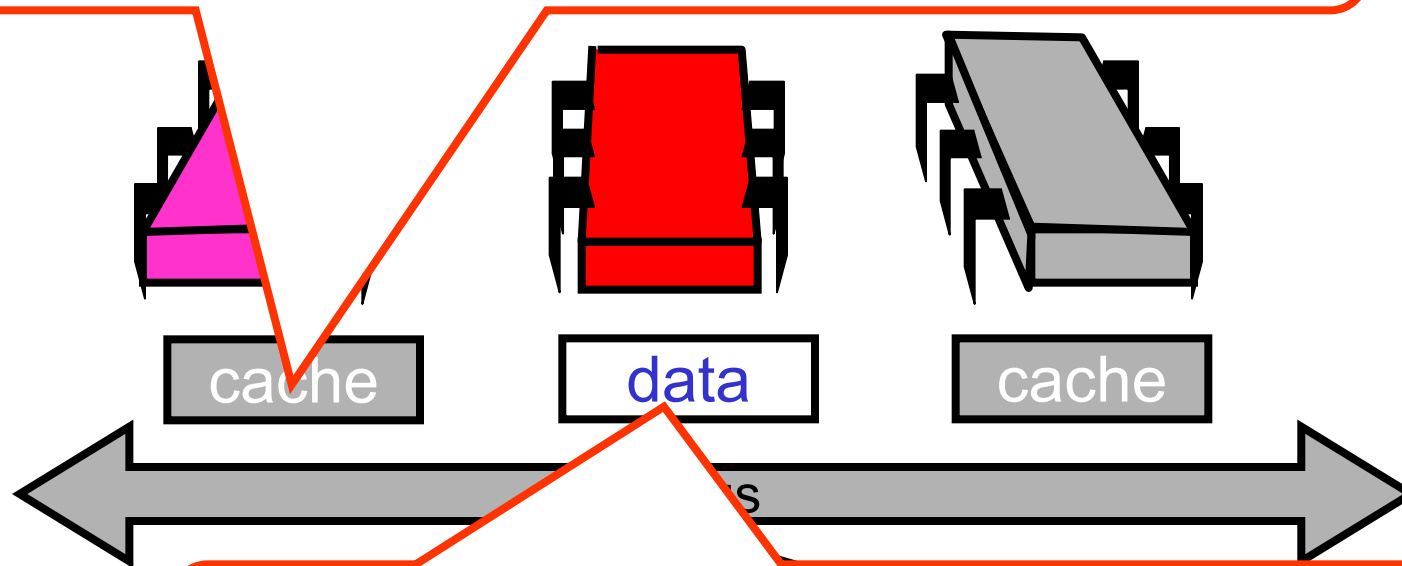


Invalidate



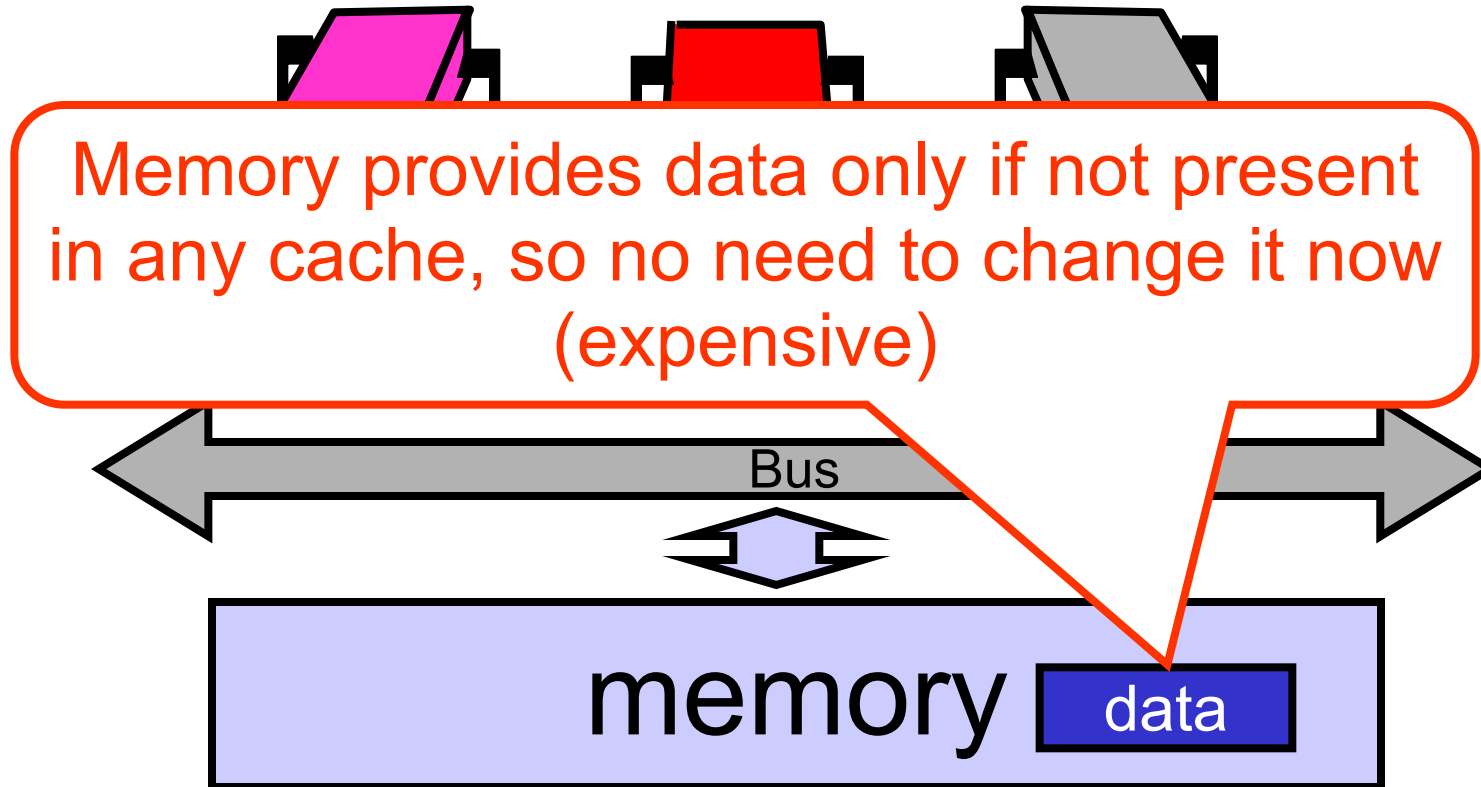
Invalidate

Other caches lose read permission



This cache acquires write permission

Invalidate



Mutual Exclusion

- What do we want to optimize?
 - Bus bandwidth used by spinning threads
 - Release/Acquire latency
 - Acquire latency for idle lock

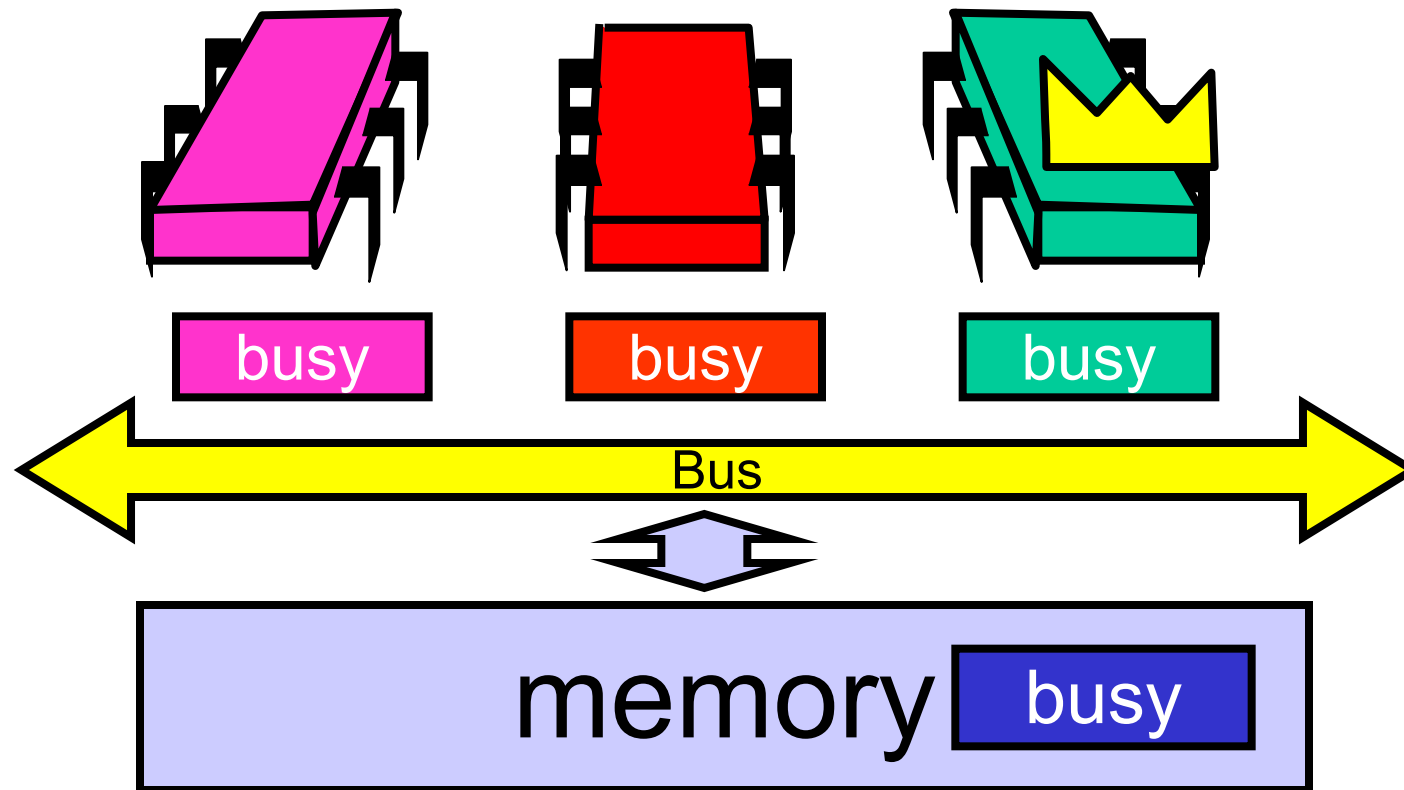
Simple TASLock

- TAS invalidates cache lines
- Spinners
 - Miss in cache
 - Go to bus
- Thread wants to release lock
 - delayed behind spinners

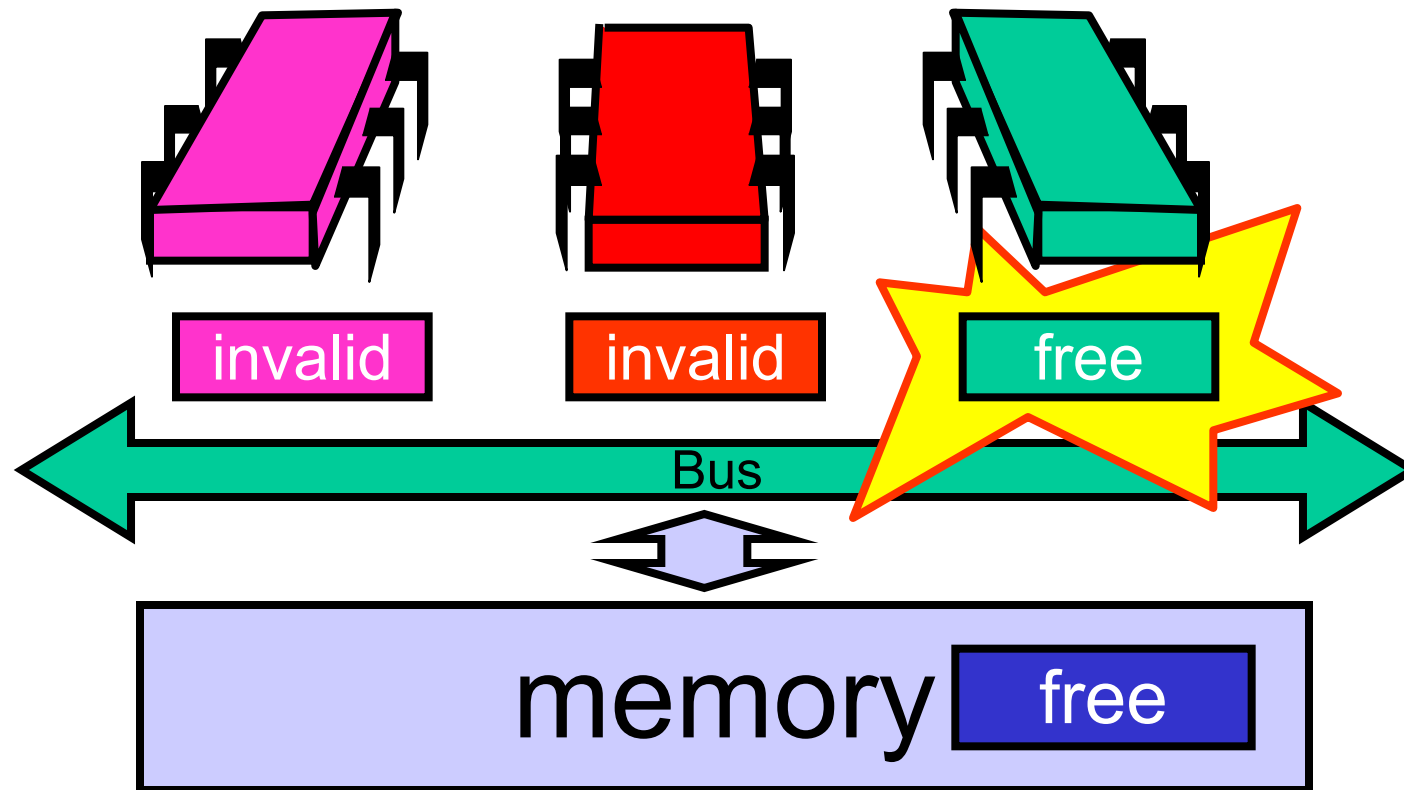
Test-and-test-and-set

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

Local Spinning while Lock is Busy

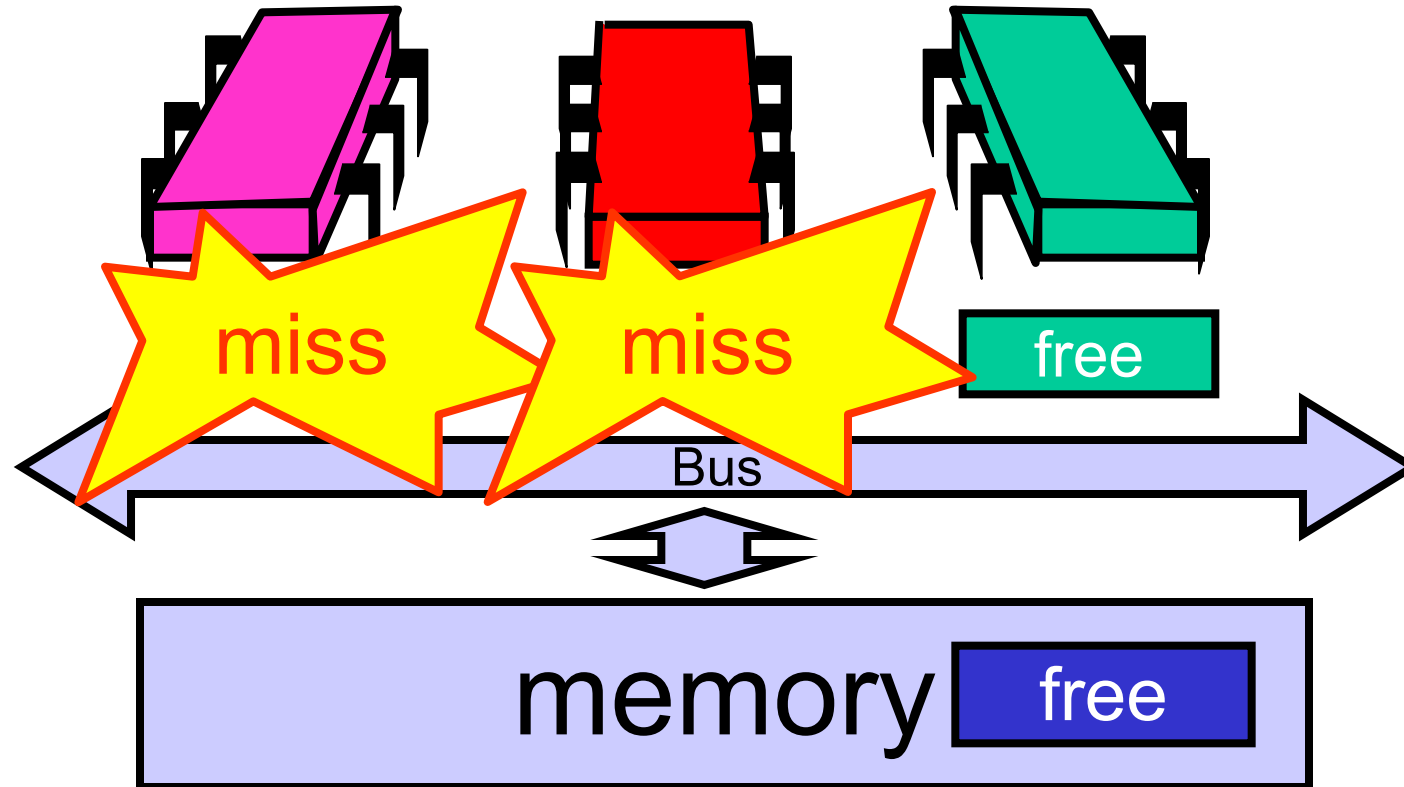


On Release



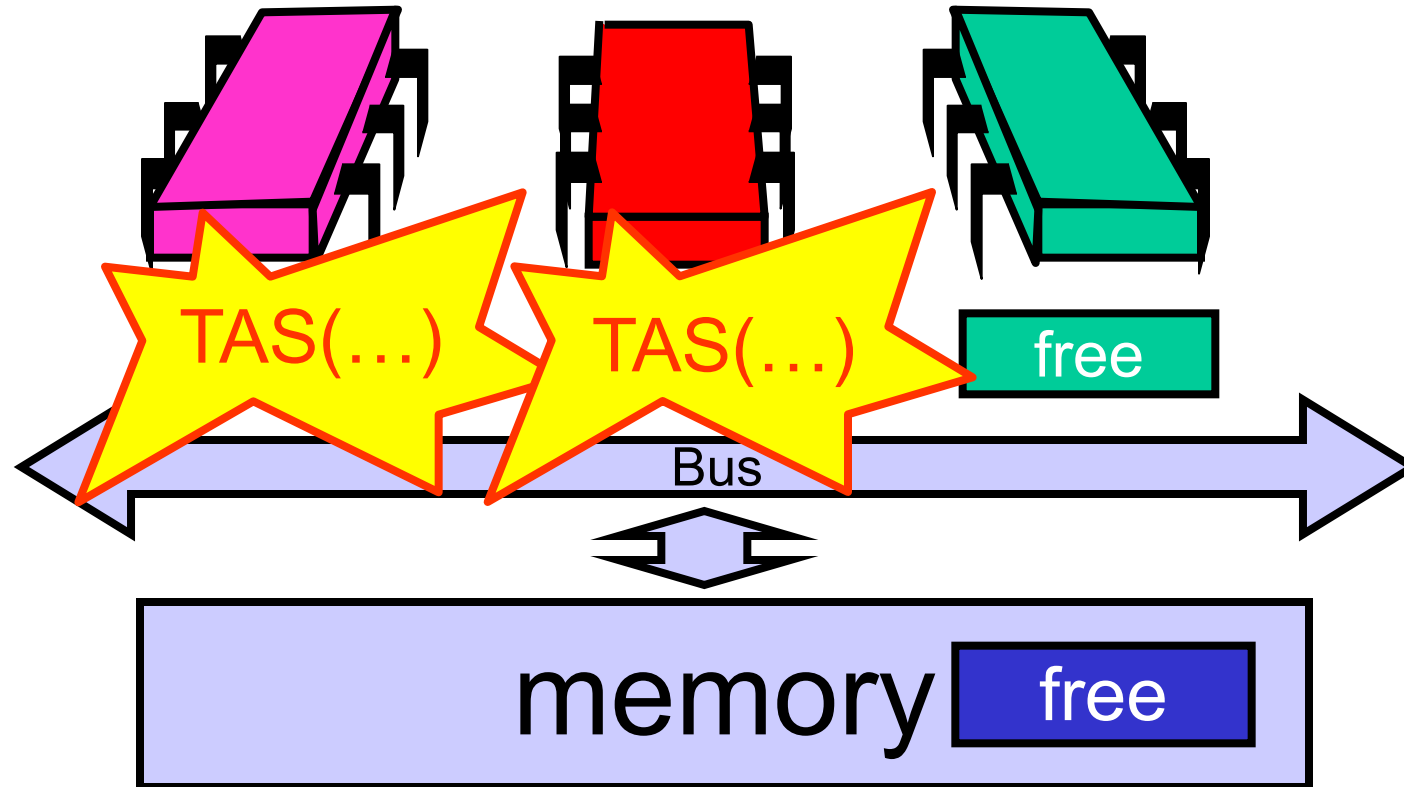
On Release

Everyone misses,
rereads



On Release

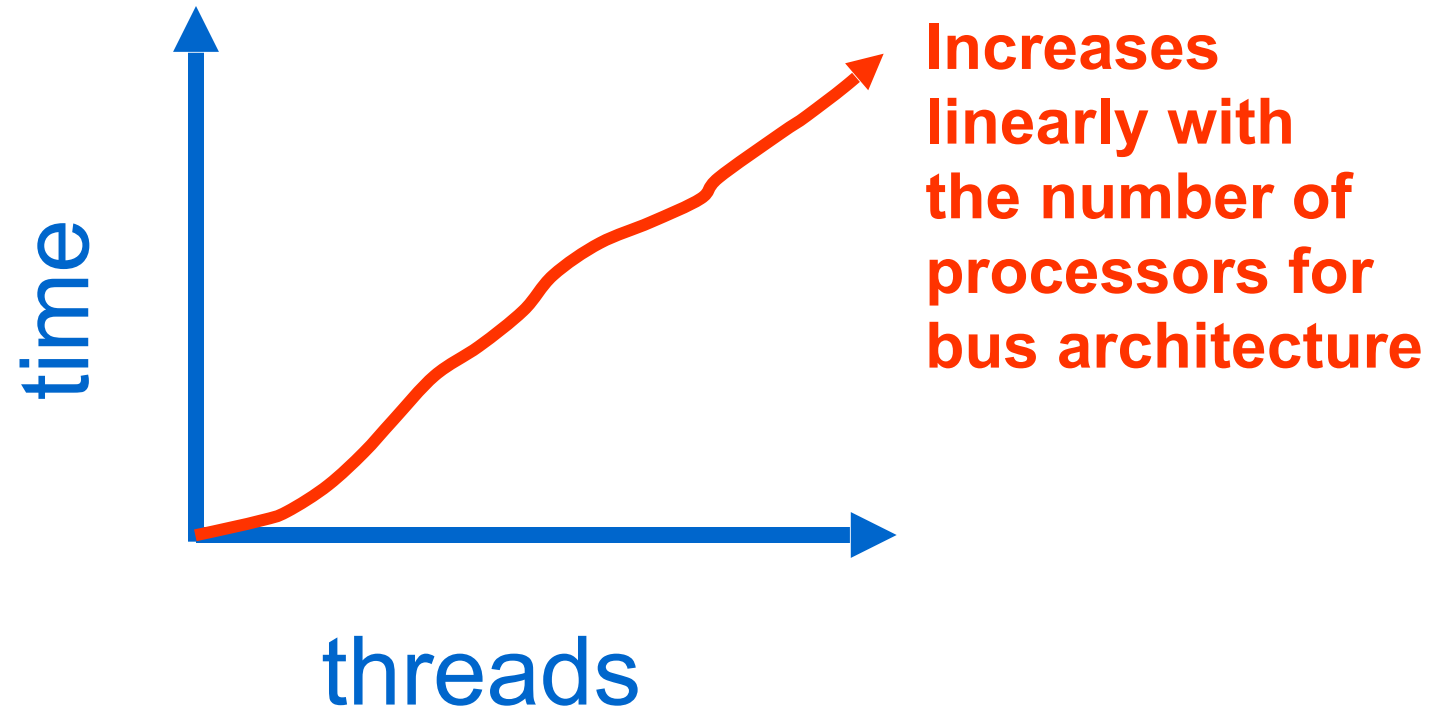
Everyone tries TAS



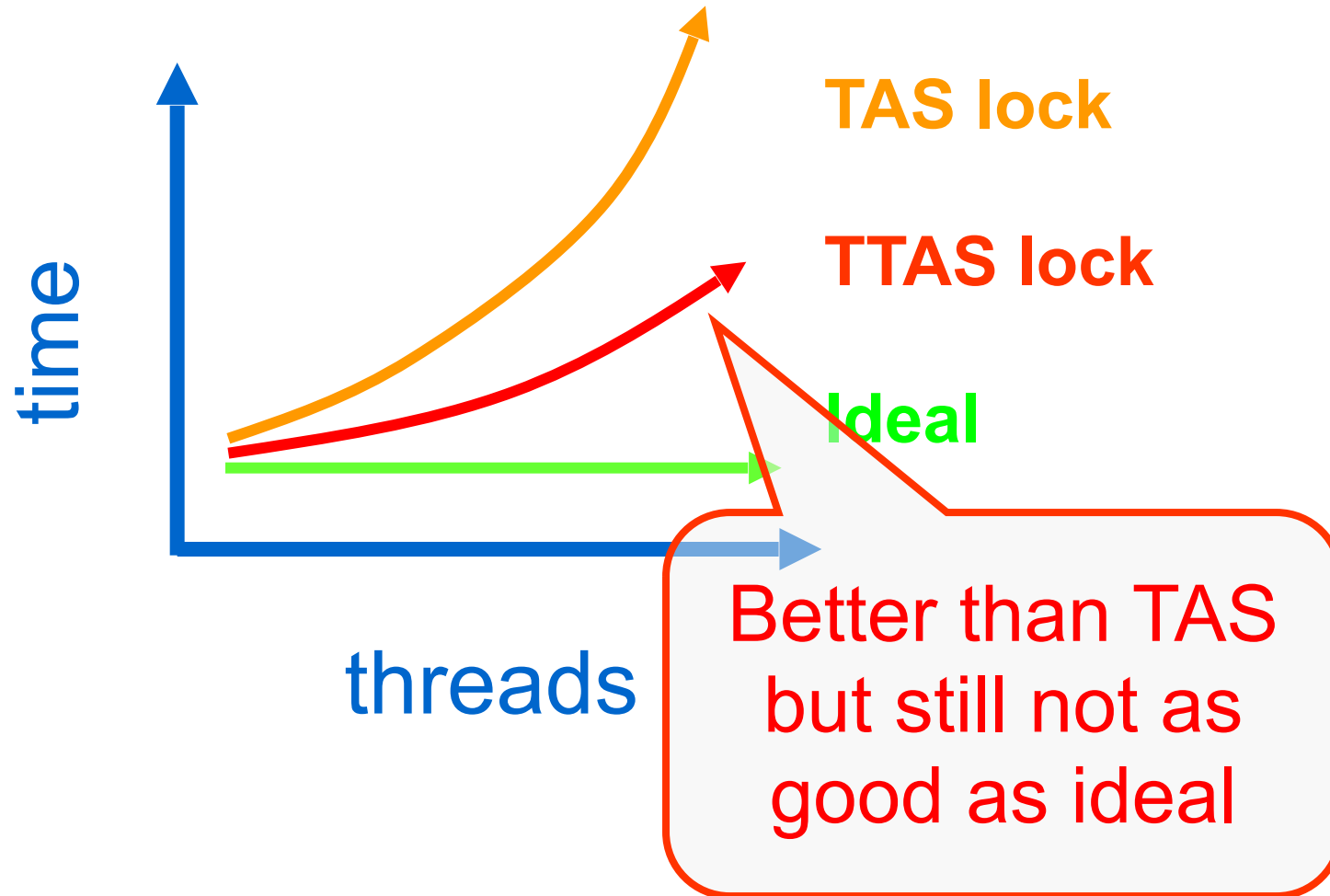
Problems

- Everyone misses
 - Reads satisfied sequentially
- Everyone does TAS
 - Invalidates others' caches
- Eventually quiesces after lock acquired
 - How long does this take?

Quiescence Time

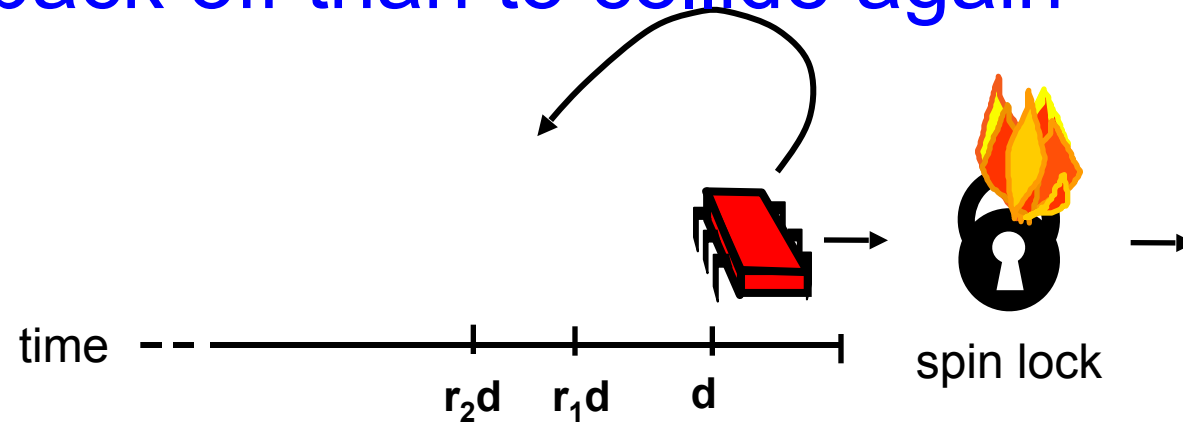


Mystery Explained

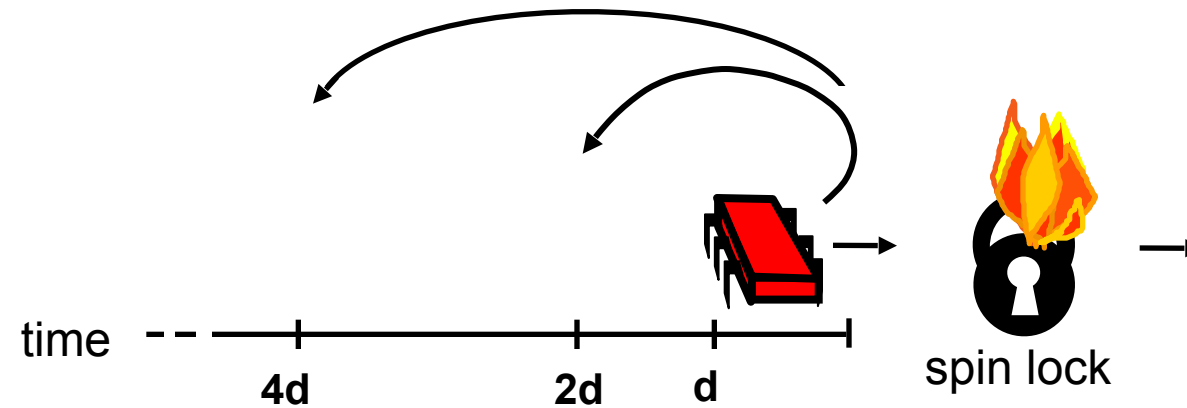


Solution: Introduce Delay

- If the lock looks free
 - But I fail to get it
- There must be contention
 - Better to back off than to collide again



Dynamic Example: Exponential Backoff



If I fail to get lock

- Wait random duration before retry
- Each subsequent failure doubles expected wait

Exponential Backoff Lock

```
class BackoffLock extends SpinLock {  
  private var delay = MIN_DELAY  
  override def lock(): Unit = {  
    while (true) {  
      while (state.get()) {}  
      if (!state.getAndSet(true)) { return } else {  
        Thread.sleep(random() % delay);  
        if (delay < MAX_DELAY) delay = 2 * delay  
      }  
    }  
  }  
}
```


Exponential Backoff Lock

```
class BackoffLock extends SpinLock {  
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        Thread.sleep(random() % delay);  
        if (delay < MAX_DELAY) delay = 2 * delay  
      }  
    }  
  }  
}
```

Fix minimum delay

Exponential Backoff Lock

```
class BackoffLock extends SpinLock {  
  private var delay = MIN_DELAY  
  override def lock(): Unit = {  
    while (true) {  
      while (state.get()) {}  
      if (!state.getAndSet(true)) { return } else {  
        Thread.sleep(random() % delay);  
        if (delay < MAX_DELAY) delay = 2 * delay  
      }  
    }  
  }  
}
```

Wait until lock looks free

Exponential Backoff Lock

```
class BackoffLock extends SpinLock {  
  private var delay = MIN_DELAY  
  override def lock(): Unit = {  
    while (true) {  
      while (state.get()) {}  
      if (!state.getAndSet(true)) { return } else {  
        Thread.sleep(random() % delay);  
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      }  
    }  
  }  
}
```

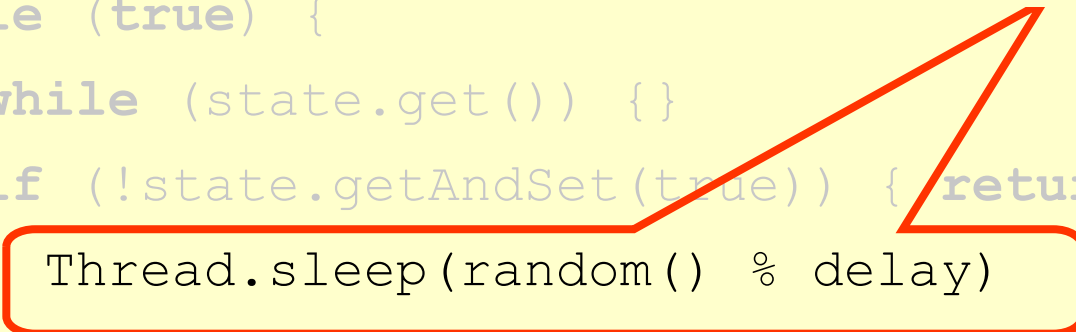
If we win, return



Exponential Backoff Lock

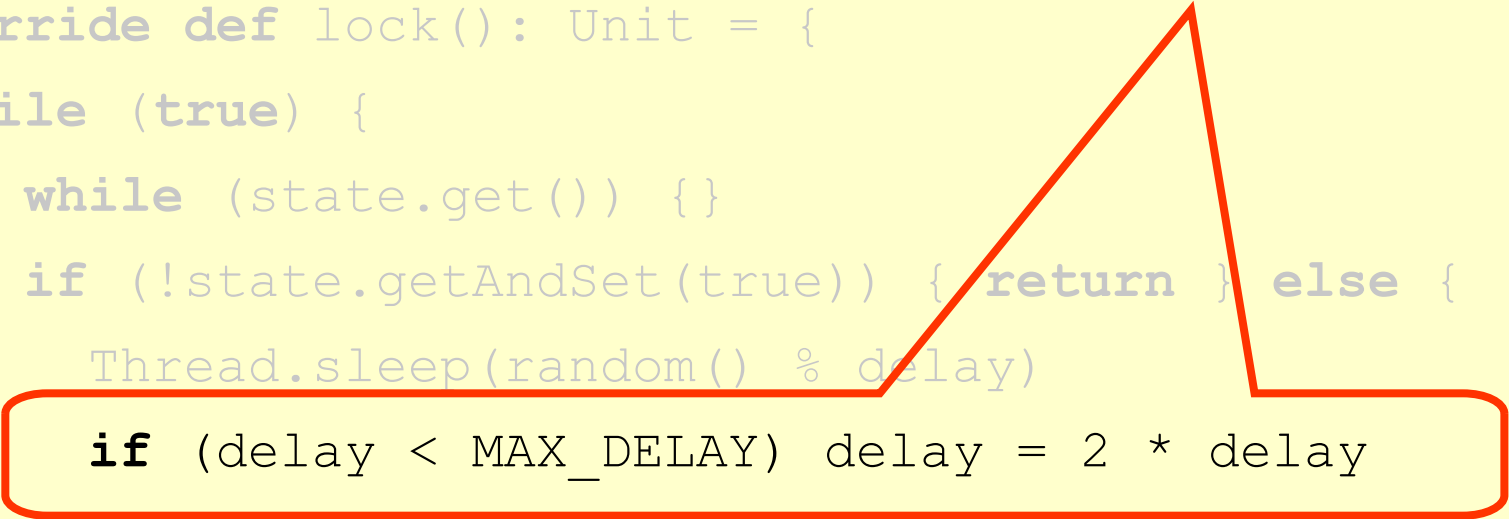
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      }  
    }  
}
```

Back off for random duration

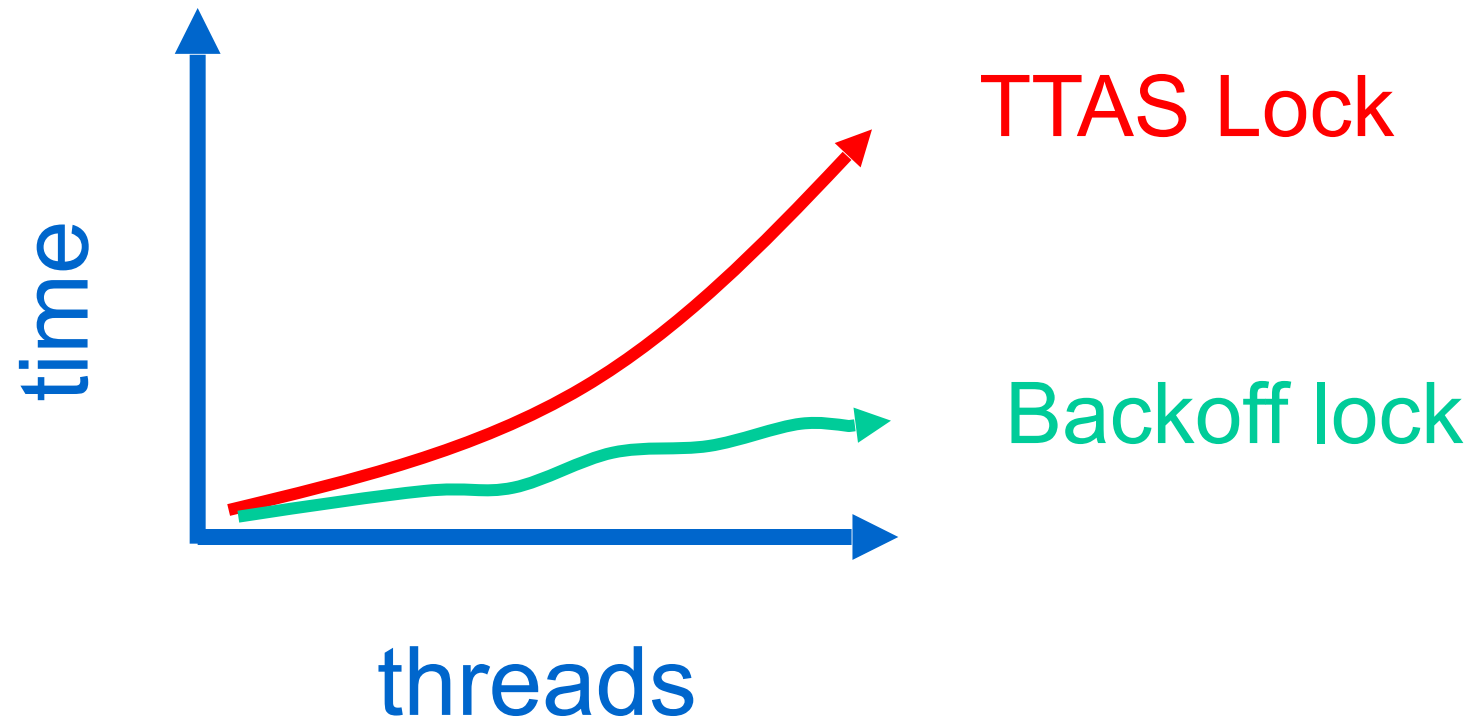


Exponential Backoff Lock

```
class BackoffLock extends SpinLock {  
  private var delay = Double max delay, within reason  
  override def lock(): Unit = {  
    while (true) {  
      while (state.get()) {}  
      if (!state.getAndSet(true)) { return } else {  
        Thread.sleep(random() % delay)  
        if (delay < MAX_DELAY) delay = 2 * delay  
      }  
    }  
  }  
}
```



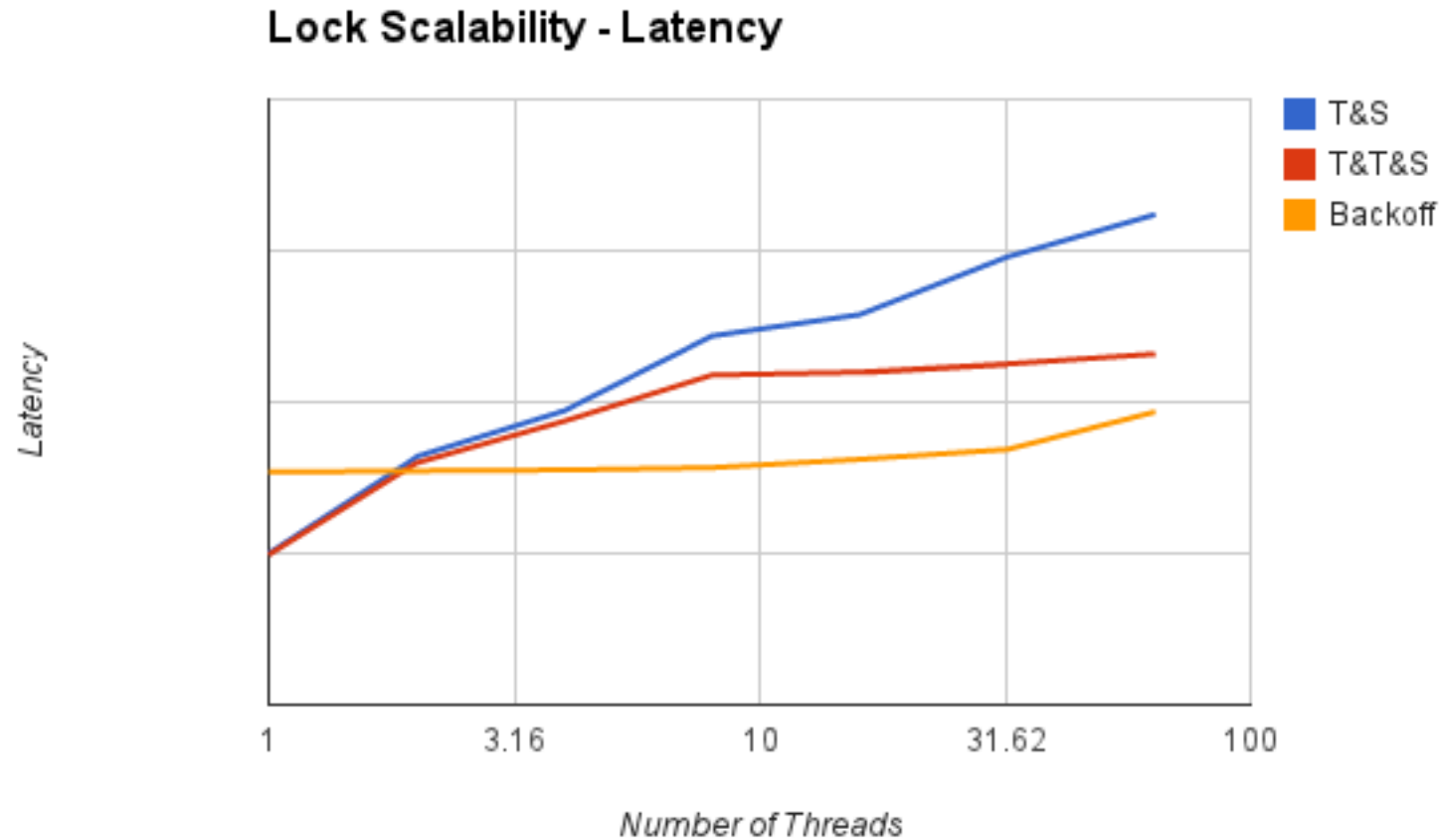
Spin-Waiting Overhead



Backoff: Other Issues

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

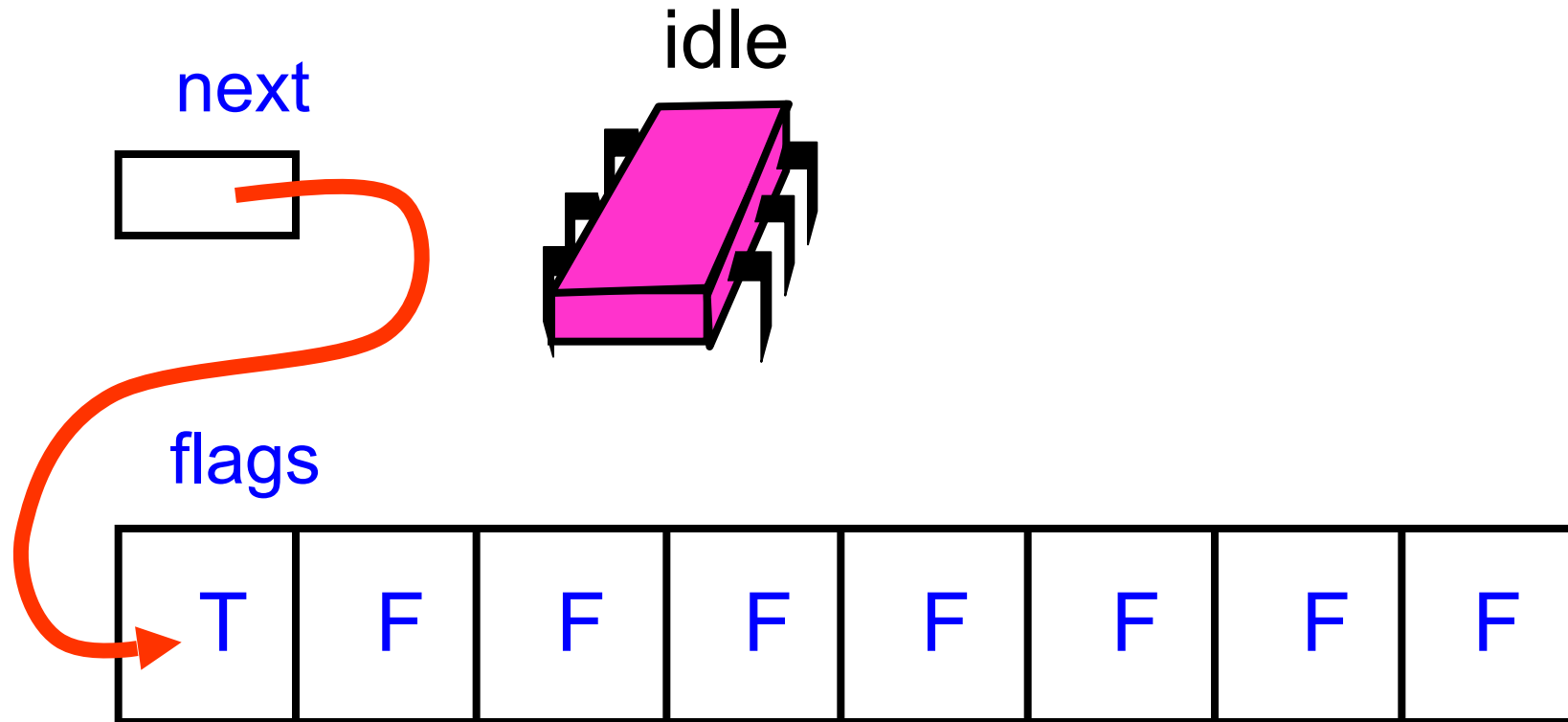
Actual Data on 40-Core Machine



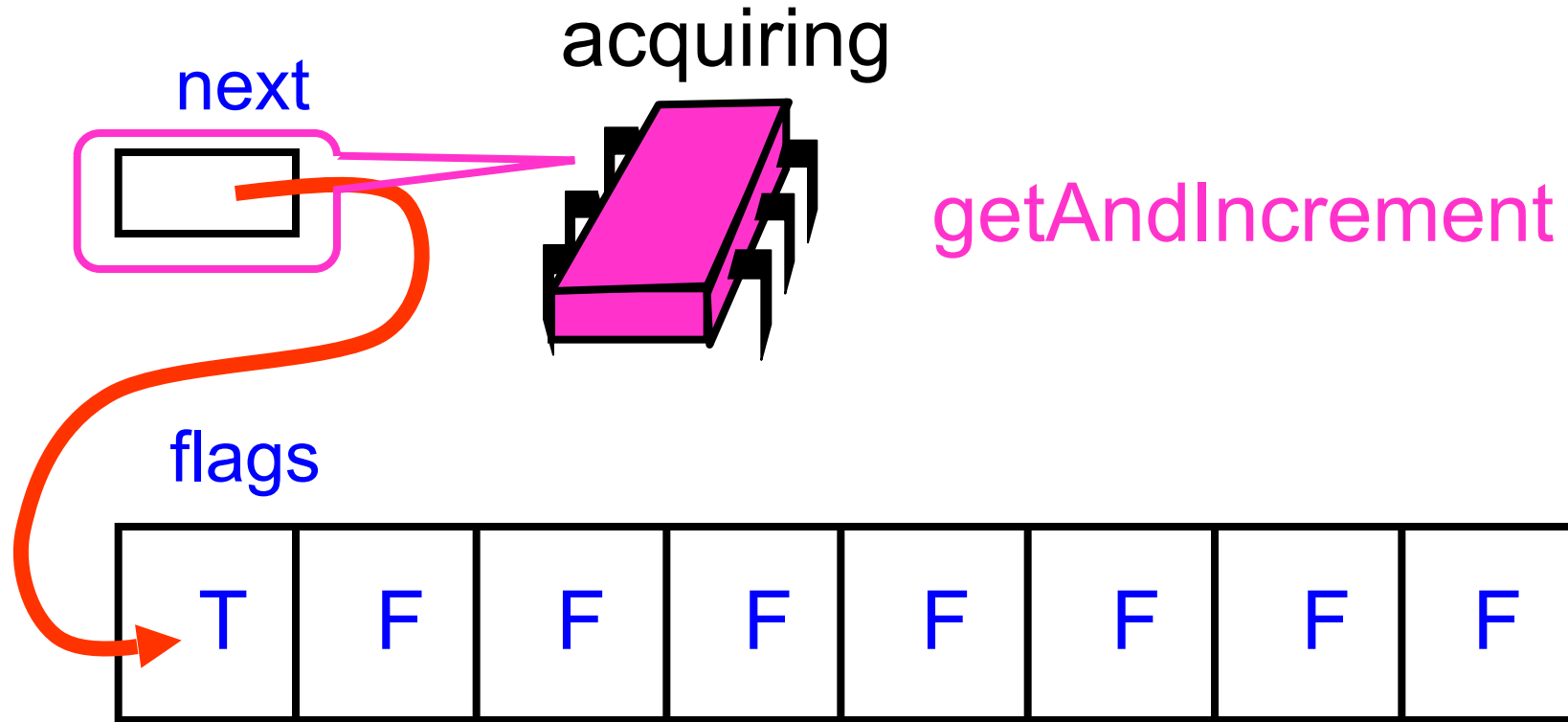
A Prominent Idea

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

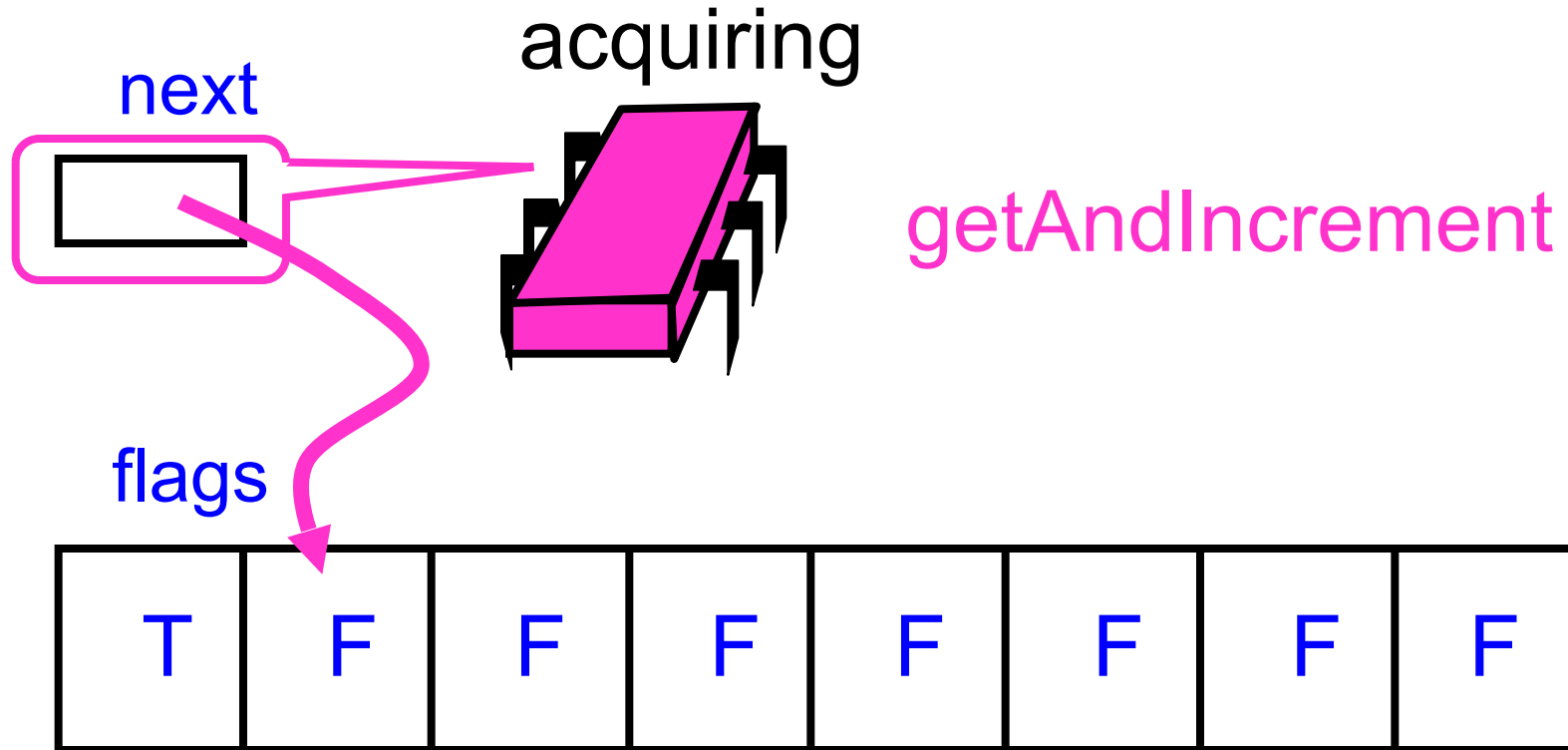
Anderson Queue Lock



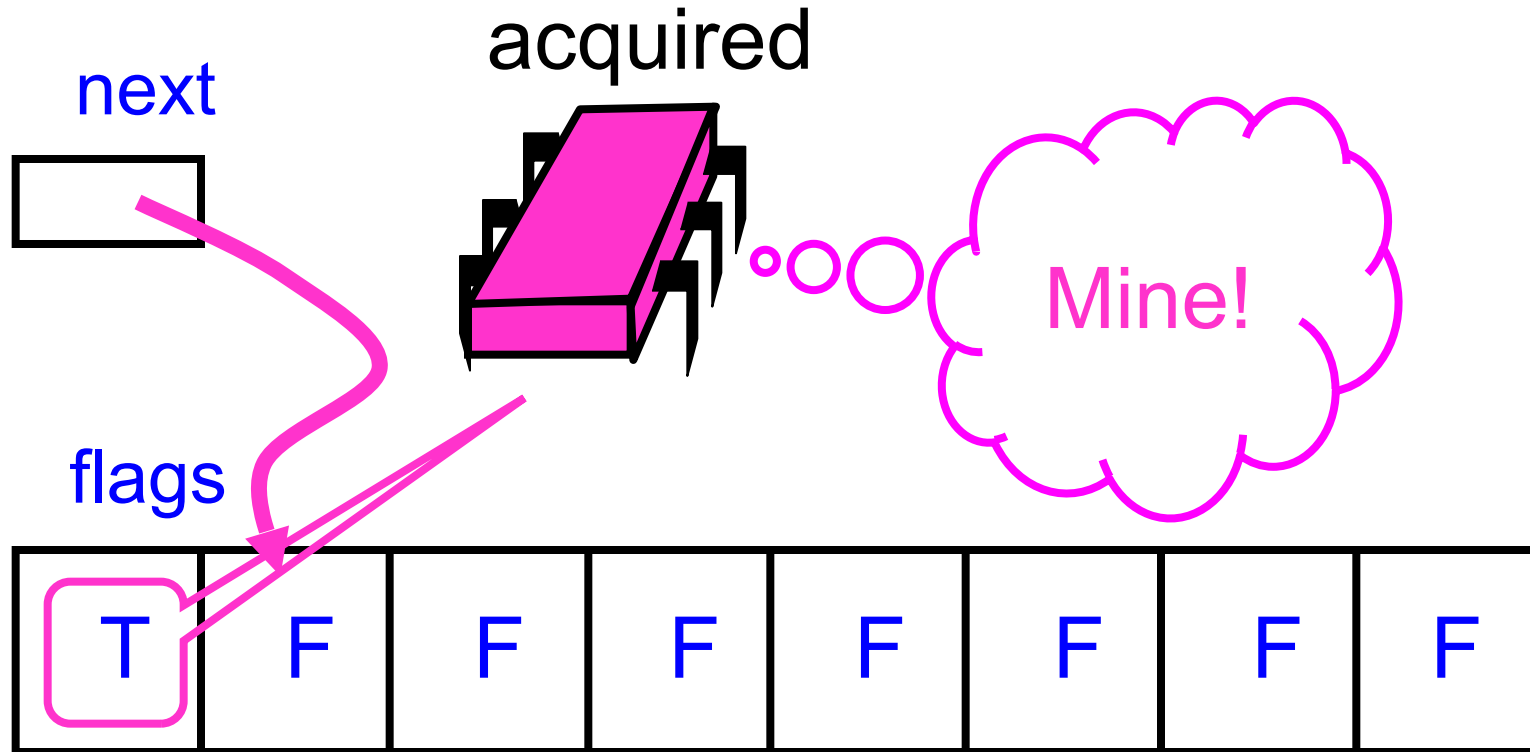
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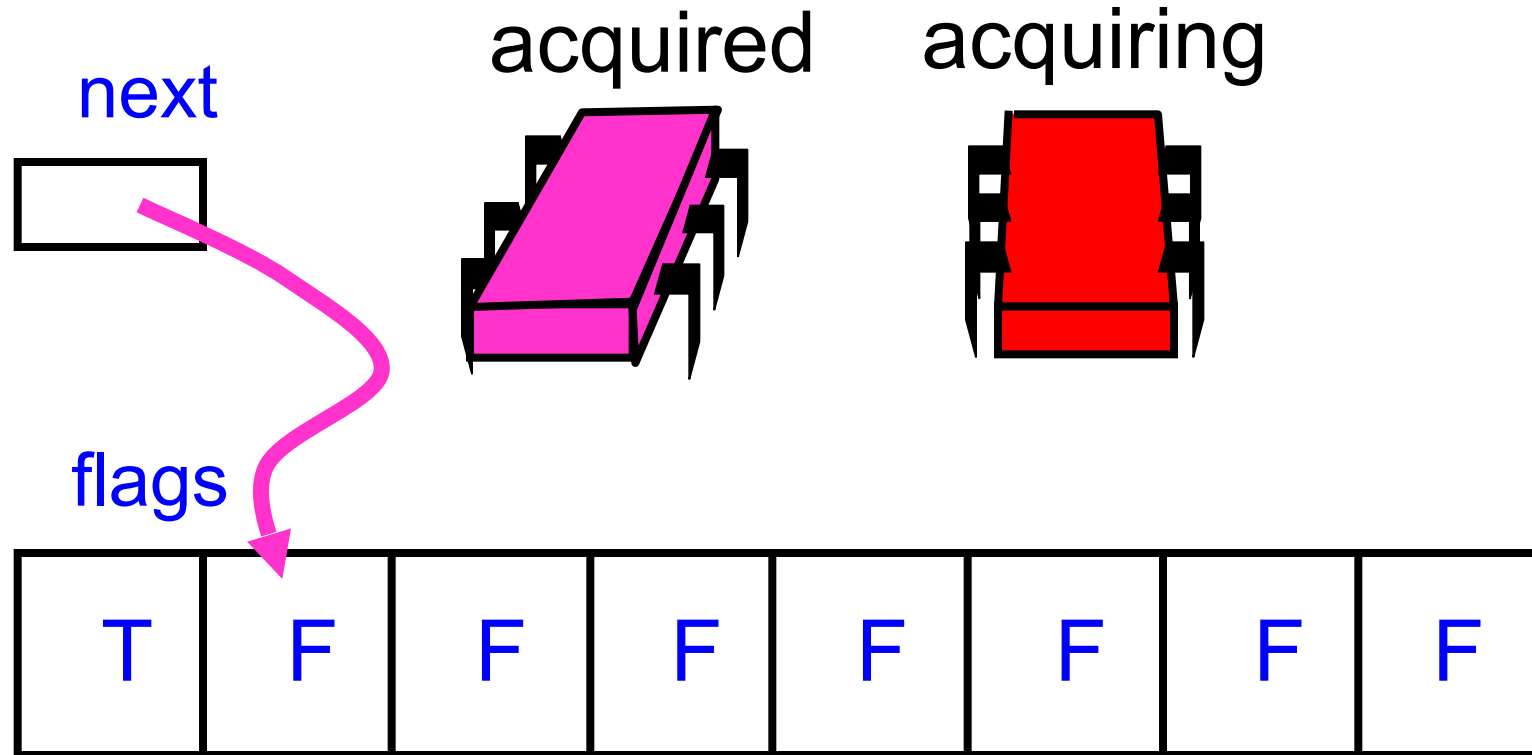
Anderson Queue Lock



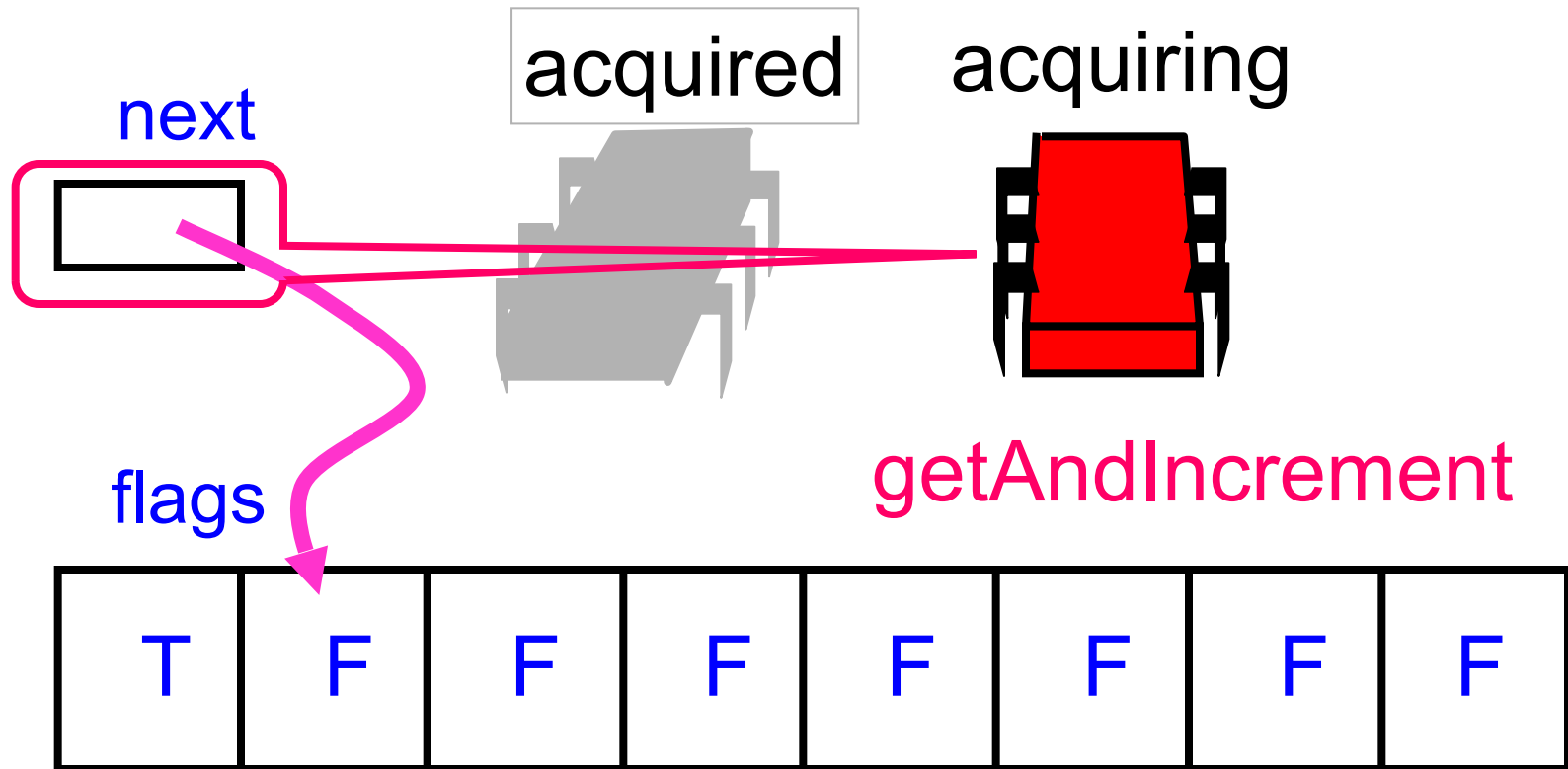
Anderson Queue Lock



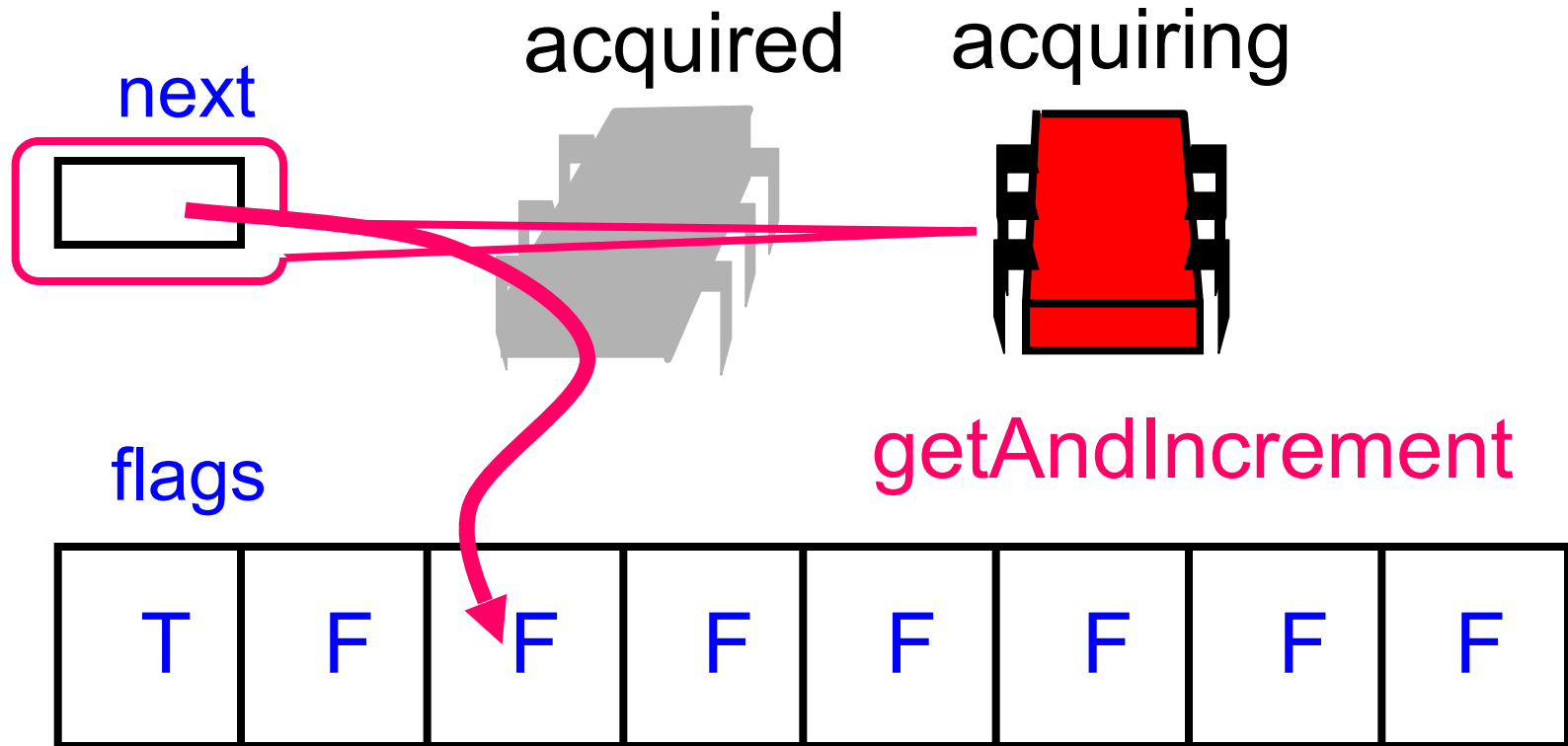
Anderson Queue Lock



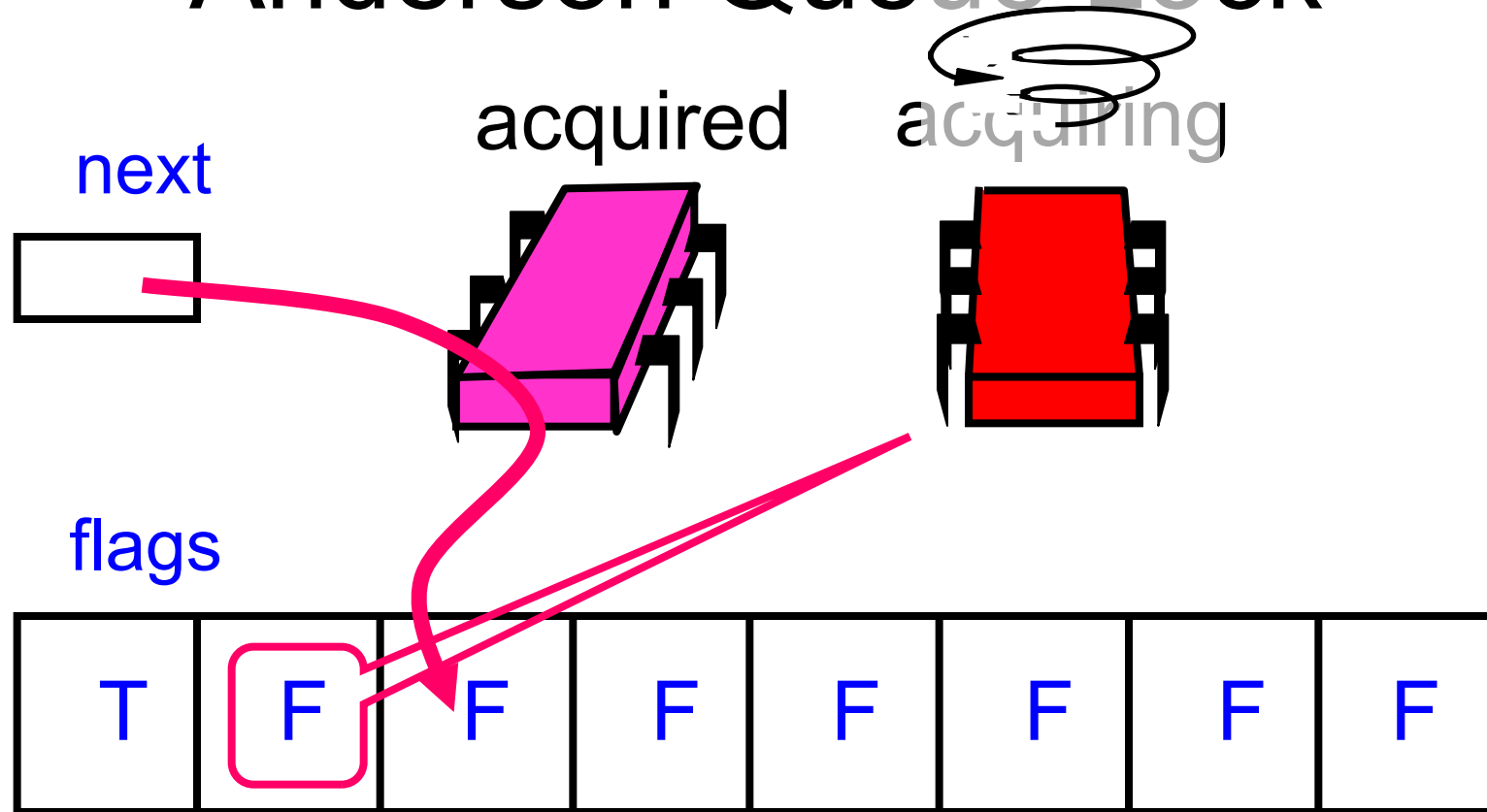
Anderson Queue Lock



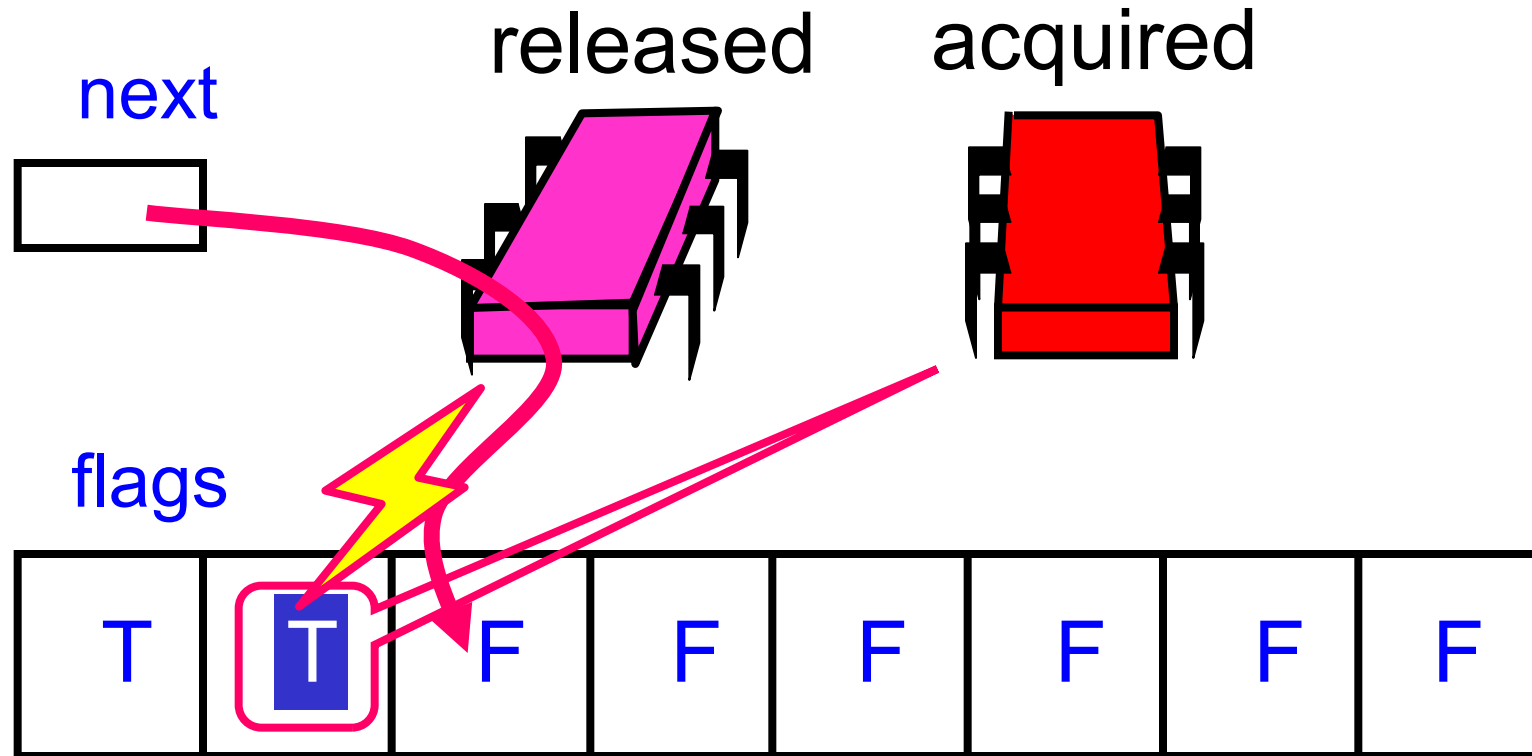
Anderson Queue Lock



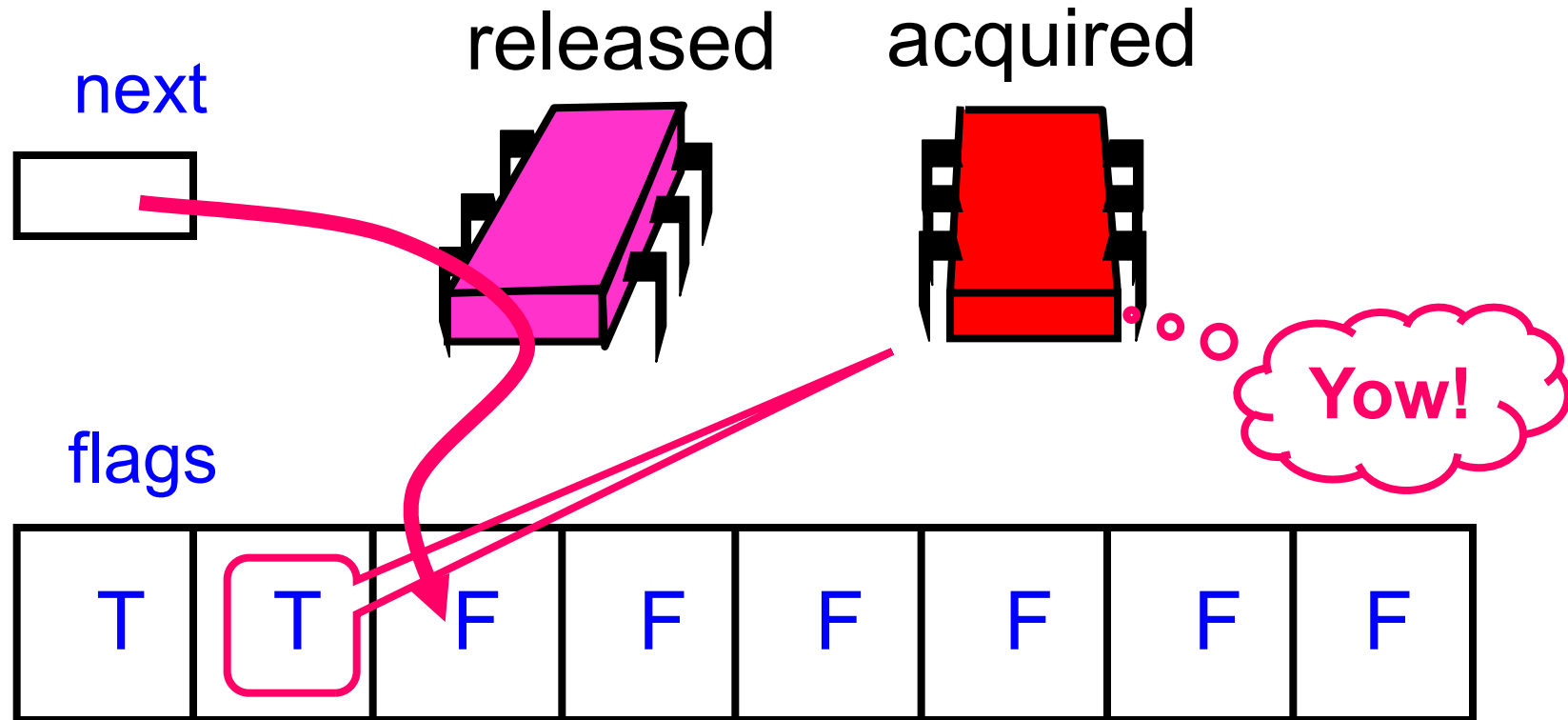
Anderson Queue Lock



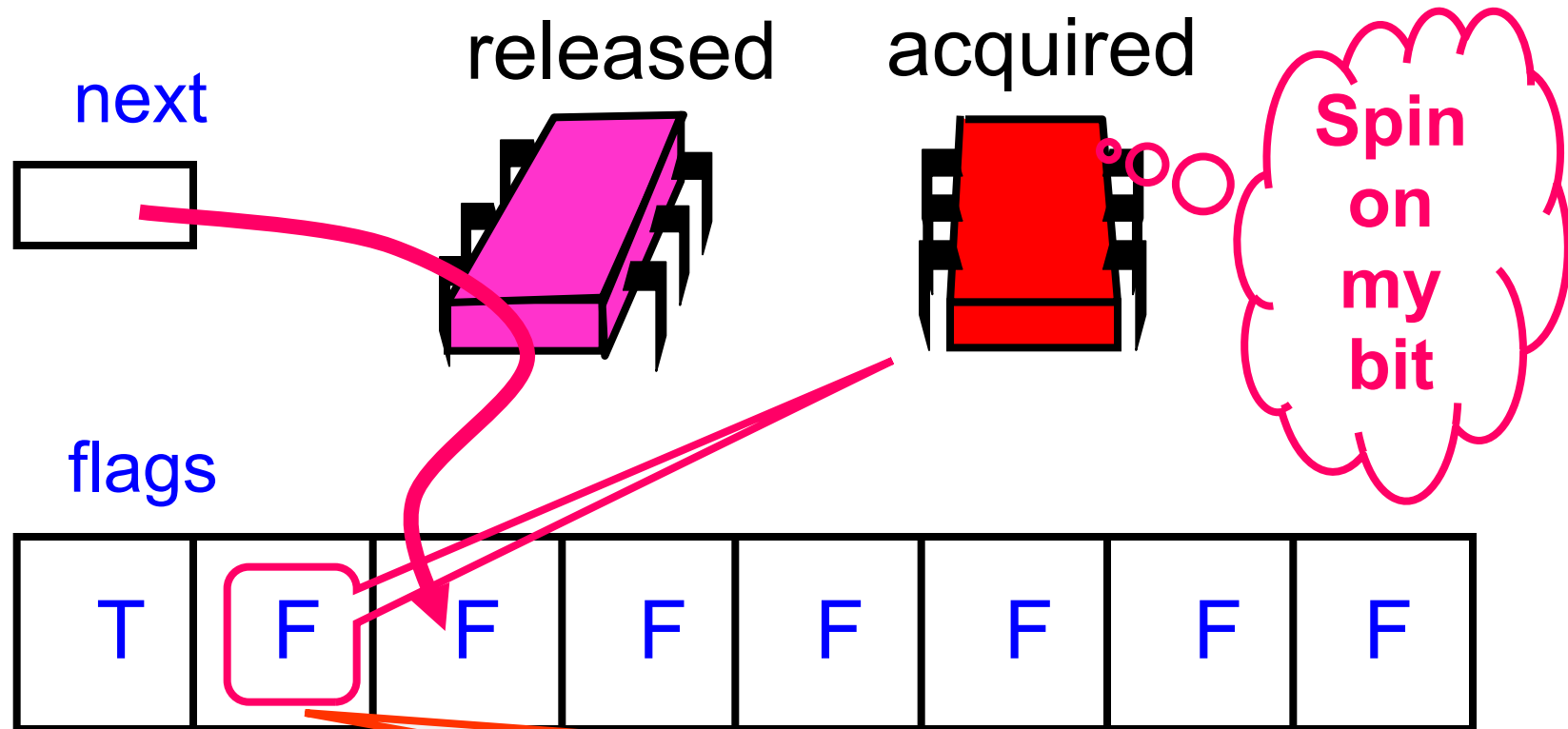
Anderson Queue Lock



Anderson Queue Lock

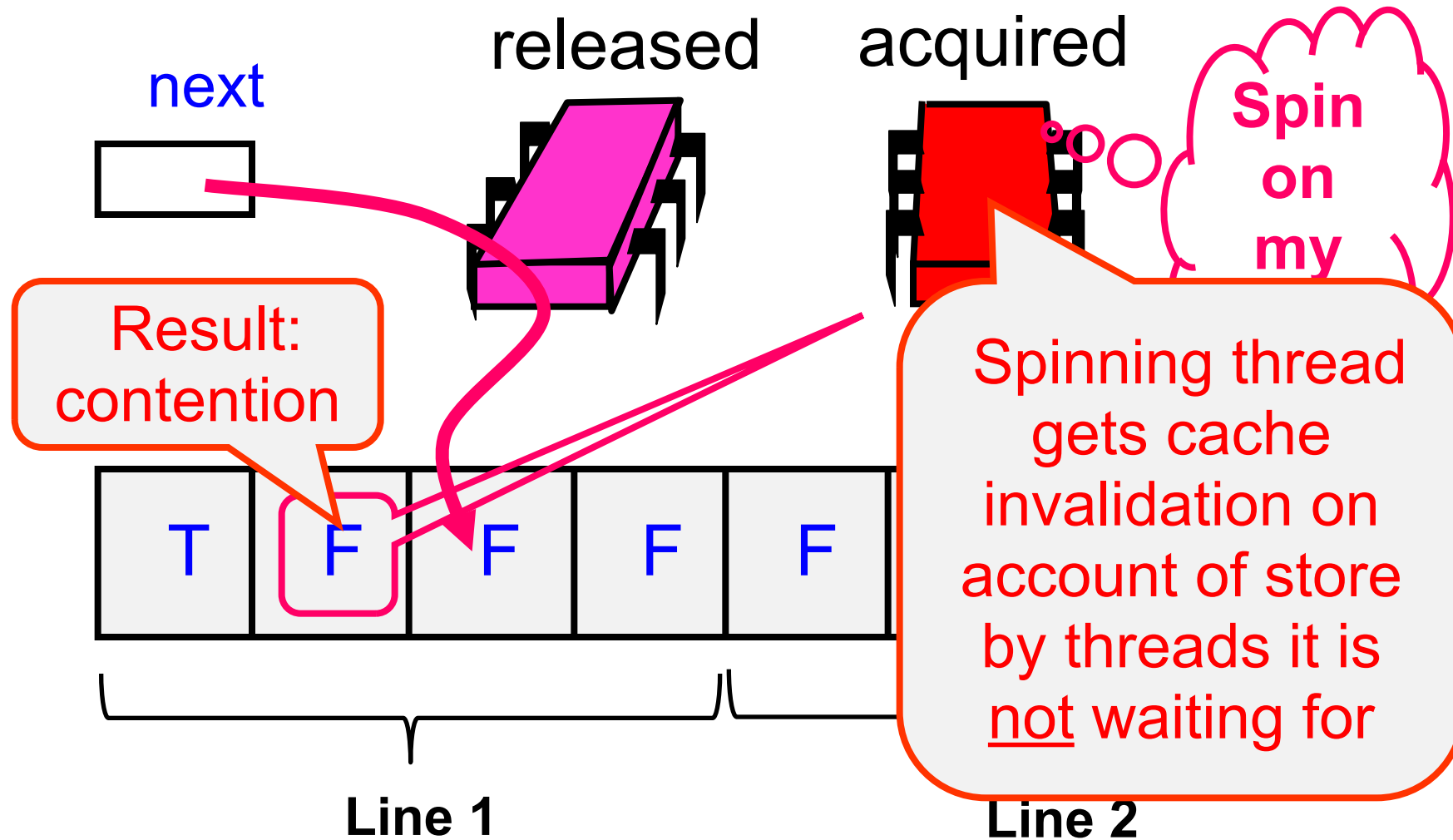


Local Spinning

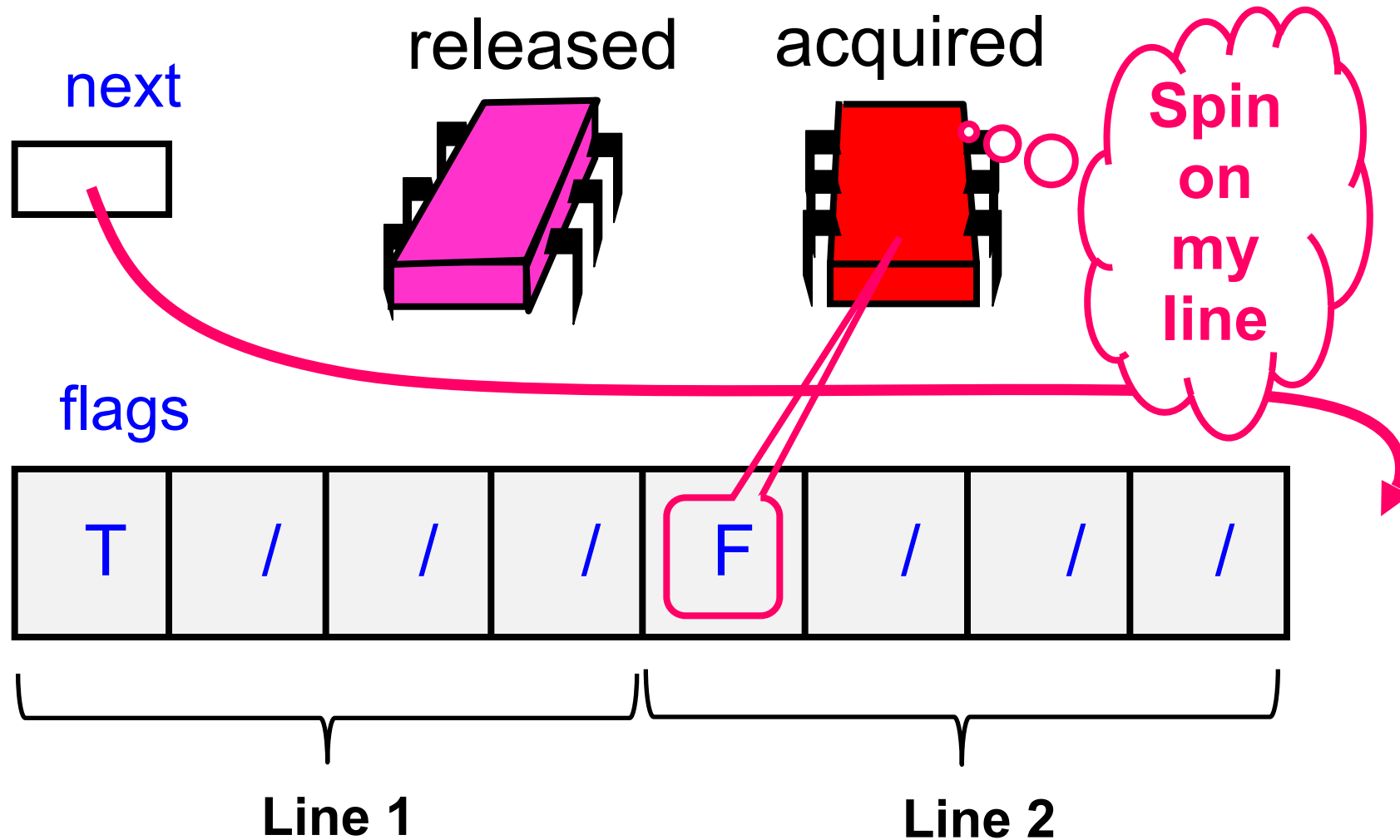


Unfortunately many bits share cache line

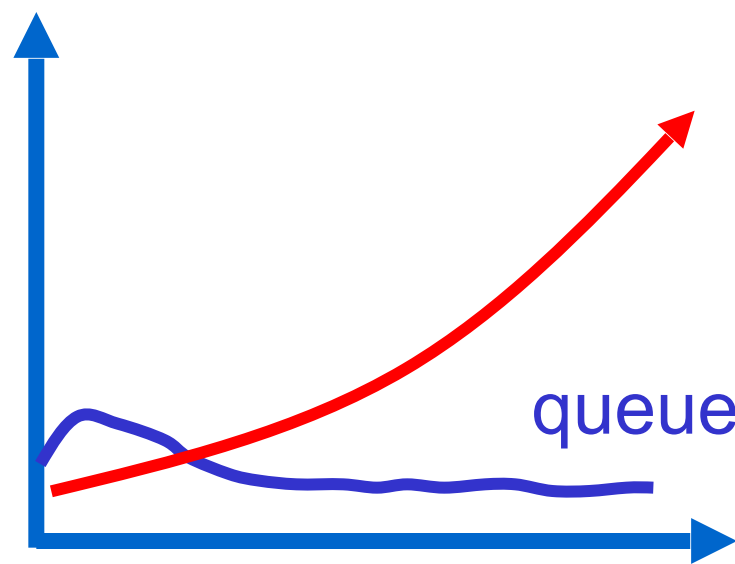
False Sharing



The Solution: Padding



Performance

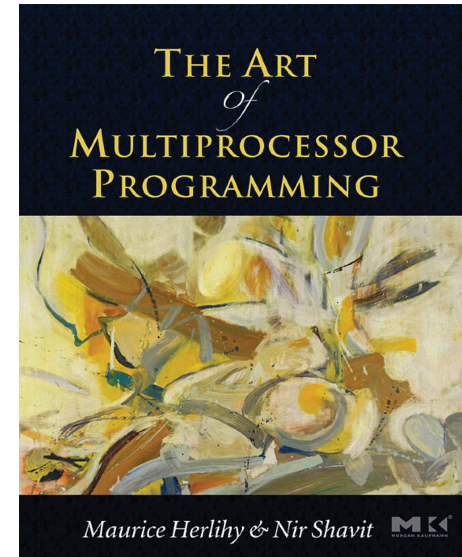


TTAS

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

More spin-locks in the Book

- CHL Lock
- MCS Lock
- Fast-path composite locks
- Hierarchical backoff locks
- ...
- No silver bullet!



Chapter 7

Mind the gap!

- ALock in Java is vulnerable to *false sharing*, which is easy to avoid in C (where you can pad and align flags) but harder in JVM, which tend to pack flags into one cache line.
- Thread-local vars can be *very slow*. One can implement them by hand as an array indexed by thread ID.
- The standard Java Random class uses an internal static lock.
- Java code for `java.util.concurrent` has lots of low-level Java locks and data structures, but it makes heavy use of the Unsafe package for cache alignment, etc.

Why should we care?

- Spin-locks are useful when *critical sections are small*, but the the numbers of threads are *large*
- Typical for *high-performance computing* (most of the tasks done in parallel) or low-level kernel drivers. Those are typically not implemented in Java. :-)
- Regular applications (desktop, web) favour the “blocking” model (threads yield the processor to each other).
- We will consider it in the next lecture.

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