Spin Locks and Contention

CS 475, Fall 2019
Concurrent & Distributed Systems

GEORGE MASON UNIVERSITY

With material from Herlihy & Shavit, Art of Multiprocessor Programming

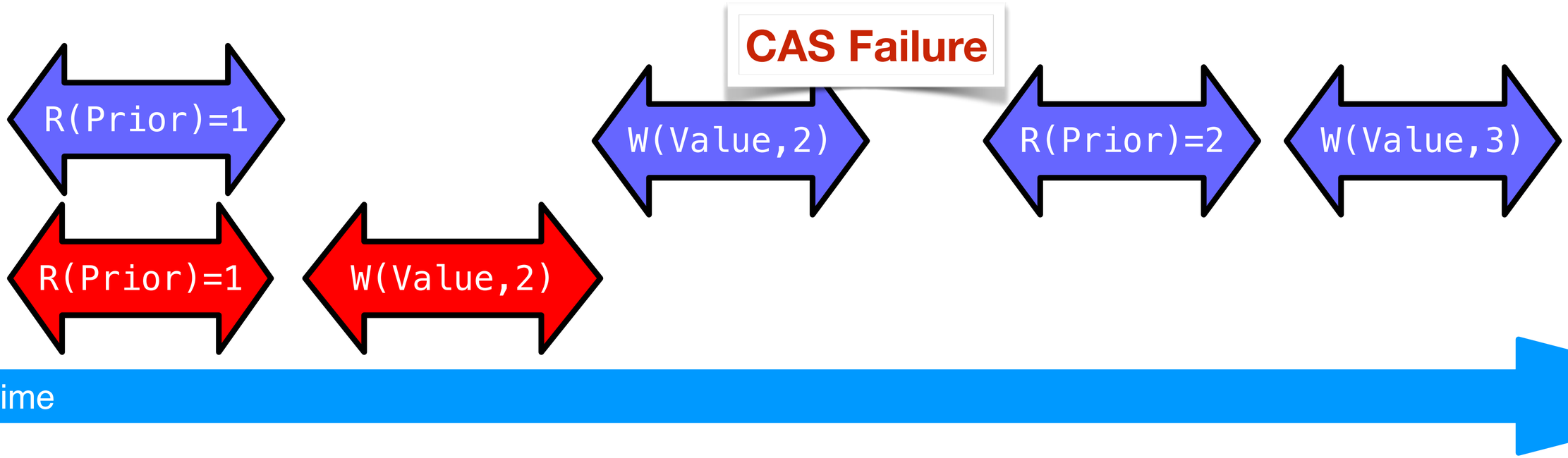
Lock-Free vs. Wait-free

- Wait-Free: each method call takes a finite number of steps to finish
- Lock-free: infinitely often some method call finishes

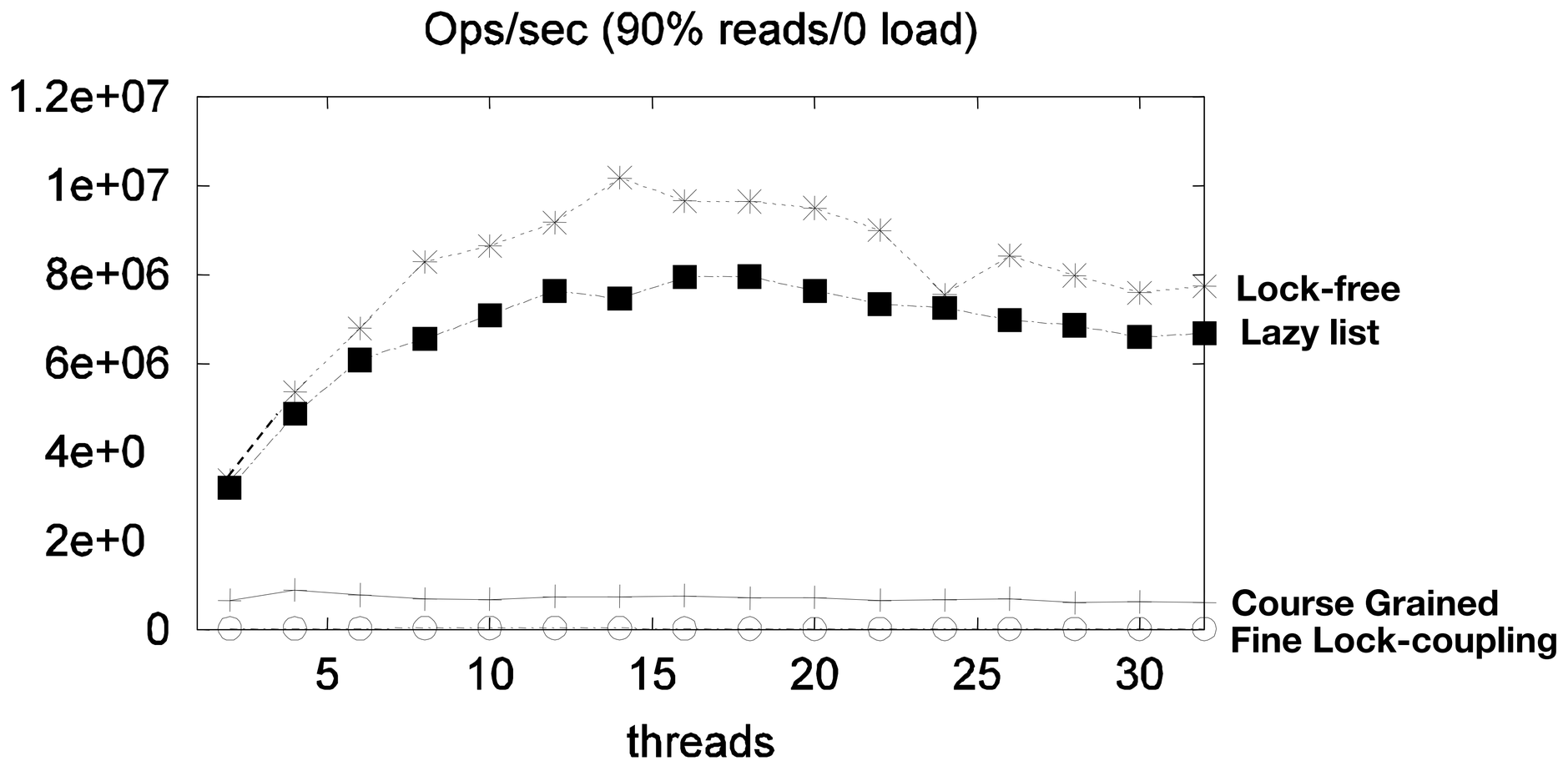
Lock-Free Increment

```
public abstract class Increment {
 private int value;

 public void increment() {
     boolean success = false;
      while(!success){
      int prior  = this.value;
       success = compareAndSet(prior, prior+1);
      }
  }
}
```



High Contains Ratio



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

- 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…

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

- Keep trying
  - "spin" or "busy-wait"
  - Good if delays are short (consider cost of switching threads)
- Give up the processor
  - Good if delays are long
  - Always good on uniprocessor

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

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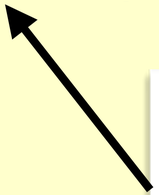
- Give up the processor
  - Good if delays are long
  - Always good on uniprocessor

Today

Peterson's Algorithm - Reminder

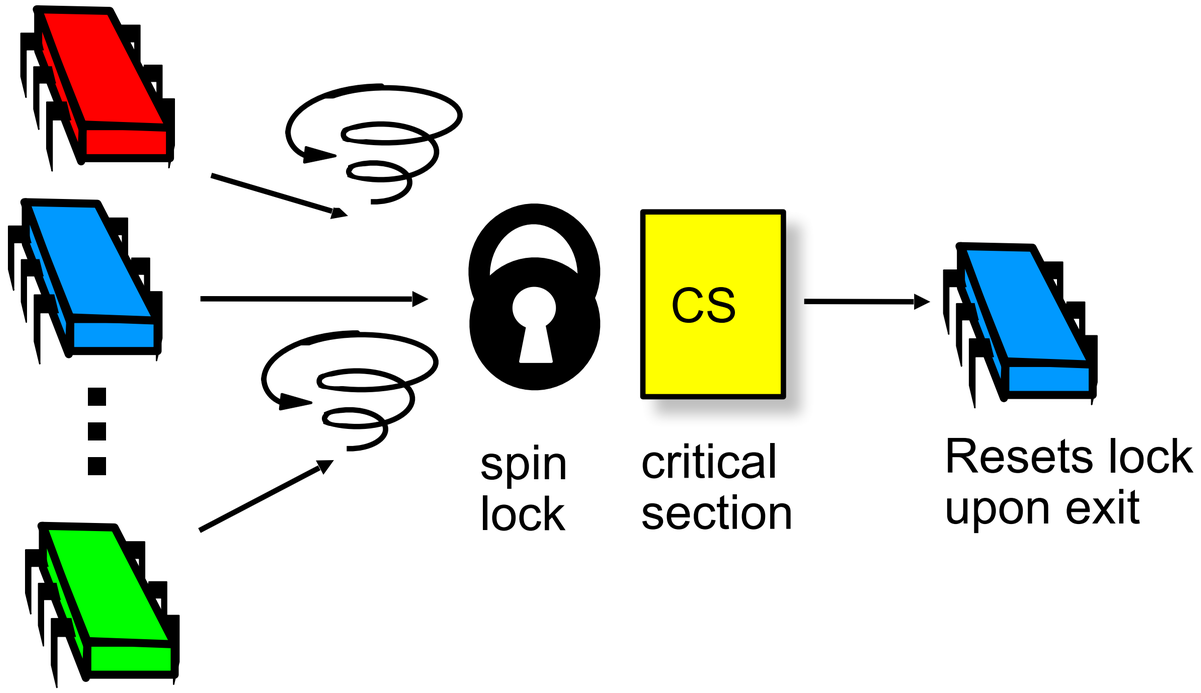
```
public void lock() {
 flag[i] = true;
 victim  = i;
 while (flag[j] && victim == i) {};
 }
public void unlock() {
 flag[i] = false;
}
```



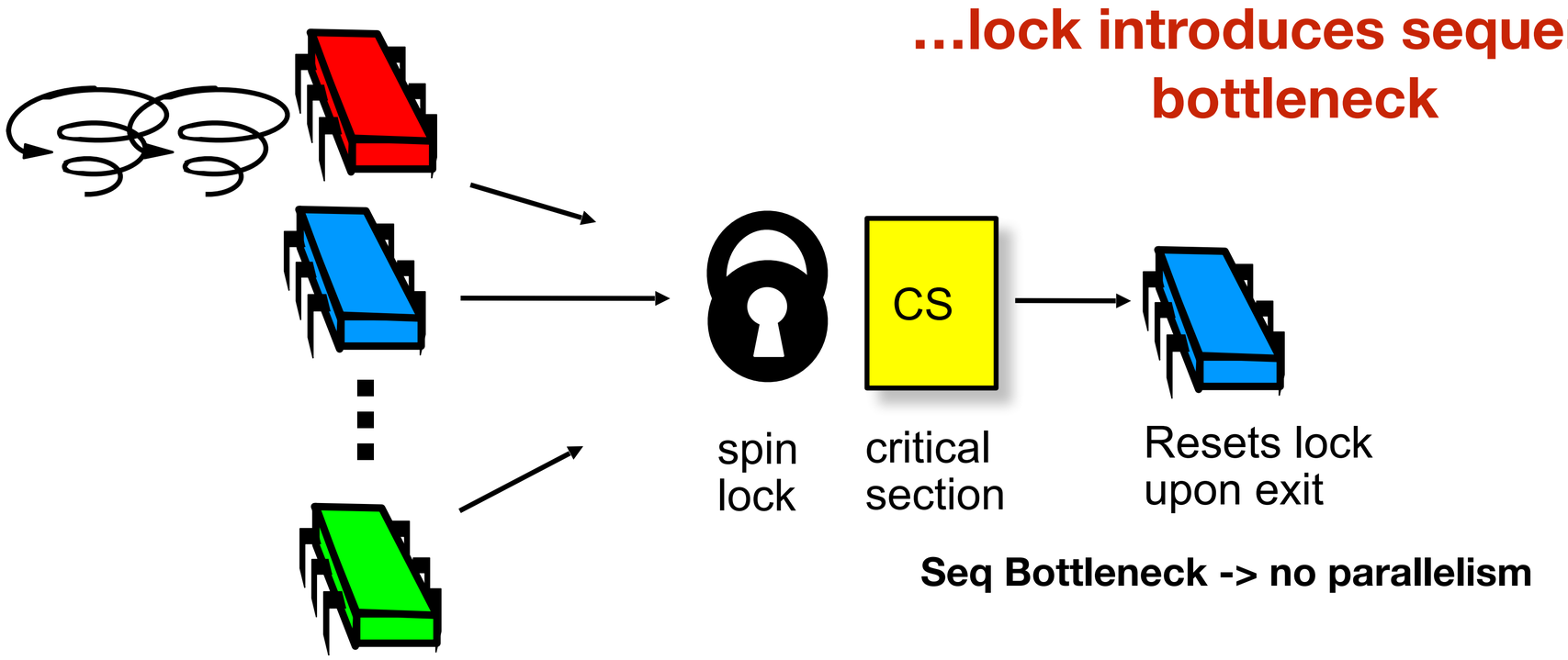
Threads "spin" in this empty loop while waiting

"Busy" waiting - thread keeps running on the CPU

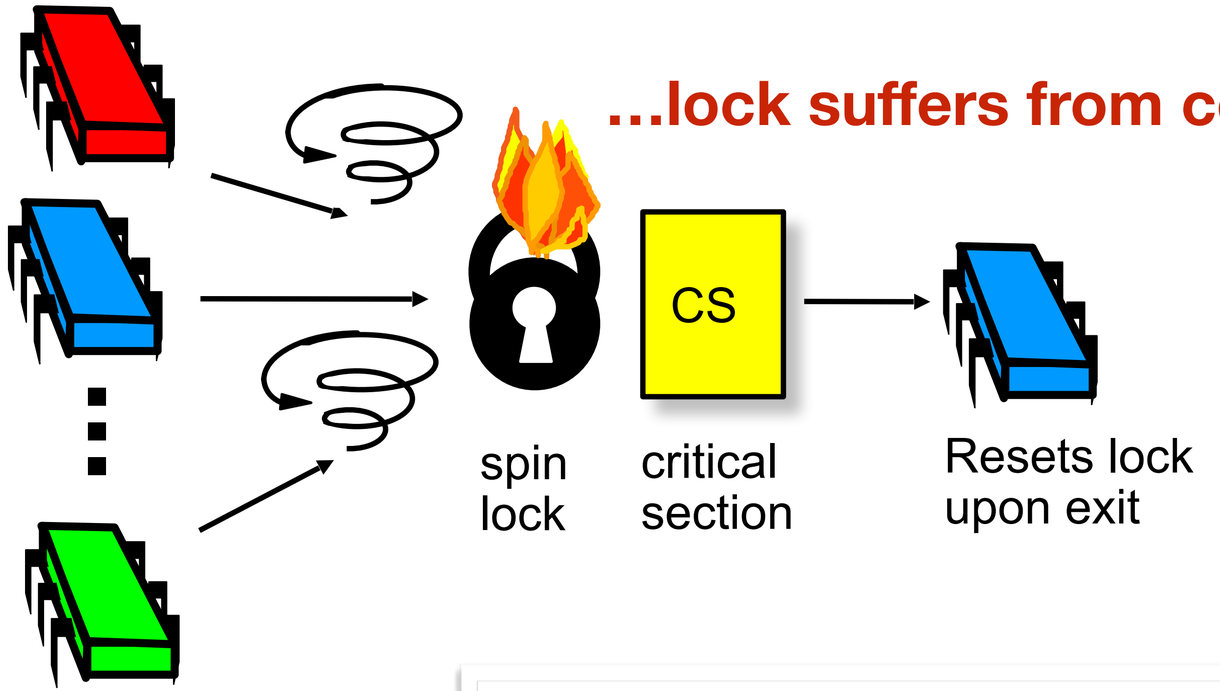
Basic Spin-Lock



Basic Spin-Lock

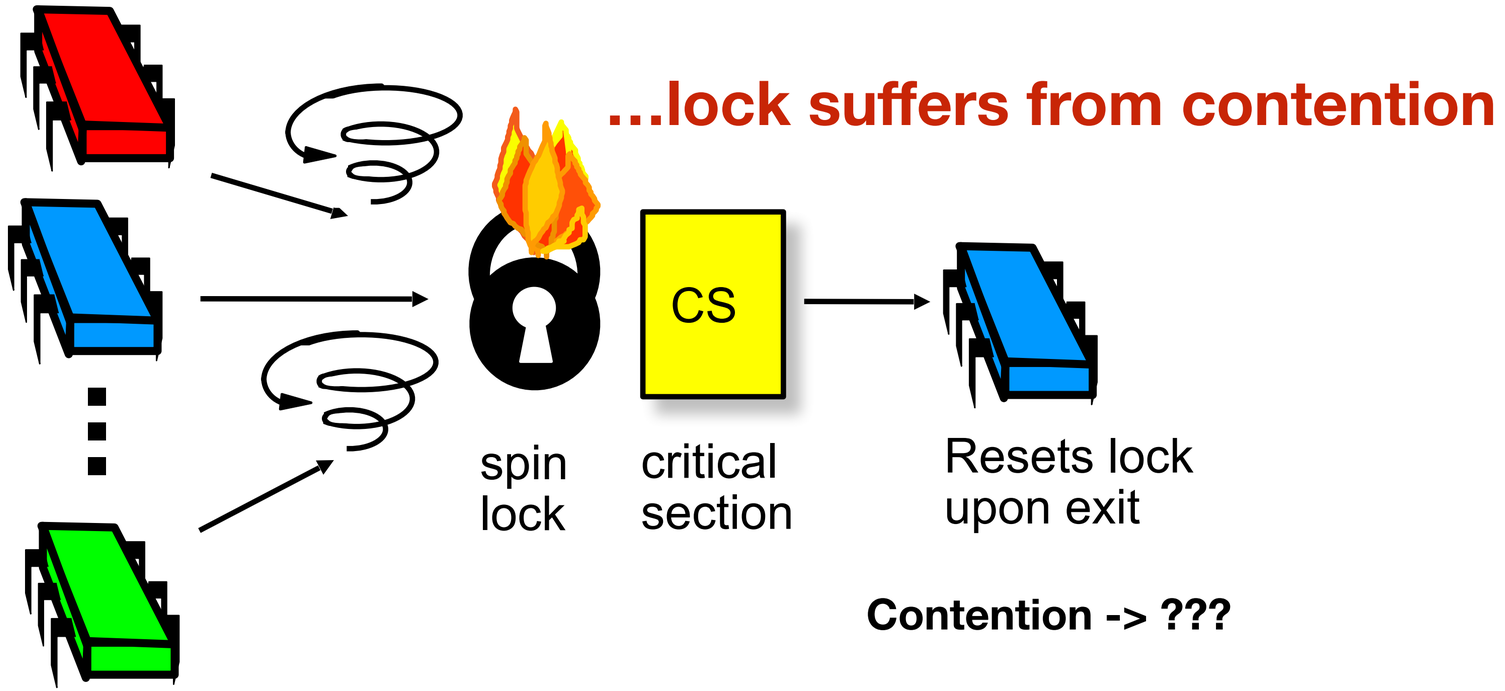


Basic Spin-Lock



Note: Contention and bottlenecking are separate phenomena

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”

Review: Test-and-Set

```
public class AtomicBoolean {
 boolean value;

 public synchronized boolean
  getAndSet(boolean newValue) {
    boolean prior = value;
    value = newValue;
    return prior;
 }
}
```

Review: Test-and-Set

```
public class AtomicBoolean {
  boolean value;

  public synchronized boolean
   getAndSet(boolean newValue) {
     boolean prior = value;
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     return prior;
  }
}
```

Package
java.util.concurrent.atomic

Review: Test-and-Set

```
public class AtomicBoolean {
 boolean value;

 public synchronized boolean
  getAndSet(boolean newValue) {
    boolean prior = value;
    value = newValue;
    return prior;
  }
}
```

Swap old and new values

Review: Test-and-Set

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

Review: Test-and-Set

```
AtomicBoolean lock
 = new AtomicBoolean(false)

…
boolean 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 {
 AtomicBoolean state =
  new AtomicBoolean(false);

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

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

Test-and-set Lock

```
class TASlock {
 AtomicBoolean state =
  new AtomicBoolean(false);

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

 void unlock() {
  state.set(fa
 }}
```

Lock state is AtomicBoolean

Test-and-set Lock

```
class TASlock {
 AtomicBoolean state =
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 void lock() {
  while (state.getAndSet(true)) {}
 }

 void unlock() {
  state.set(f
 }}
```

Keep trying until lock acquired

Test-and-set Lock

```
class TASlock {
 AtomicBoolean state =
  new At
 void lock() {
  while (state.getAndSet(true)) {}
 }
 void unlock() {
  state.set(false);
 }}
```

Release lock by resetting state to false

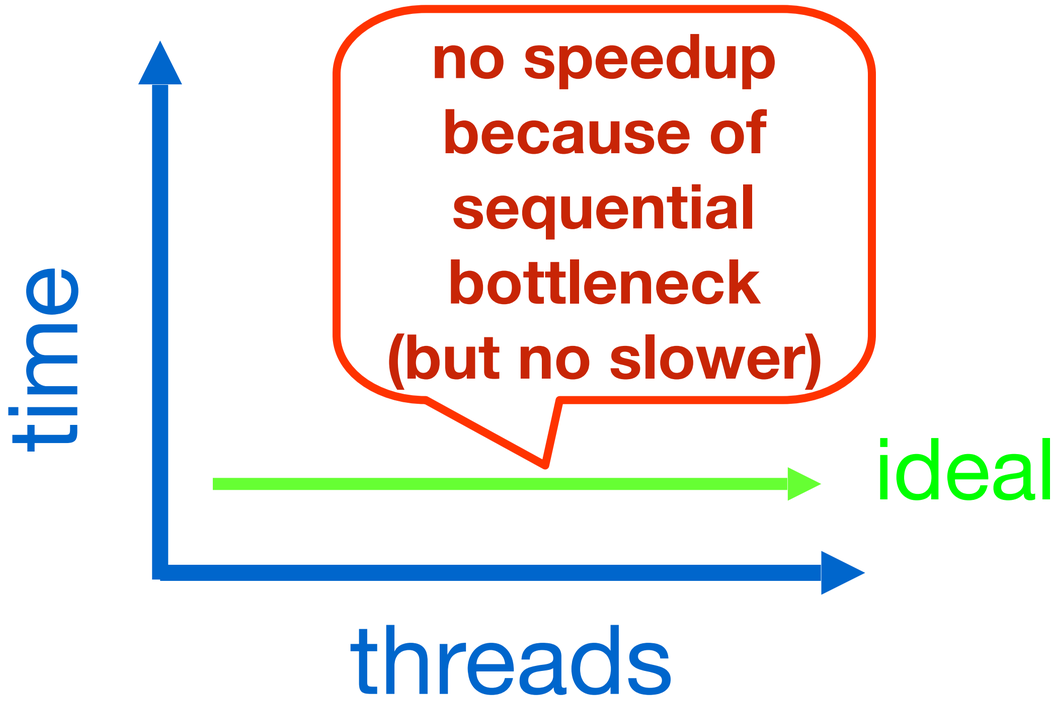
Space Complexity

- 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 Ω(n) lower bound?
- We used an atomic Read/Modify/Write operation
  - Under the covers uses some special hardware features, *not* just the synchronized keyword as in the slides (if so, still O(n)?)

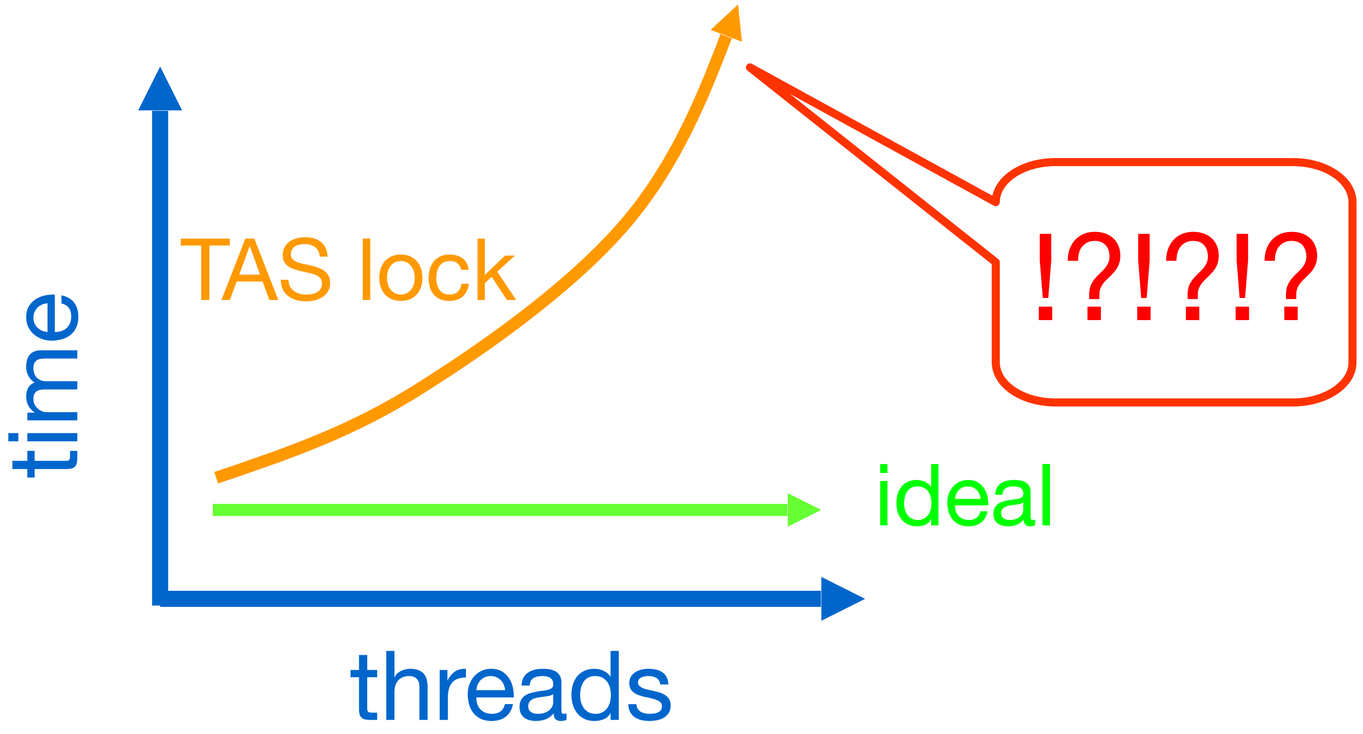
Performance

- Experiment
  - n threads
  - Increment shared counter 1 million times
- How long should it take?
- How long does it take?

Graph


no speedup
because of
sequential
bottleneck
(but no slower)
time
ideal
threads

Mystery #1



Adding MORE threads makes it SLOWER!

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 {
 AtomicBoolean state =
  new AtomicBoolean(false);

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

Test-and-test-and-set Lock

```
class TTASlock {
 AtomicBoolean state =
  new AtomicBoolean(false);

 void lock() {
  while (true) {
   while (state.get()) {}
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    return;
 }
}
```

Wait until lock looks free

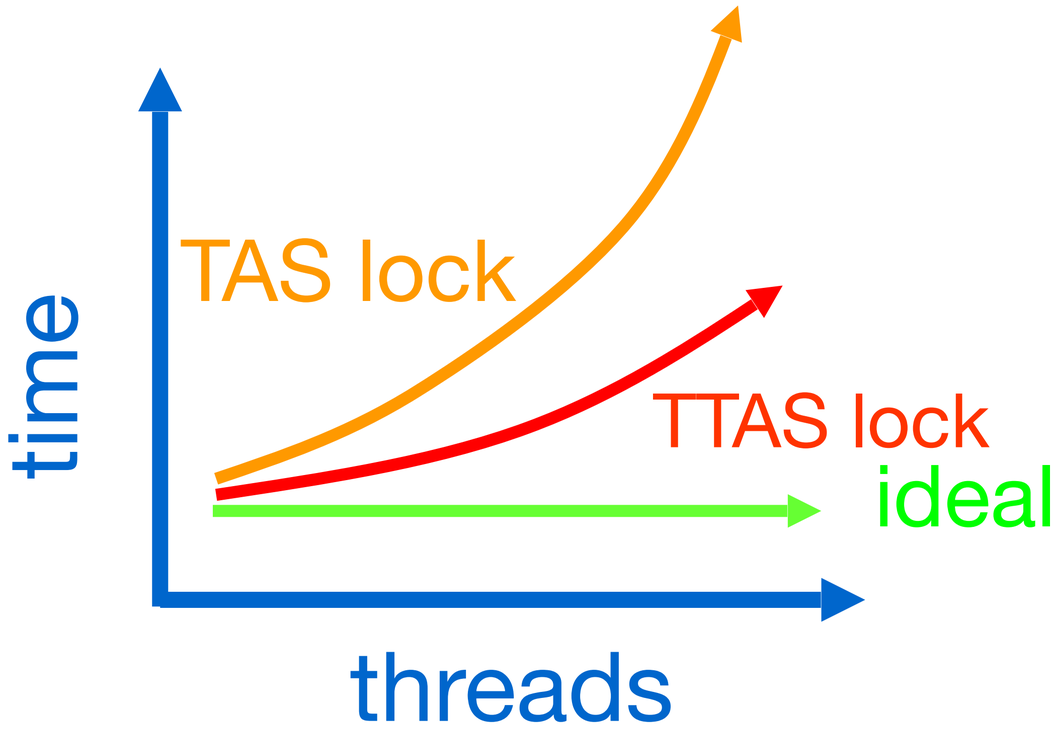
Test-and-test-and-set Lock

```
class TTASlock {
 AtomicBoolean state =
  new AtomicBoolean(false);

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

Then try to acquire it

Mystery #2



Mystery

- Both
  - TAS and TTAS
  - Do the same thing (in our model)
- Except that
  - TTAS performs much 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 …

CPU Architectures

Kinds of Architectures

- SISD (Uniprocessor)
  - Single instruction stream
  - Single data stream
- SIMD (Vector)
  - Single instruction
  - Multiple data
- MIMD (Multiprocessors)
  - Multiple instruction
  - Multiple data.

Kinds of Architectures

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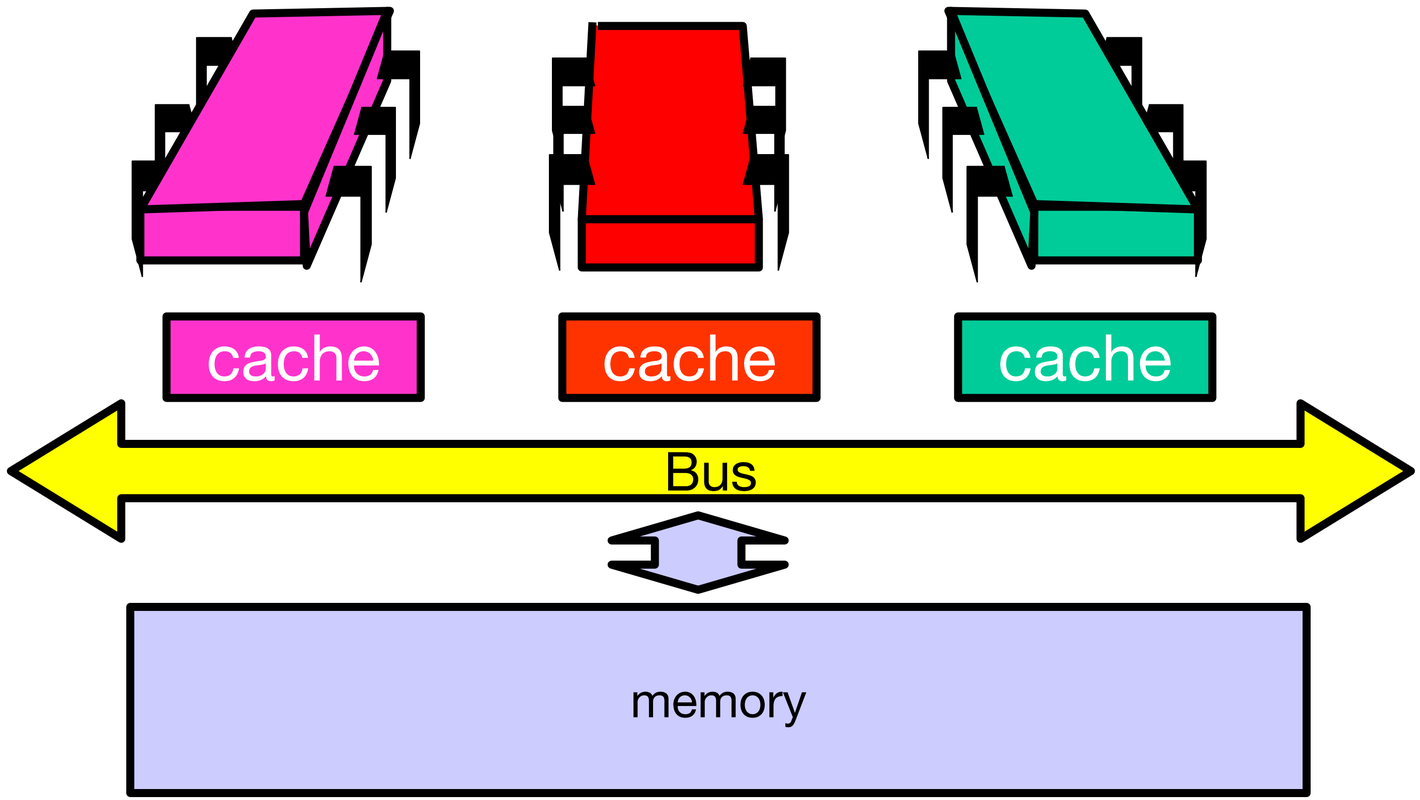
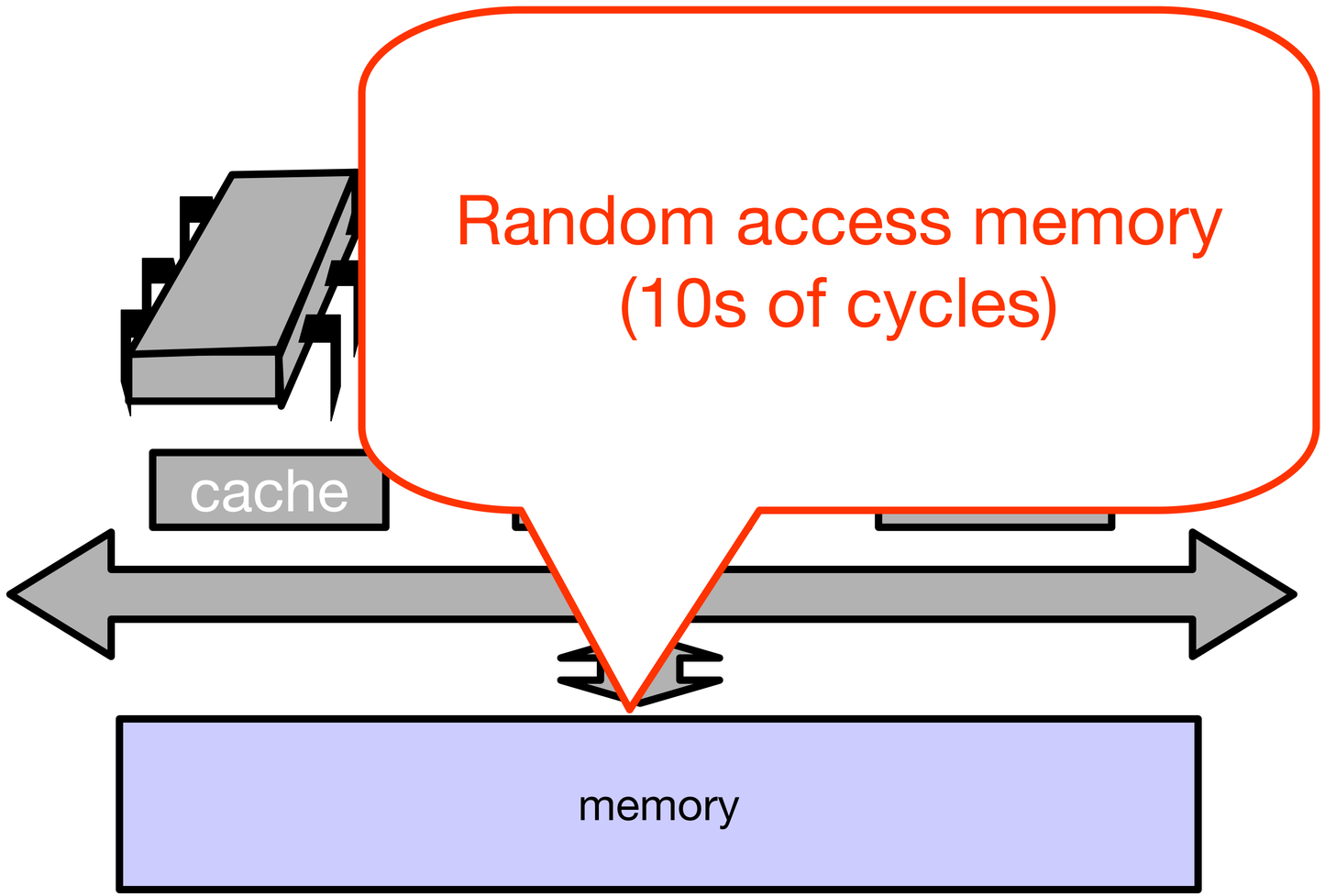
Most modern desktop/laptop CPUs

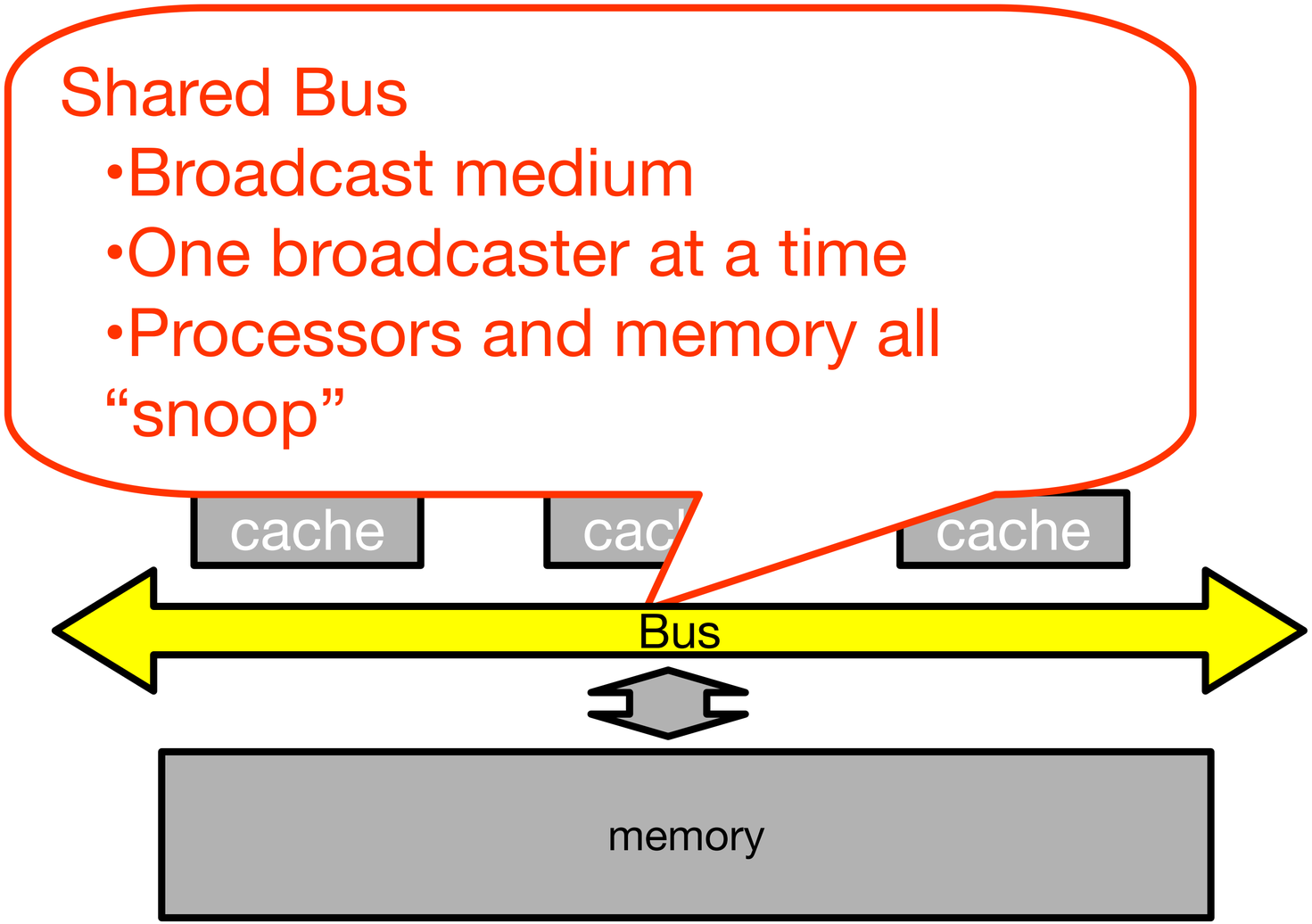
MIMD Bus-Based Architectures



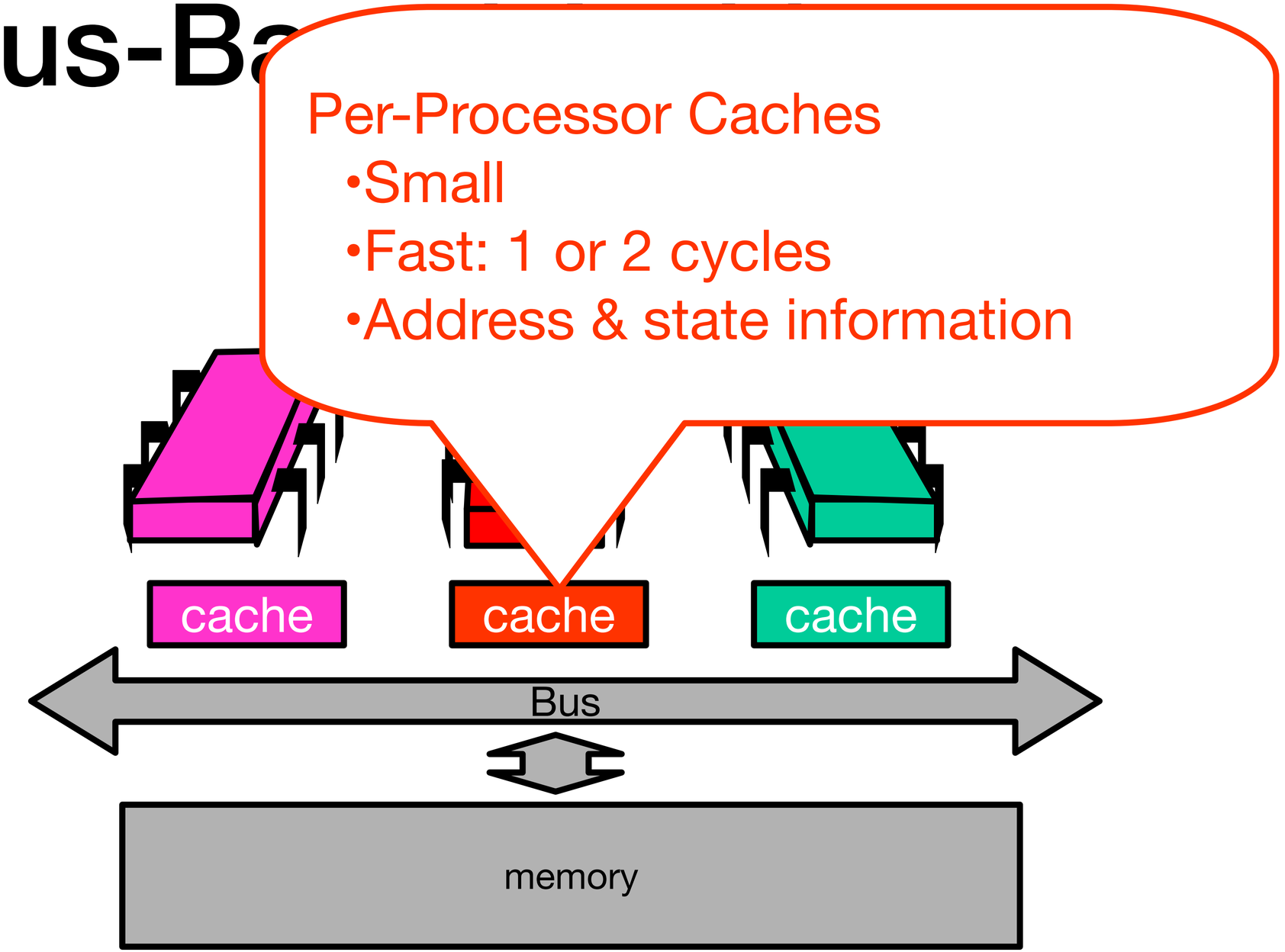
Bus-Based Architectures



Bus-Based Architectures



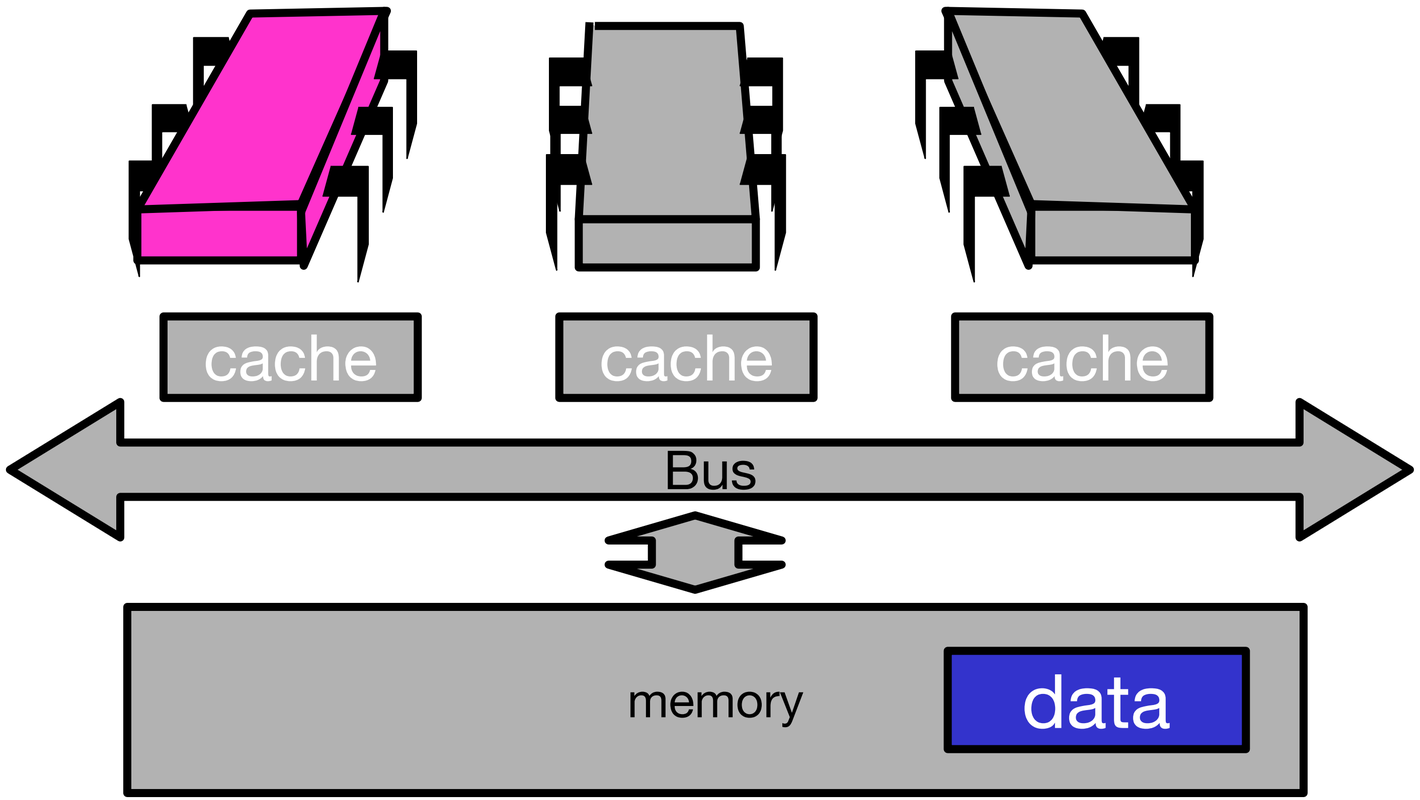
Bus-Ba


Per-Processor Caches
•Small
•Fast: 1 or 2 cycles
•Address & state information
cache
cache
cache
Bus
memory

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™

Processor Issues Load Request



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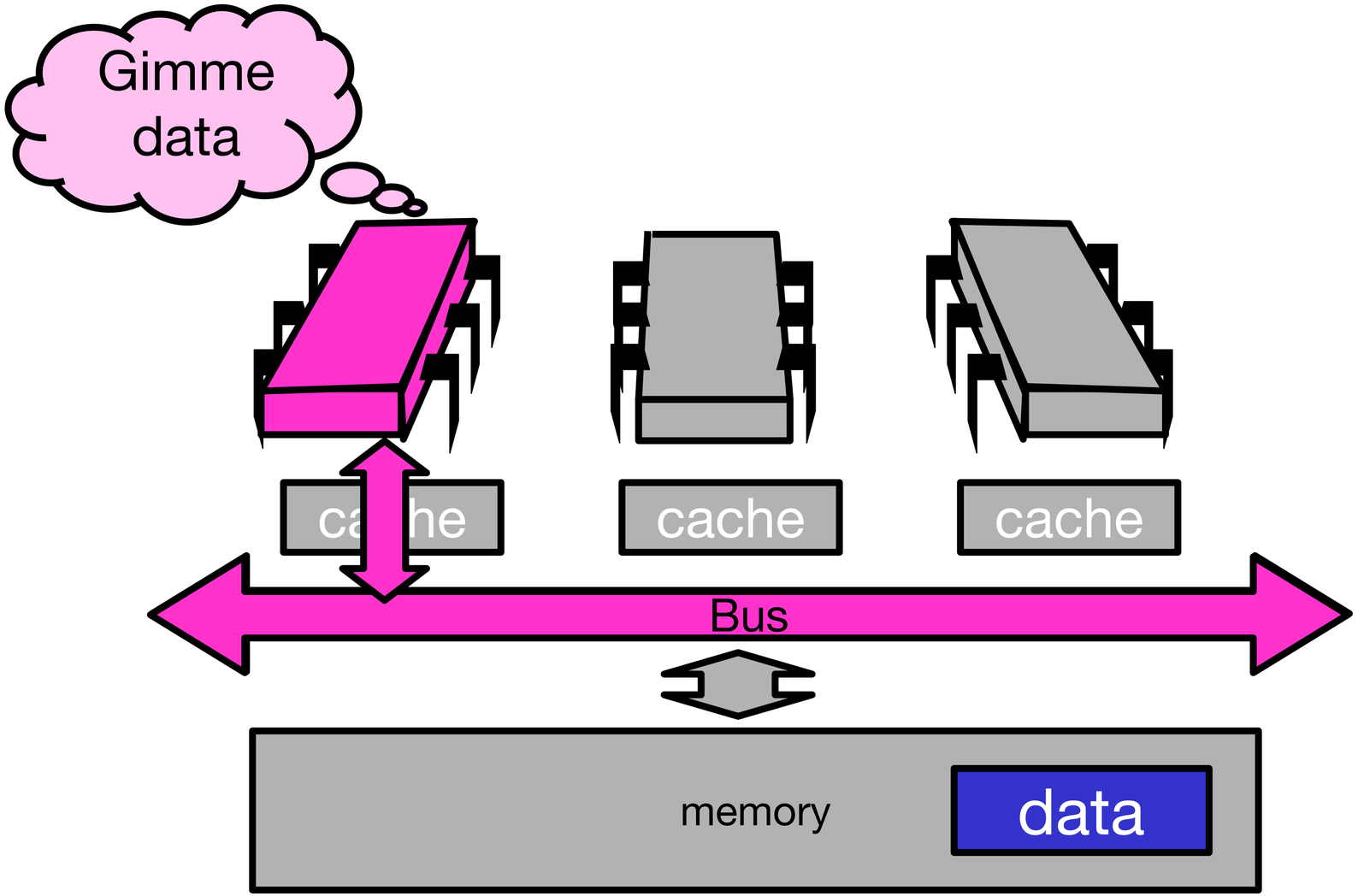
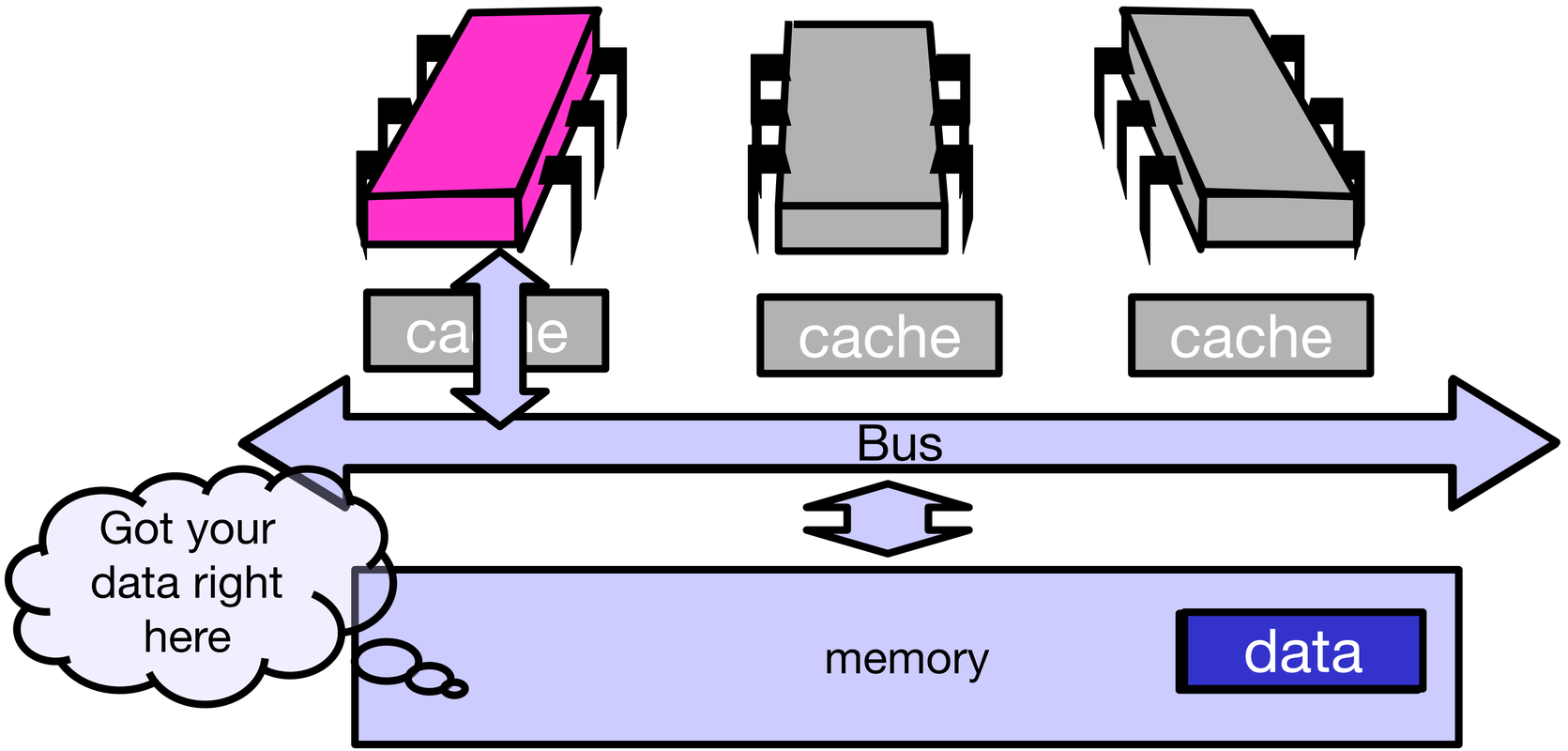
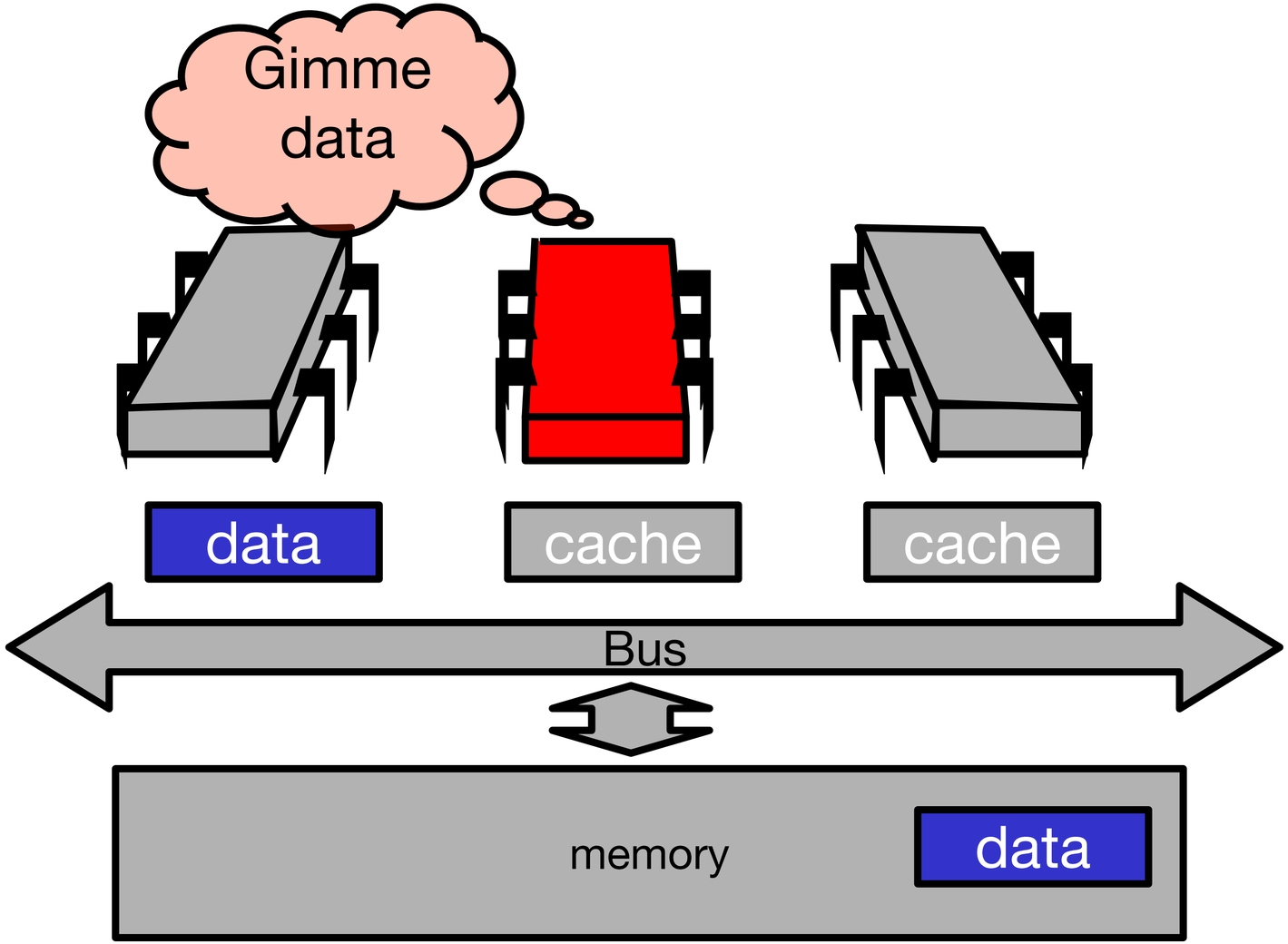


Memory Responds



Art of Multiprocessor Programming

Processor Issues Load Request



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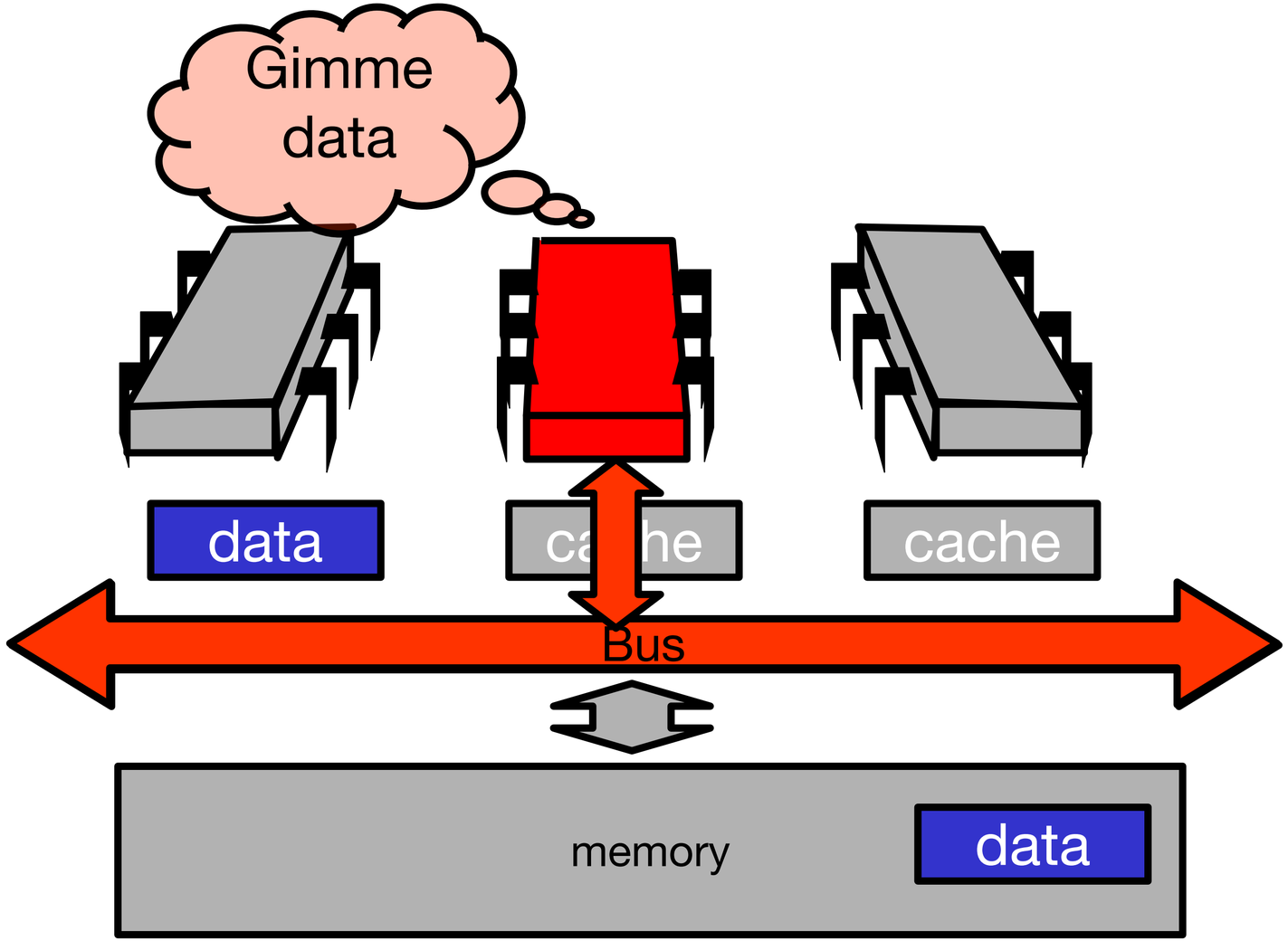

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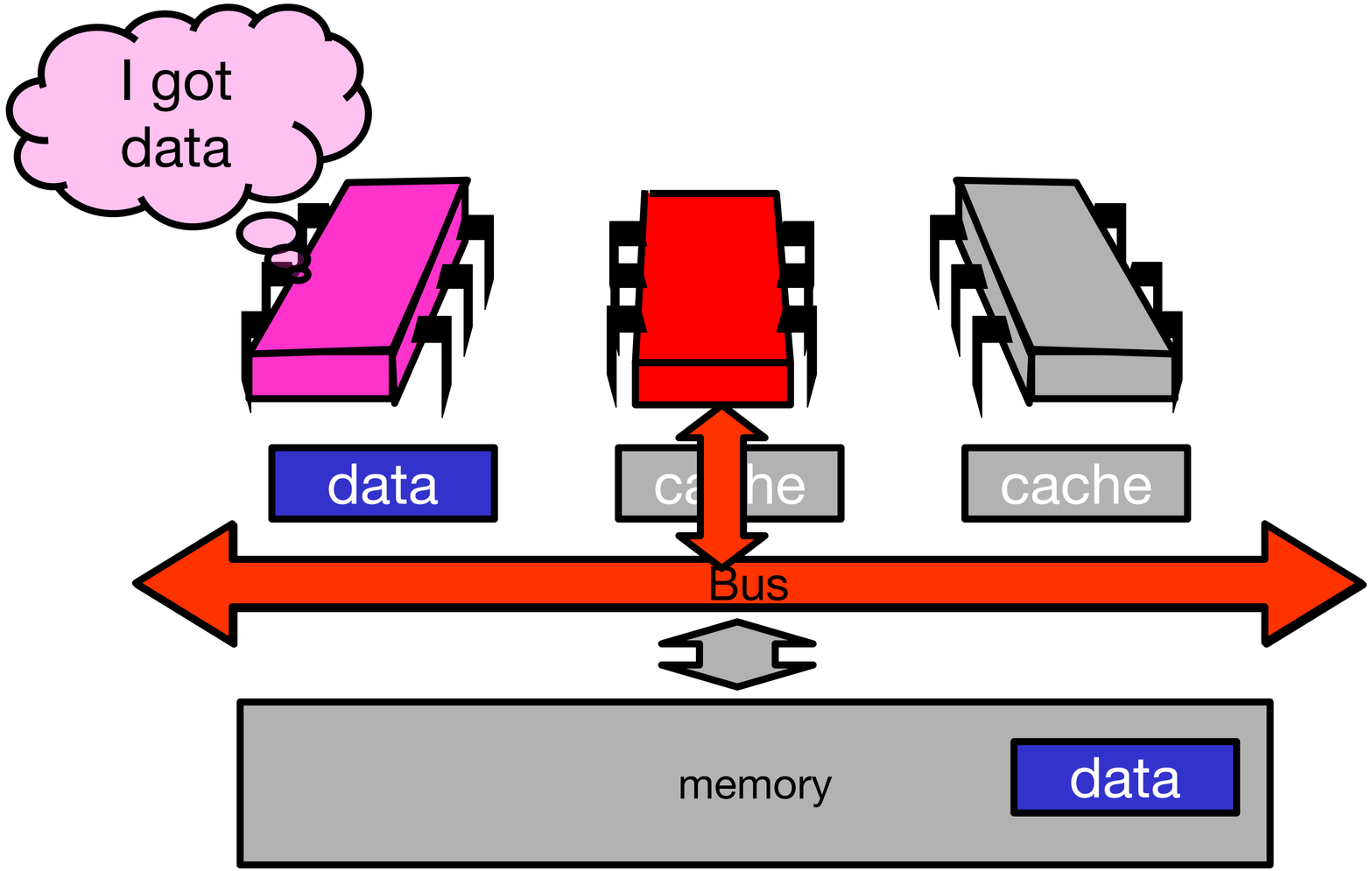
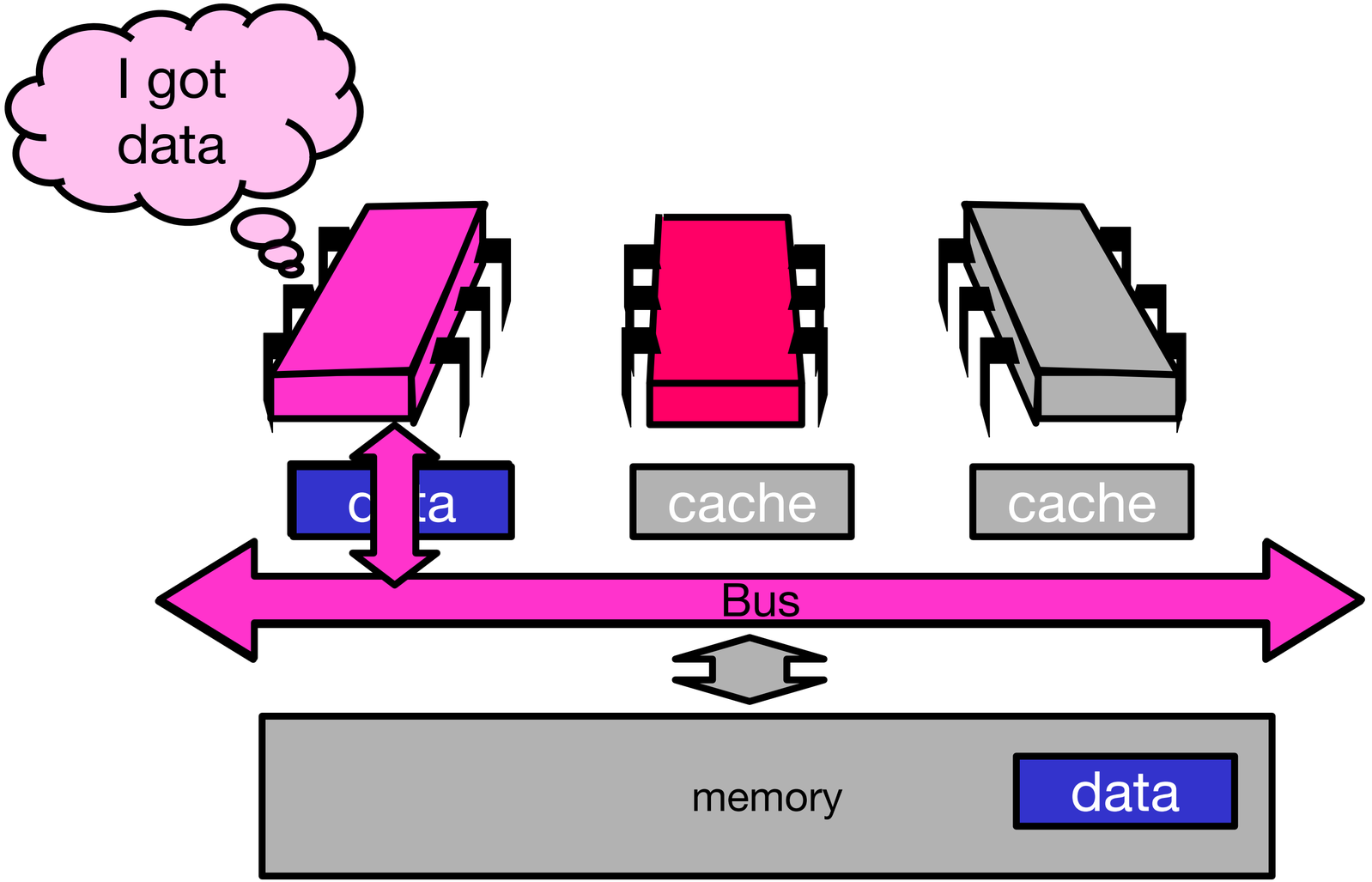
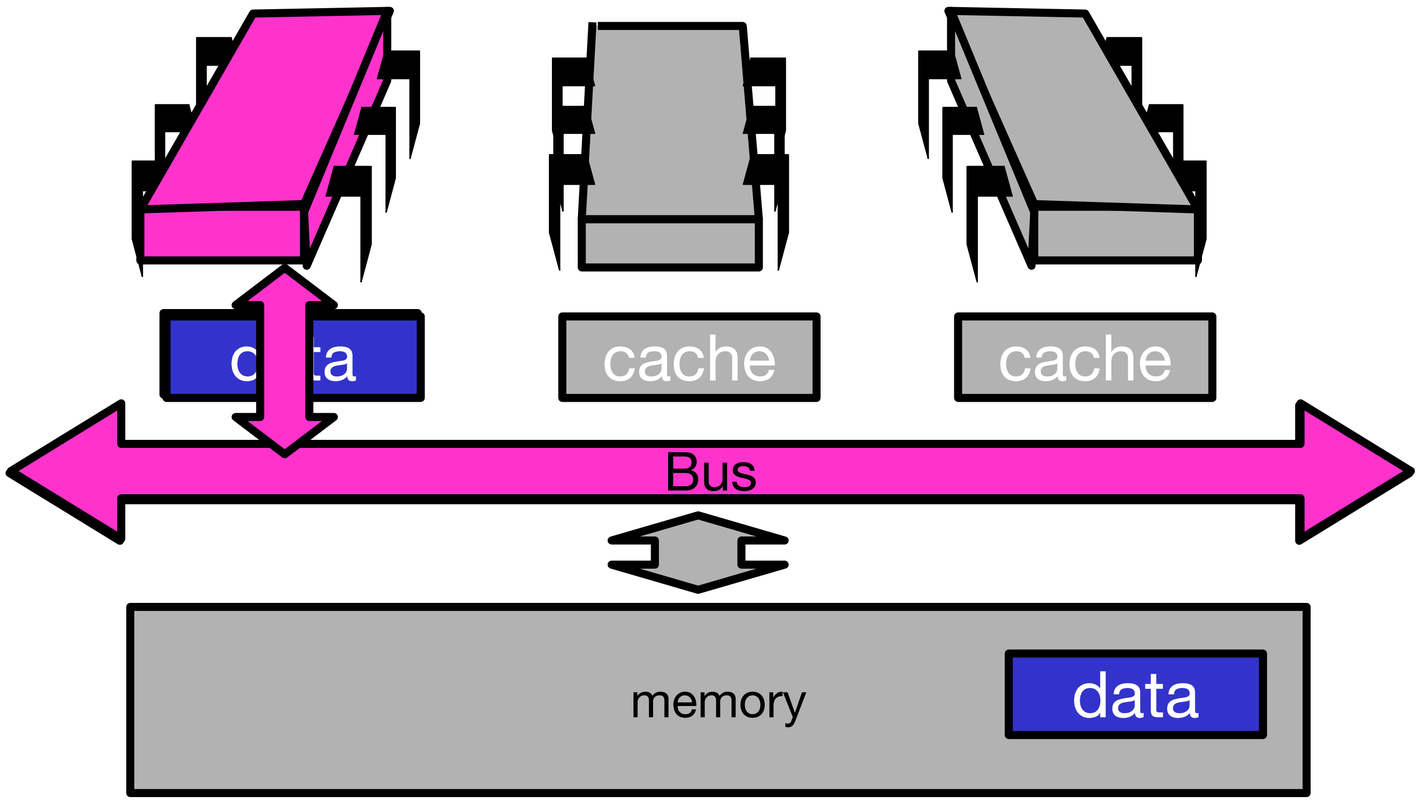


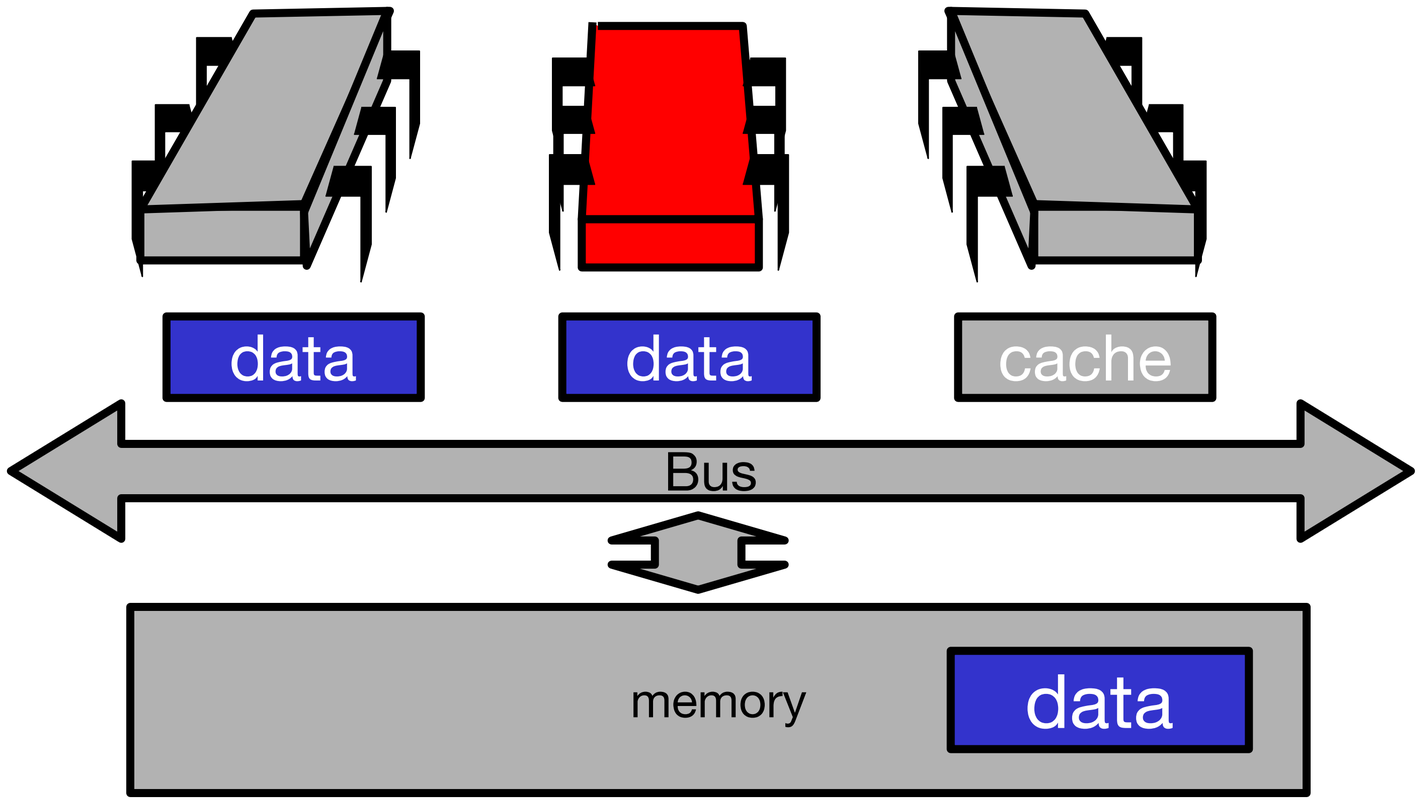
Other Processor Responds



Other Processor Responds



Modify Cached Data



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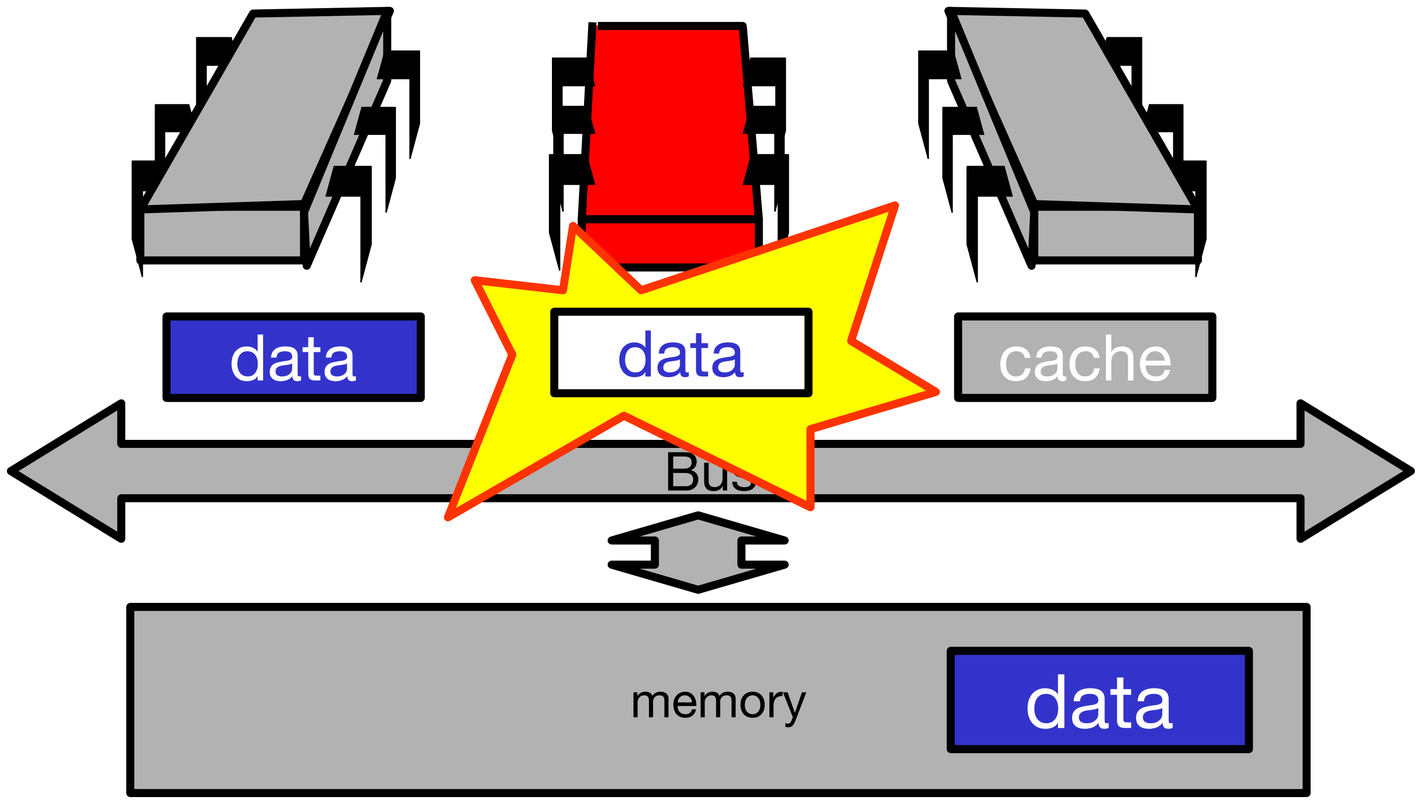

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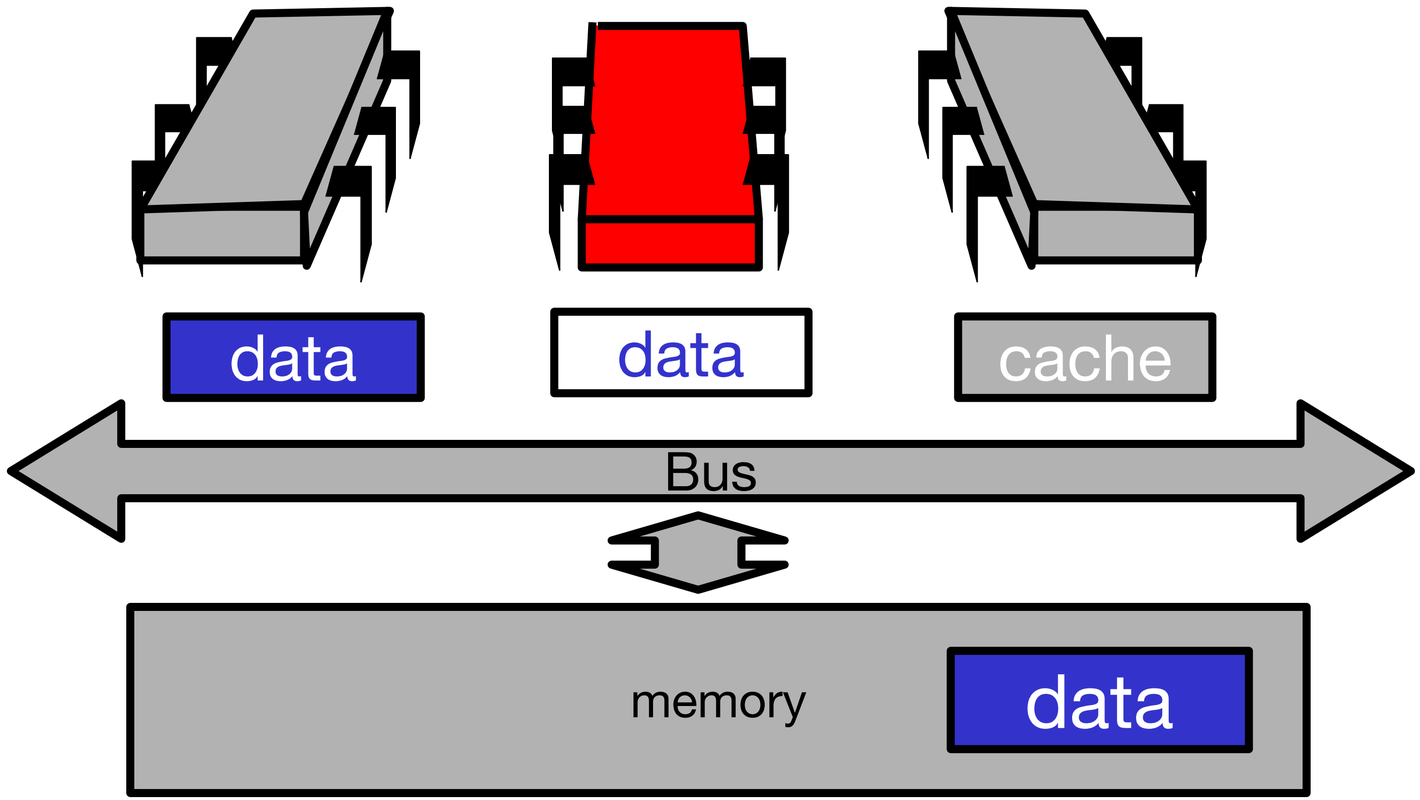

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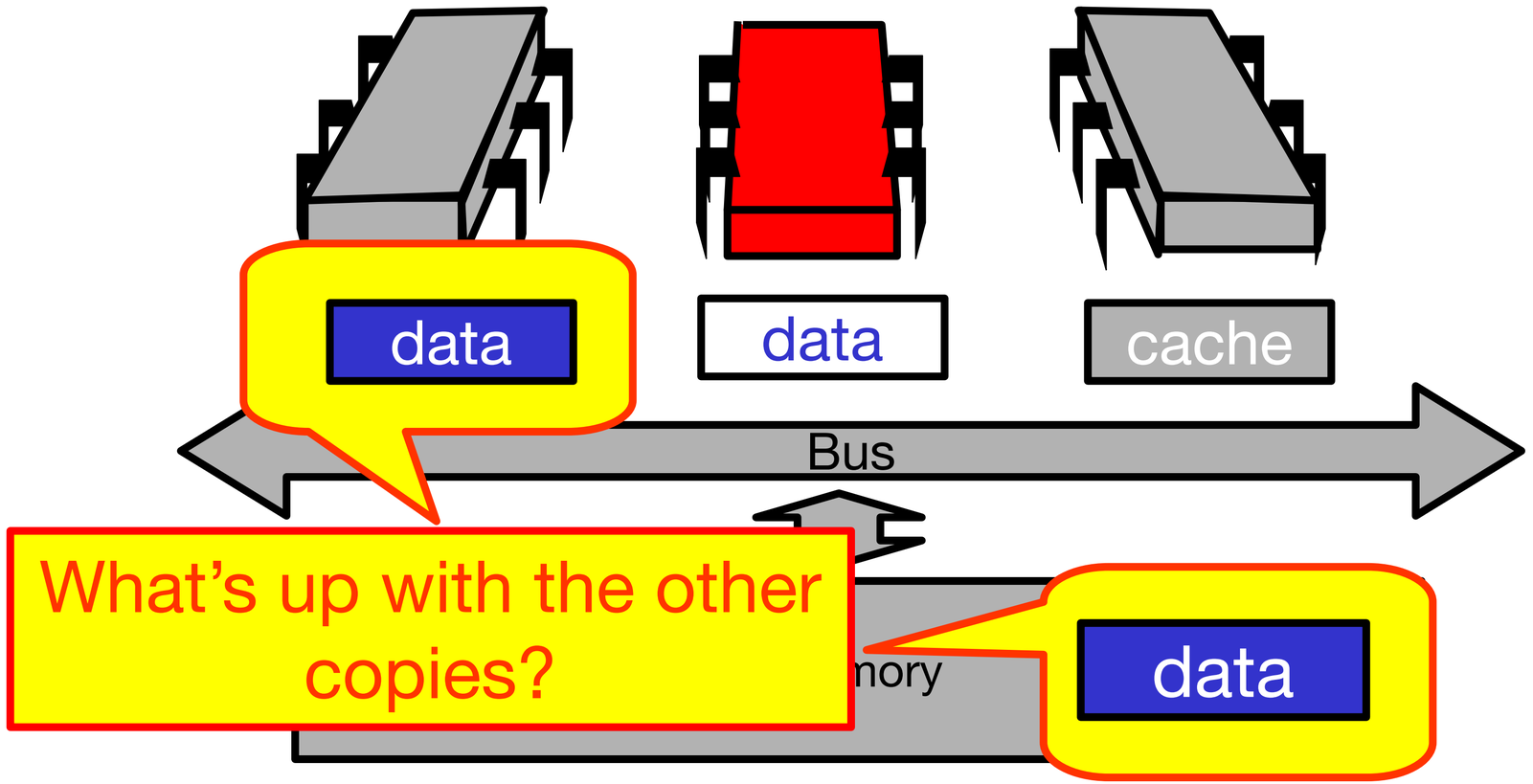


Cache Coherence

- 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?

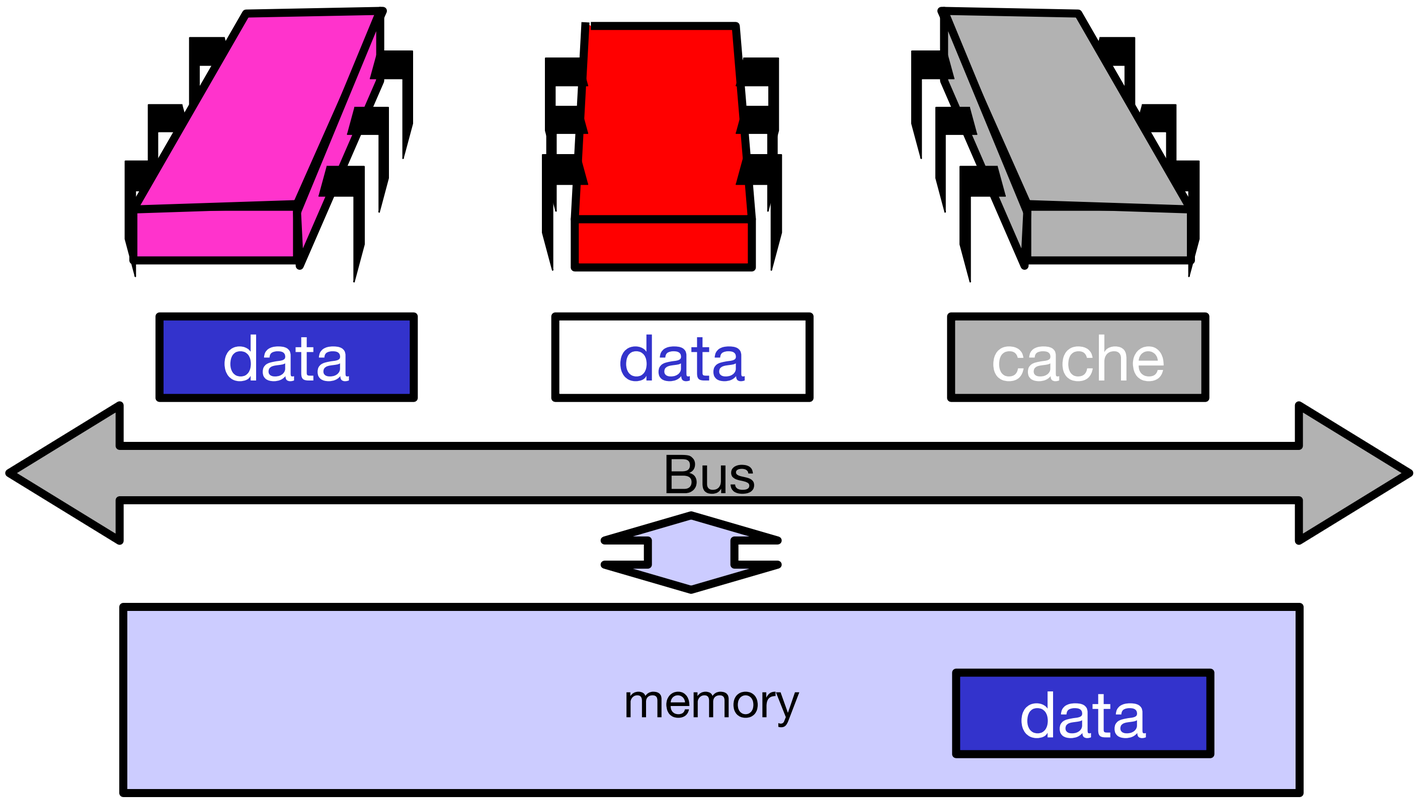
Write-Back Caches

- 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 …

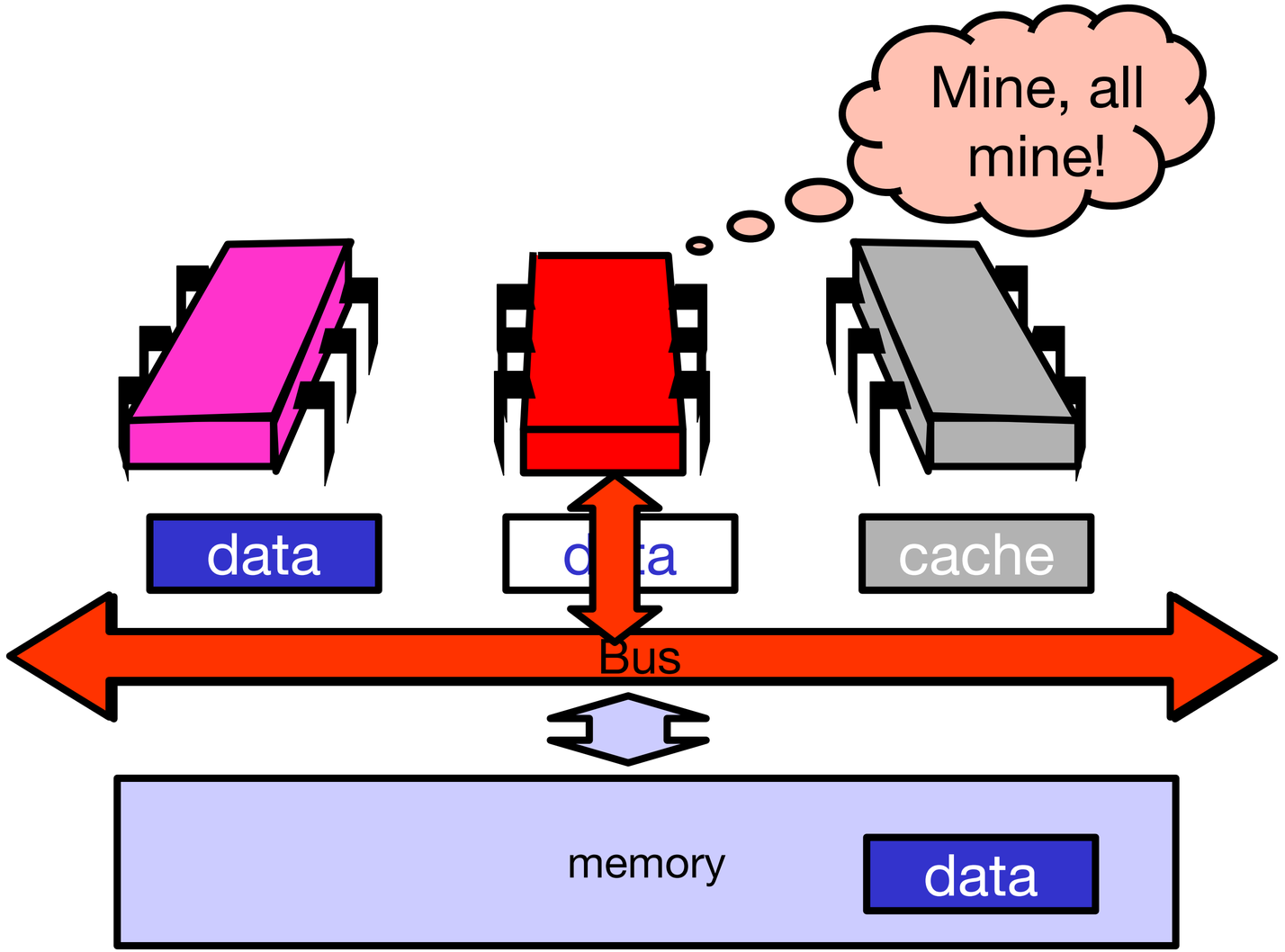
Write-Back Caches

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

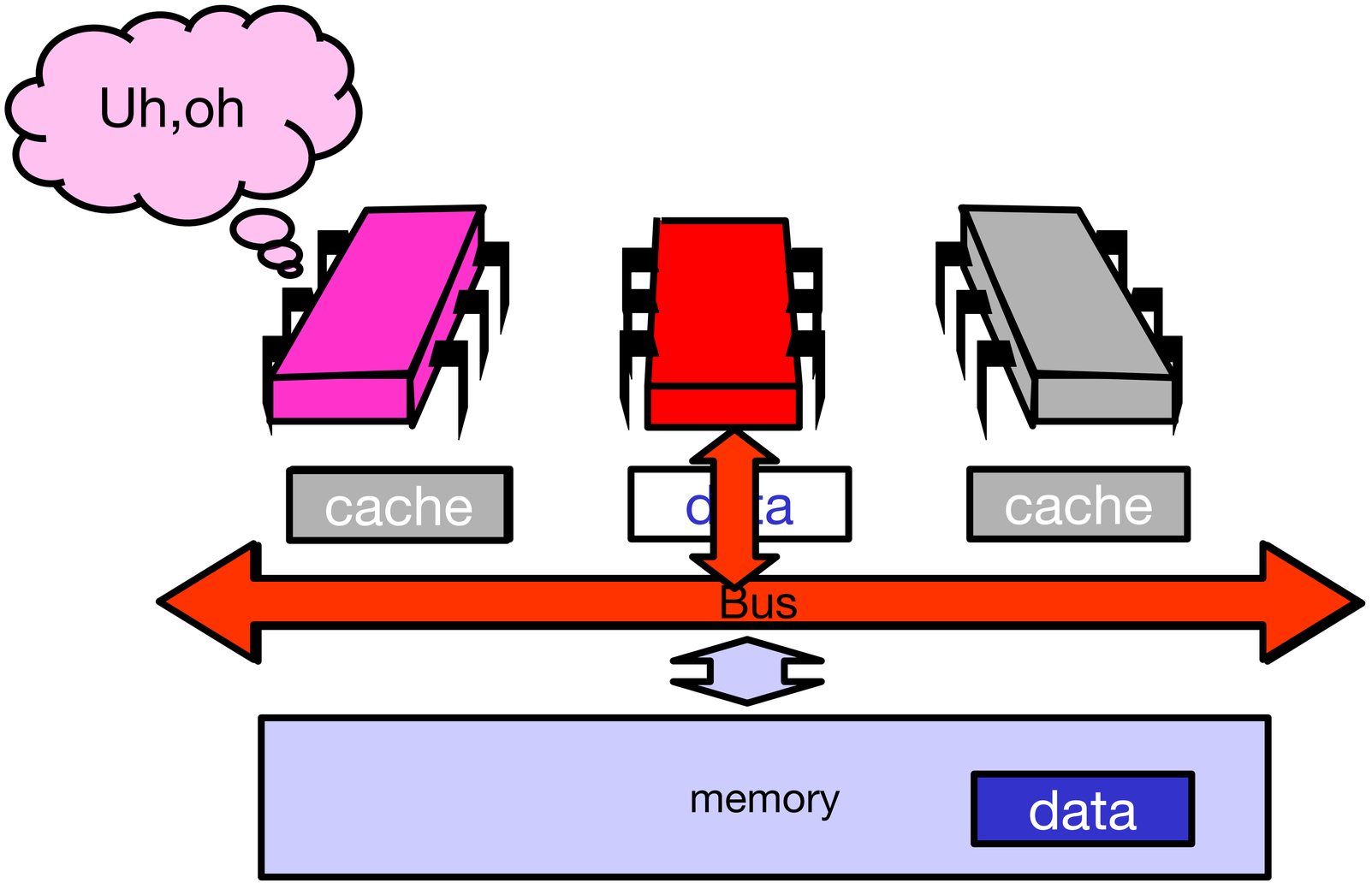
Invalidate



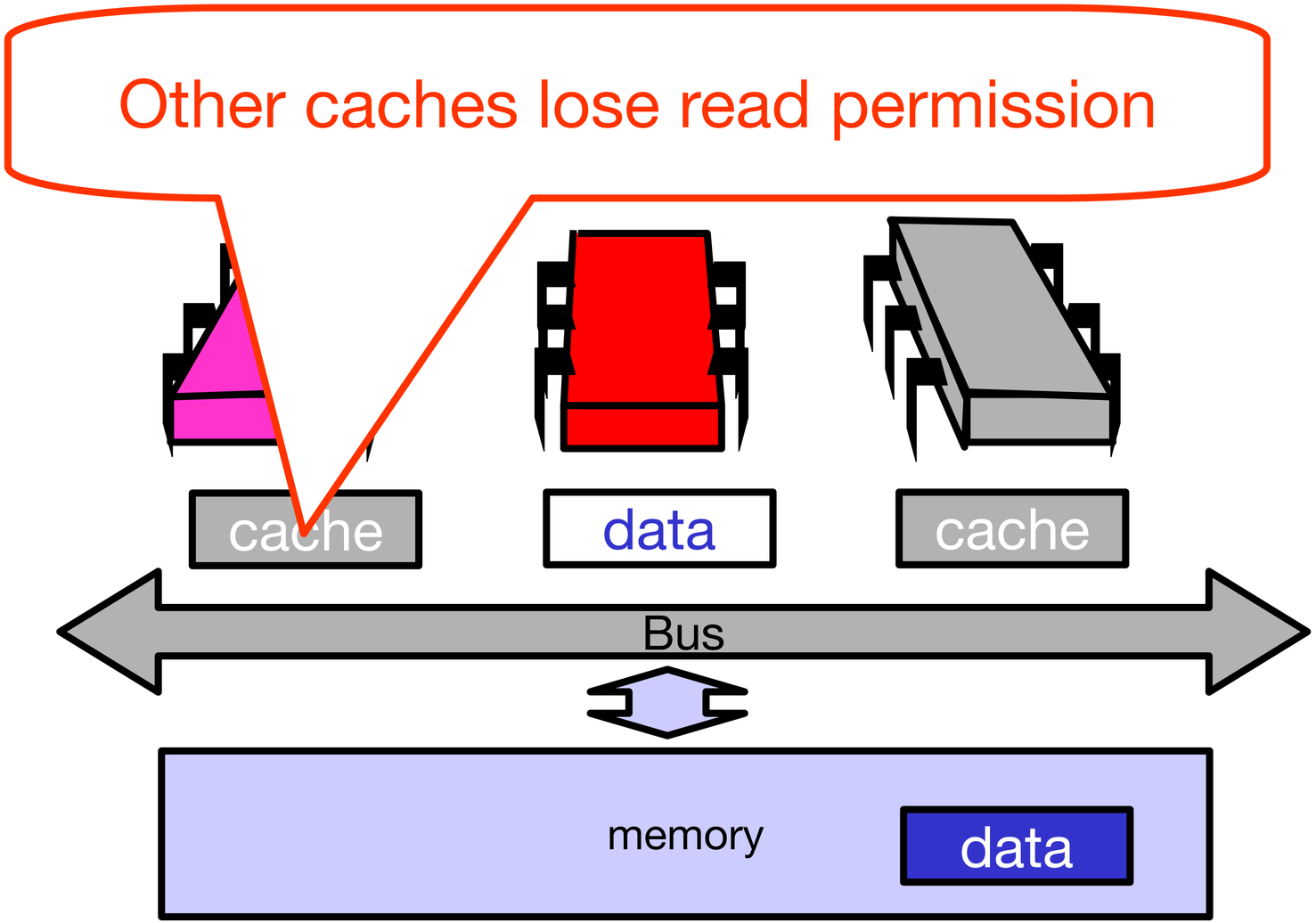
Invalidate



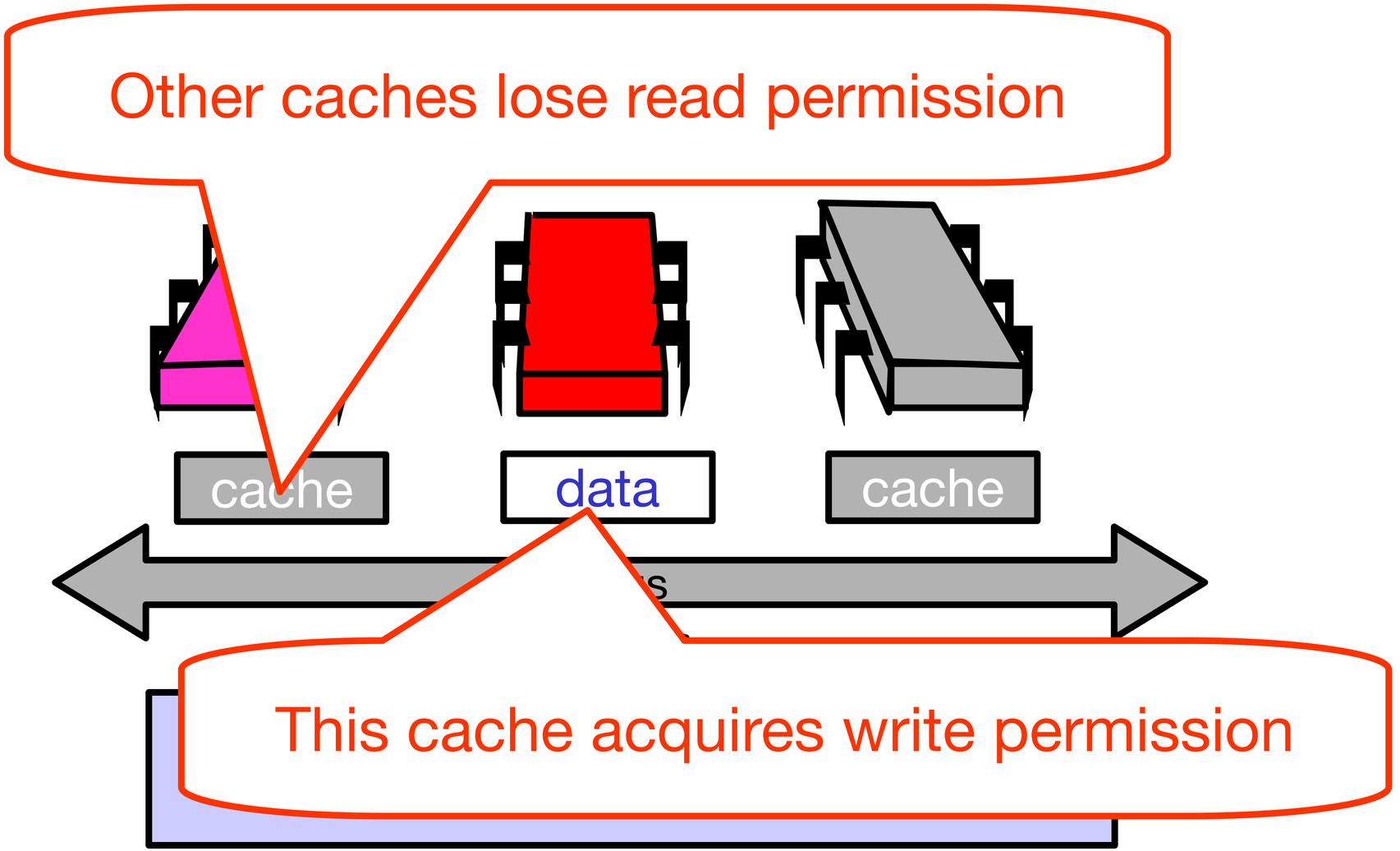
Invalidate



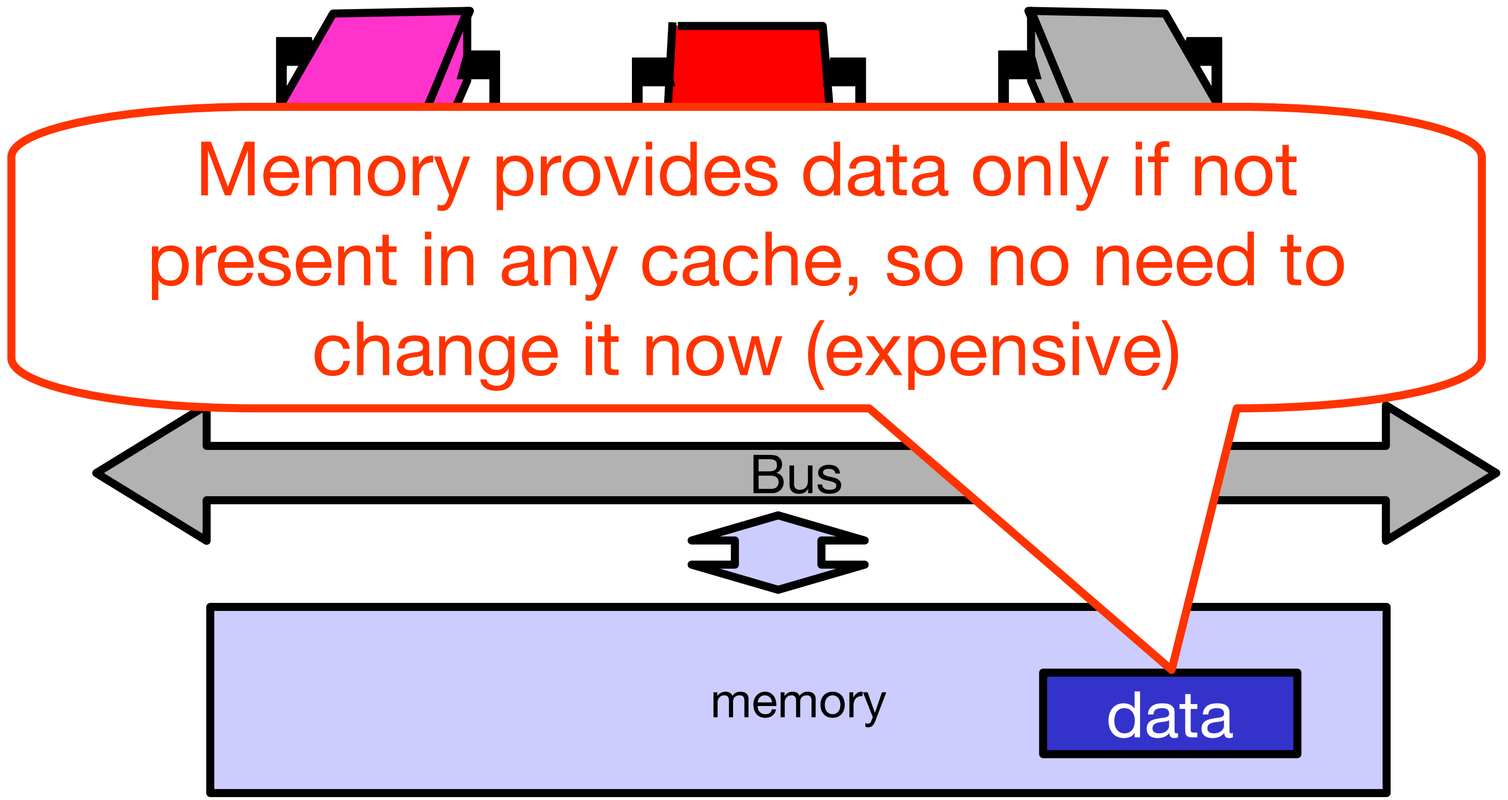
Invalidate


Other caches lose read permission
cache
data
cache
Bus
memory
data

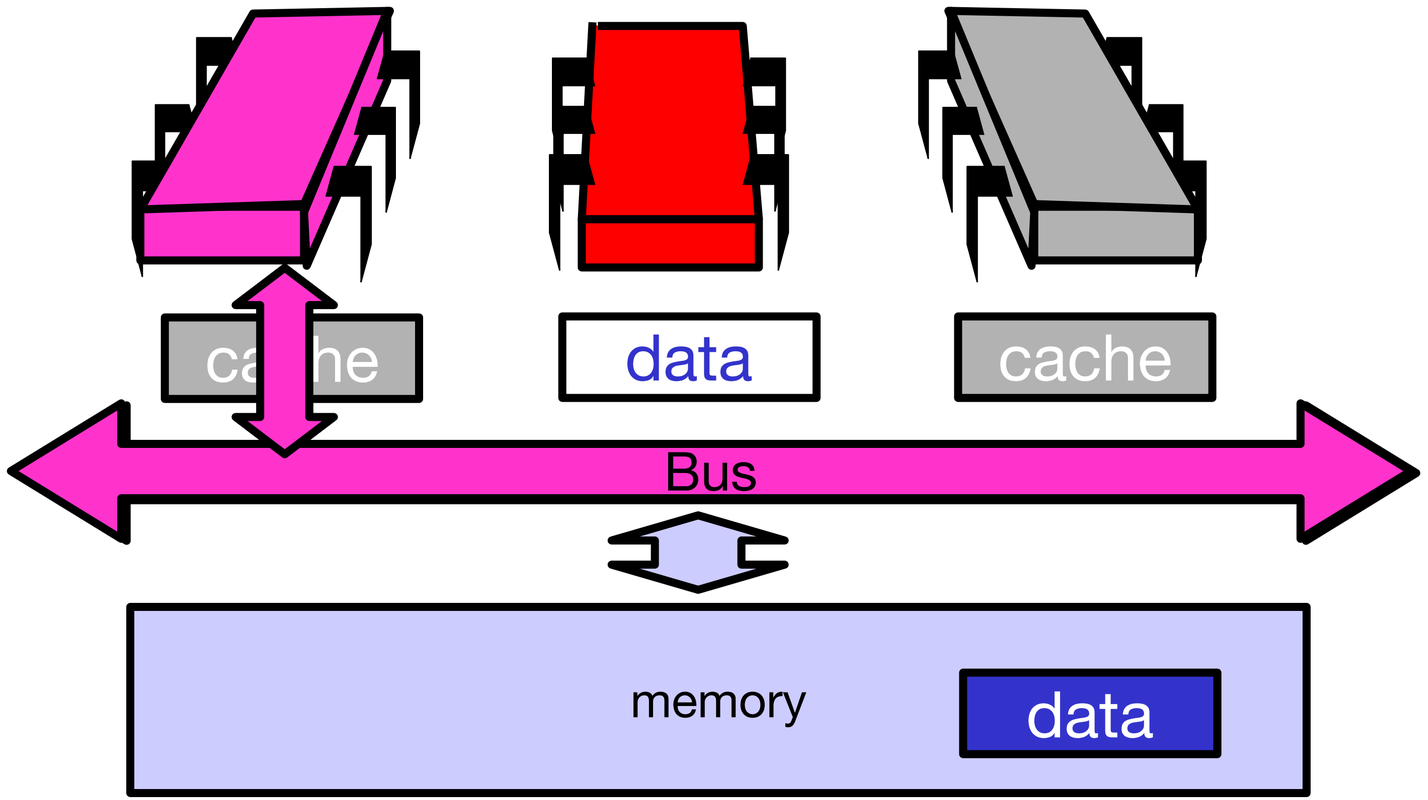
Invalidate


Other caches lose read permission
cache
data
cache
This cache acquires write permission

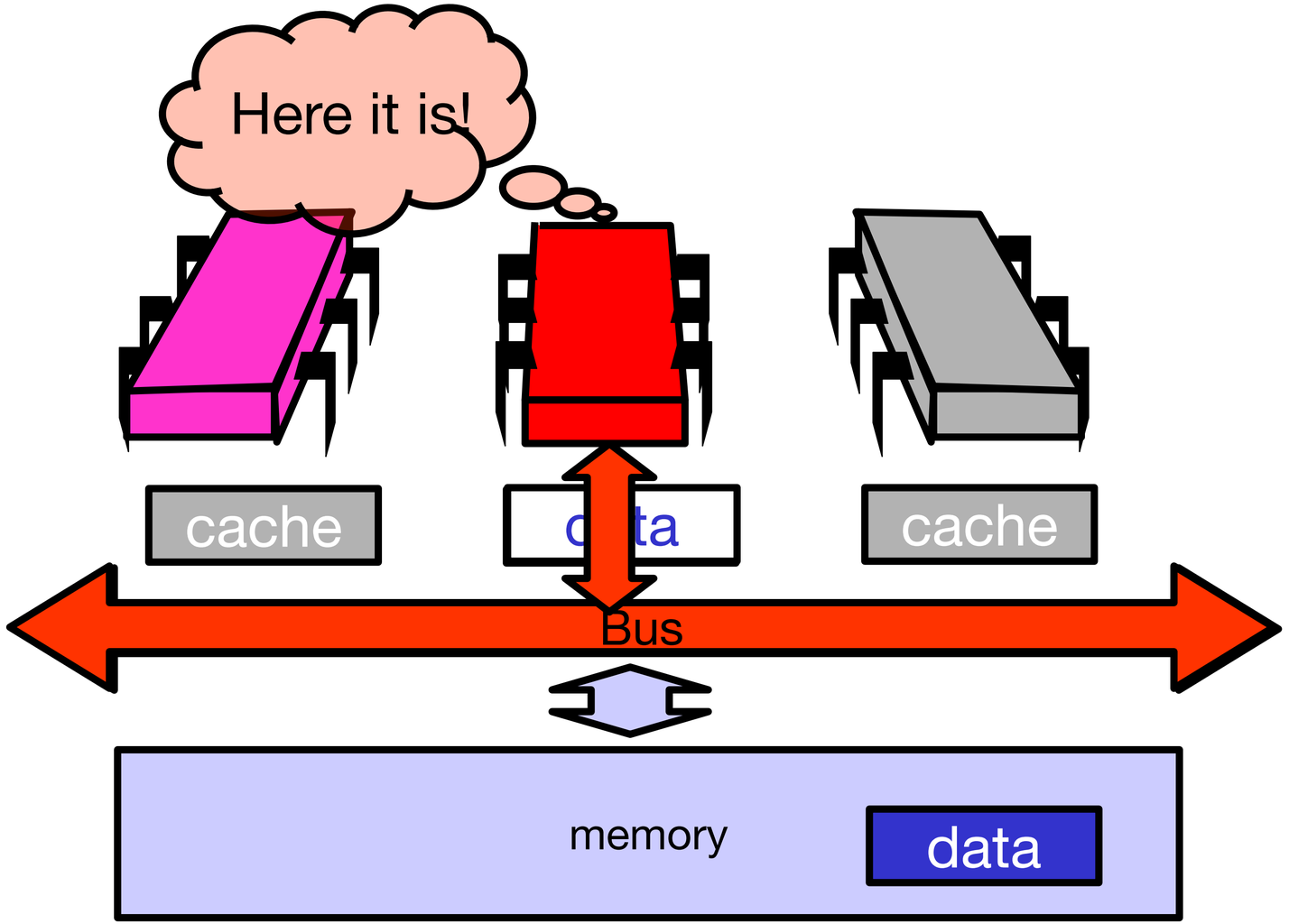
Invalidate


Memory provides data only if not present in any cache, so no need to change it now (expensive)
Bus
memory
data

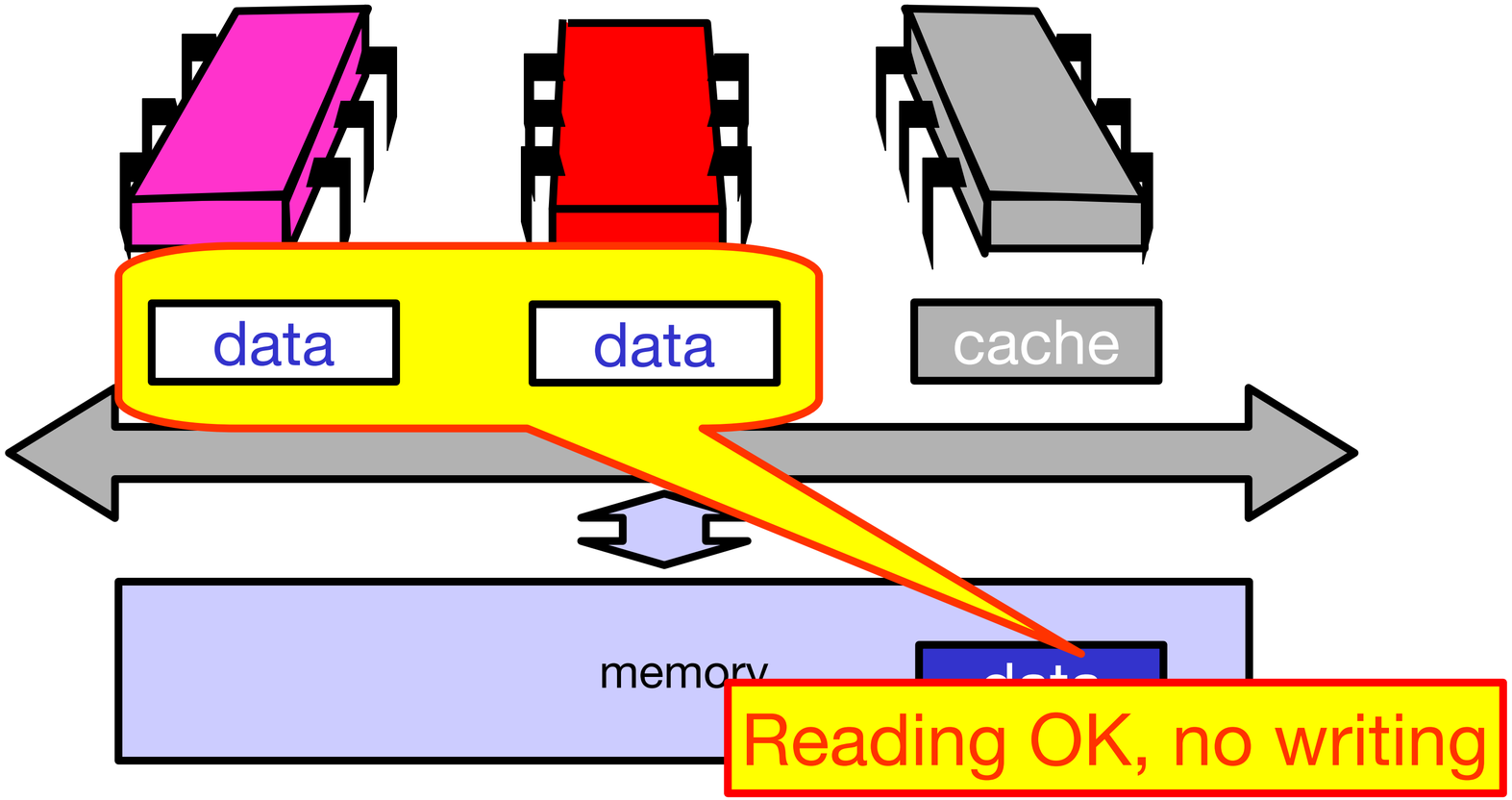
Another Processor Asks for Data



Owner Responds



End of the Day …



Mutual Exclusion

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

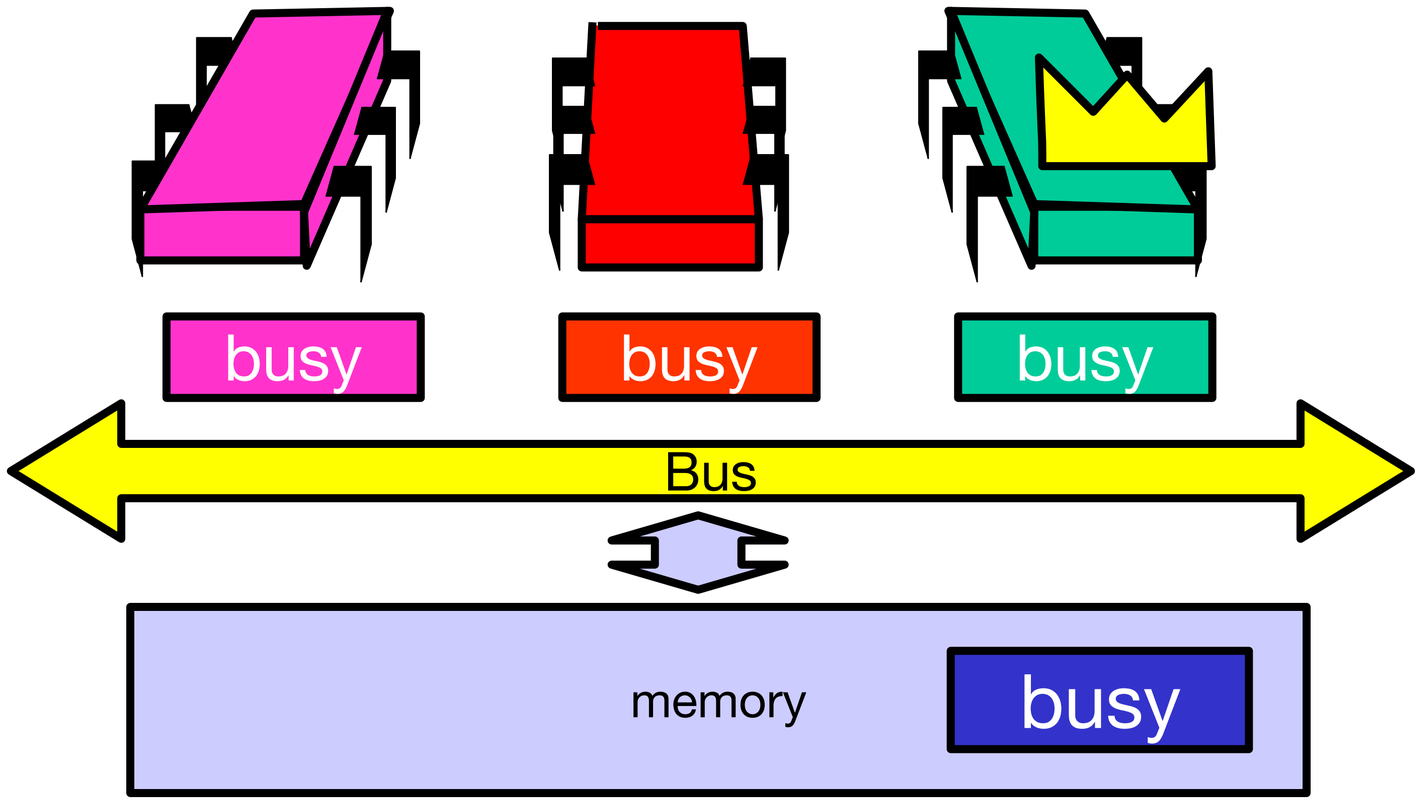
Simple TASLock

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

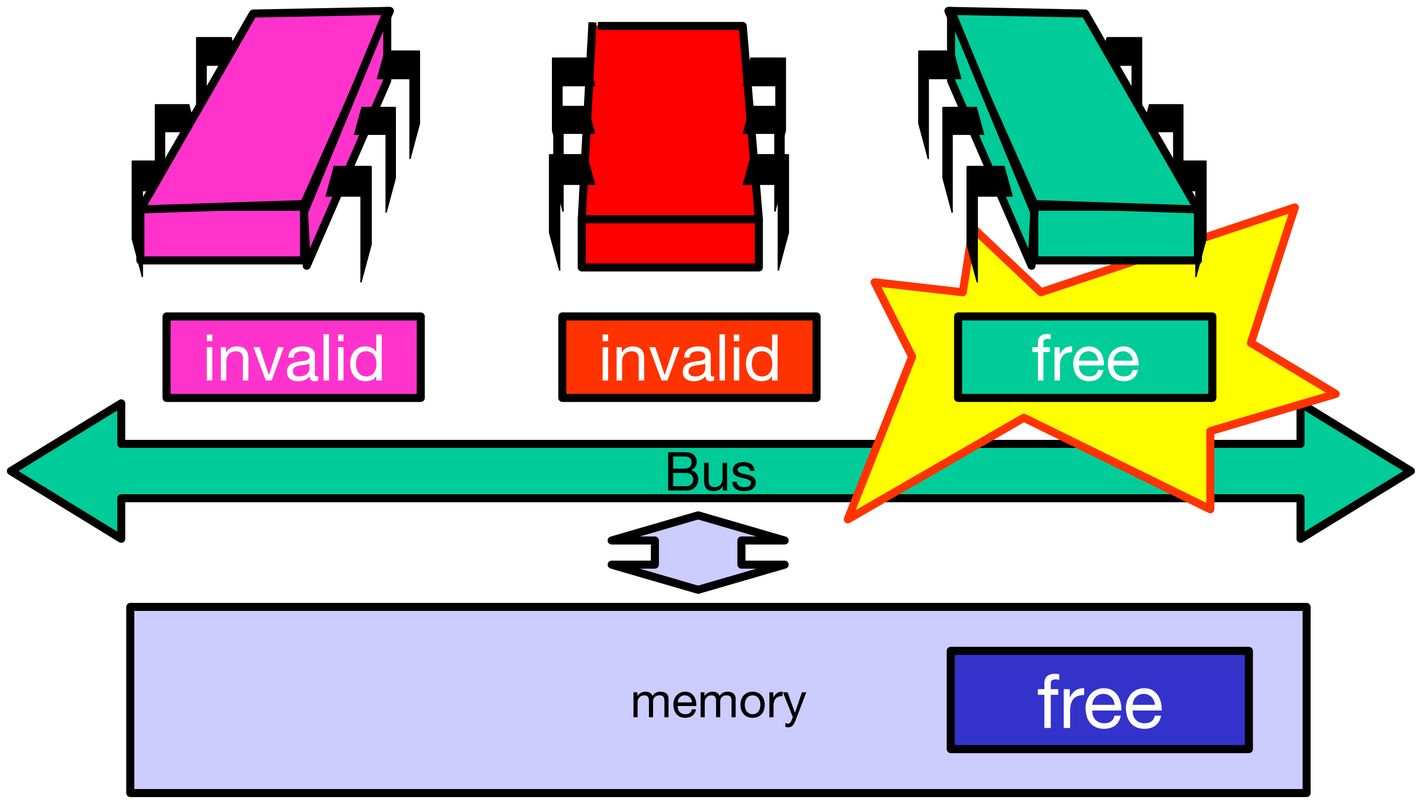
Test-and-test-and-set

- 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

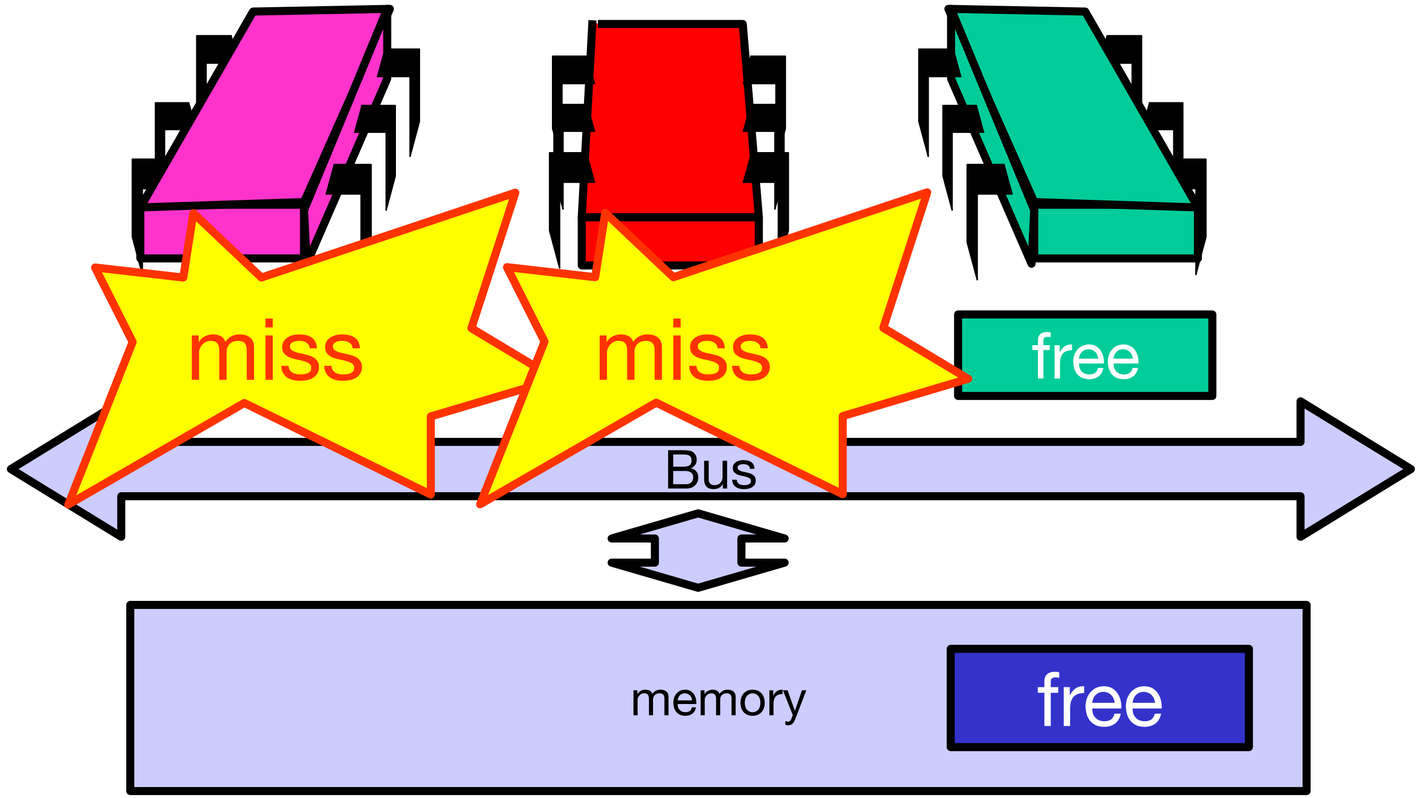


On Release



On Release

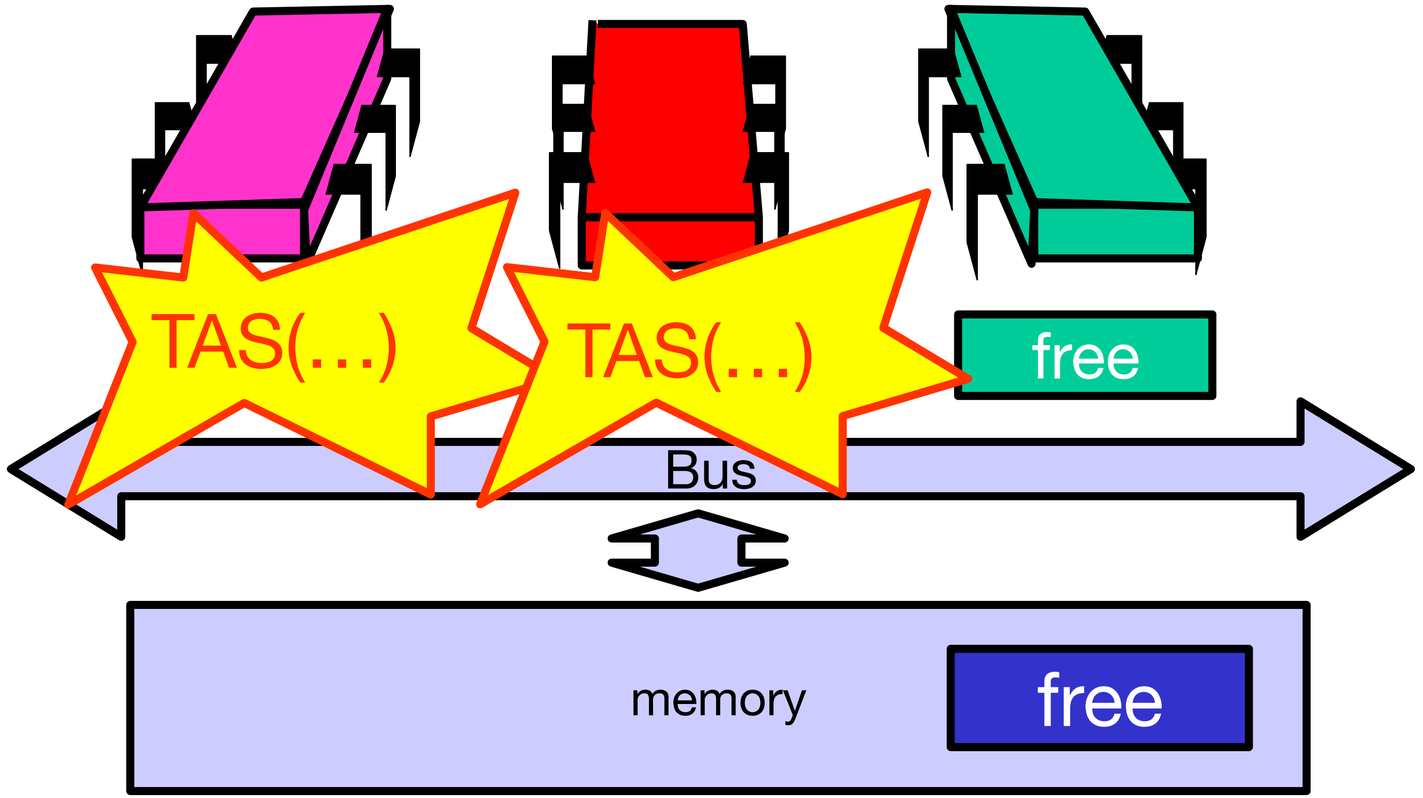
Everyone misses, rereads



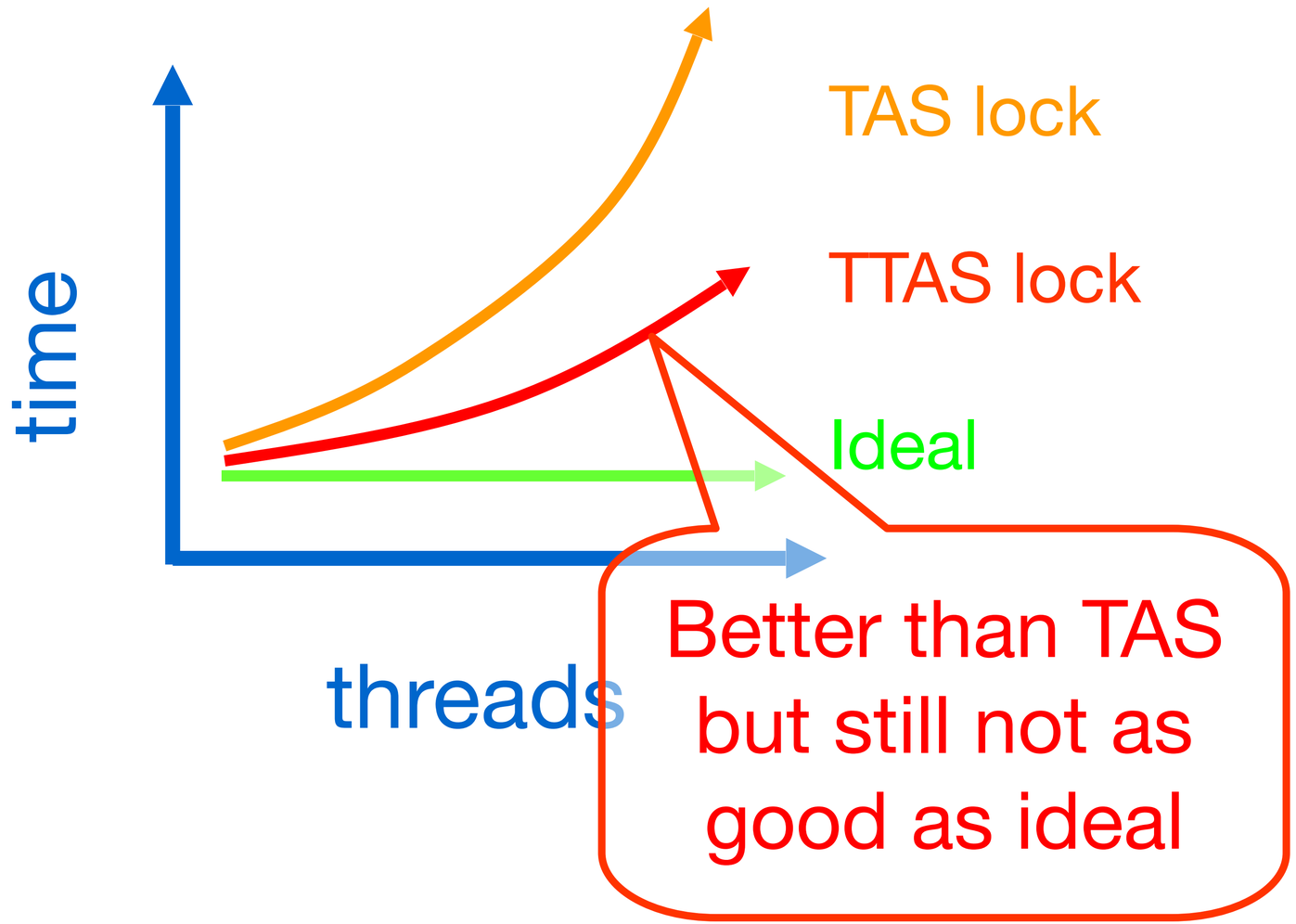
(1)

On Release

Everyone tries TAS



Mystery Explained

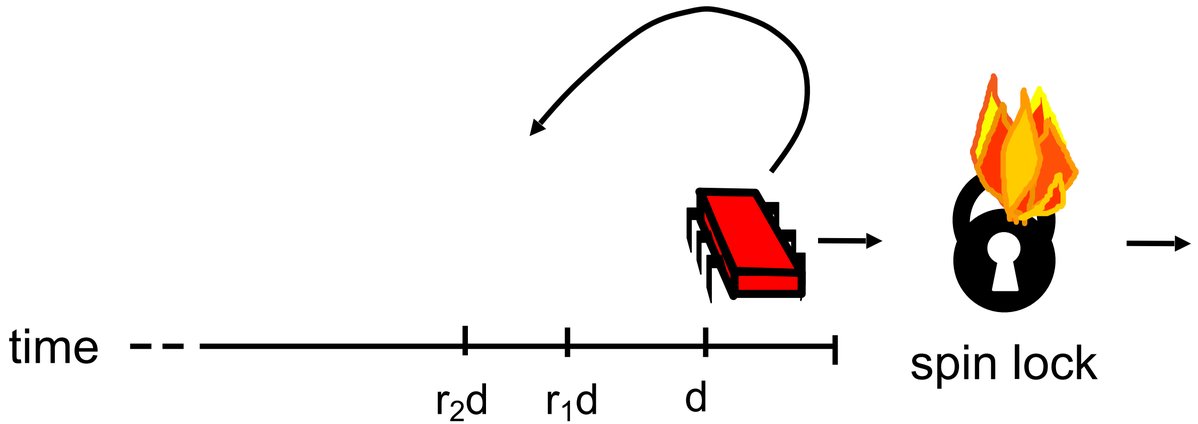


Problems

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

Solution: Introduce Delay

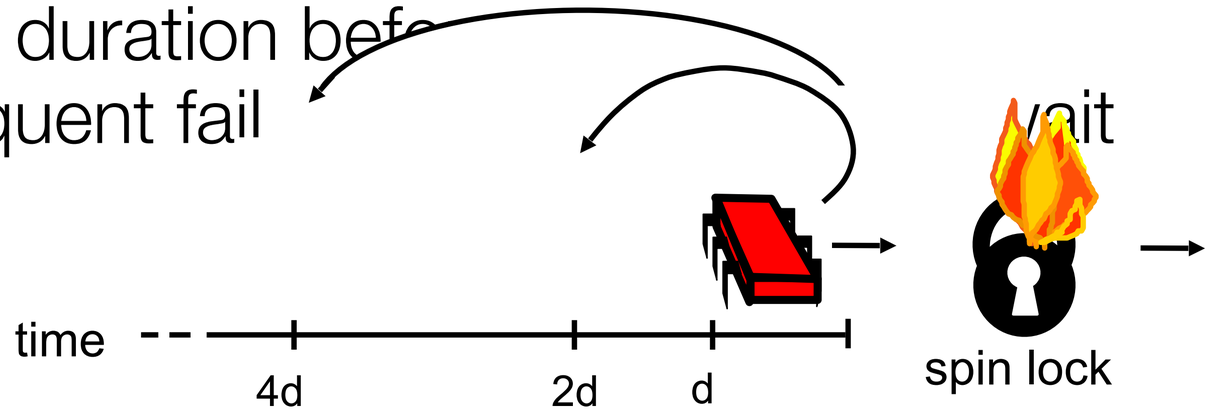
- If the lock looks free
- But I fail to get it
- There must be lots of contention
- Better to back off than to collide again



Dynamic Example: Exponential Backoff

If I fail to get lock

- wait random duration befo
- Each subsequent fail



Exponential Backoff Lock

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

Exponential Backoff Lock

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public class Backoff implements lock {
 public void lock() {
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 }}}
```

Fix minimum delay

Exponential Backoff Lock

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

Wait until lock looks free

Exponential Backoff Lock

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

If we win, return

Exponential Backoff Lock

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

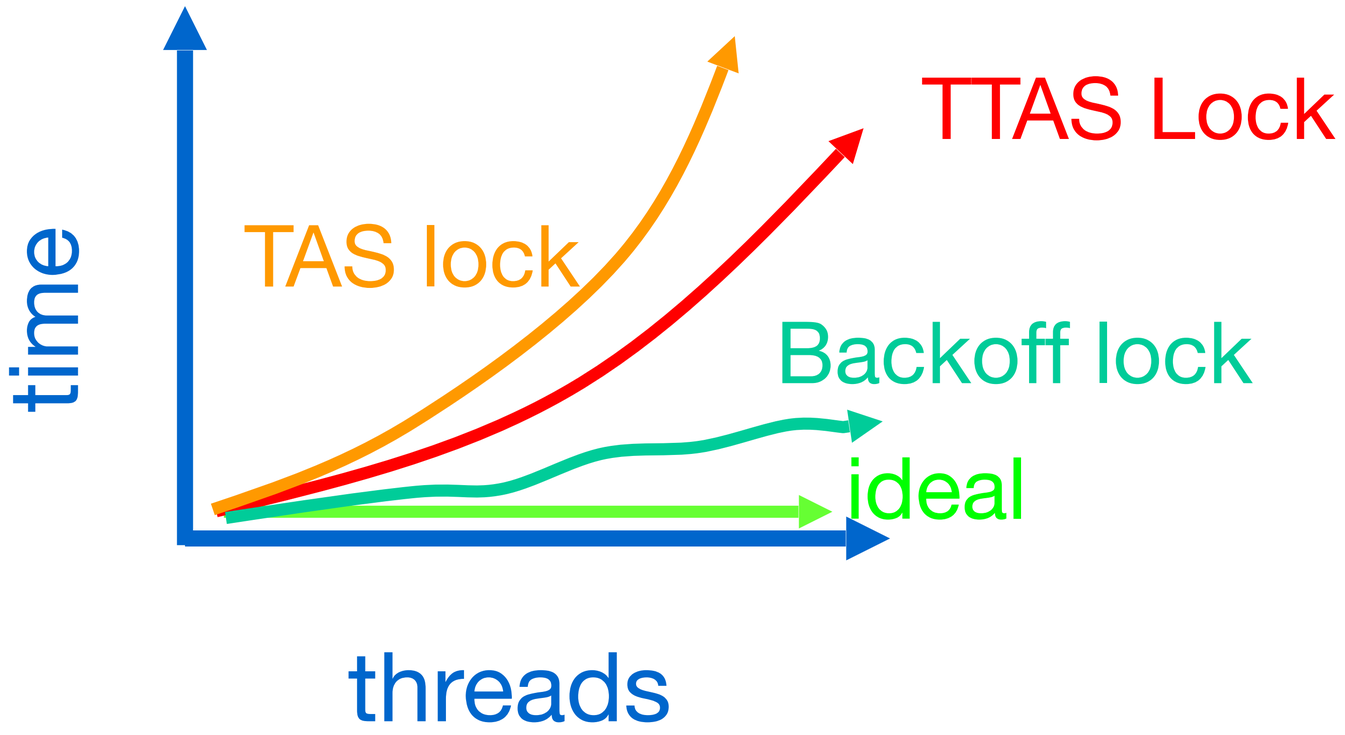
Back off for random duration

Exponential Backoff Lock

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

Double max delay, within reason

Spin-Waiting Overhead



Backoff: Other Issues

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

Moral of the story?

- EVEN IF we do pretty good with parallelizing most parts our application, we can still see slowdown from **contention** for locks
- For resources infrequently contended, spin locks can be fast because no context switch is necessary
- But, contention in spin locks can have repercussions due to hardware architectures

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