

04 Spin Locks and Contention

CS 6868: Concurrent Programming

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Focus so far: Correctness

- Models
 - Accurate (*we never lied to you*)
 - But idealised (*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*)

Kinds of Architectures

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

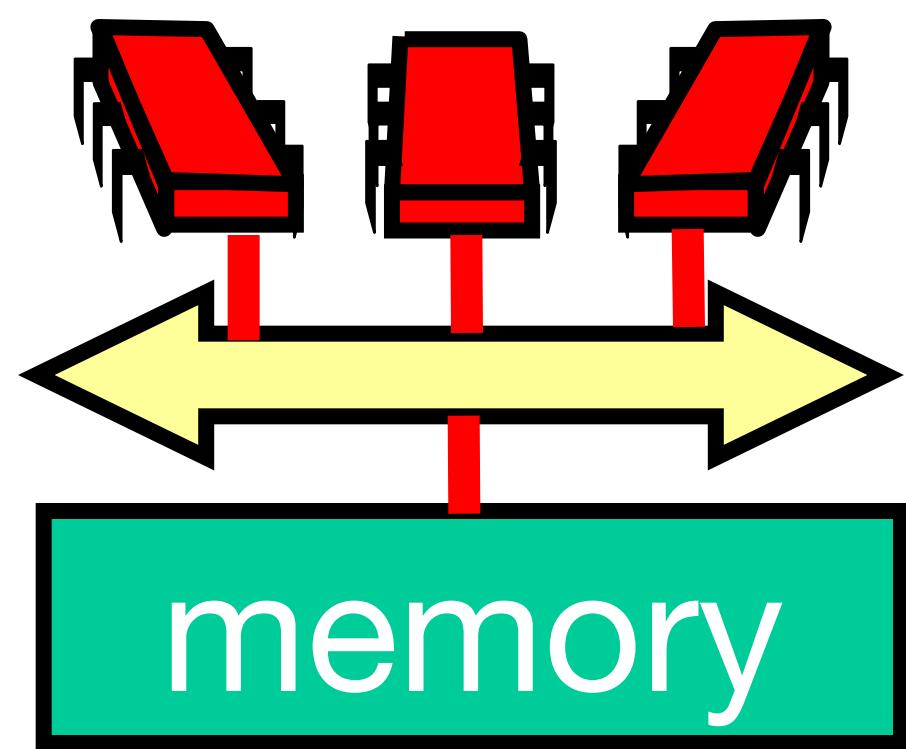
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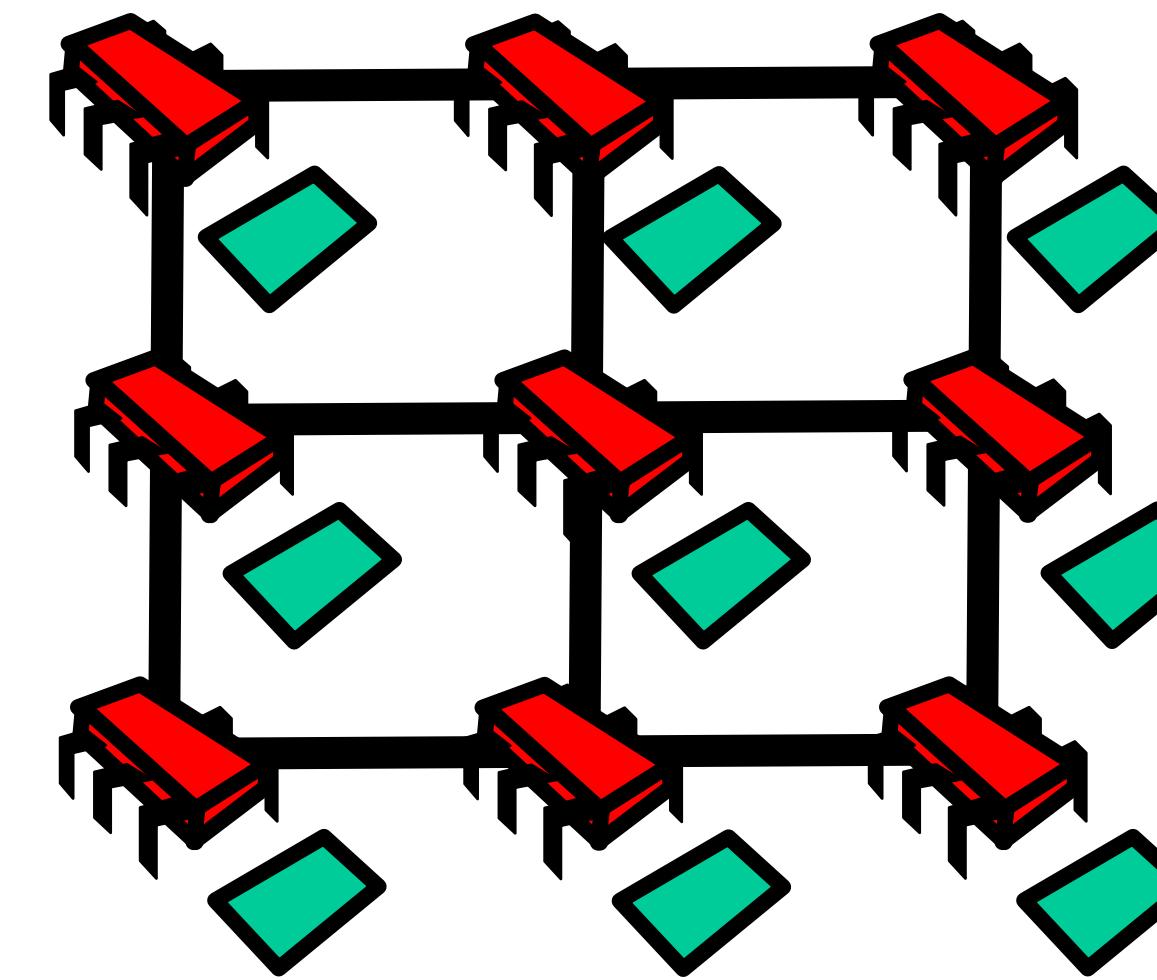


Our Focus

MIMD Architectures



Shared Bus



Distributed

- Memory Contention
- Communication Contention
- Communication Latency

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?

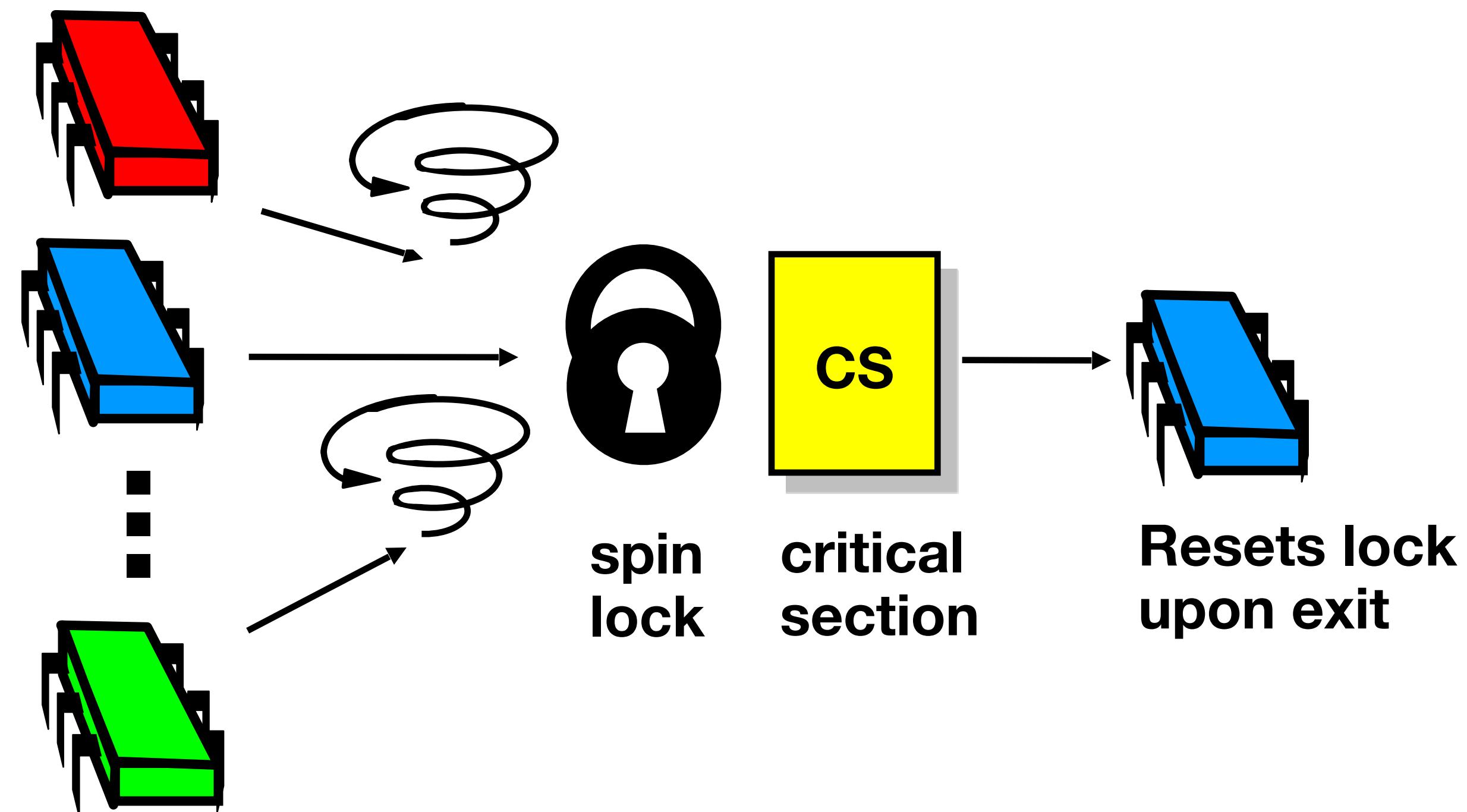
- Keep trying
 - “spin” or “busy-wait”
 - Good if delays are short
- Give up the processor
 - Good if delays are long
 - Always good on uniprocessor

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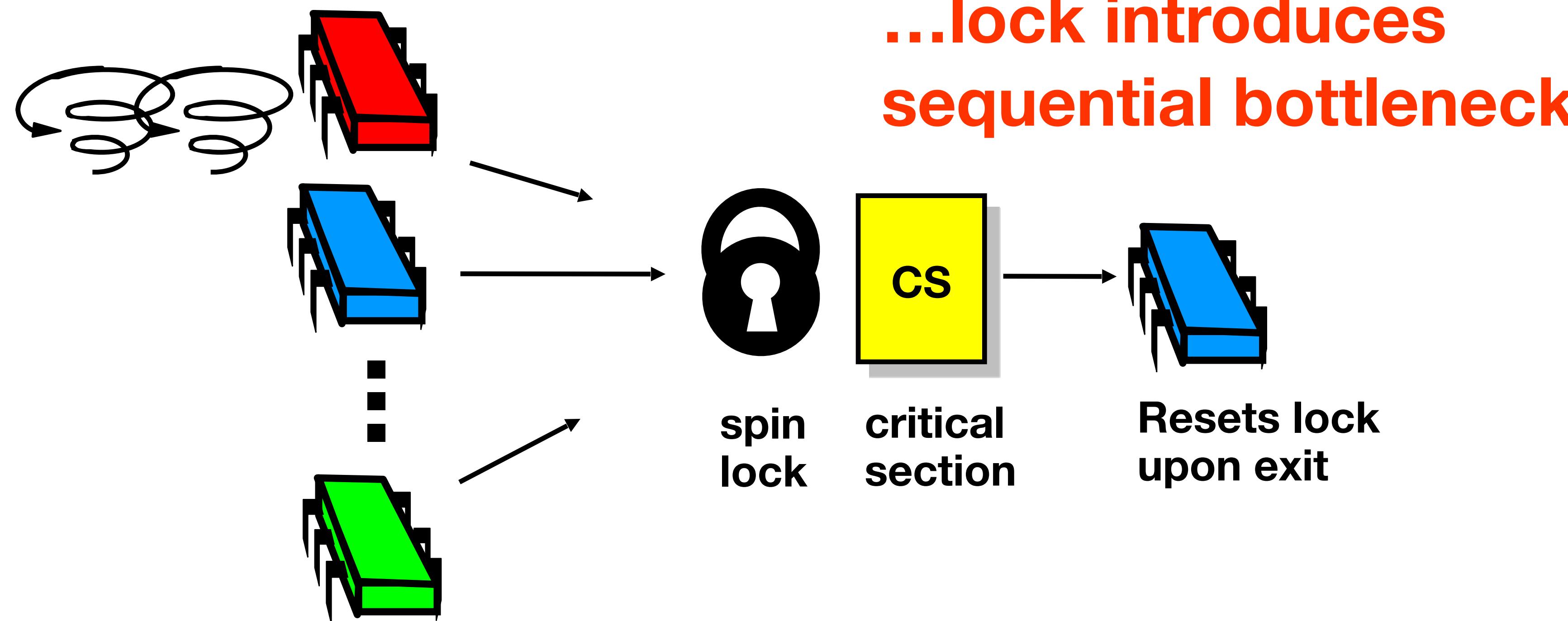
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Our Focus

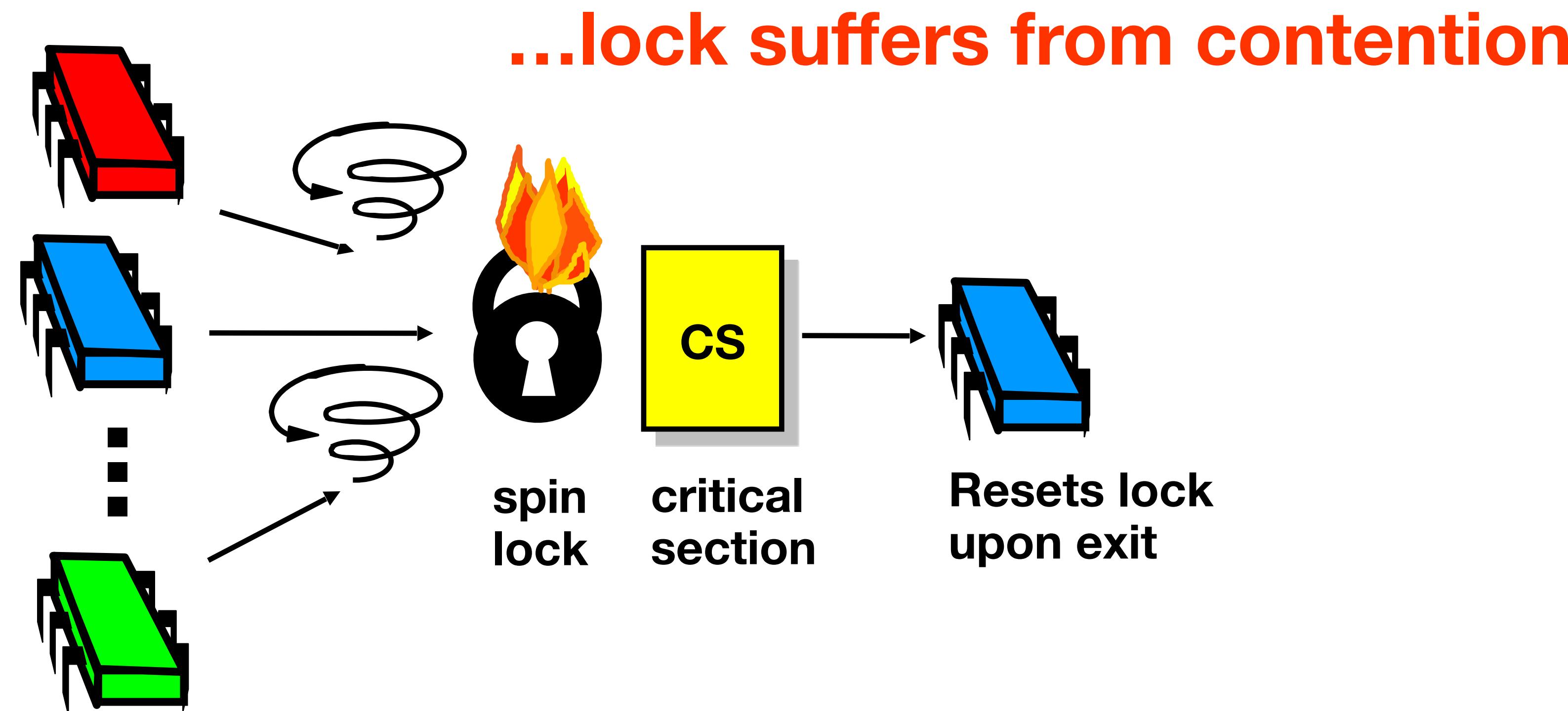
Basic Spin Lock



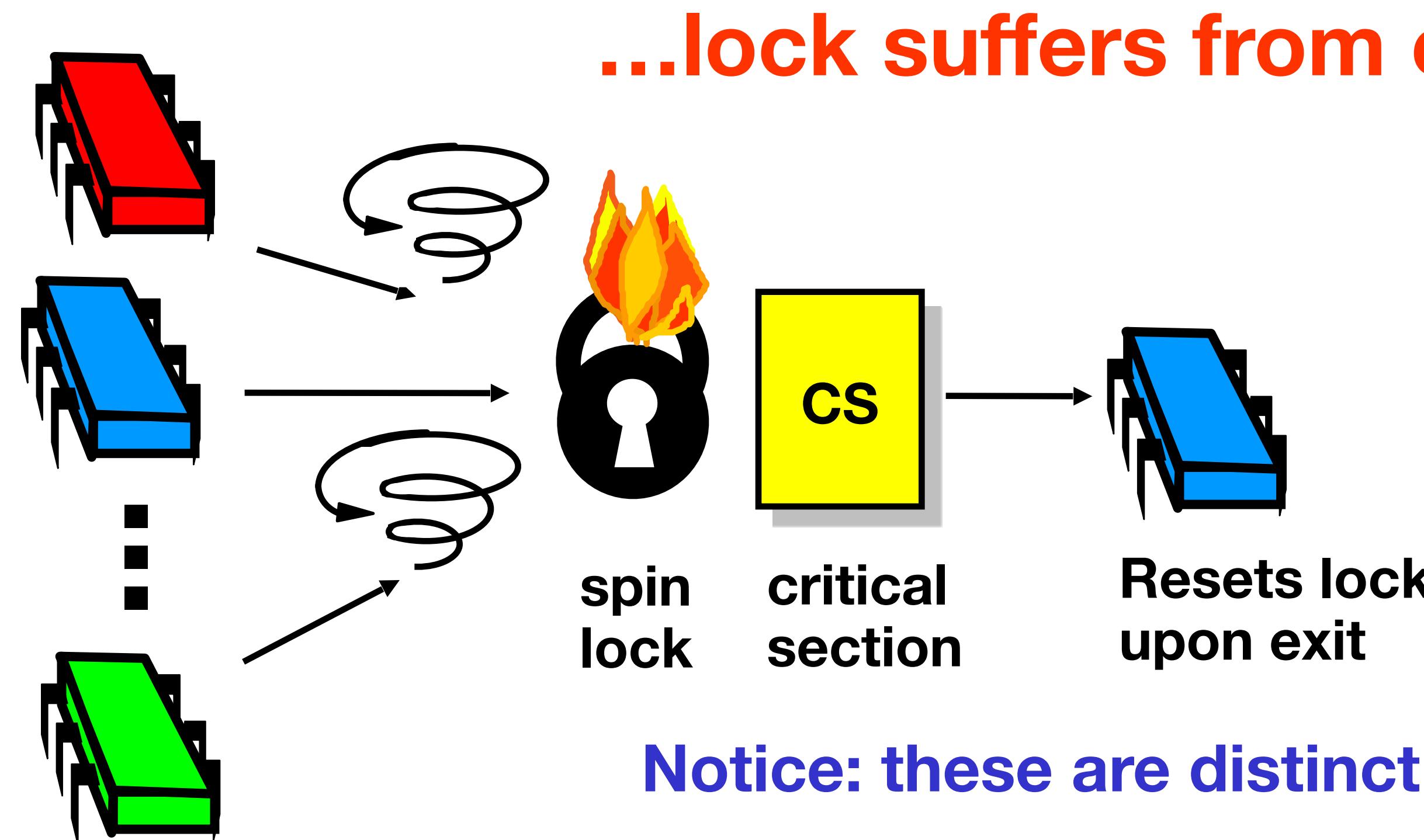
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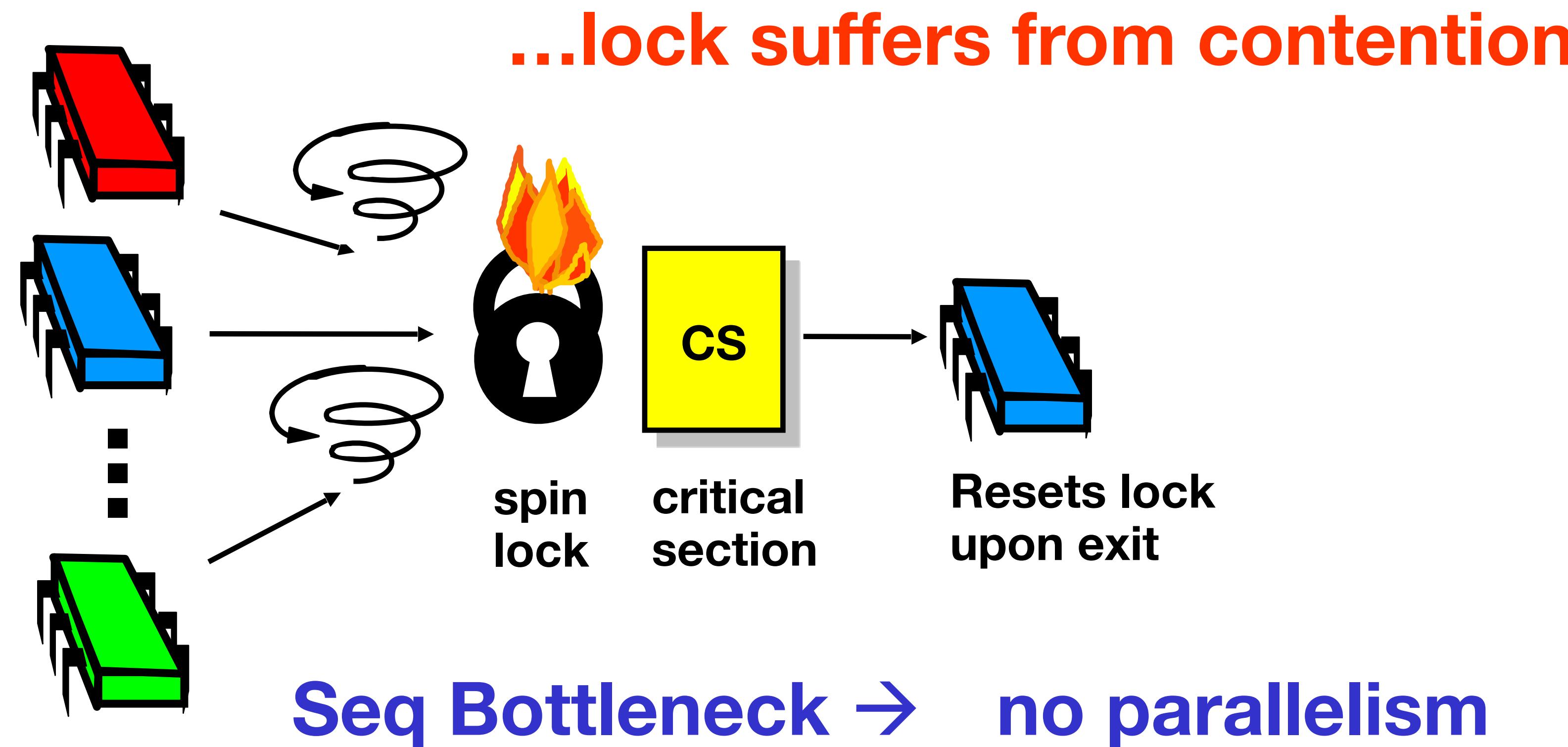
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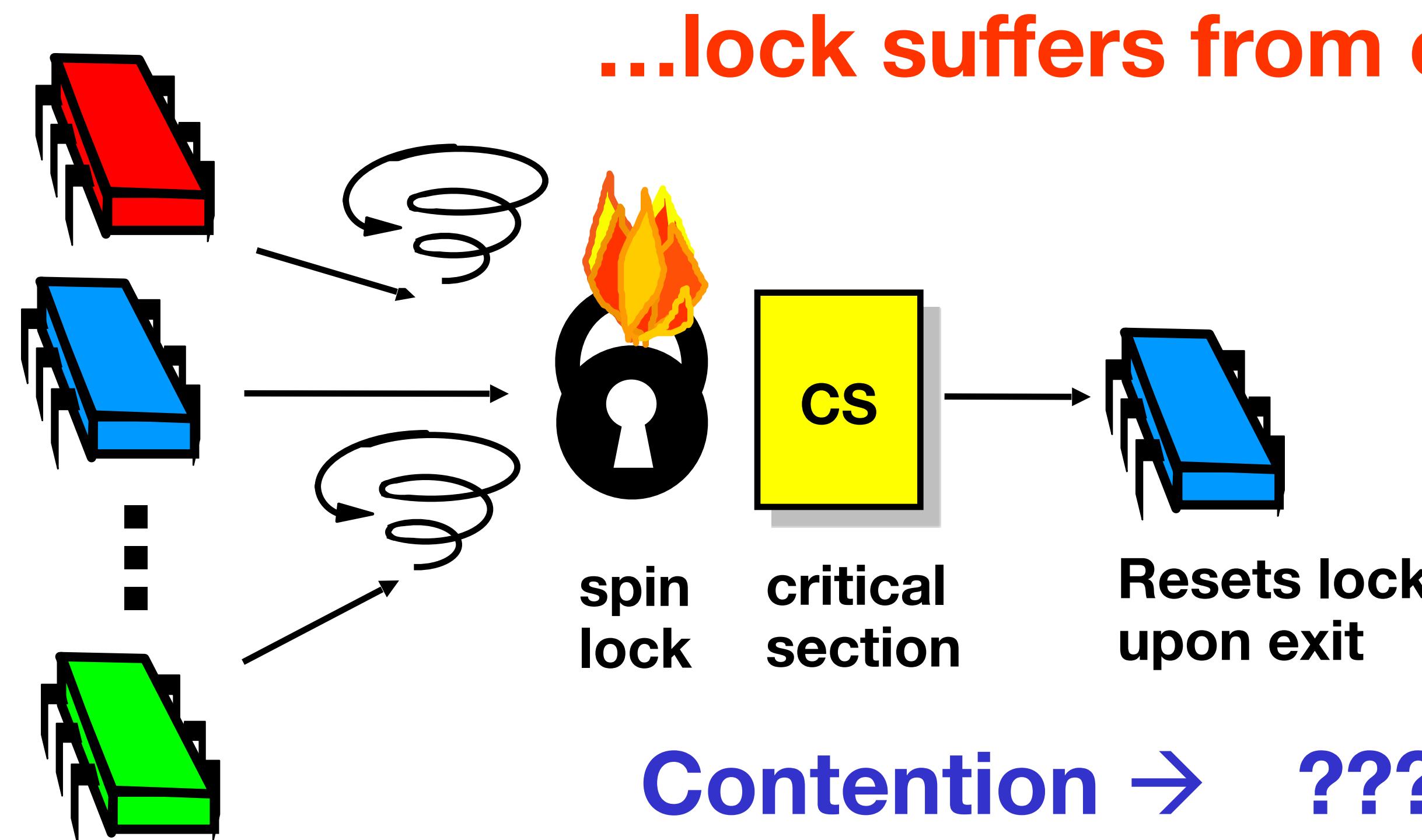
Basic Spin Lock



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 “exchange”

`Atomic.exchange : 'a Atomic.t -> 'a -> 'a`

is semantically equivalent to

```
let exchange (r : 'a Atomic.t) (v : 'a) : 'a =
  let old = Atomic.get r in
  Atomic.set r v;
  old
```

but atomic

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 (TASLock)

```
module TASLock : Lock.LOCK = struct
  type t = { state : bool Atomic.t }

  let create () = { state = Atomic.make false }

  let lock t =
    (* Keep spinning until we successfully acquire the lock *)
    (* Atomic.exchange sets the value and returns the old value *)
    while Atomic.exchange t.state true do
      (* Spin – this is where the thread wastes CPU cycles *)
      ()
    done

  let unlock t = Atomic.set t.state false
end
```

Demo

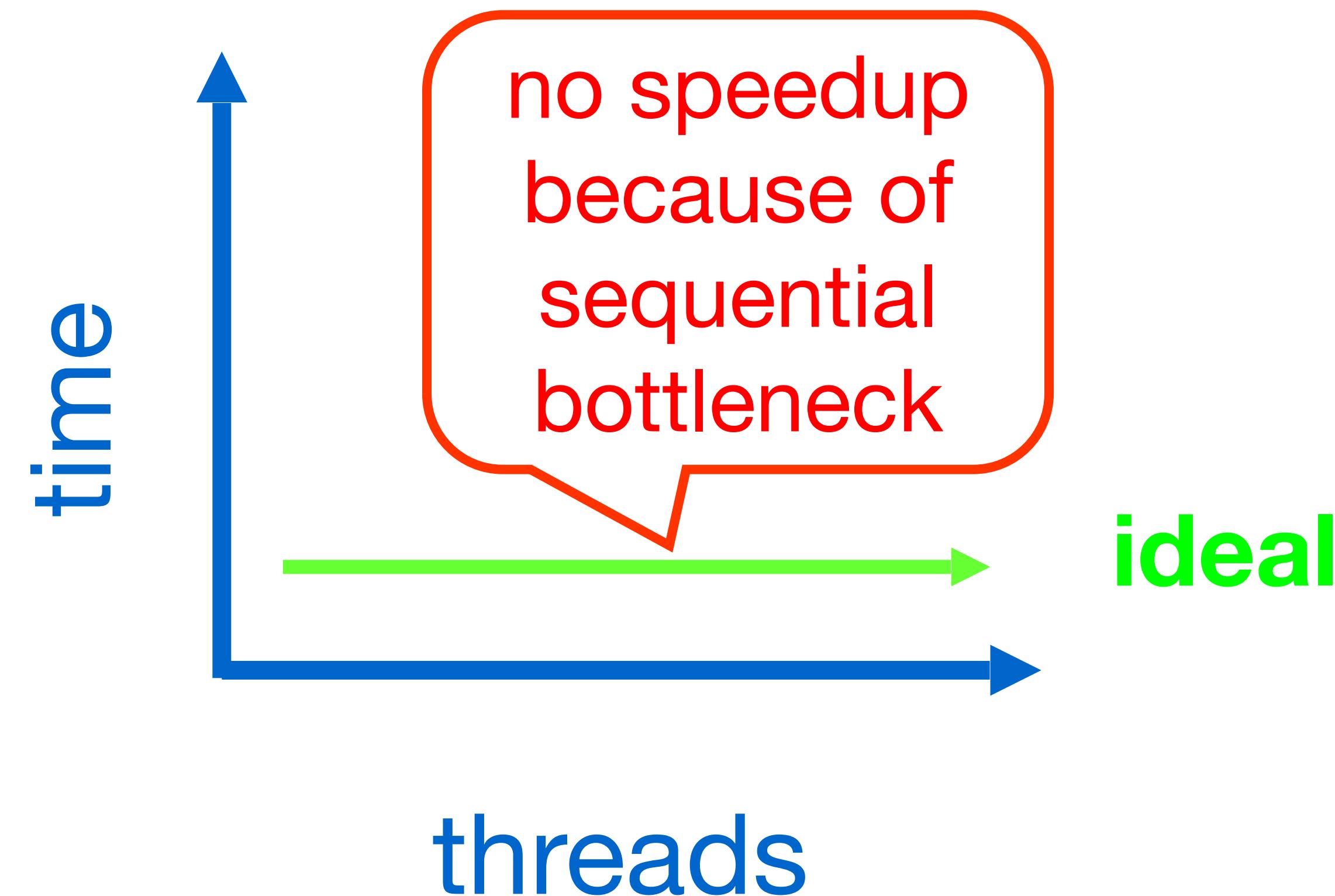
Space Complexity

- TAS spin-lock has a 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 an RMW operation...

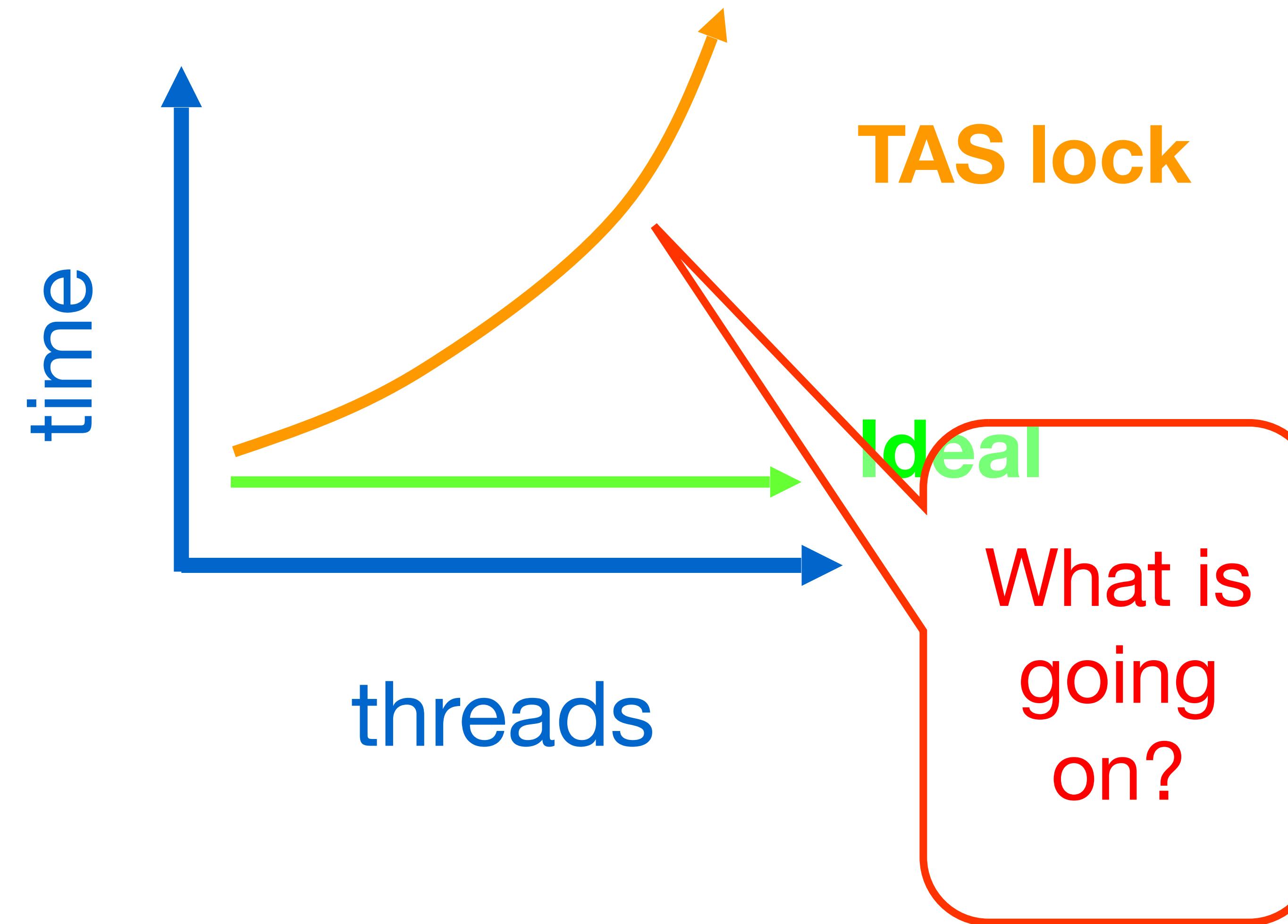
Space Complexity

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

Time taken



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

```
module TTASLock : Lock.LOCK = struct
  type t = { state : bool Atomic.t }

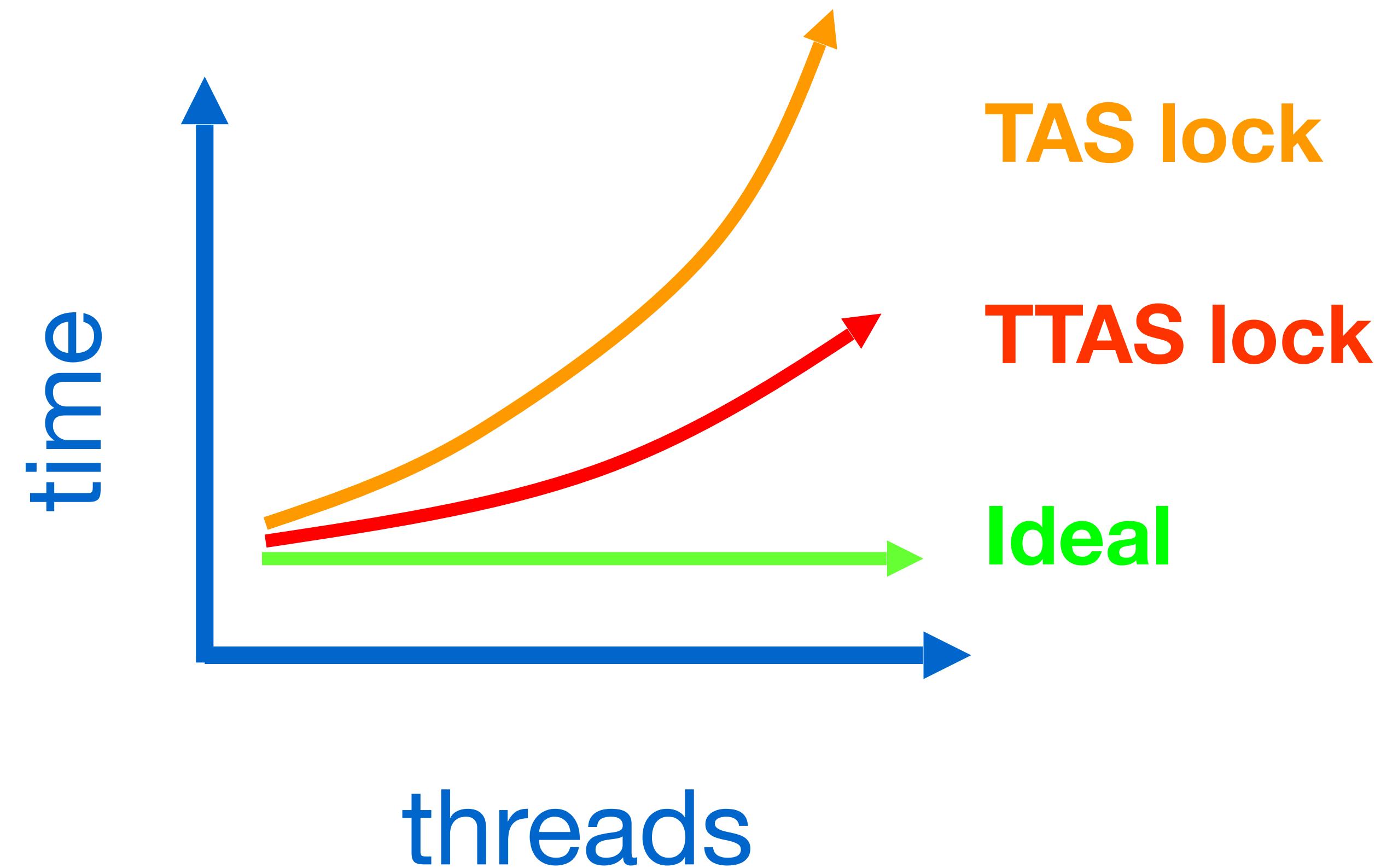
  let create () = { state = Atomic.make false }

  let unlock t = Atomic.set t.state false
```

```
let lock t =
  (* Outer loop: keep trying until we get the lock *)
  while
    (* Inner loop: spin-read until lock appears free *)
    while Atomic.get t.state do () done;
    (* Lock looks free, try to acquire with exchange *)
    Atomic.exchange t.state true
  do
    (* If we're here, exchange returned true *)
    (* Somebody has the lock; spin-read again *)
    ()
  done
  (* If we exit the while loop, exchange returned false
   => we have the lock! *)
end
```

Demo

Mystery #2



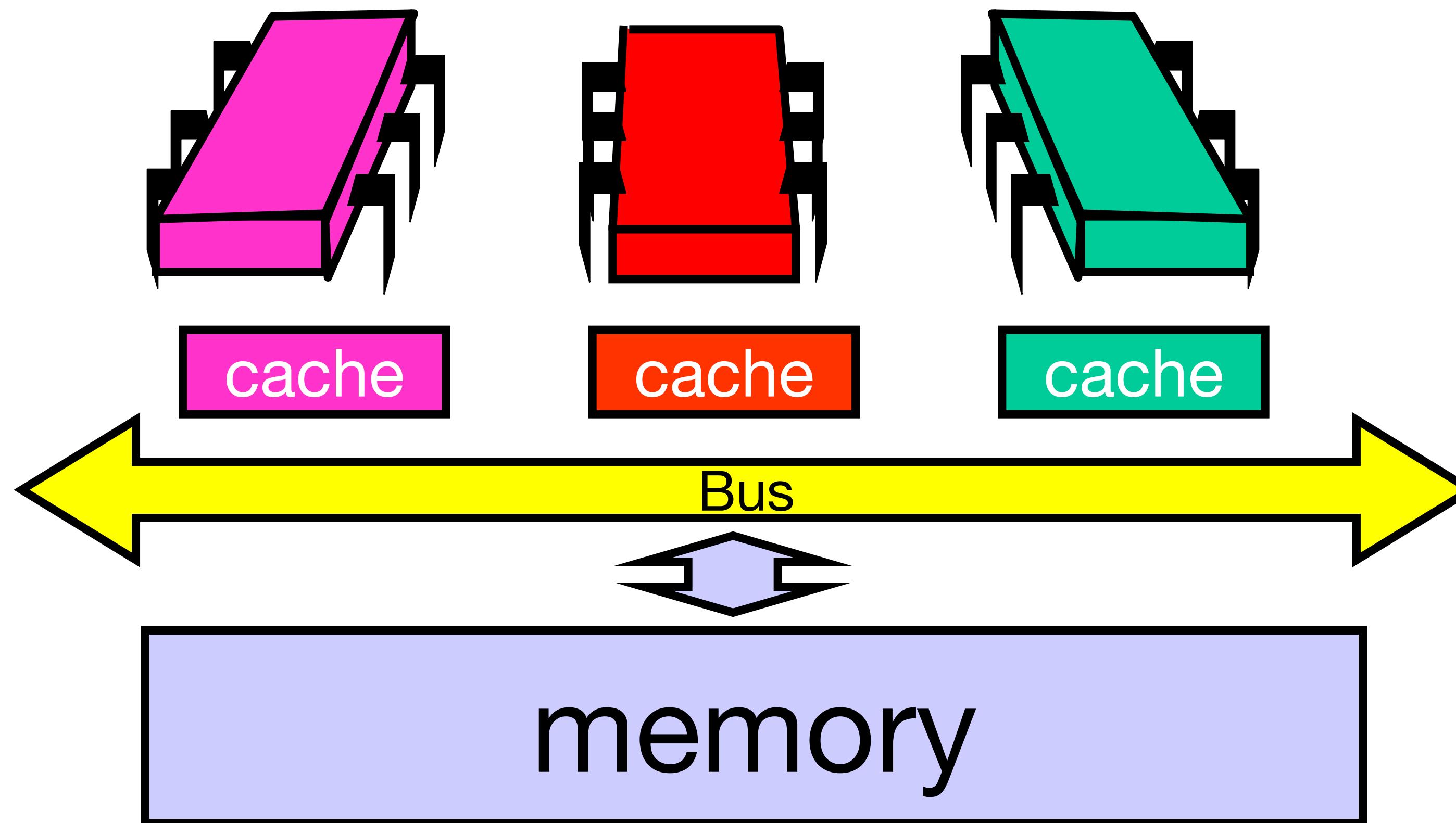
Mystery

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

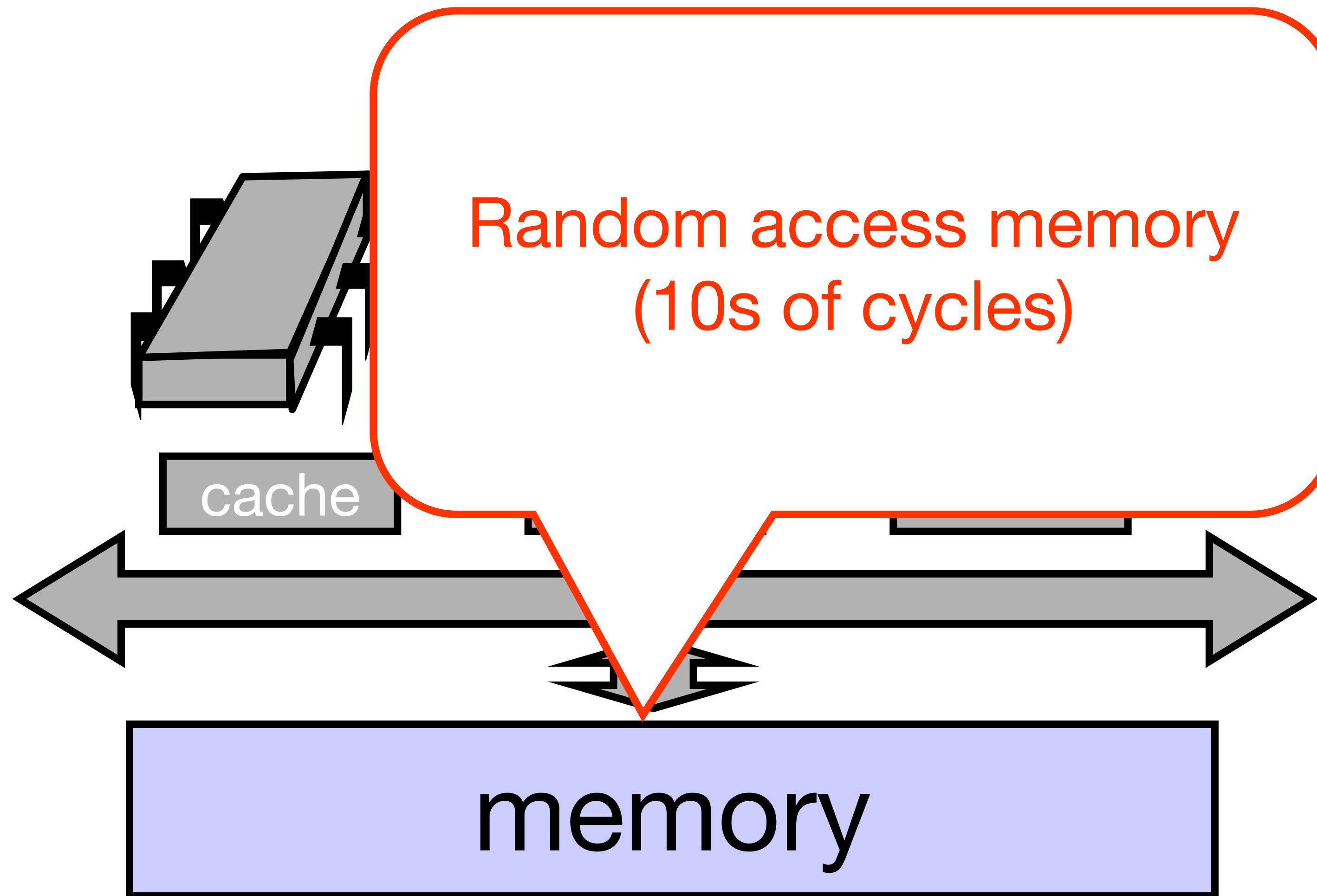
Opinion

- 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 ...

Bus-based Architectures



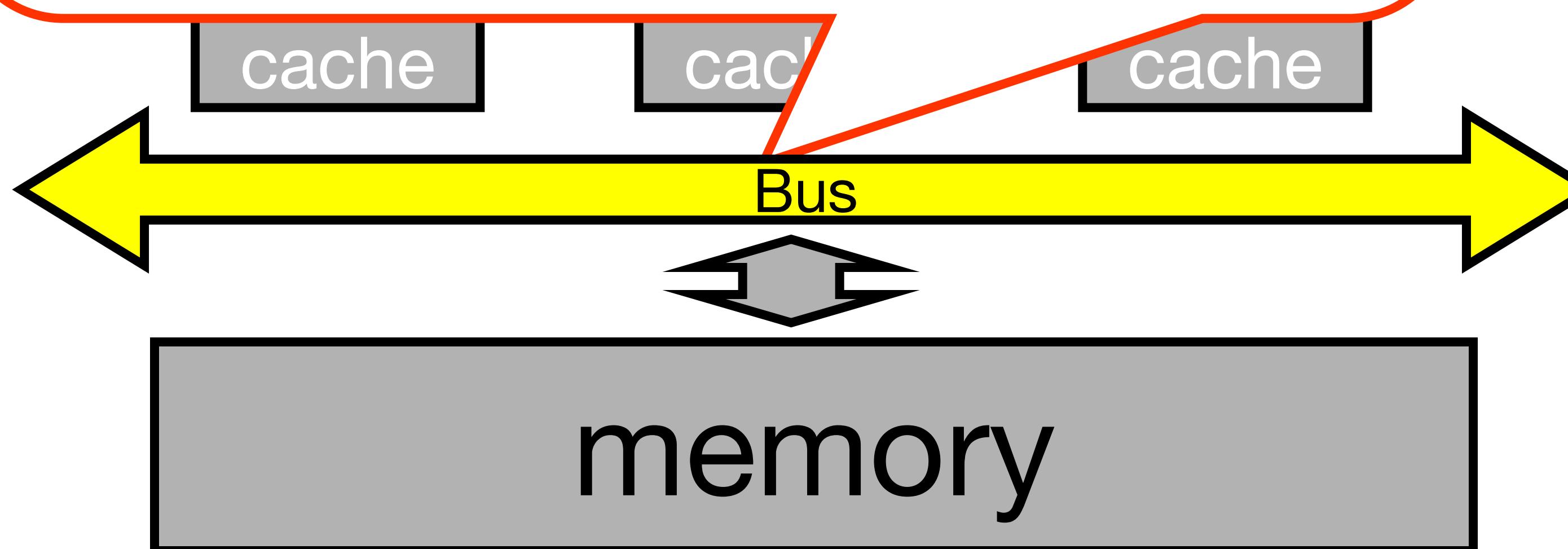
Bus-based Architectures



Bus-based Architectures

Shared Bus

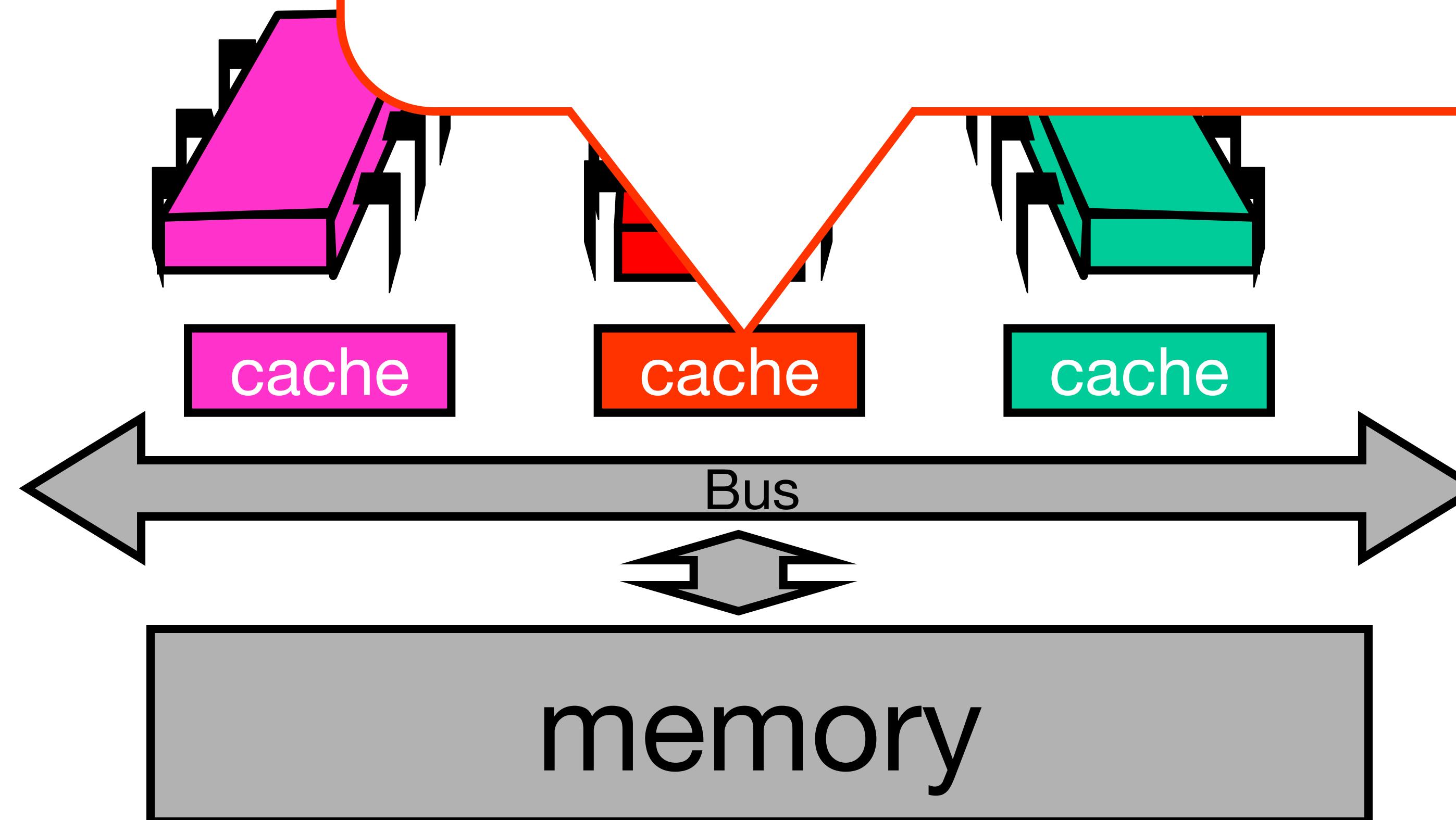
- Broadcast medium
- One broadcaster at a time
- Processors and memory all “snoop”



Bus-based Architecture

Per-Processor Caches

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



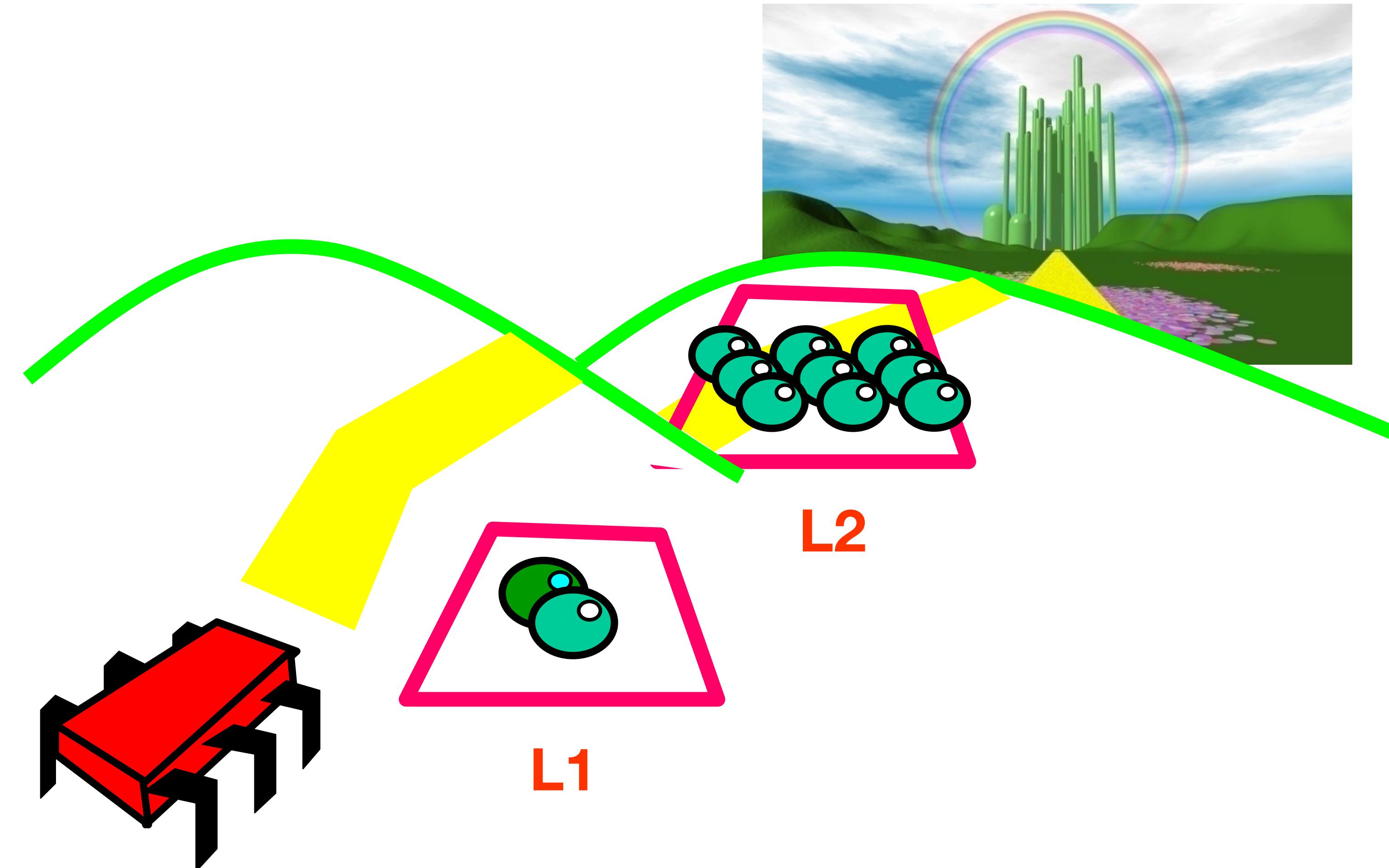
Granularity

- Caches operate at a larger granularity than a word
- **Cache line:** fixed-size block containing the address (today 64 or 128 bytes)

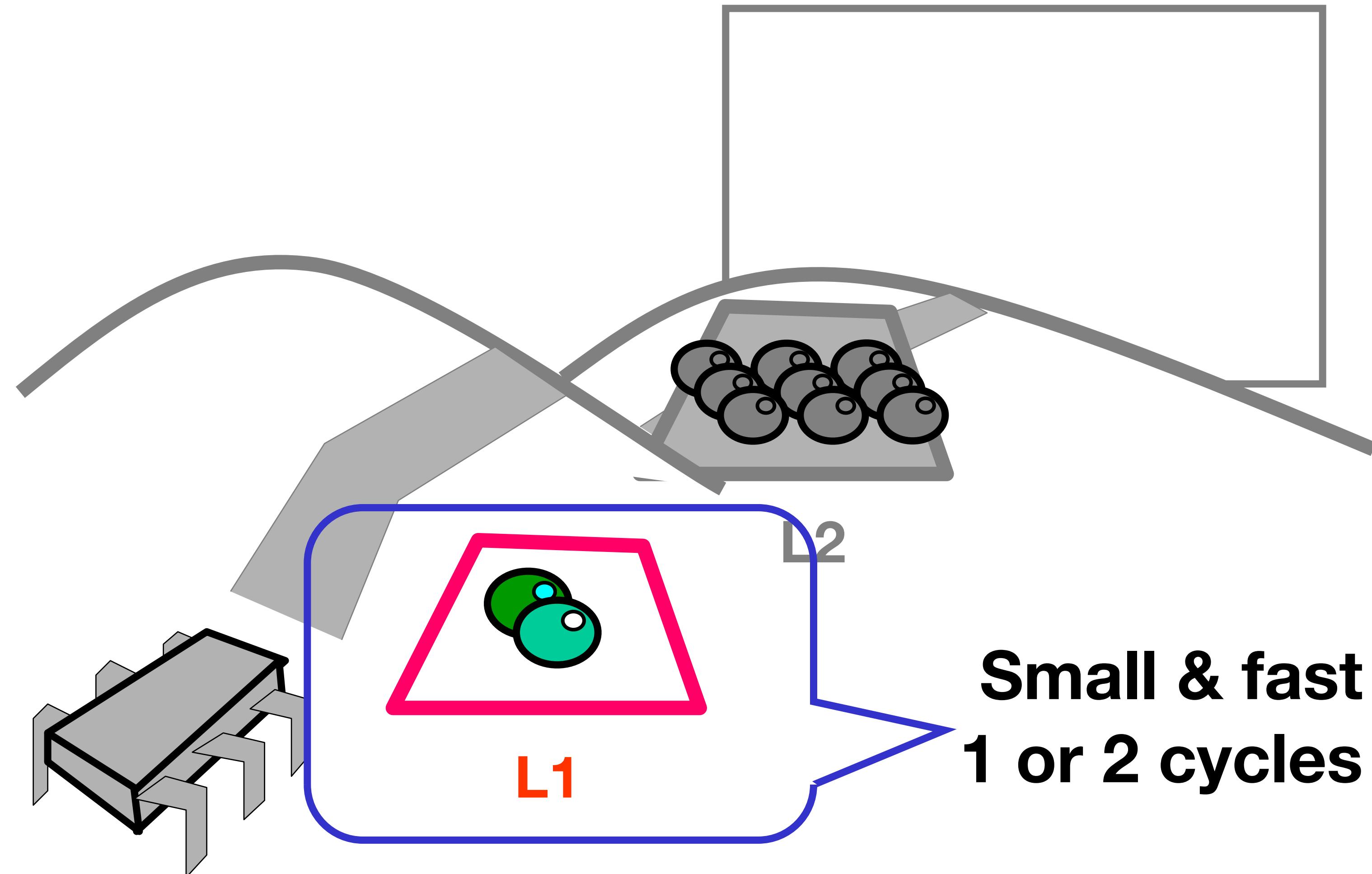
Locality

- 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

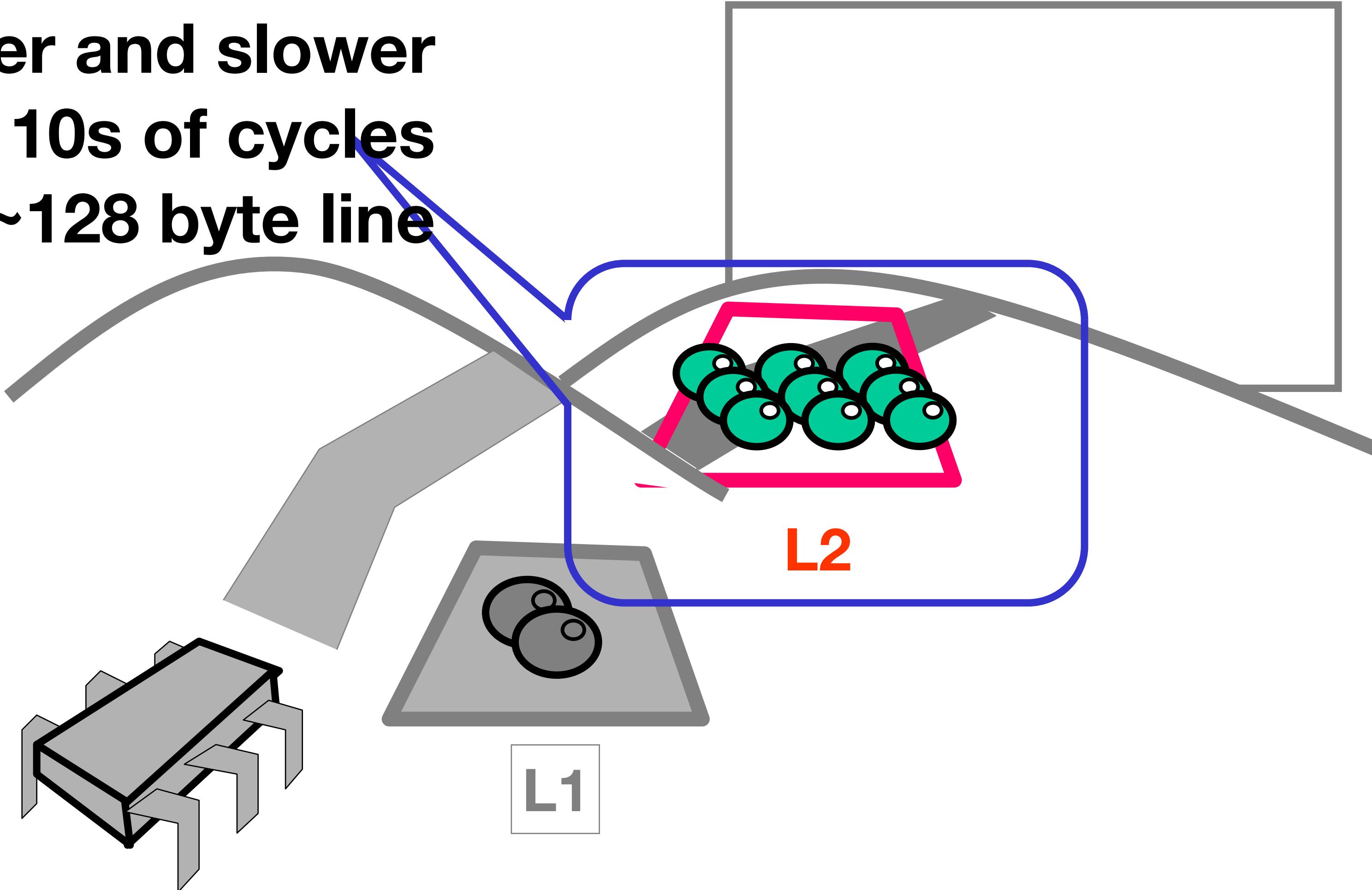


L1 and L2 caches



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

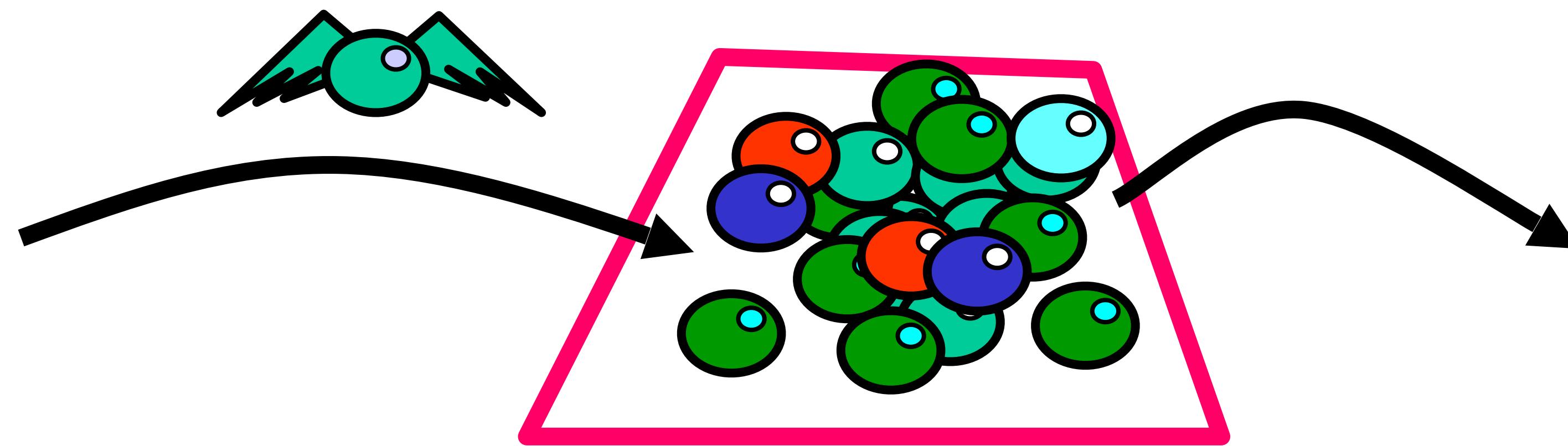
- This model is *still* a simplification
 - But not in any essential way
 - Illustrates basic principles
- Will discuss complexities later

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

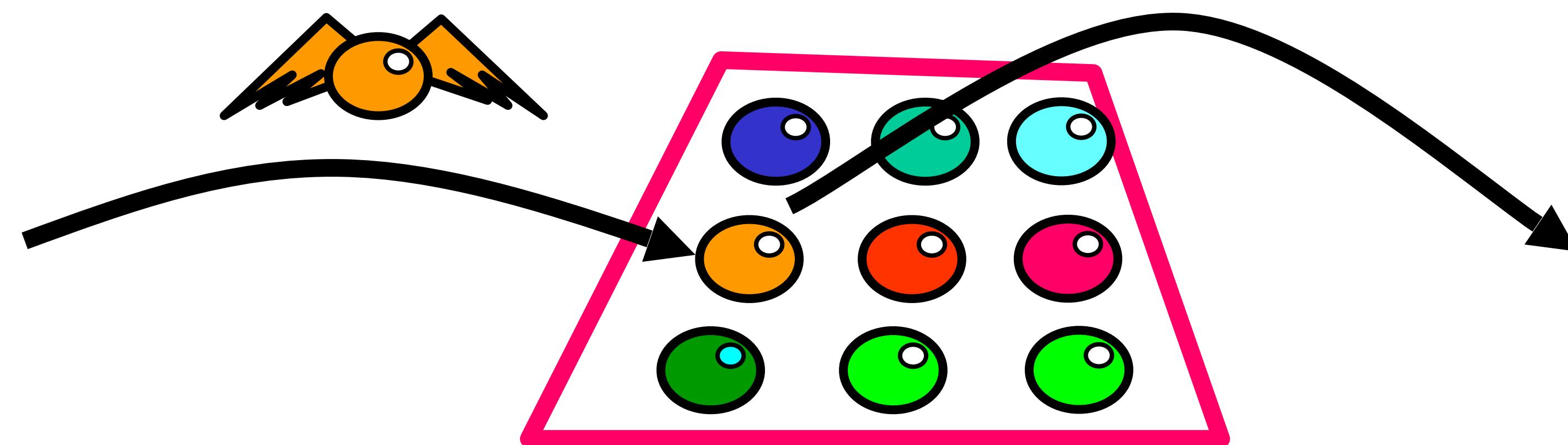
Fully Associative Cache

- Any line can be anywhere in the cache
 - Advantage: can replace any line
 - Disadvantage: hard to find lines



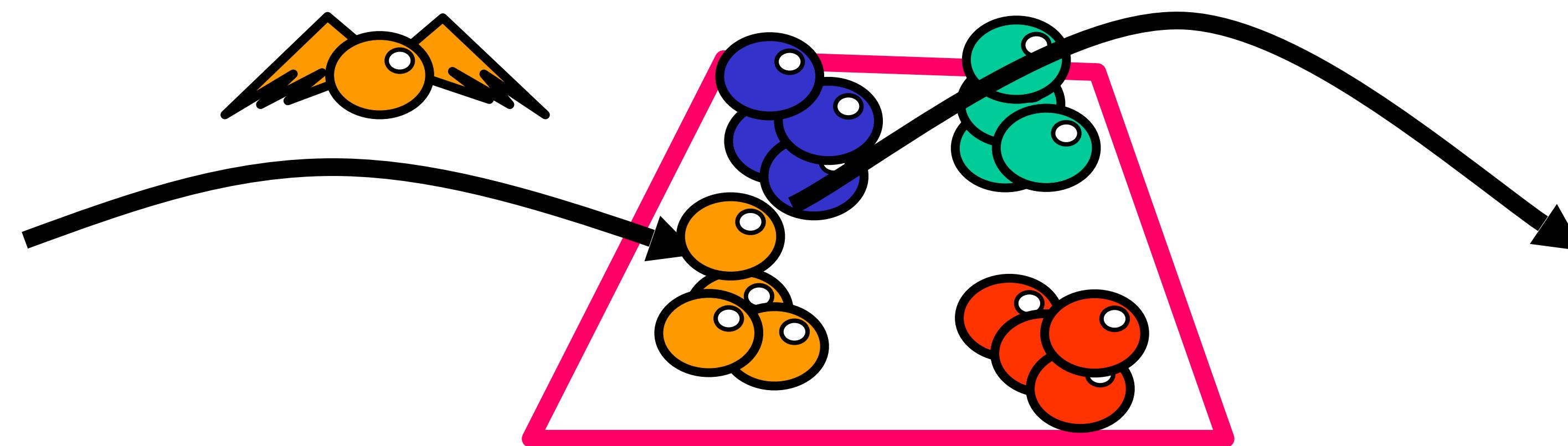
Direct Mapped Cache

- Every address has exactly 1 slot
 - Advantage: easy to find a line
 - Disadvantage: must replace fixed line



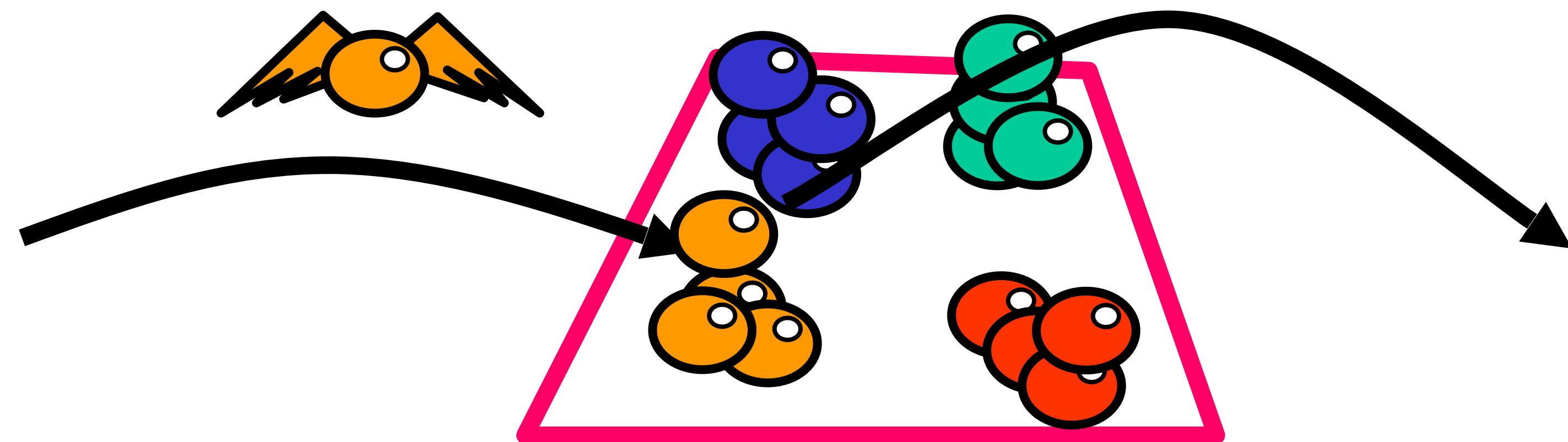
K-way set associative cache

- Each slot holds k lines
 - Advantage: pretty easy to find a line
 - Advantage: some choice in replacing line



Multicore Set Associativity

- k is 8 or even 16 and growing...
 - Why? Because cores share sets
 - Threads cut effective size if accessing different data



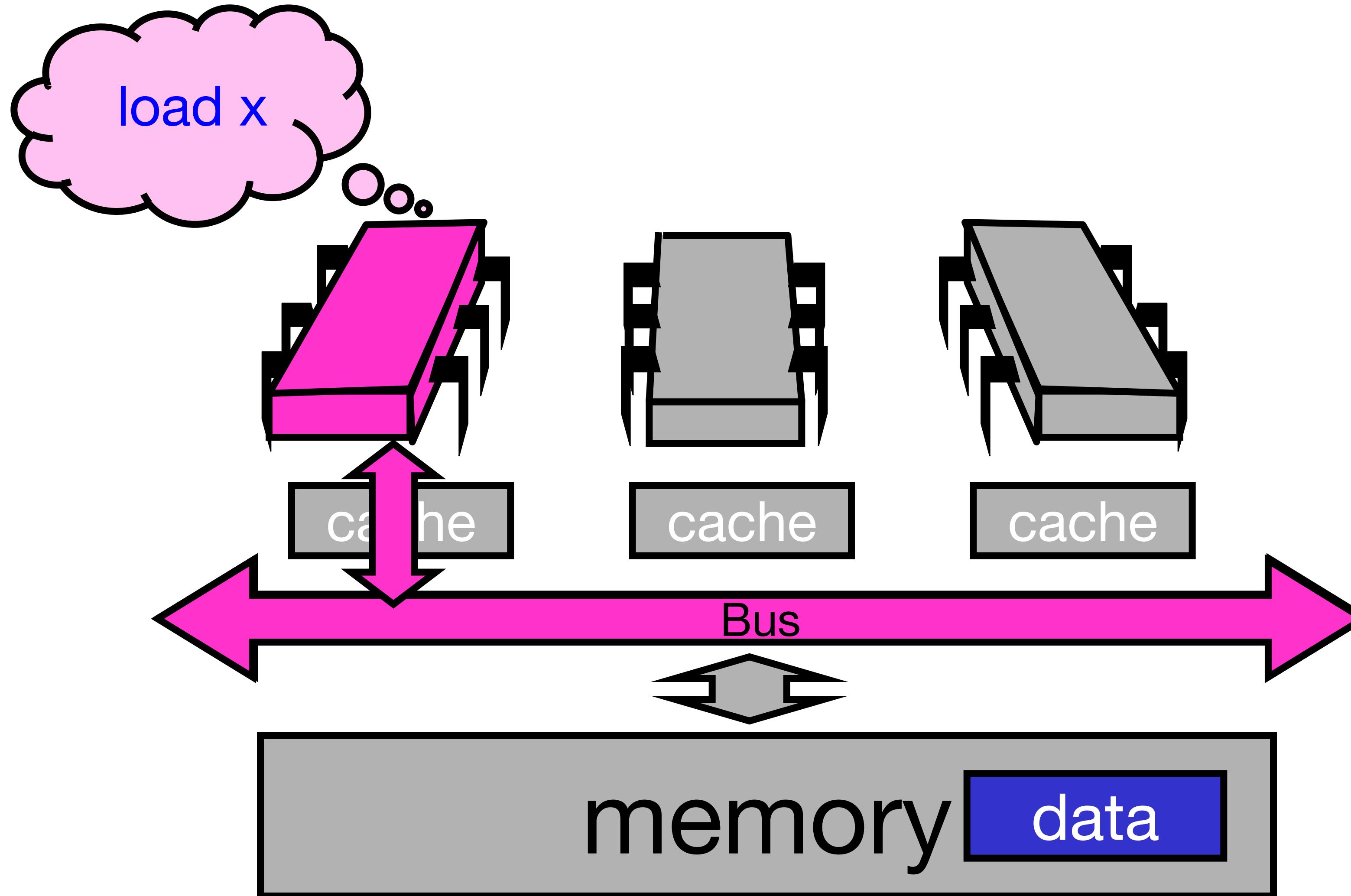
Cache Coherence

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

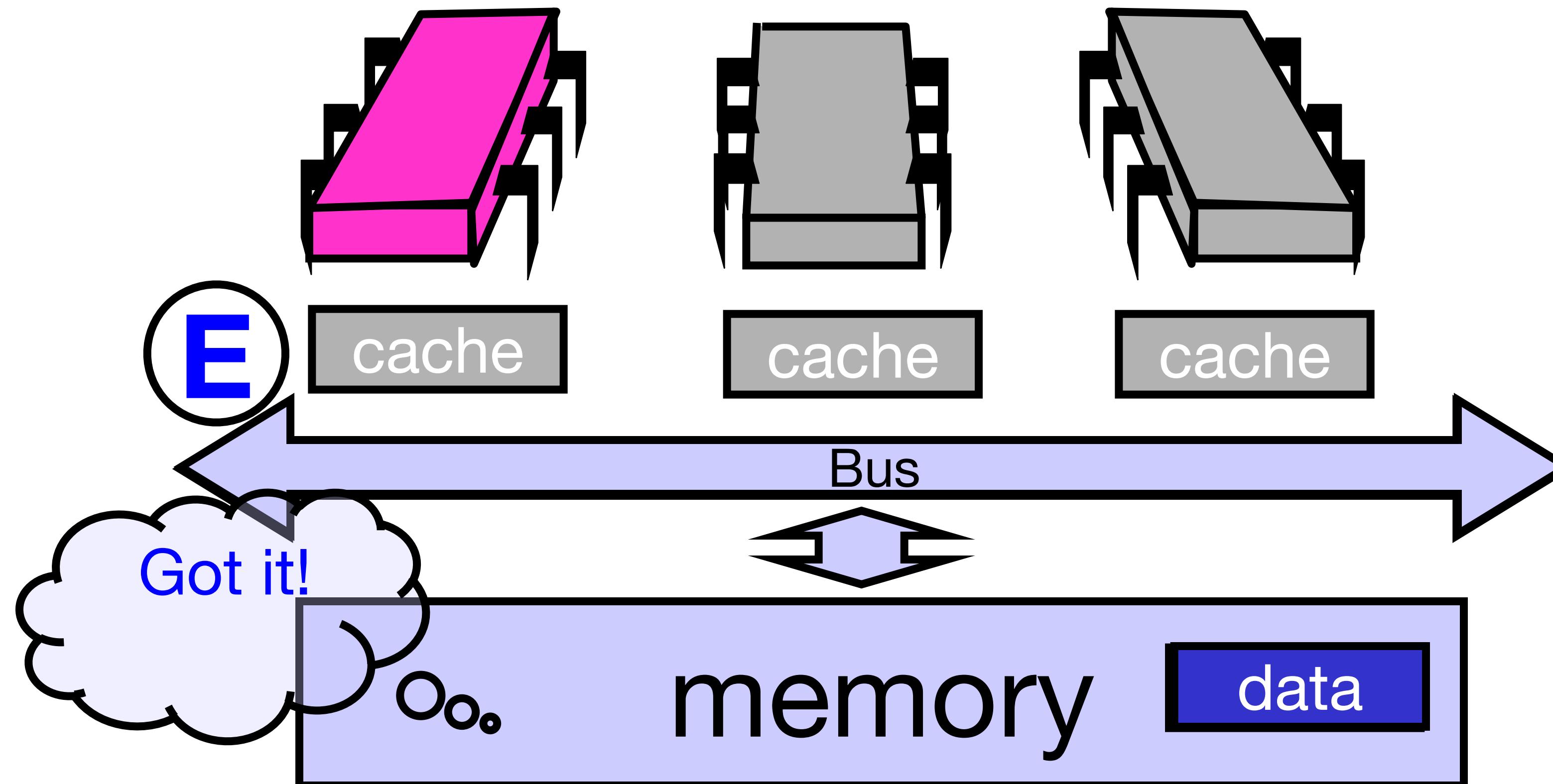
MESI

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

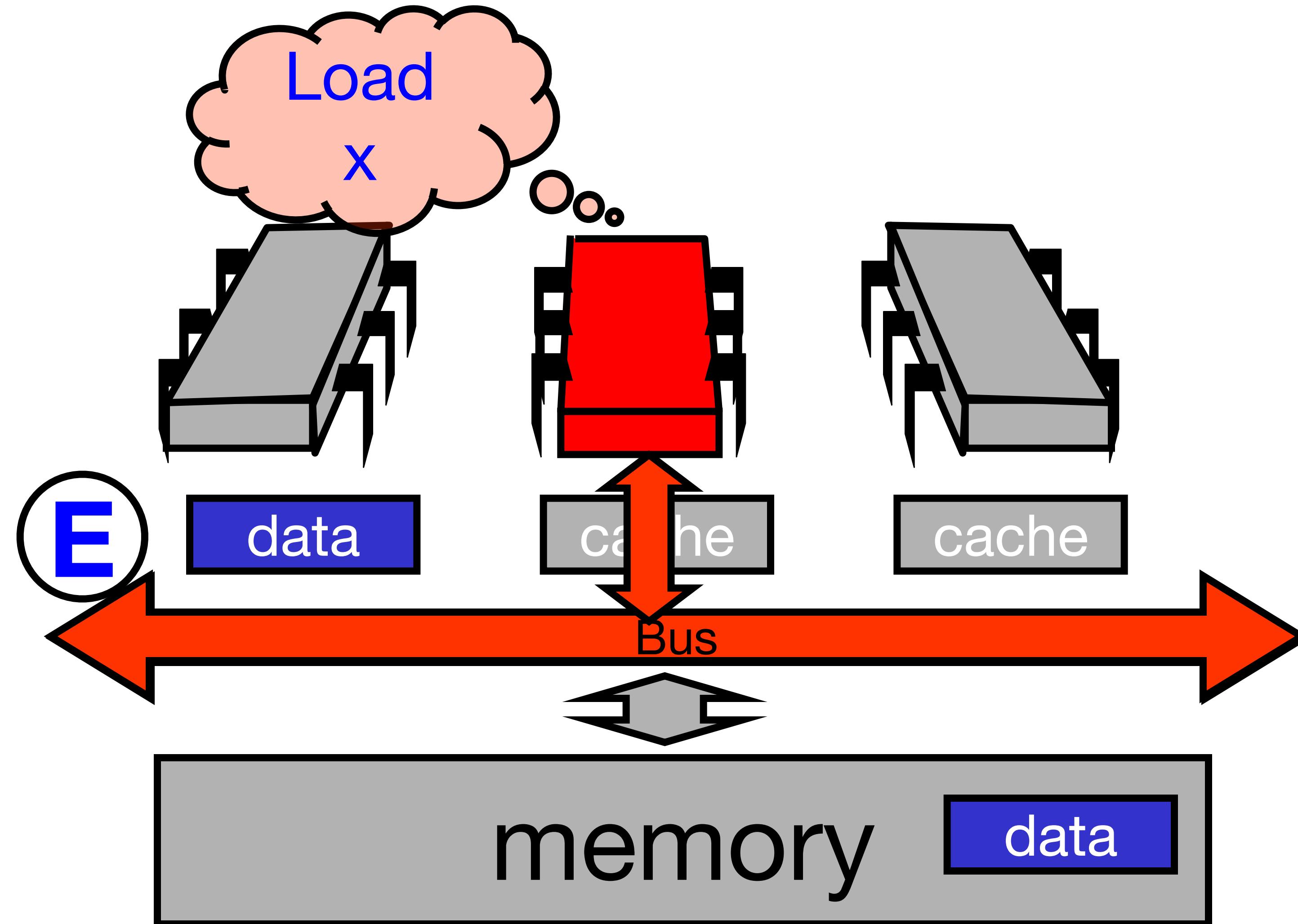
Processor Issues Load Request



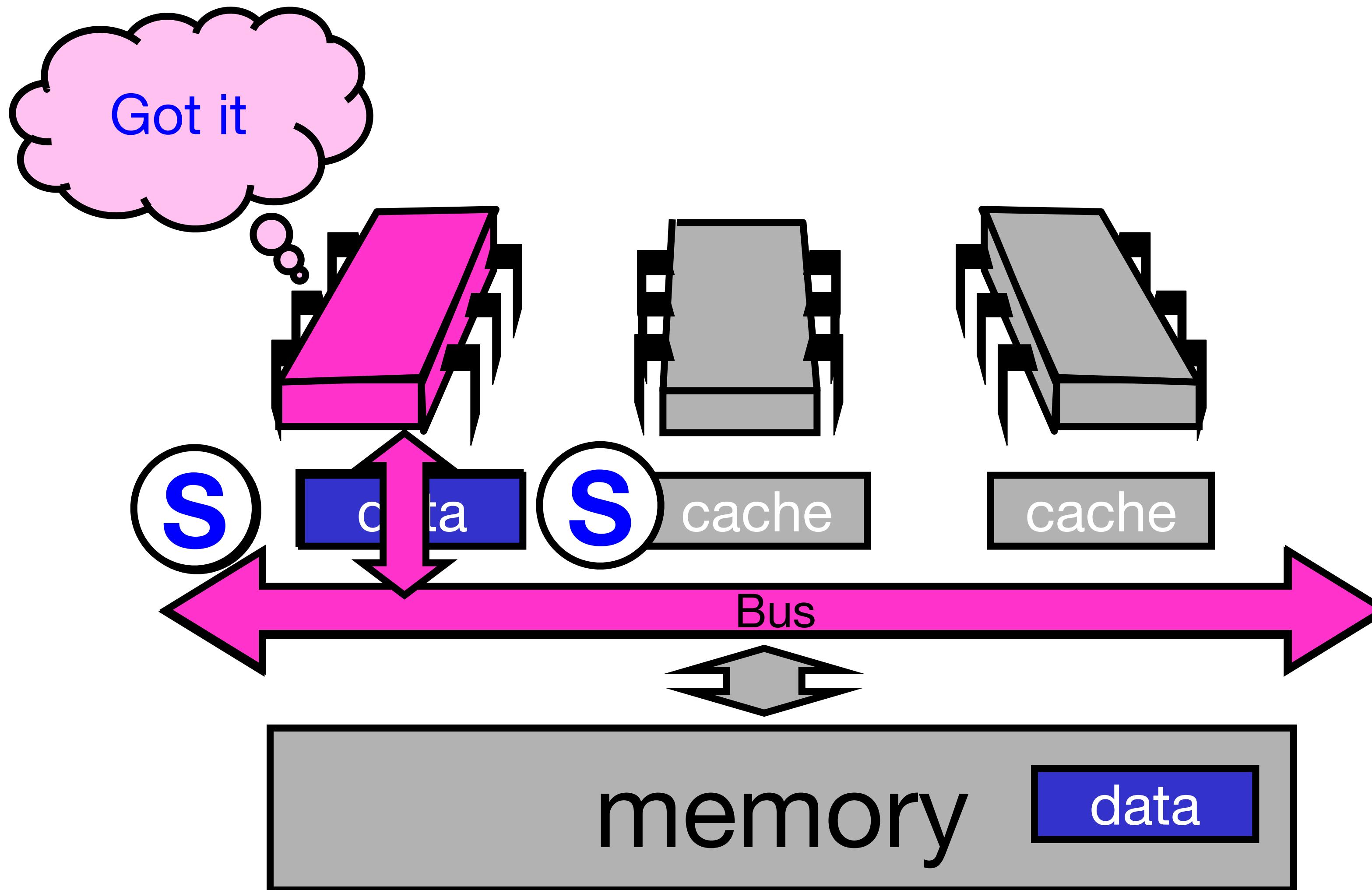
Memory Responds



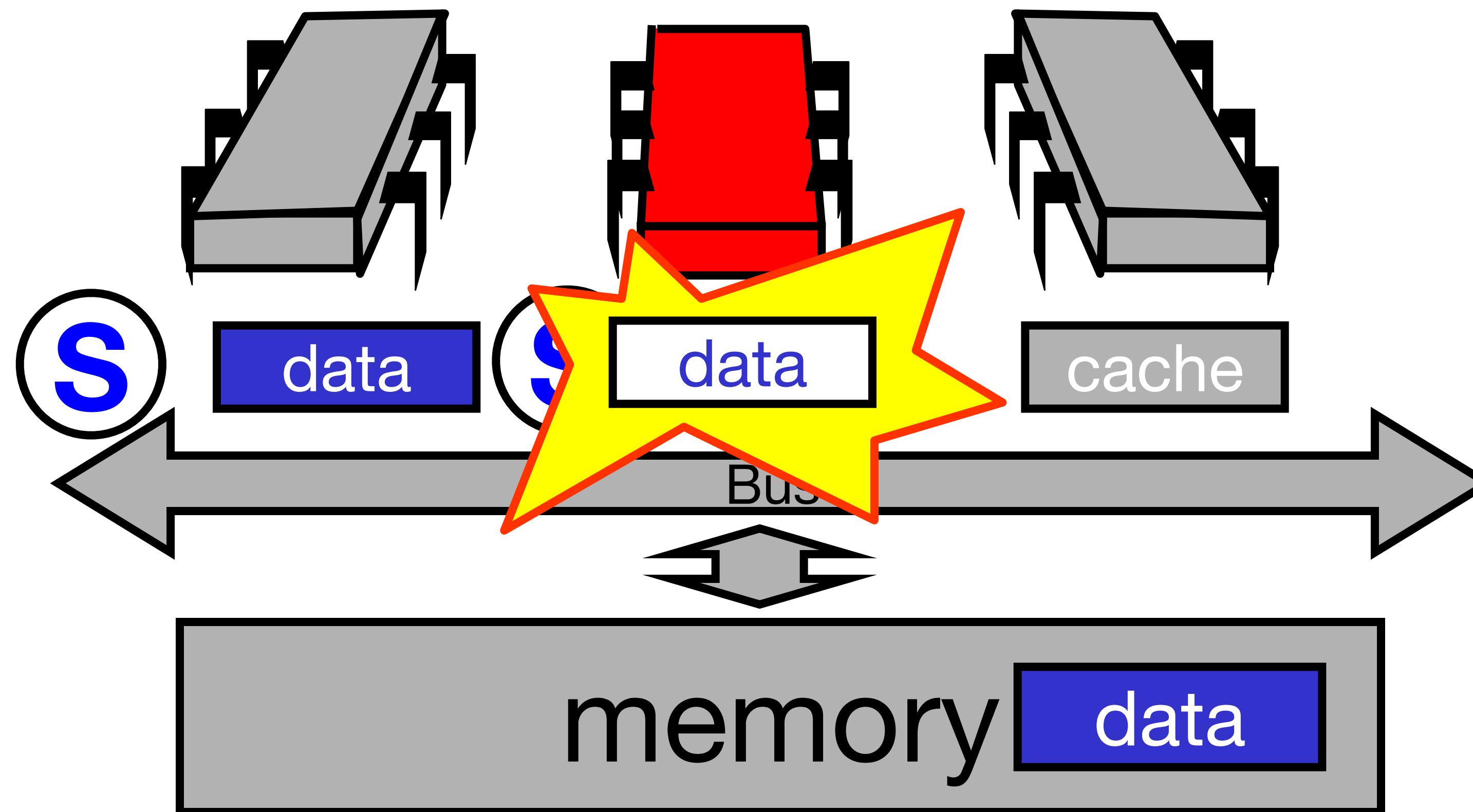
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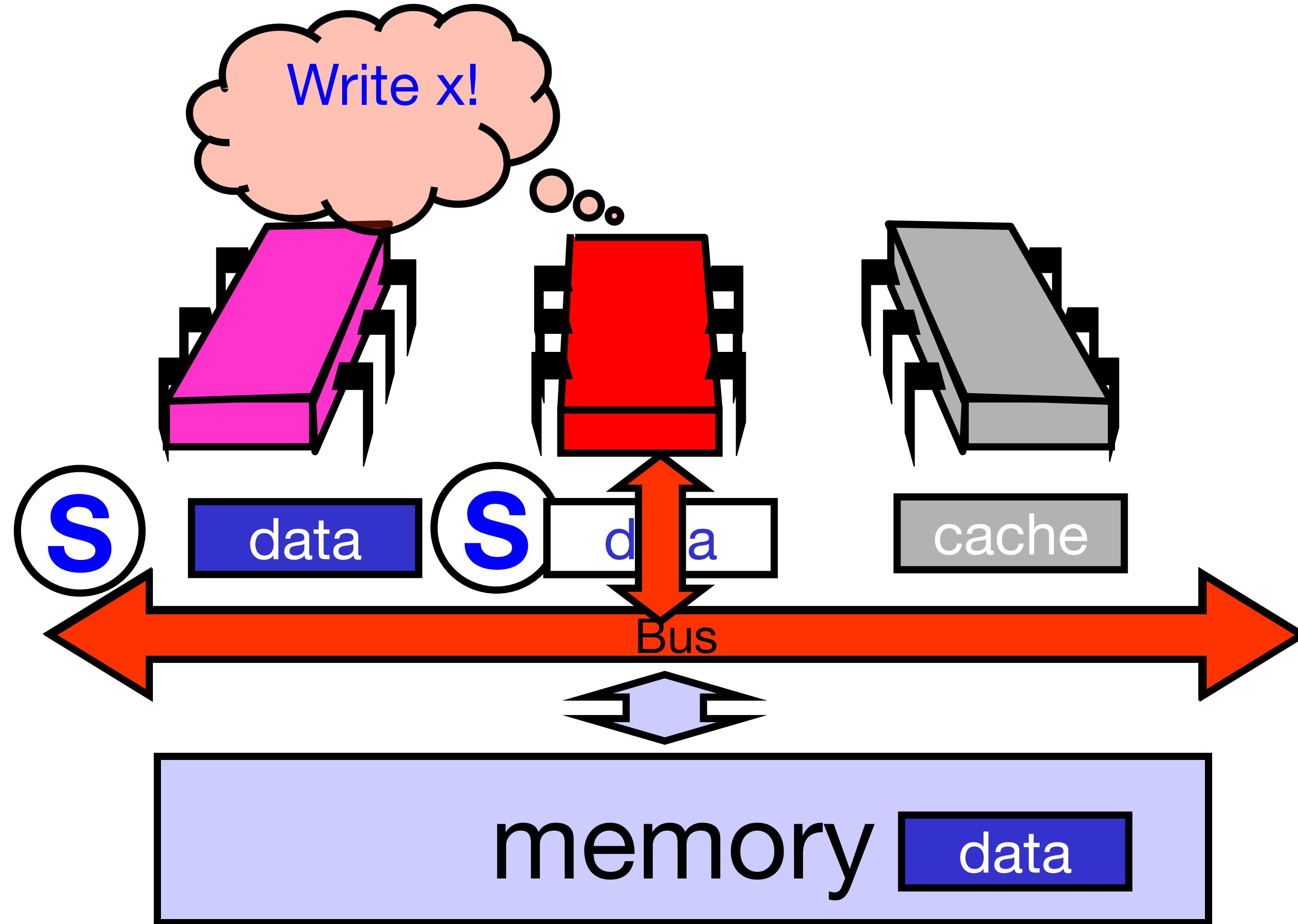
Other Processor Responds



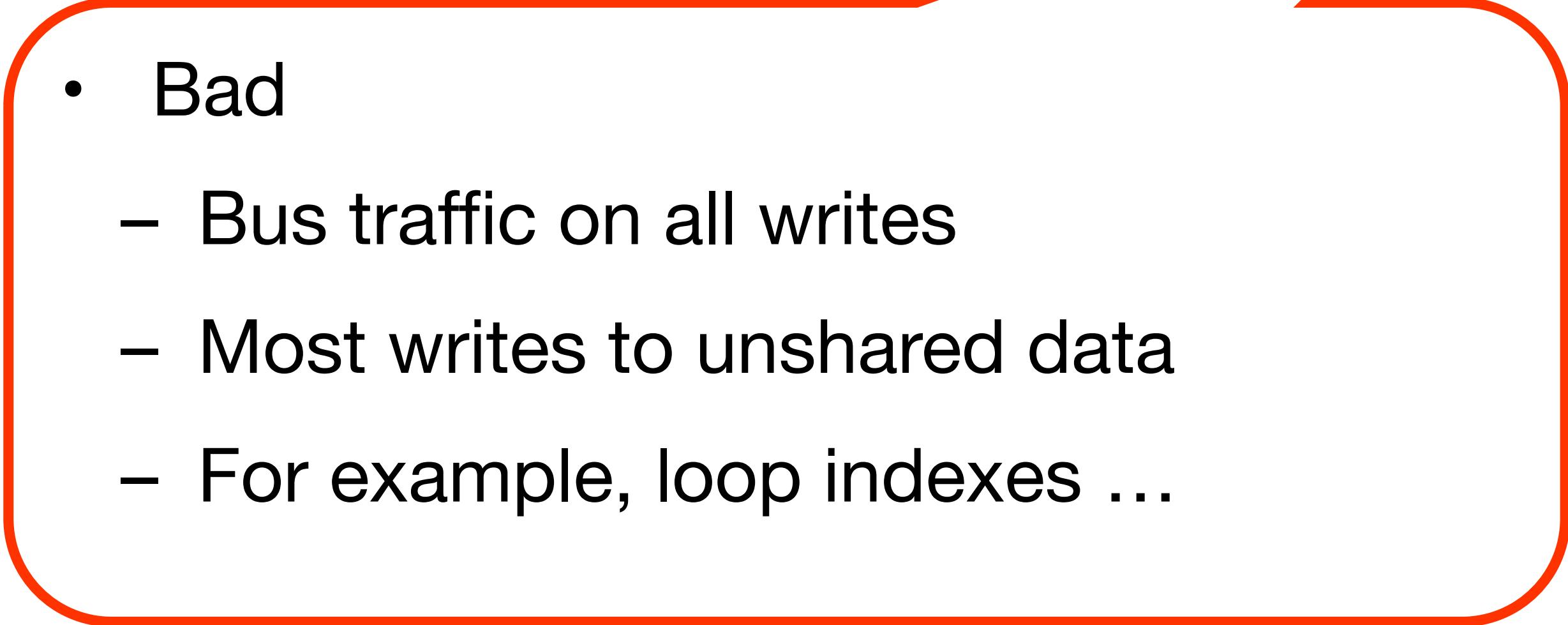
Processor Issues Load Request



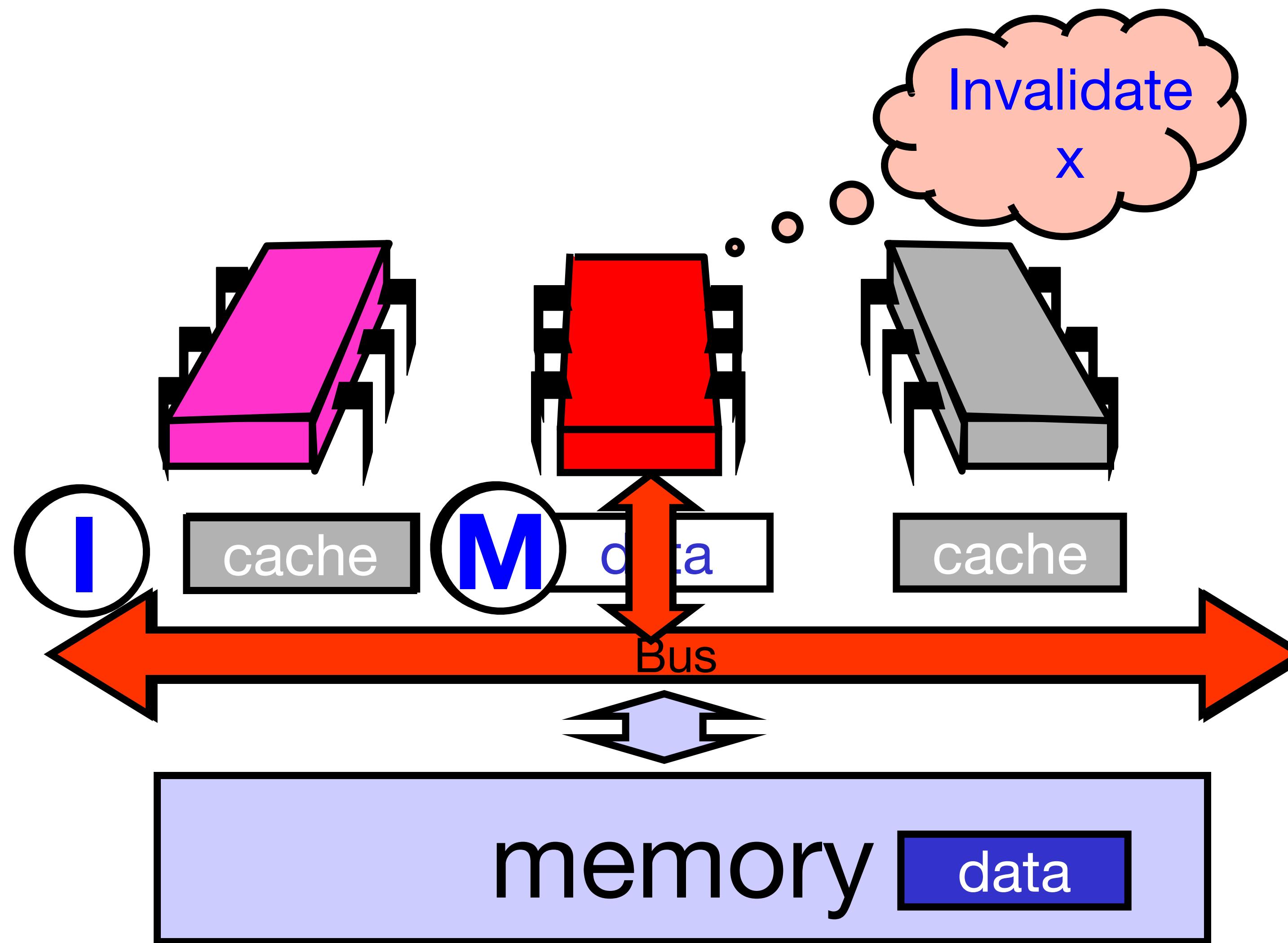
Write-through Cache



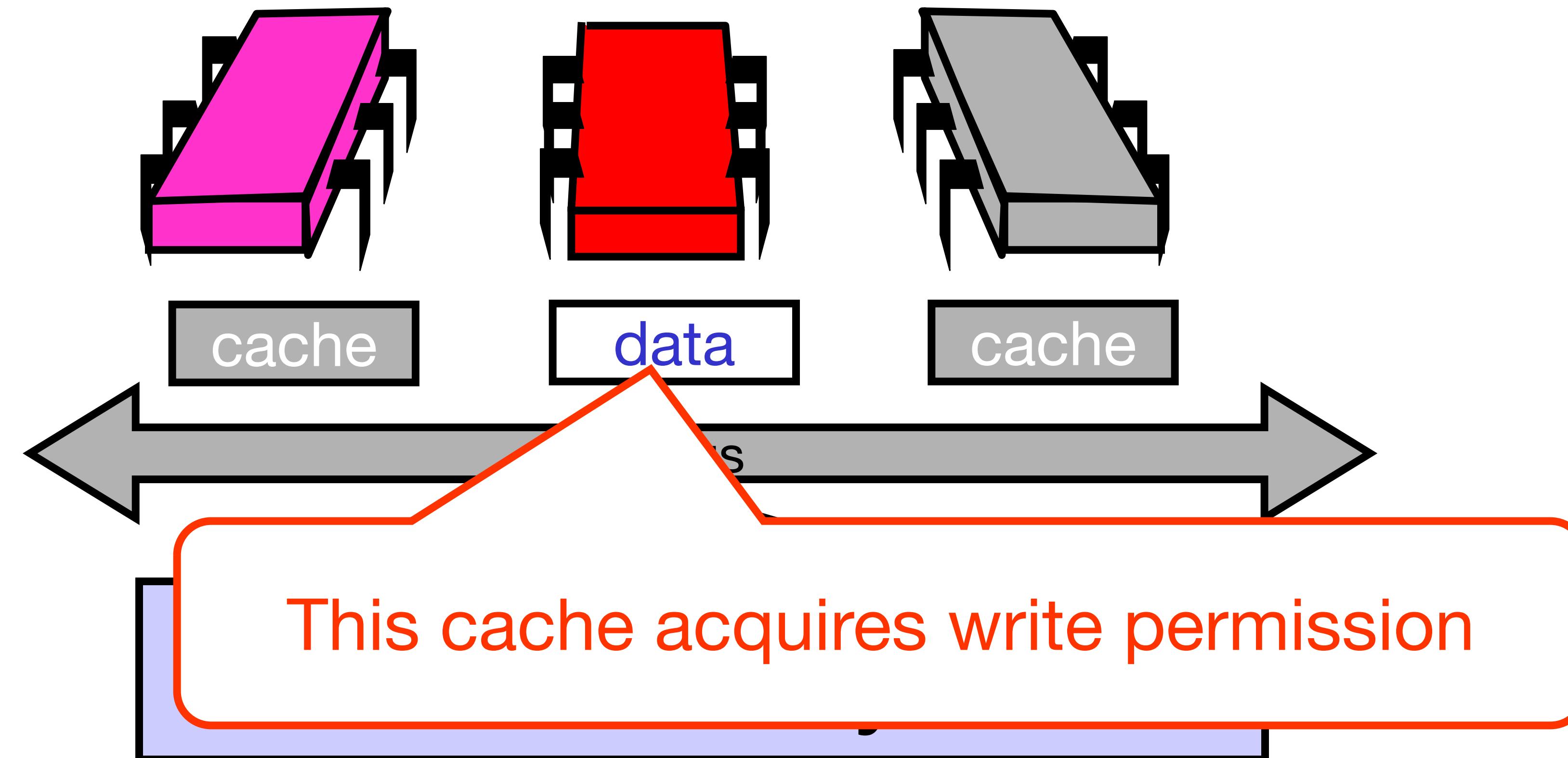
Write-through Cache

- 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 ...
- “show stoppers”
- 

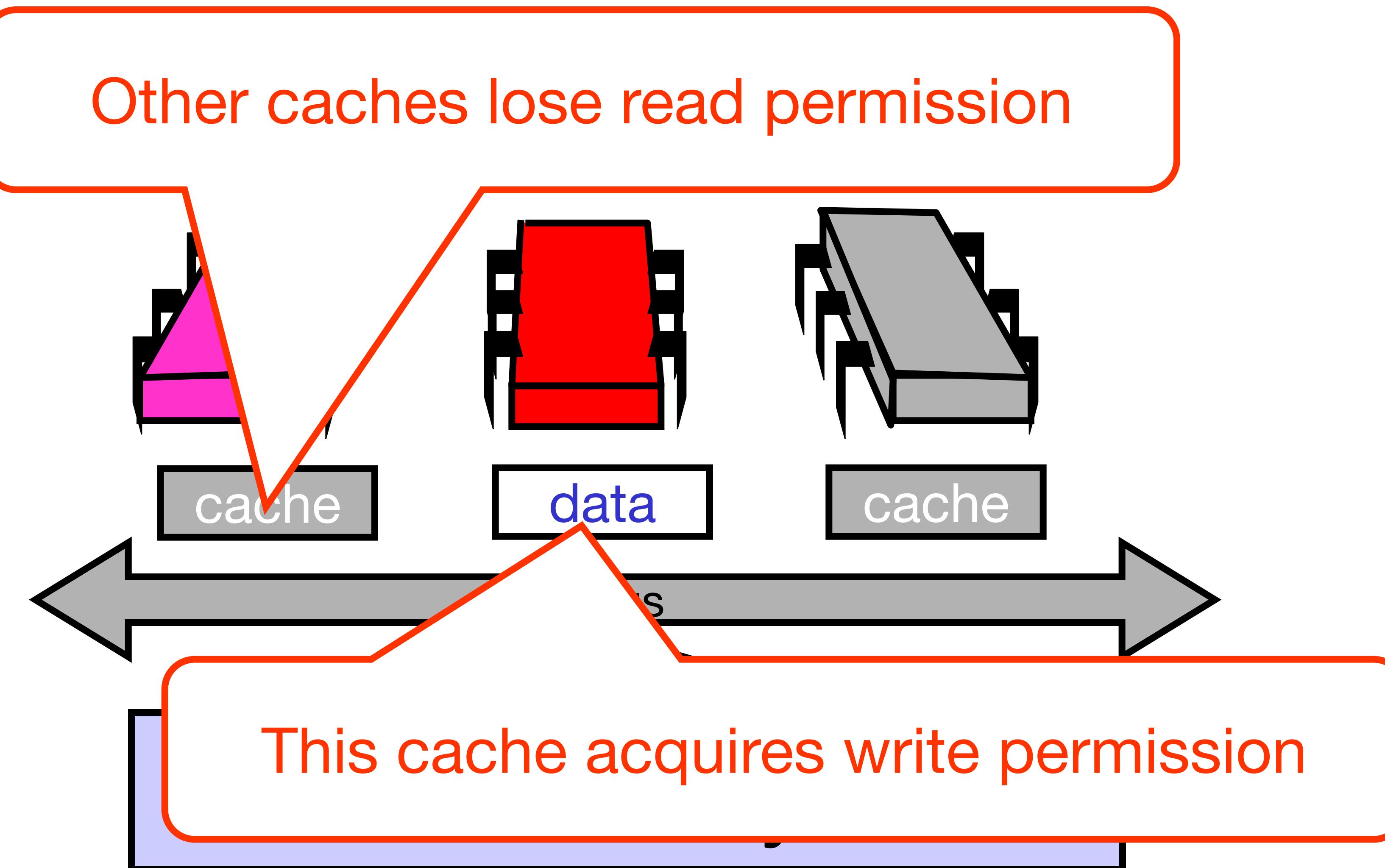
Invalidate



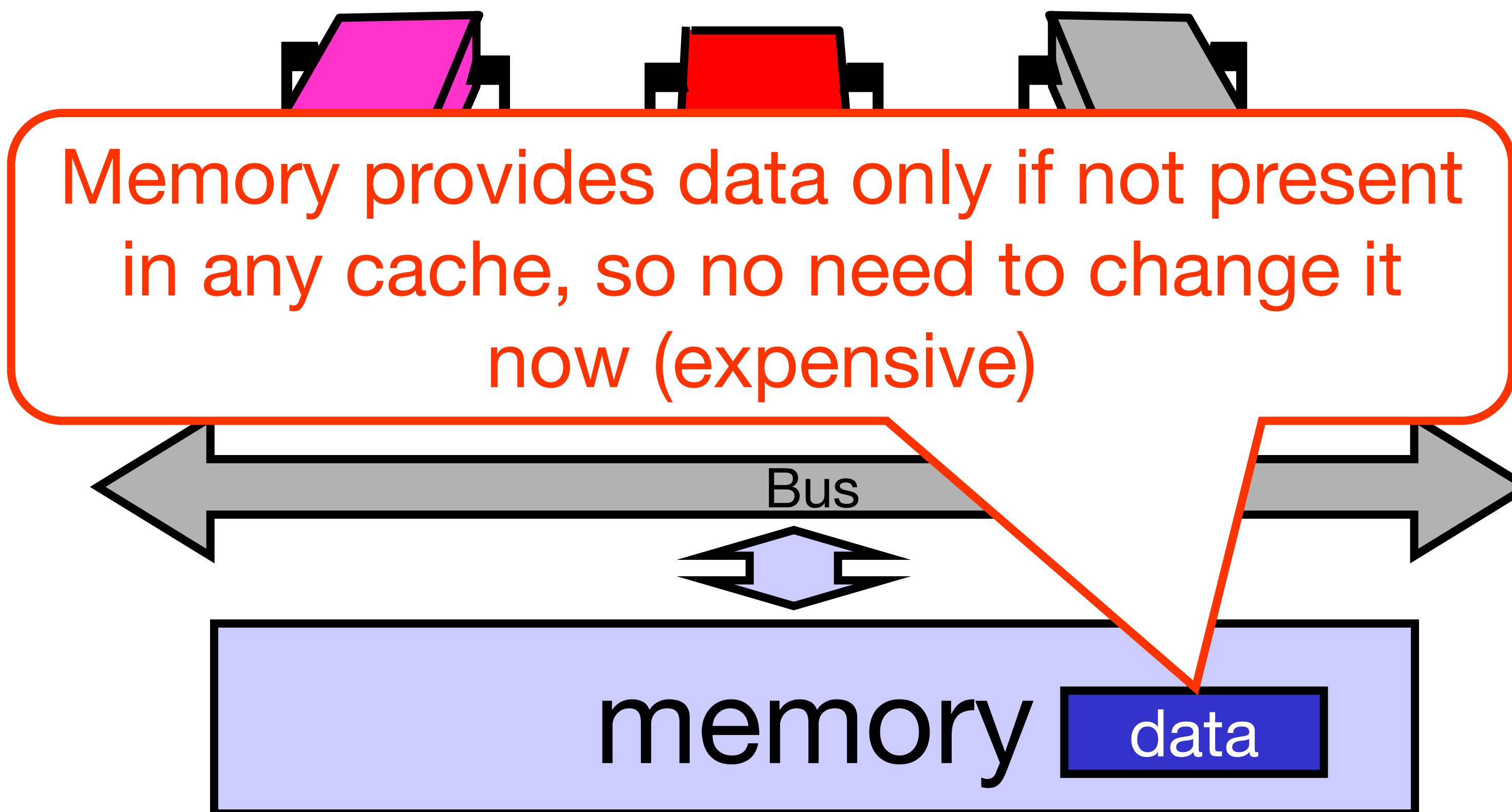
Invalidate



Invalidate



Invalidate



Mutual Exclusion

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

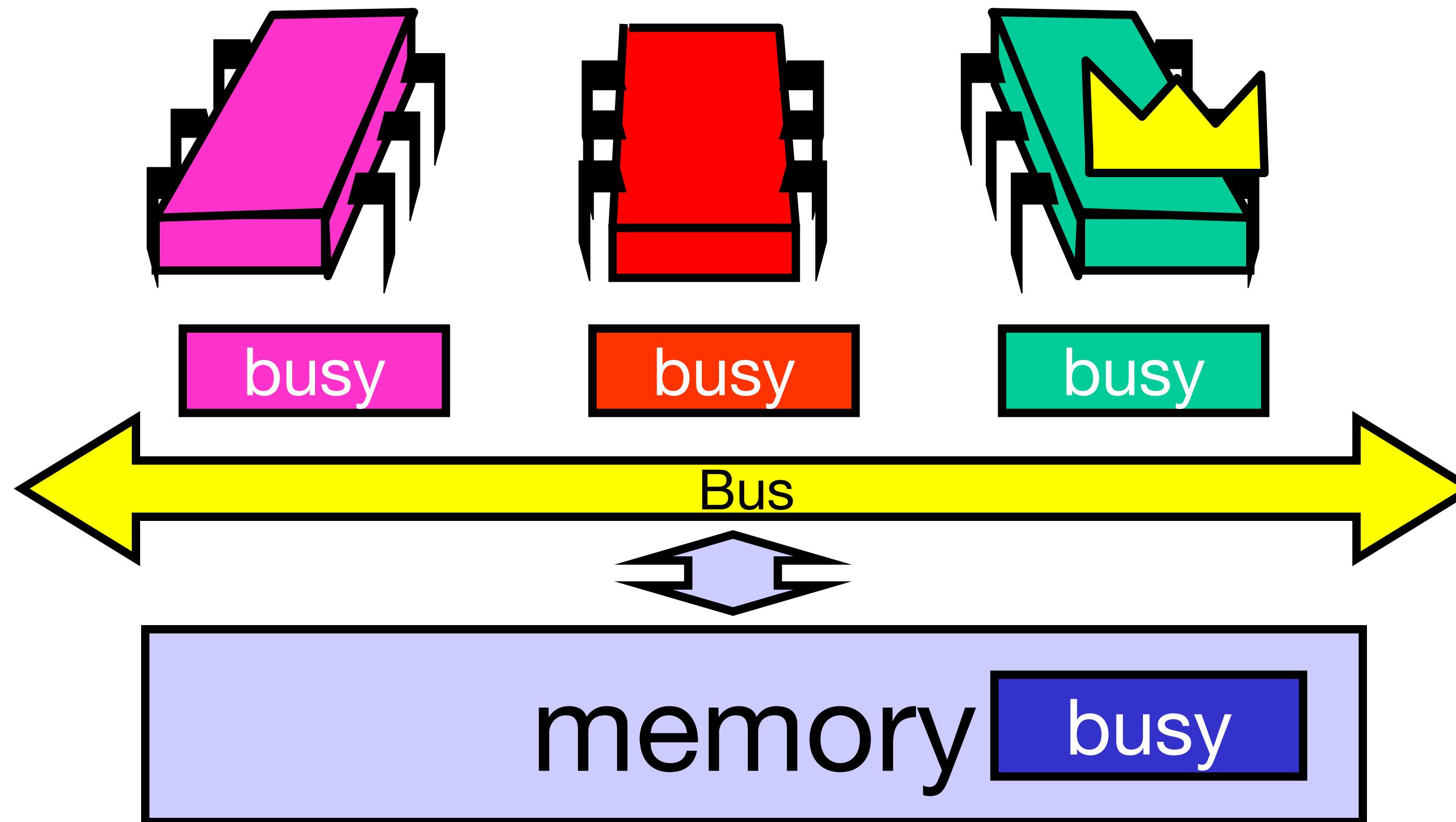
Test-and-set Lock (TASLock)

- TAS *invalidates* (I) cache lines
- Spinners
 - Miss in cache
 - Go to bus
- Cache line **bounces** between all the spinners in modified (M) state
- Thread wants to release lock
 - delayed behind spinners

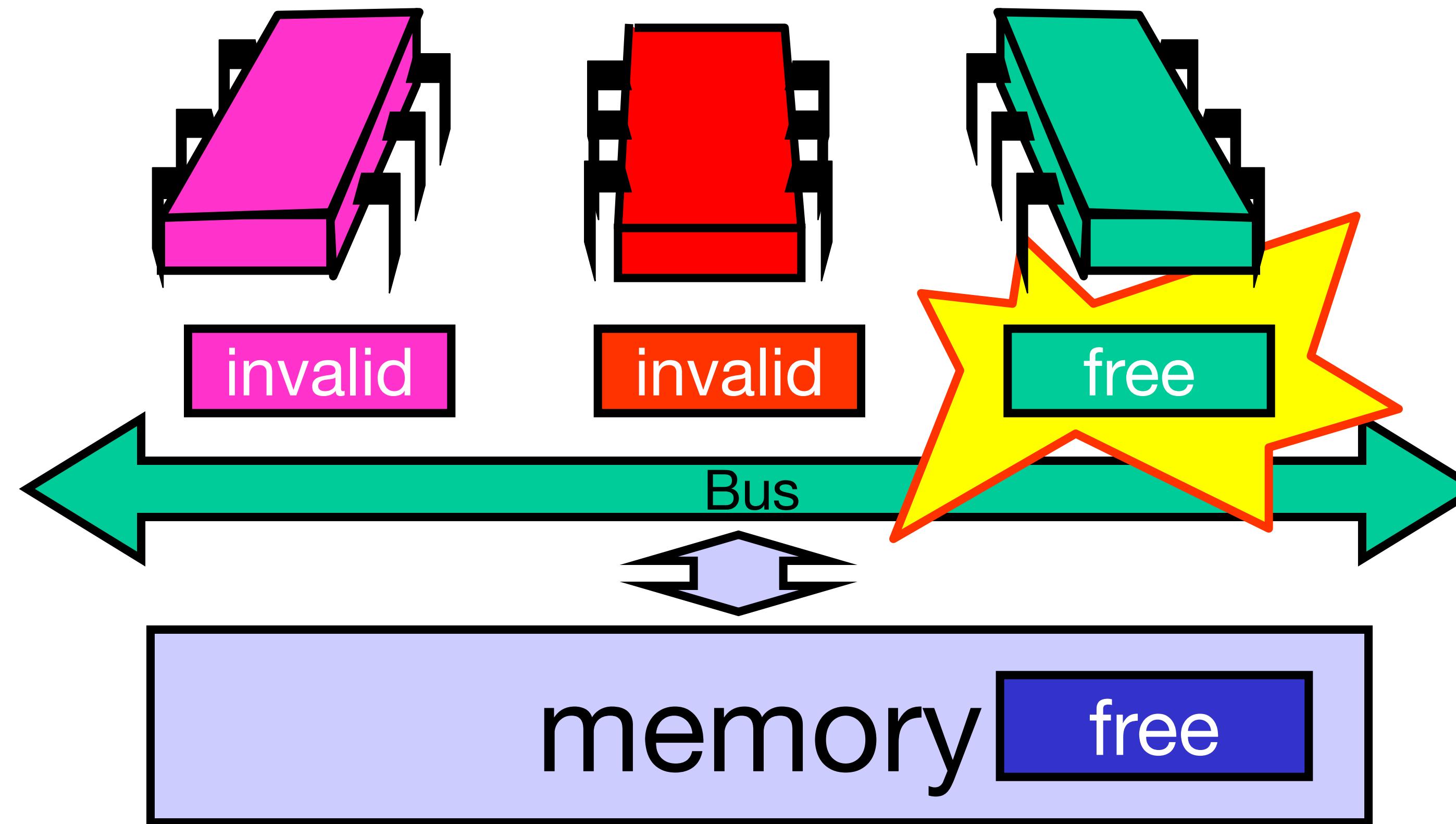
Test-and-test-and-set Lock (TTASLock)

- Wait until lock “looks” free
 - Spin on local cache
 - Cache line is in Shared (S) state
 - No bus use while lock busy
- Problem: when lock is released
 - Invalidation storm ...

Local spinning while lock is busy

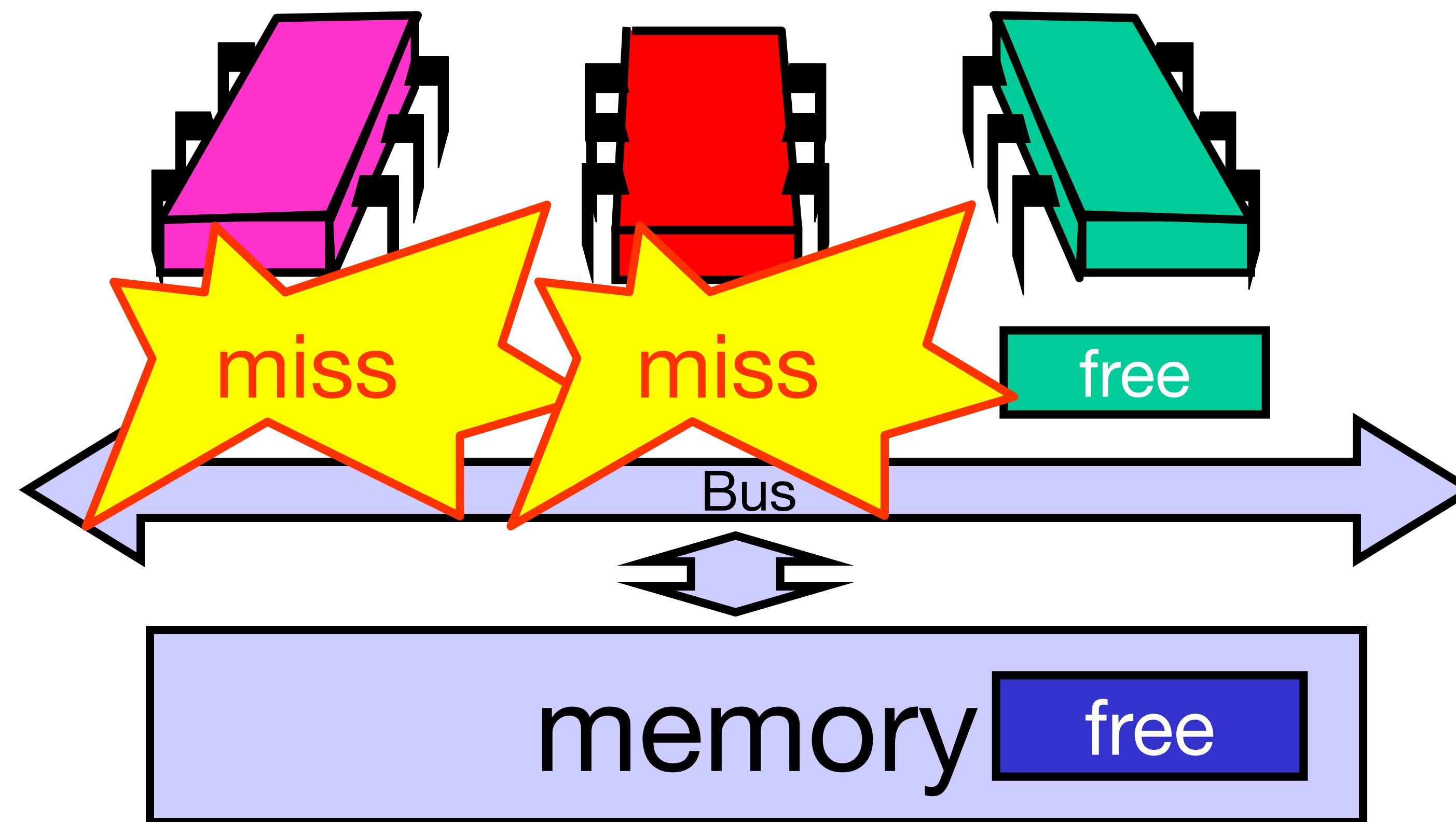


On Release



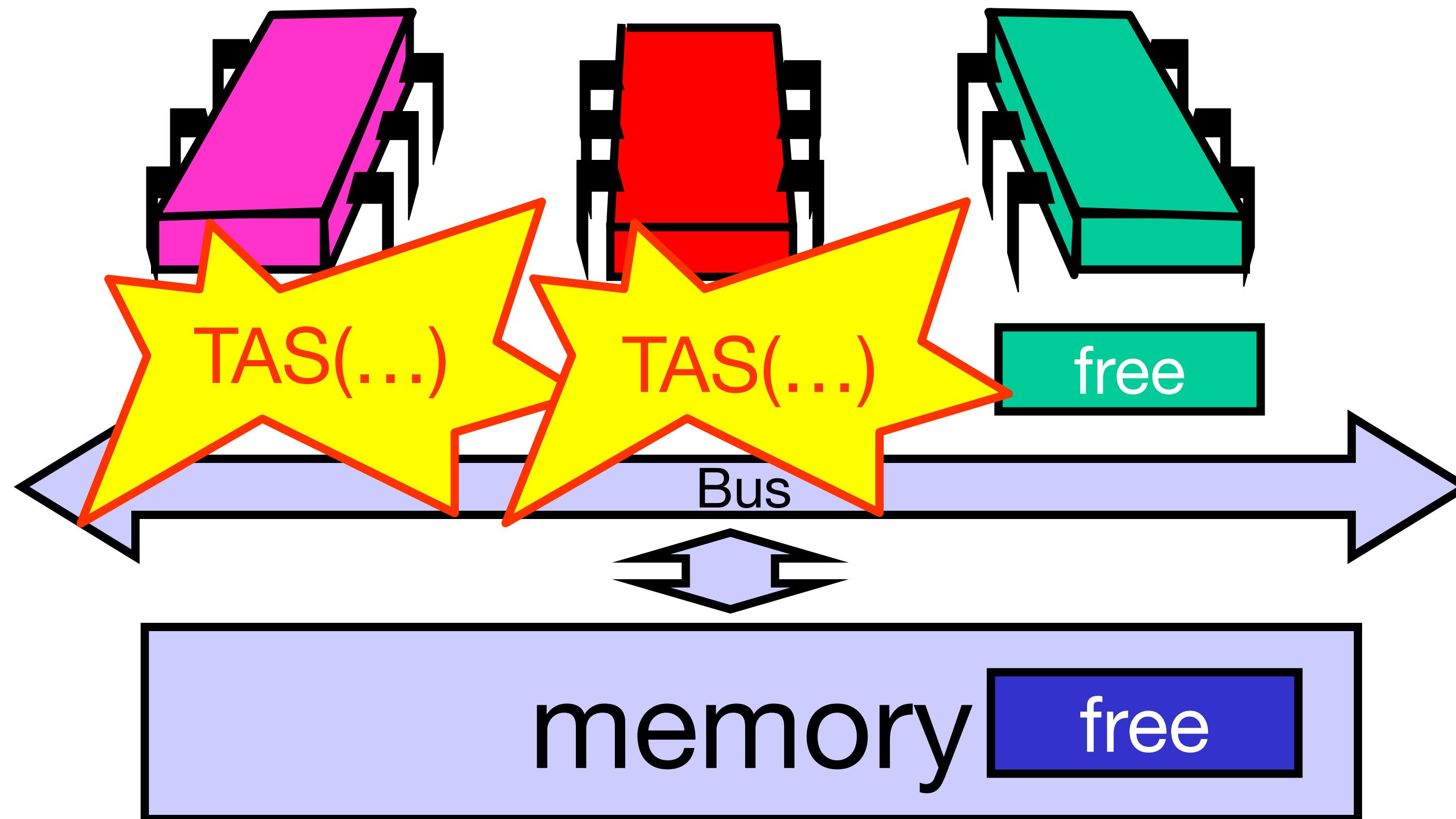
On Release

Everyone misses,
rereads



On Release

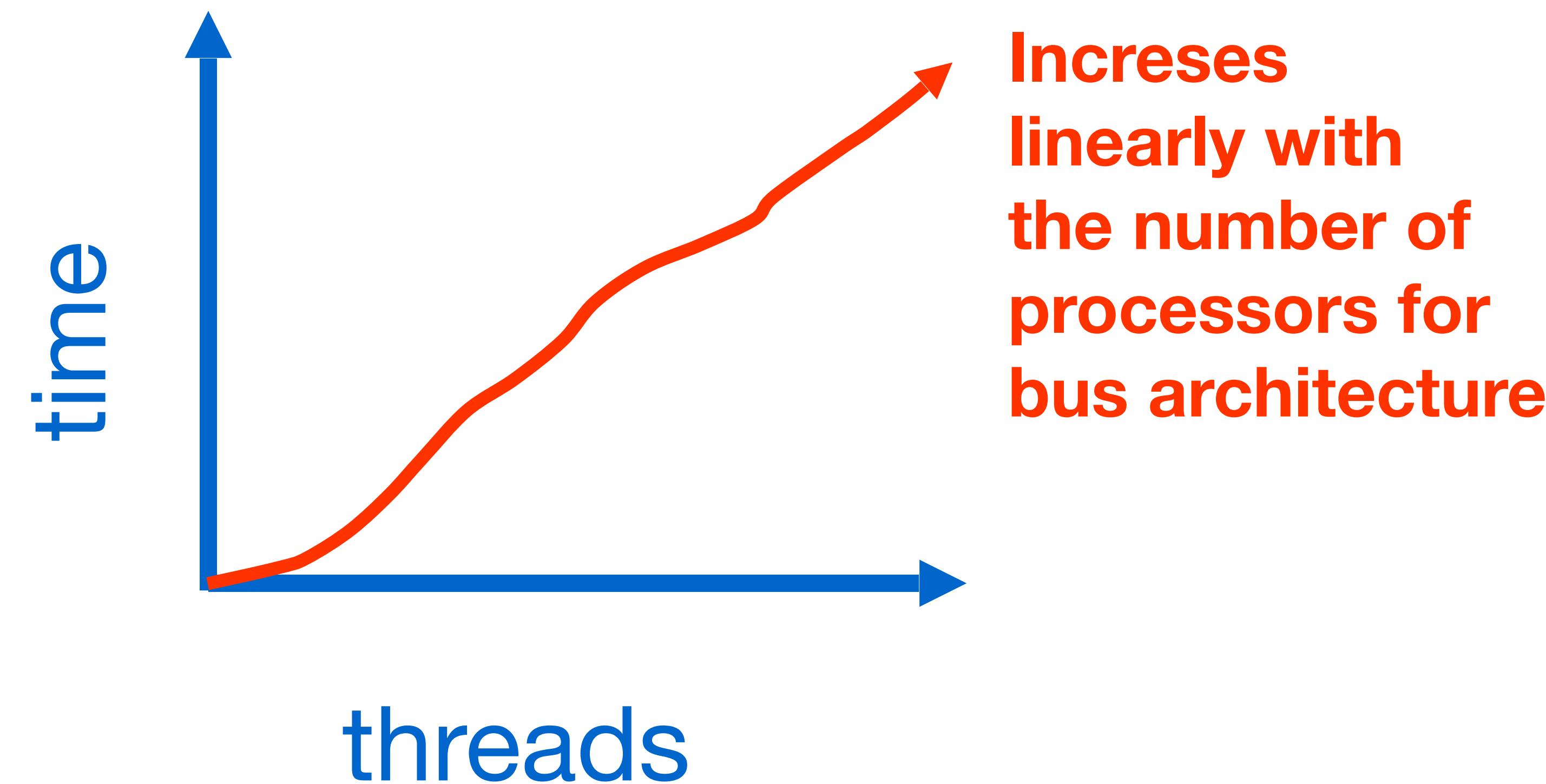
Everyone tries TAS



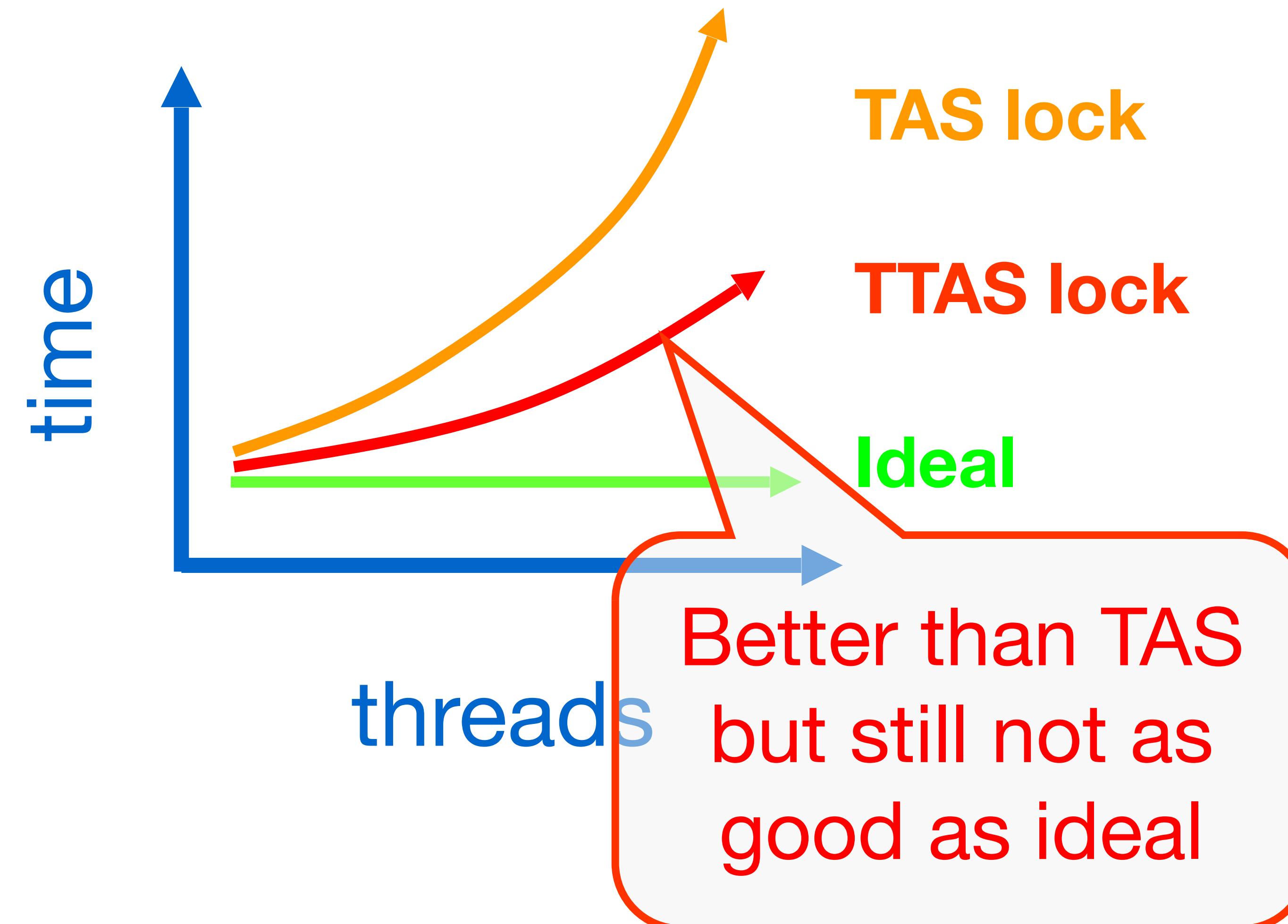
Problems

- Everyone misses
 - Reads satisfied sequentially
- Everyone does TAS
 - Invalidates others' caches
- Eventually ***quiesces*** after lock acquired
- ***Quiescence duration*** is the time between lock release and lock acquire
 - How long does this take?

Quiescence Time

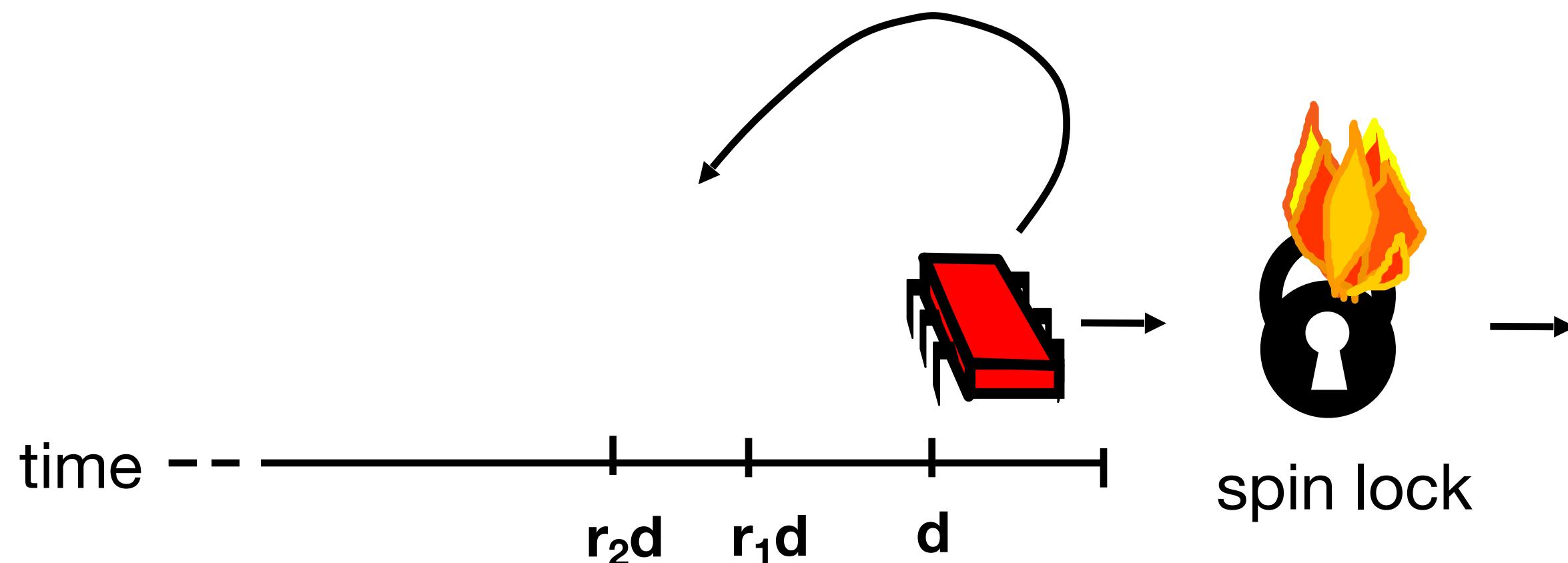


Mystery Explained

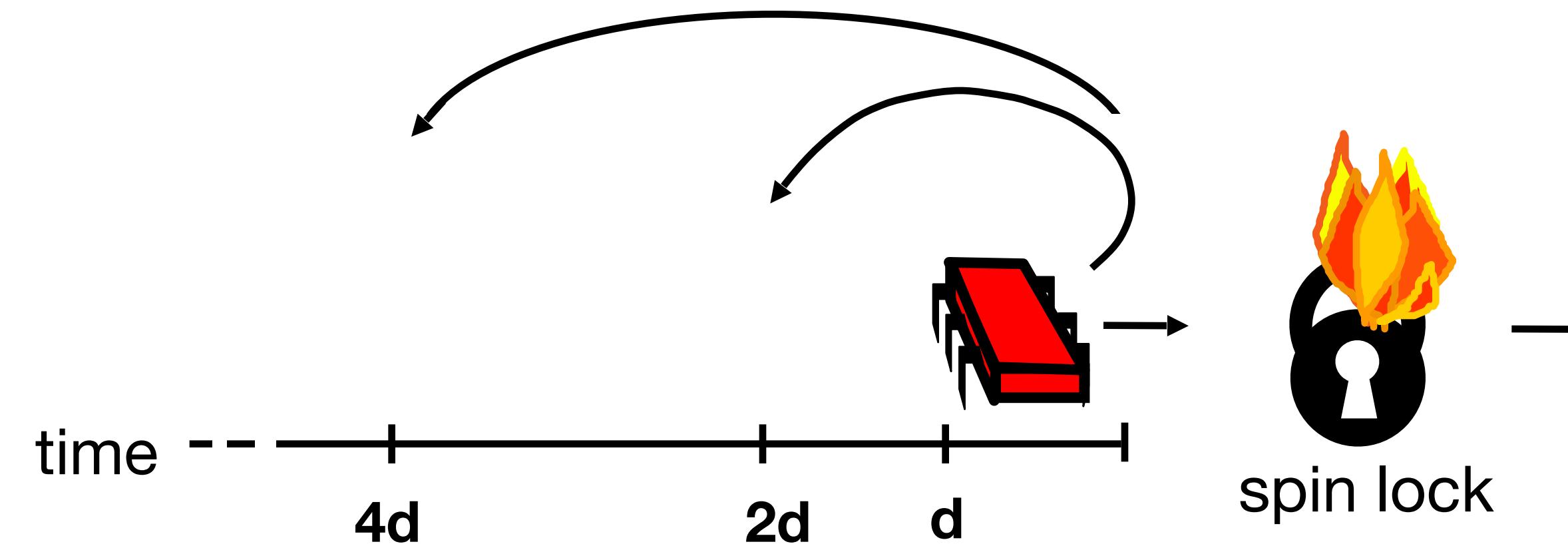


Solution: Introduce Delay

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



Dynamic Solution – Exponential backoff



If I fail to get lock

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

Exponential Backoff

```
module Backoff = struct
  type t = { min_delay : int; max_delay : int; mutable limit : int }

  let create min_delay max_delay = { min_delay; max_delay; limit = min_delay }

  let backoff t =
    (* Backoff for a random duration between 0 and 'limit' using cpu_relax *)
    (* Randomization prevents synchronized collisions between threads *)
    let delay = Random.int (t.limit + 1) in
    for _ = 1 to delay do
      Domain.cpu_relax ()
      (* Instructs the core to slow down fast(er than sleep()) *)
    done;
    (* Exponentially increase the limit, capped at max_delay *)
    t.limit <- min t.max_delay (t.limit * 2)
end
```

BackoffLock

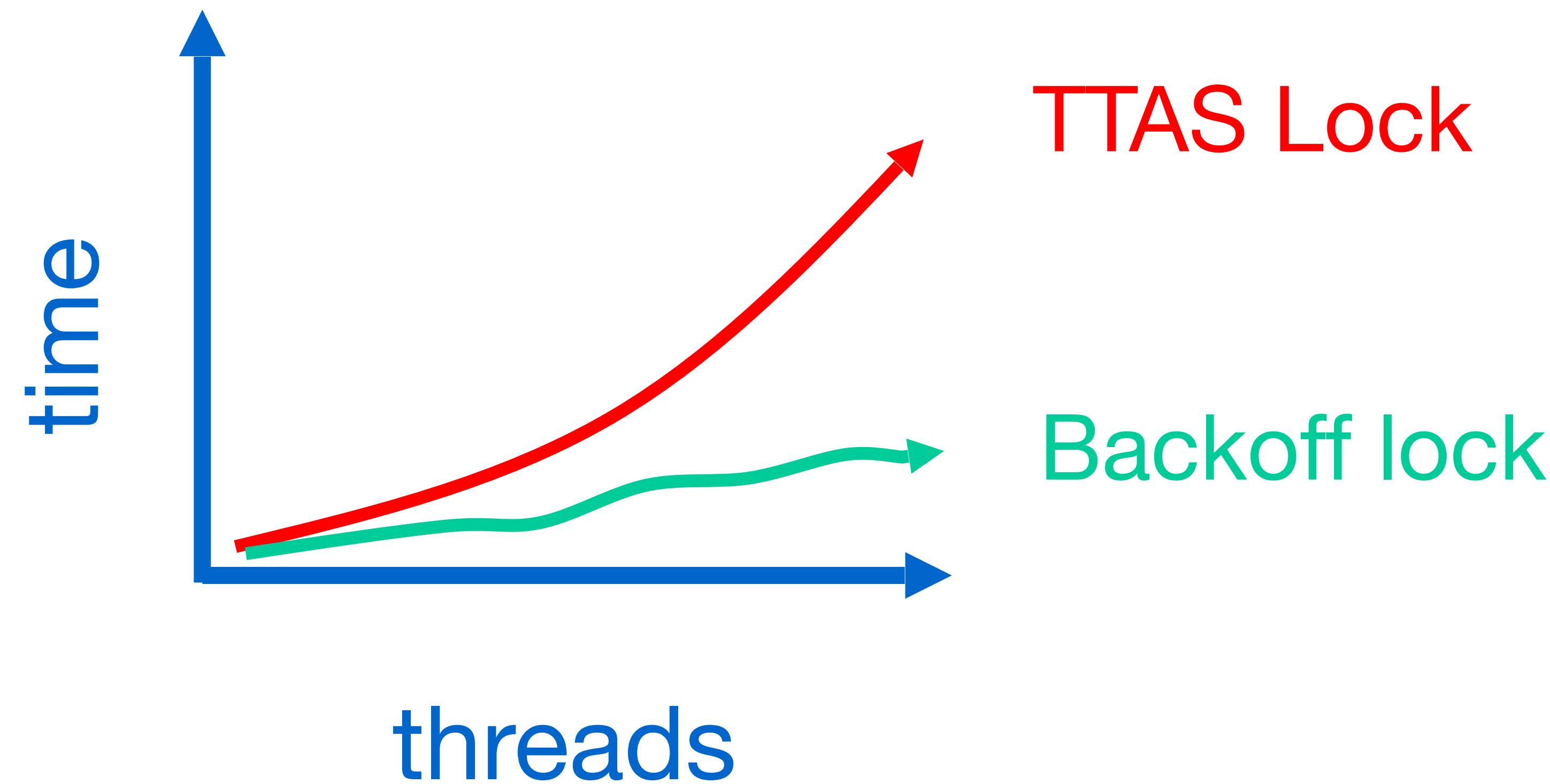
```
module MakeBackoffLock (P : BACKOFF_PARAMS) : Lock.LOCK = struct
  type t = { state : bool Atomic.t }

  let create () = { state = Atomic.make false }

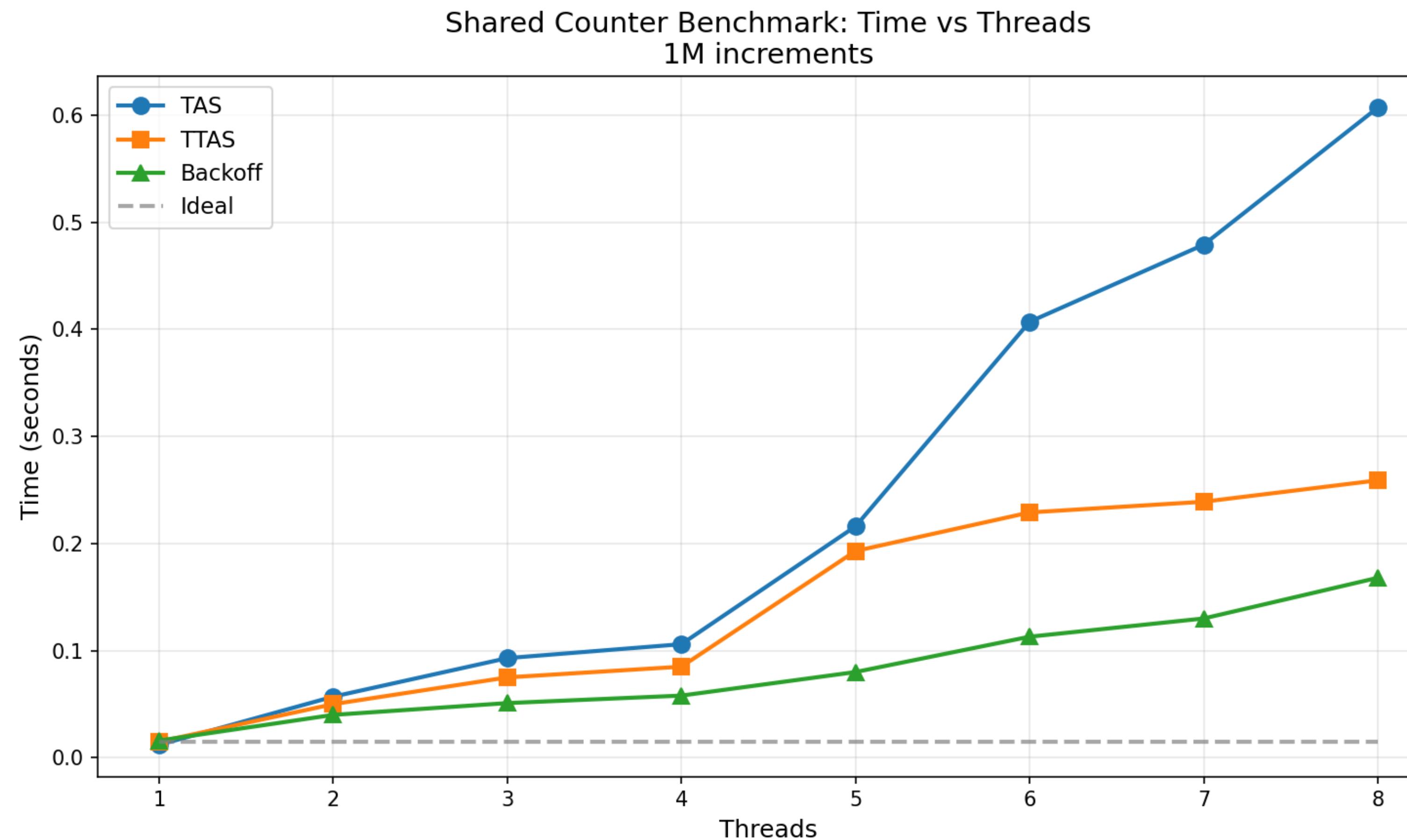
  let lock t =
    let backoff = Backoff.create P.min_delay P.max_delay in
    (* Outer loop: keep trying until we get the lock *)
    while
      (* Inner loop: spin-read until lock appears free *)
      while Atomic.get t.state do
        ()
      done;
      (* Lock looks free, try to acquire *)
      Atomic.exchange t.state true
    do
      (* Failed to acquire – back off before trying again *)
      Backoff.backoff backoff
    done

    let unlock t = Atomic.set t.state false
  end
```

Spin-waiting Overhead



Results on 8-core M2 Apple Silicon



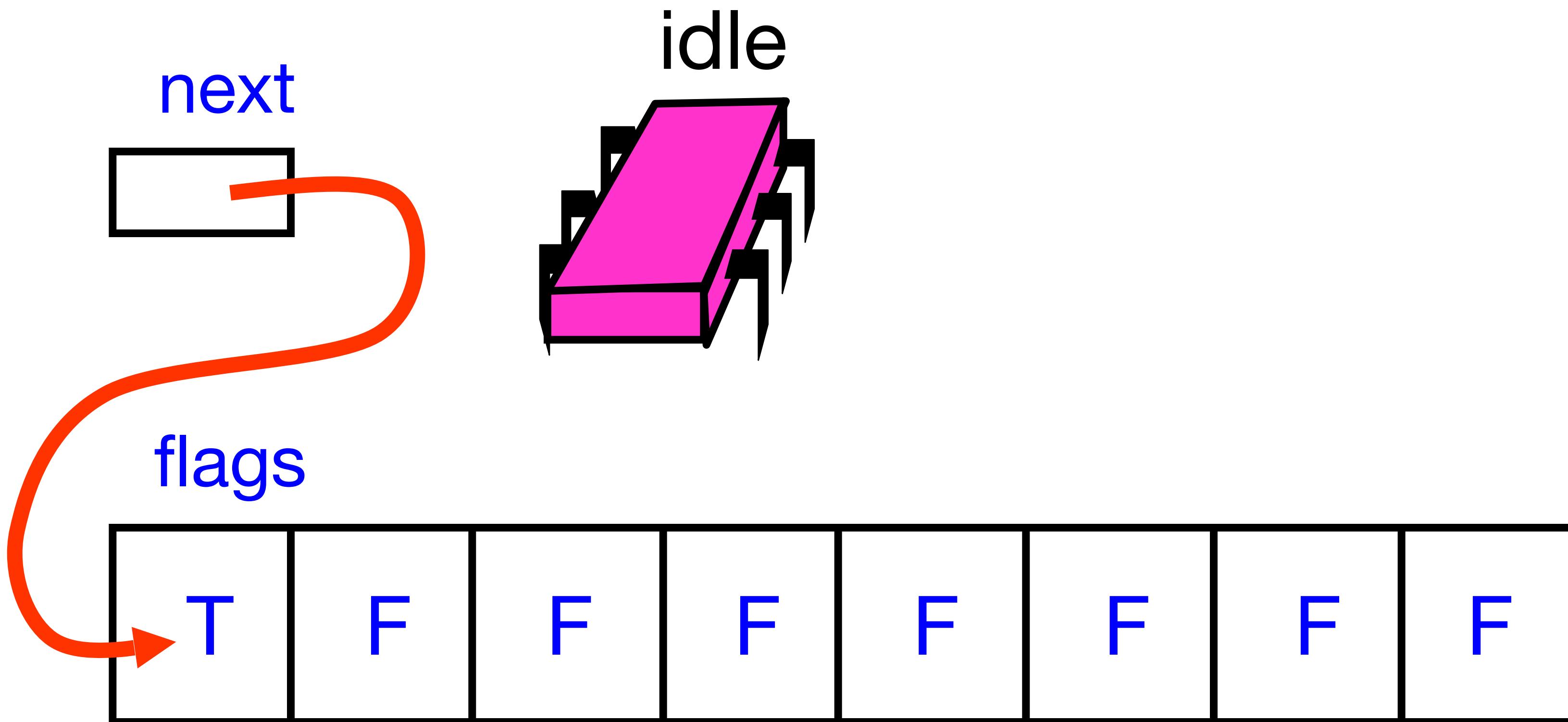
Backoff: Other issues

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

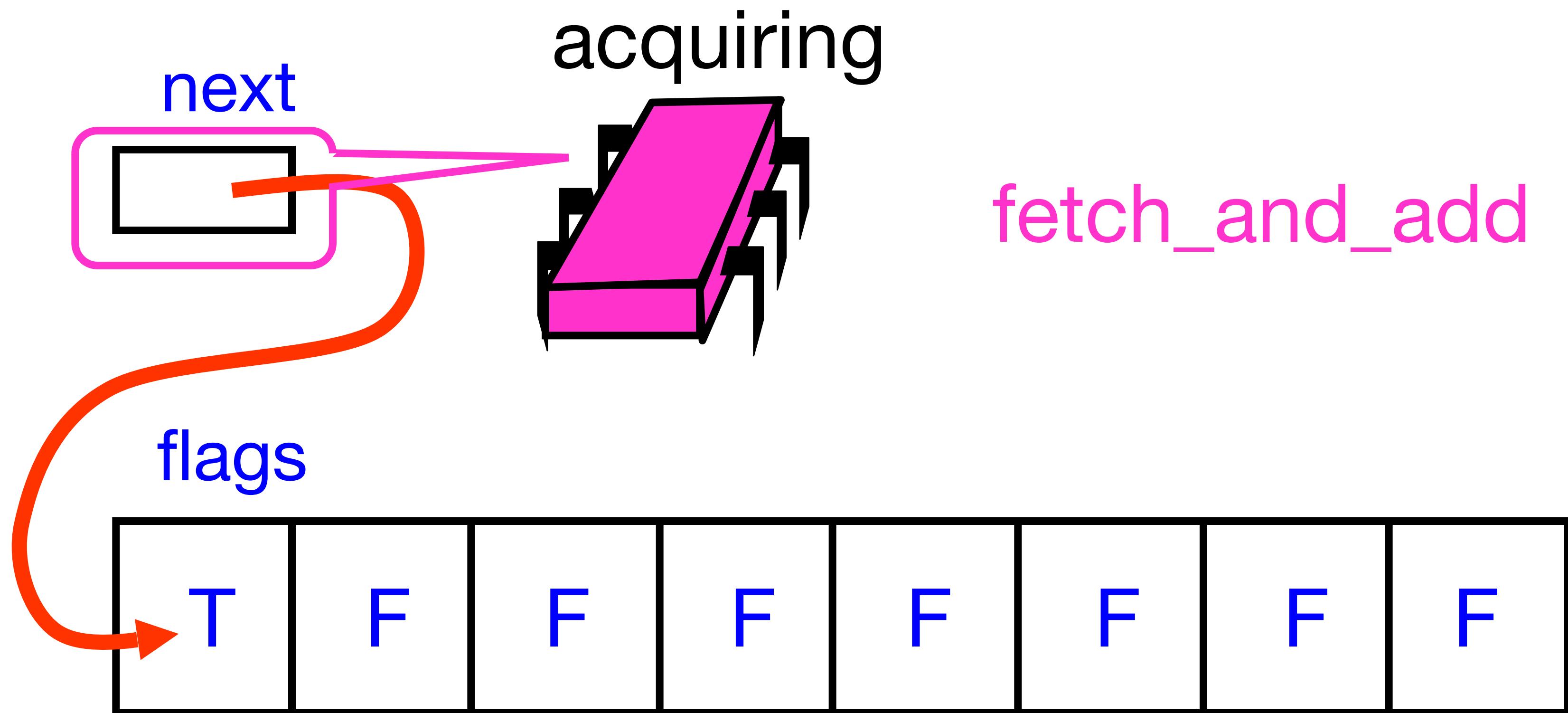
Idea

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

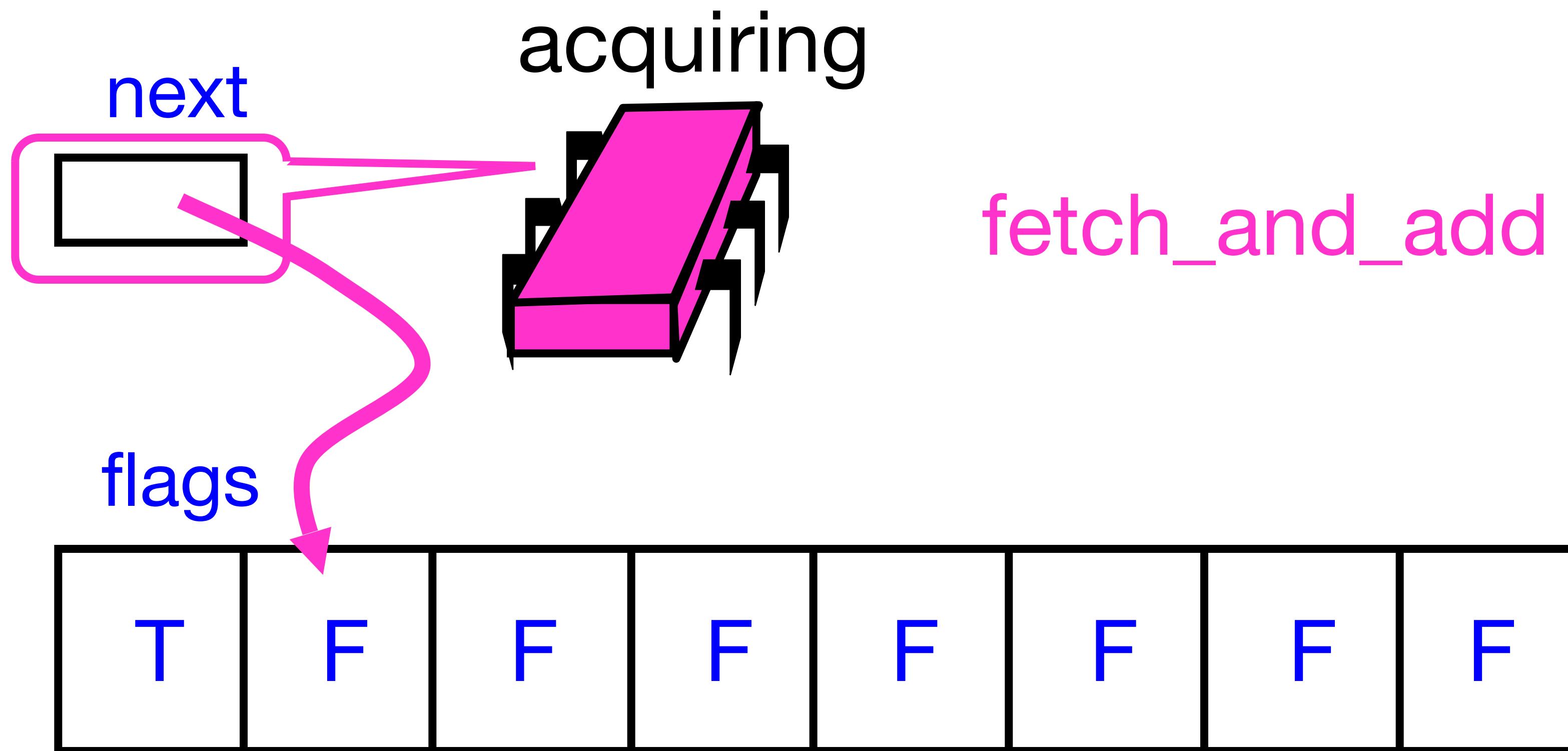
Anderson Queue Lock



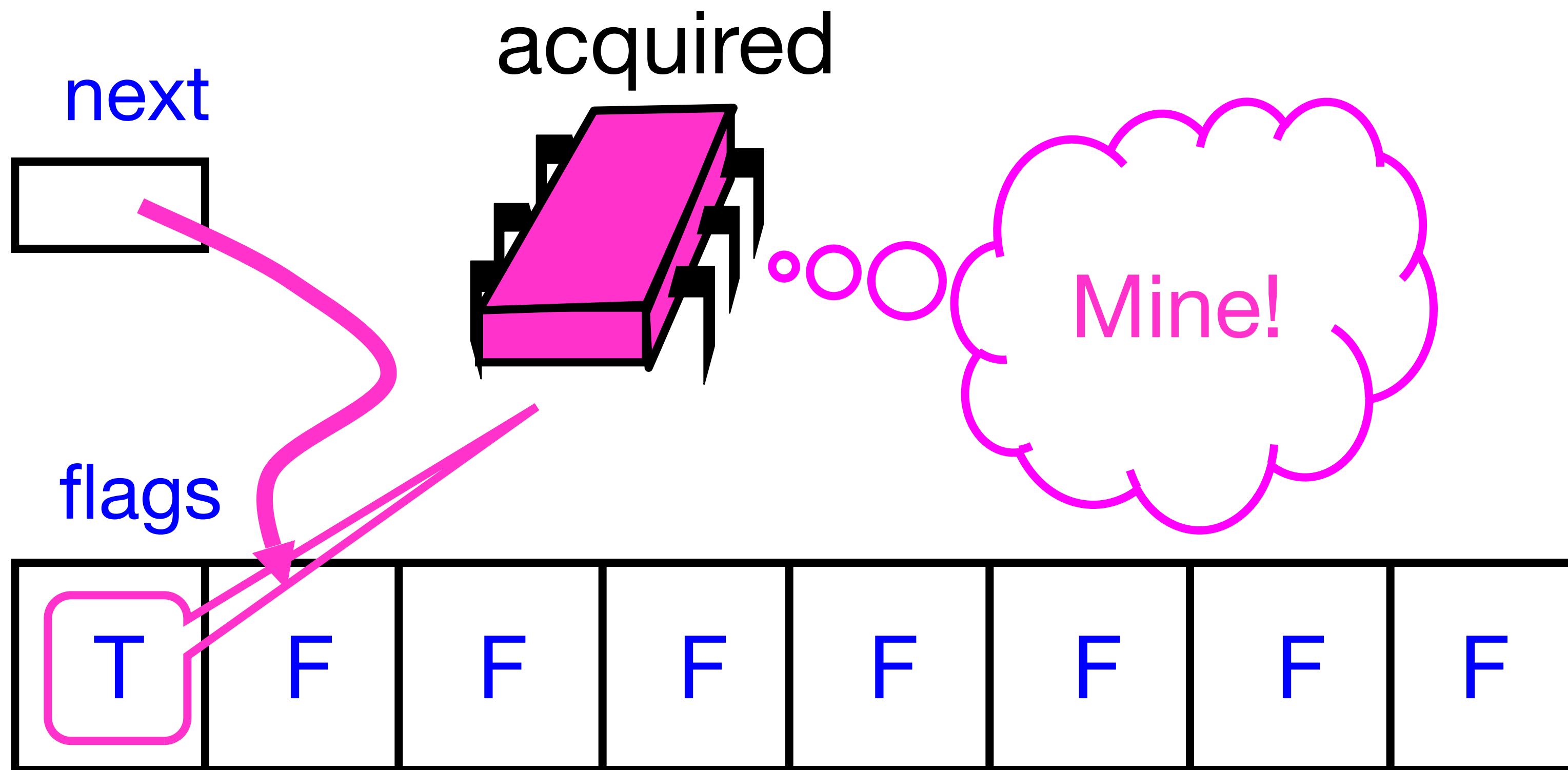
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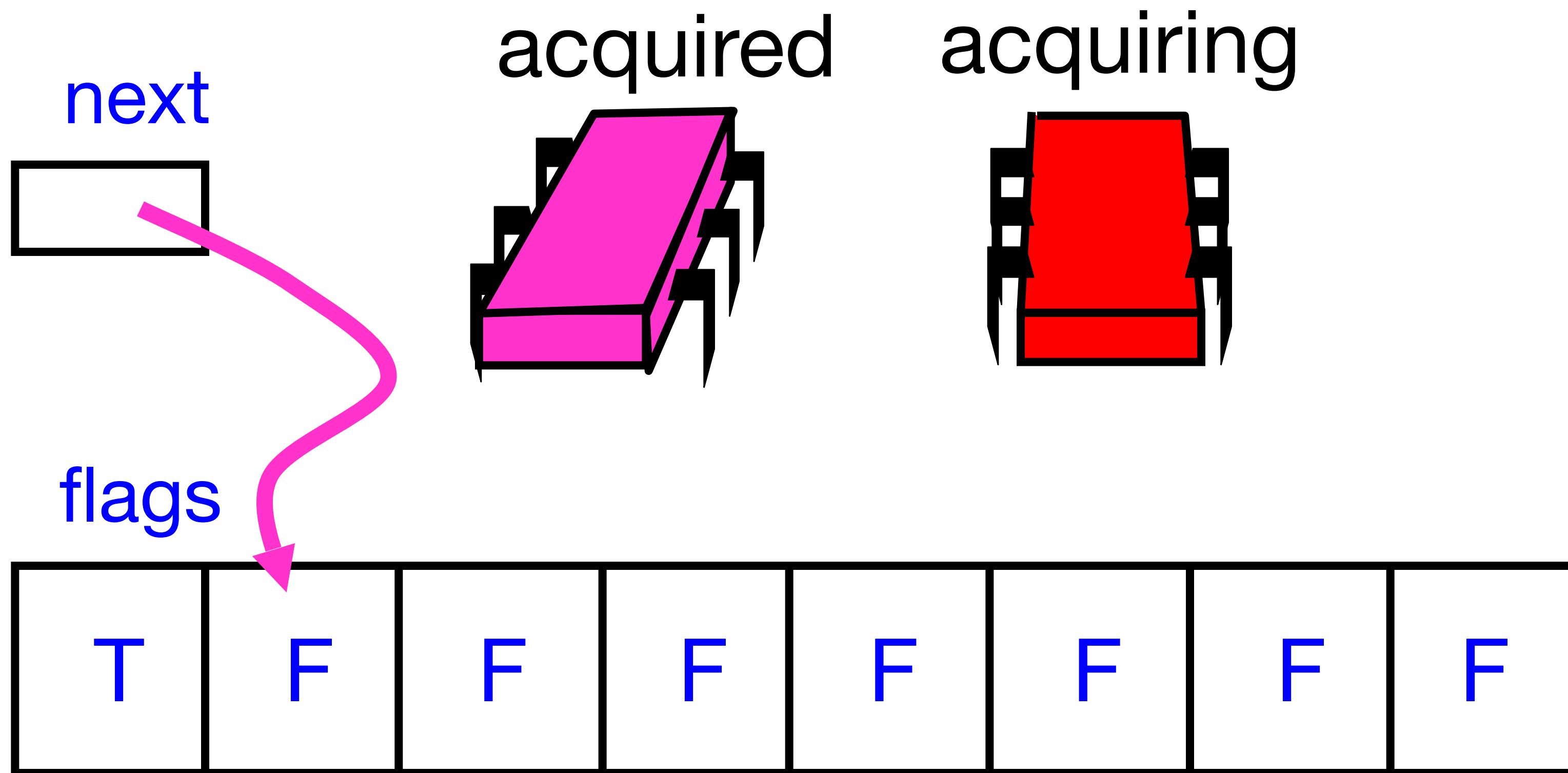
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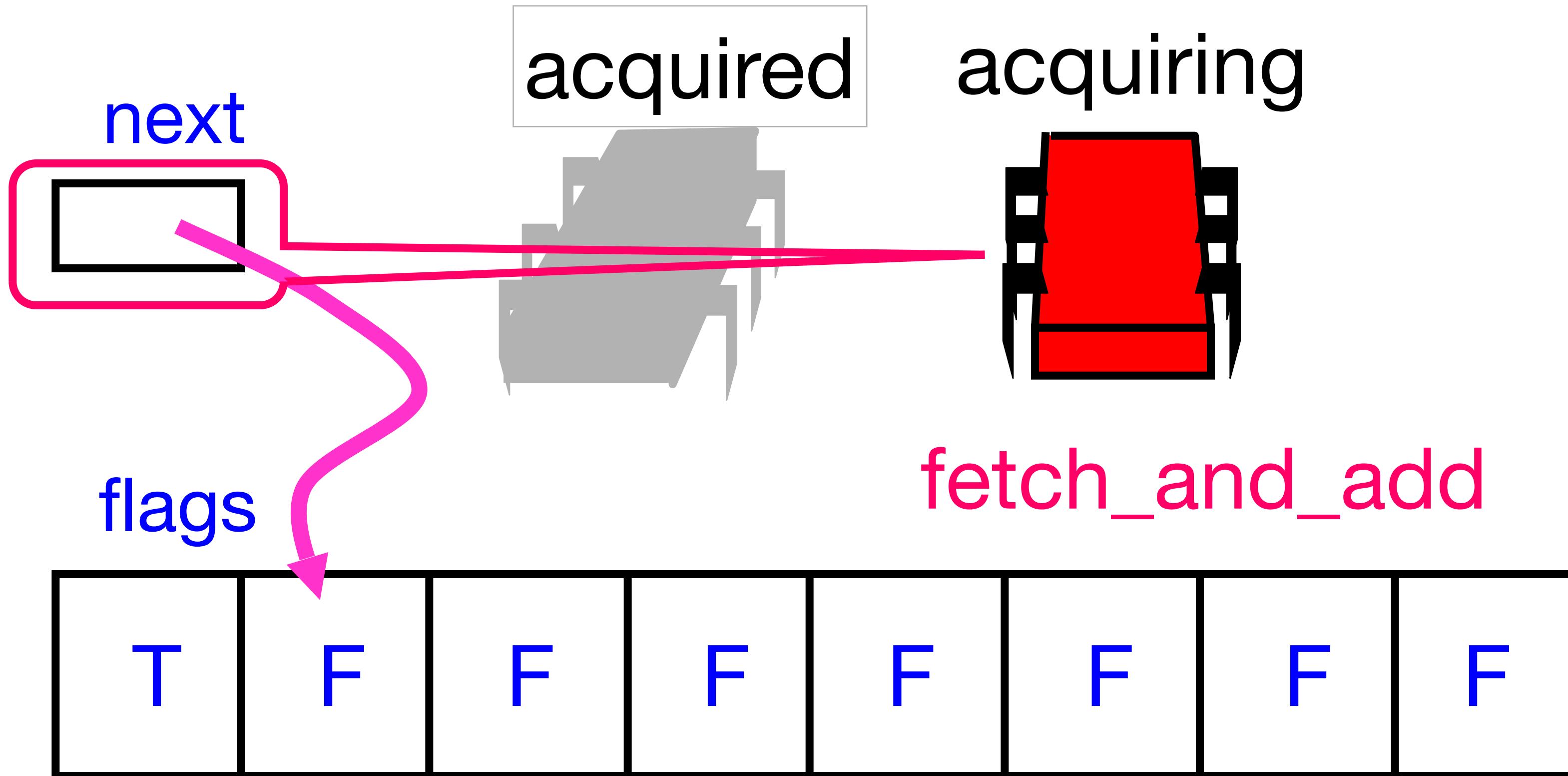
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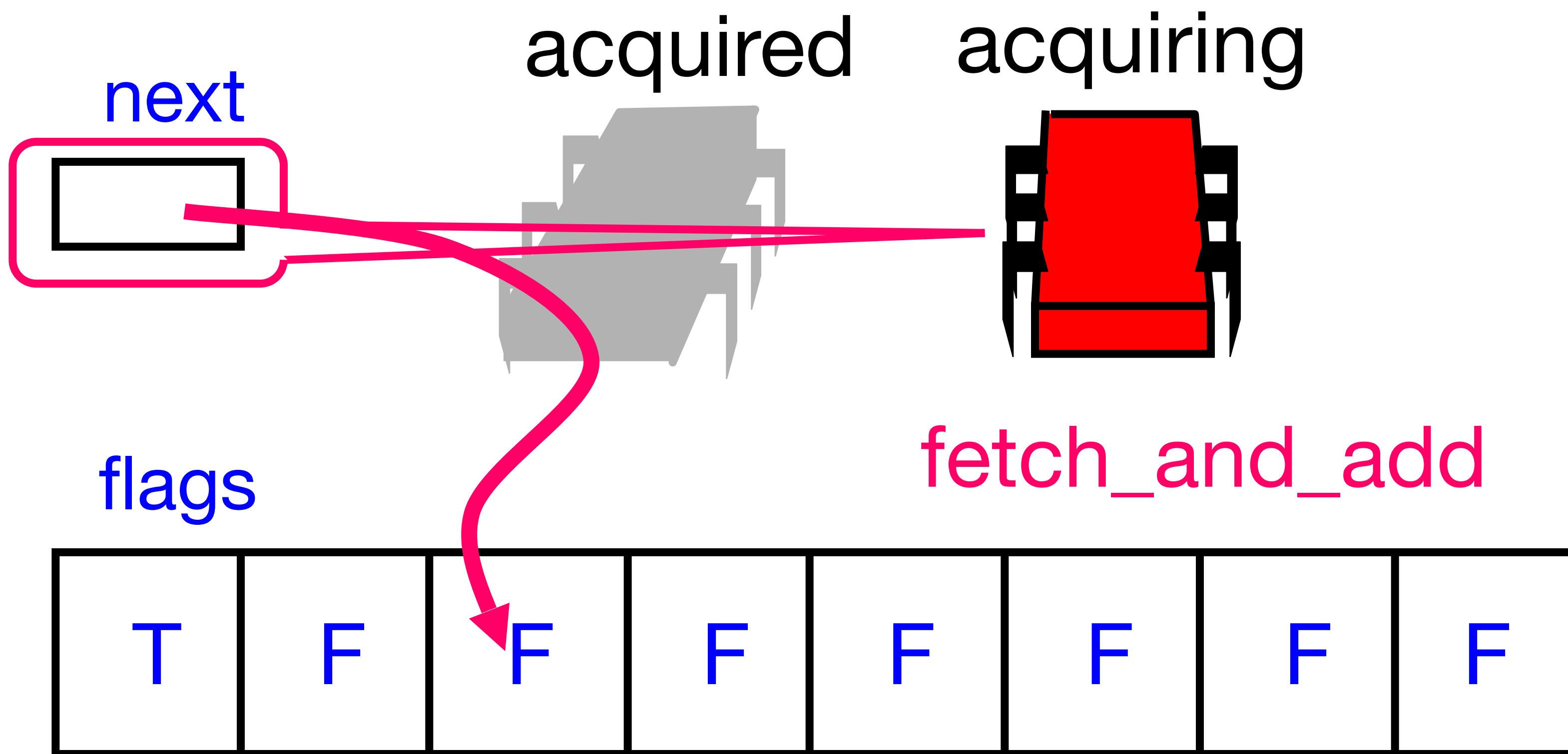
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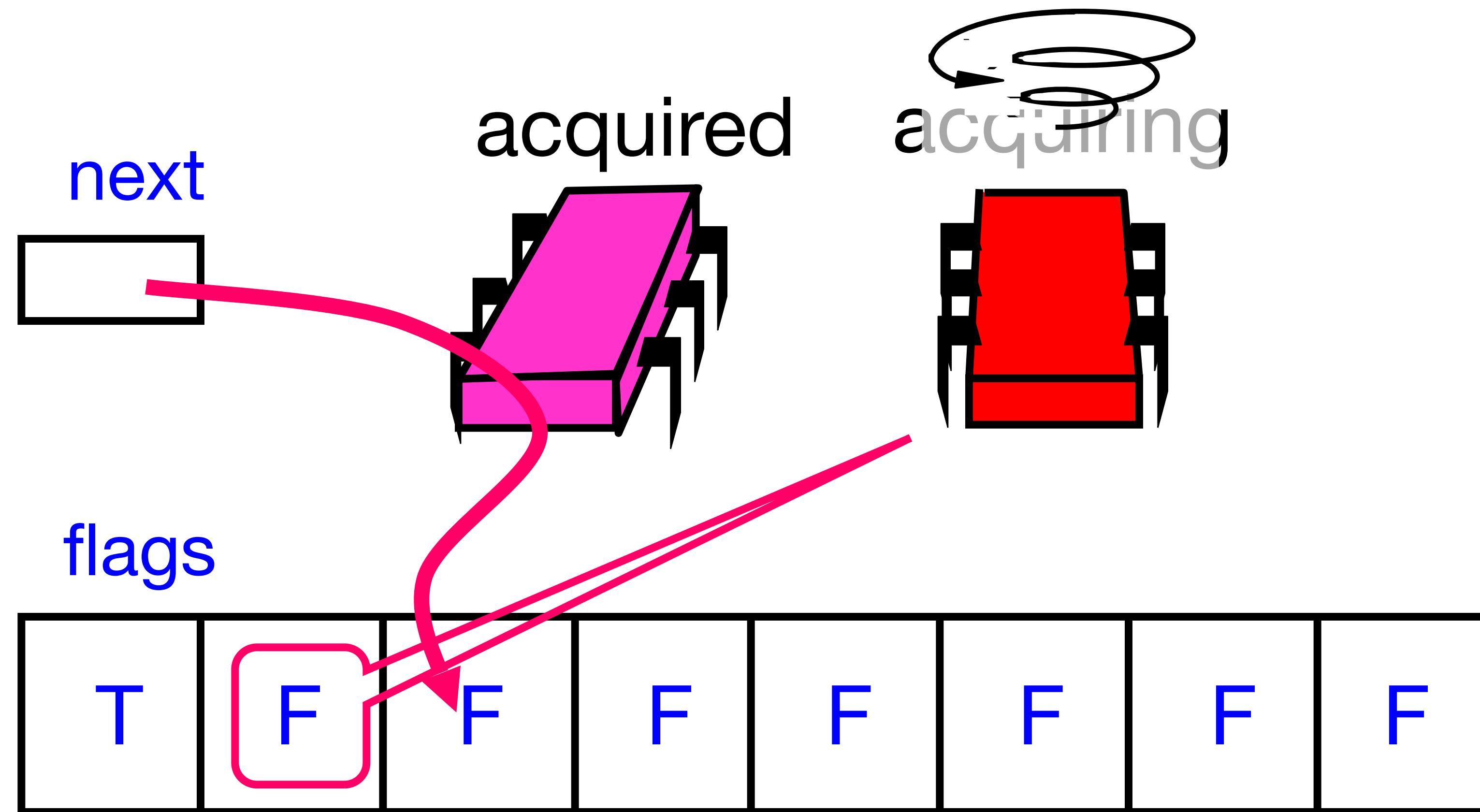
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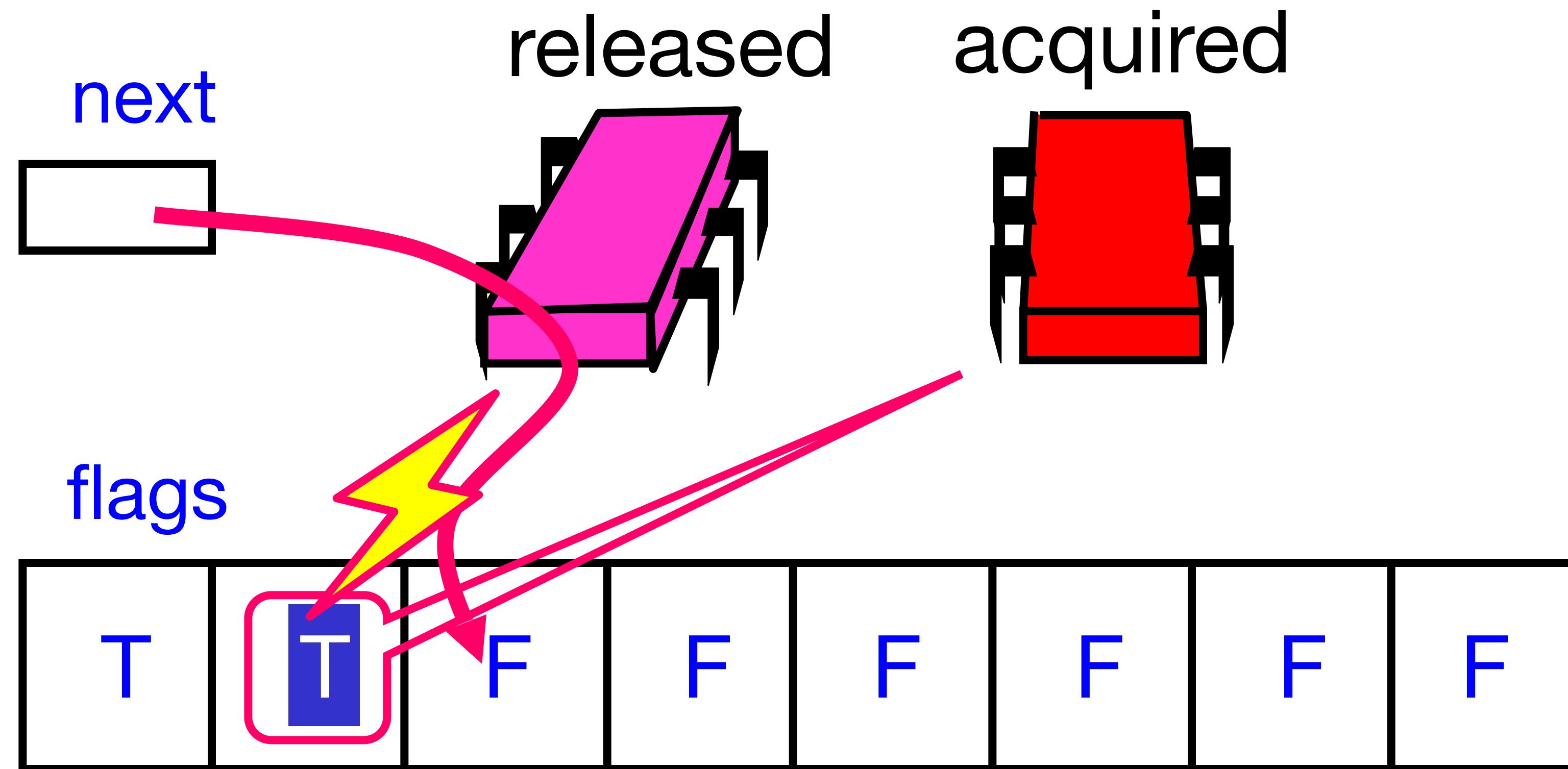
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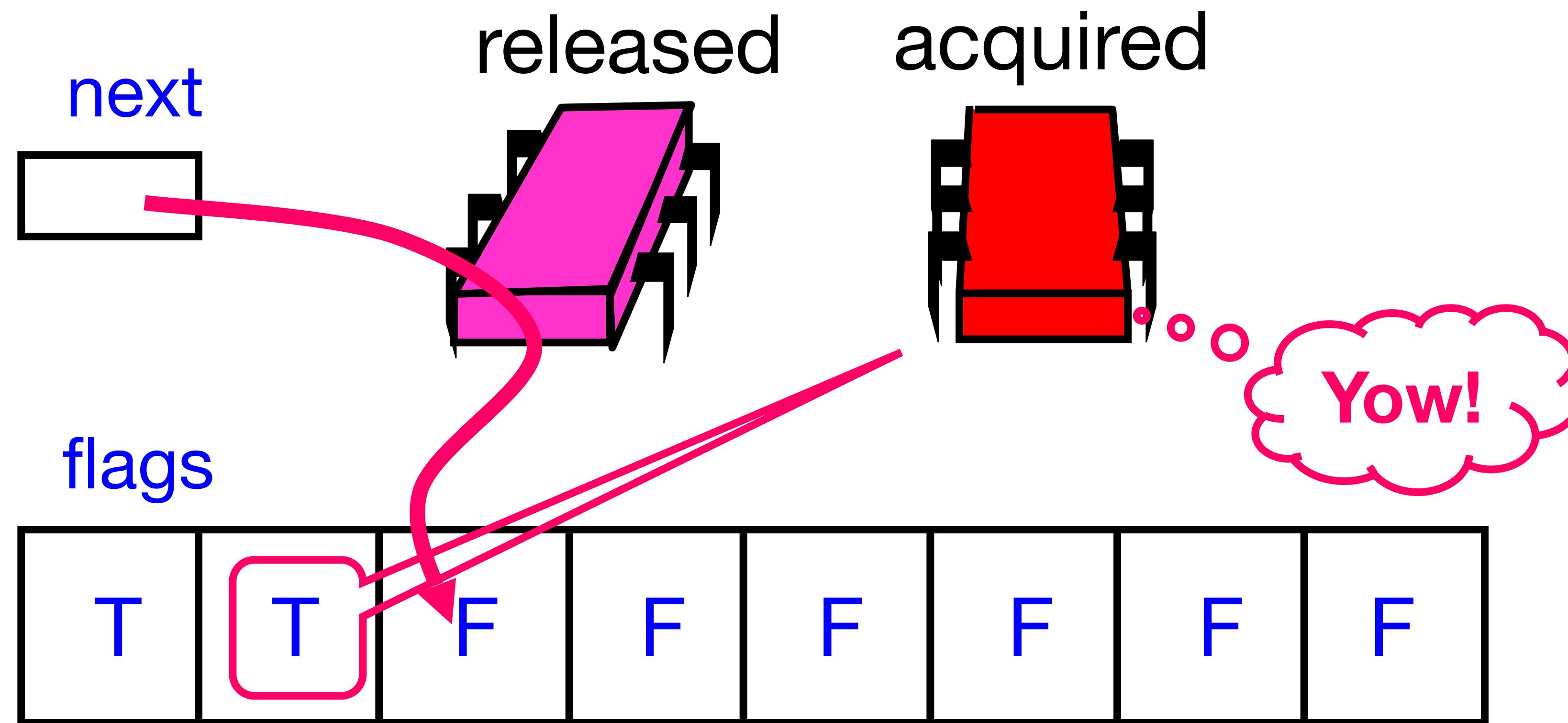
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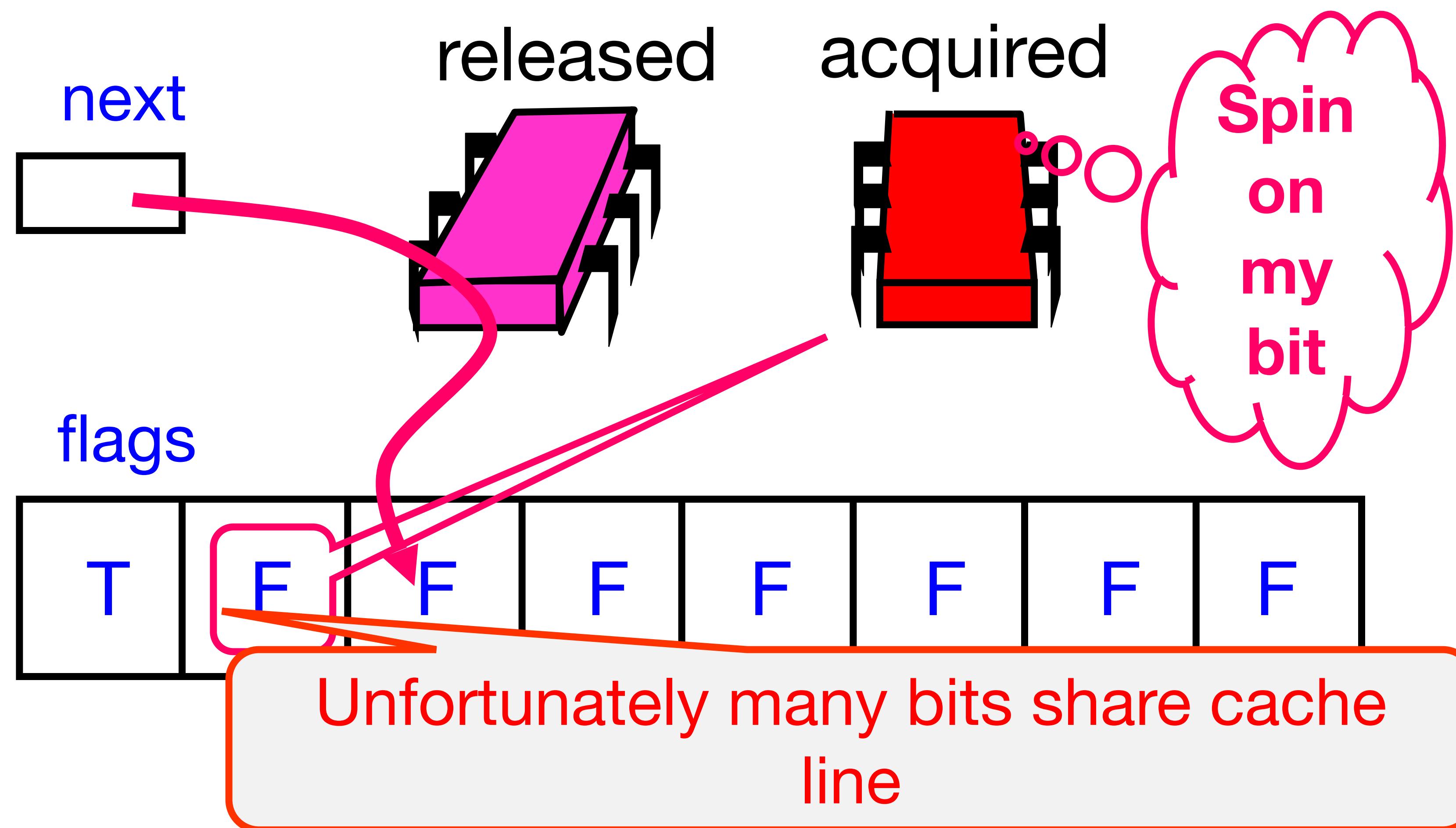
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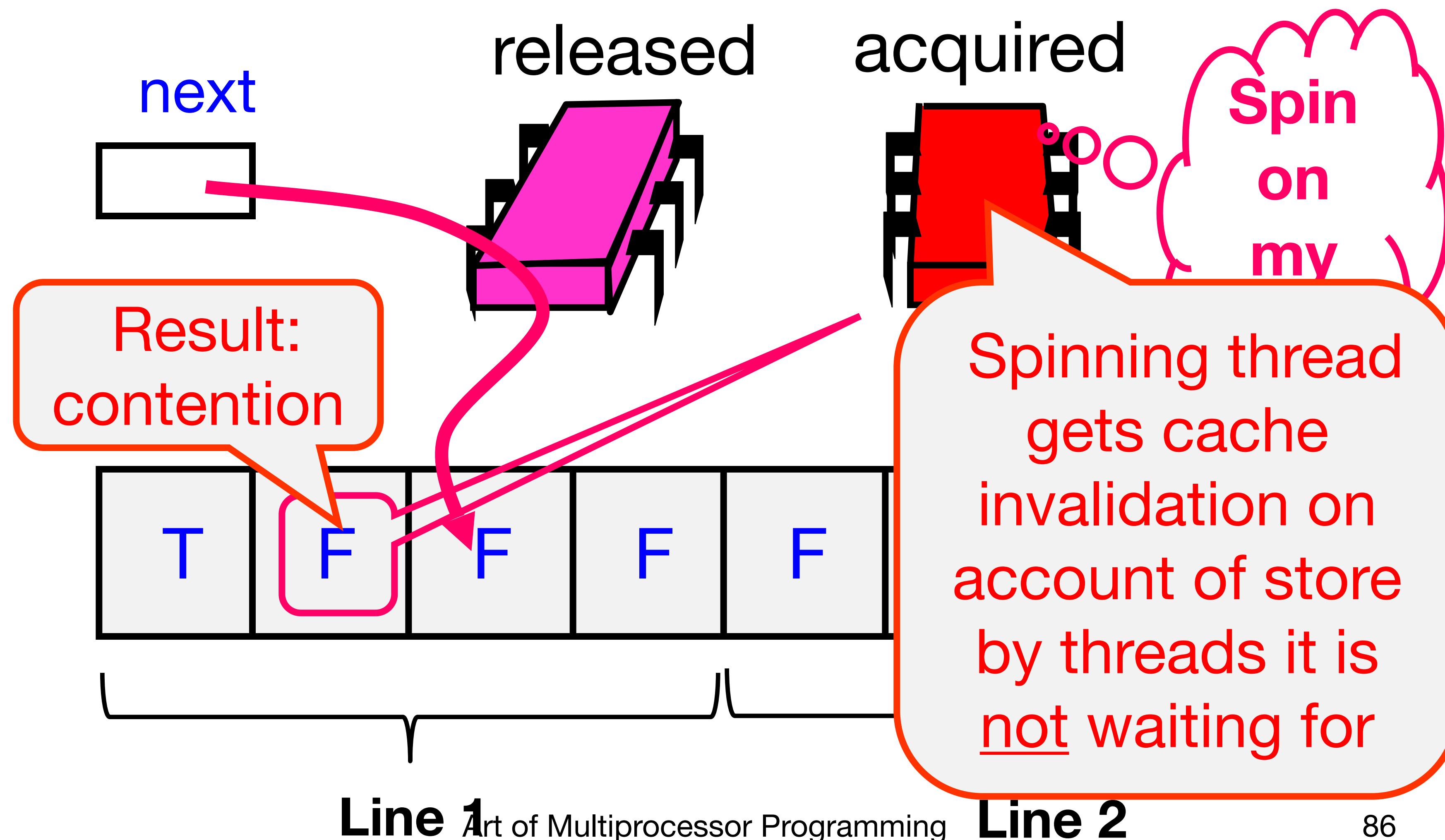
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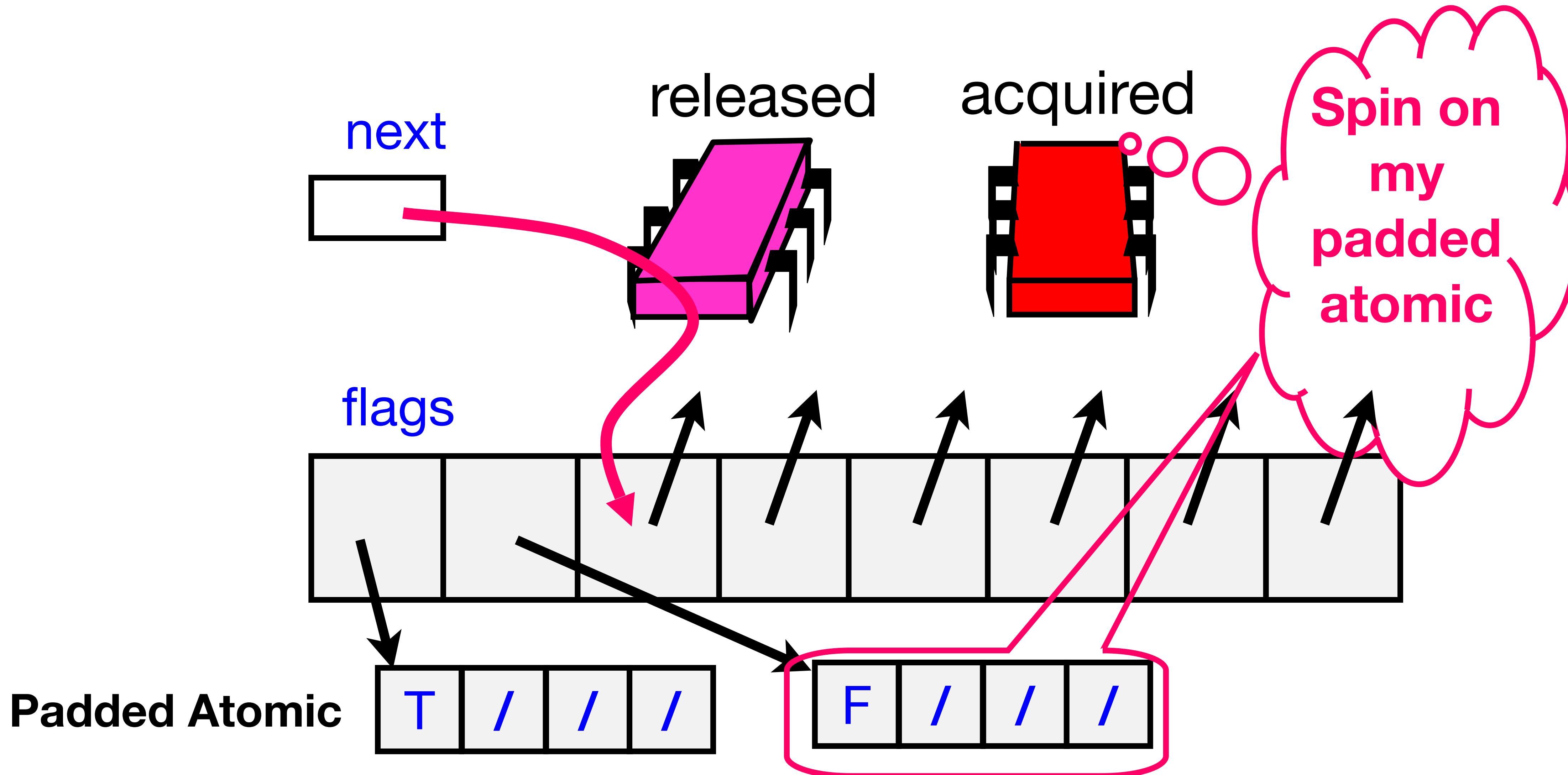
Local Spinning



False Sharing



OCaml Solution: Heap-separated allocation + padding



OCaml ALock

```
type t = {  
  flags : bool Atomic.t array;  
  tail : int Atomic.t;  
  capacity : int;  
  my_slot : int Domain.DLS.key;  
}
```

```
let create_with_capacity capacity =  
  if capacity <= 0 then  
    invalid_arg "ALock capacity must be positive";  
  
  (* Create array of atomic booleans using  
   * make_contended to prevent false sharing *)  
let flags =  
  Array.init capacity (fun i ->  
    (* Only slot 0 starts as true (available) *)  
    Atomic.make_contended (i = 0))  
in  
{  
  flags;  
  tail = Atomic.make 0;  
  capacity;  
  (* DLS for remembering slot taken by domain *)  
  my_slot = Domain.DLS.new_key (fun () -> -1);  
}
```

OCaml ALock

```
let lock t =
  (* Get my slot using atomic fetch-and-increment *)
  let slot = (Atomic.fetch_and_add t.tail 1) mod t.capacity in

  (* Store slot in domain-local storage for unlock *)
  Domain.DLS.set t.my_slot slot;

  (* Cache the flag reference to avoid repeated array indexing *)
  let my_flag = t.flags.(slot) in

  (* Spin on MY flag until it becomes true *)
  (* This is the key: each thread spins on a DIFFERENT location *)
  while not (Atomic.get my_flag) do
    Domain.cpu_relax ()
  done
```

OCaml ALock

```
let unlock t =
  (* Get my slot from domain-local storage *)
  let slot = Domain.DLS.get t.my_slot in

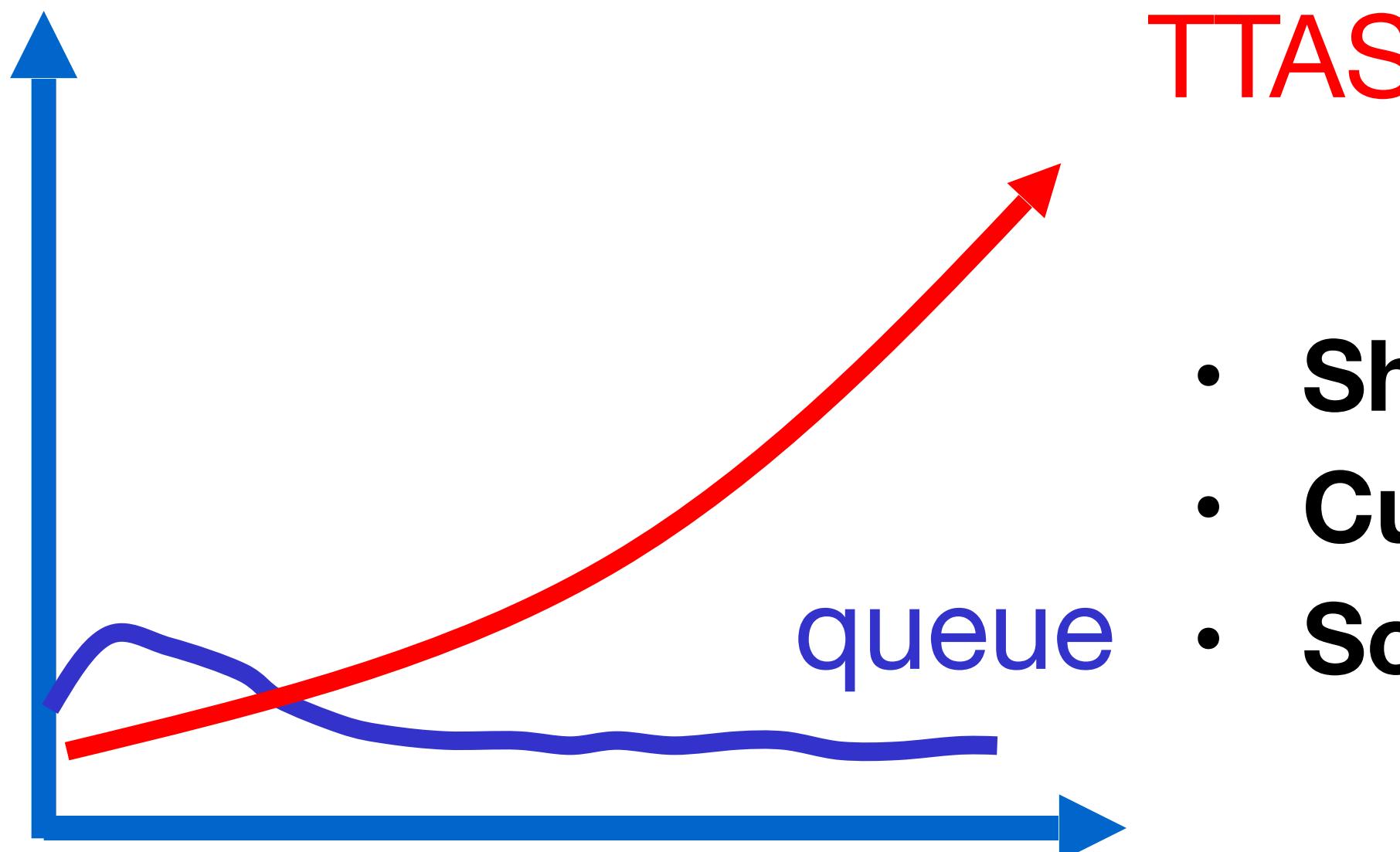
  if slot = -1 then
    failwith "unlock called without corresponding lock";

  (* Cache flag references *)
  let my_flag = t.flags.(slot) in
  let next_slot = (slot + 1) mod t.capacity in
  let next_flag = t.flags.(next_slot) in

  (* Clear my flag *)
  Atomic.set my_flag false;

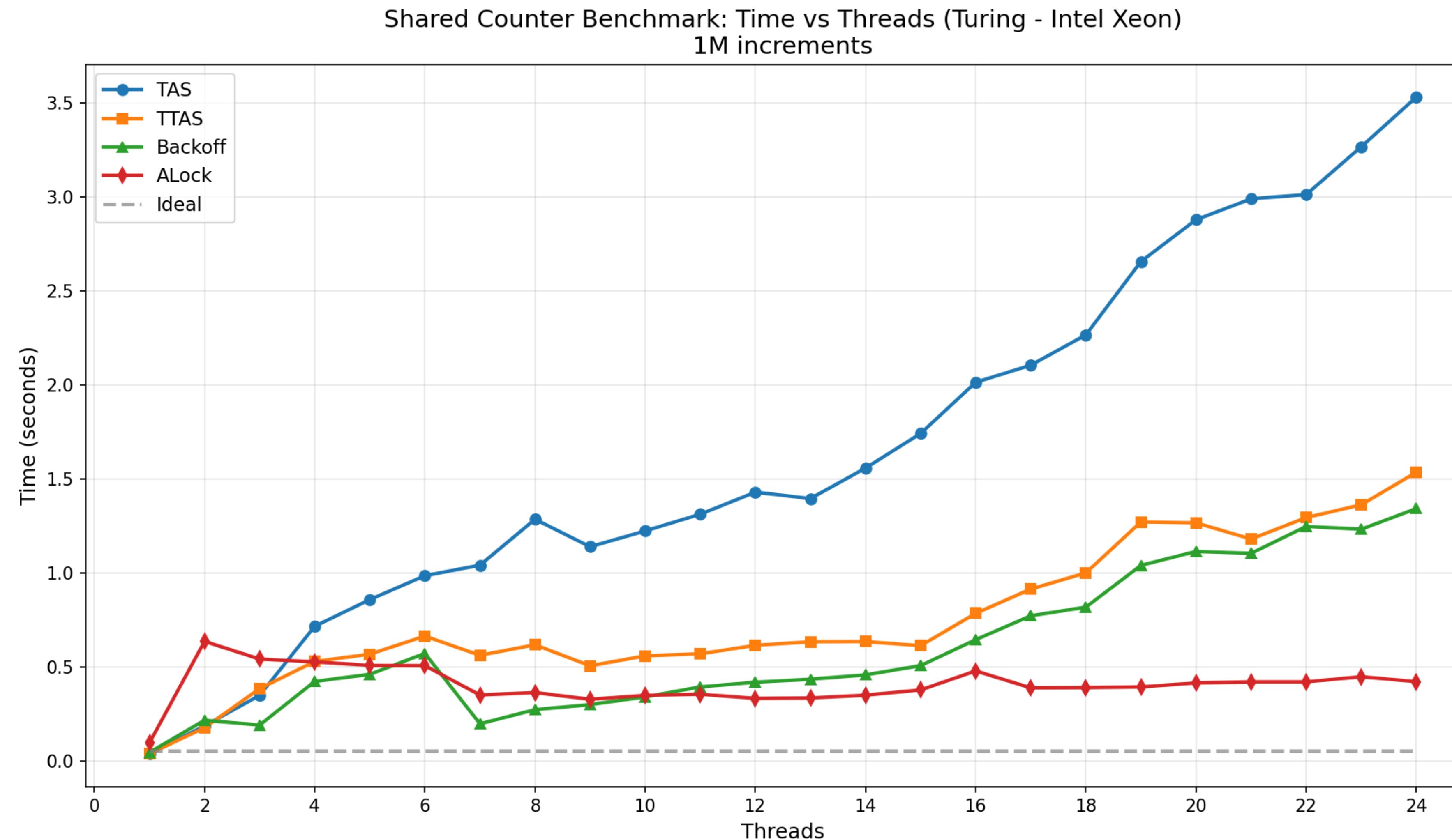
  (* Signal the next thread *)
  Atomic.set next_flag true
```

Performance



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

Results on 28-core Intel Xeon Gold 5120

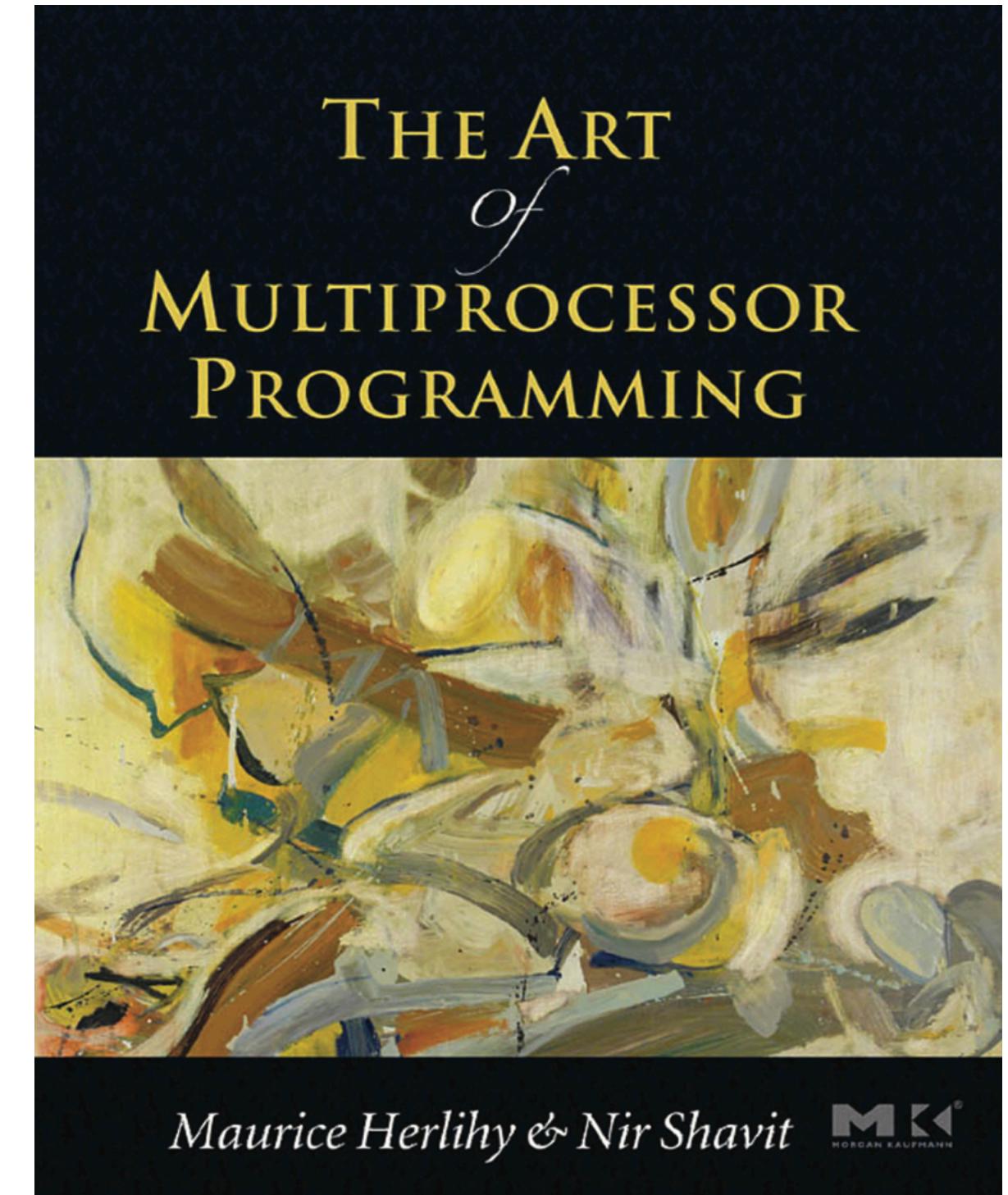


Anderson Queue Lock

- Good
 - First truly scalable lock
 - Simple, easy to implement
 - Back to FCFS order (like Bakery)
- Bad
 - Space hog...
 - One bit per thread → one cache line per thread
 - What if unknown number of threads?
 - What if small number of actual contenders?

More Spinlocks in the Book

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



Chapter 7



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