Spin Locks and Contention

Companion slides for

The Art of Multiprocessor Programming

by Maurice Herlihy & Nir Shavit

Focus so far: Correctness

- 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)

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

- SISD (Uniprocessor)
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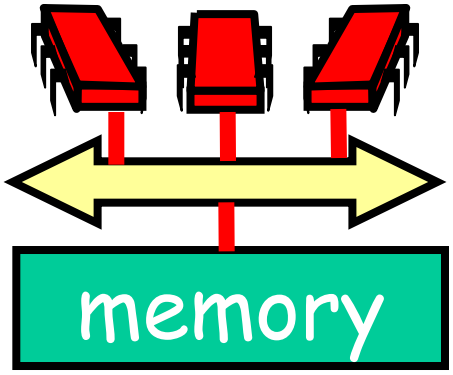
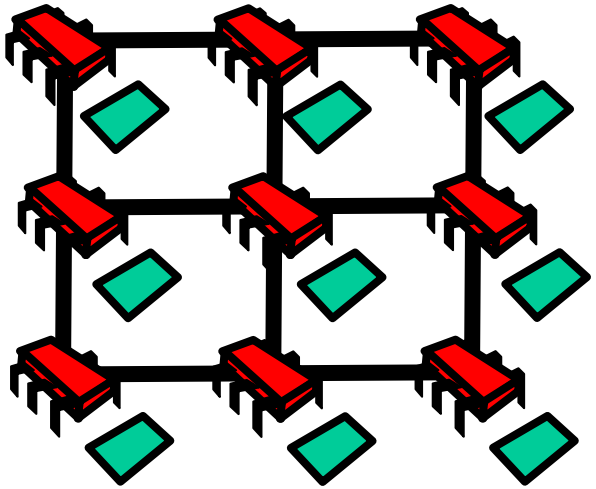
Our space

MIMD Architectures



Shared Bus



Distributed

- Memory Contention
- Communication Contention
- Communication Latency

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
- 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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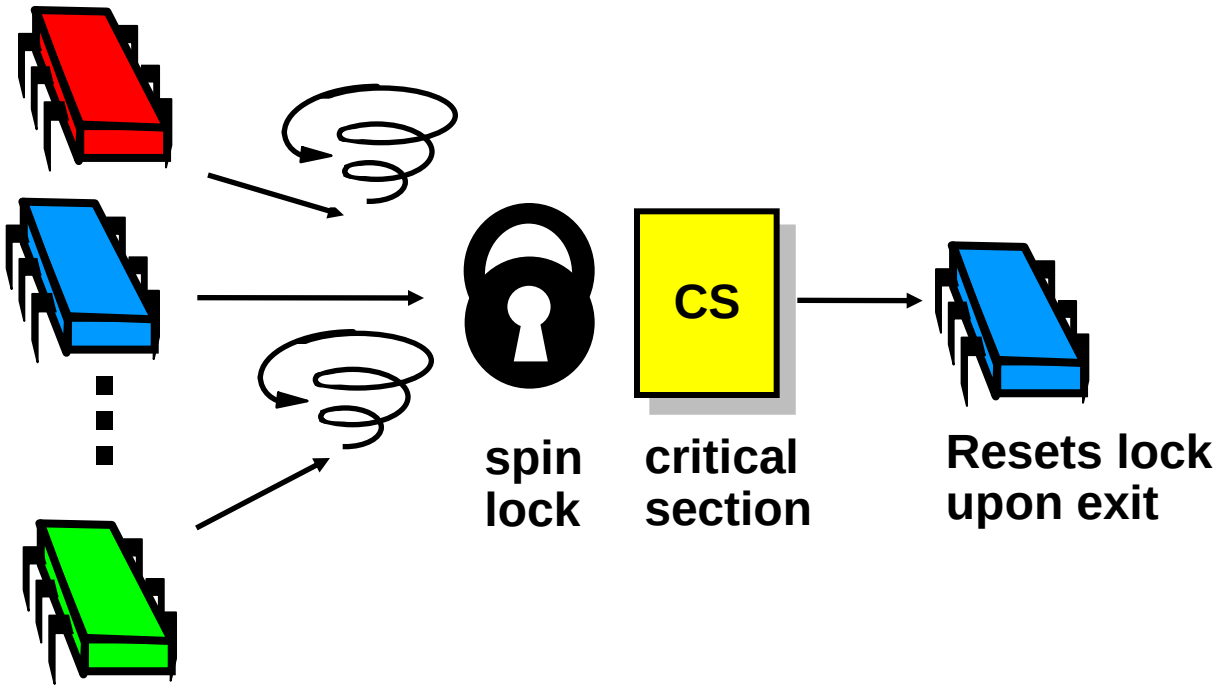
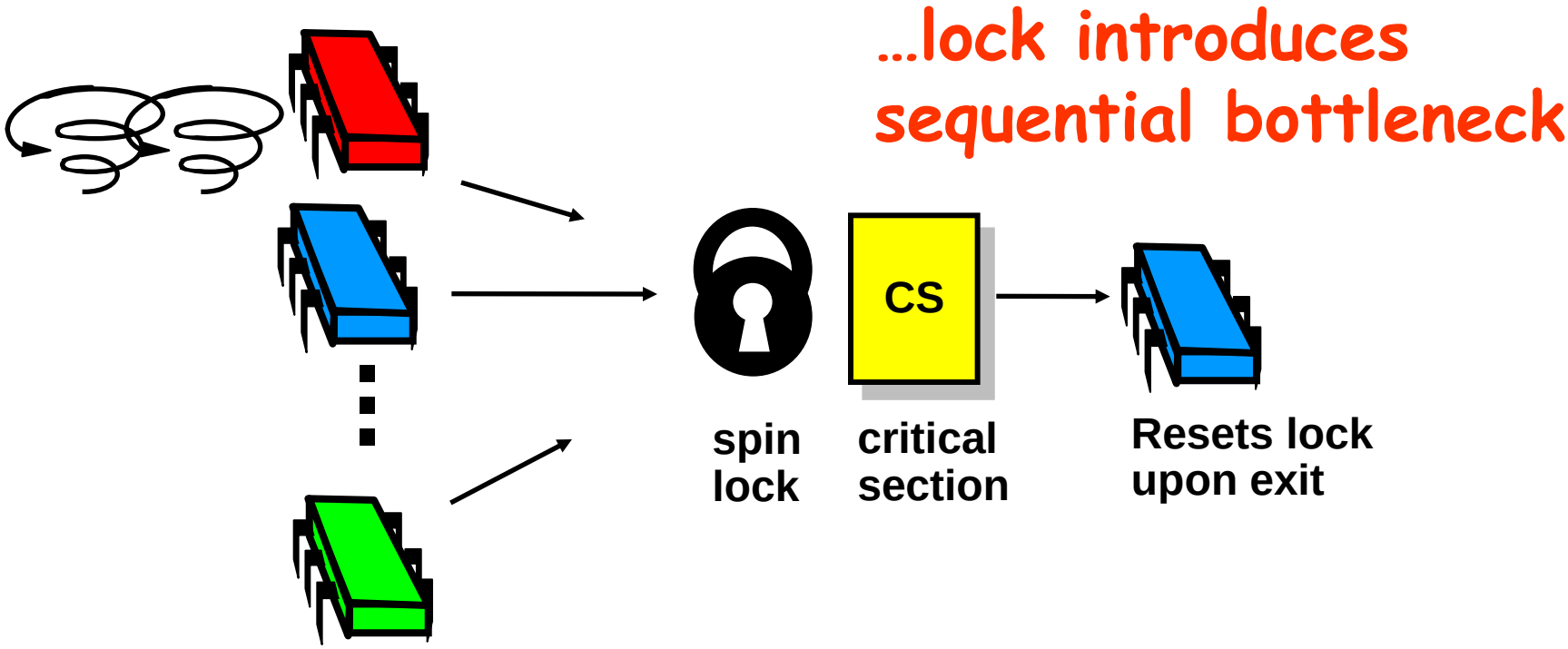
our focus

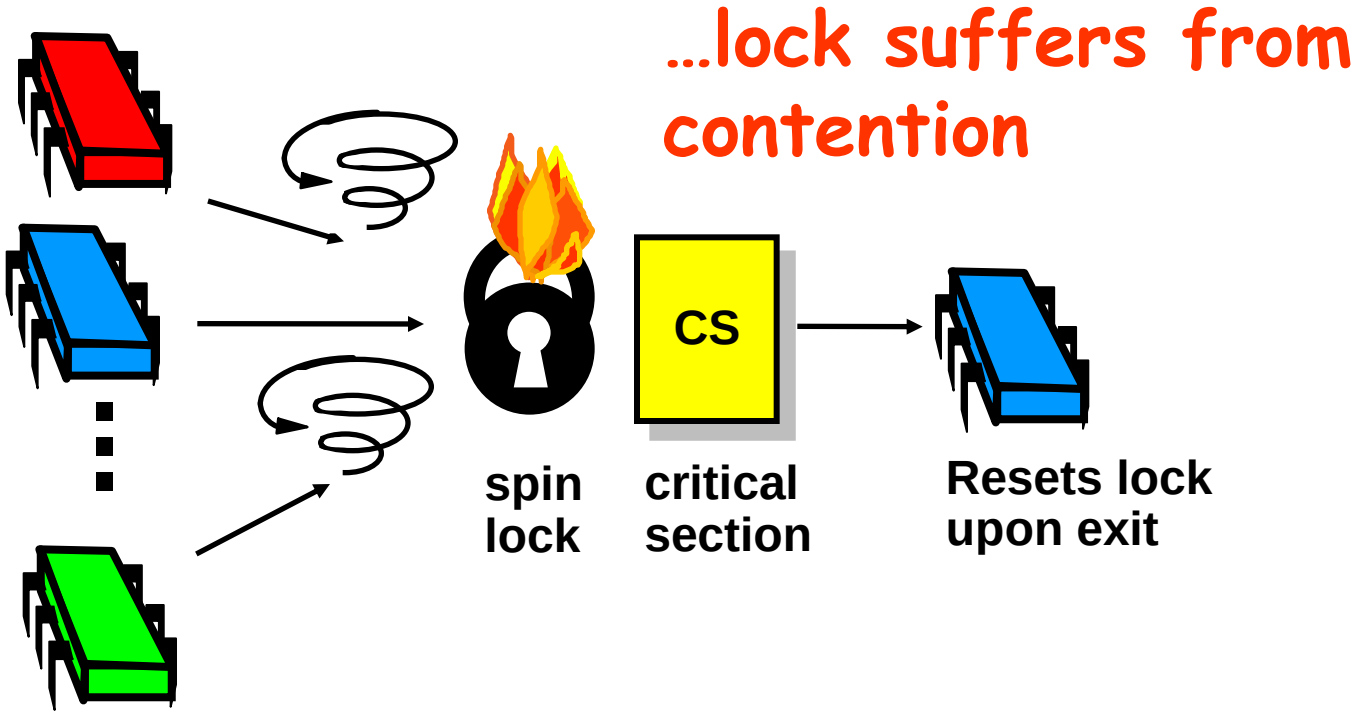
Basic Spin-Lock



Basic Spin-Lock



Basic Spin-Lock



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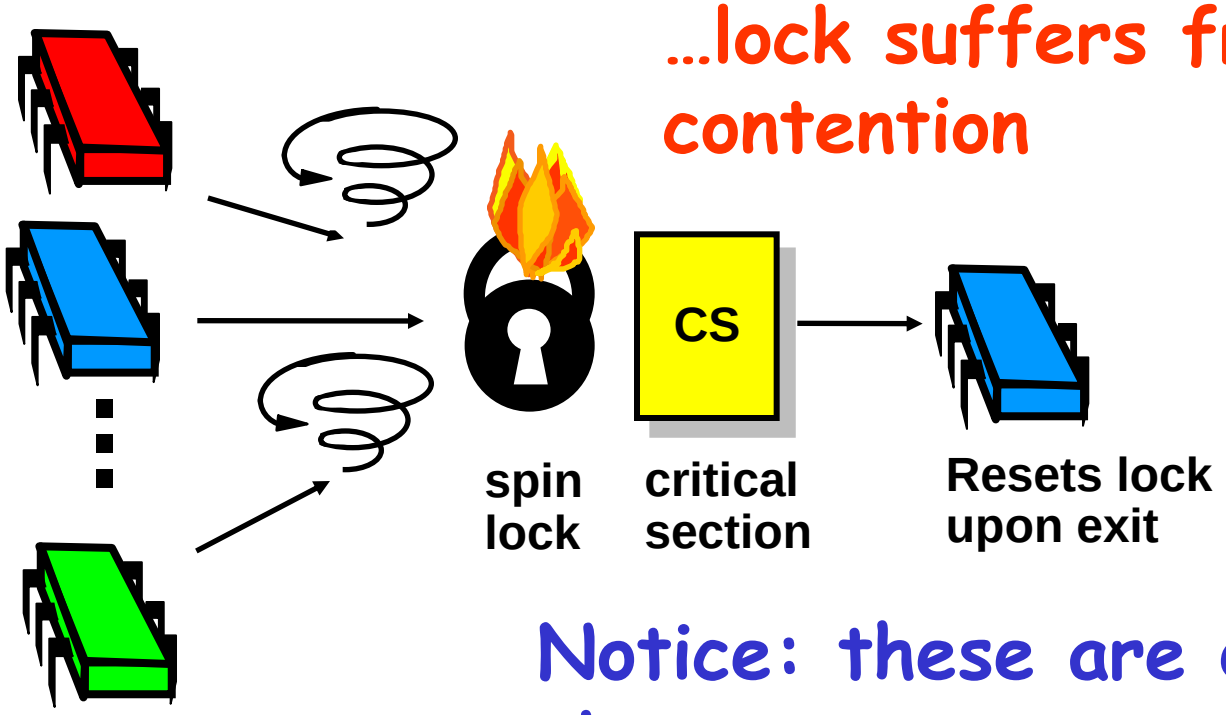
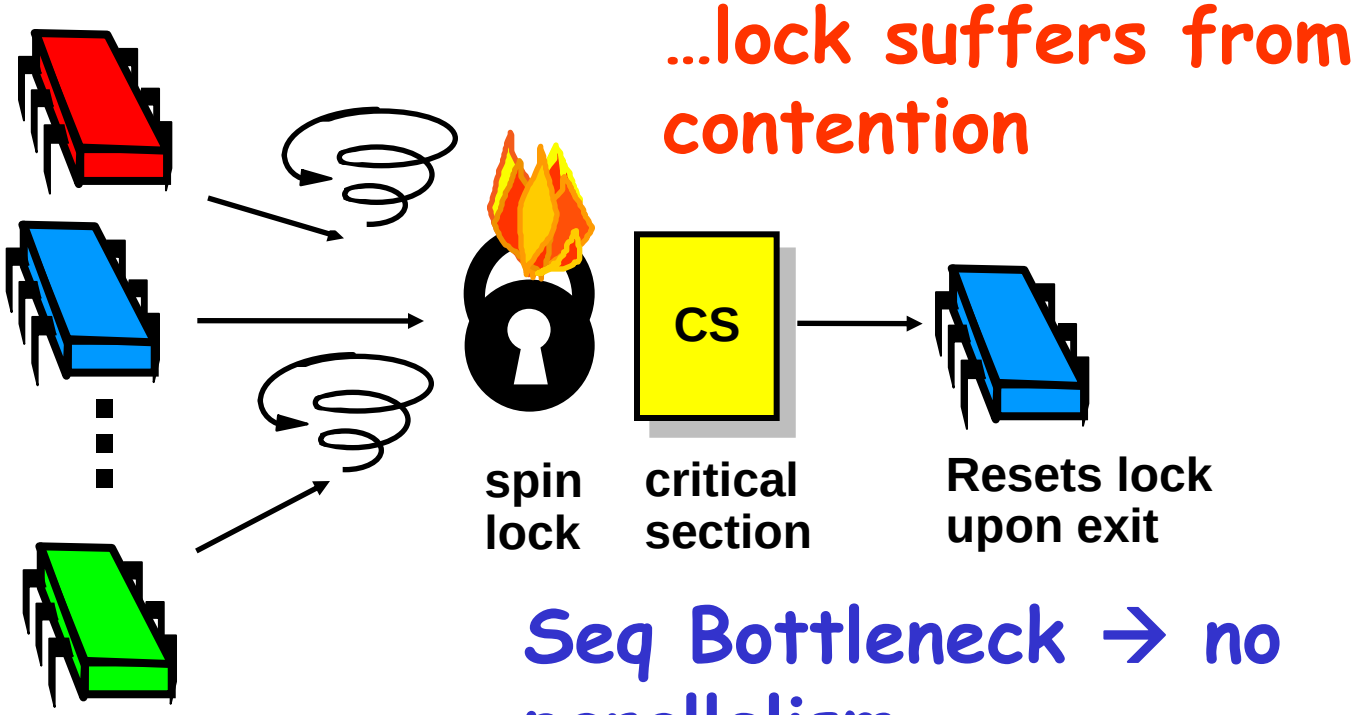


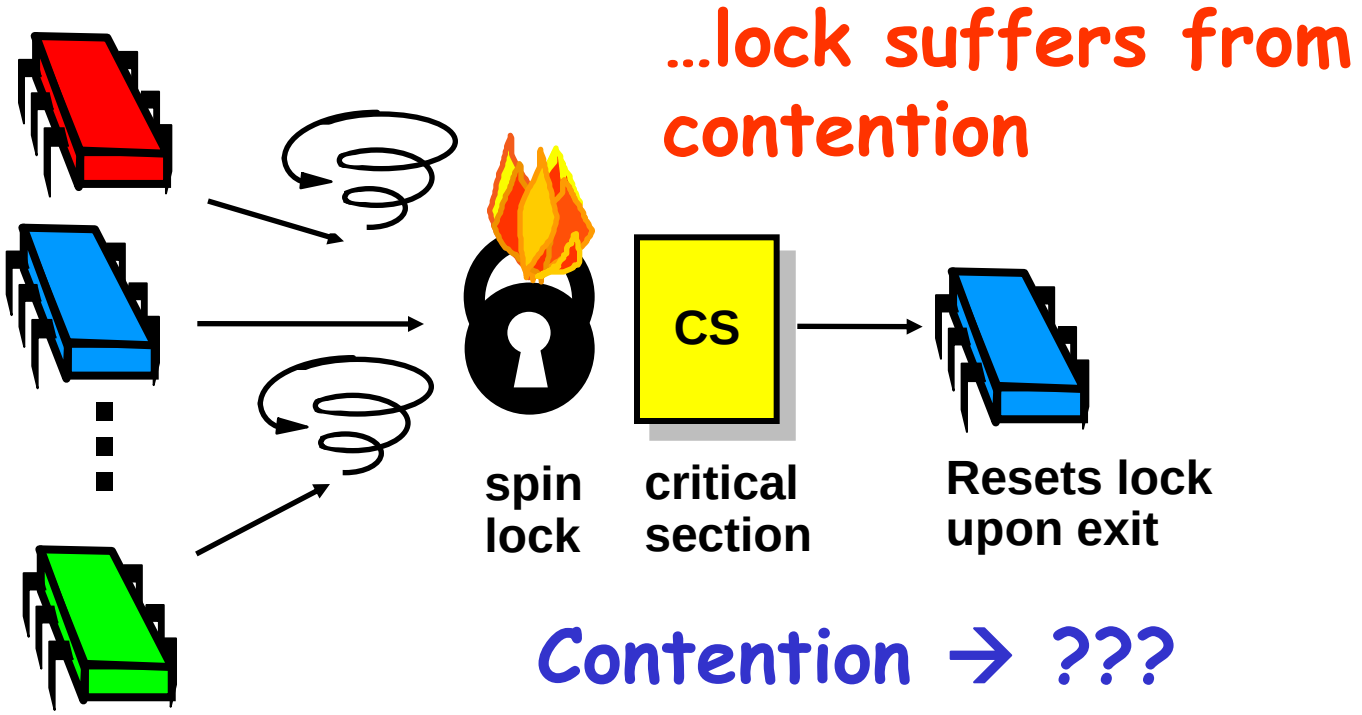
Notice: these are distinct phenomena

Basic Spin-Lock



Seq Bottleneck → no parallelism

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
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    return prior;
  }
}
```

Package
java.util.concurrent.atomic

Review: Test-and-Set

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public class AtomicBoolean {
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 public synchronized boolean
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    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 =
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 void lock() {
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 }

 void unlock() {
  state
 }}
```

Lock state is AtomicBoolean

Test-and-set Lock

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

 void unlock() {
  sta
 }}
```

Keep trying until lock acquired

Test-and-set Lock

```
class TA
 AtomicB
  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 $\Omega(n)$ lower bound?
- We used a RMW operation…

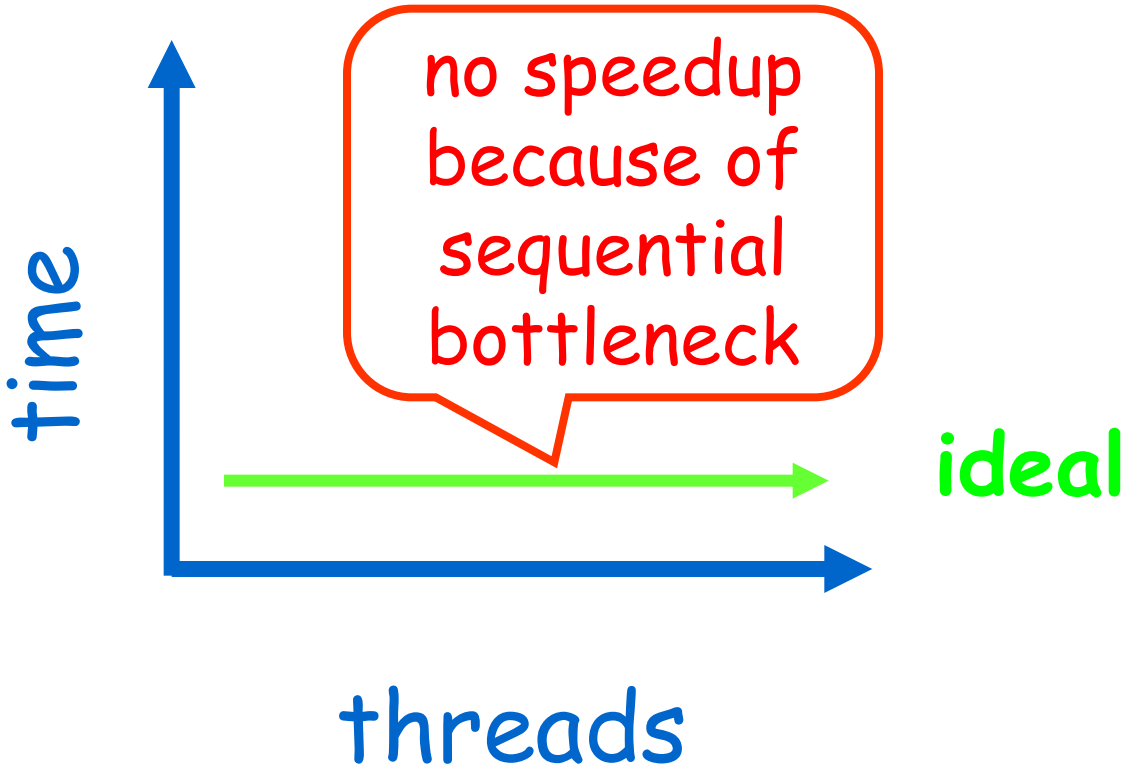
Performance

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

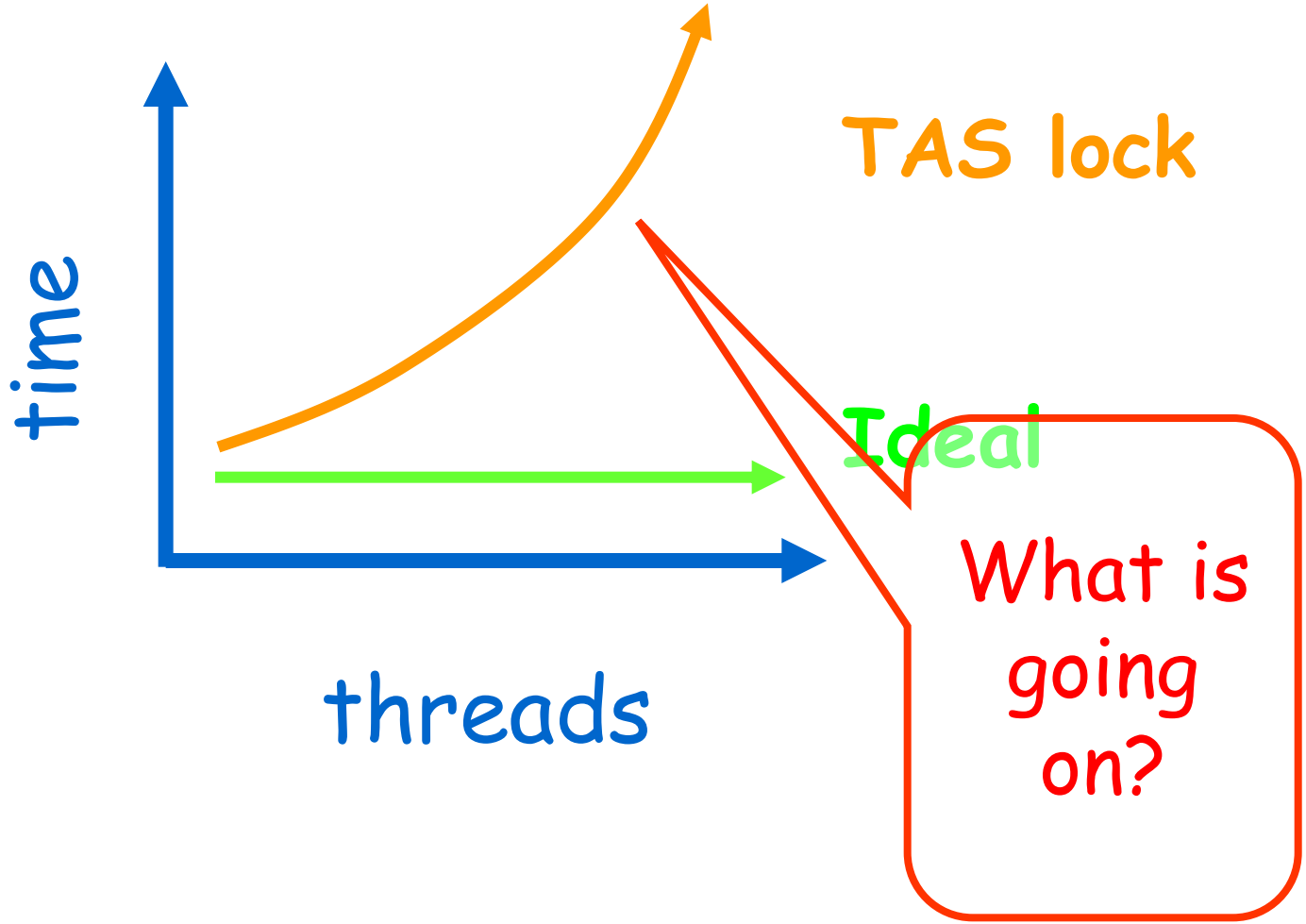
Exercise !!

- Use
  - Test and set
  - Test and test and set
  - Compare and exchange
  - Fetch and add
  - Other synchronization primitives
- On
  - Various hardwares

Graph


no speedup
because of
sequential
bottleneck
time
ideal
threads

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 {
 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 =
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 void lock() {
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Wait until lock looks free

Test-and-test-and-set Lock

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 void lock() {
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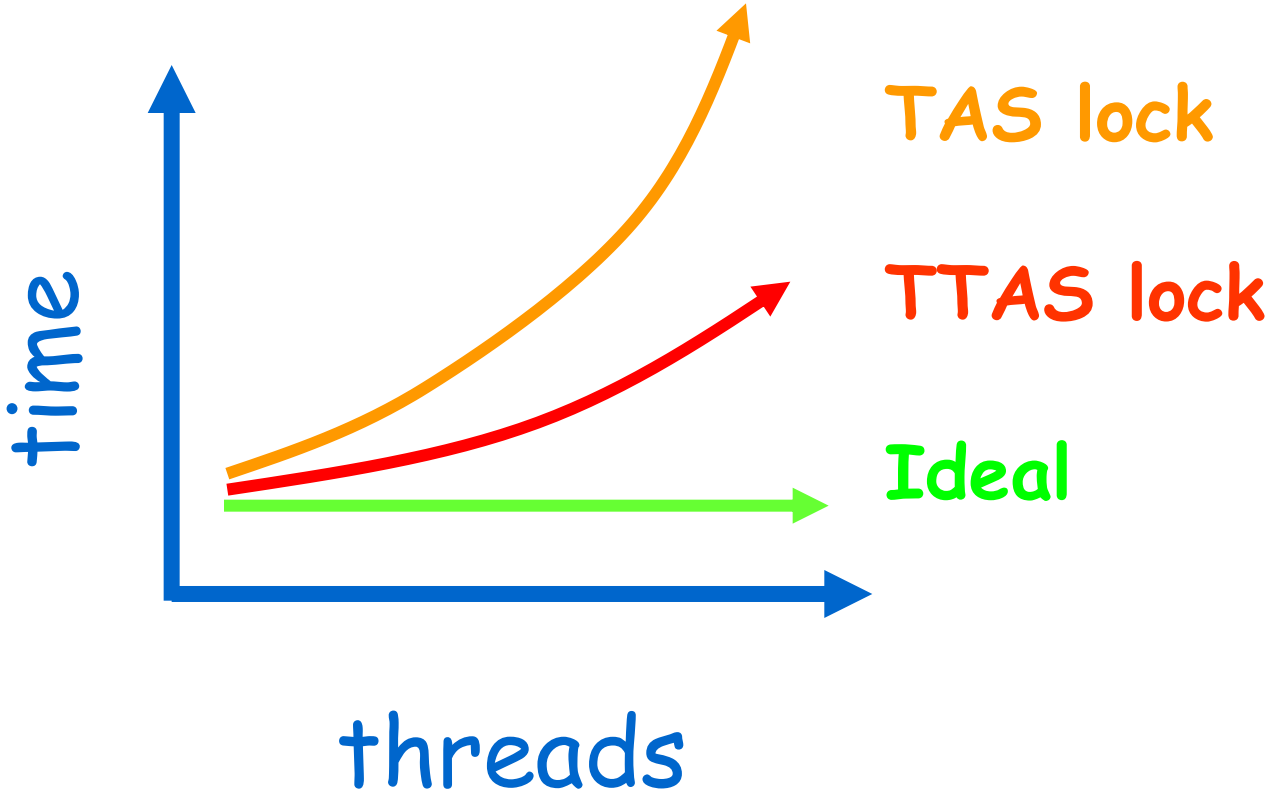
  }
}
```

Then try to acquire it

Mystery #2



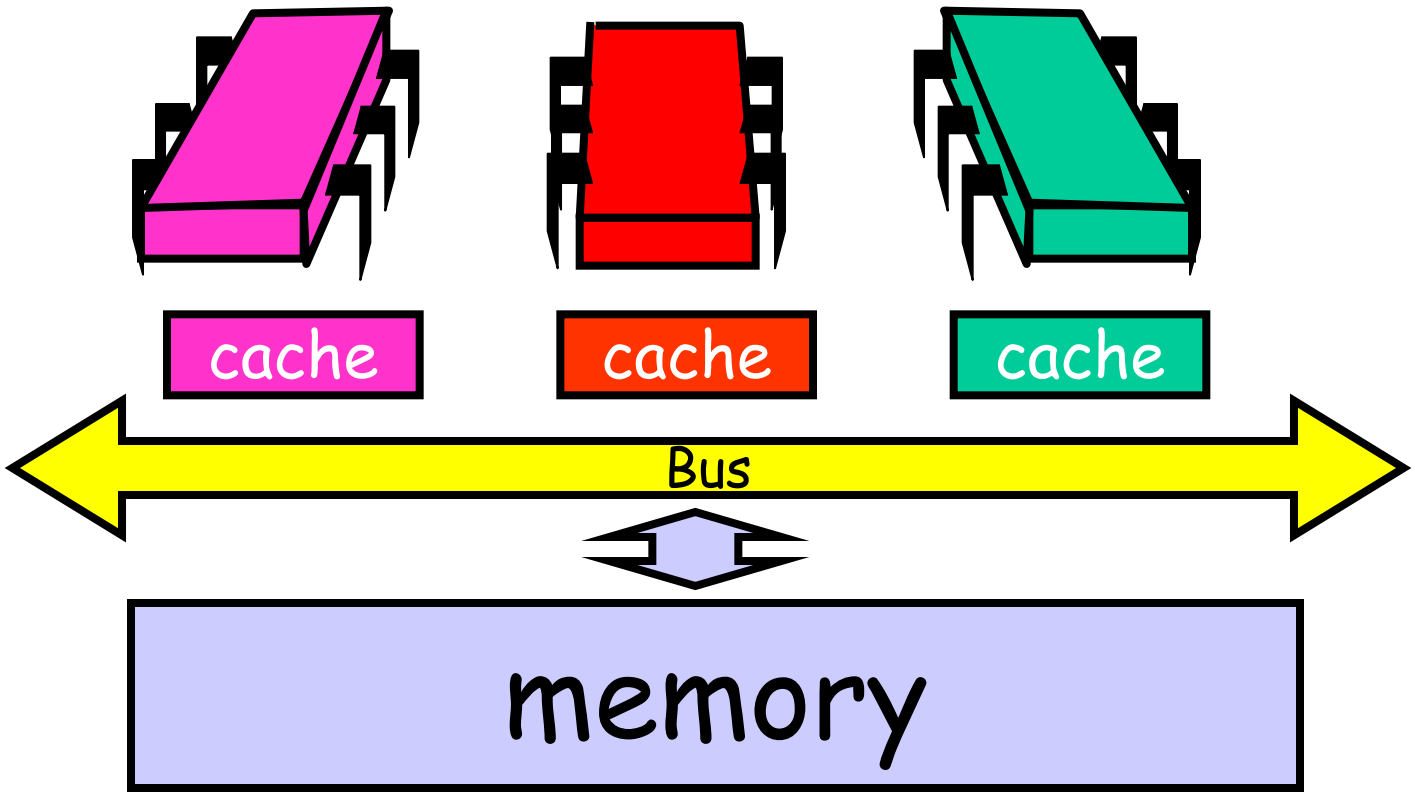
Mystery

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

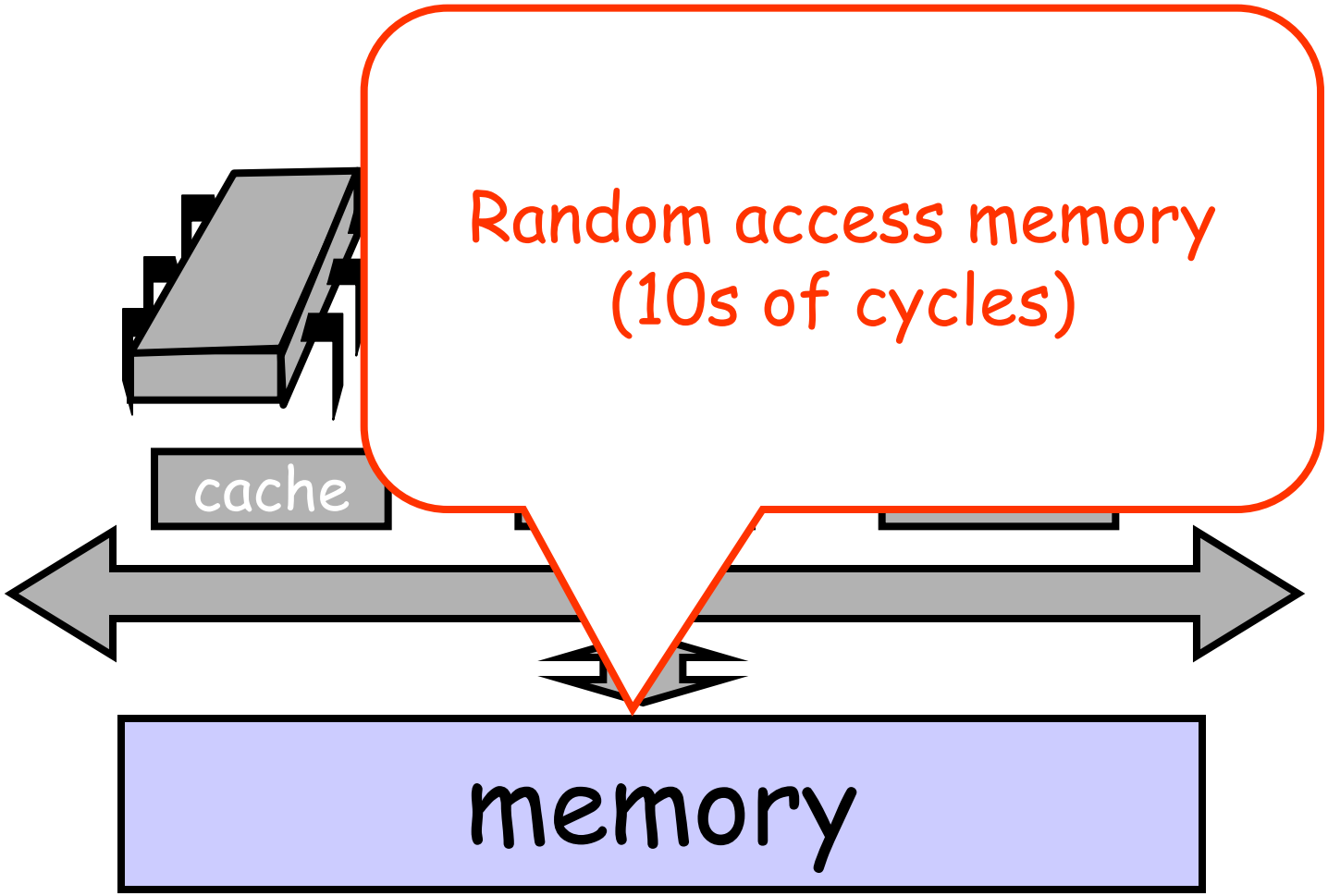
Opinion

- 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 …

Bus-Based Architectures



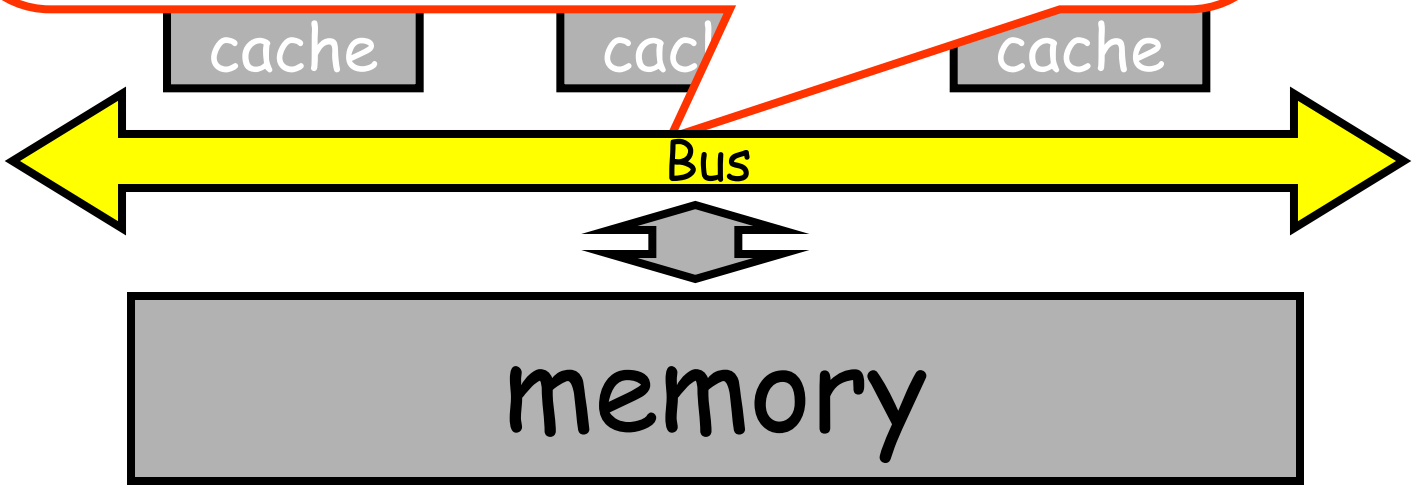
Bus-Based Architectures



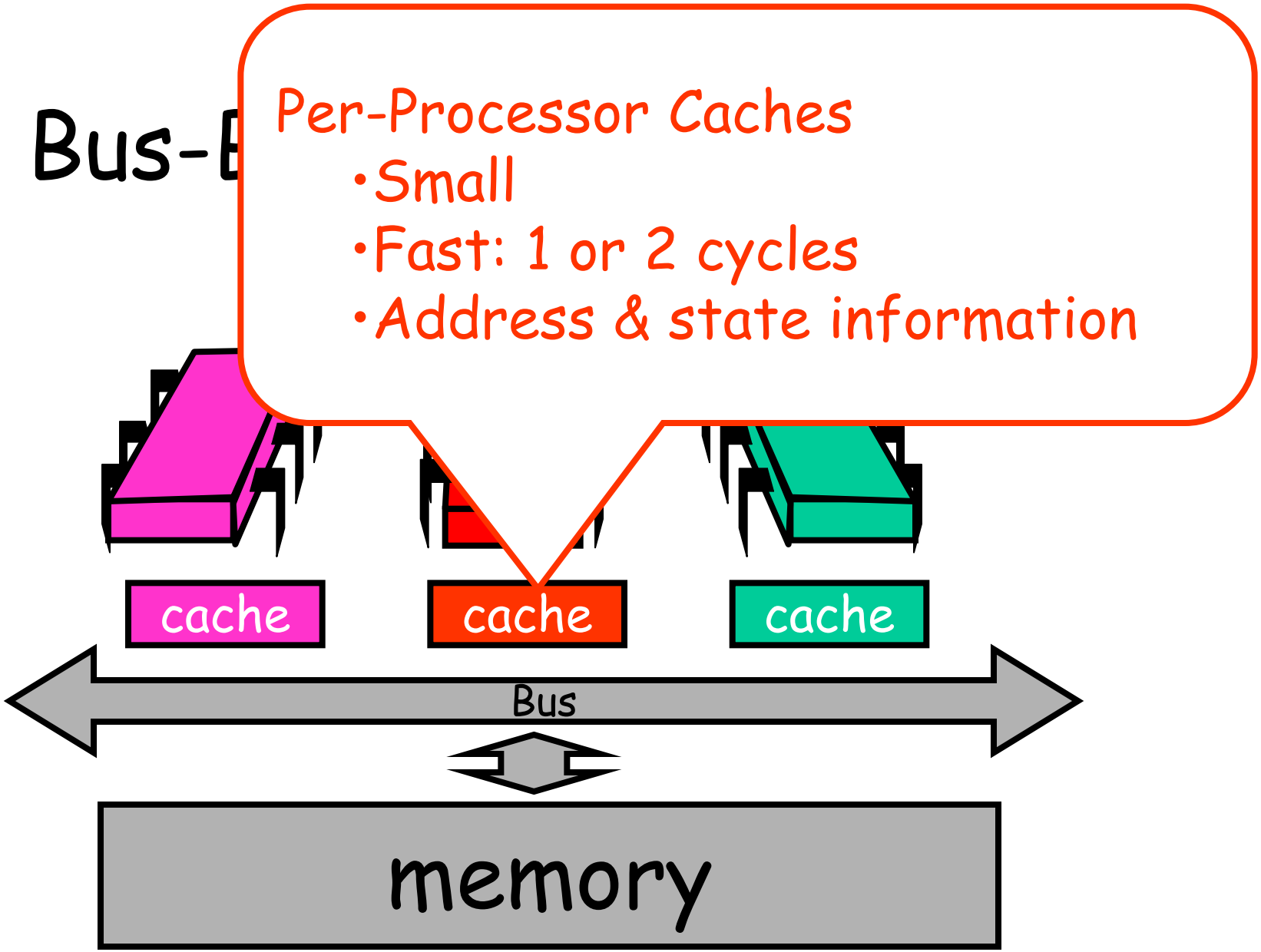
Bus-Based Architectures

Shared Bus

- broadcast medium
- One broadcaster at a time
- Processors and memory all "snoop"



Bus-B


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™

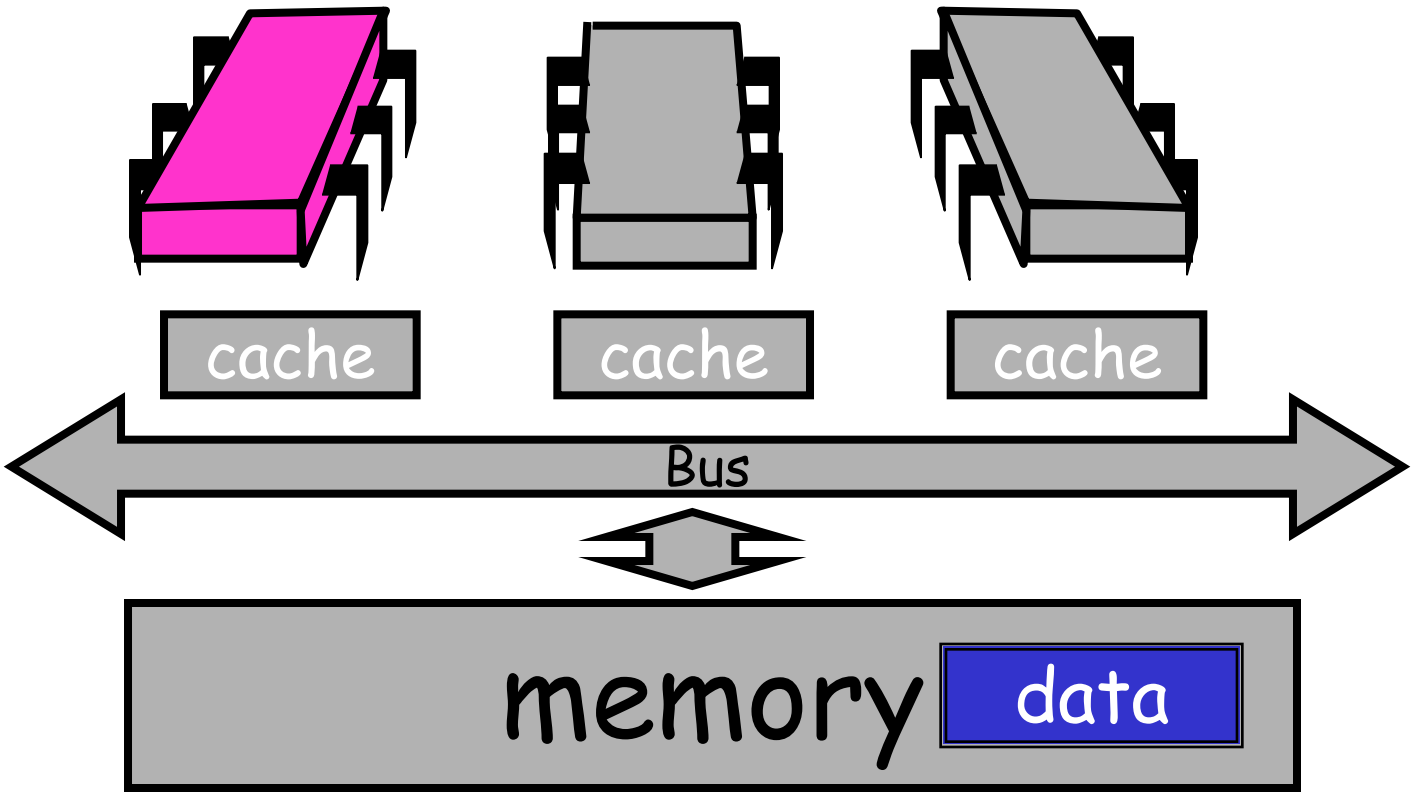
Jargon Watch

- 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

Processor Issues Load Request



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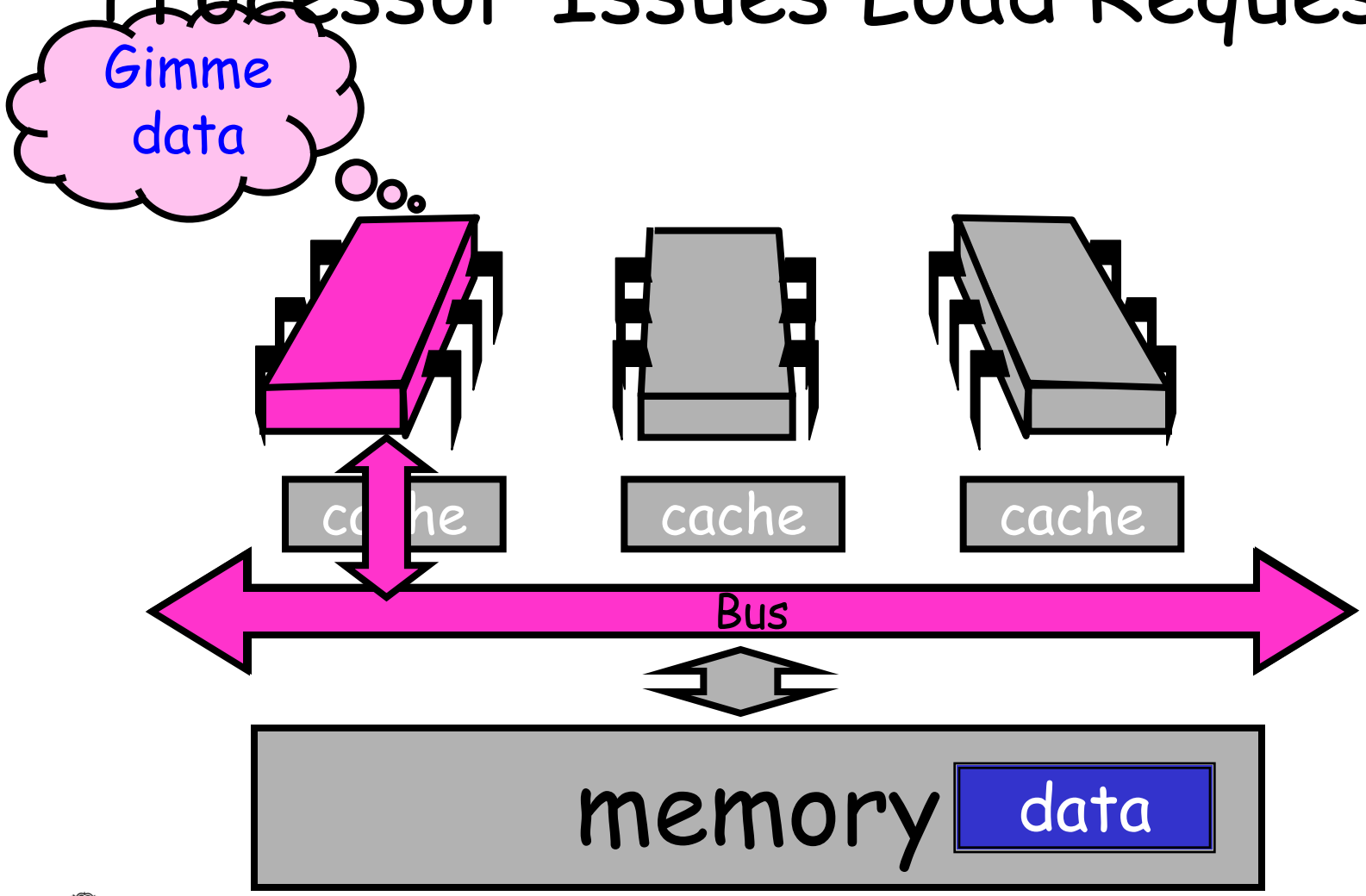
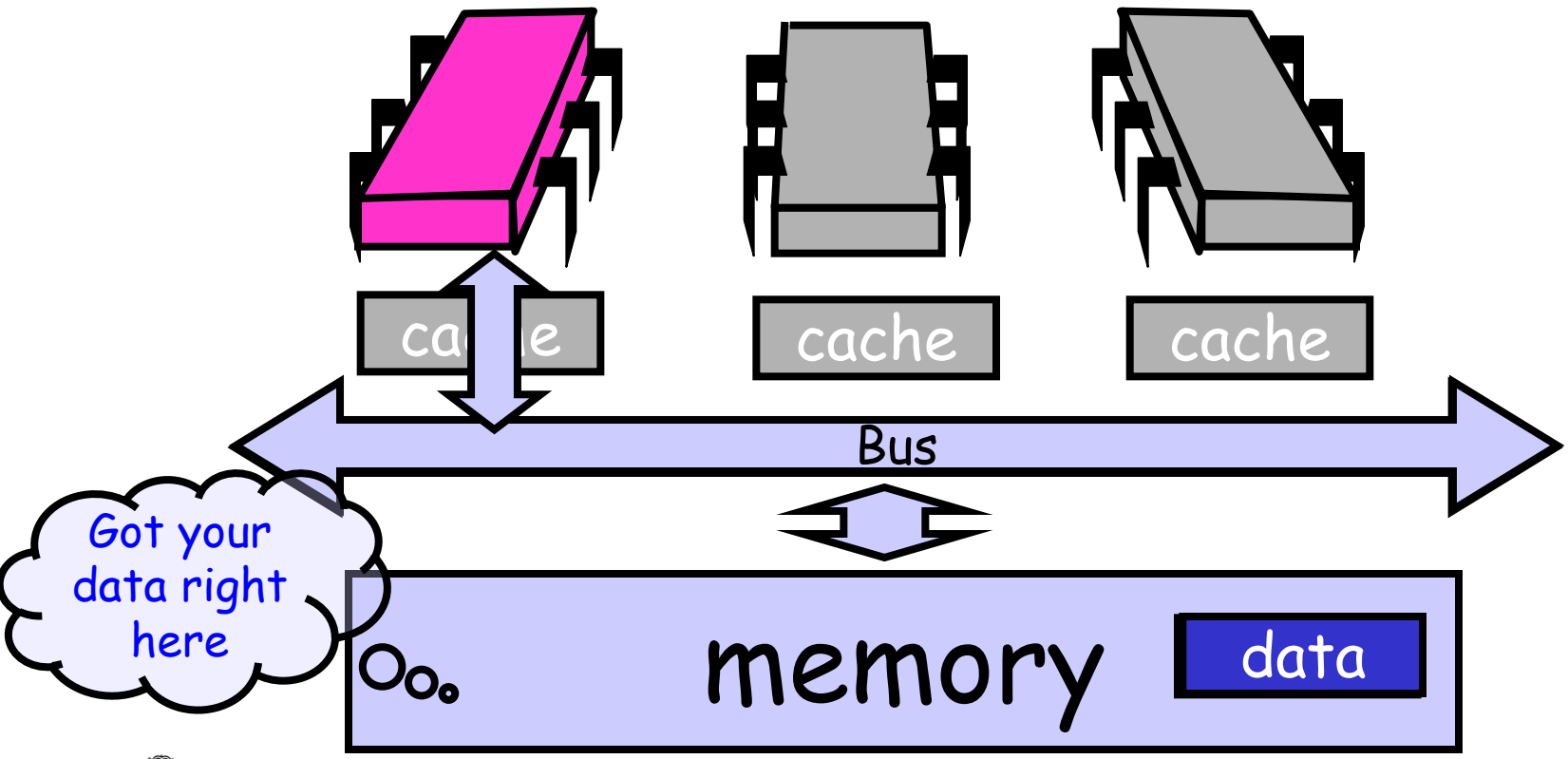


Memory Responds



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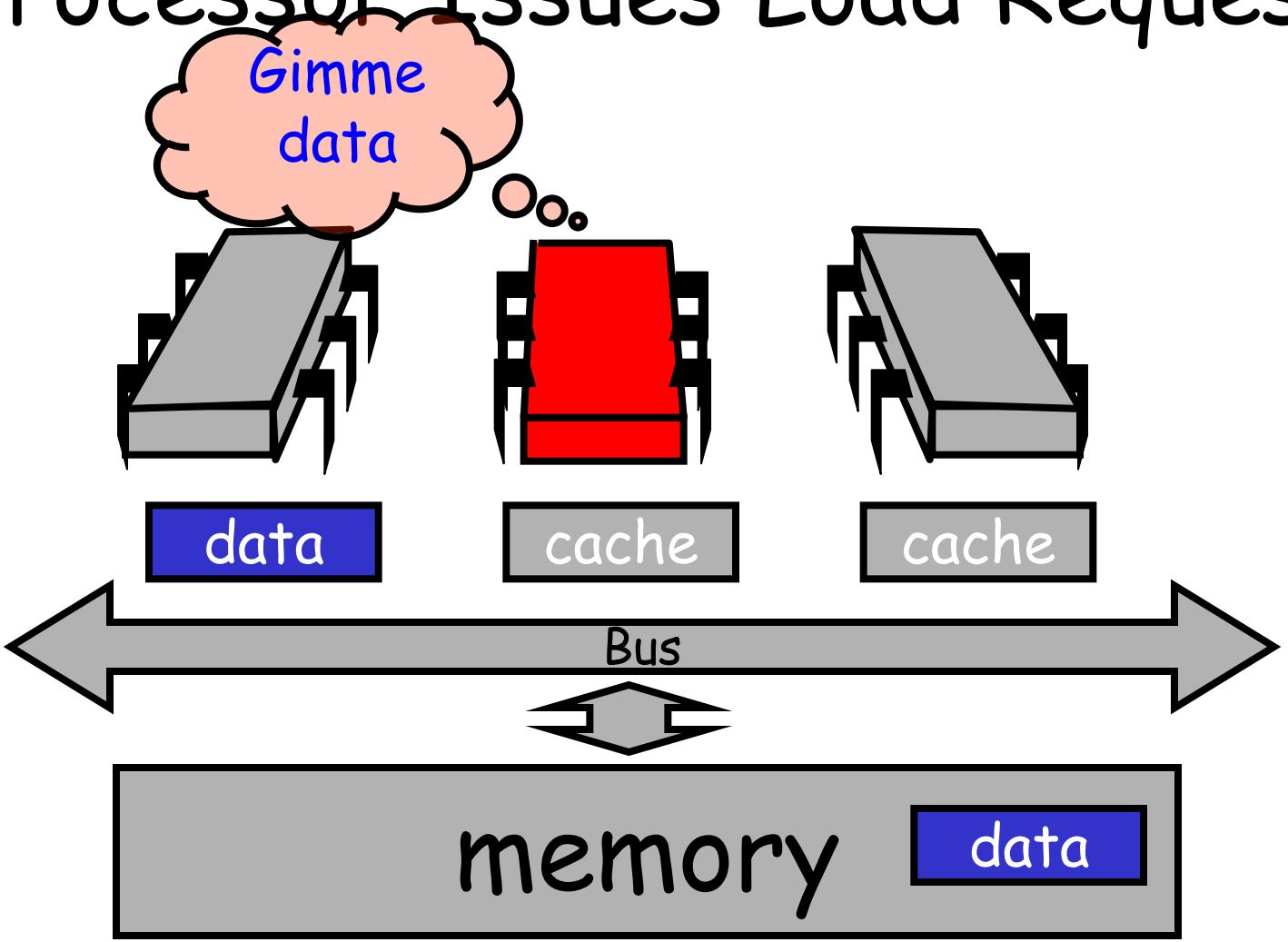

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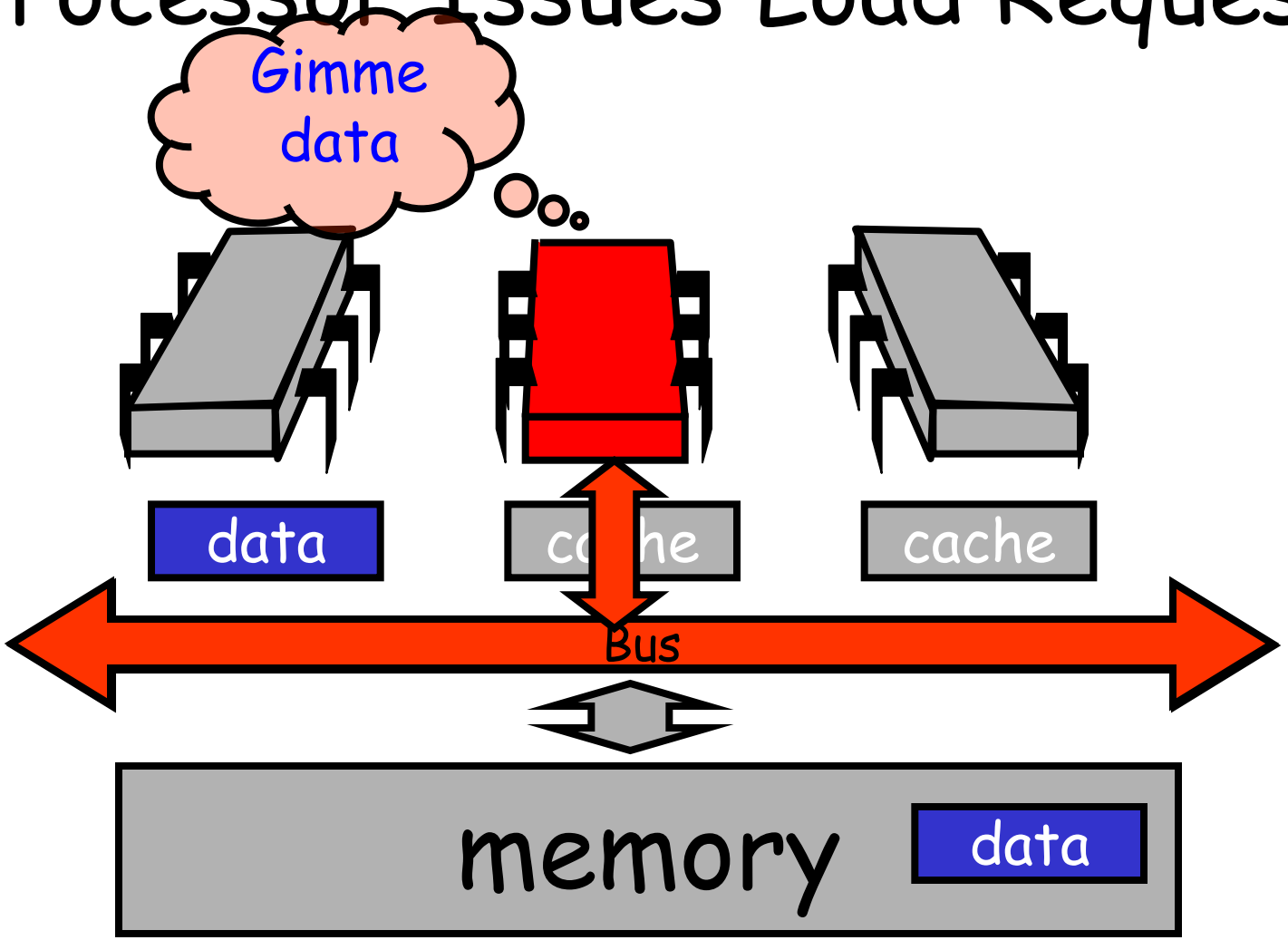

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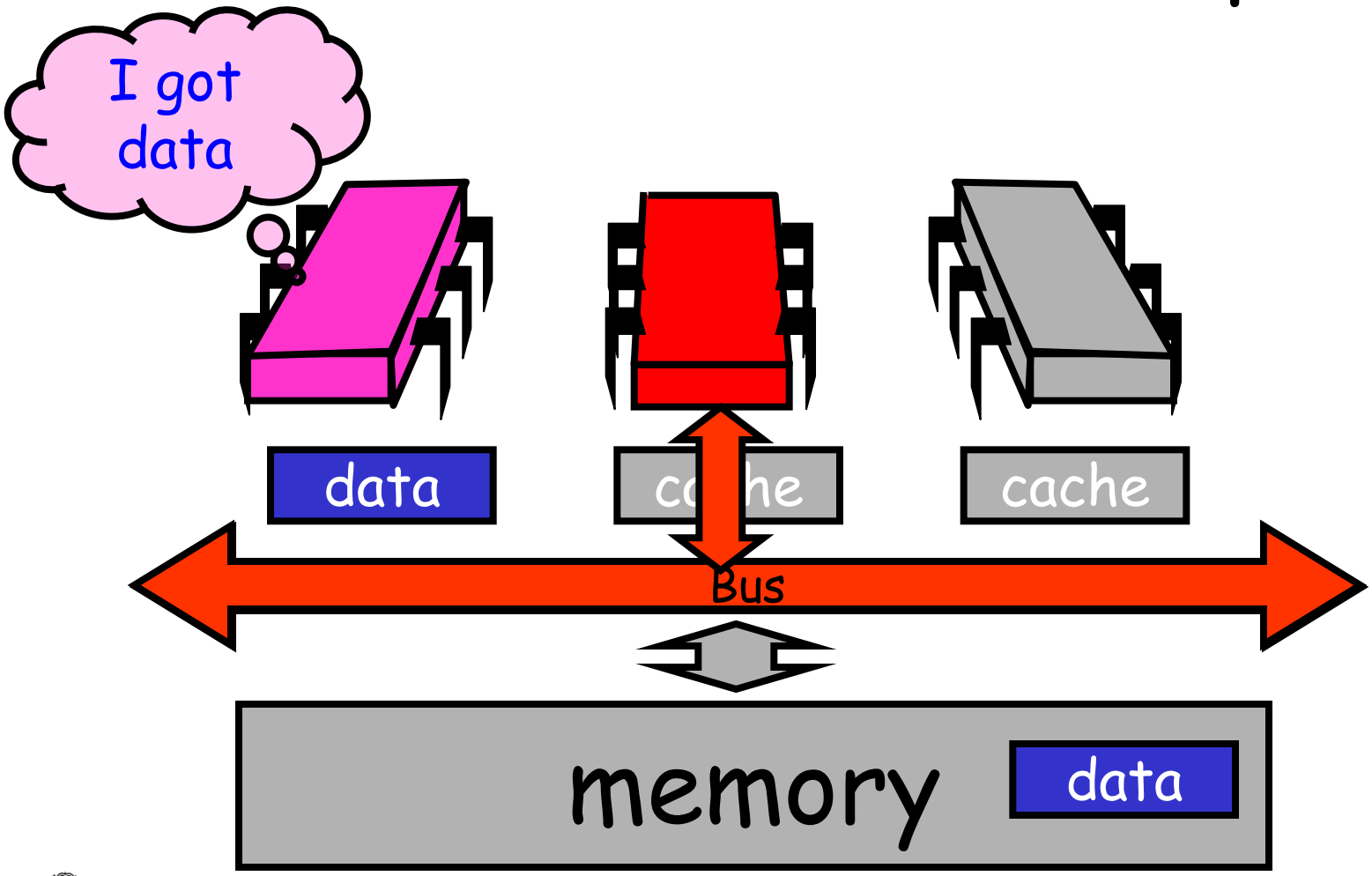
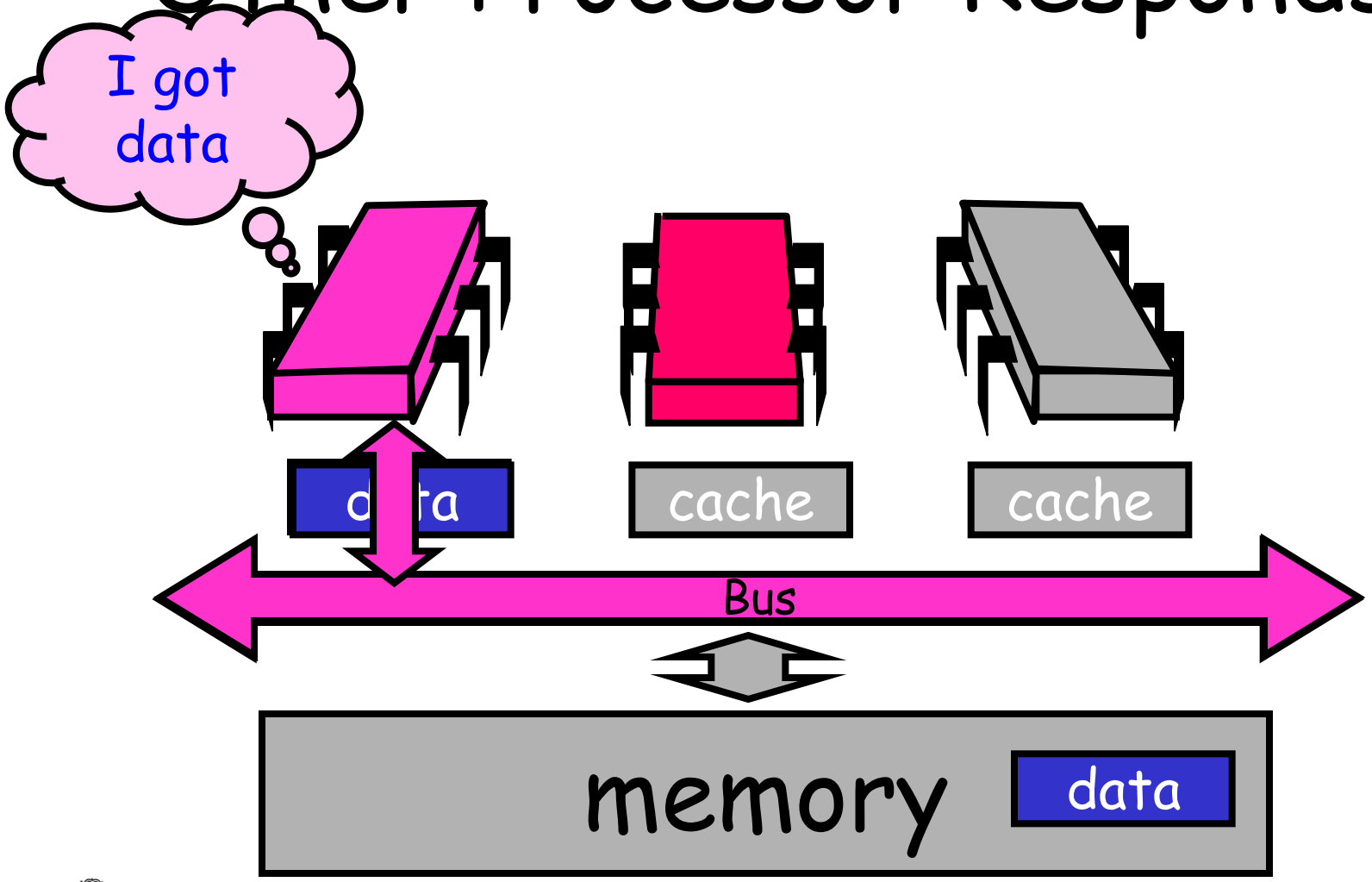


Other Processor Responds



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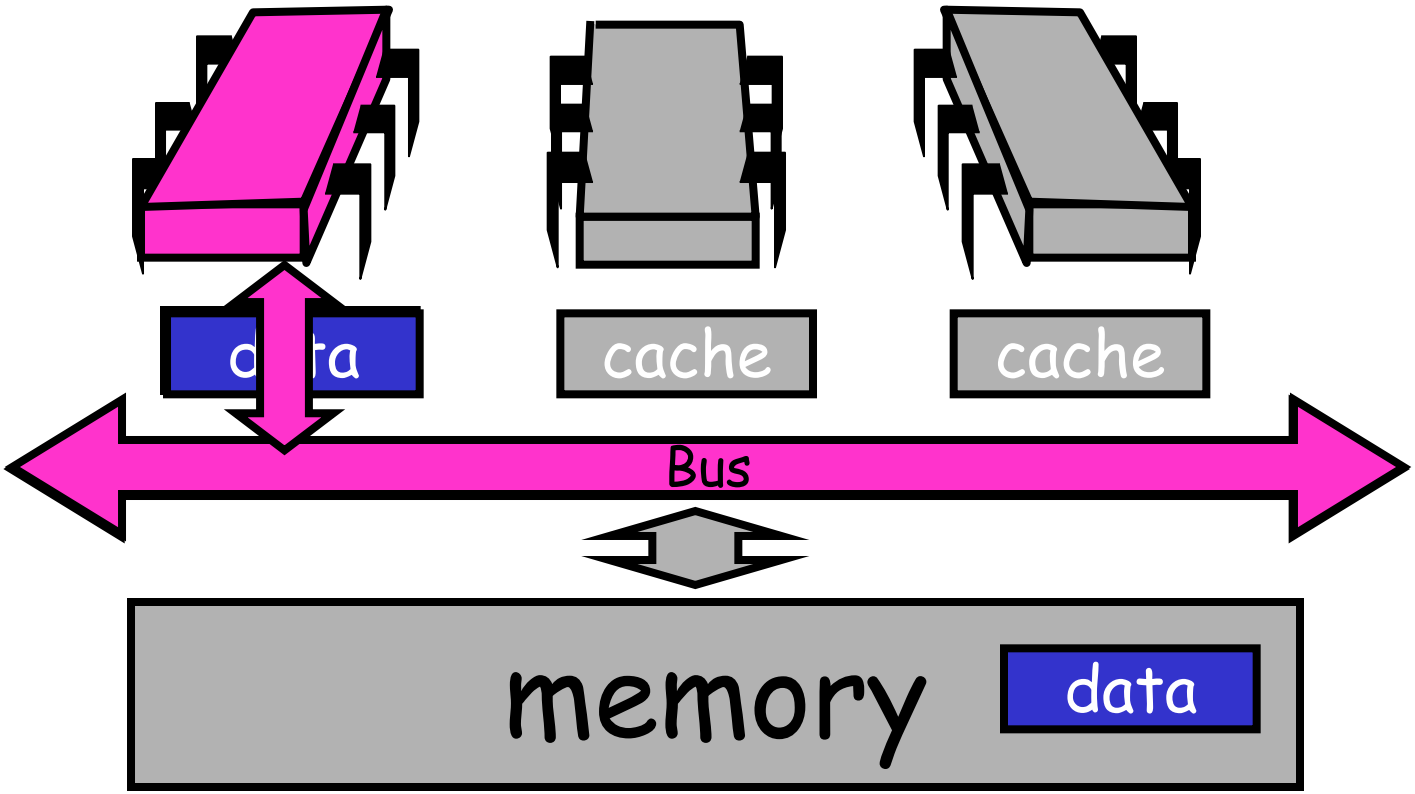
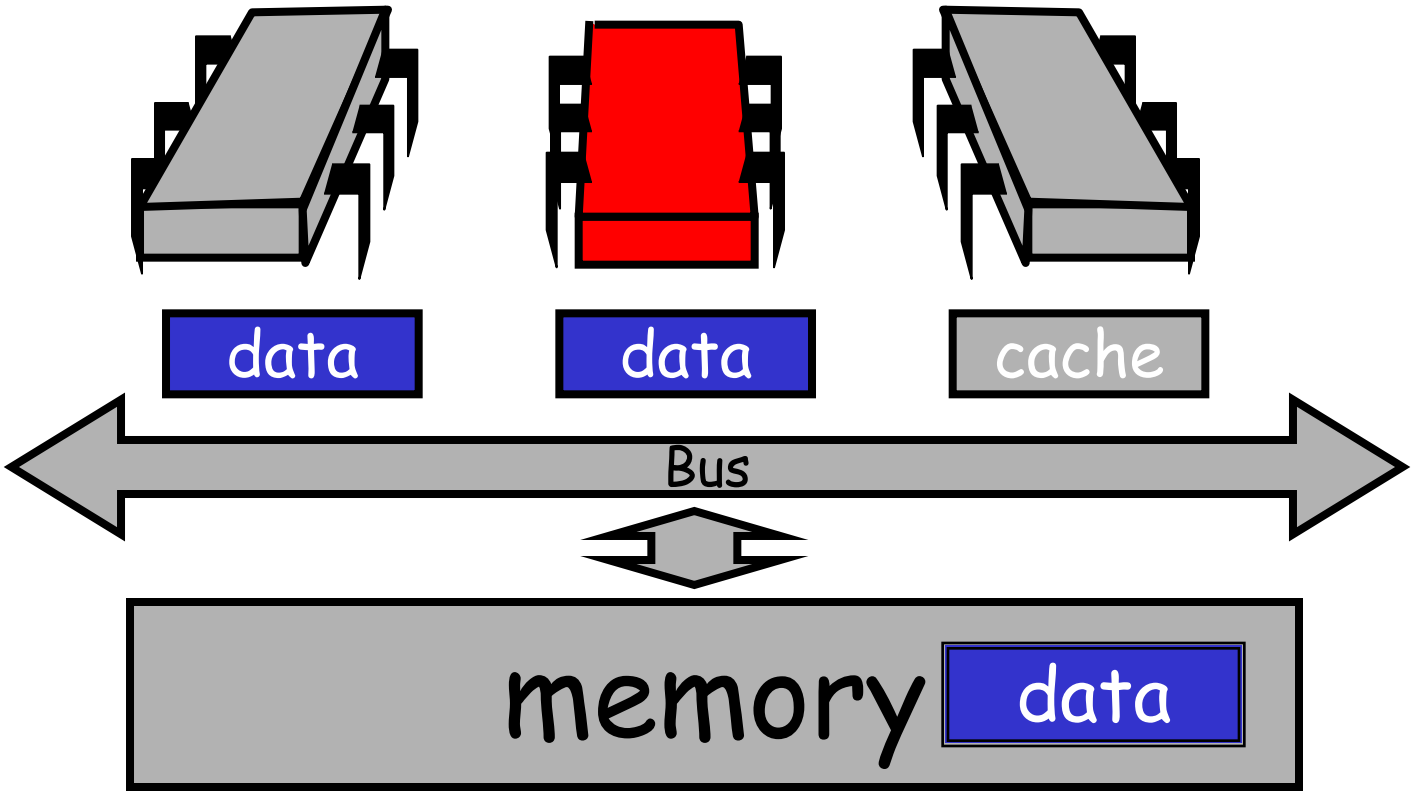


Modify Cached Data



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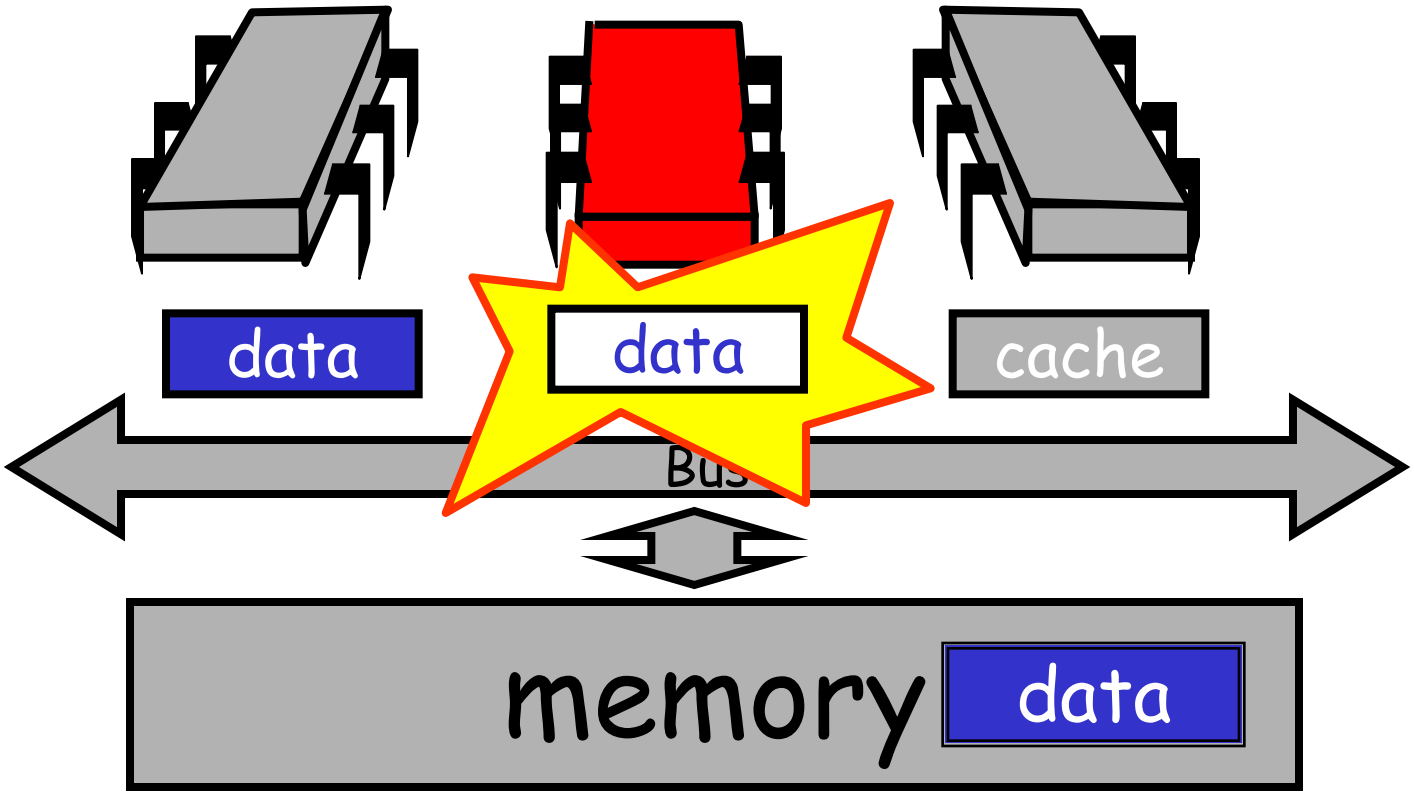

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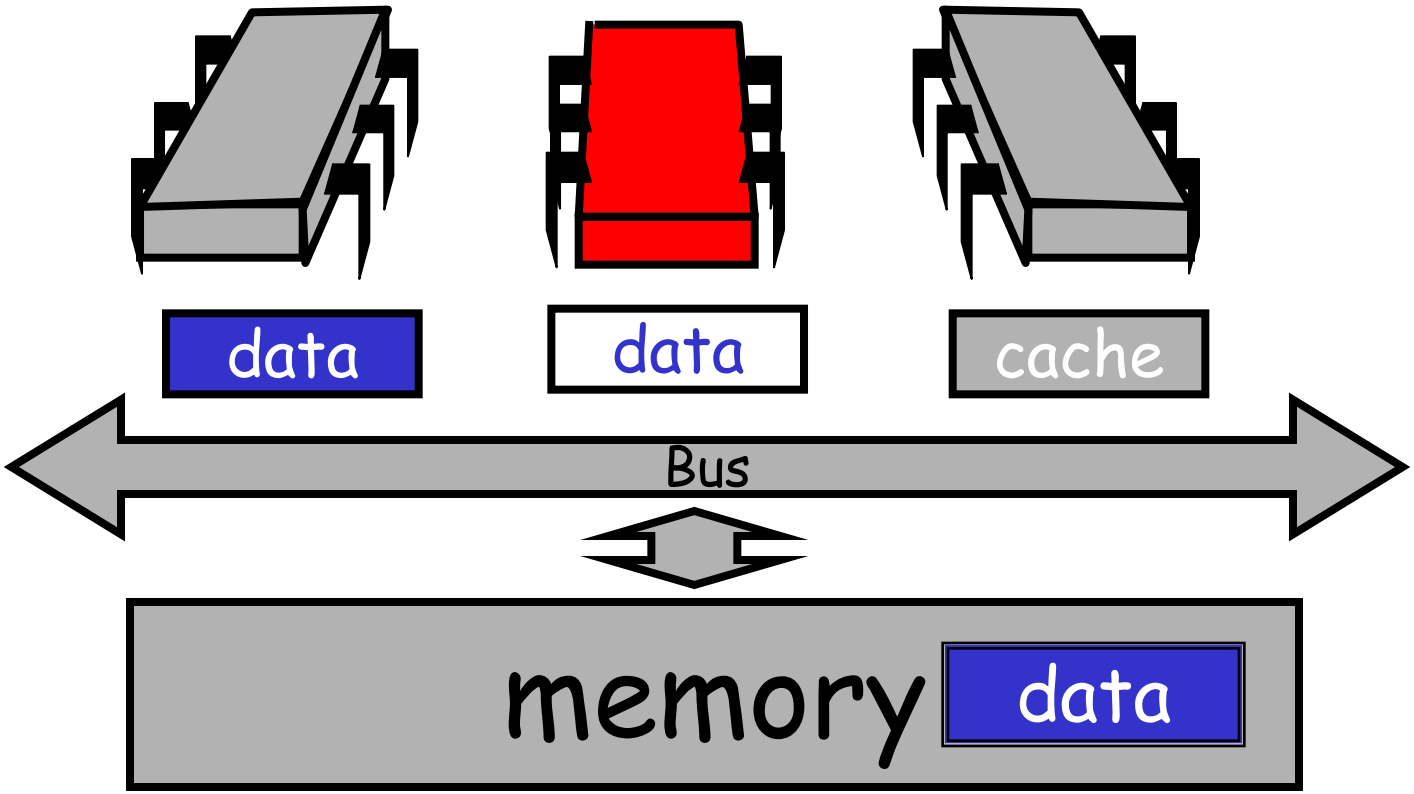

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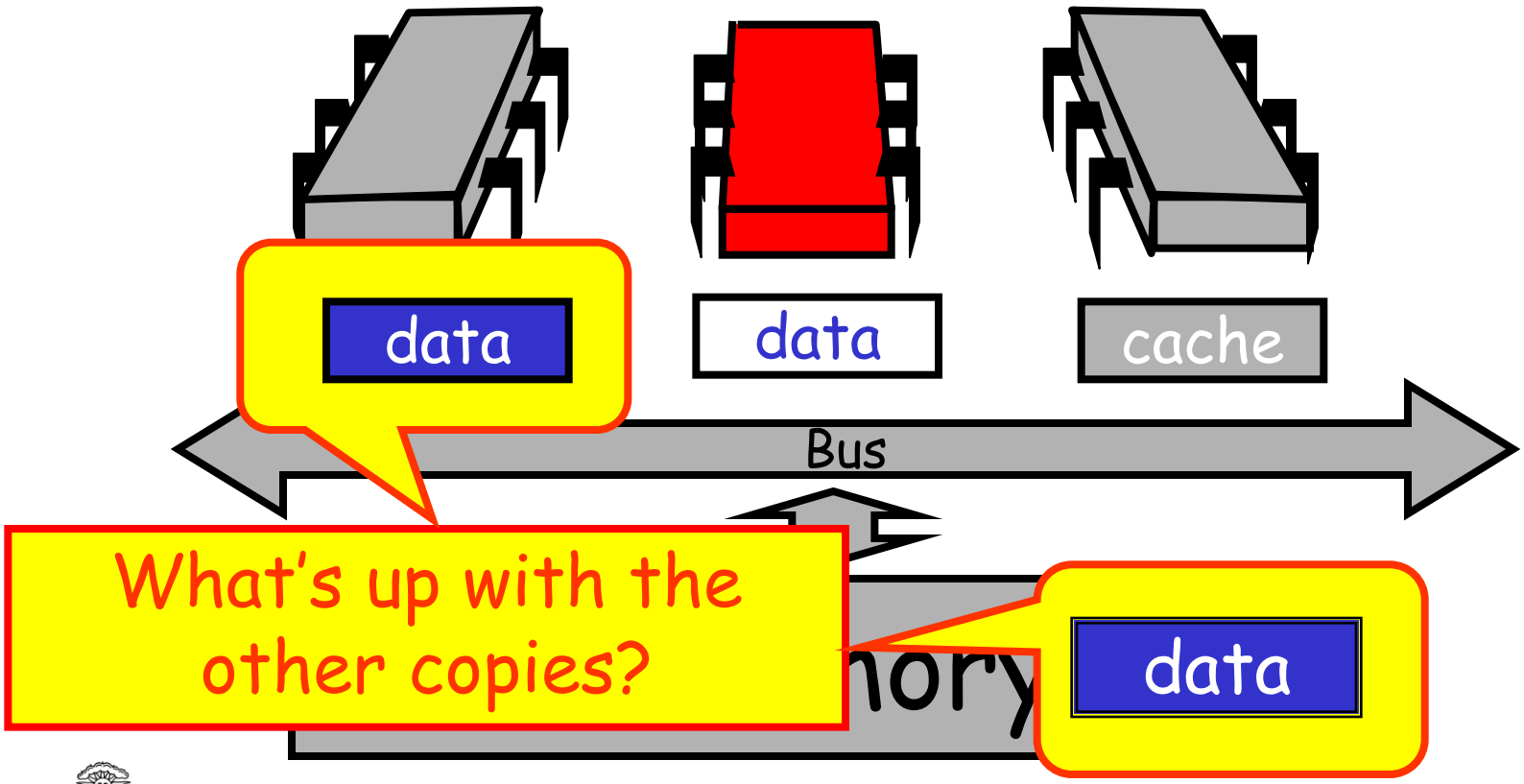


Cache Coherence

- 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?

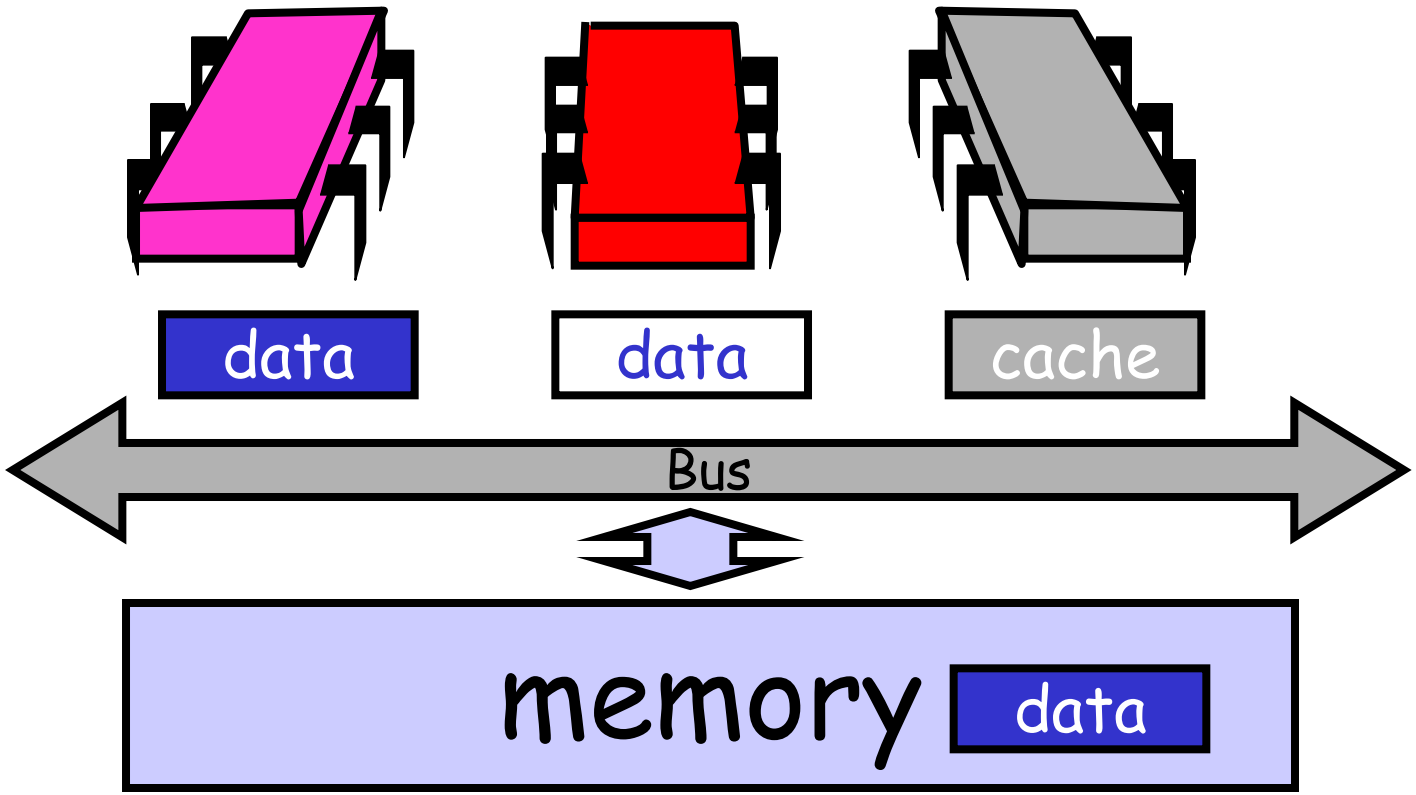
Write-Back Caches

- 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



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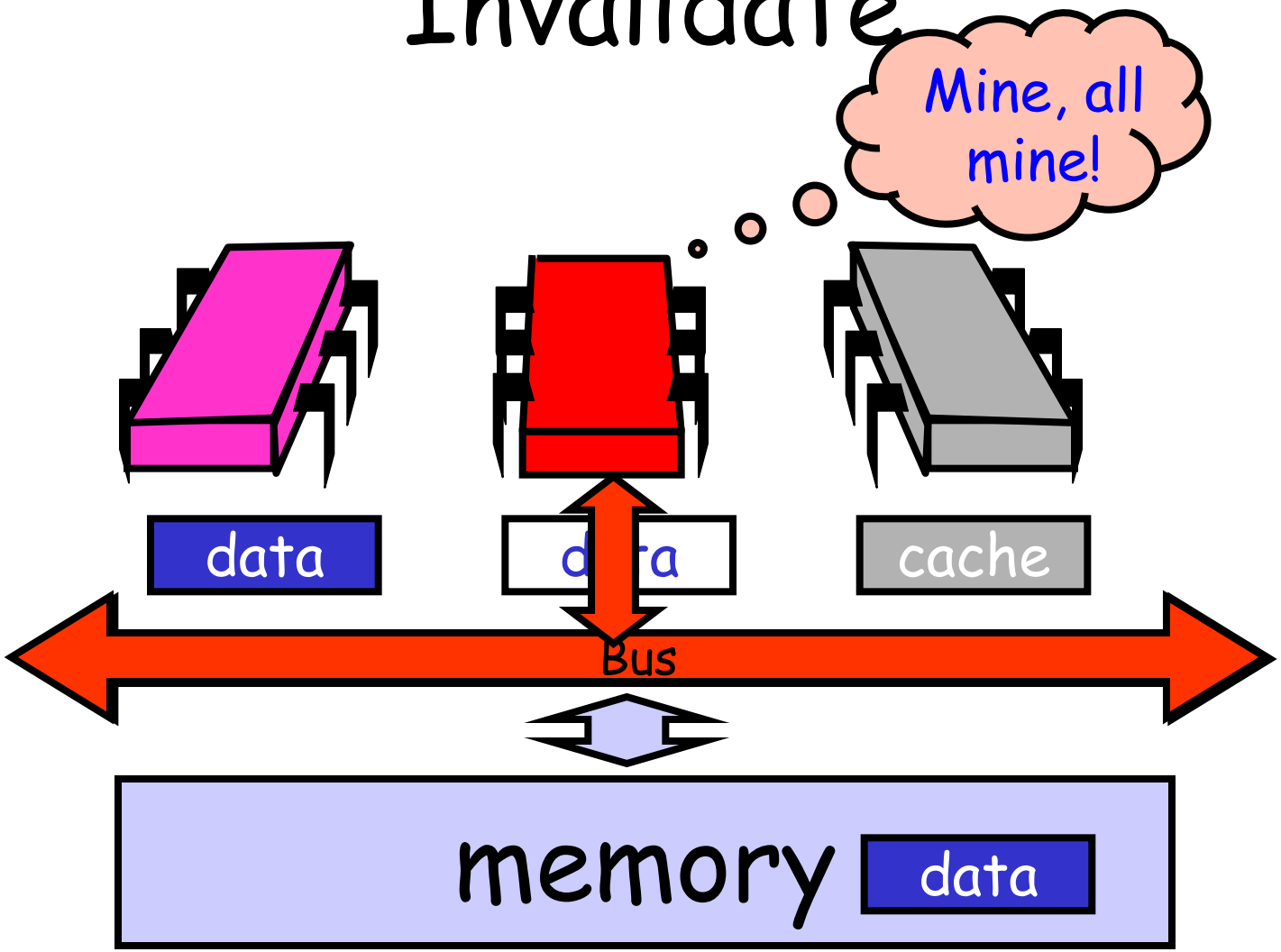

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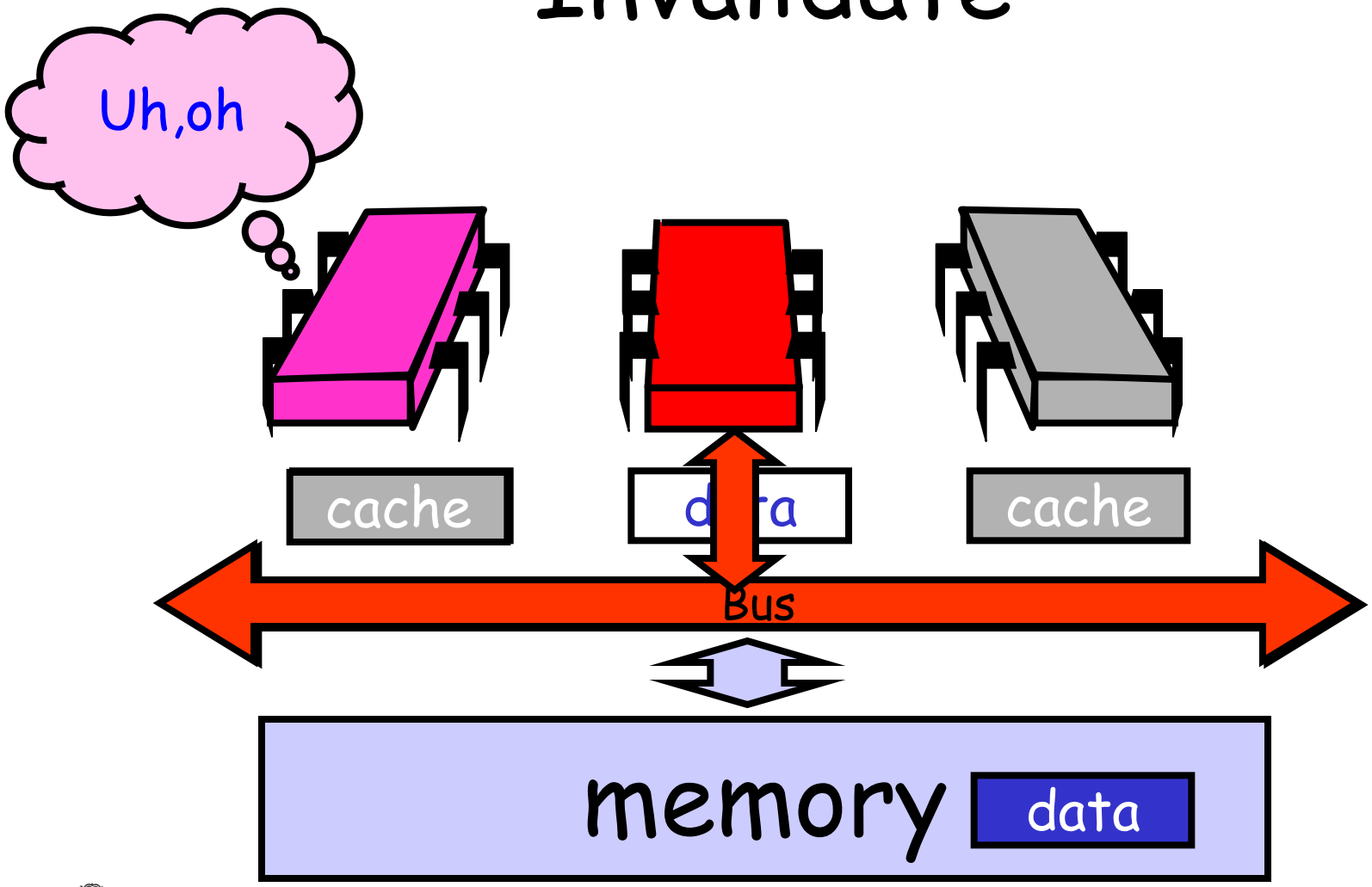

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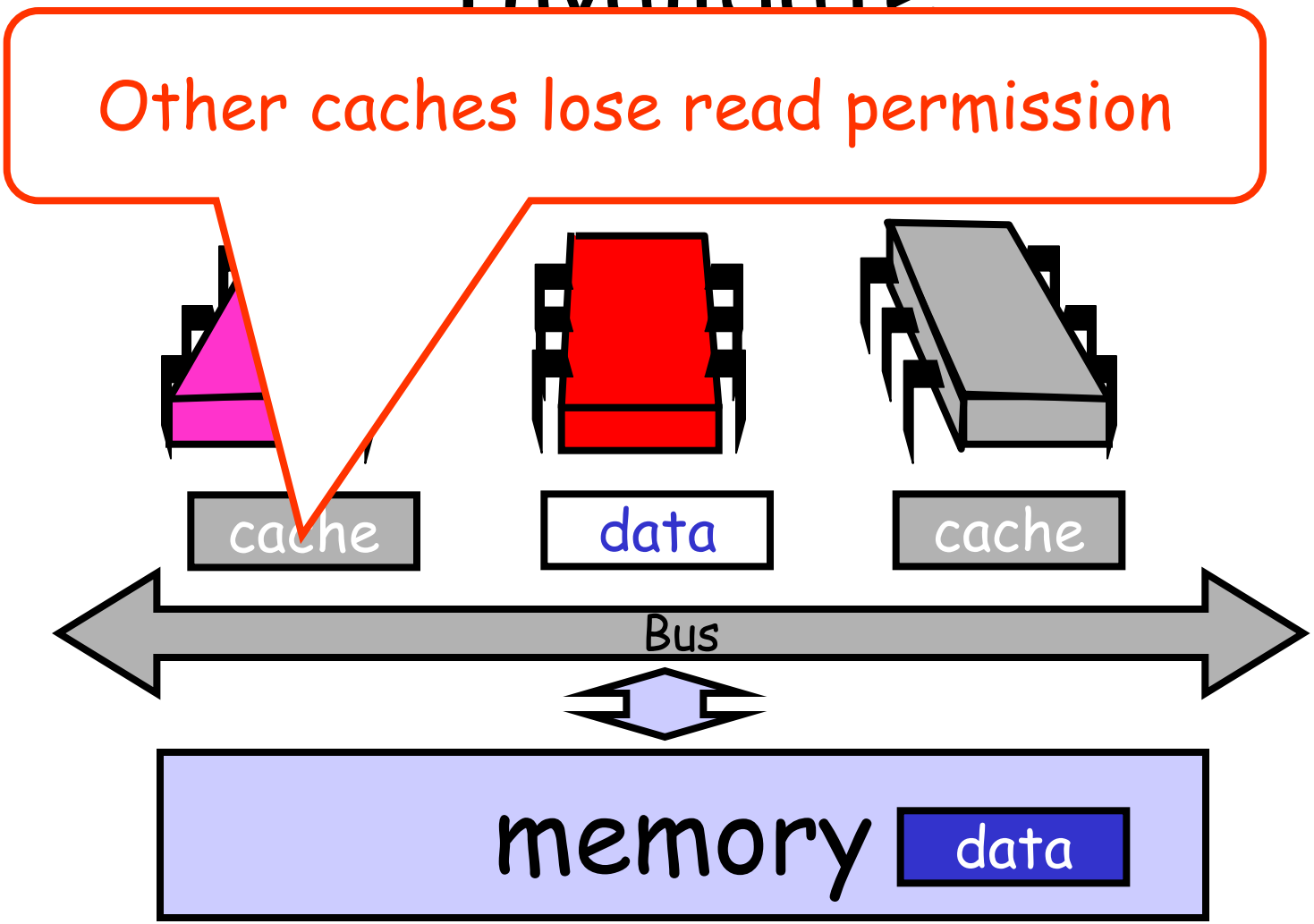
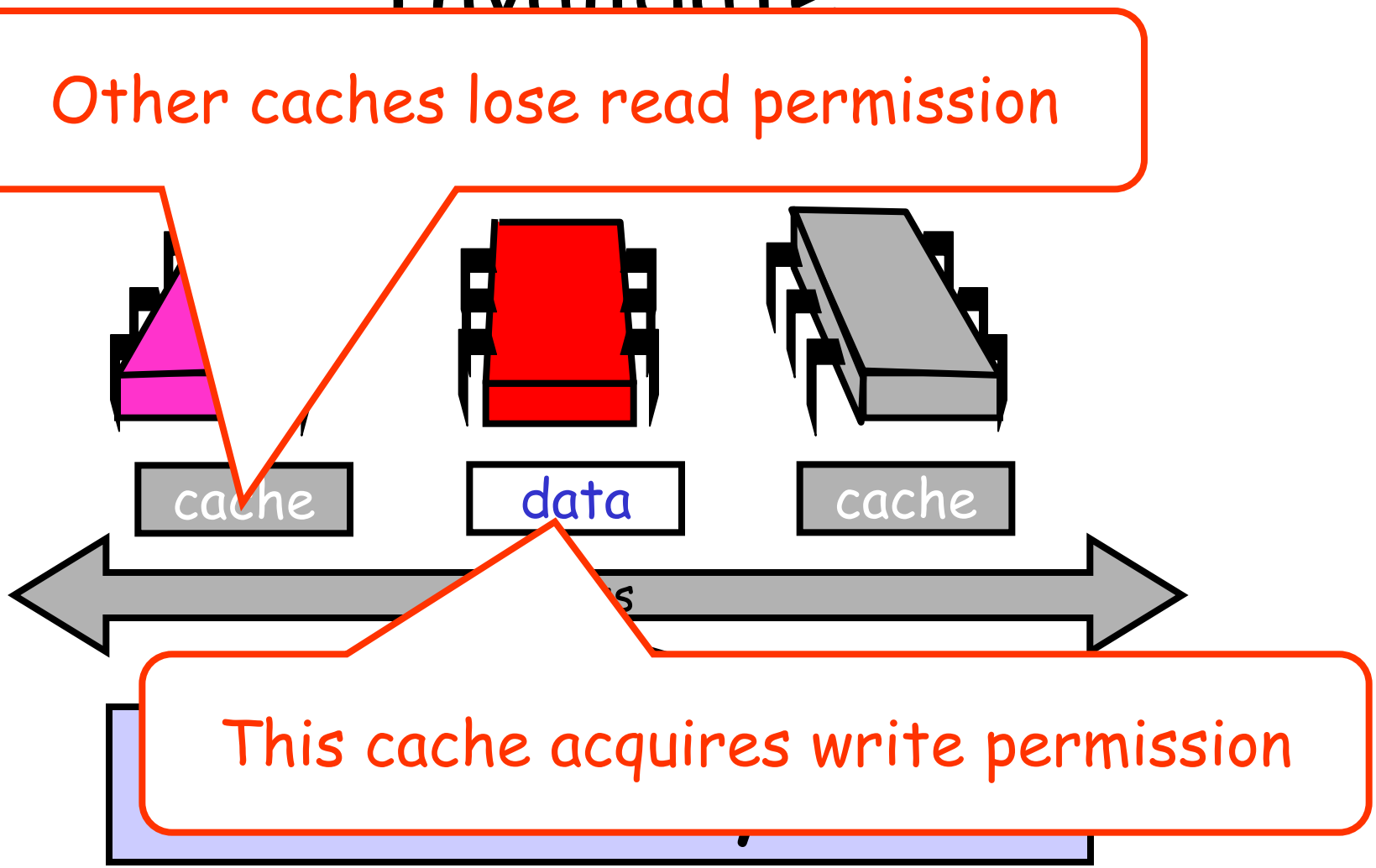
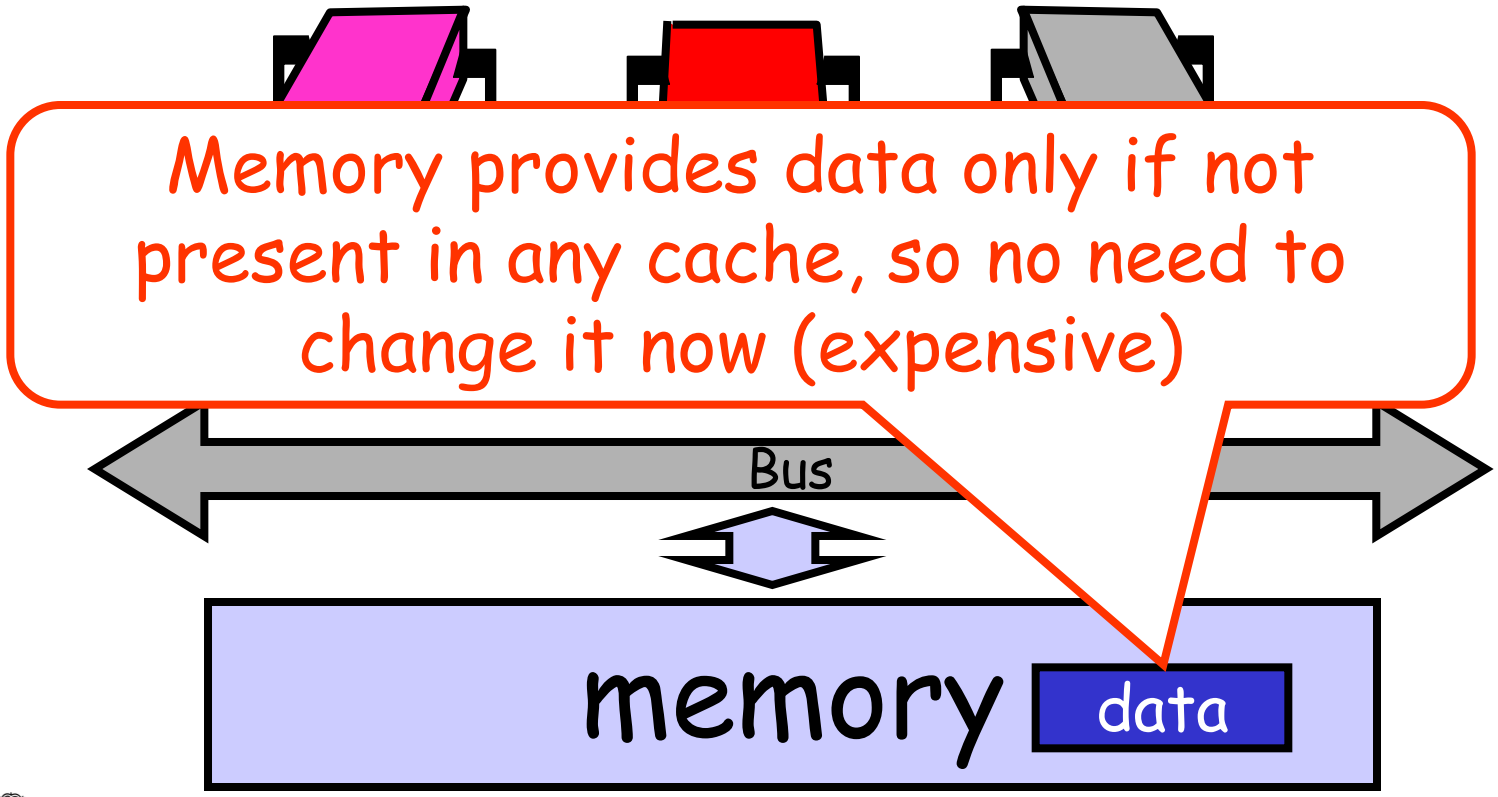

Other caches lose read permission
cache
data
cache
Bus
memory
data

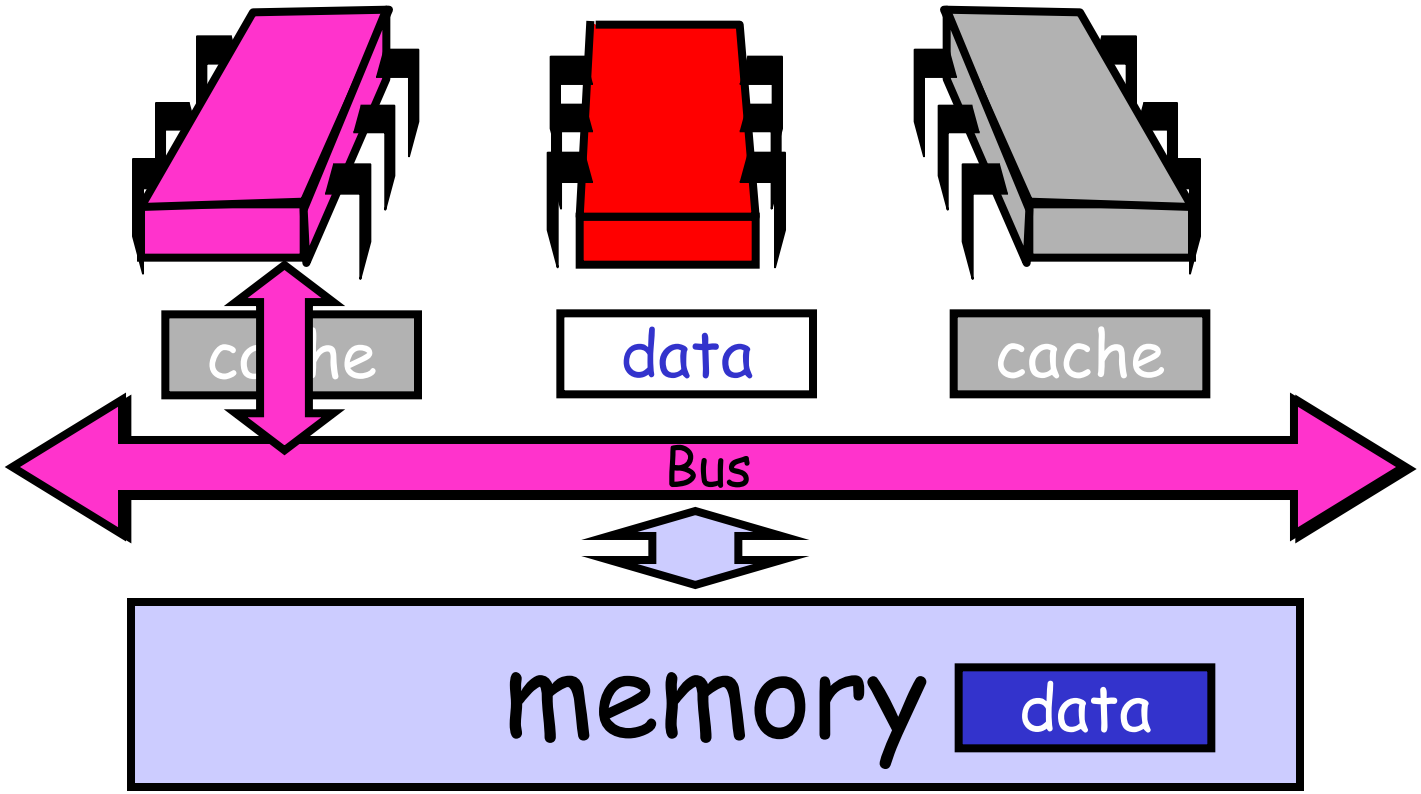
Invalidate


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

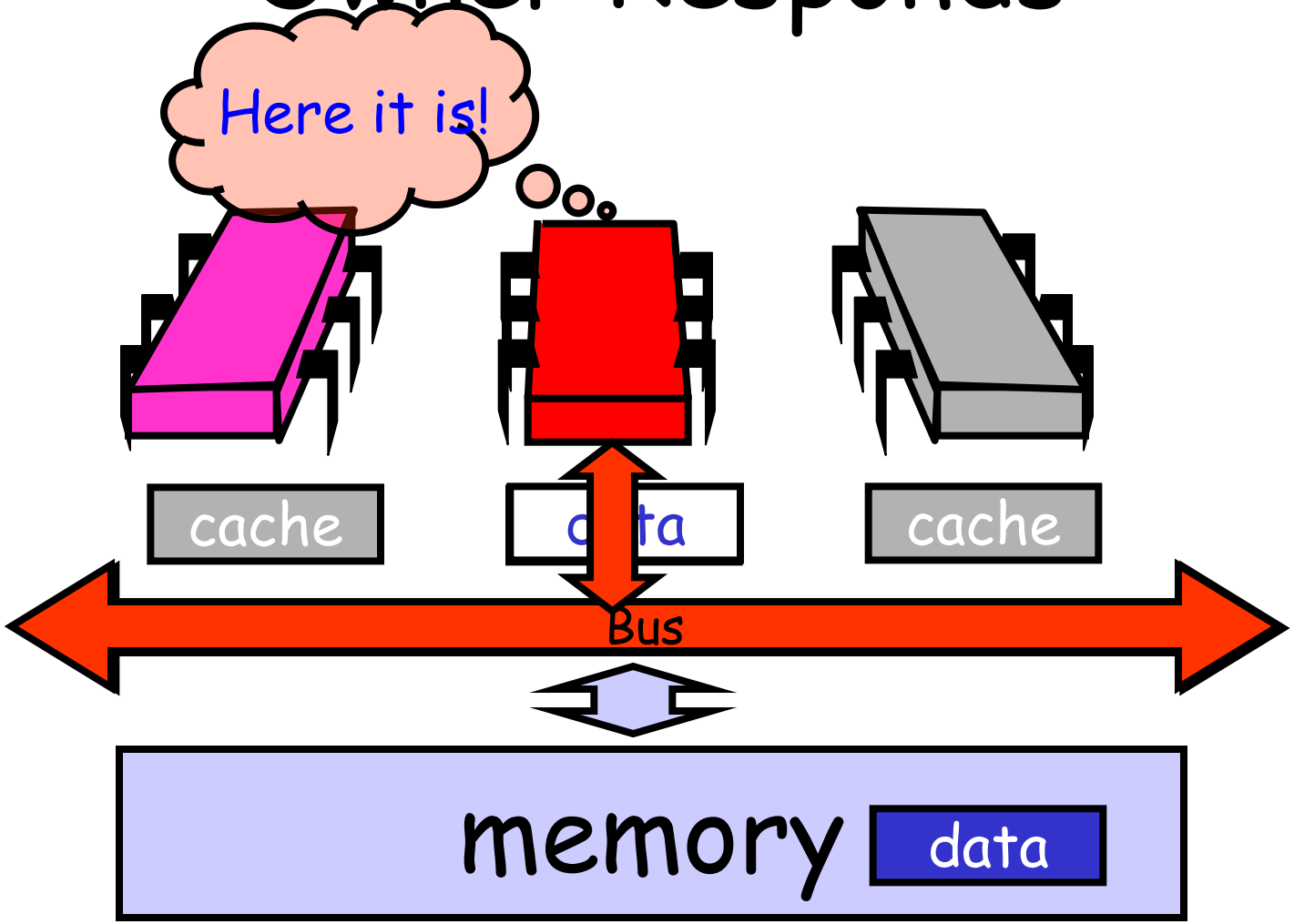
Invalidate


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

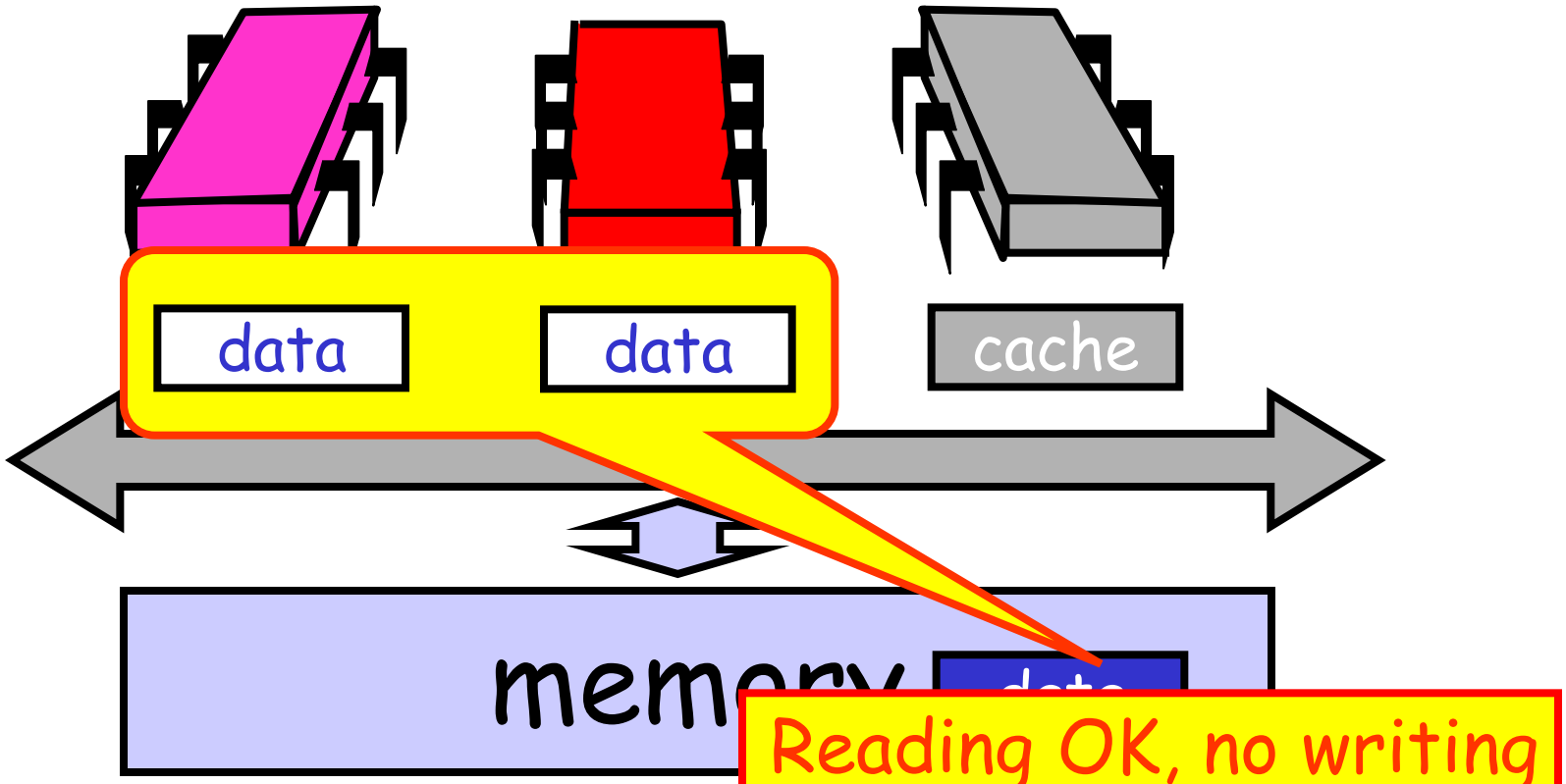
Another Processor Asks for Data



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

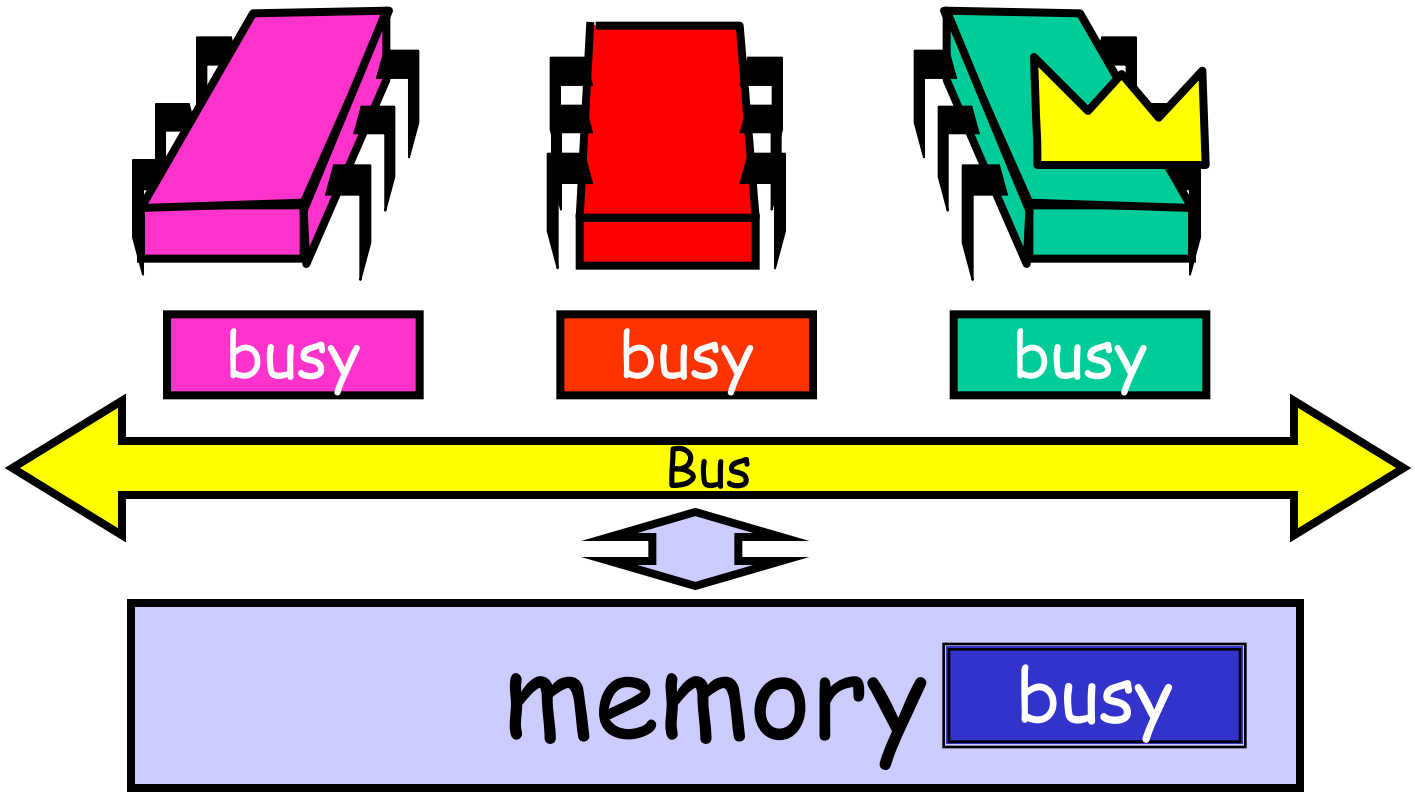
Simple TASLock

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

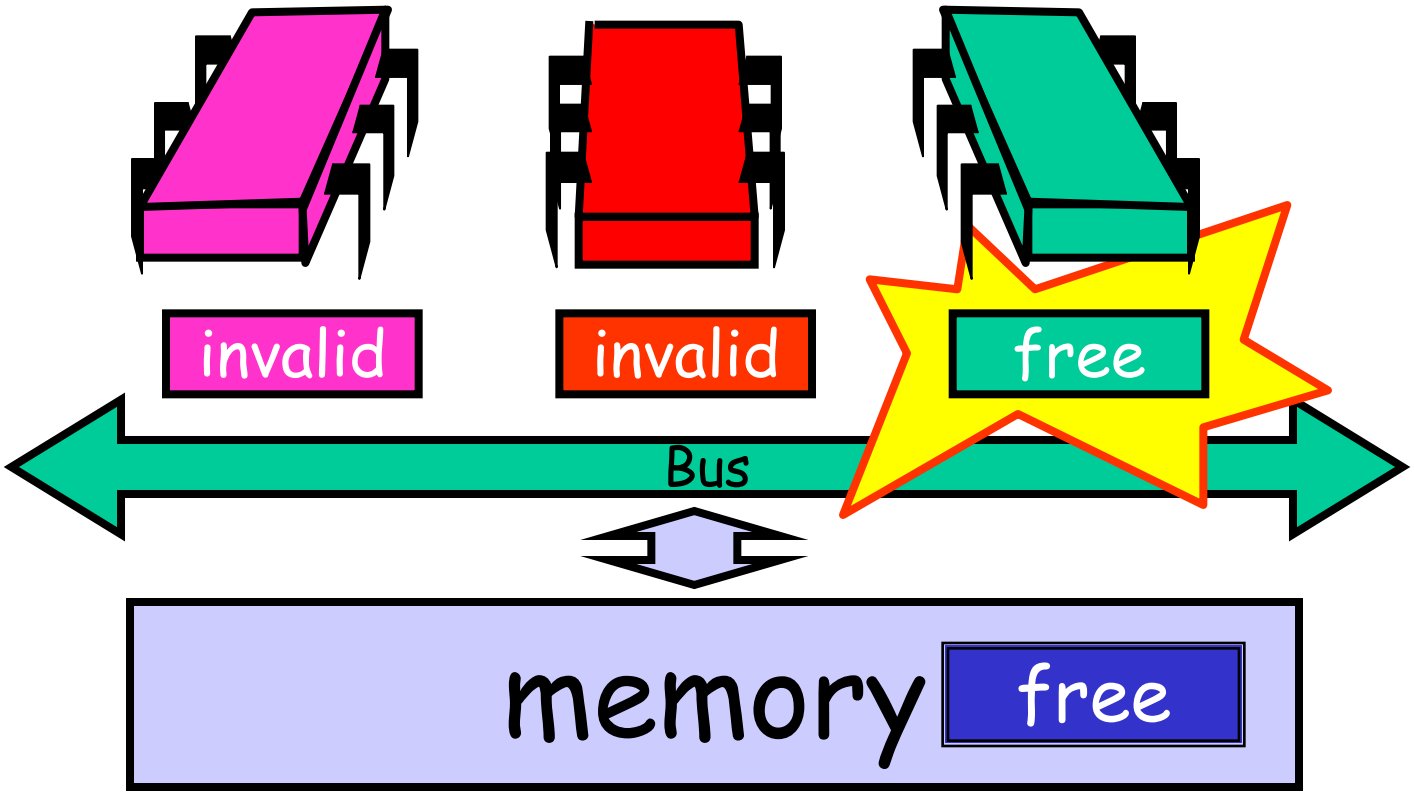
Test-and-test-and-set

- 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

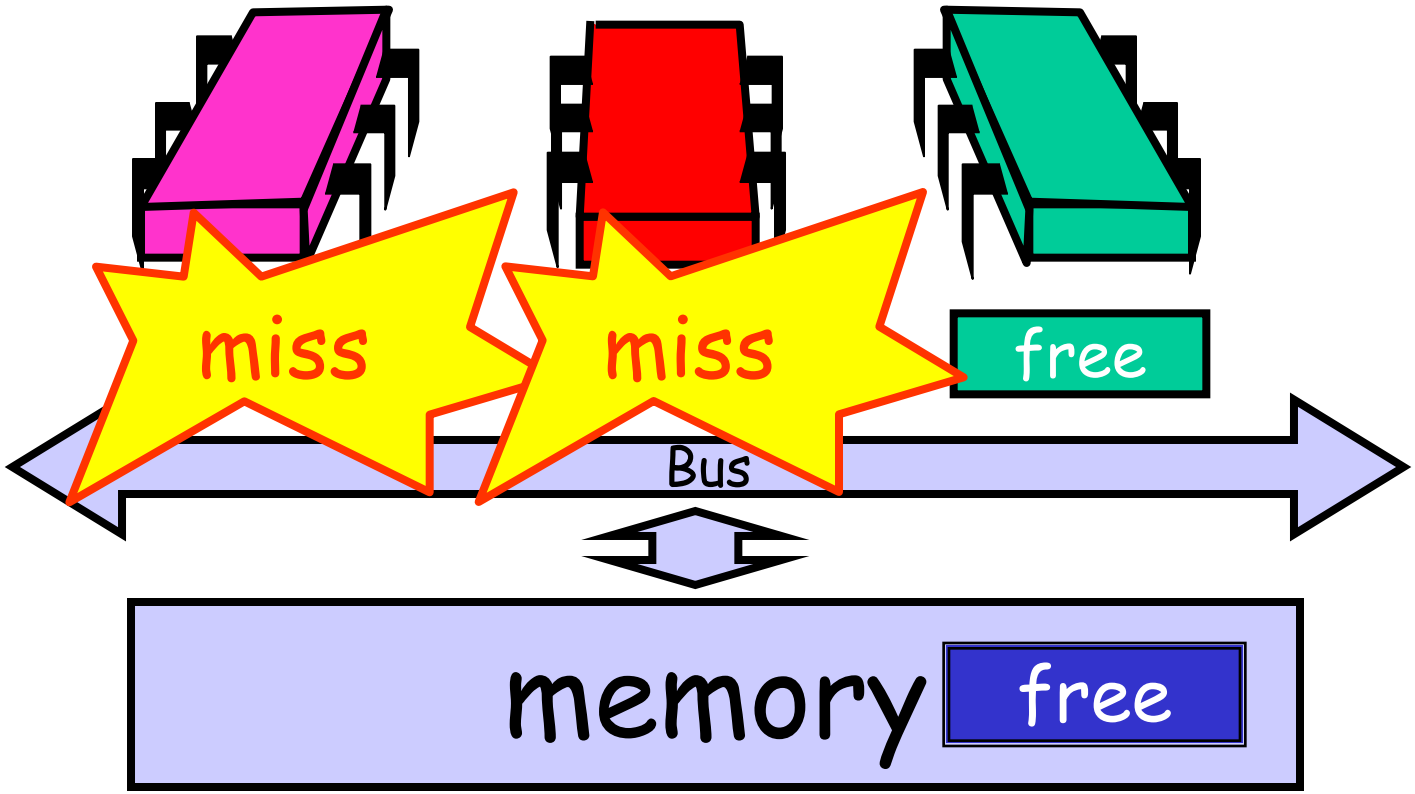


On Release



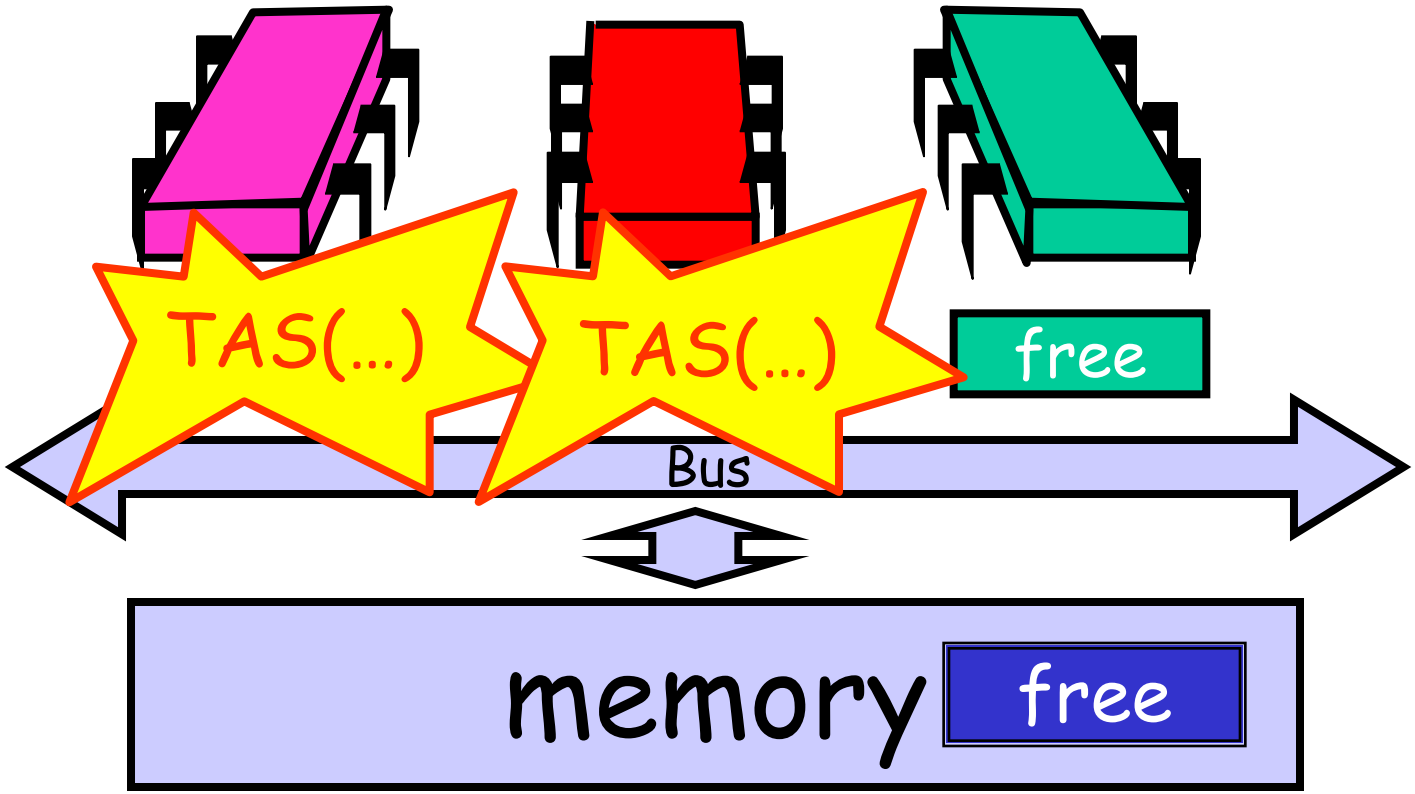
On Release

Everyone misses, rereads



On Release

Everyone tries TAS



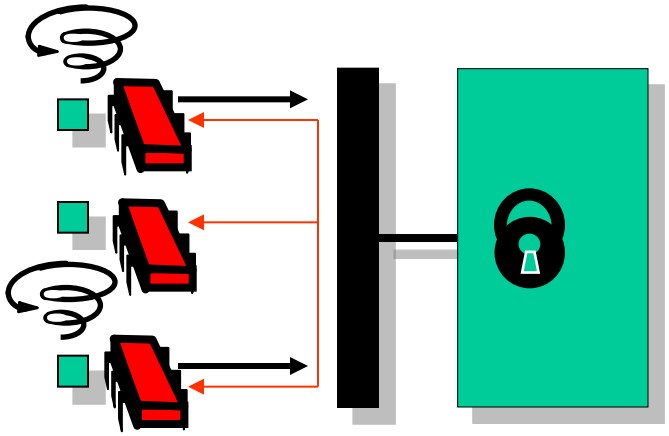
Problems

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

Measuring Quiescence Time

X = time of ops that don't use the bus

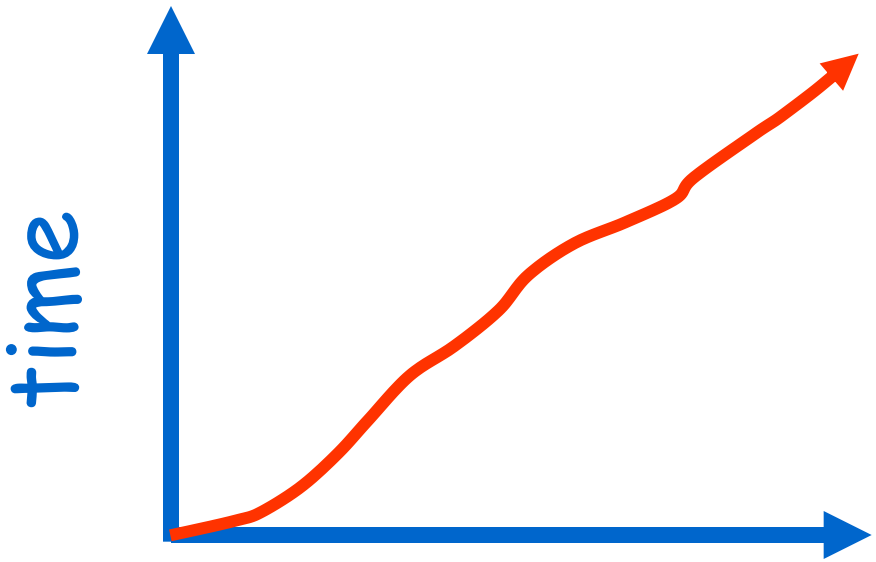
Y = time of ops that cause intensive bus traffic



In critical section, run ops X then ops Y. As long as Quiescence time is less than X, no drop in performance.

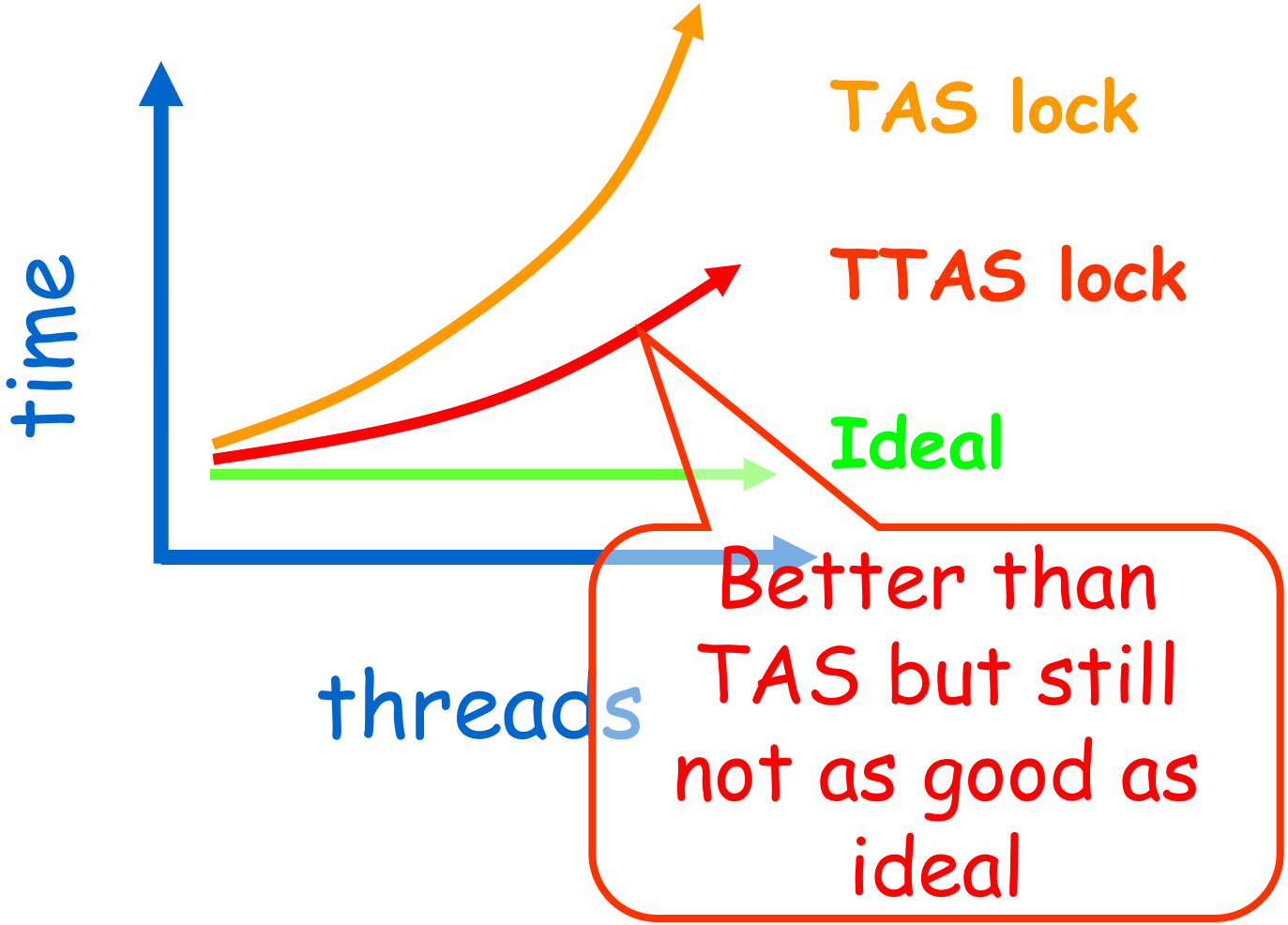
By gradually varying X, can determine the exact time to quiesce.

Quiescence Time



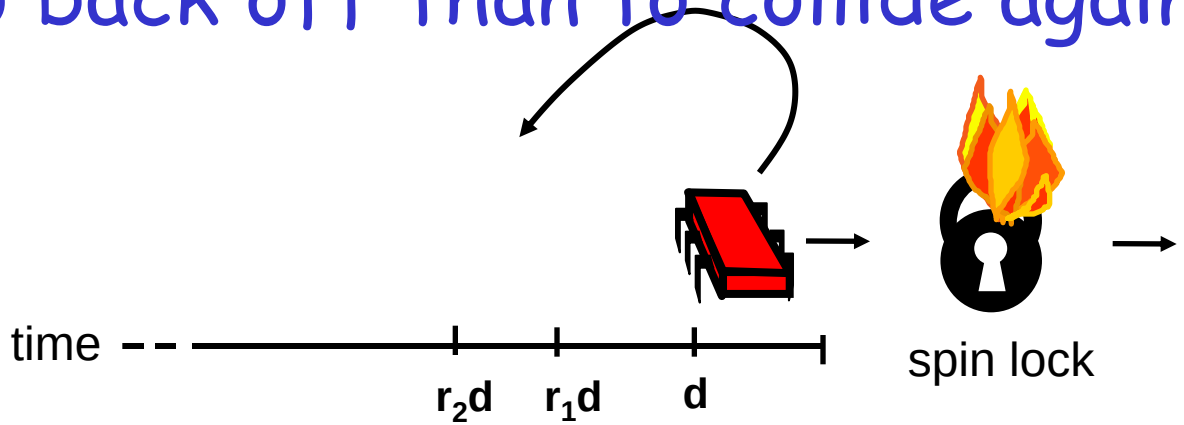
Increses linearly with the number of processors for bus architecture

Mystery Explained

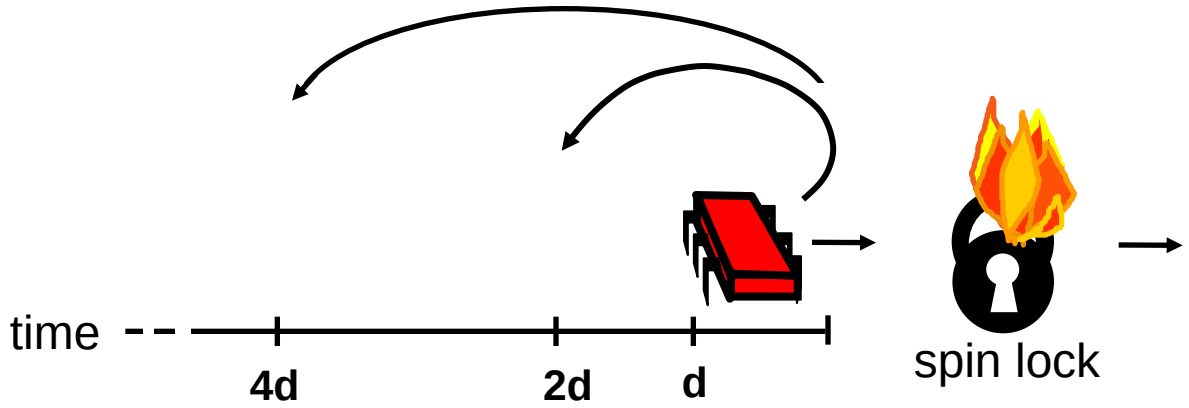


Solution: Introduce Delay

- 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 before retry
- Each subsequent failure doubles expected wait

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

```
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;
 }}}
```

Fix minimum delay

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
 }}}
```

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

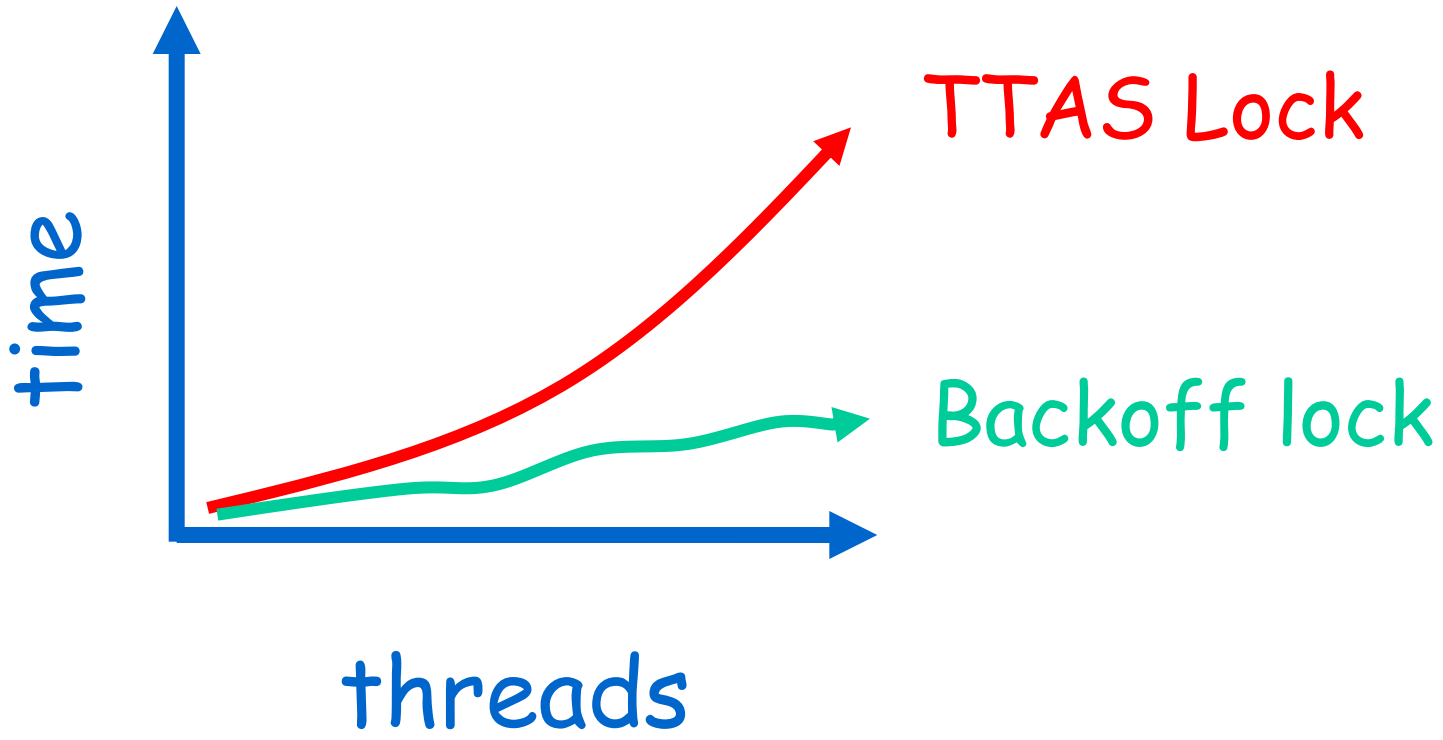
Back off for random duration

Exponential Backoff Lock

```
public class Backoff implements lock {
 publ
  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



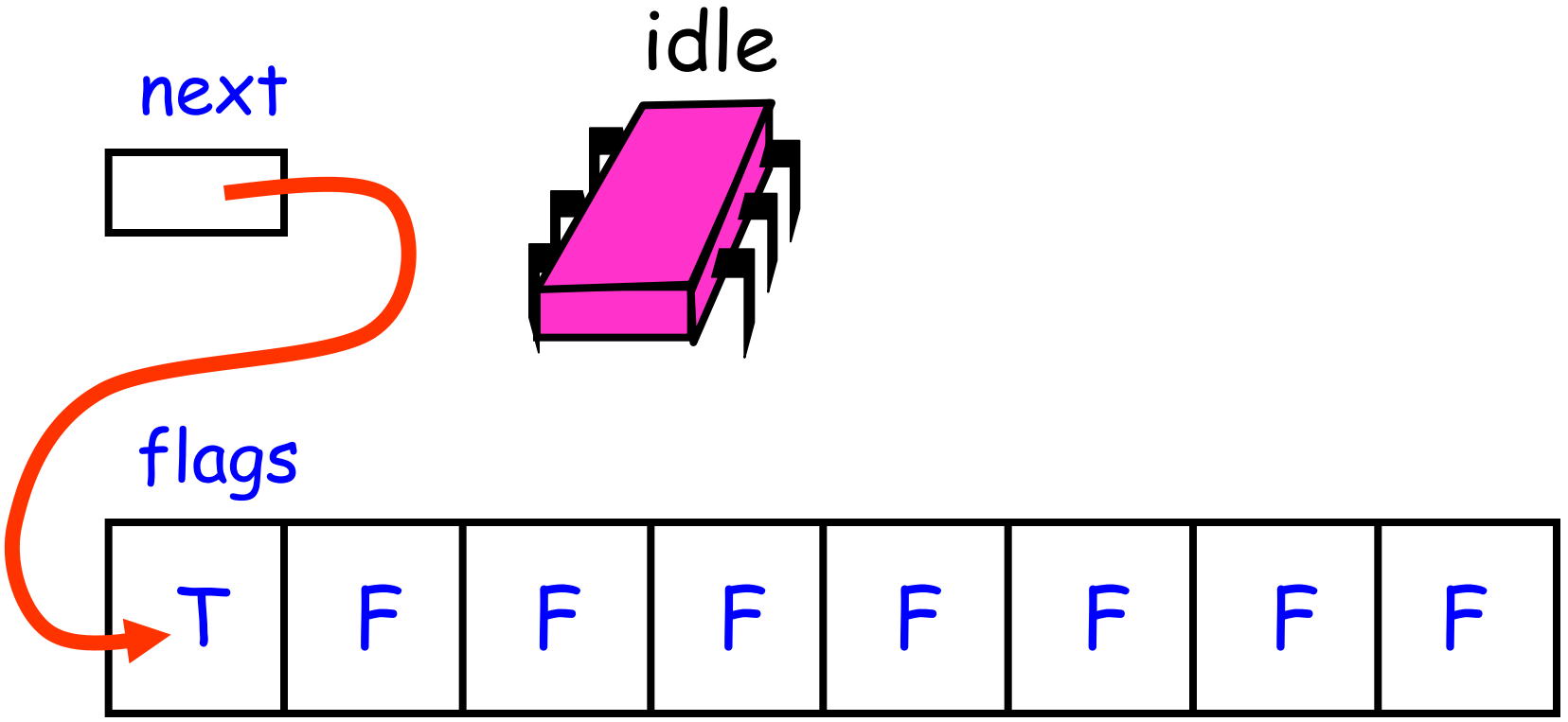
Backoff: Other Issues

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

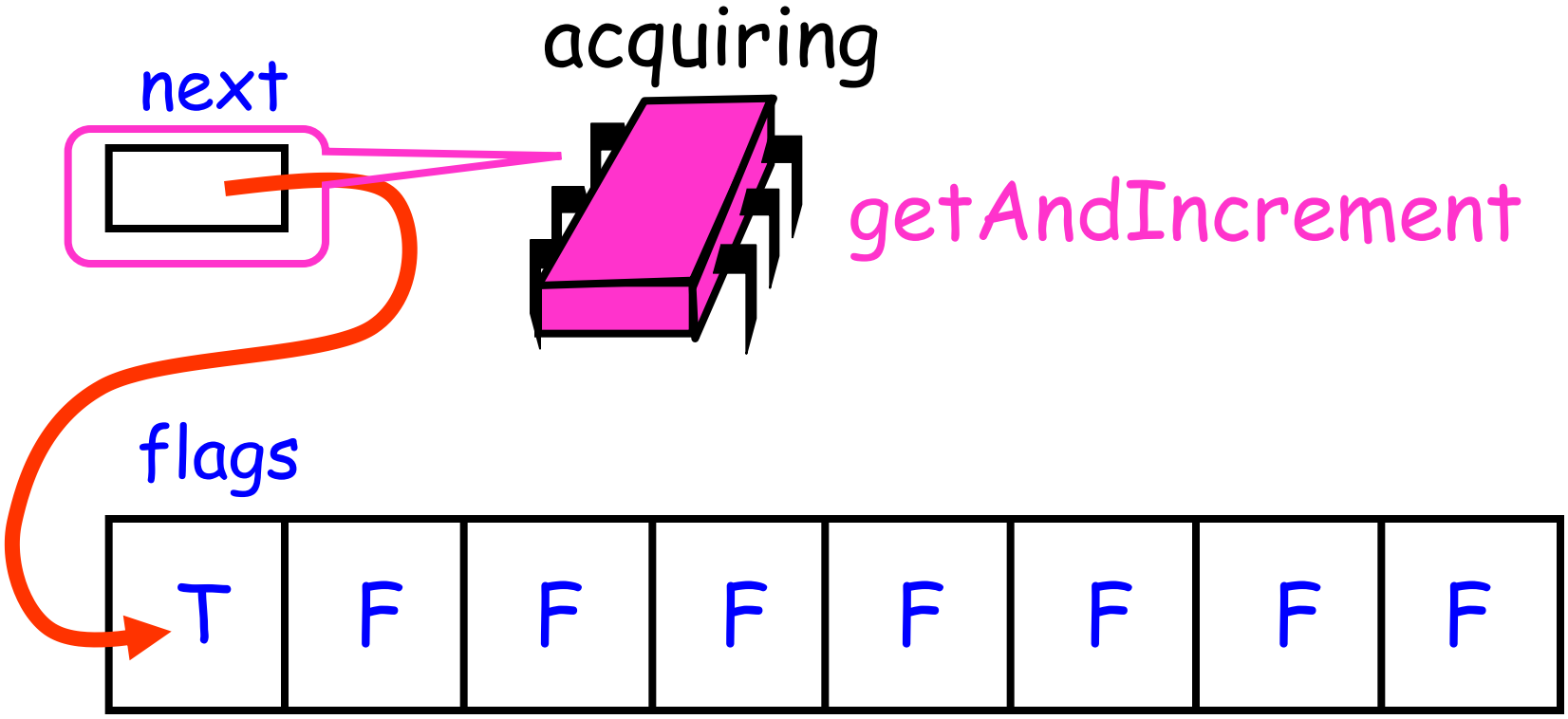
Idea

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

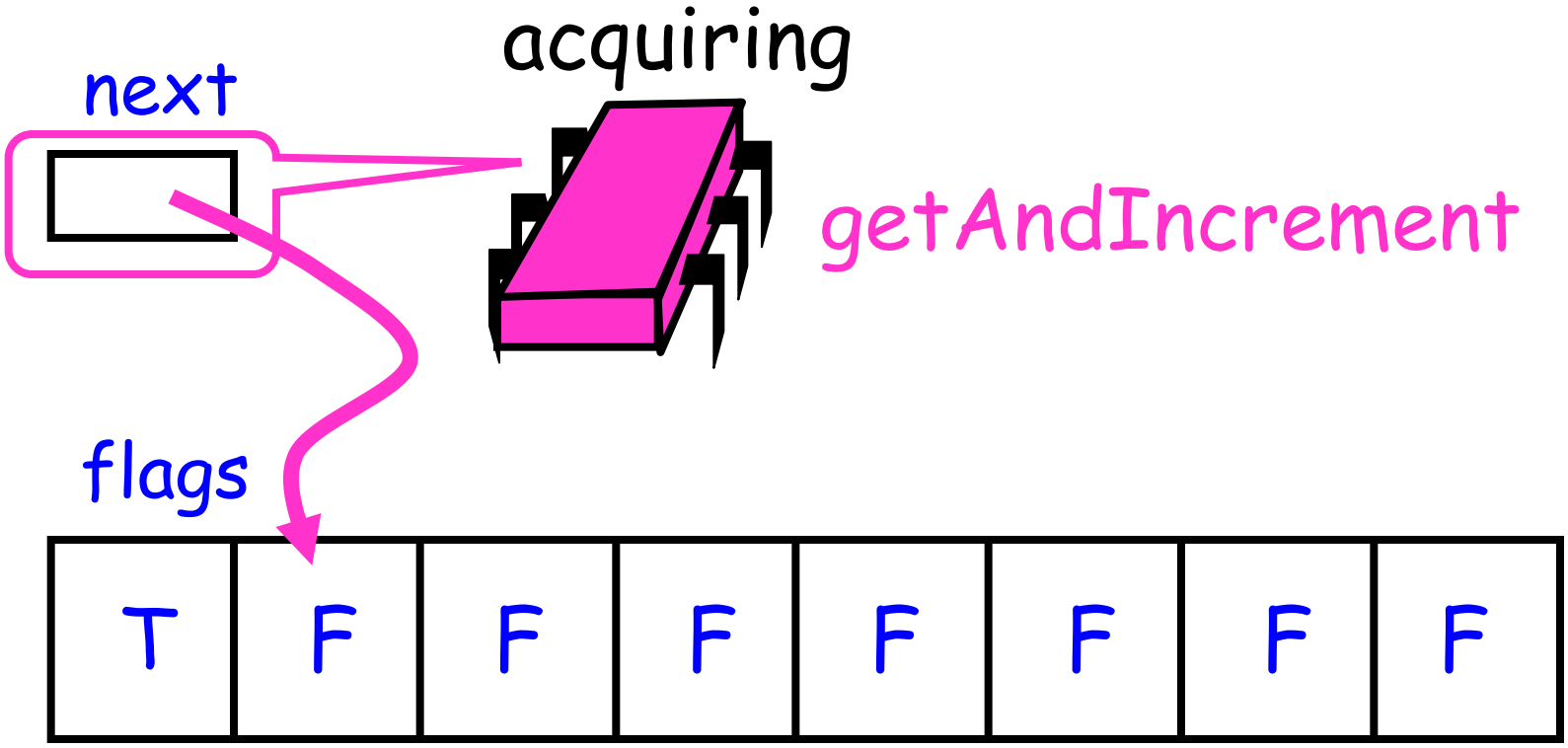
Anderson Queue Lock



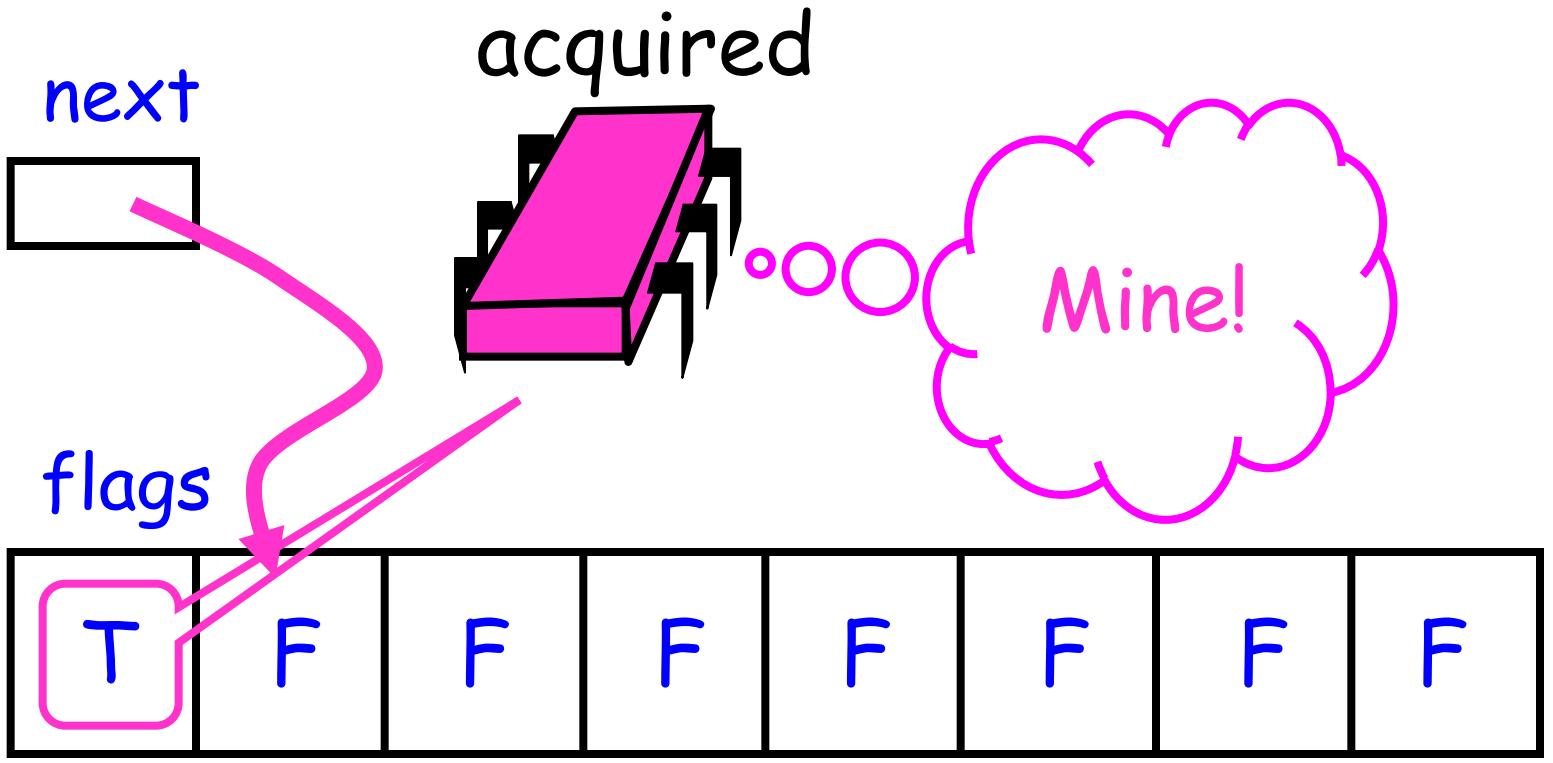
Anderson Queue Lock



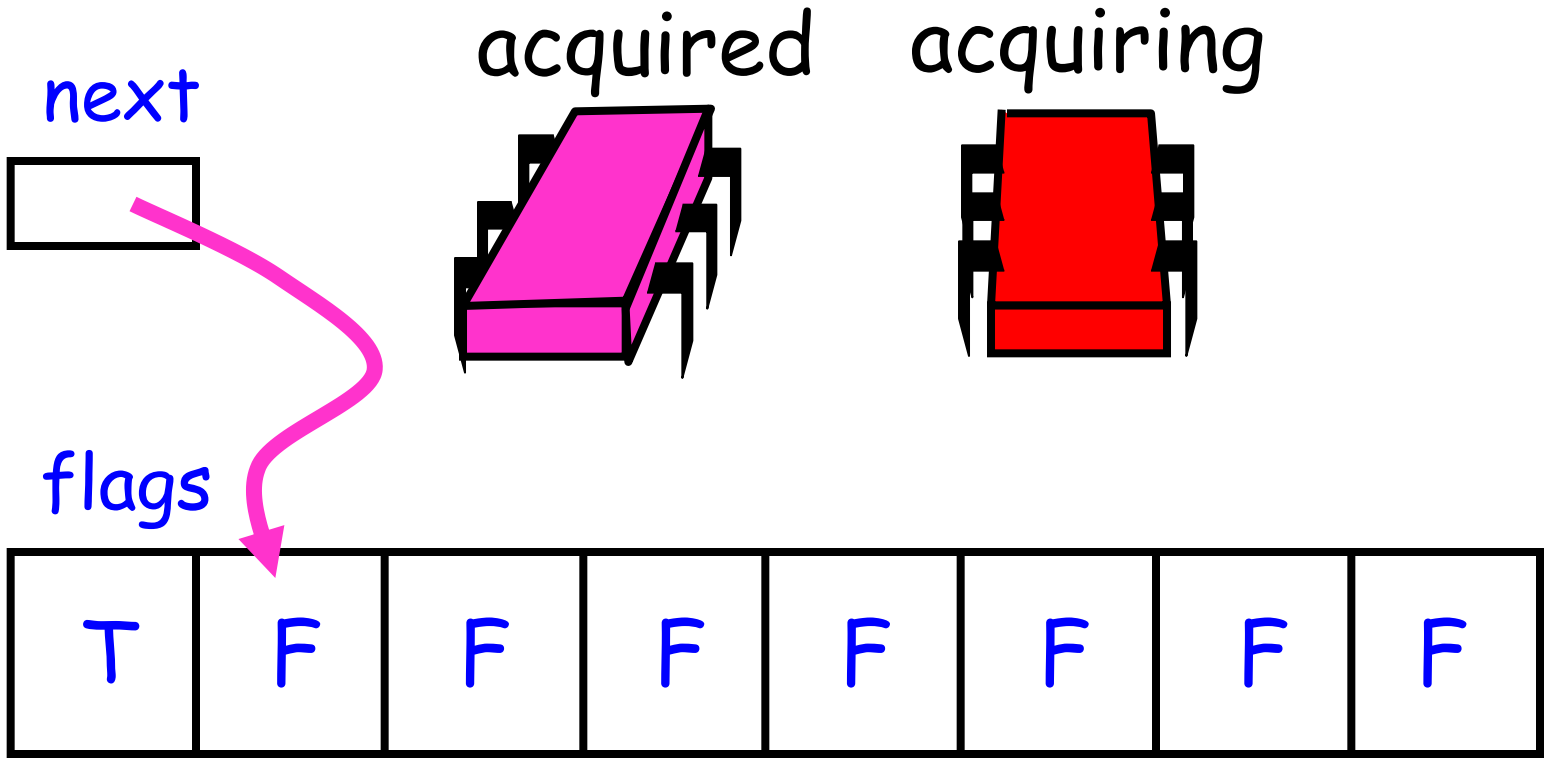
Anderson Queue Lock



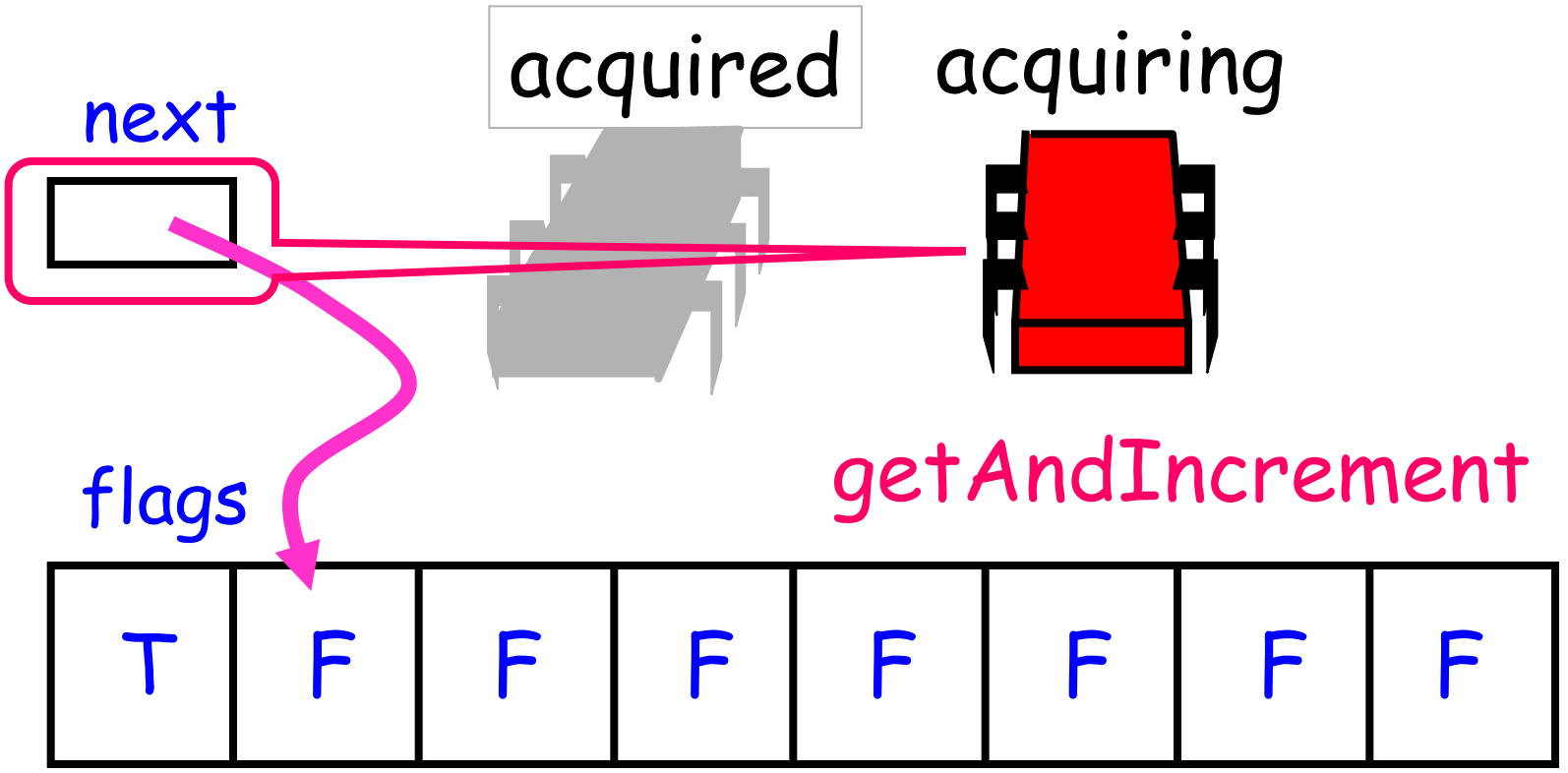
Anderson Queue Lock



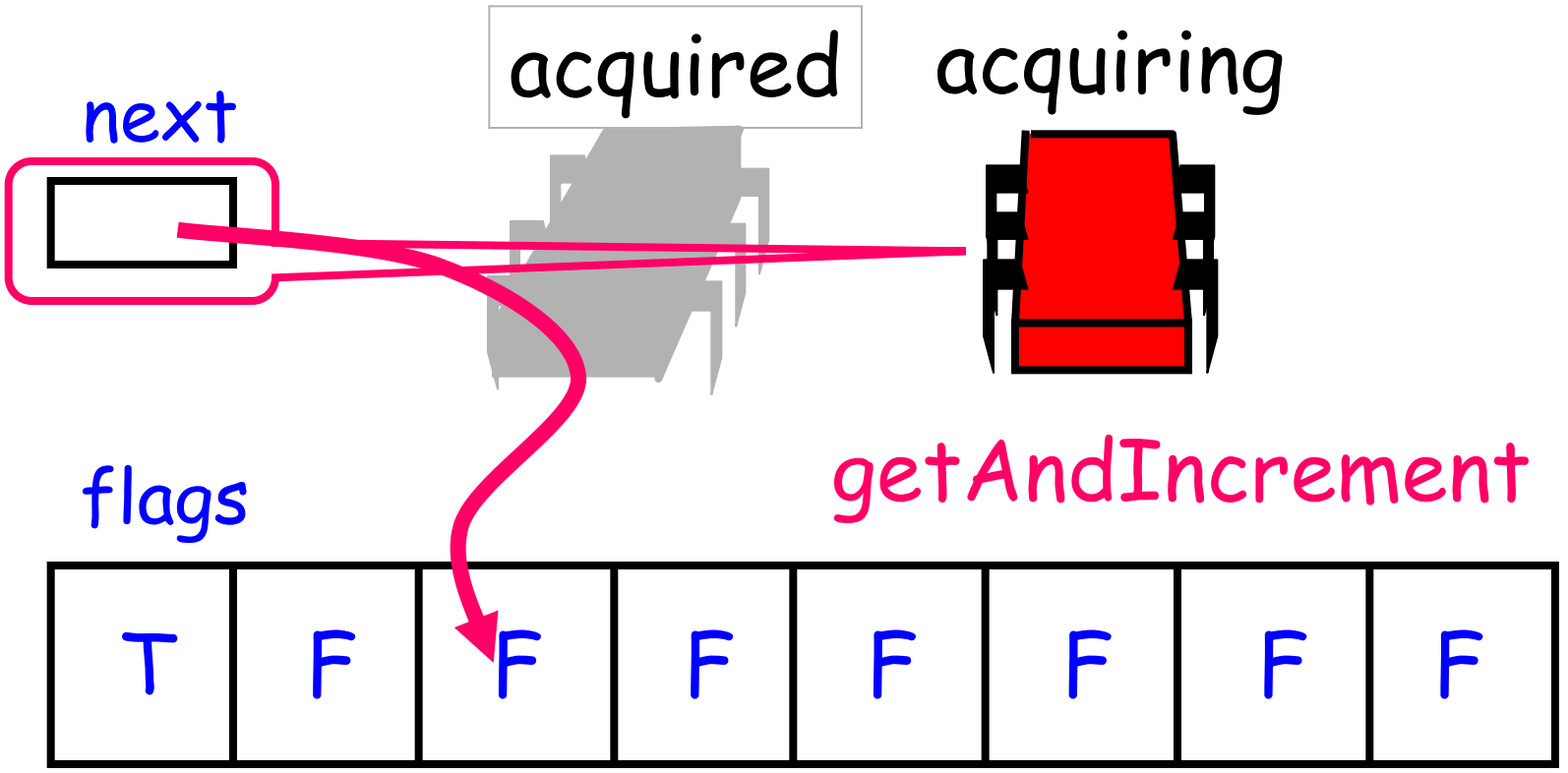
Anderson Queue Lock



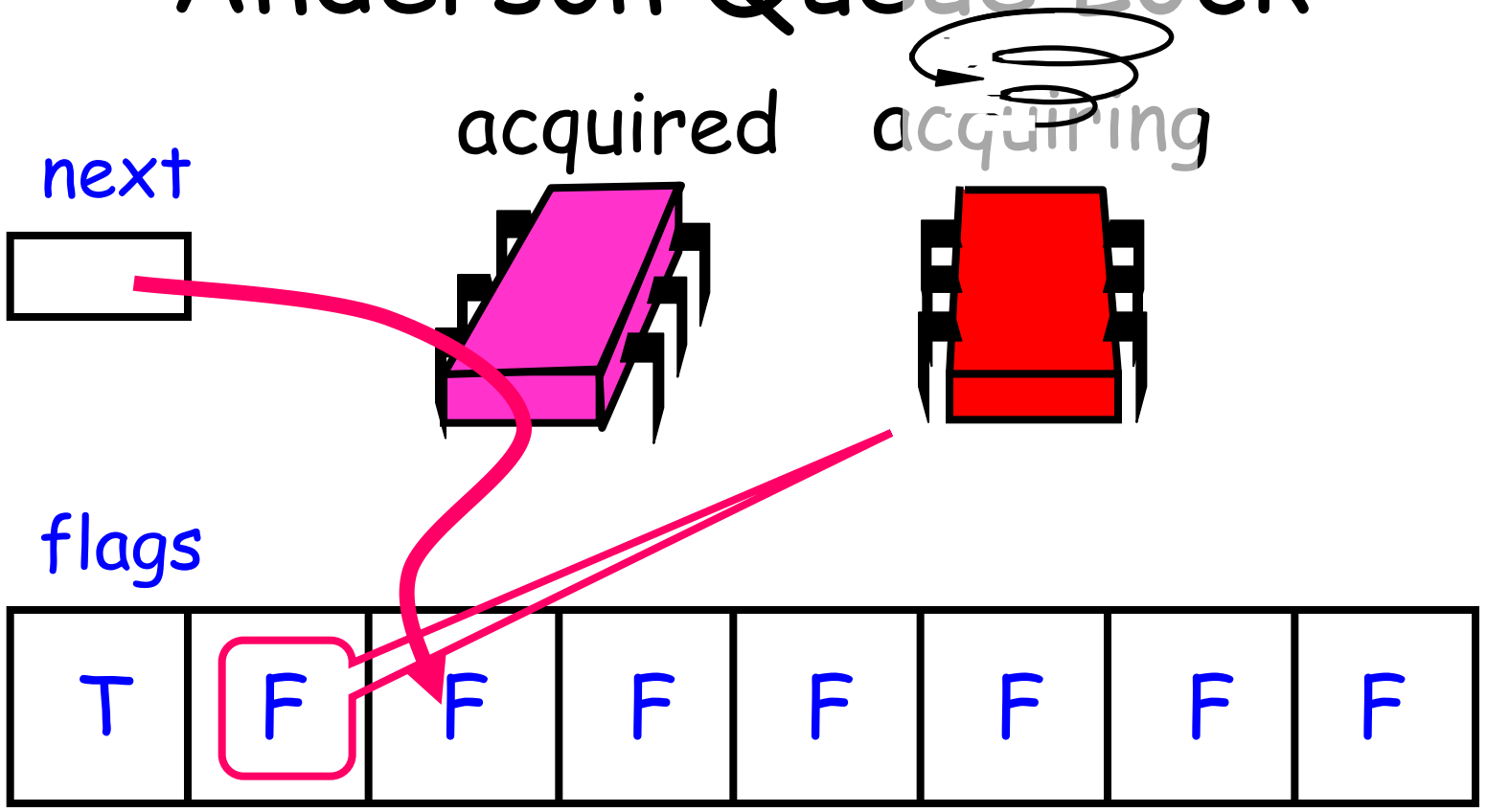
Anderson Queue Lock



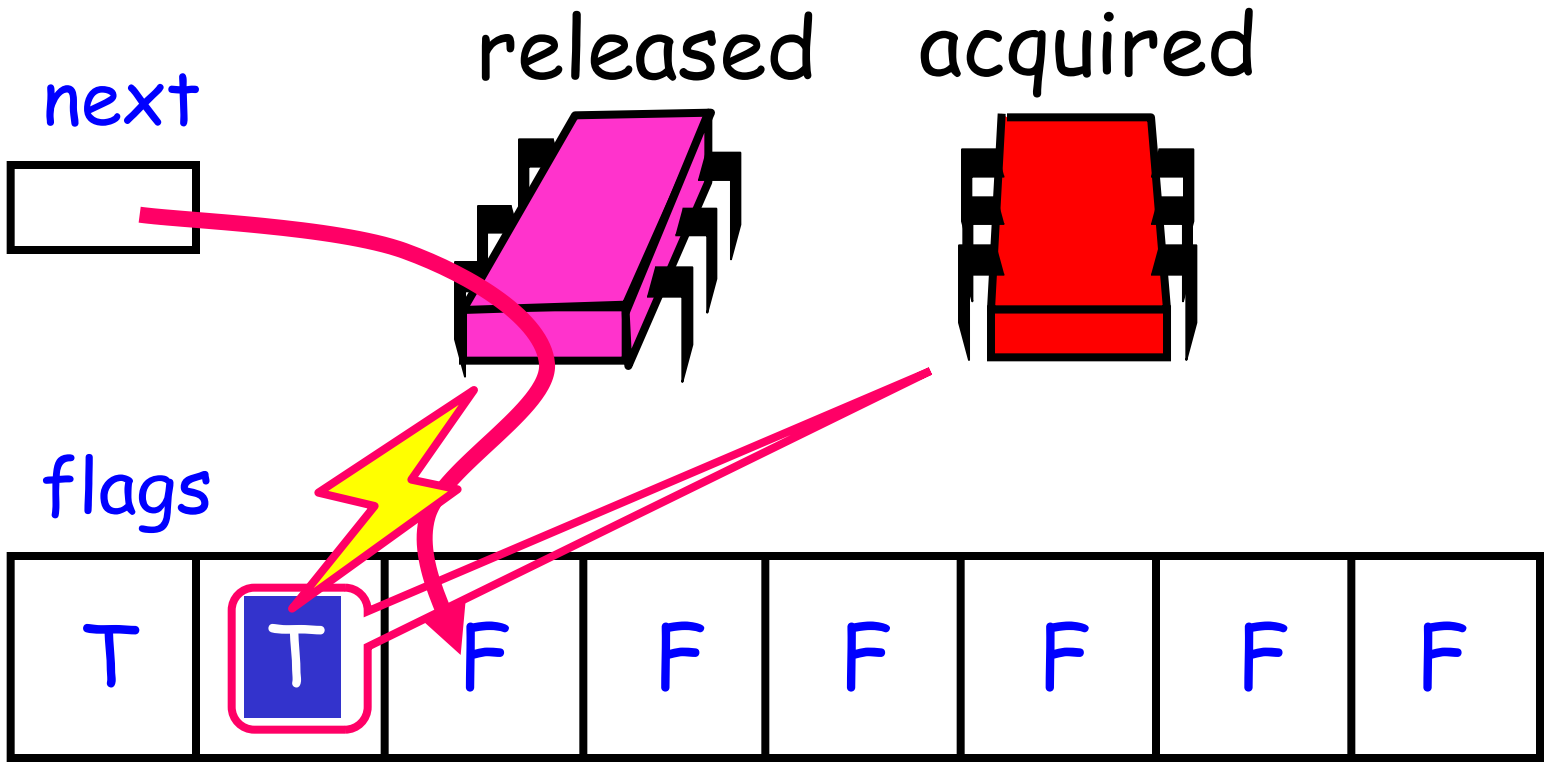
Anderson Queue Lock



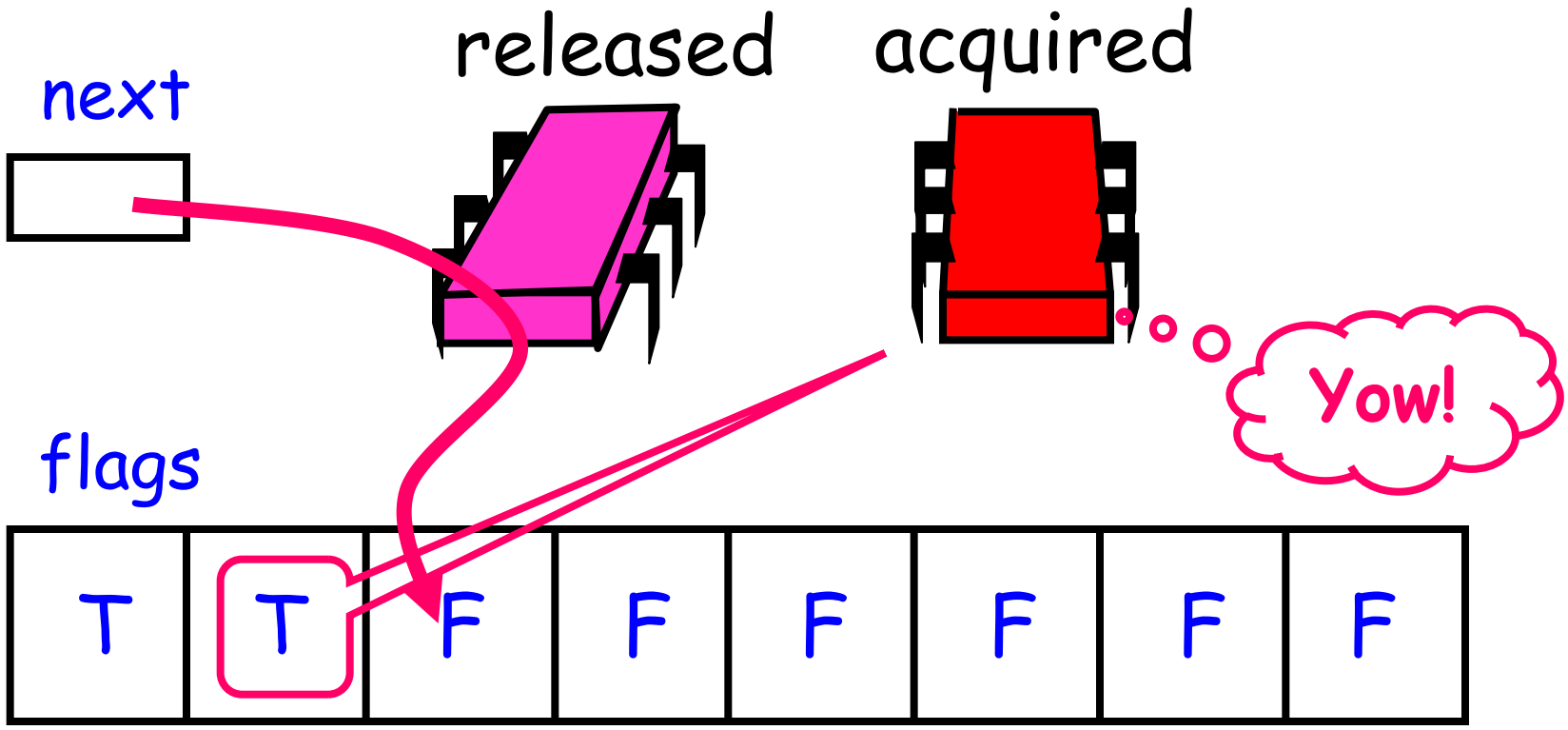
Anderson Queue Lock



Anderson Queue Lock



Anderson Queue Lock



Anderson Queue Lock

```
class ALock implements Lock {
 boolean[] flags={true,false,…,false};
 AtomicInteger next
  = new AtomicInteger(0);
 int[] slot = new int[n];
```

Anderson Queue Lock

```
class ALock implements Lock {
 boolean[] flags={true,false,…,false};
 AtomicInteger next
  = new AtomicInteger(0);
 int[] slot = new int[n];
```

One flag per thread

Anderson Queue Lock

```
class ALock implements Lock {
 boolean[] flags={true,false,…,false};
 AtomicInteger next
  = new AtomicInteger(0);
 int[] slot = new int[n];
```

Next flag to use

Anderson Queue Lock

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

Thread-local variable

Anderson Queue Lock

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

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

Anderson Queue Lock

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

public unlock() {
 flags[(mySlot+1) % n]
}
```

Take next slot

Anderson Queue Lock

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

public unlock() {
 flags[(mySlot+1)
}
```

Spin until told to go

Anderson Queue Lock

```
public lock() {
 int slot[i]=next.getAndIncrement();
 while (!flags[slot[i] % n]) {};
 flags[slot[i] % n] = false;
}

public unlock() {
 flags[slot[i]
}
```

Prepare slot for re-use

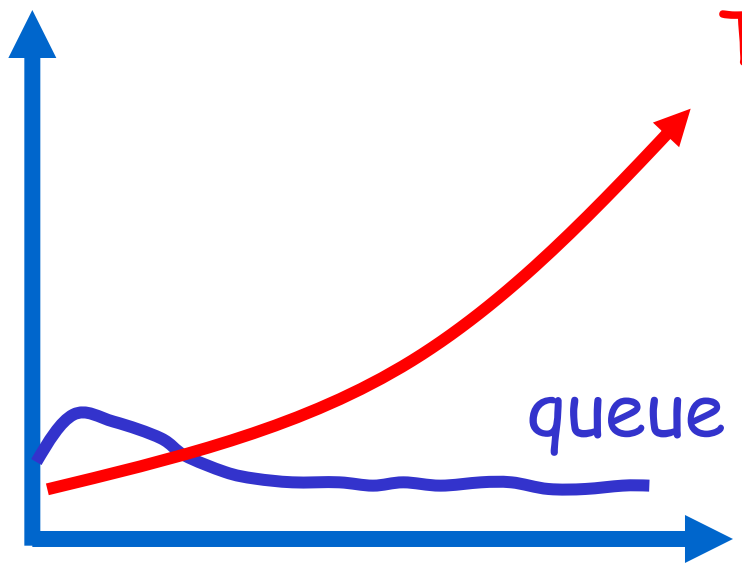
Anderson Queue Lock

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

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

Tell next thread to go

Performance



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

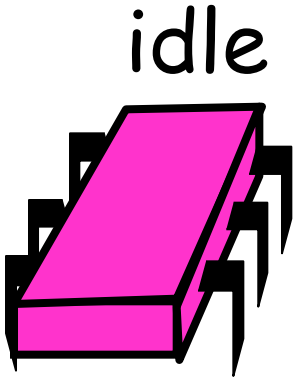
Anderson Queue Lock

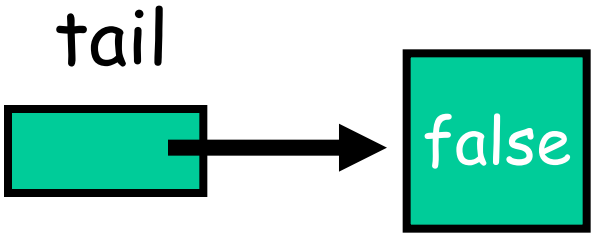
- Good
  - First truly scalable lock
  - Simple, easy to implement
- Bad
  - Space hog
  - One bit per thread
    - Unknown number of threads?
    - Small number of actual contenders?

CLH Lock

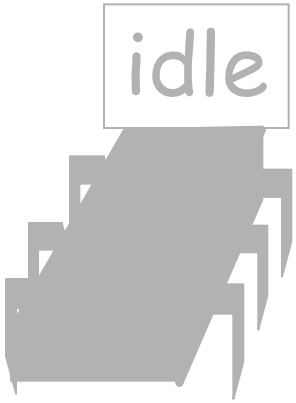
- FIFO order
- Small, constant-size overhead per thread

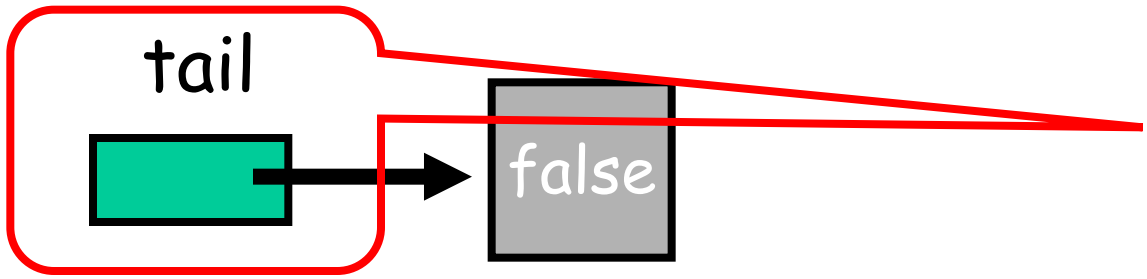
Initially





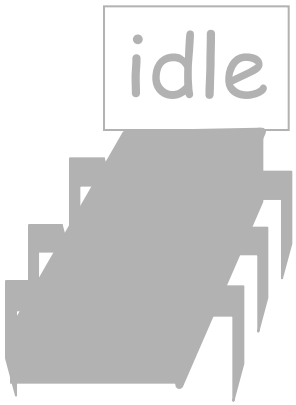
Initially

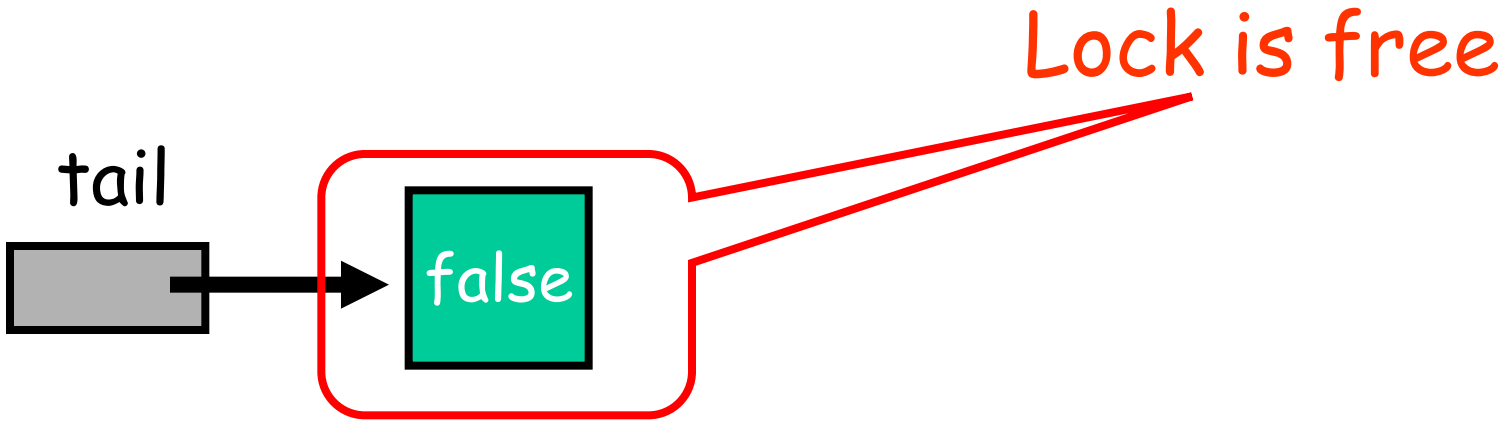




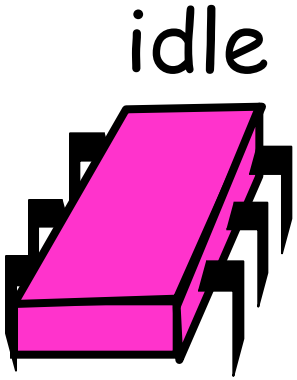
Queue tail

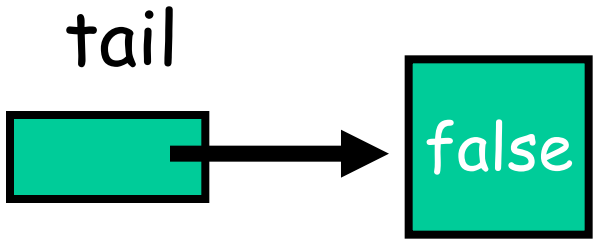
Initially





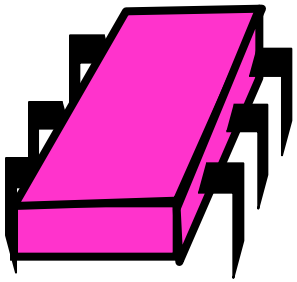
Initially

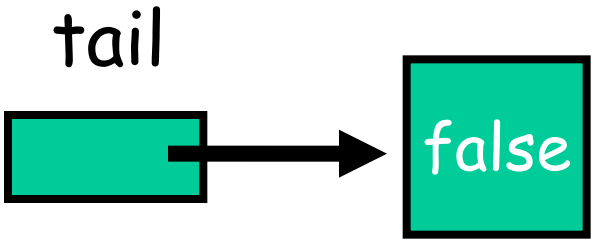




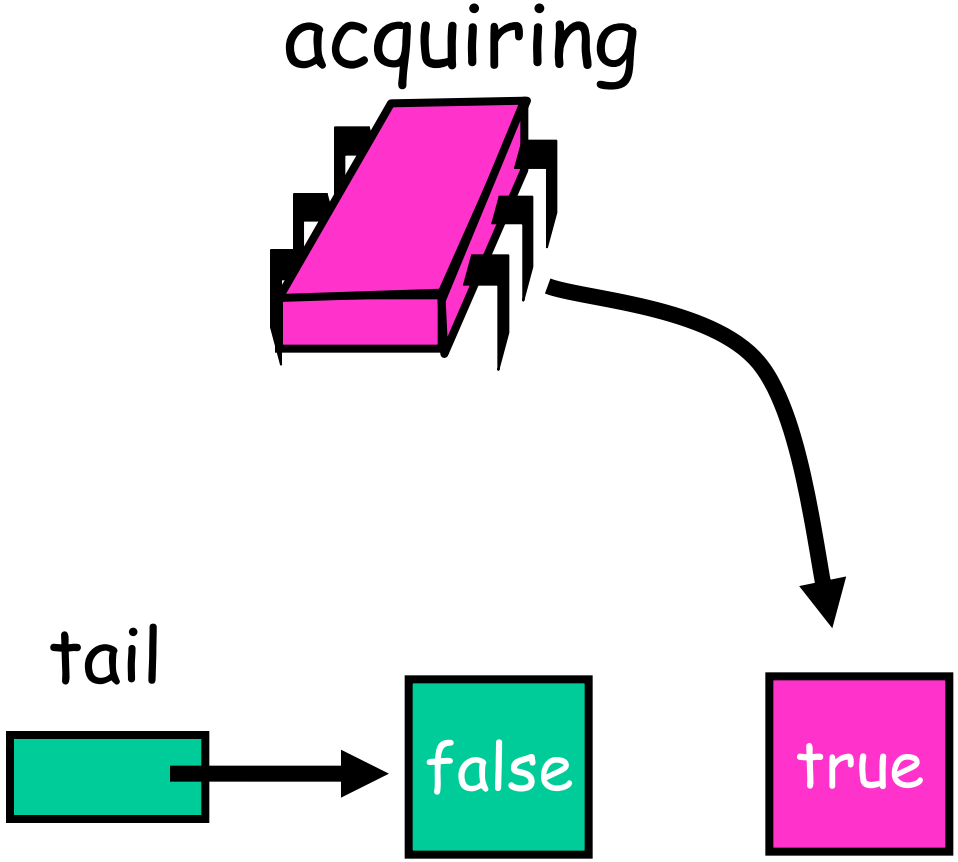
Purple Wants the Lock

acquiring

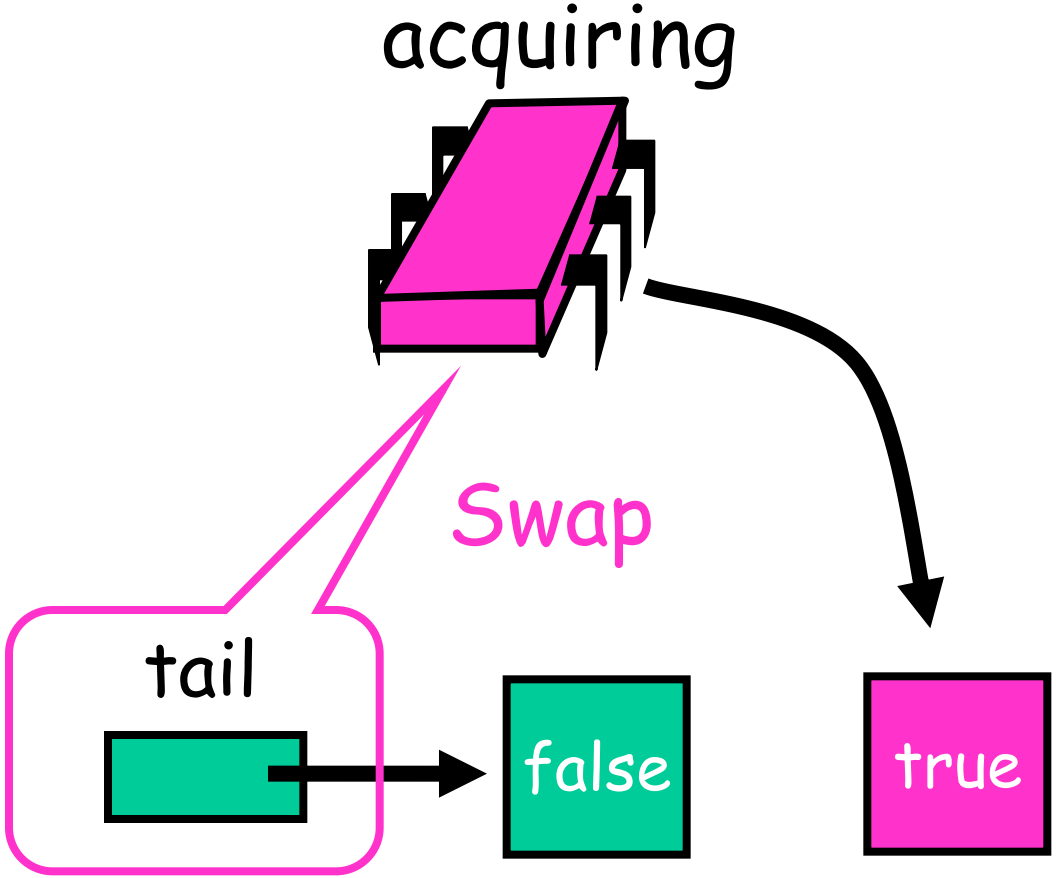




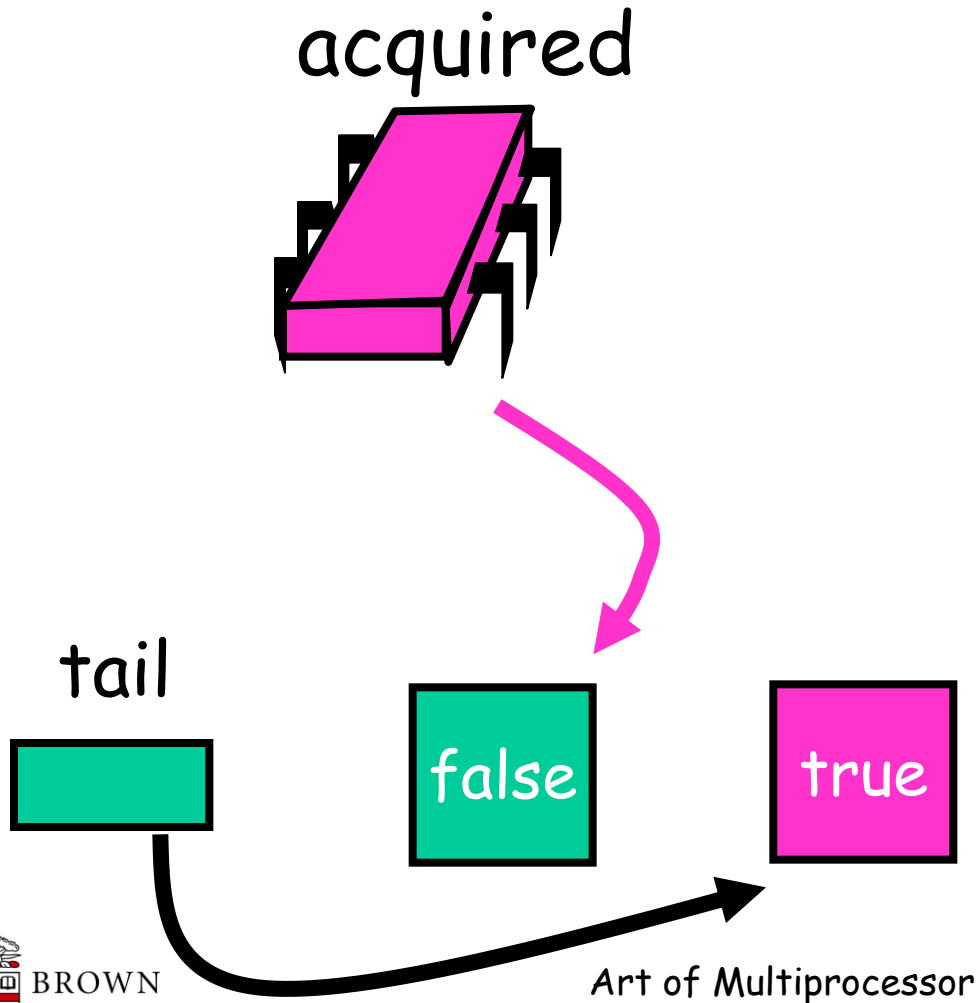
Purple Wants the Lock



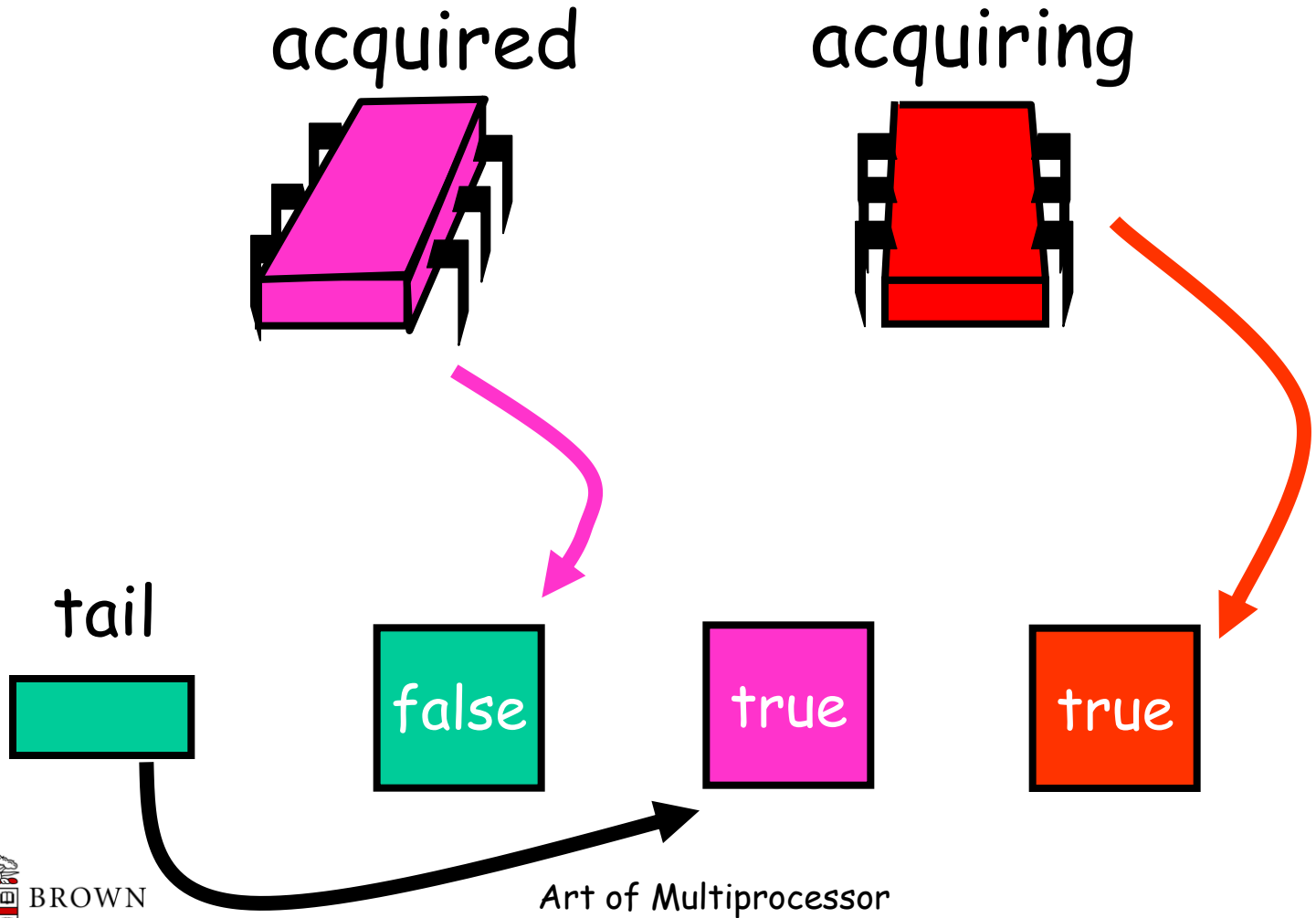
Purple Wants the Lock



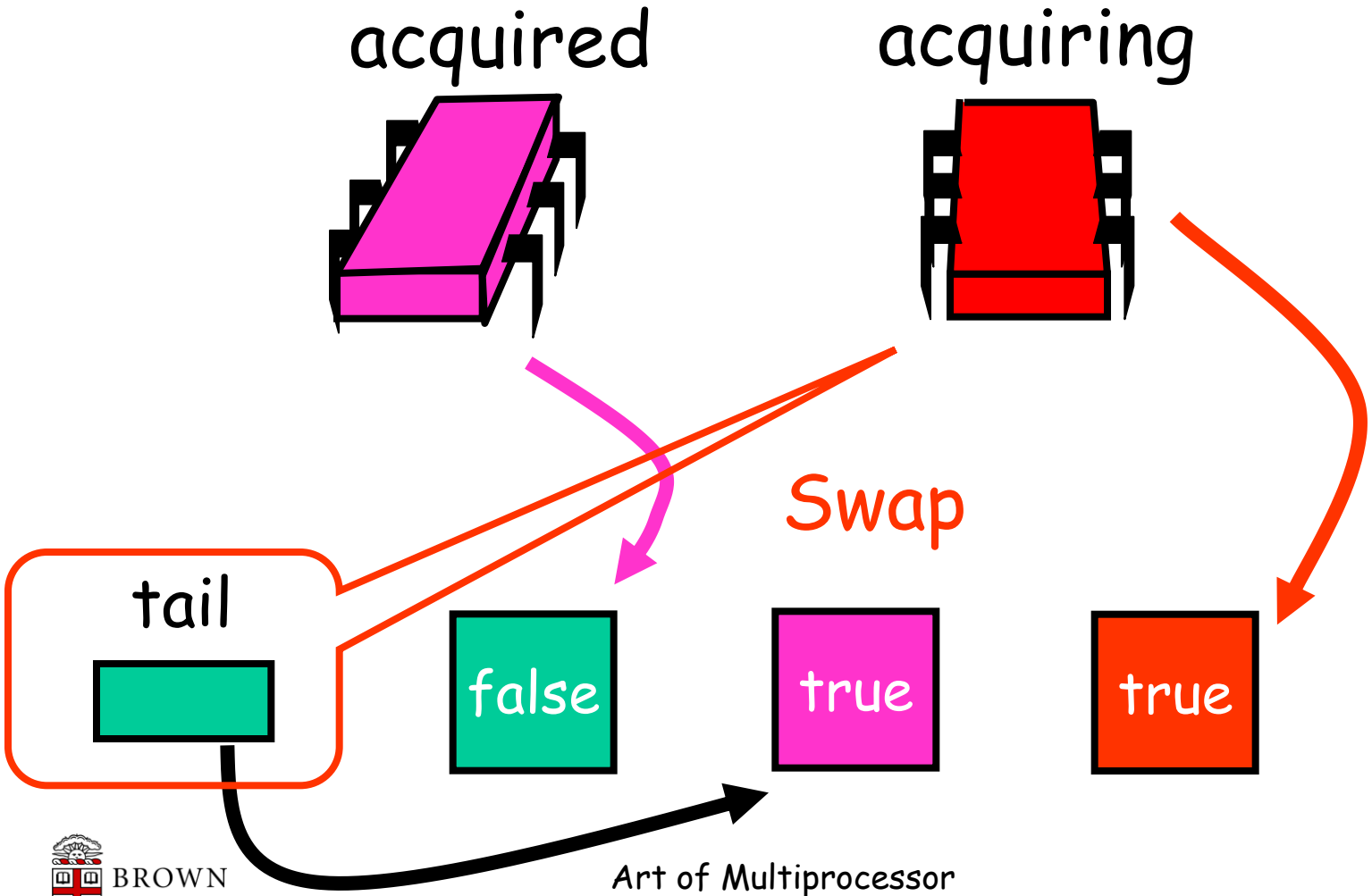
Purple Has the Lock



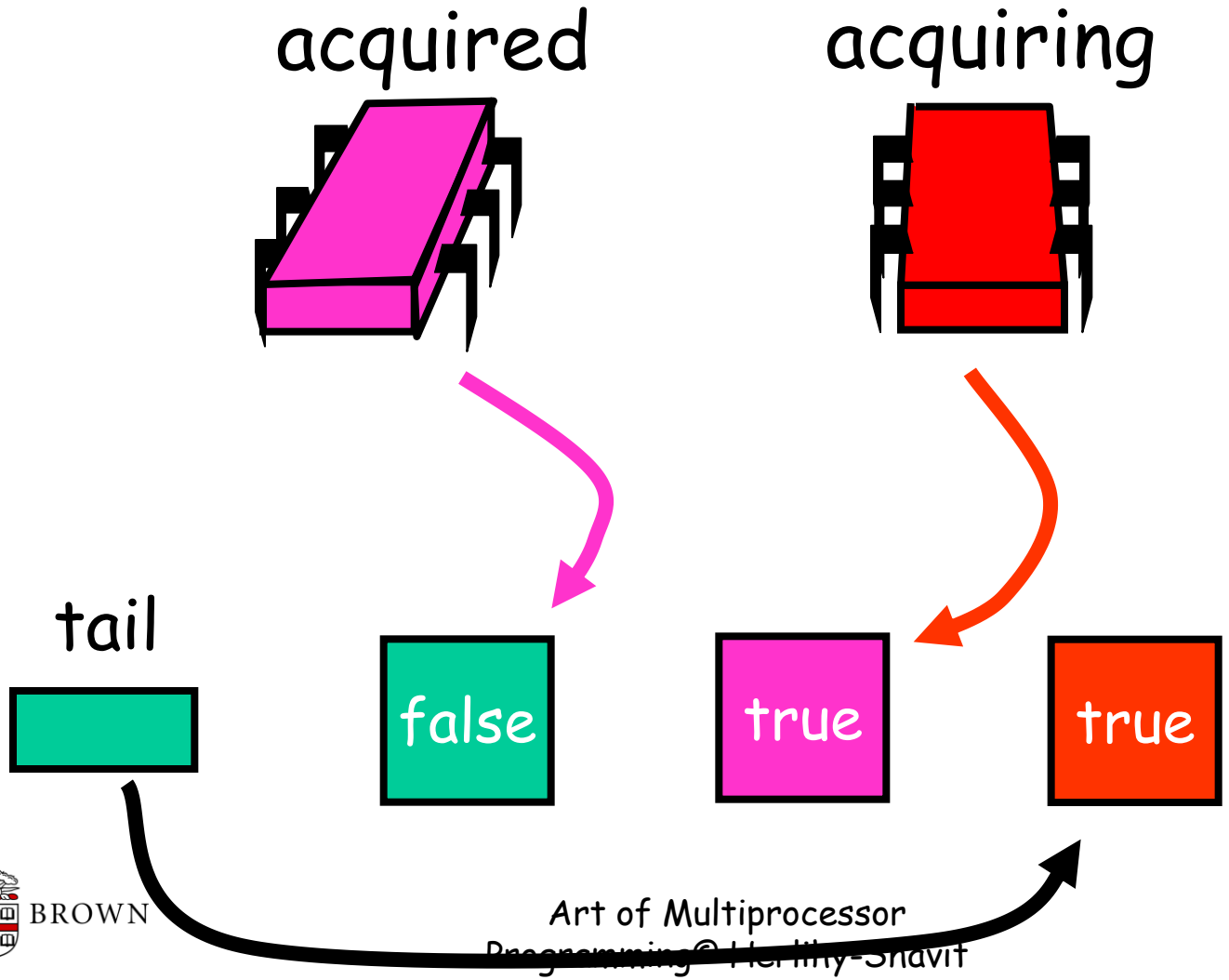
Red Wants the Lock



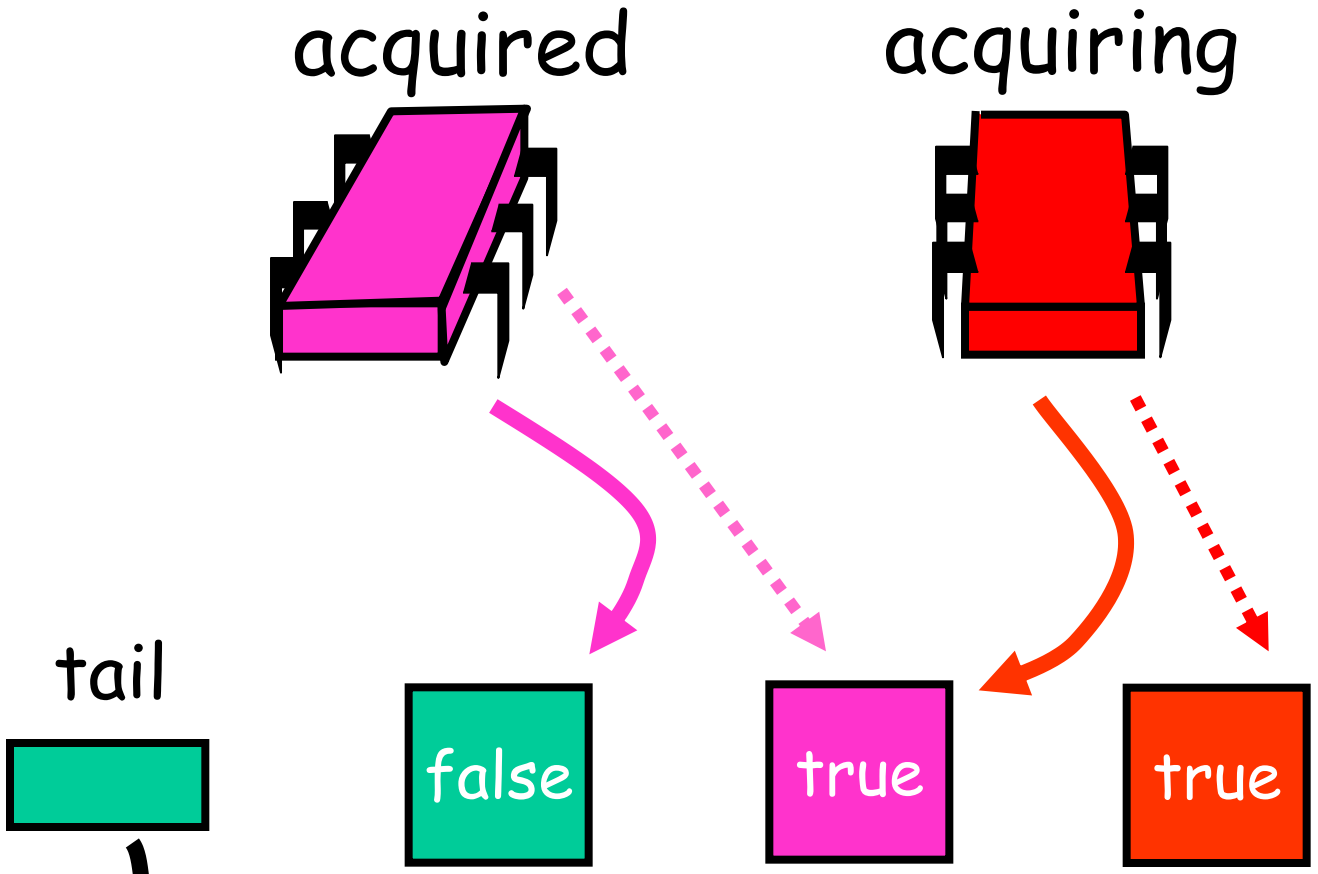
Red Wants the Lock



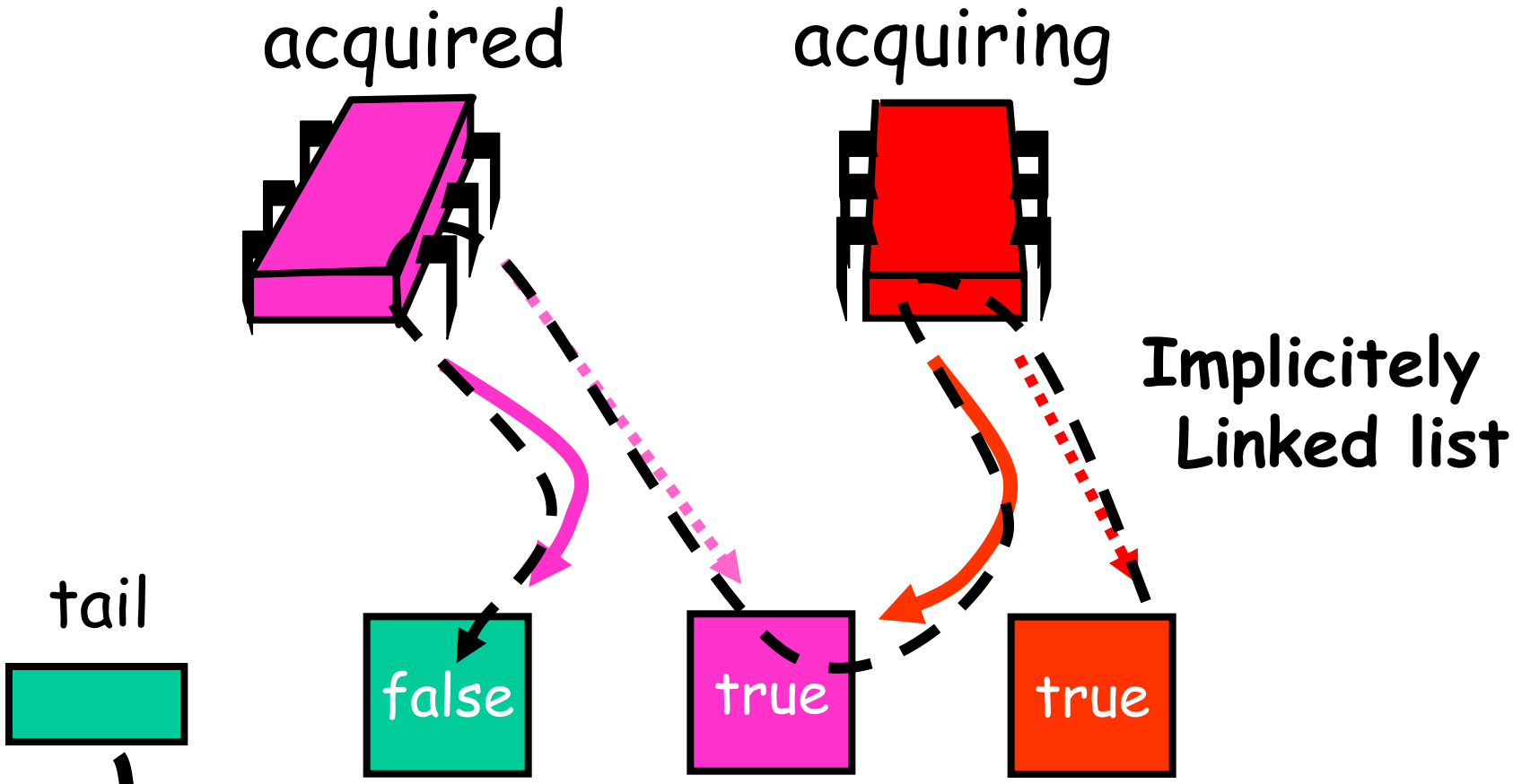
Red Wants the Lock



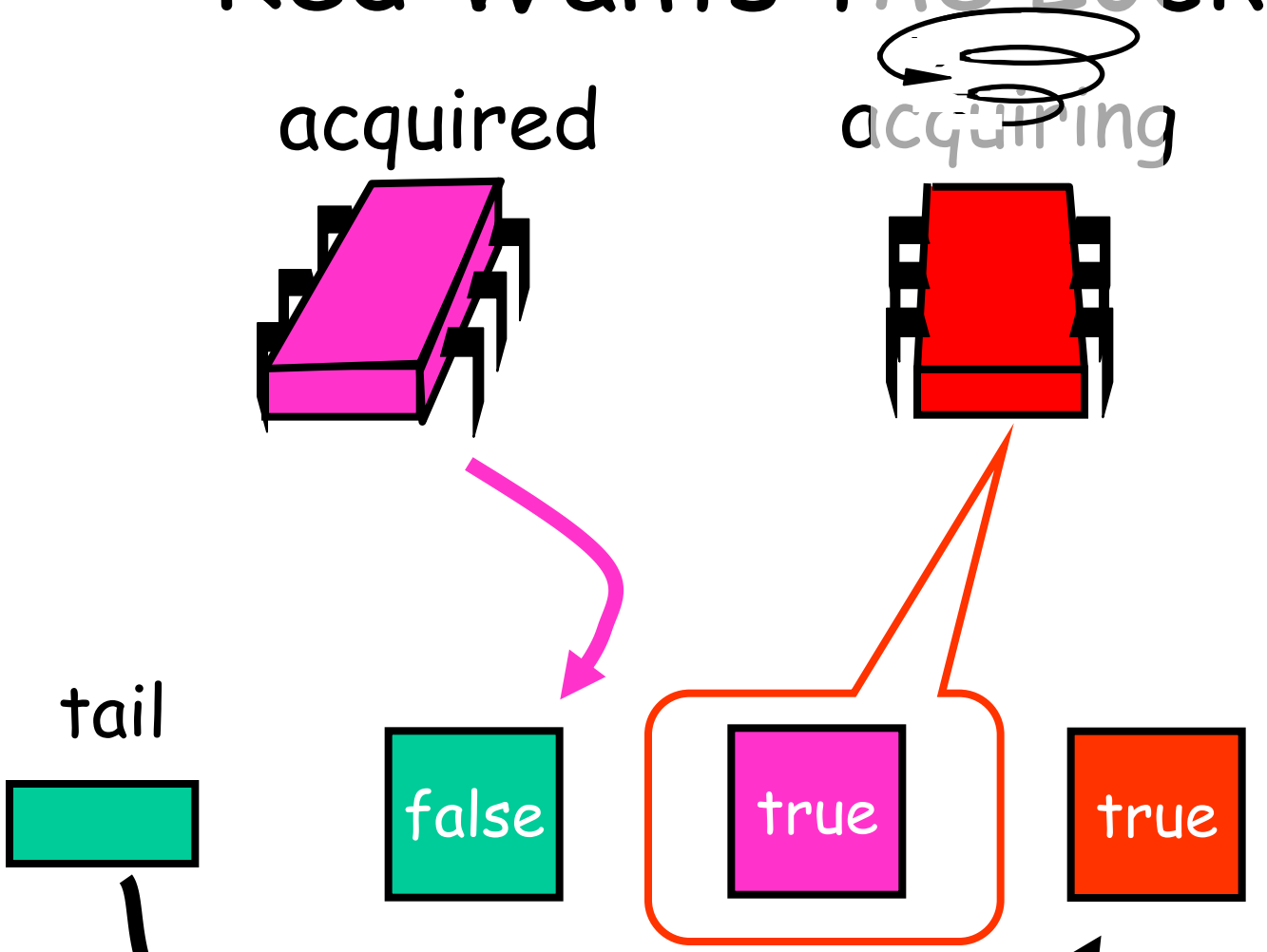
Red Wants the Lock



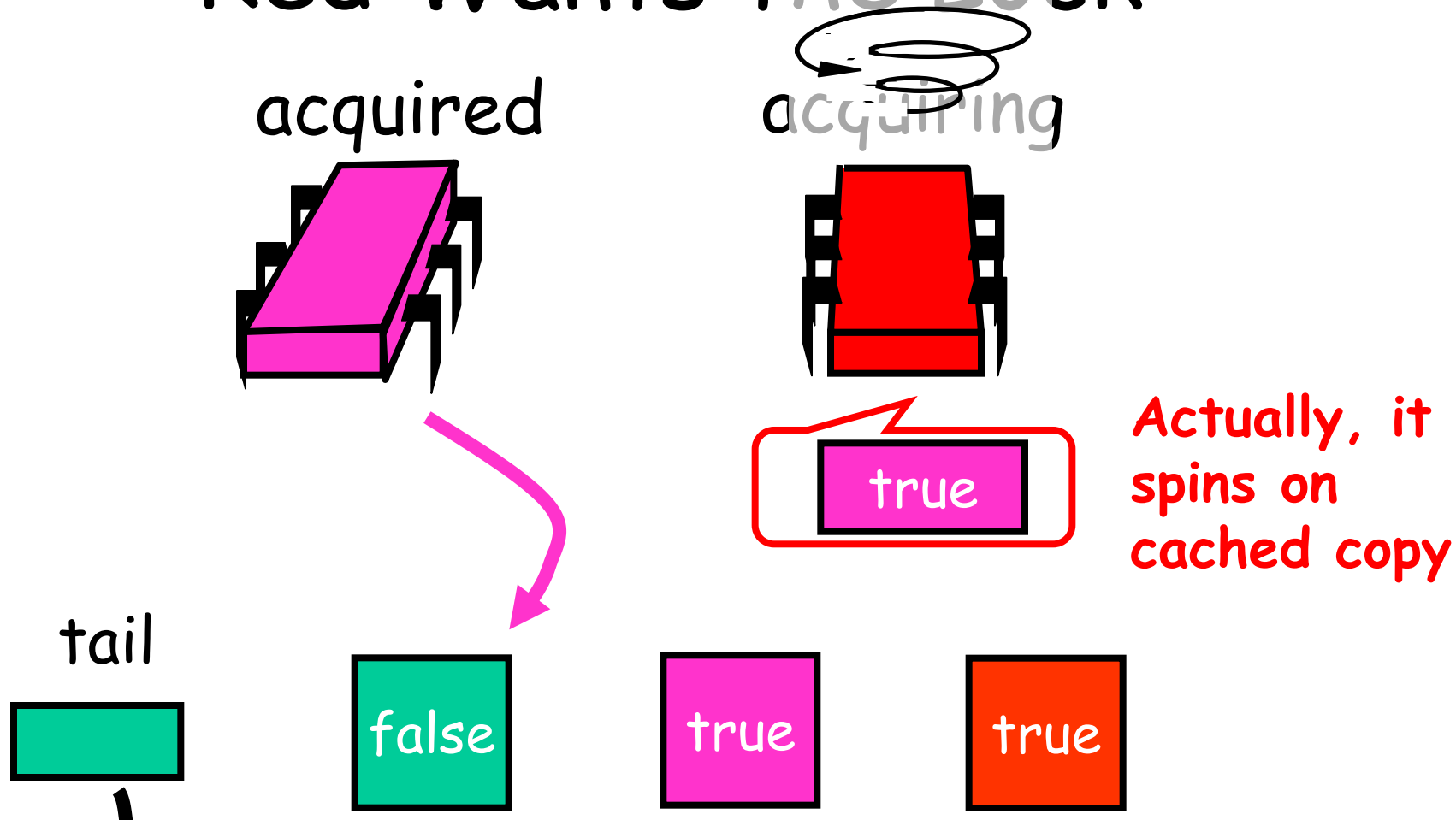
Red Wants the Lock



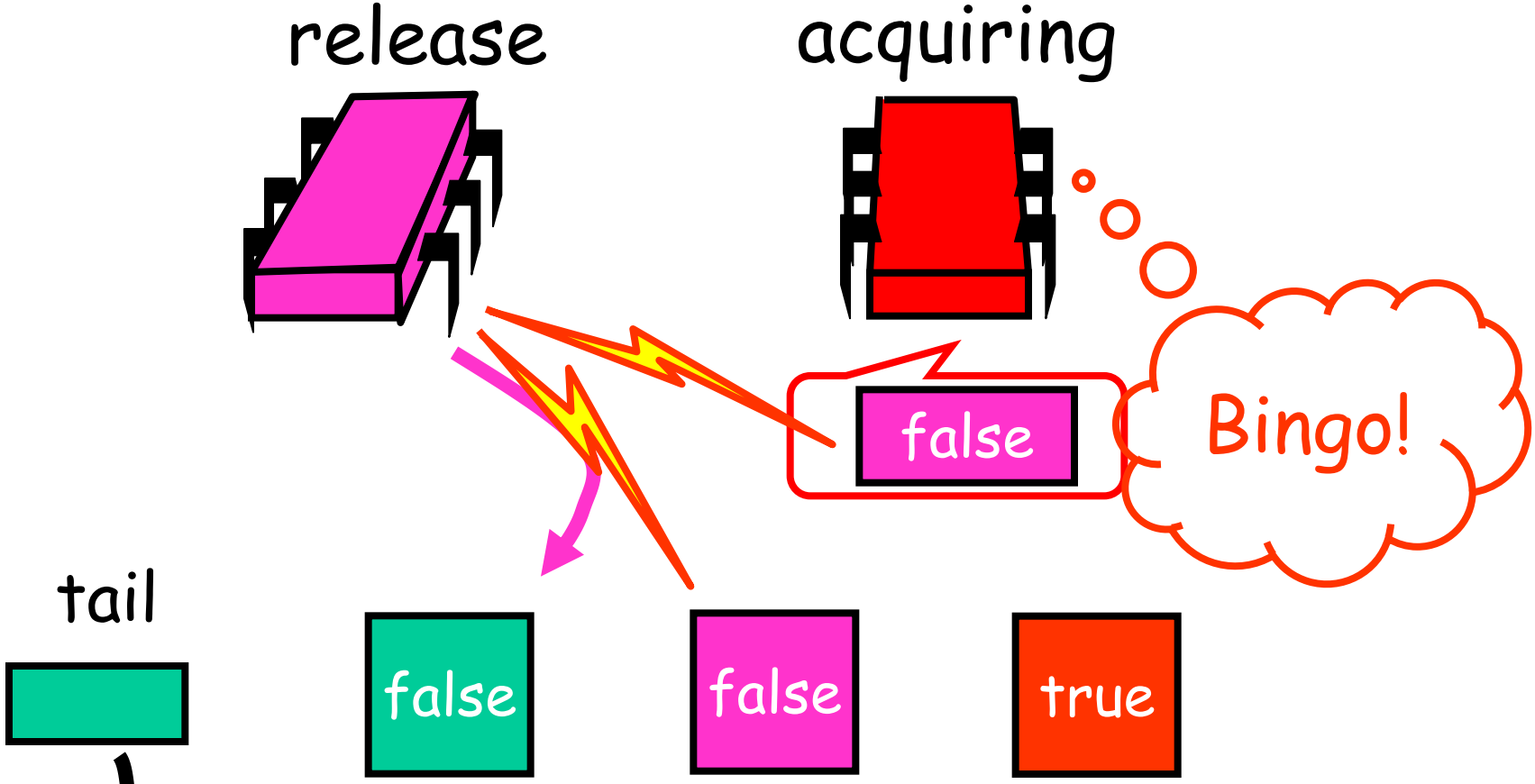
Red Wants the Lock



Red Wants the Lock

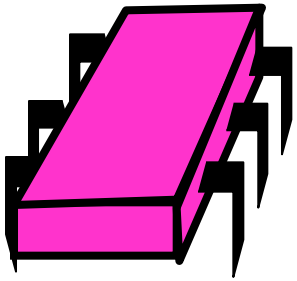


Purple Releases

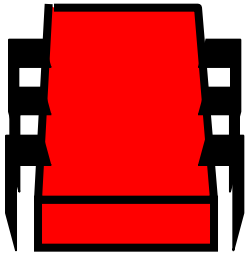


Purple Releases

released



acquired



tail

Space Usage

- Let
  - L = number of locks
  - N = number of threads
- ALock
  - O(LN)
- CLH lock
  - O(L+N)

CLH Queue Lock

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

CLH Queue Lock

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

Not released yet

CLH Queue Lock

```
class CLHLock implements Lock {
 AtomicReference<Qnode> tail;
 ThreadLocal<Qnode> myNode
     = new Qnode();
 public void lock() {
  Qnode pred
     = tail.getAndSet(myNode);
  while (pred.locked) {}
 }}
```

CLH Queue Lock

```
class CLHLock implements Lock {
 AtomicReference<Qnode> tail;
 ThreadLocal<Qnode> myNode
     = new Qnode();
 public void lock() {
  Qnode pred
     = tail.getAndSet(myNode);
  while (pred.locked) {}
 }}
```

Tail of the queue

CLH Queue Lock

```
class CLHLock implements Lock {
 AtomicReference<Qnode> tail;
 ThreadLocal<Qnode> myNode
     = new Qnode();
 public void lock() {
  Qnode pred
    = tail.getAndSet(myNode);
  while (pred.locked) {}
 }}
```

Thread-local Qnode

CLH Queue Lock

```
class CLHLock implements Lock {
 AtomicReference<Qnode> tail;
 ThreadLocal<Qnode> myNode
     = new Qnode();
 public void lock() {
  Qnode pred
     = queue.getAndSet(myNode);
  while (pred.locked) {}
 }}
```

Swap in my node

CLH Queue Lock

```
class CLHLock implements Lock {
 AtomicReference<Qnode> tail;
 ThreadLocal<Qnode> myNode
     = new Qnode();
 public void lock() {
  Qnode pred
     = queue.getAndSet(myNode);
  while (pred.locked) {}
 }}
```

Spin until predecessor releases lock

CLH Queue Lock

```
Class CLHLock implements Lock {
 …
 public void unlock() {
  myNode.locked.set(false);
  myNode = pred;
 }
}
```

CLH Queue Lock

```
Class CLHLock implements Lock {
 …
 public void unlock() {
  myNode.locked.set(false);
  myNode = pred;
 }
}
```

Notify successor

CLH Queue Lock

```
Class CLHLock implements Lock {
 …
 public void unlock() {
  myNode.locked.set(false);
  myNode = pred;
 }
}
```

Recycle predecessor's node

CLH Queue Lock

```
Class CLHLock implements Lock {
 …
 public void unlock() {
  myNode.locked.set(false);
  myNode = pred;
 }
}
```

(notice that we actually don't reuse myNode. Code in Handout shows how its done.)

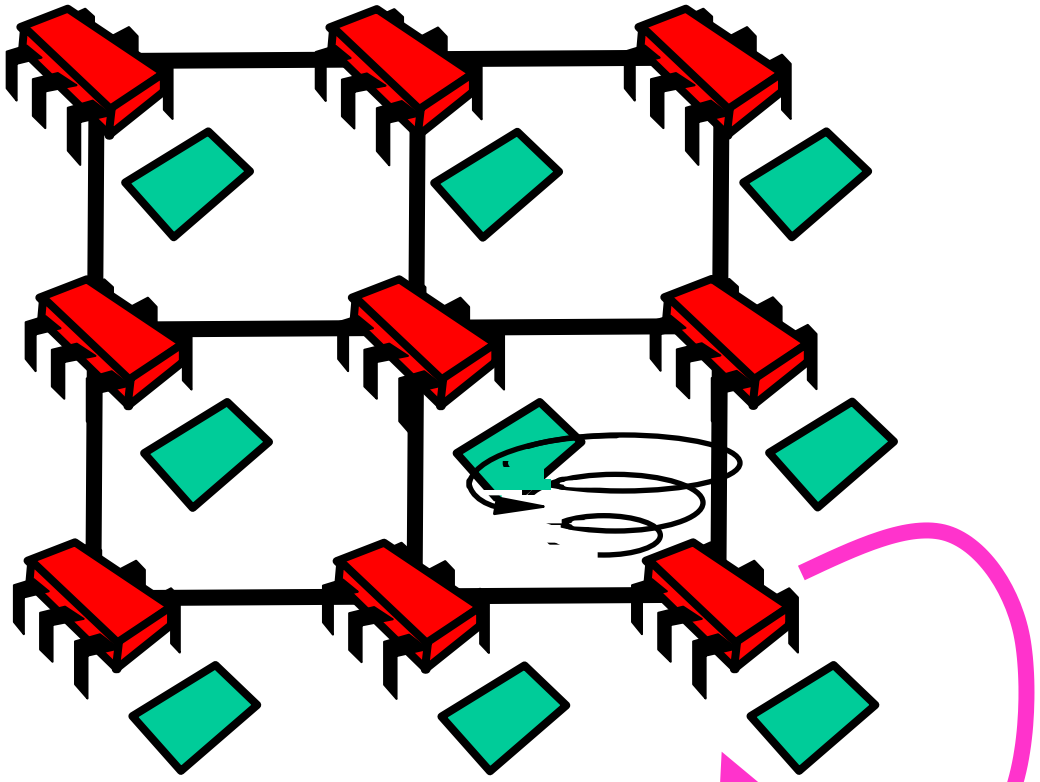
CLH Lock

- Good
  - Lock release affects predecessor only
  - Small, constant-sized space
- Bad
  - Doesn't work for uncached NUMA architectures

NUMA Architecturs

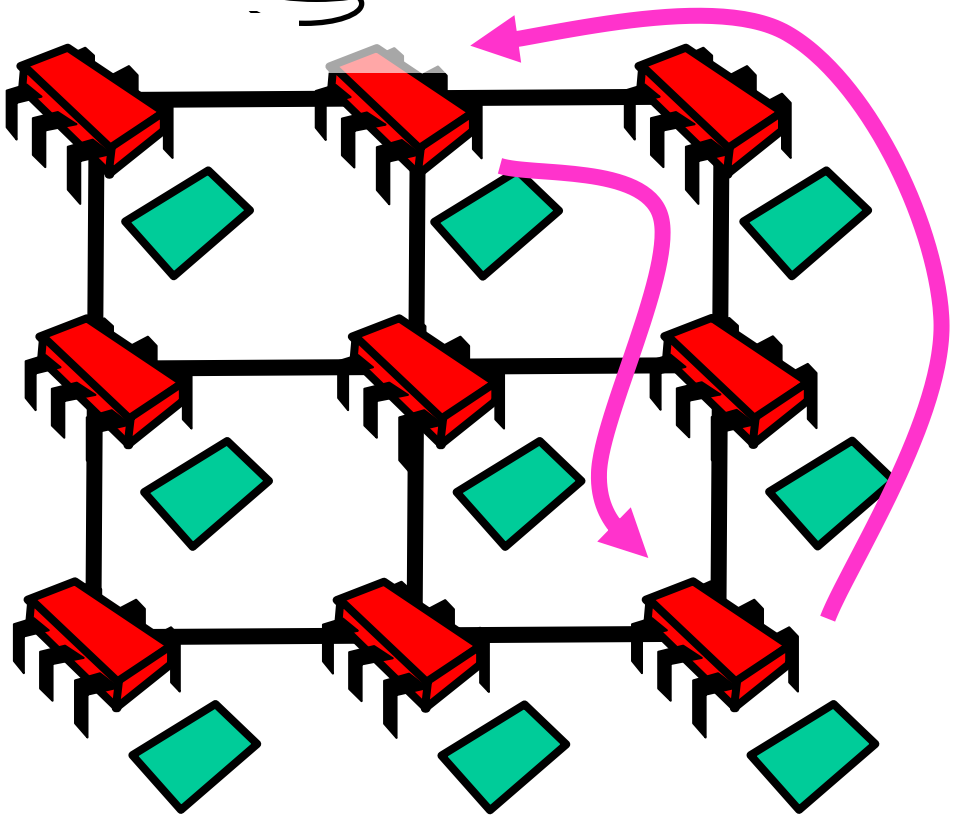
- Acronym:
  - **N**on-**U**niform **M**emory **A**rchitecture
- Illusion:
  - Flat shared memory
- Truth:
  - No caches (sometimes)
  - Some memory regions faster than others

NUMA Machines



Spinning on local memory is fast

NUMA Machines



Spinning on remote memory is slow

CLH Lock

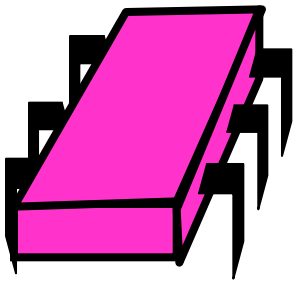
- Each thread spin's on predecessor's memory
- Could be far away …

MCS Lock

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

Initially

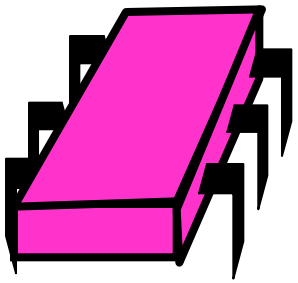
idle



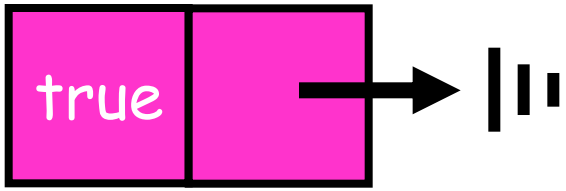
tail

Acquiring

acquiring

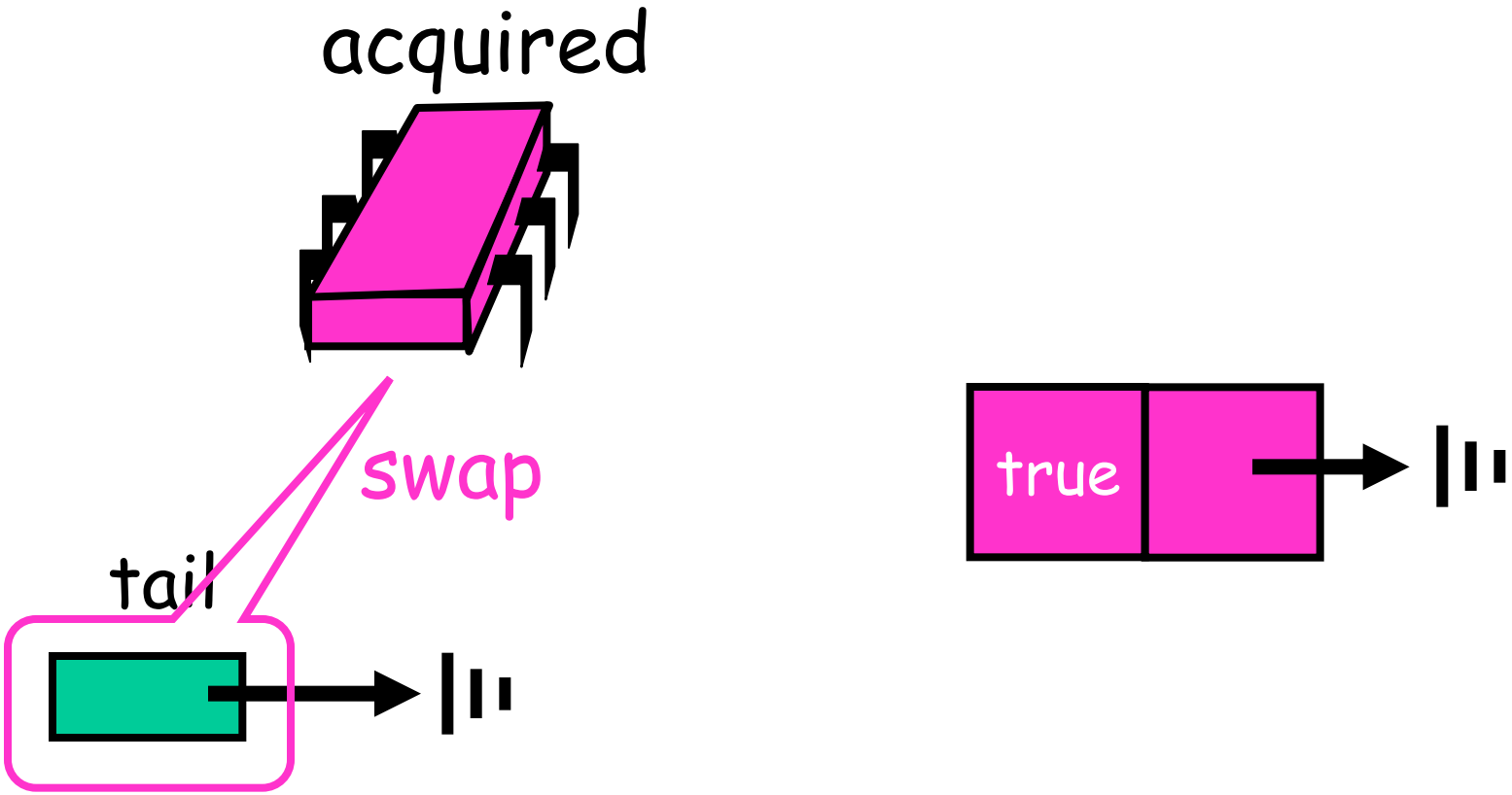


(allocate Qnode)

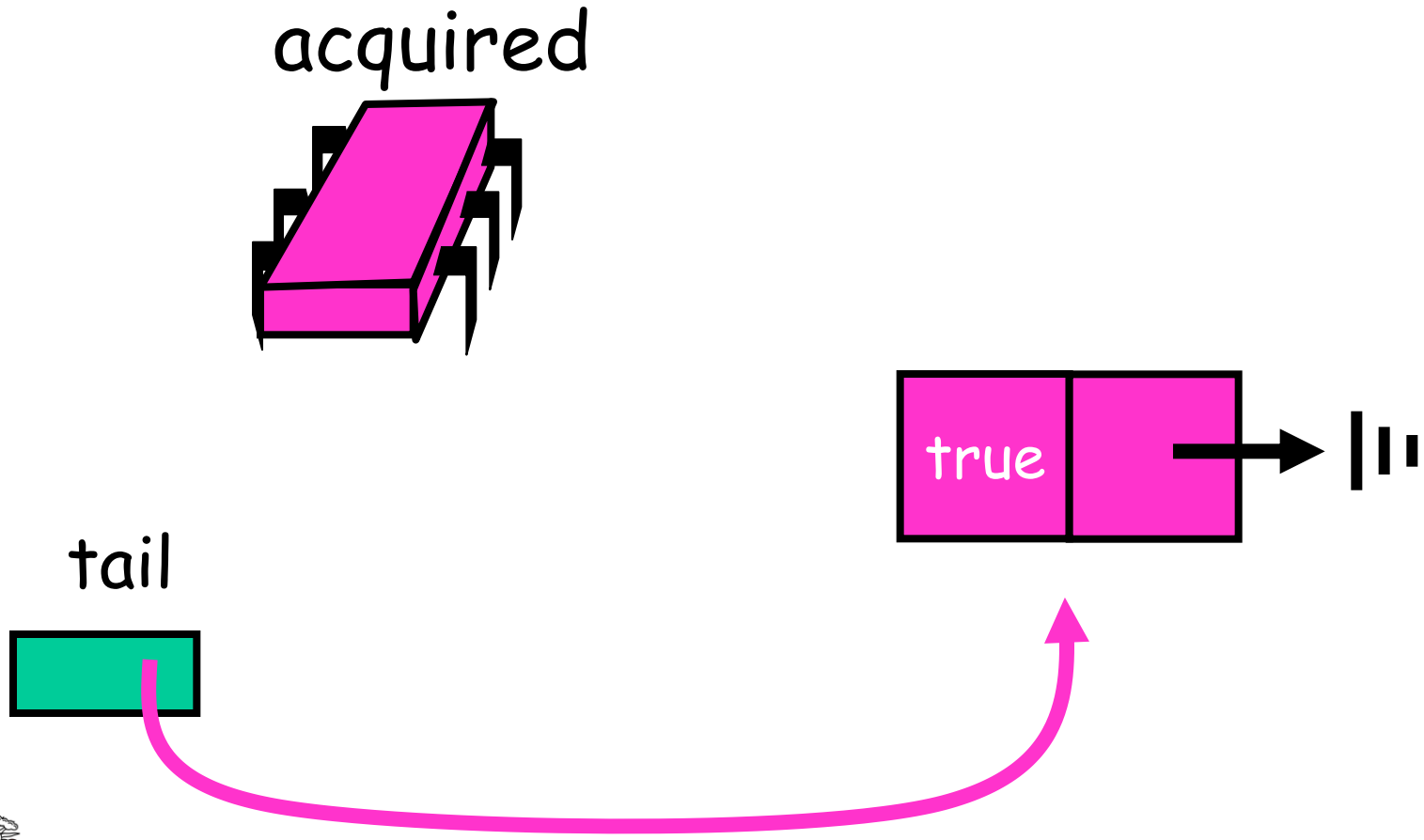


queue

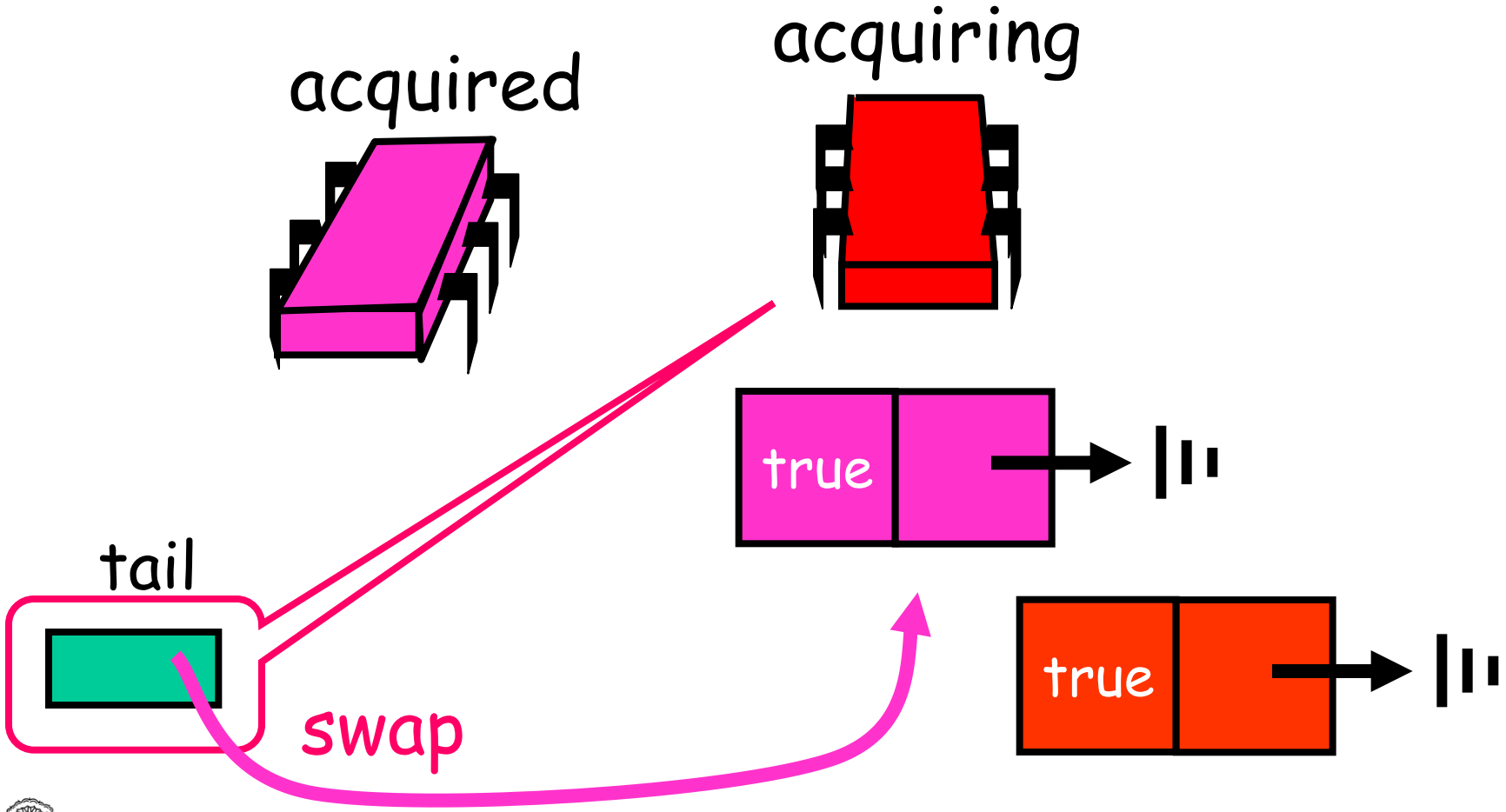
Acquiring



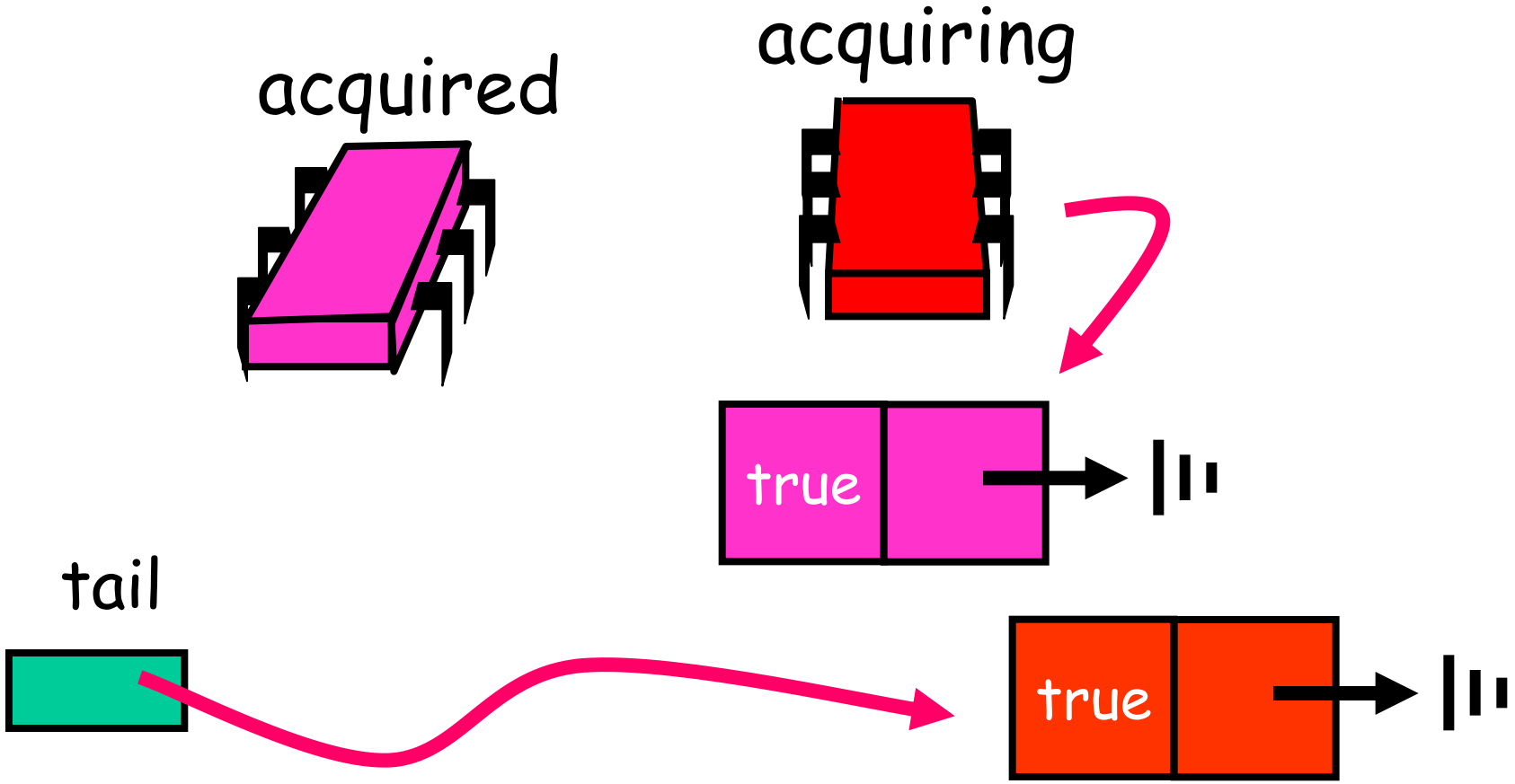
Acquired



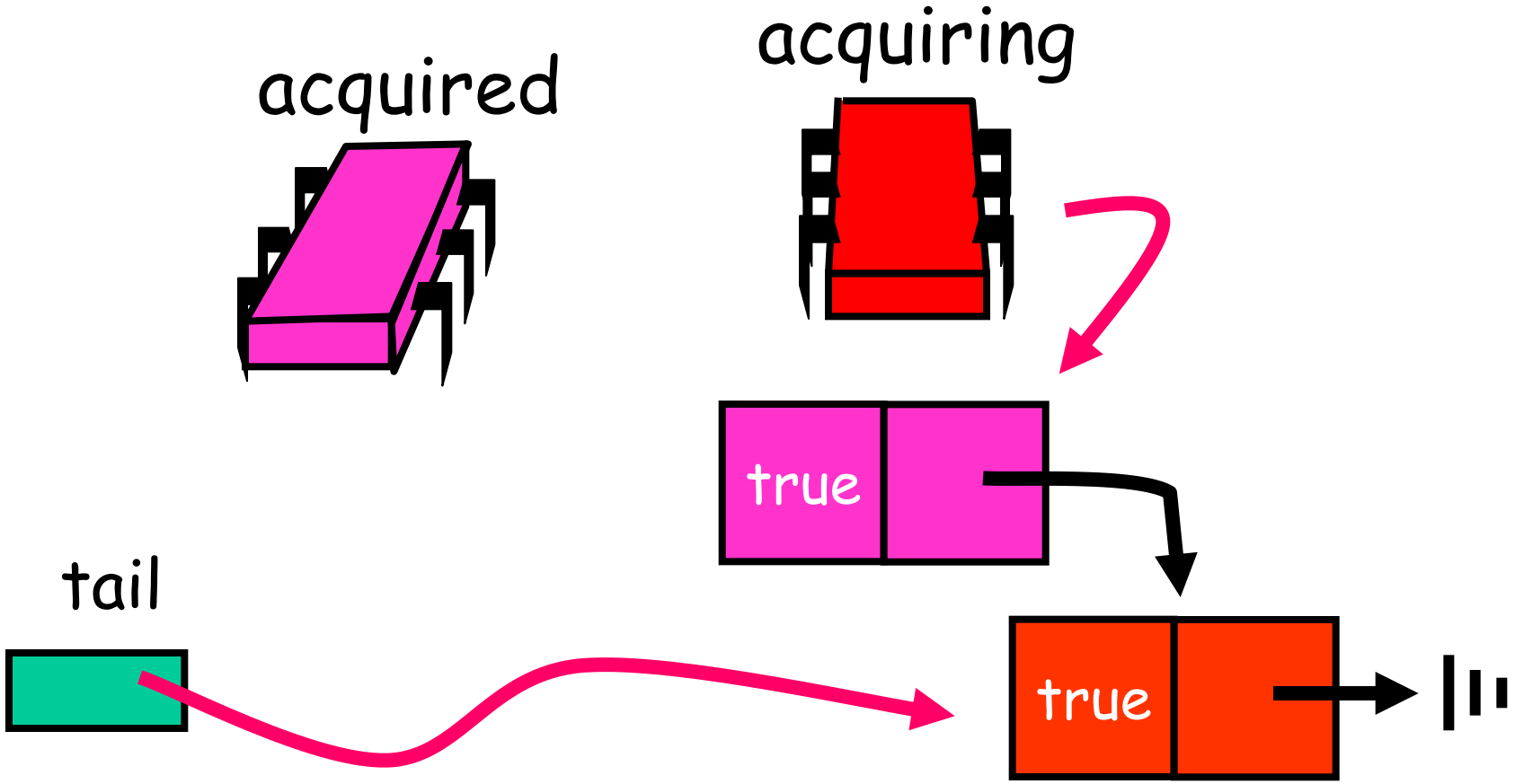
Acquiring



Acquiring



Acquiring



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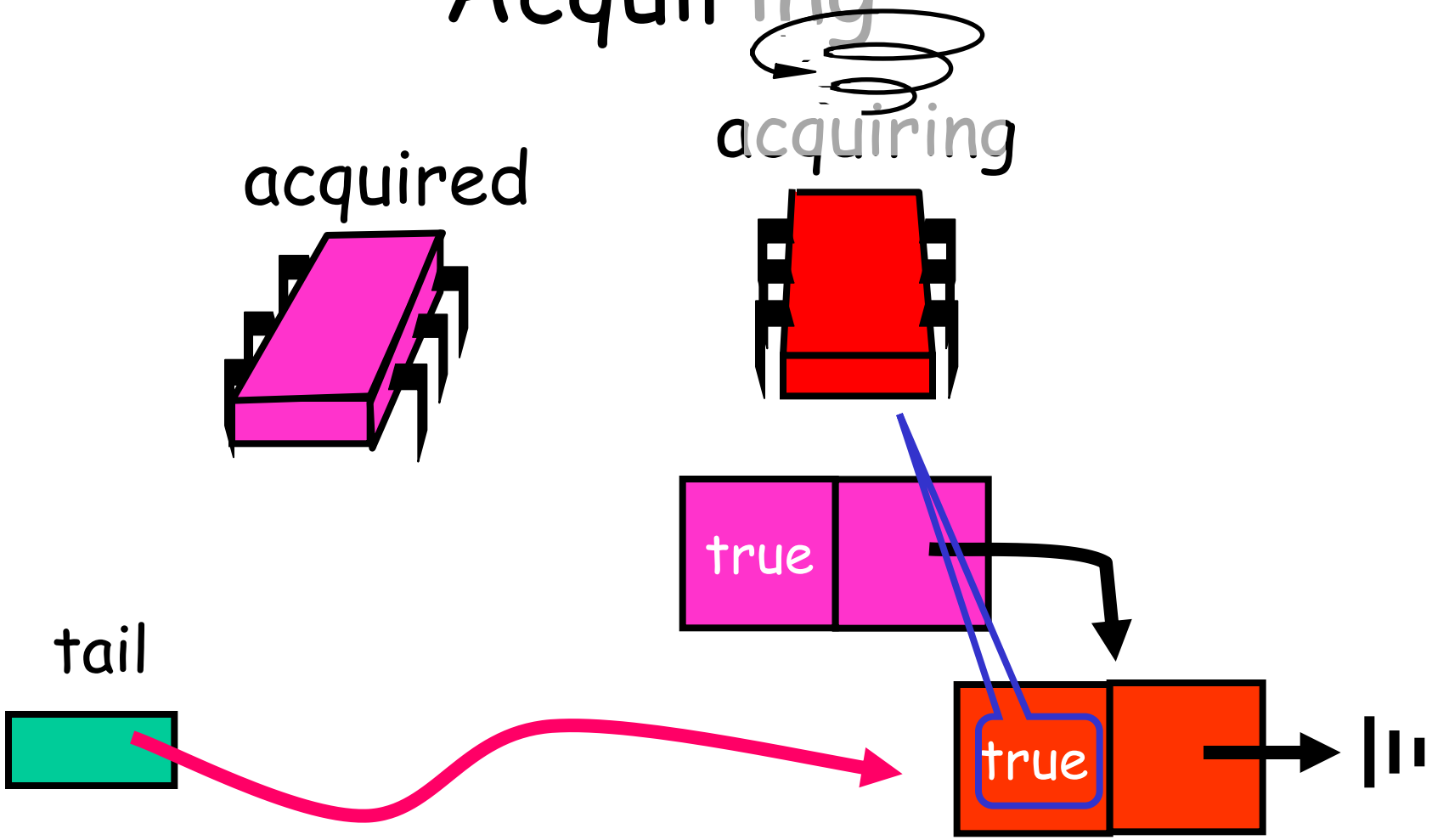
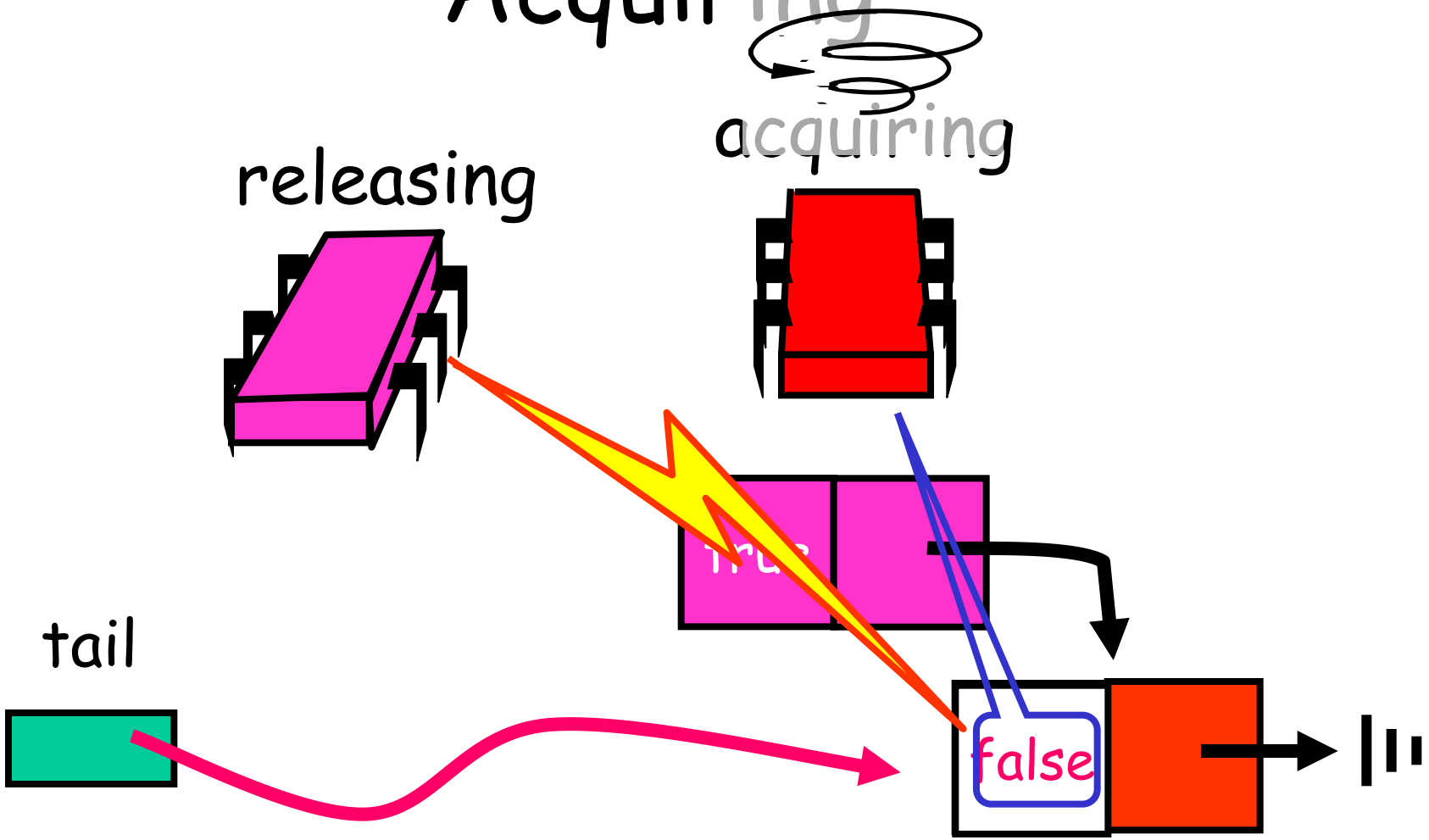
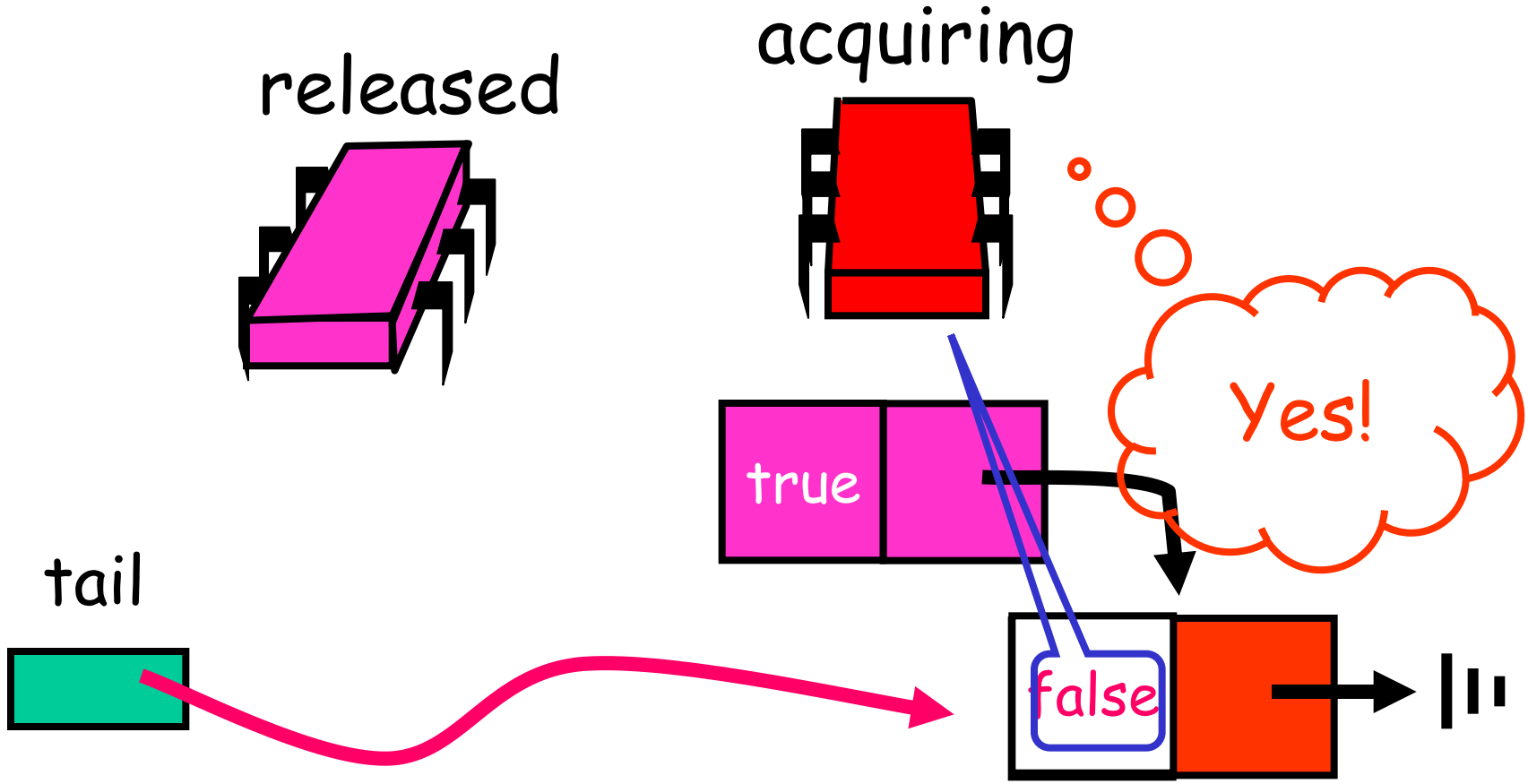


Acquiring



Acquiring



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) {}
  }}}
```

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) {}
  }}}
```

Make a QNode

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 of queue

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) {}
  }}}
```

Fix if queue was non-empty

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) {}
  }}}
```

Wait until unlocked

MCS Queue Unlock

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

MCS Queue Lock

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

Missing successor?

MCS Queue Lock

If really no successor, return

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

MCS Queue Lock

Otherwise wait for successor to catch up

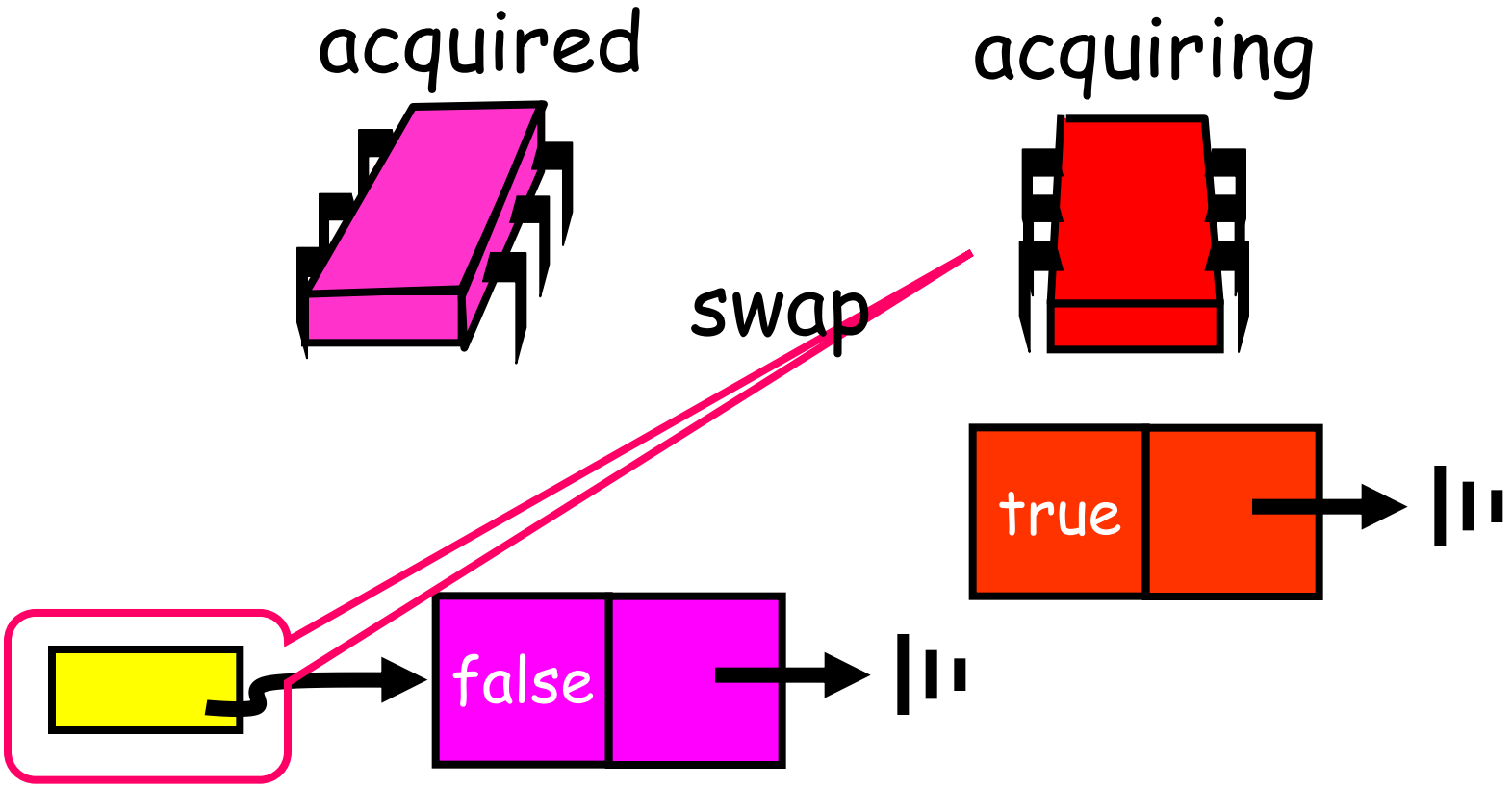
```
public void unlock() {
 if (qnode.next == null) {
  if (tail.CAS(qnode, null)
   return;
  while (qnode.next == null) {}
 }
 qnode.next.locked = false;
}}
```

MCS Queue Lock

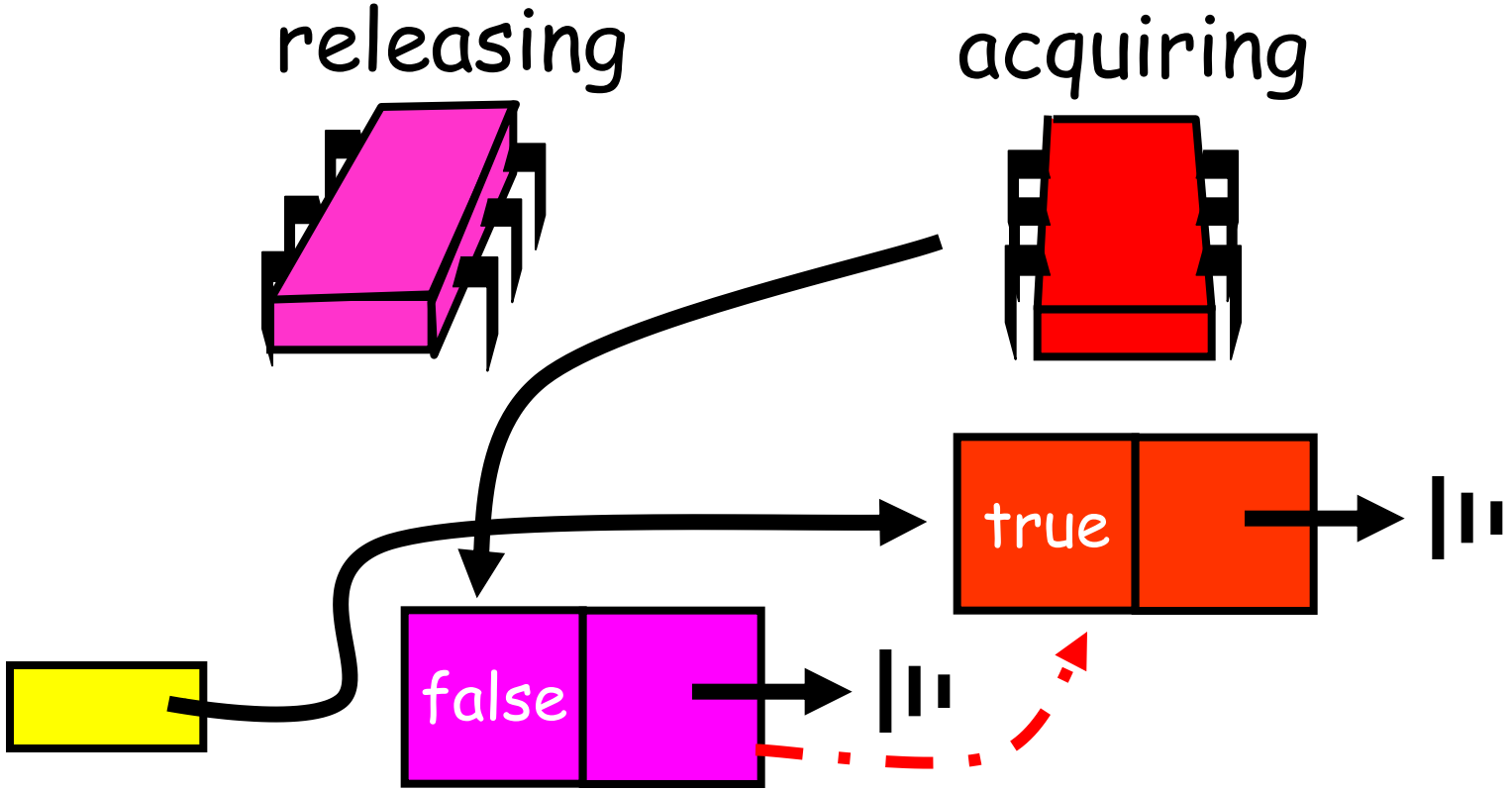
```
class MCSLock implements Lock {
 AtomicRef
 public vo
  if (qnode.next == null) {
   if (tail.CAS(qnode, null)
    return;
   while (qnode.next == null) {}
  }
 qnode.next.locked = false;
}}
```

Pass lock to successor

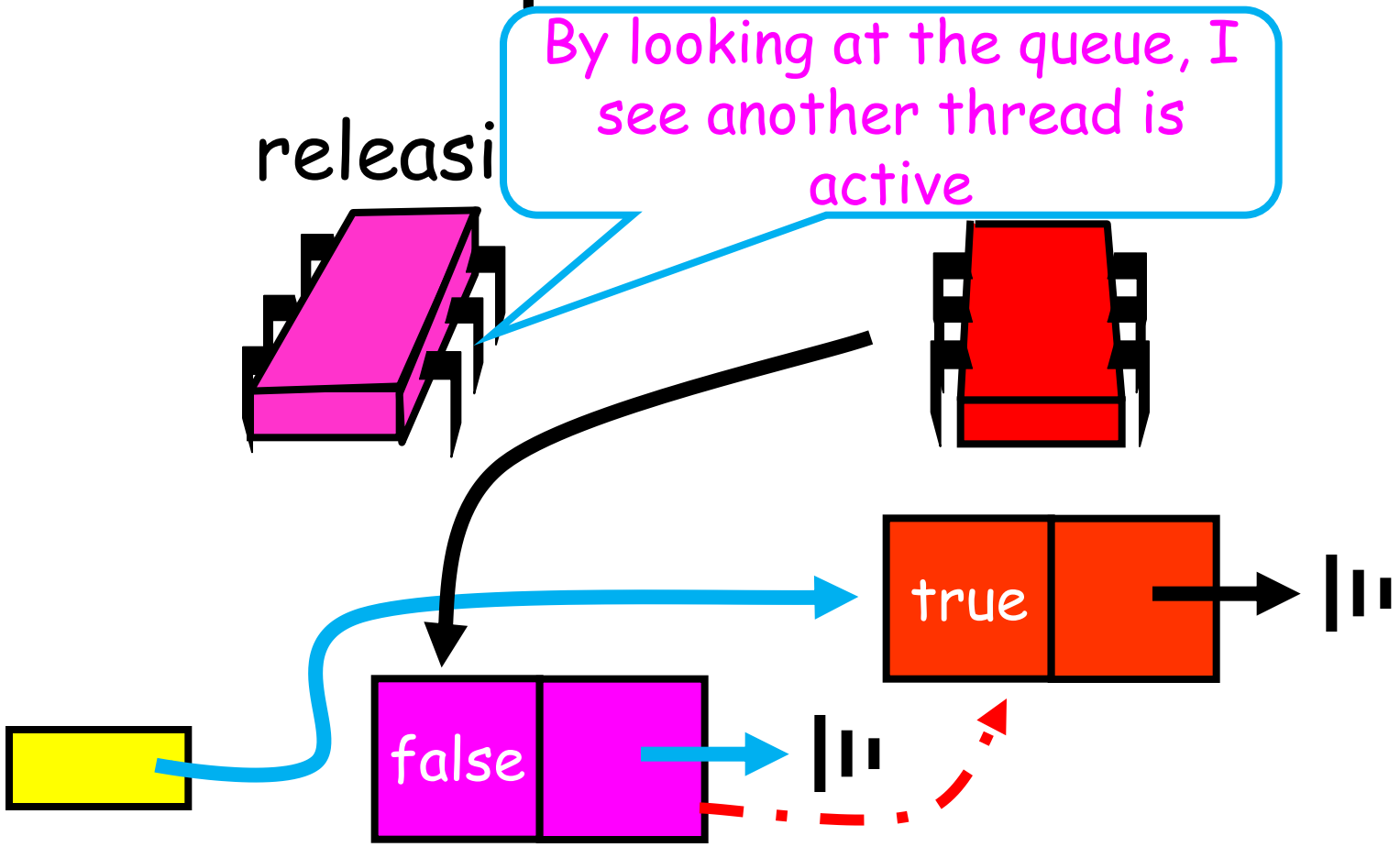
Purple Got the lock; Red requesting



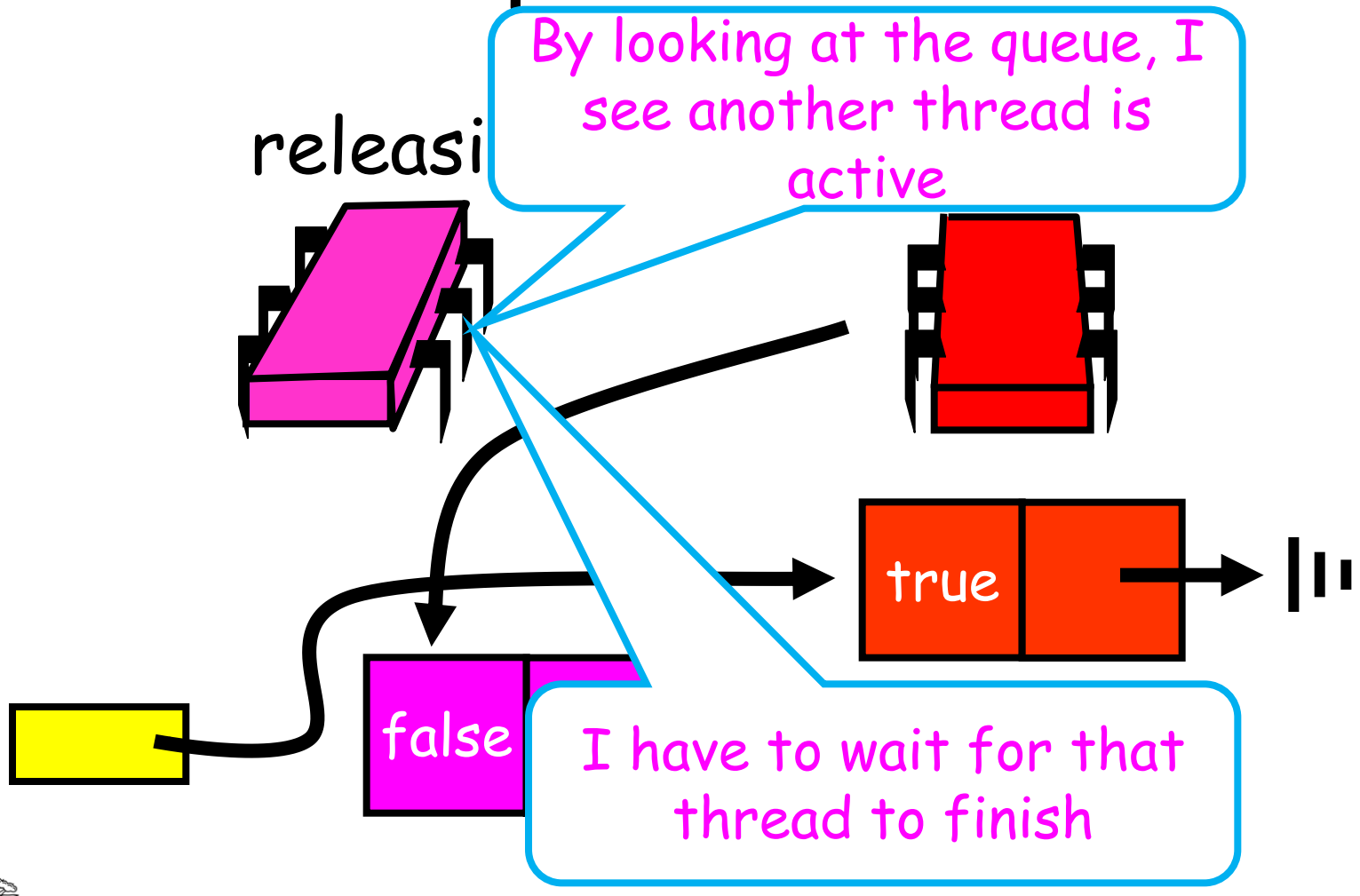
Purple Release; Red isn't quite finished



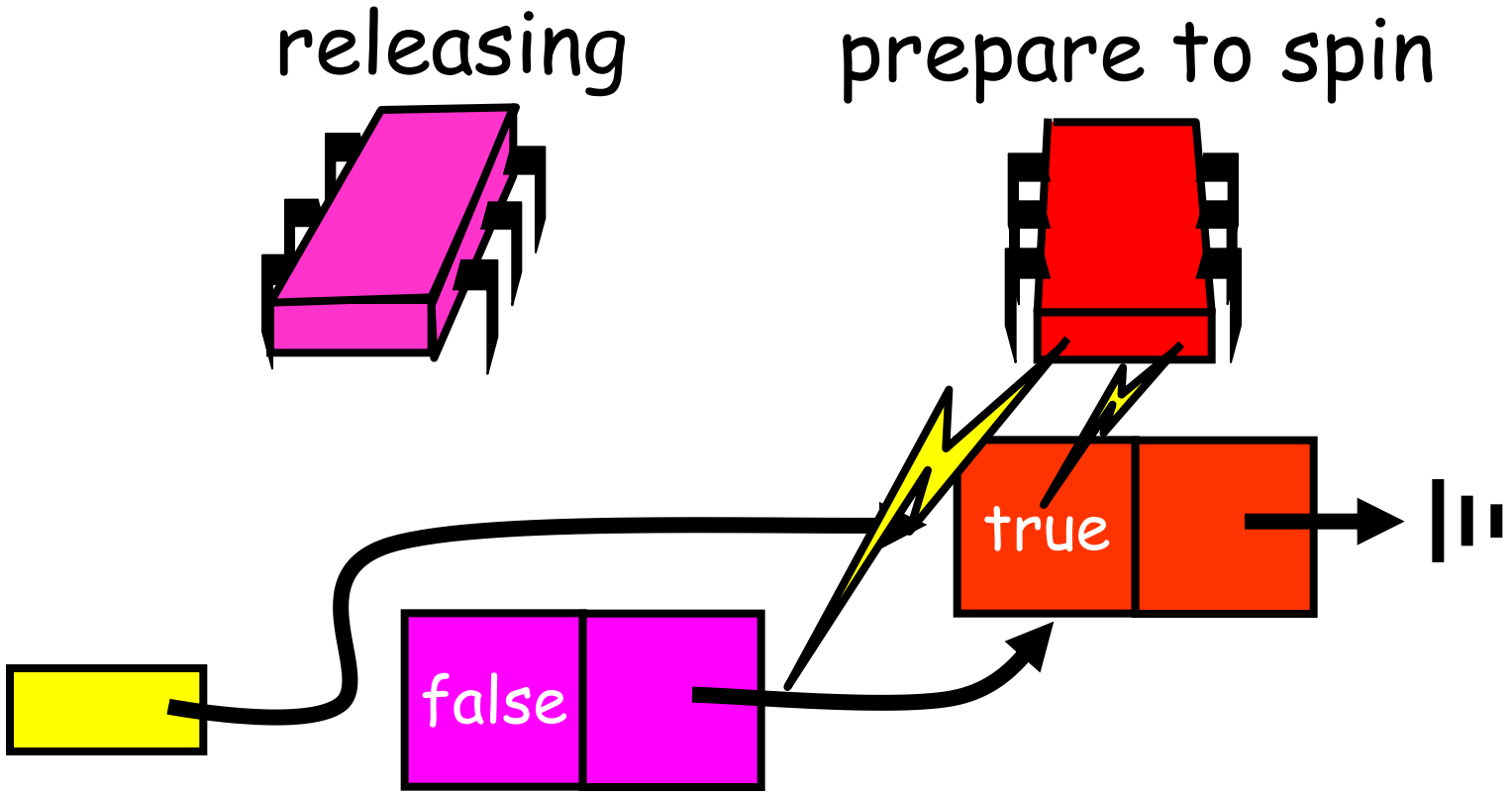
Purple Release



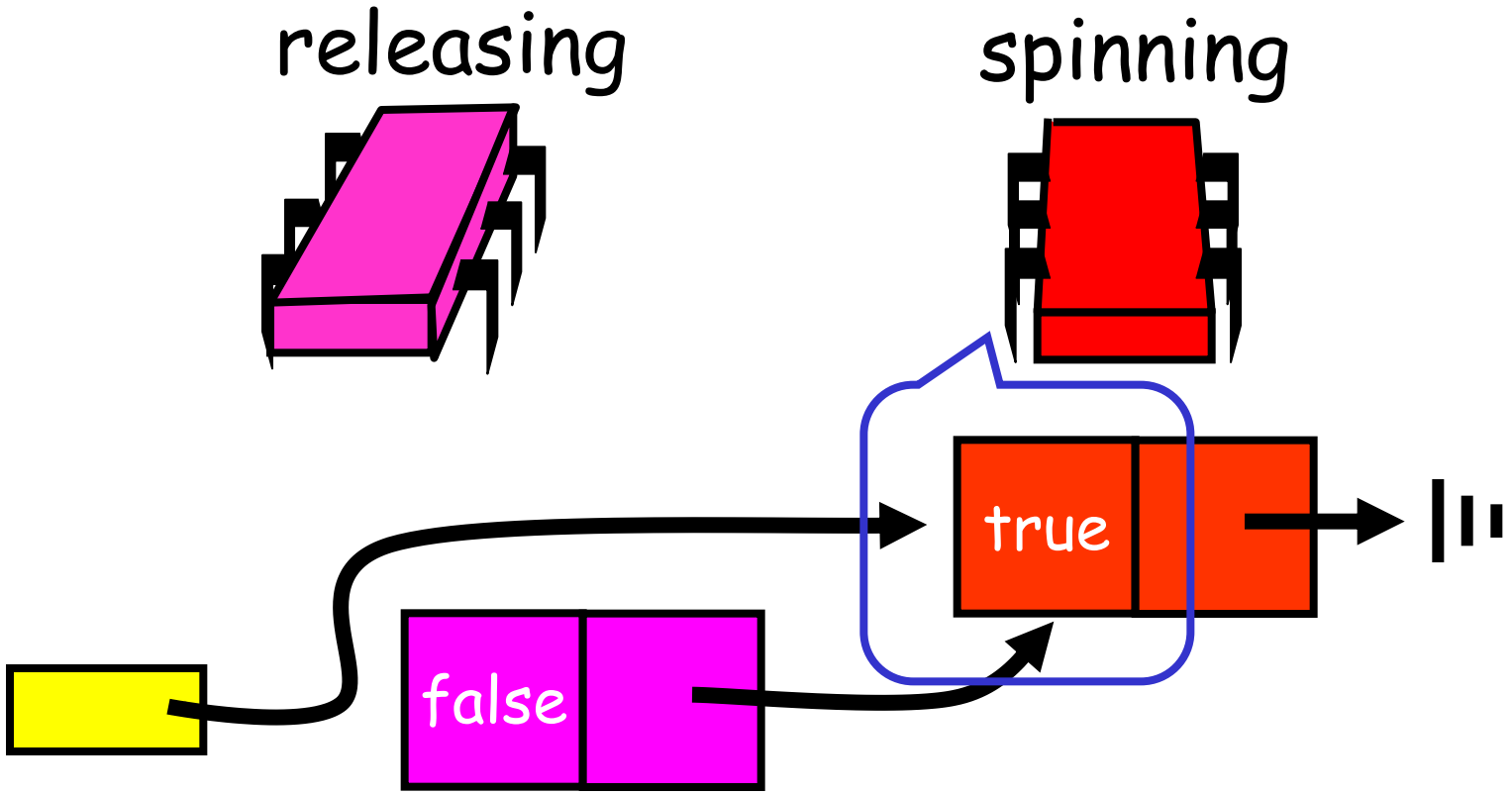
Purple Release



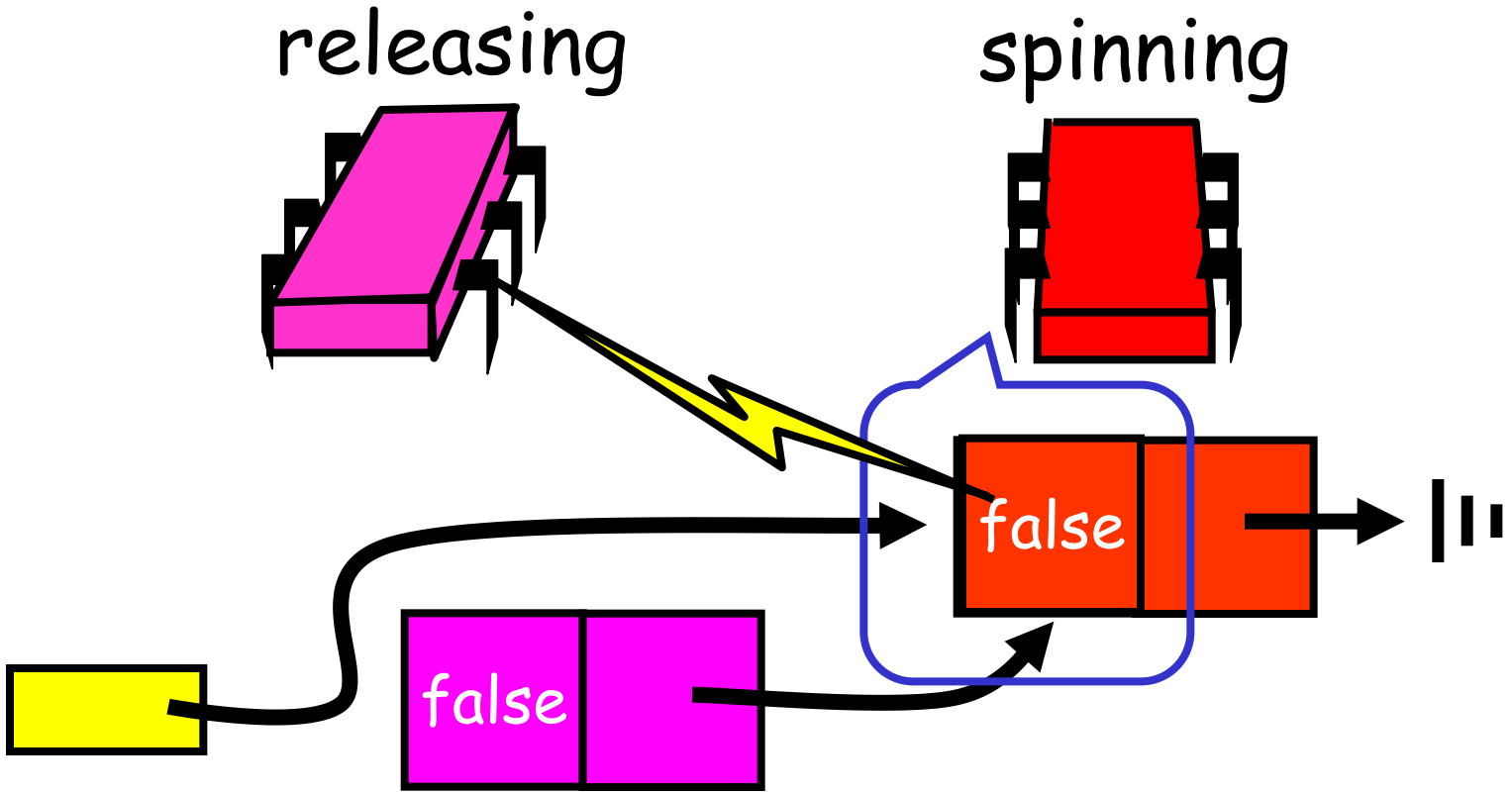
Purple Release



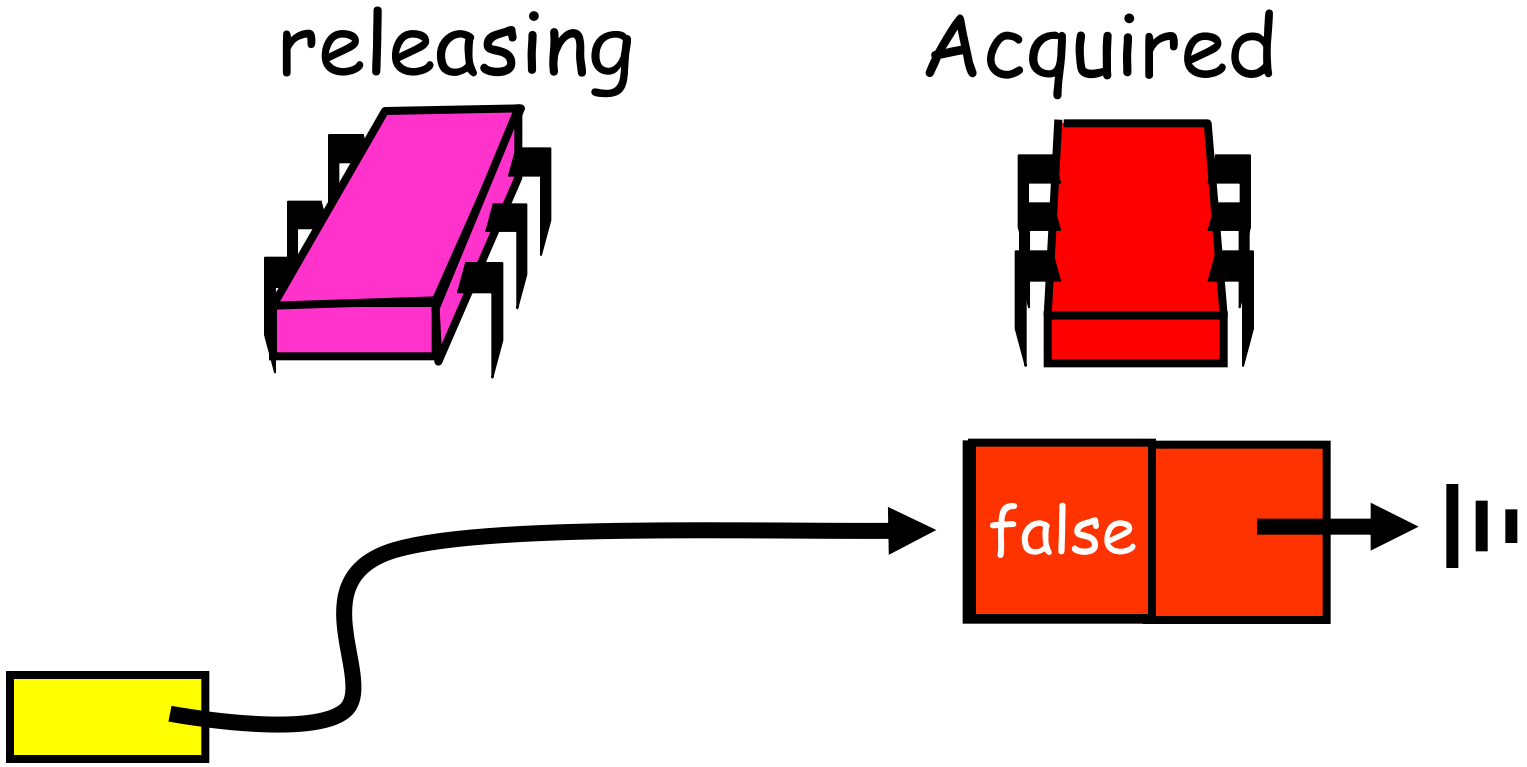
Purple Release



Purple Release



Purple Release



Abortable Locks

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

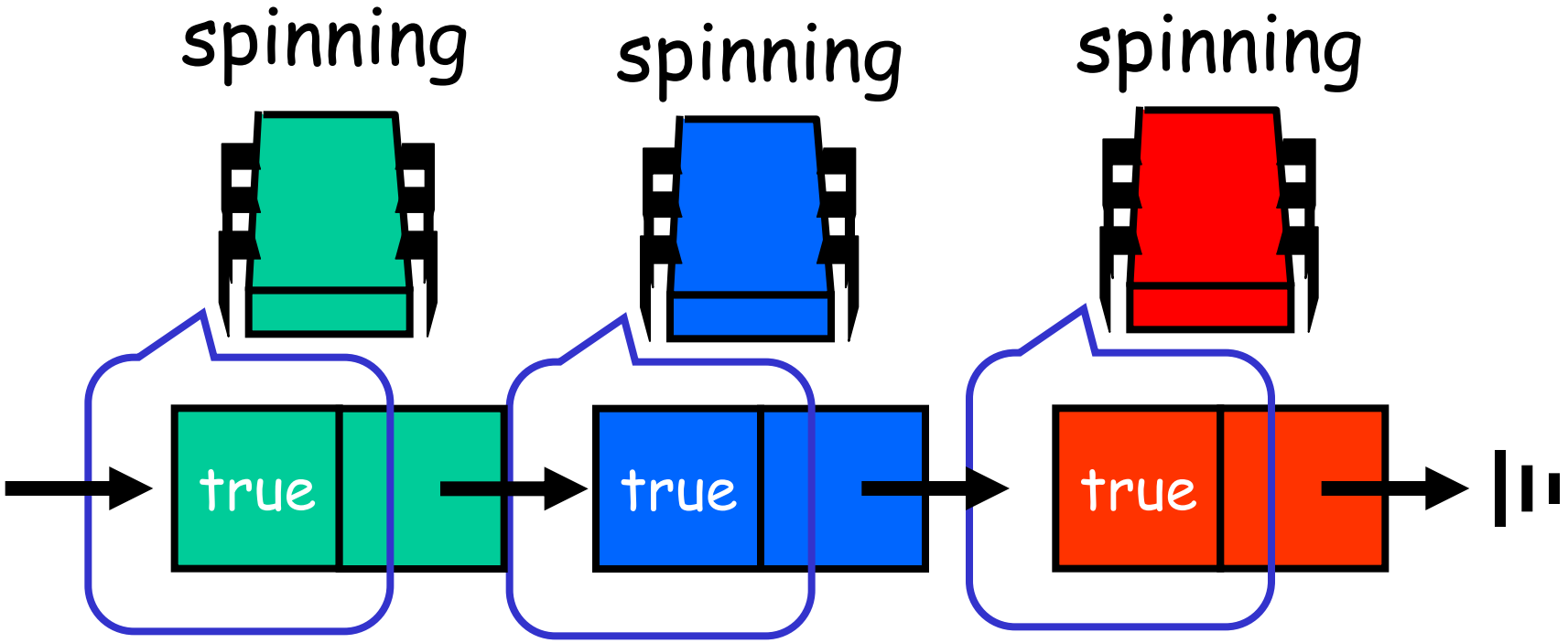
Back-off Lock

- Aborting is trivial
  - Just return from lock() call
- Extra benefit:
  - No cleaning up
  - Wait-free
  - Immediate return

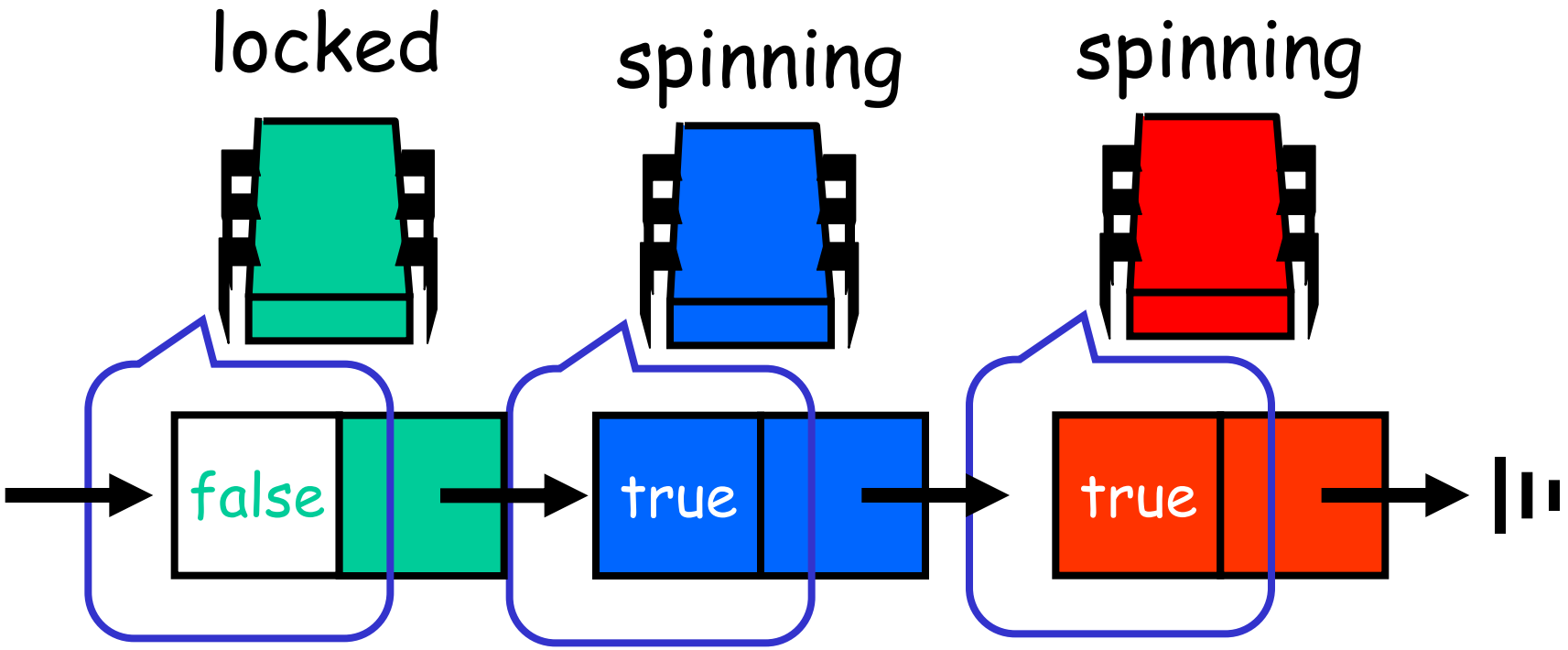
Queue Locks

- Can't just quit
  - Thread in line behind will starve
- Need a graceful way out

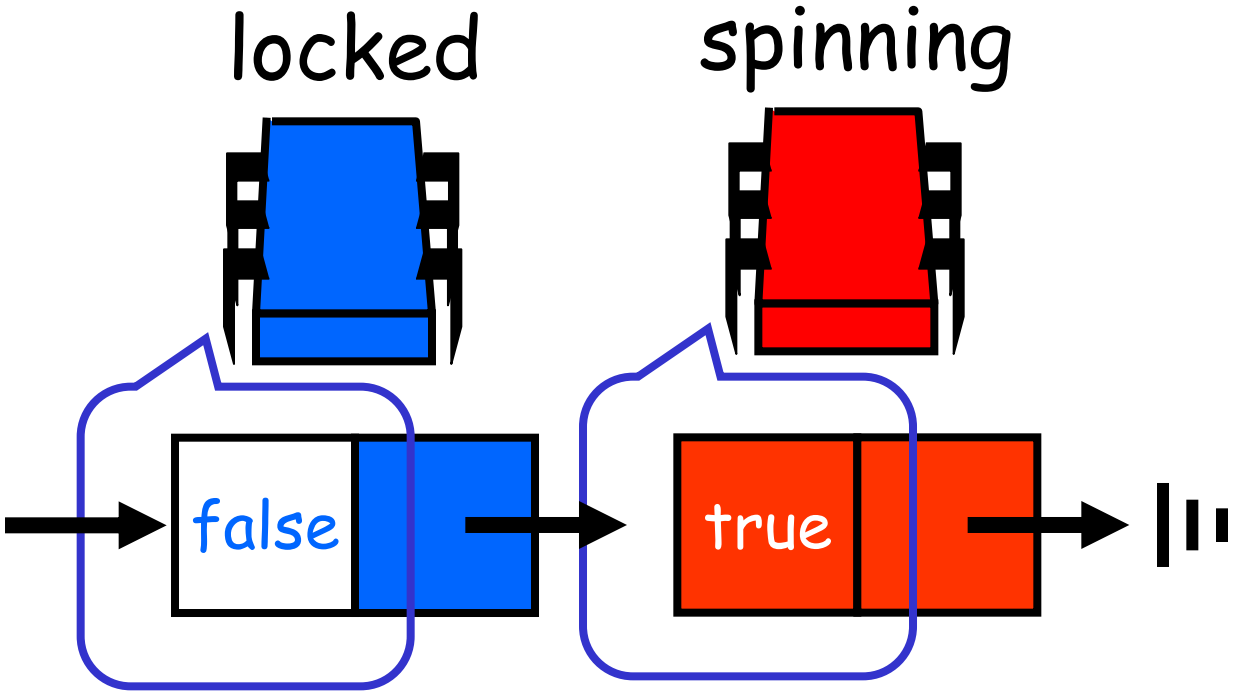
Queue Locks



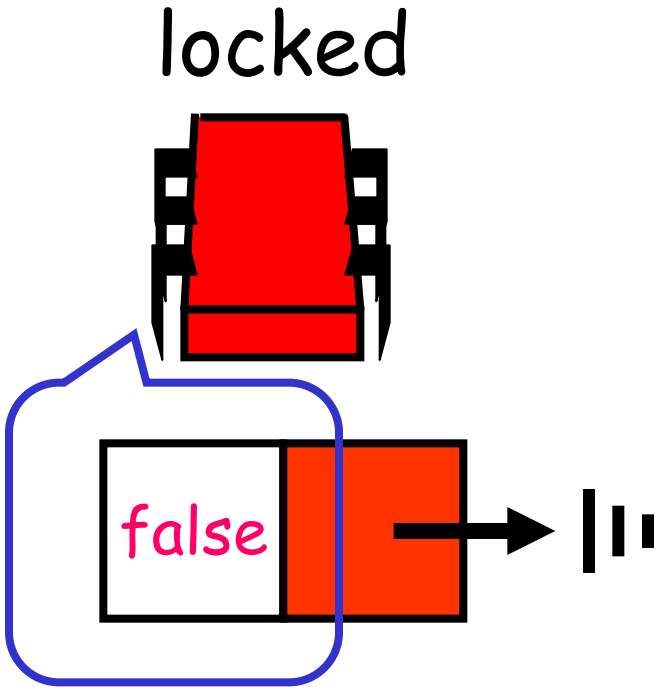
Queue Locks



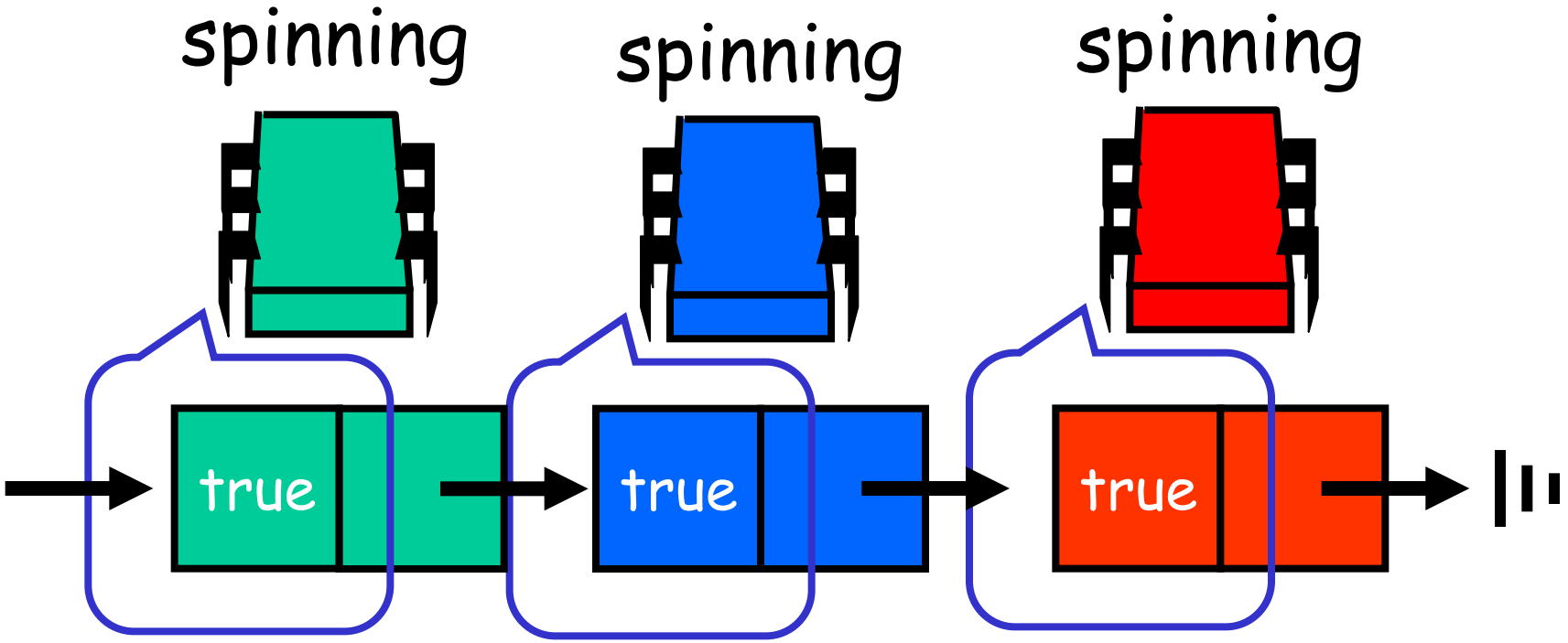
Queue Locks



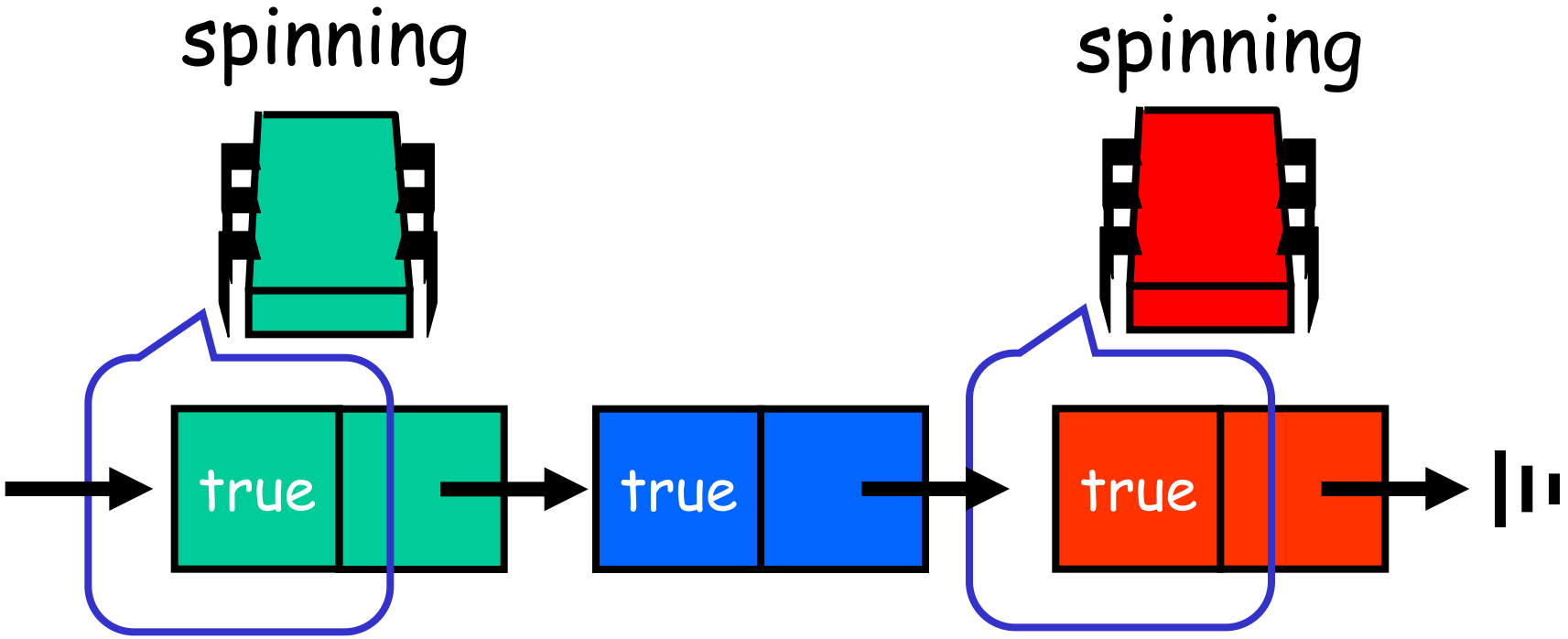
Queue Locks



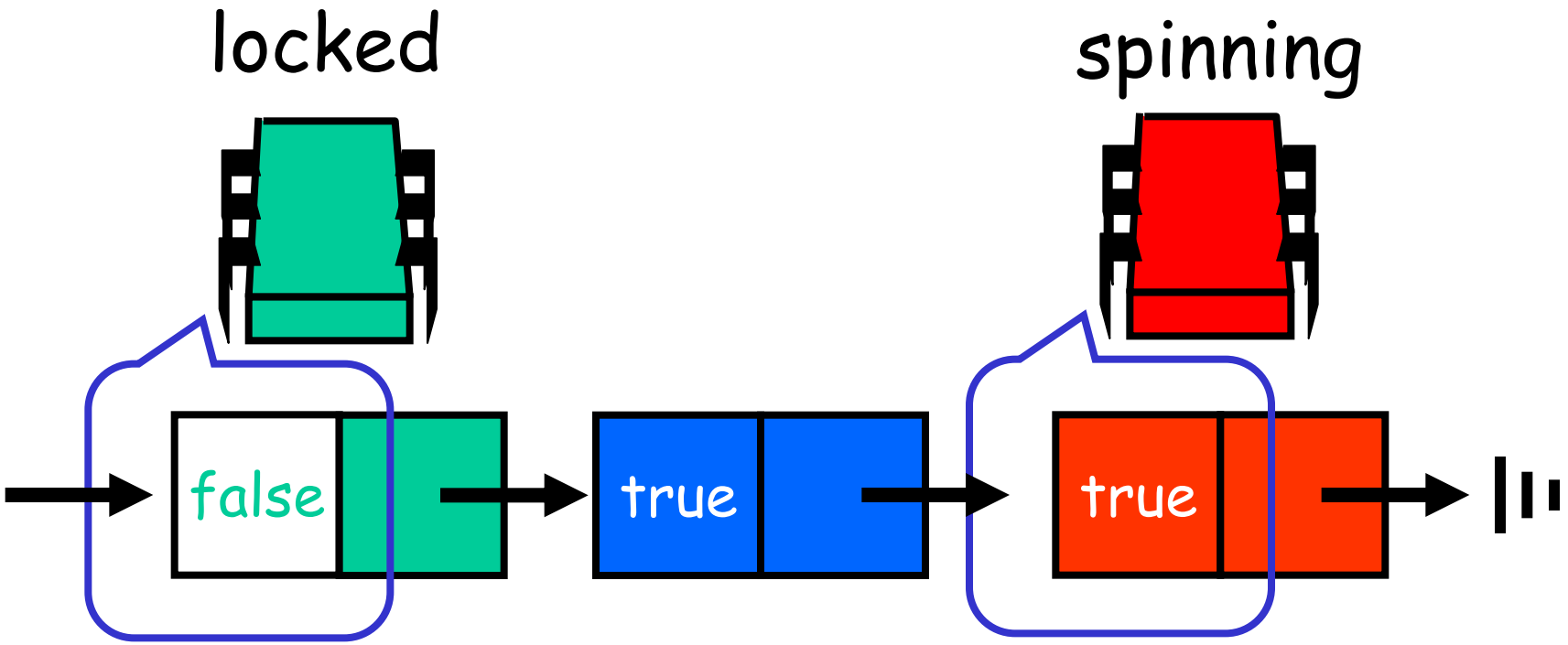
Queue Locks



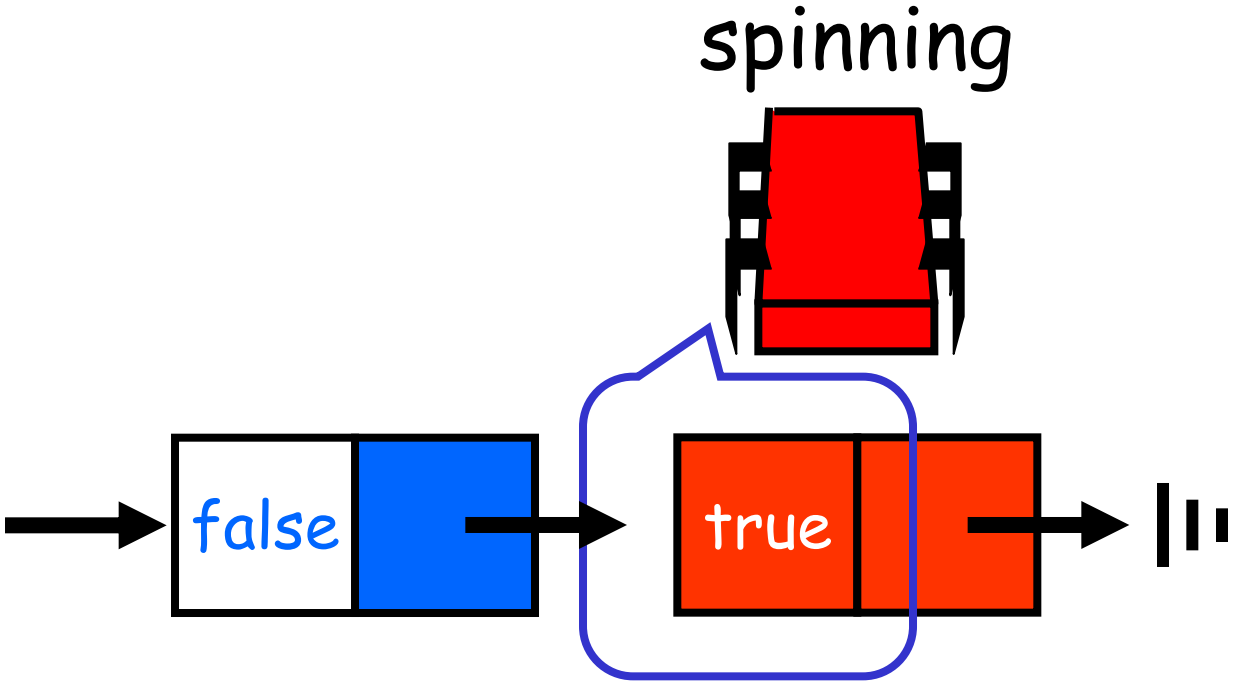
Queue Locks



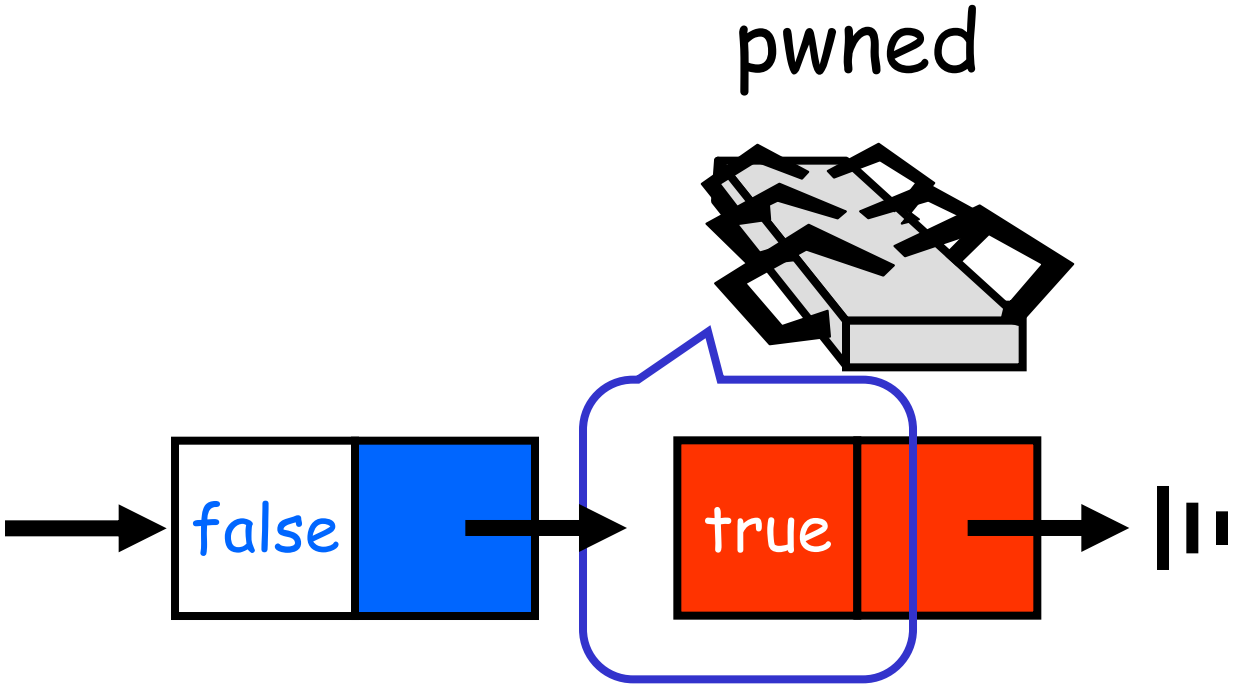
Queue Locks



Queue Locks



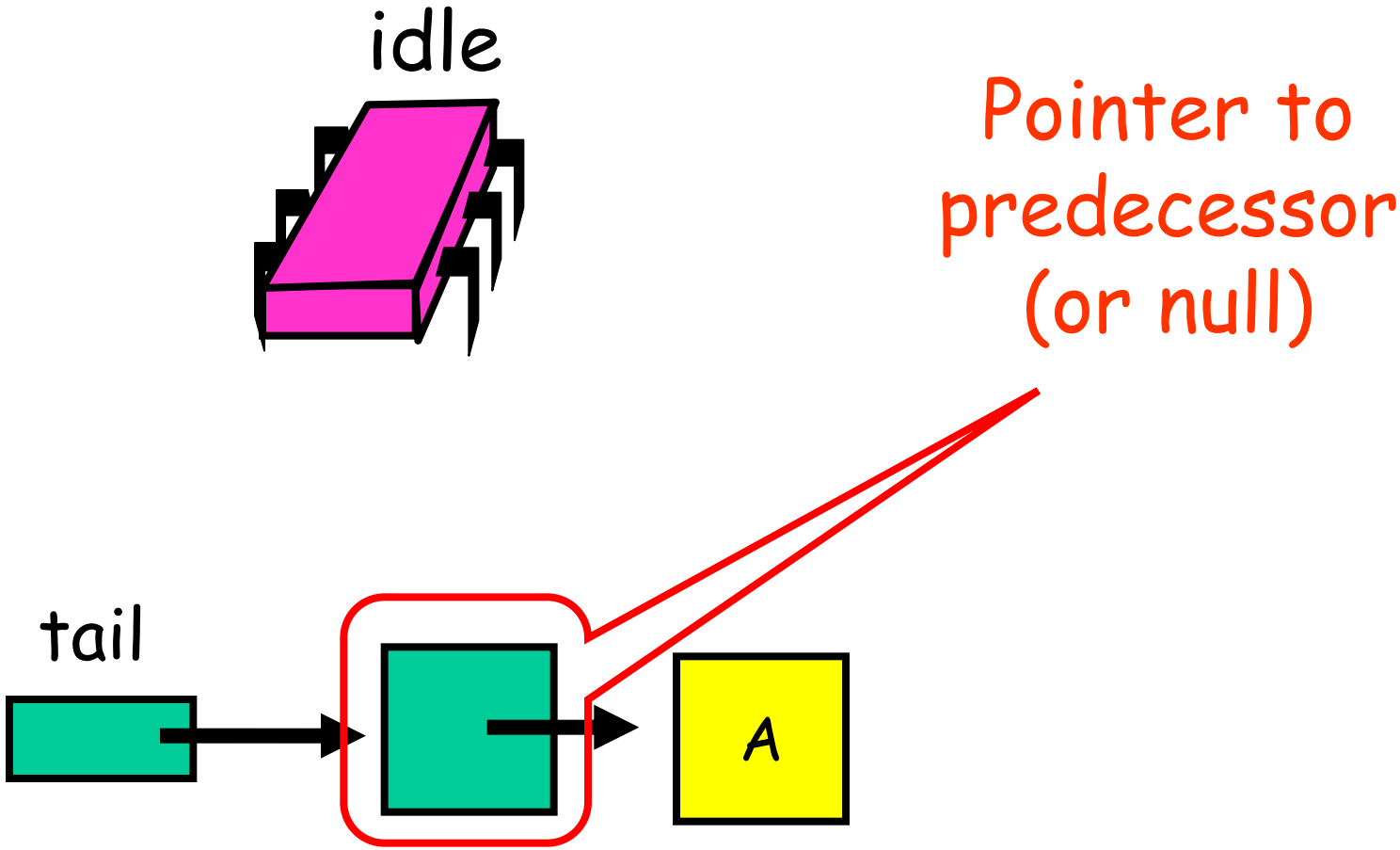
Queue Locks



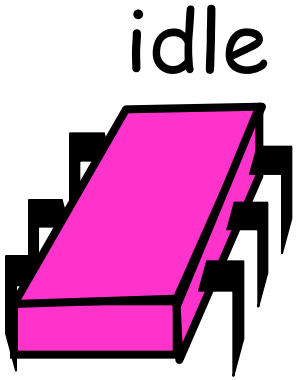
Abortable CLH Lock

- When a thread gives up
  - Removing node in a wait-free way is hard
- Idea:
  - let successor deal with it.

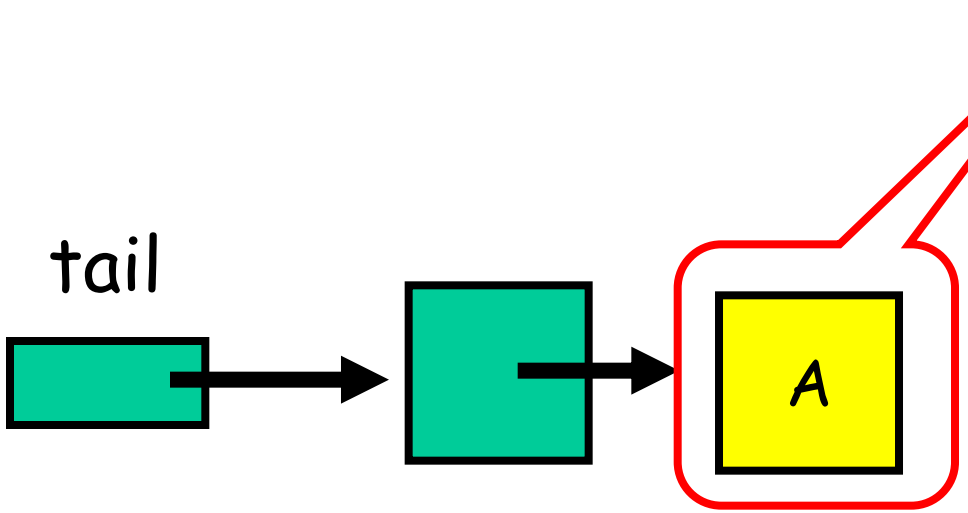
Initially



Initially

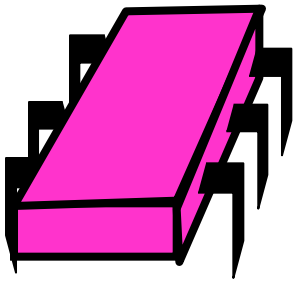


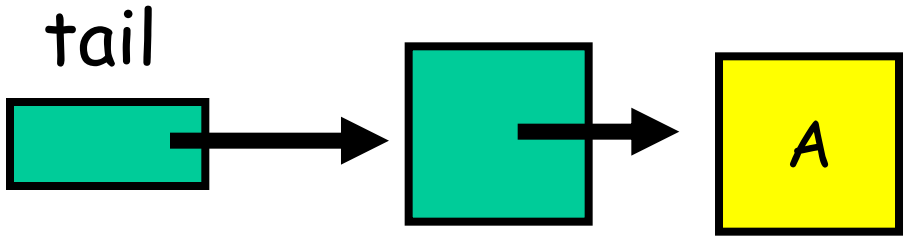
Distinguished available node means lock is free



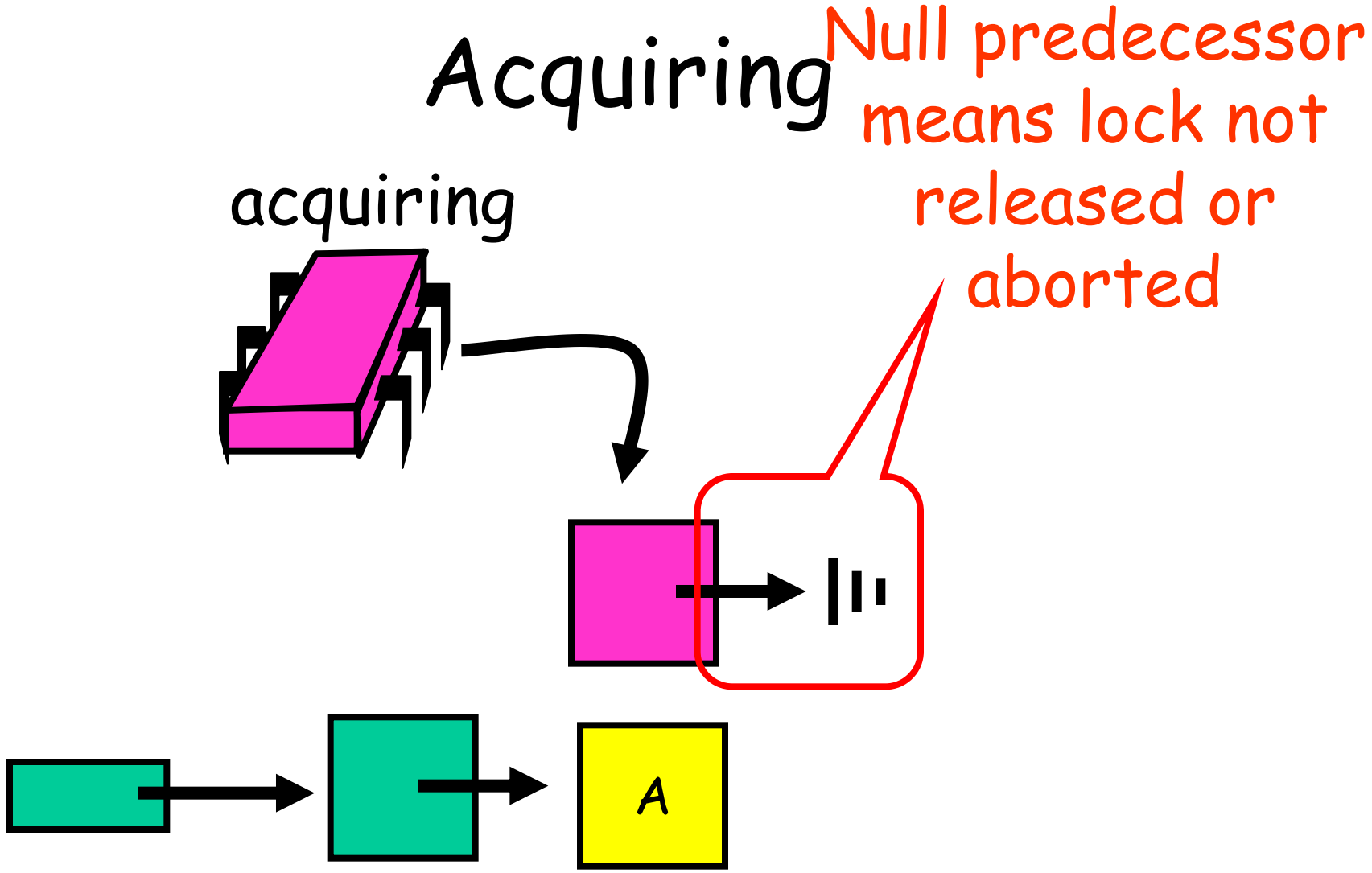
Acquiring

acquiring

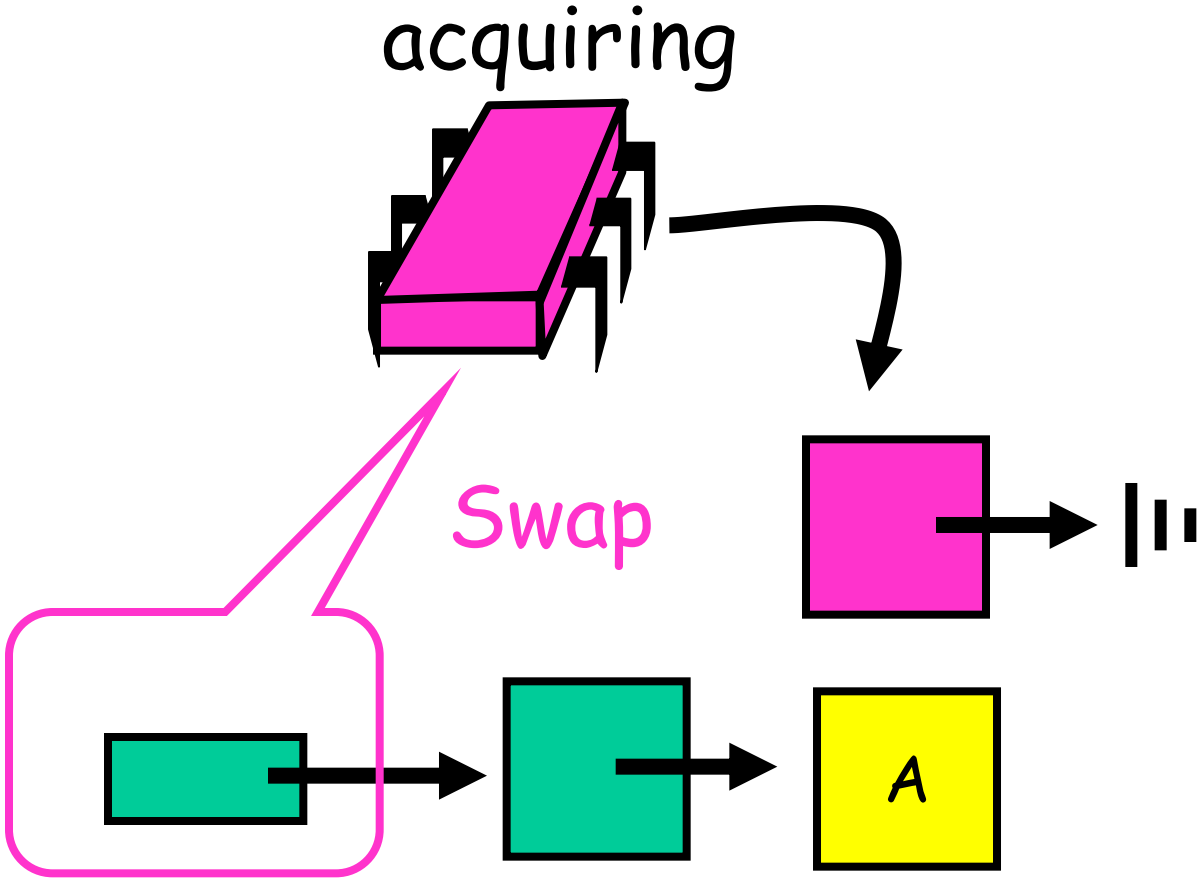




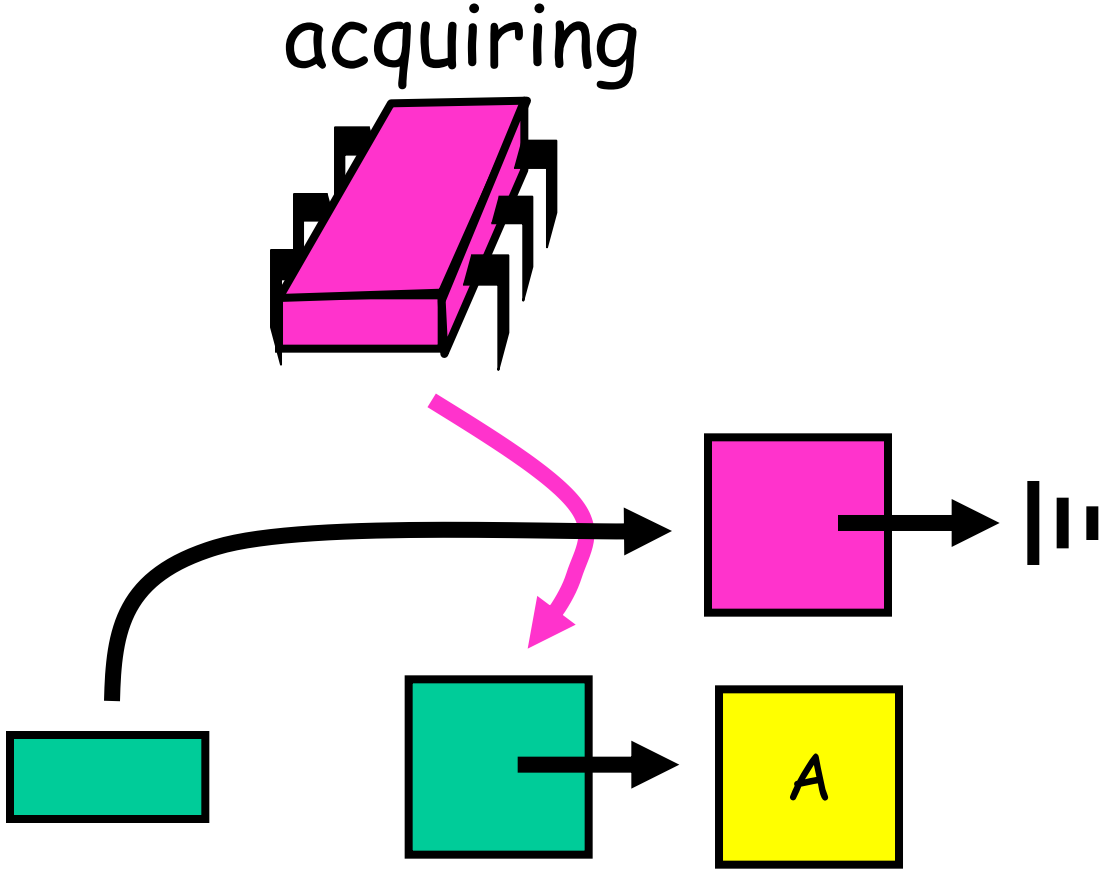
Acquiring


Null predecessor means lock not released or aborted
acquiring
A

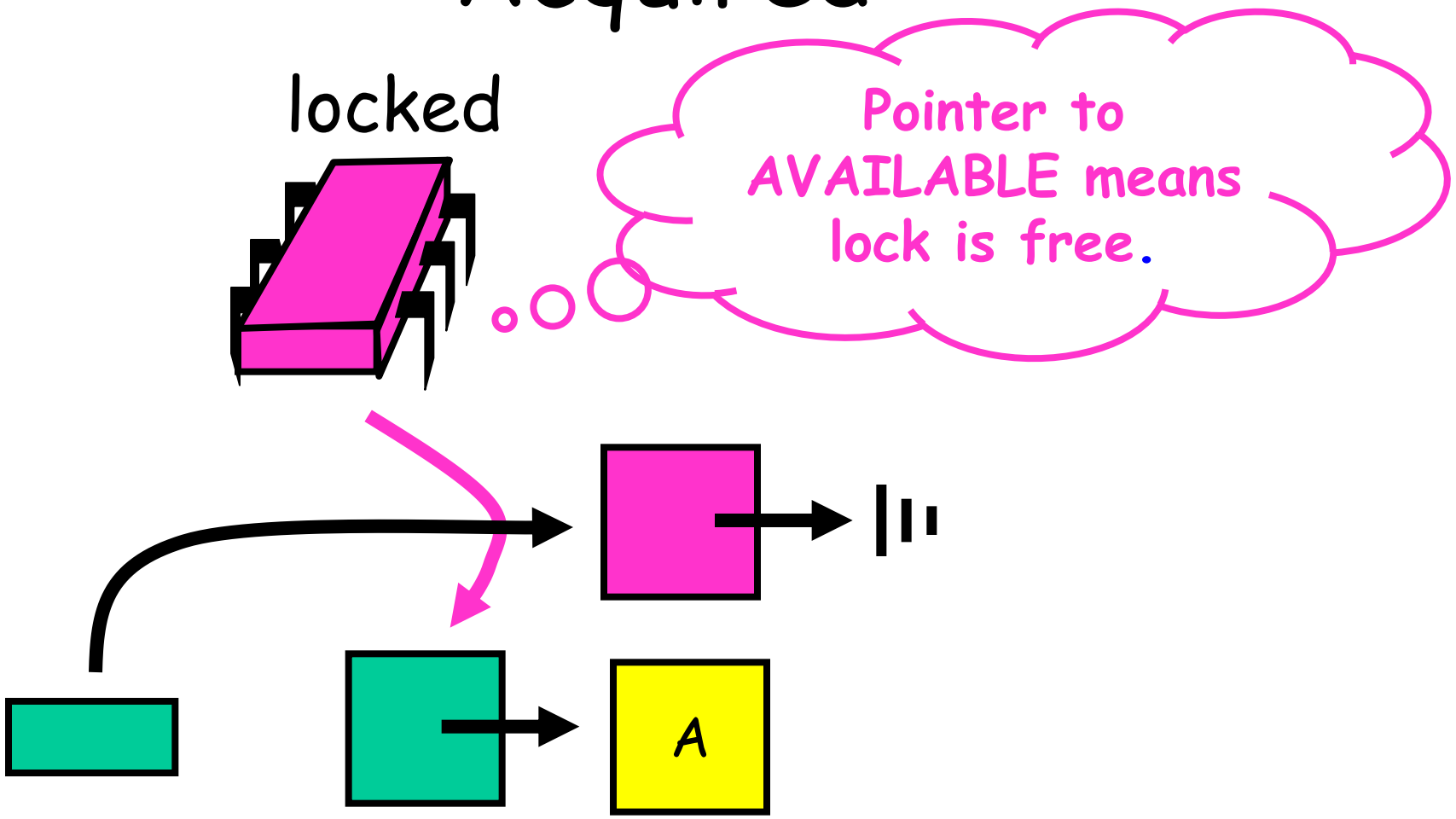
Acquiring



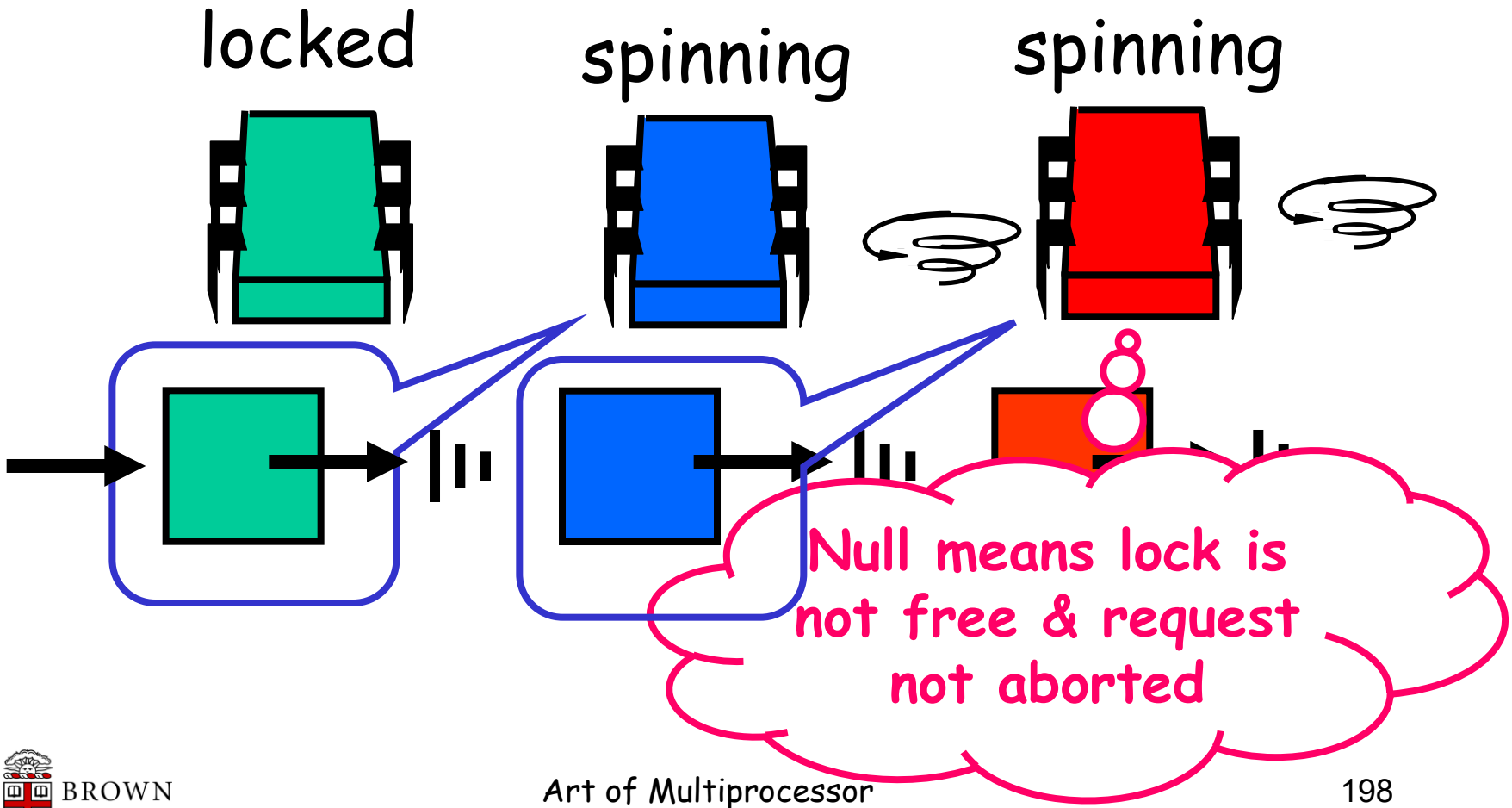
Acquiring



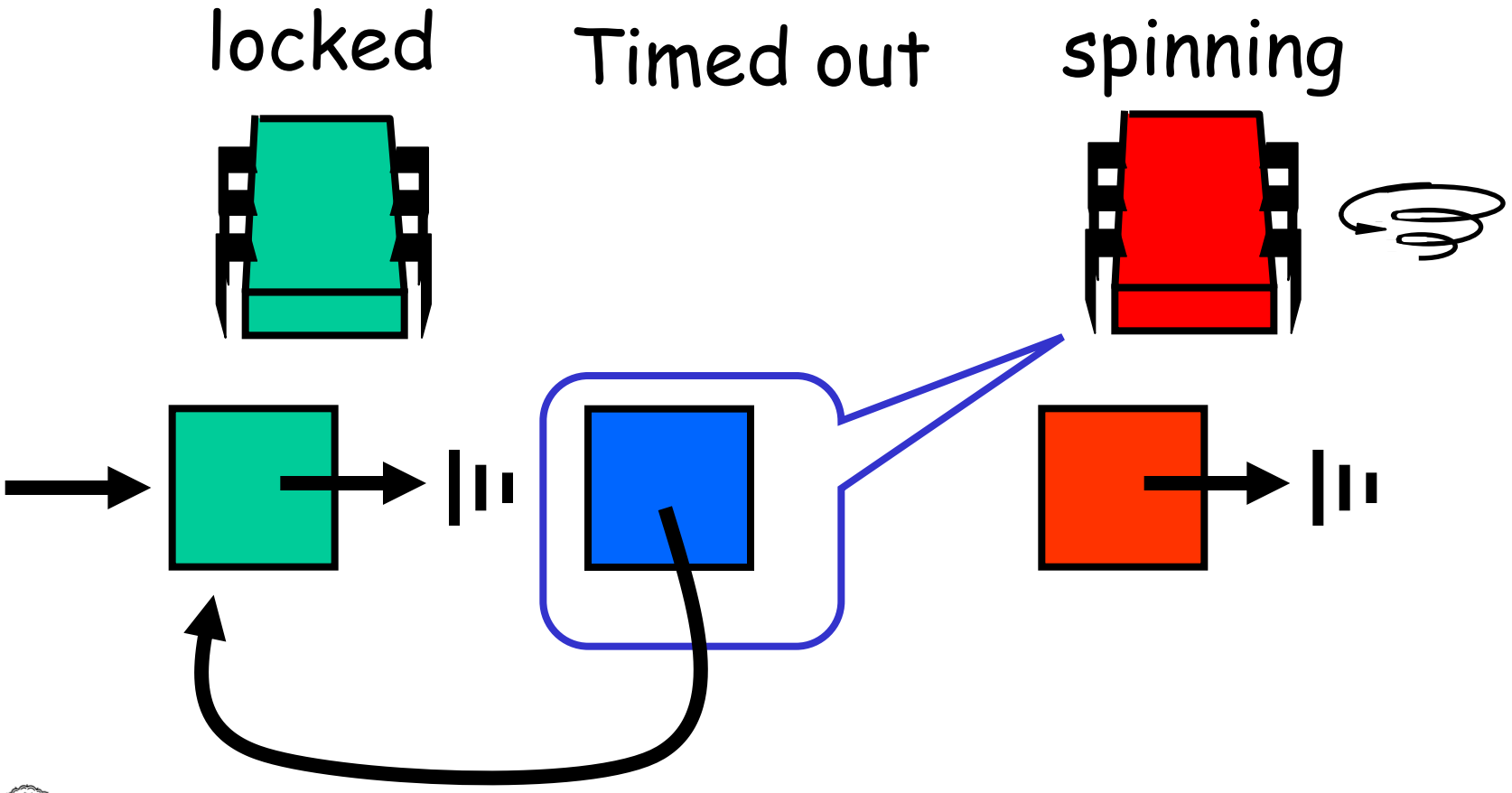
Acquired



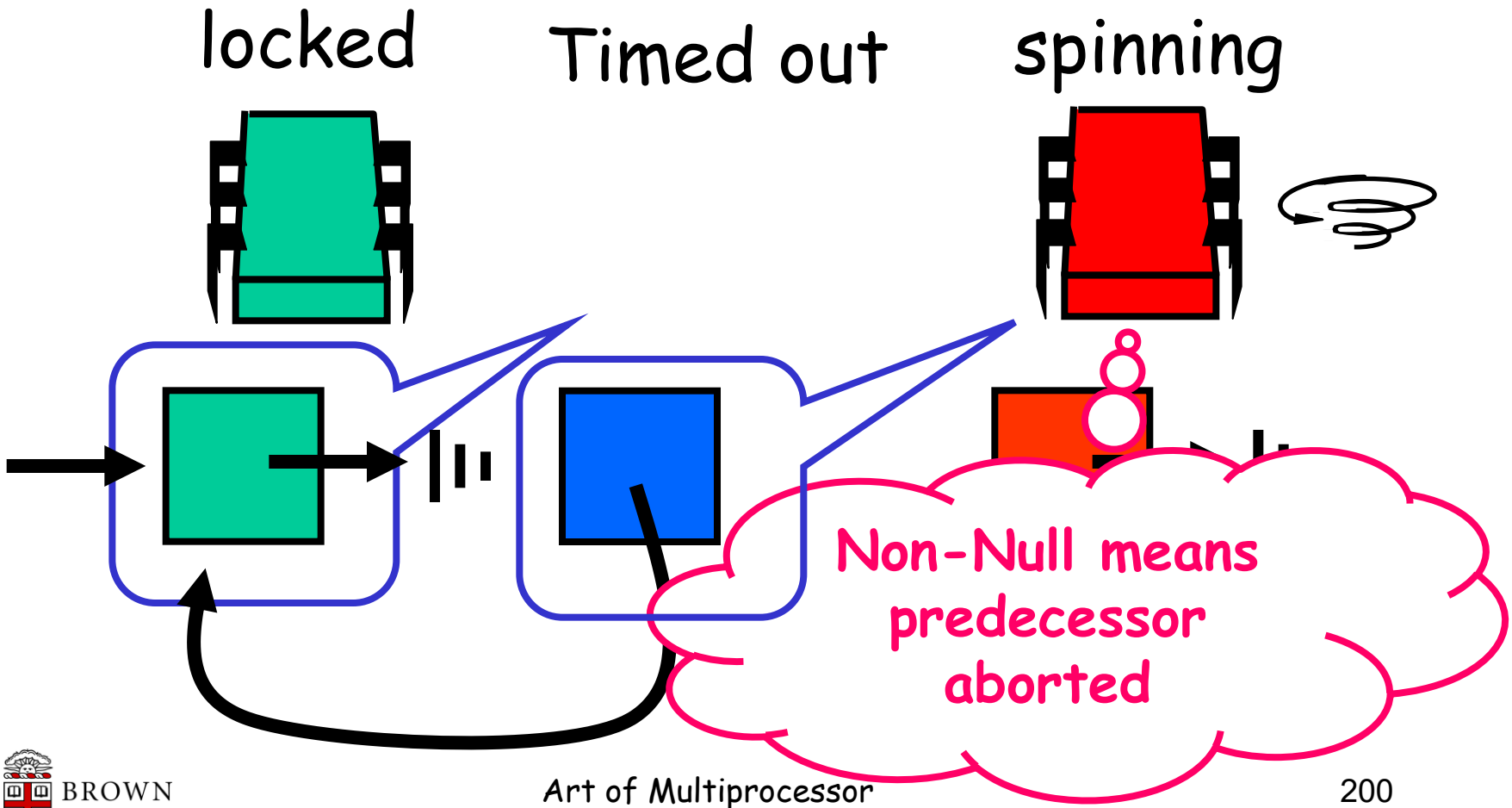
Normal Case


locked
spinning
spinning
Null means lock is not free & request not aborted

One Thread Aborts

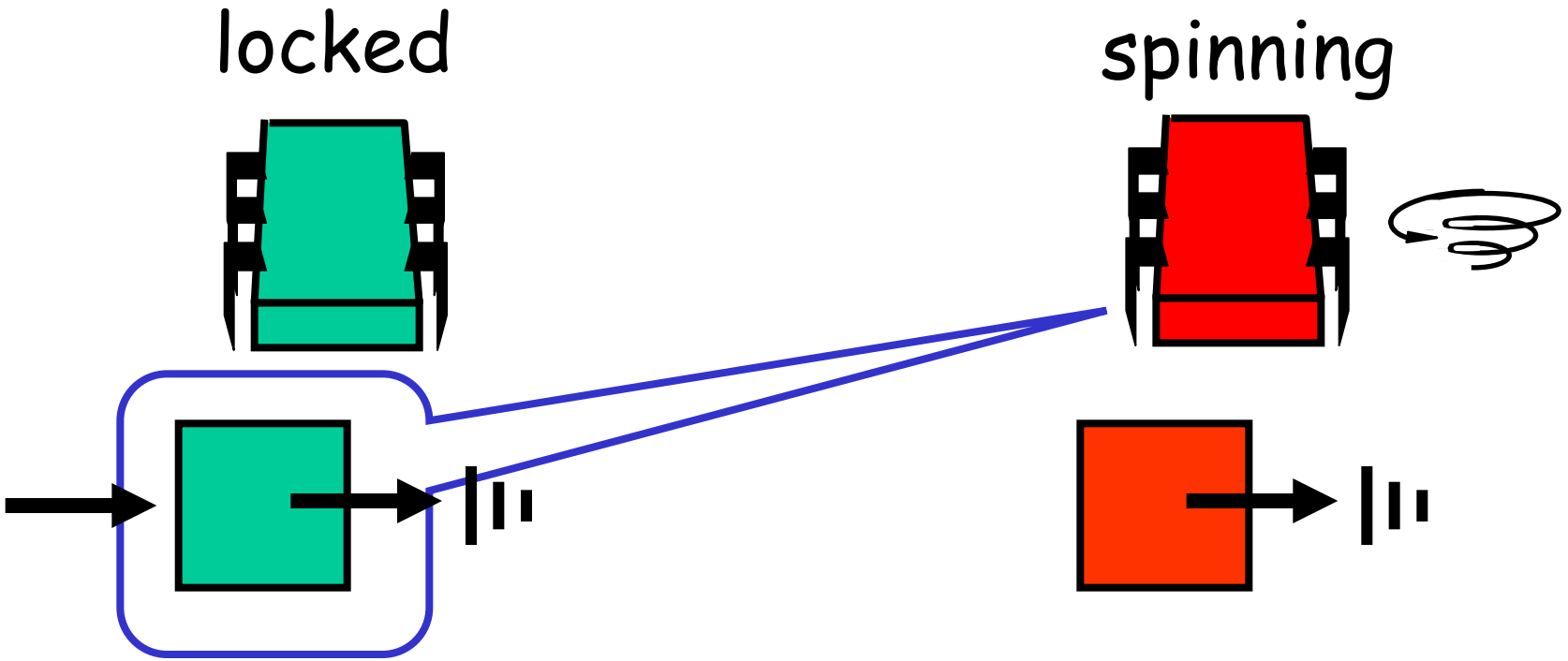


Successor Notices

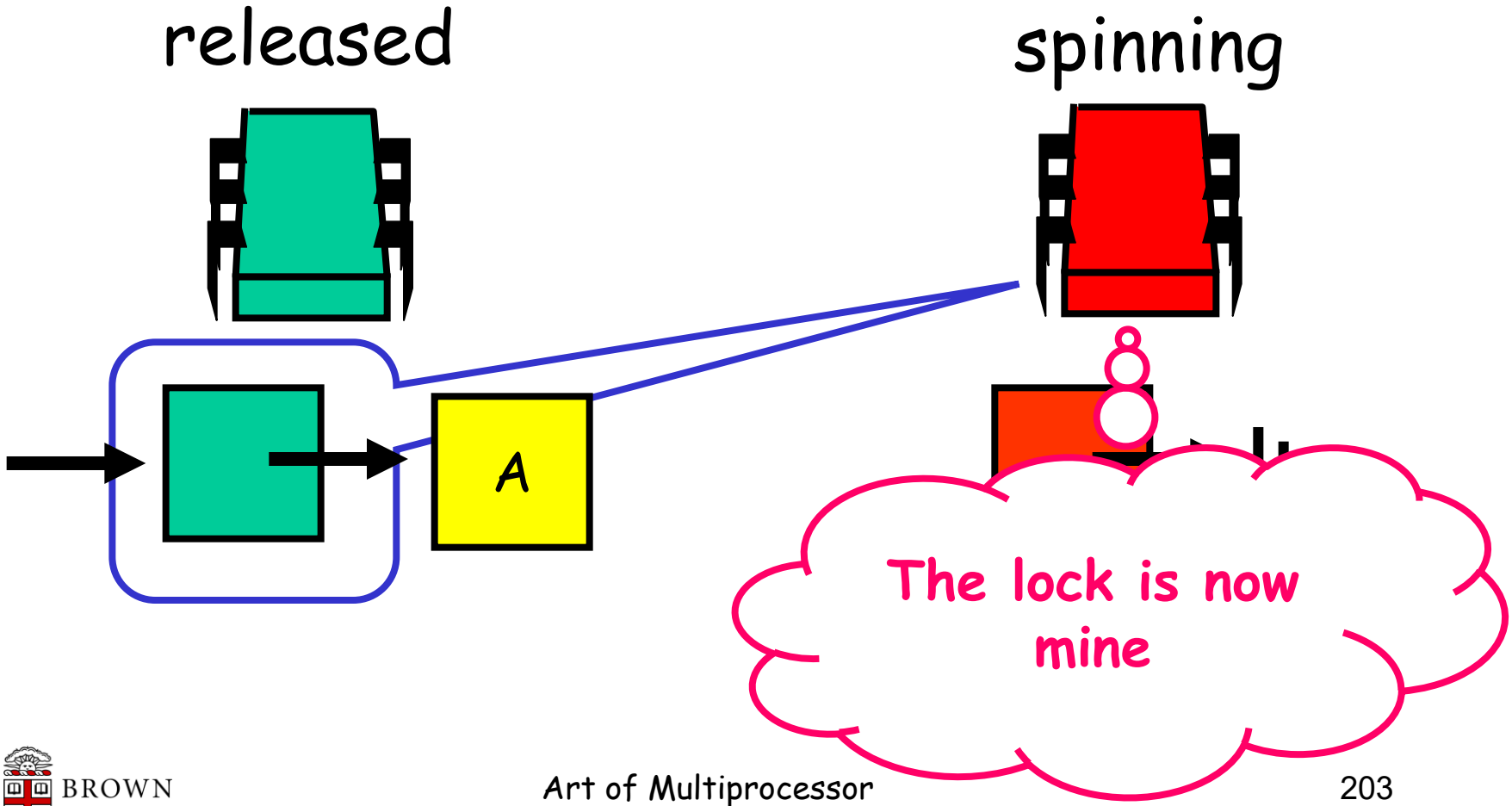


Recycle Predecessor's Node

Spin on Earlier Node



Spin on Earlier Node



Time-out Lock

```
public class TOLock implements Lock {
  static Qnode AVAILABLE
    = new Qnode();
  AtomicReference<Qnode> tail;
  ThreadLocal<Qnode> myNode;
```

Time-out Lock

```
public class TOLock implements Lock {
  static Qnode AVAILABLE
    = new Qnode();
  AtomicReference<Qnode> tail;
  ThreadLocal<Qnode> myNode;
```

Distinguished node to signify free lock

Time-out Lock

```
public class TOLock implements Lock {
  static Qnode AVAILABLE
    = new Qnode();
  AtomicReference<Qnode> tail;
  ThreadLocal<Qnode> myNode;
```

Tail of the queue

Time-out Lock

```
public class TOLock implements Lock {
  static Qnode AVAILABLE
    = new Qnode();
  AtomicReference<Qnode> tail;
  ThreadLocal<Qnode> myNode;
```

Remember my node …

Time-out Lock

```
public boolean lock(long timeout) {
  Qnode qnode = new Qnode();
  myNode.set(qnode);
  qnode.prev = null;
  Qnode myPred = tail.getAndSet(qnode);
  if (myPred== null
      || myPred.prev == AVAILABLE) {
      return true;
   }
…
```

Time-out Lock

```
public boolean lock(long timeout) {
  Qnode qnode = new Qnode();
  myNode.set(qnode);
  qnode.prev = null;
  Qnode myPred = tail.getAndSet(qnode);
  if (myPred == null
      || myPred.prev == AVAILABLE) {
     return true;
   }
```

Create & initialize node

Time-out Lock

```
public boolean lock(long timeout) {
  Qnode qnode = new Qnode();
  myNode.set(qnode);
  qnode.prev = null;
  Qnode myPred = tail.getAndSet(qnode);
  if (myPred == null
      || myPred.prev == AVAILABLE) {
     return true;
   }
```

Swap with tail

Time-out Lock

```
public boolean lock(long timeout) {
  Qnode qnode = new Qnode();
  myNode.set(qnode);
  qnode.prev = null;
  Qnode myPred = tail.getAndSet(qnode);
  if (myPred == null
      || myPred.prev == AVAILABLE) {
      return true;
  }
  ...
```

If predecessor absent or released, we are done

Time-out Lock

```
…
  long start = now();
  while (now()- start < timeout) {
    Qnode predPred = myPred.prev;
    if (predPred == AVAILABLE) {
      return true;
    } else if (predPred != null) {
      myPred = predPred;
    }
  }
  …
```

Time-out Lock

```
…
  long start = now();
  while (now()- start < timeout) {
    Qnode predPred = myPred.prev;
    if (predPred == AVAILABLE) {
      return true;
    } else if (predPred != null) {
      myPred = predPred;
    }
  }
  …
```

Keep trying for a while …

Time-out Lock

```
…
  long start = now();
  while (now()- start < timeout) {
    Qnode predPred = myPred.prev;
    if (predPred == AVAILABLE) {
      return true;
    } else if (predPred != null) {
      myPred = predPred;
    }
  }
…
```

Spin on predecessor's prev field

Time-out Lock

```
…
  long start = now();
  while (now()- start < timeout) {
    Qnode predPred = myPred.prev;
    if (predPred == AVAILABLE) {
      return true;
    } else if (predPred != null) {
      myPred = predPred;
    }
  }
  …
```

Predecessor released lock

Time-out Lock

```
…
  long start = now();
  while (now()- start < timeout) {
    Qnode predPred = myPred.prev;
    if (predPred == AVAILABLE) {
      return true;
    } else if (predPred != null) {
      myPred = predPred;
    }
  }
  …
```

Predecessor aborted, advance one

Time-out Lock

```
…
if (!tail.compareAndSet(qnode, myPred))
    qnode.prev = myPred;
    return false;
  }
}
```

Time-out Locks

```
…
if (!tail.compareAndSet(qnode, myPred))
    qnode.prev = myPred;
    return false;
  }
}
```

Do I have a successor? If CAS fails: I do have a successor, tell it about myPred

Time-out Locks

```
…
if (!tail.compareAndSet(qnode, myPred))
    qnode.prev = myPred;
    return false;
  }
}
```

If CAS succeeds: no successor, simply return false

Time-Out Unlock

```
public void unlock() {
  Qnode qnode = myNode.get();
  if (!tail.compareAndSet(qnode, null))
    qnode.prev = AVAILABLE;
}
```

Time-out Unlock

```
public void unlock() {
  Qnode qnode = myNode.get();
  if (!tail.compareAndSet(qnode, null))
    qnode.prev = AVAILABLE;
}
```

If CAS failed: exists successor, notify successor it can enter

Timing-out Lock

```
public void unlock() {
  Qnode qnode = myNode.get();
  if (!tail.compareAndSet(qnode, null))
    qnode.prev = AVAILABLE;
}
```

CAS successful: set tail to null, no clean up since no successor waiting

One Lock To Rule Them All?

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