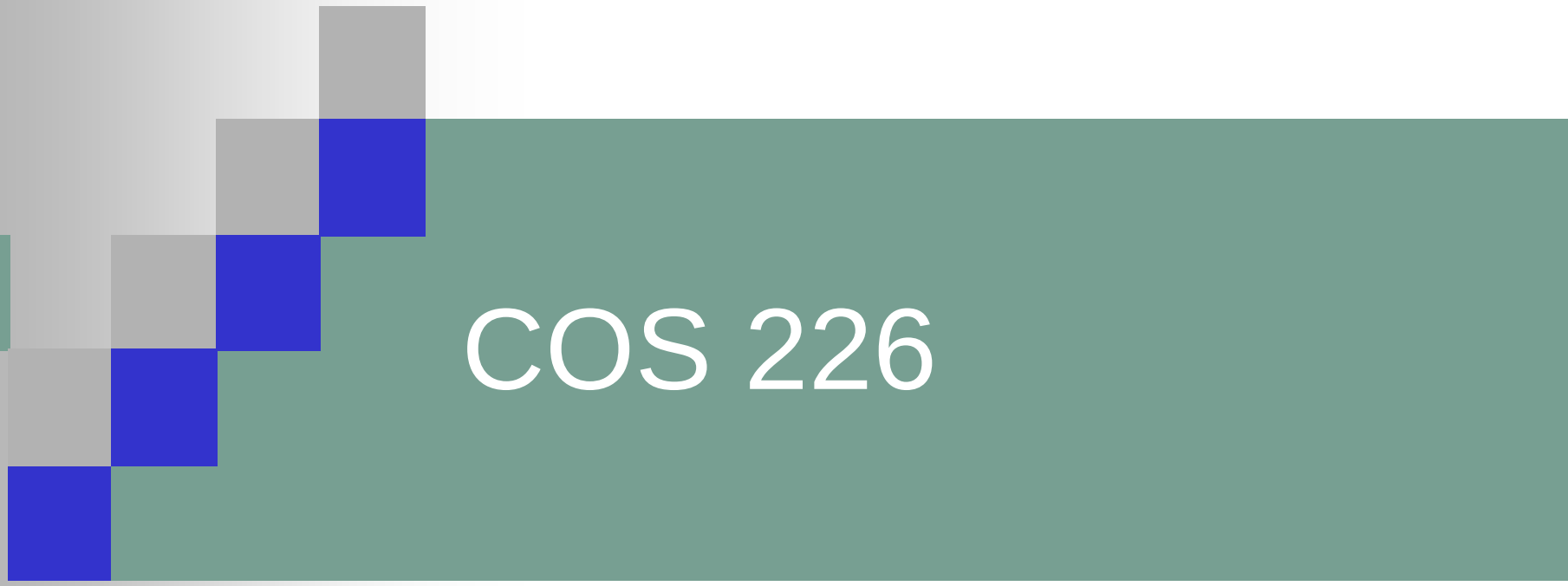
Department of Computer Science

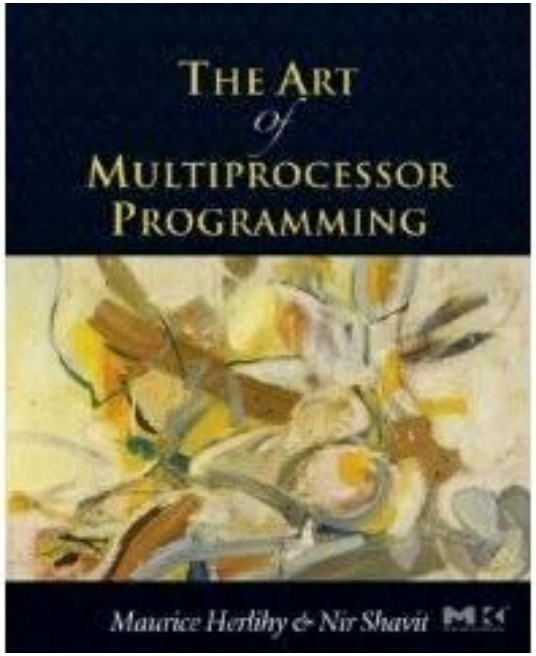


COS 226

Chapter 7

Spin Locks and Contention

Acknowledgement



- Some of the slides are taken from the companion slides for “The Art of Multiprocessor Programming” by Maurice Herlihy & Nir Shavit

Concurrency issues

- Memory contention:
  - Not all processors can access the same memory at the same time and if they try they will have to queue
- Contention for communication medium:
  - If everyone wants to communicate at the same time, some of them will have to wait
- Communication latency:
  - If takes more time for a processor to communicate with memory or with another processor.

New goals

- Think of performance, not just correctness and progress
- Understand the underlying architecture
- Understand how the architecture affects performance

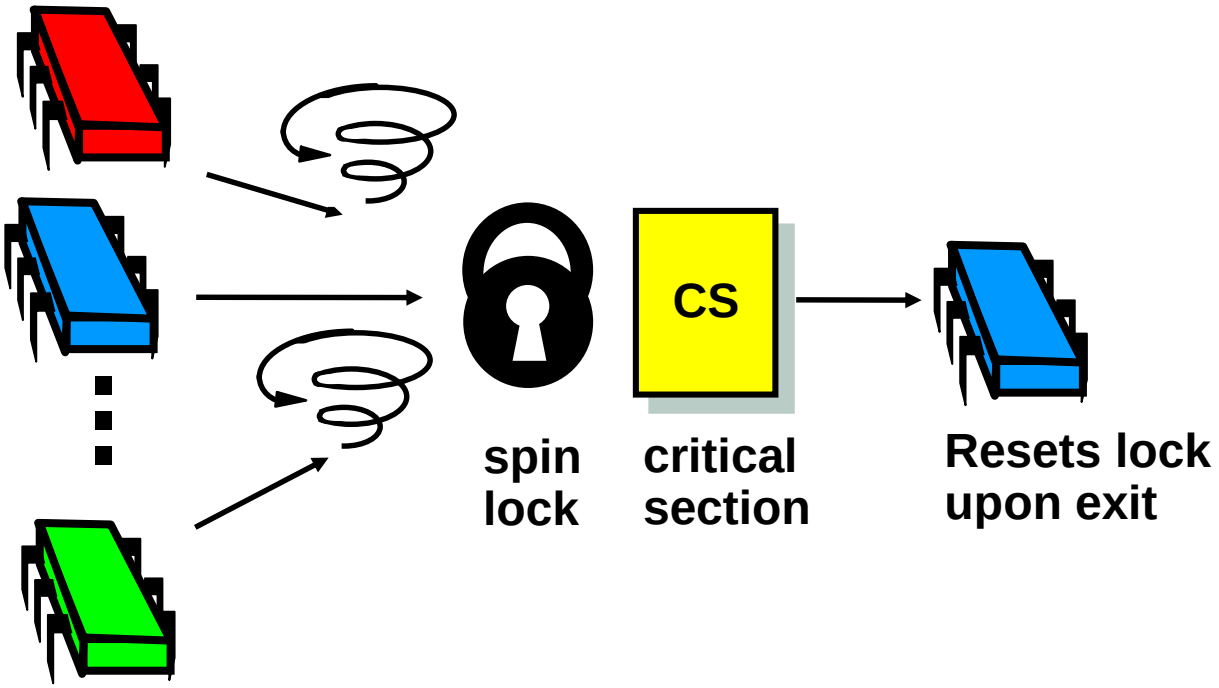
- Start with Mutual Exclusion

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

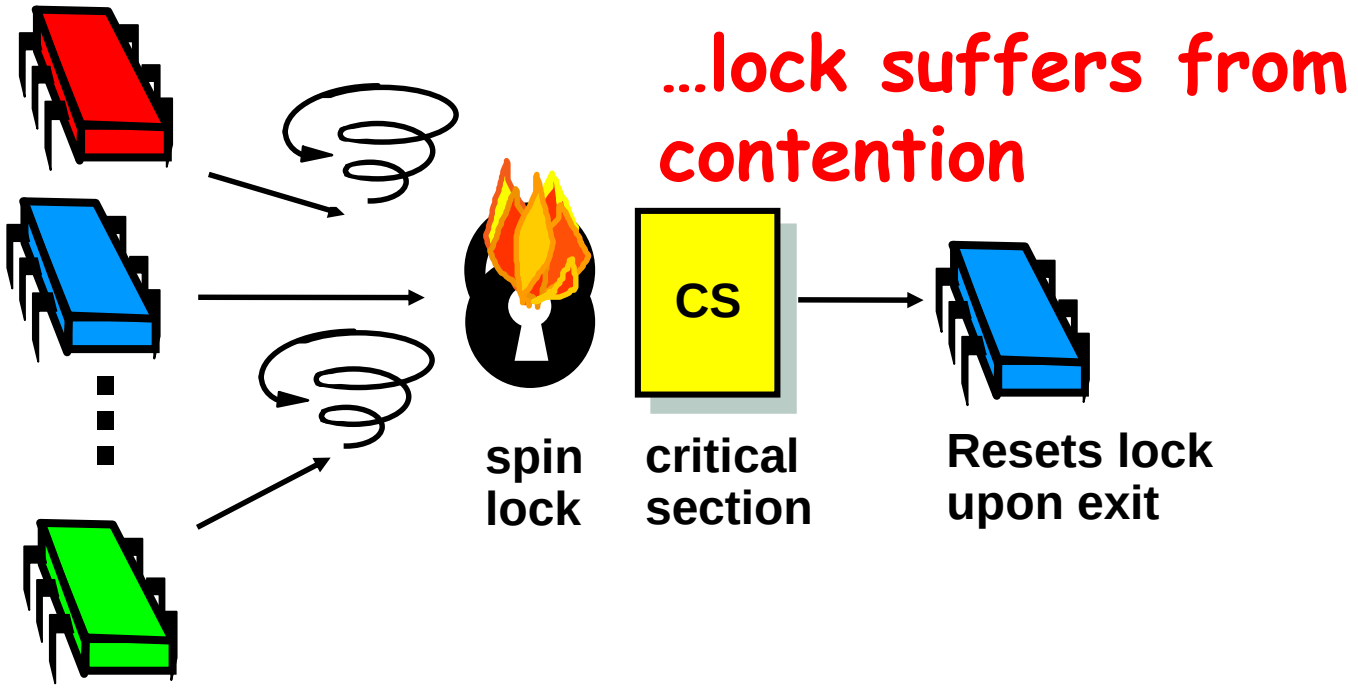
- Keep trying
  - "spin" or "busy-wait"
  - Good if delays are short
- Give up the processor
  - Suspend yourself and ask the schedule to create another thread on your processor
  - Good if delays are long
  - Always good on uniprocessor

our focus

Basic Spin-Lock



Basic Spin-Lock



Contention

- Contention:
  - When multiple threads try to acquire a lock at the same time
- High contention:
  - There are many such threads
- Low contention:
  - The opposite

Welcome to the real world

- Java Lock interface
  - java.util.concurrent.locks package

```
Lock mutex = new LockImpl (…);
…
mutex.lock();
try {
    …
} finally {
    mutex.unlock();
}
```

Why don’t we just use the Filter or Bakery Locks?

- The principal drawback is the need to read and write *n* distinct locations where *n* is the number of concurrent threads
- This means that the locks require space linear in *n*

What about the Peterson lock?

```
class Peterson implements Lock {
private boolean[] flag = new boolean[2];
private int victim;
public void lock() {
   int i = ThreadID.get();
   int j = 1 - i;
   flag[i] = true;
   victim  = i;
   while (flag[j] && victim == i) {};
}
```

Peterson lock?

- It is not our logic that fails, but our assumptions about the real world
- We assumed that read and write operations are atomic
- Our proof relied on the assumption that any two memory accesses by the same thread, even to different variables, take place in program order

Why does it not take place in program order?

- Modern multiprocessors do not guarantee program order
- Due to:
  - Compilers
    - reorder instructions to enhance performance
  - Multiprocessor hardware itself
    - writes to multiprocessor memory do not necessarily take effect when they are issued
    - writes to shared memory are buffered and written to memory only when needed

What about the Peterson lock?

```
class Peterson implements Lock {
private boolean[] flag = new boolean[2];
private int victim;
public void lock() {
   int i = ThreadID.get();
   int j = 1 - i;
   flag[i] = true;
   victim  = i;
   while (flag[j] && victim == i) {};
}
```

Important that these steps take place in program order

How can one fix this?

- Memory barriers (or memory fences) can be used to force outstanding operations to take effect
- It is the programmer's responsibility to know when to insert a memory barrier
- However, memory barriers are expensive

Memory barriers

- Synchronization instructions such as getAndSet() or compareAndSet() often include memory barriers
- As do reads and writes to **volatile** fields

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;
    value = newValue;
    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(false);
 }}
```

Lock state is AtomicBoolean

Test-and-set Lock

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

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

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

Keep trying until lock acquired

Test-and-set Lock

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

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

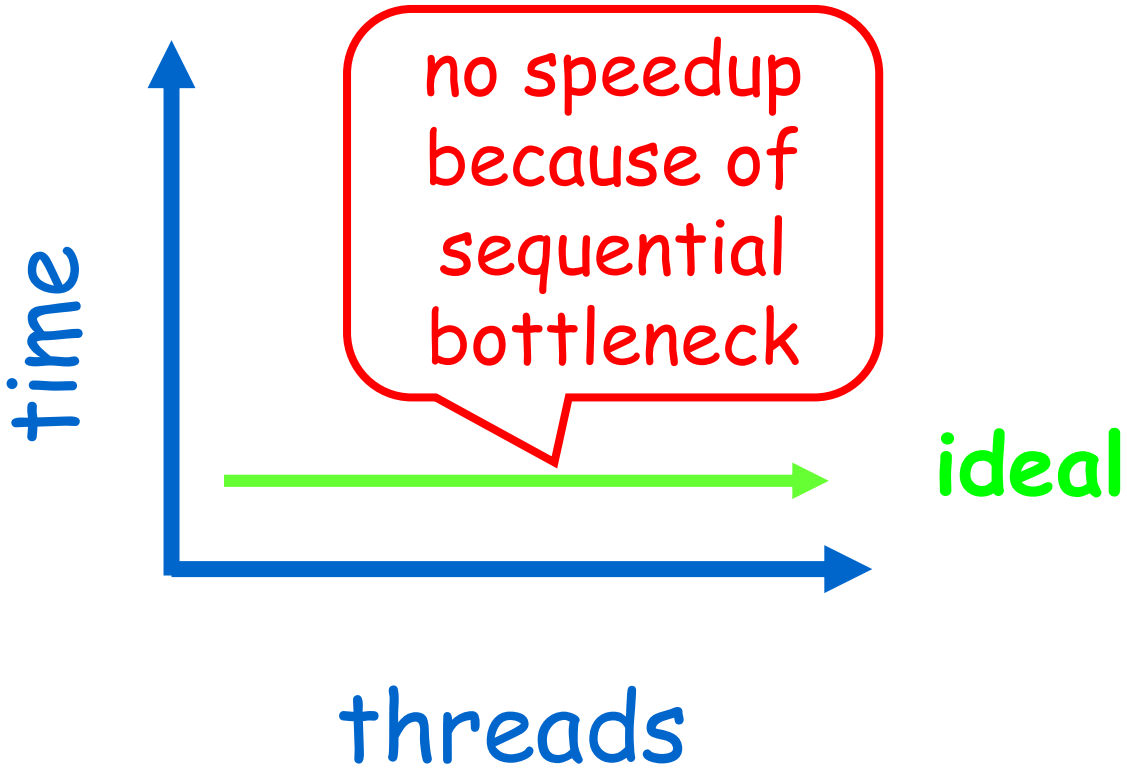
 void unlock() {
  state.set(false);
 }}
```

Release lock by resetting state to false

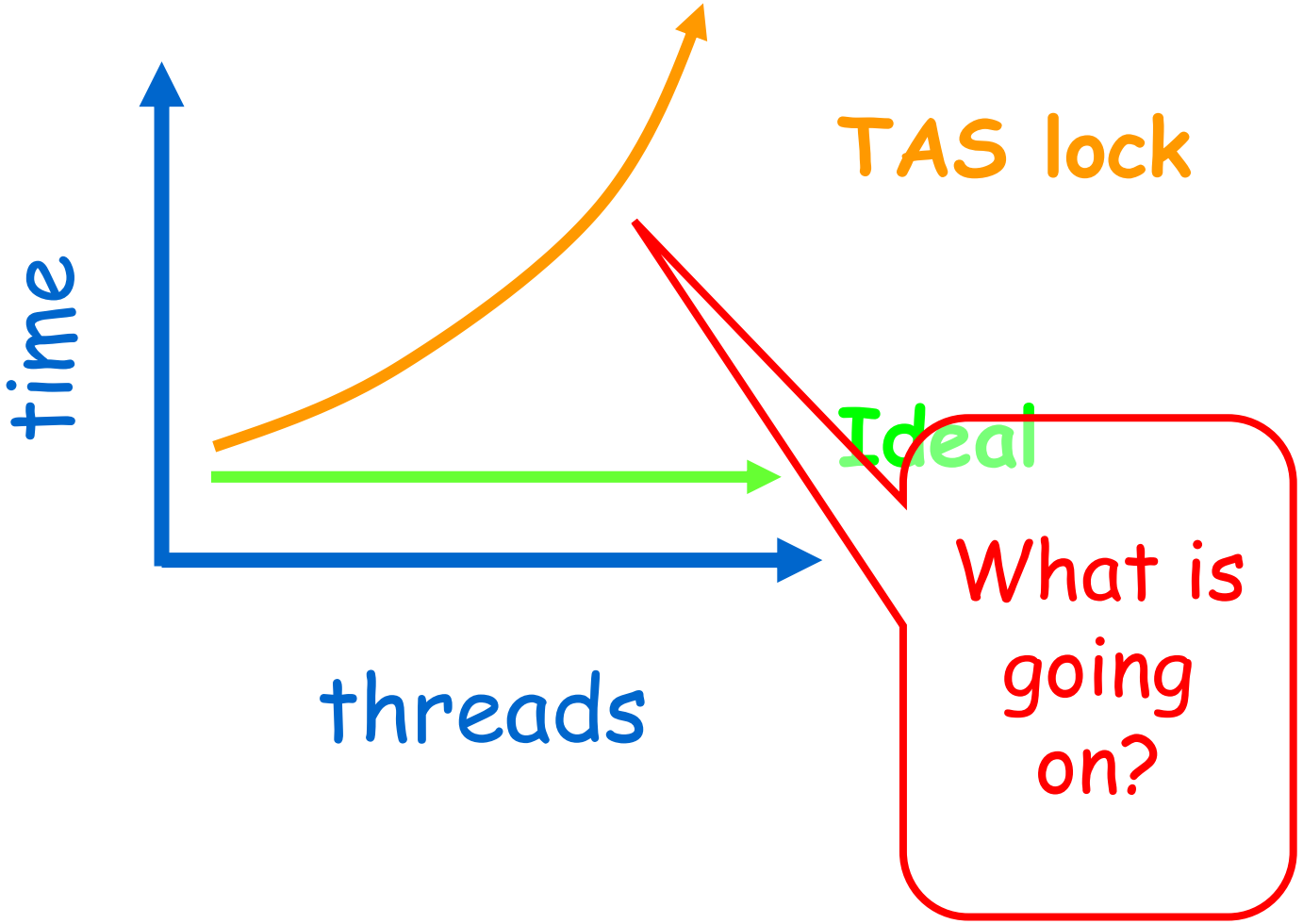
Performance

- 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
time
ideal
threads

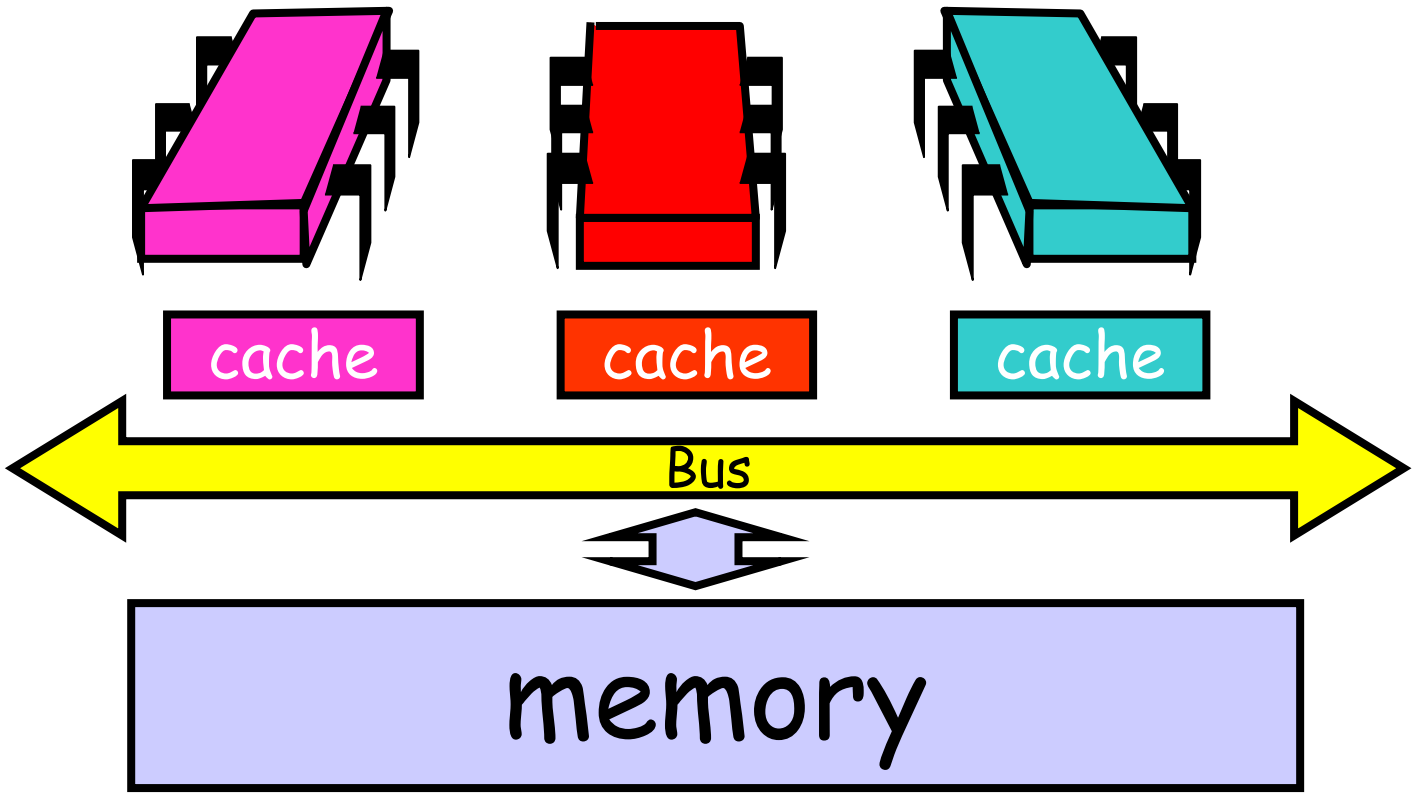
Mystery #1



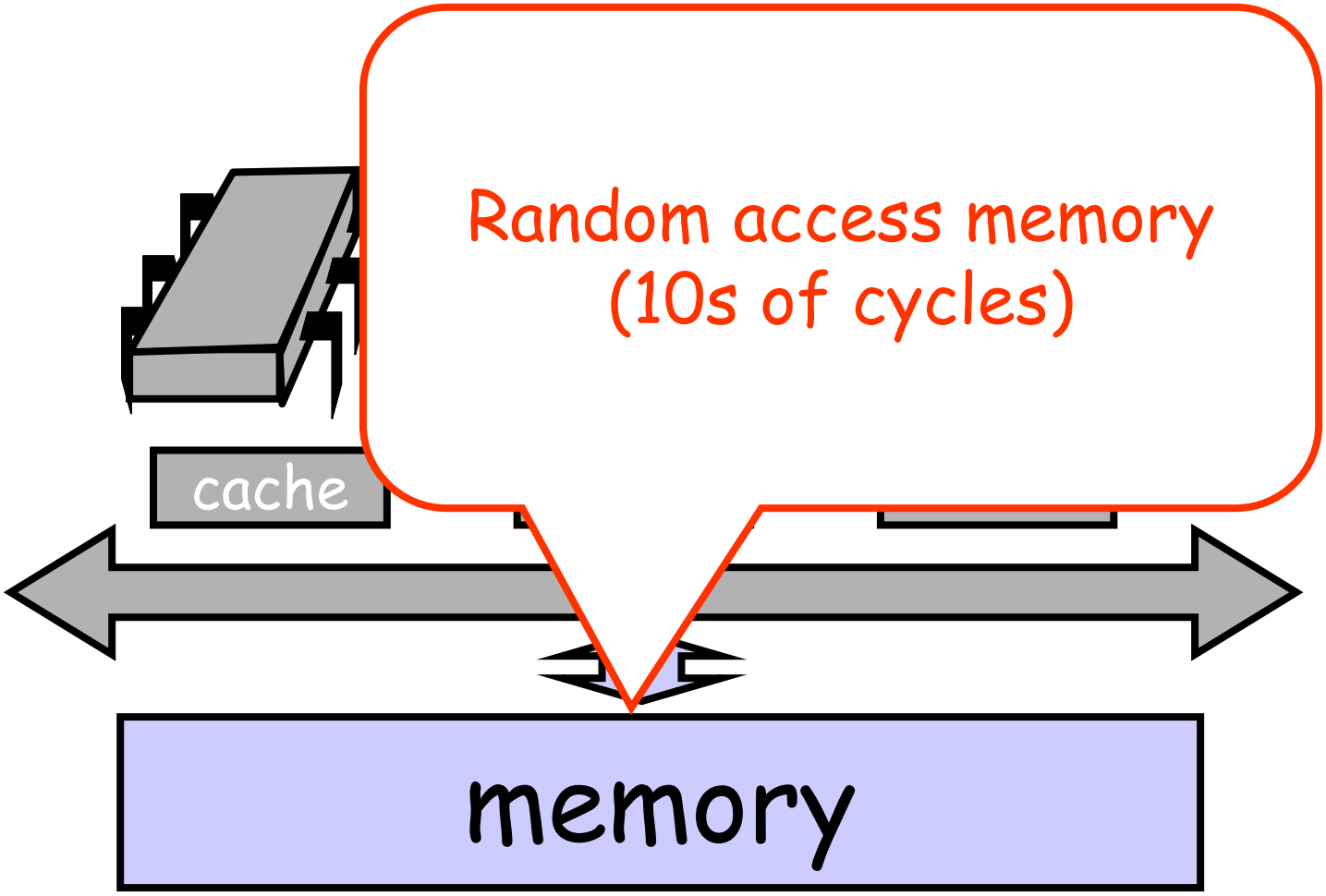
Questions

- Why is TAS so bad (so much worse than ideal)?

Bus-Based Architectures



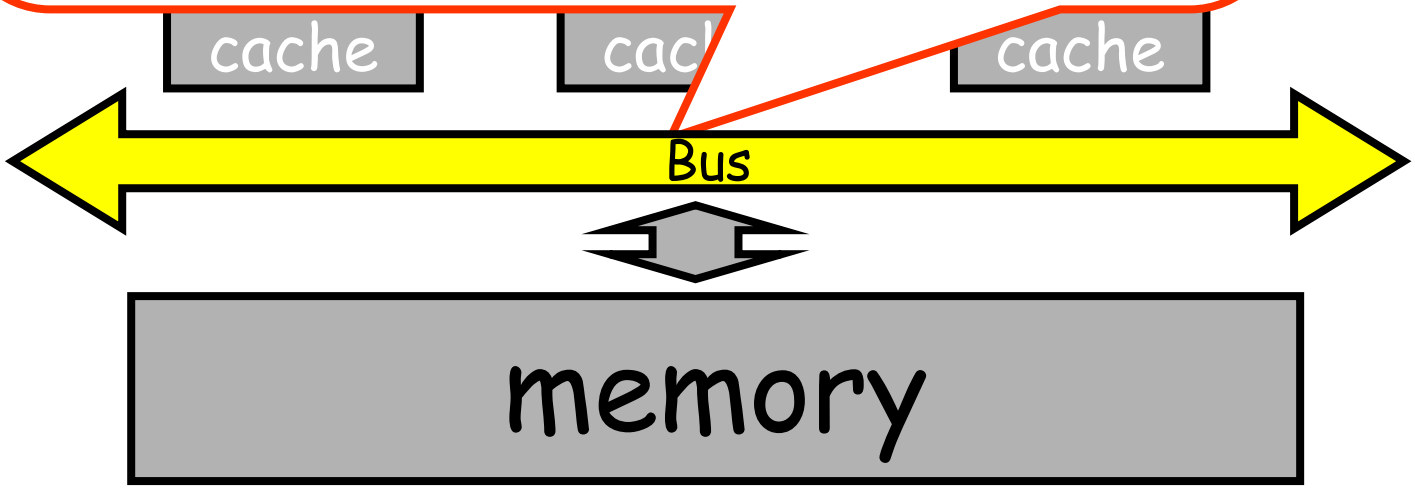
Bus-Based Architectures



Bus-Based Architectures

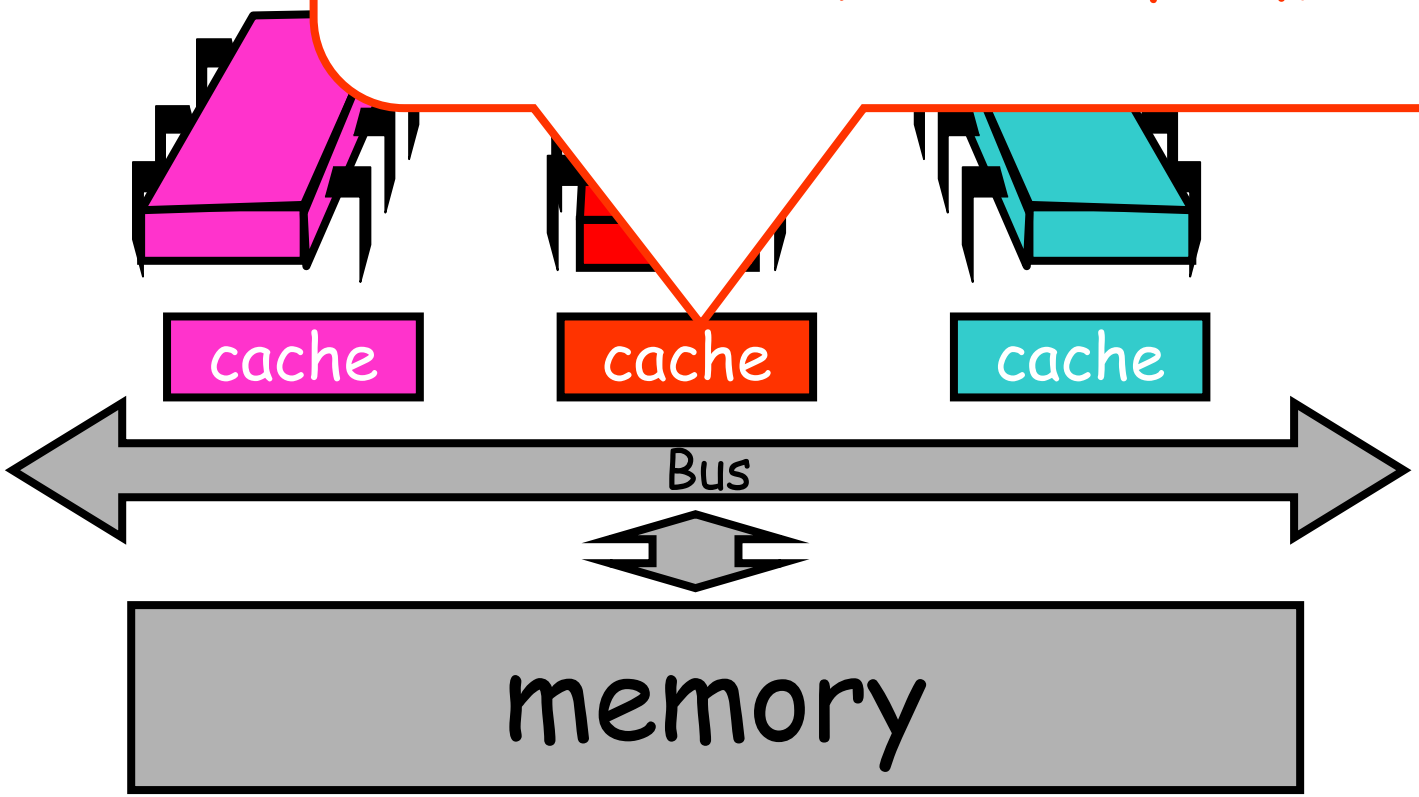
Shared Bus

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



Bus-Bas

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



Jargon Watch

- Cache hit
  - “I found what I wanted in my cache”
  - Good Thing™

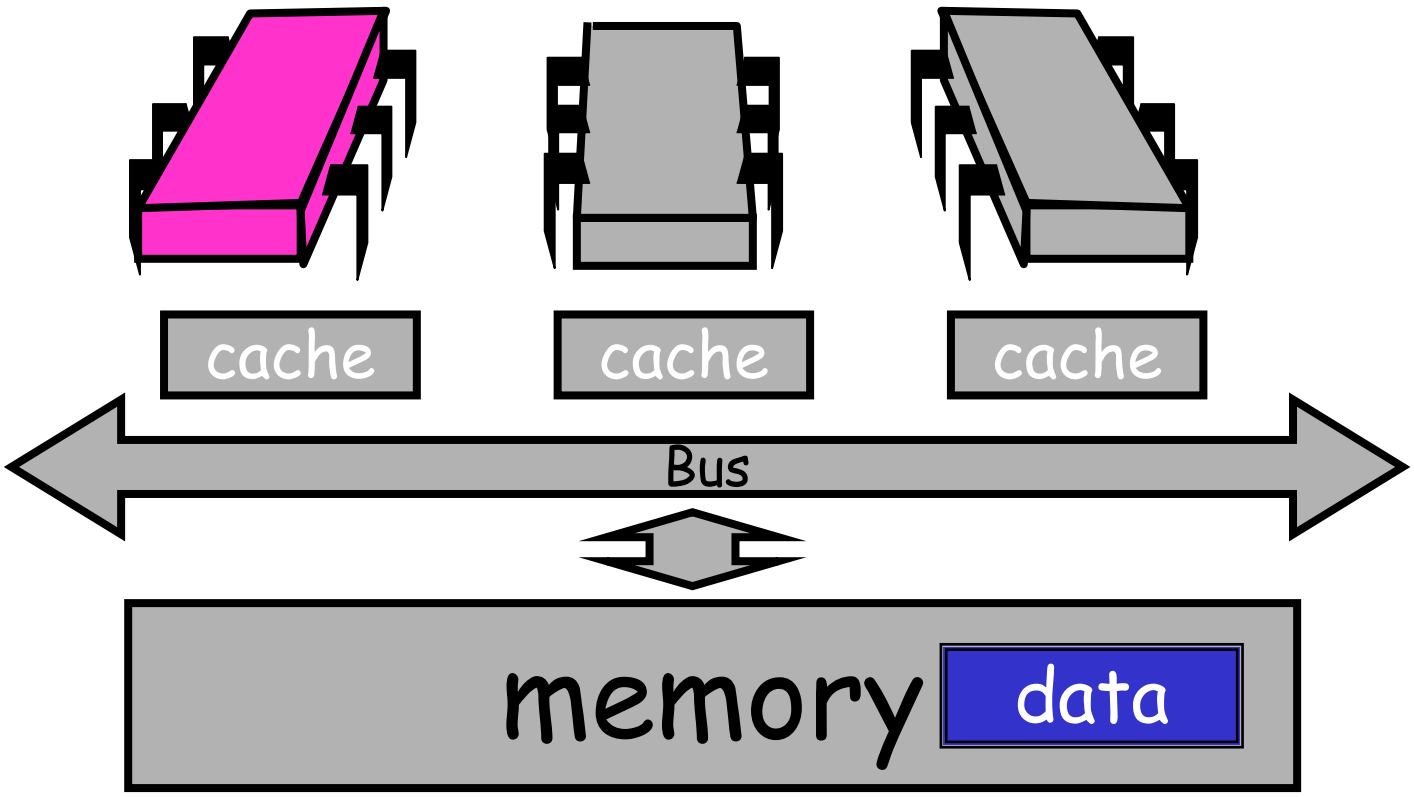
Jargon Watch

- 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™

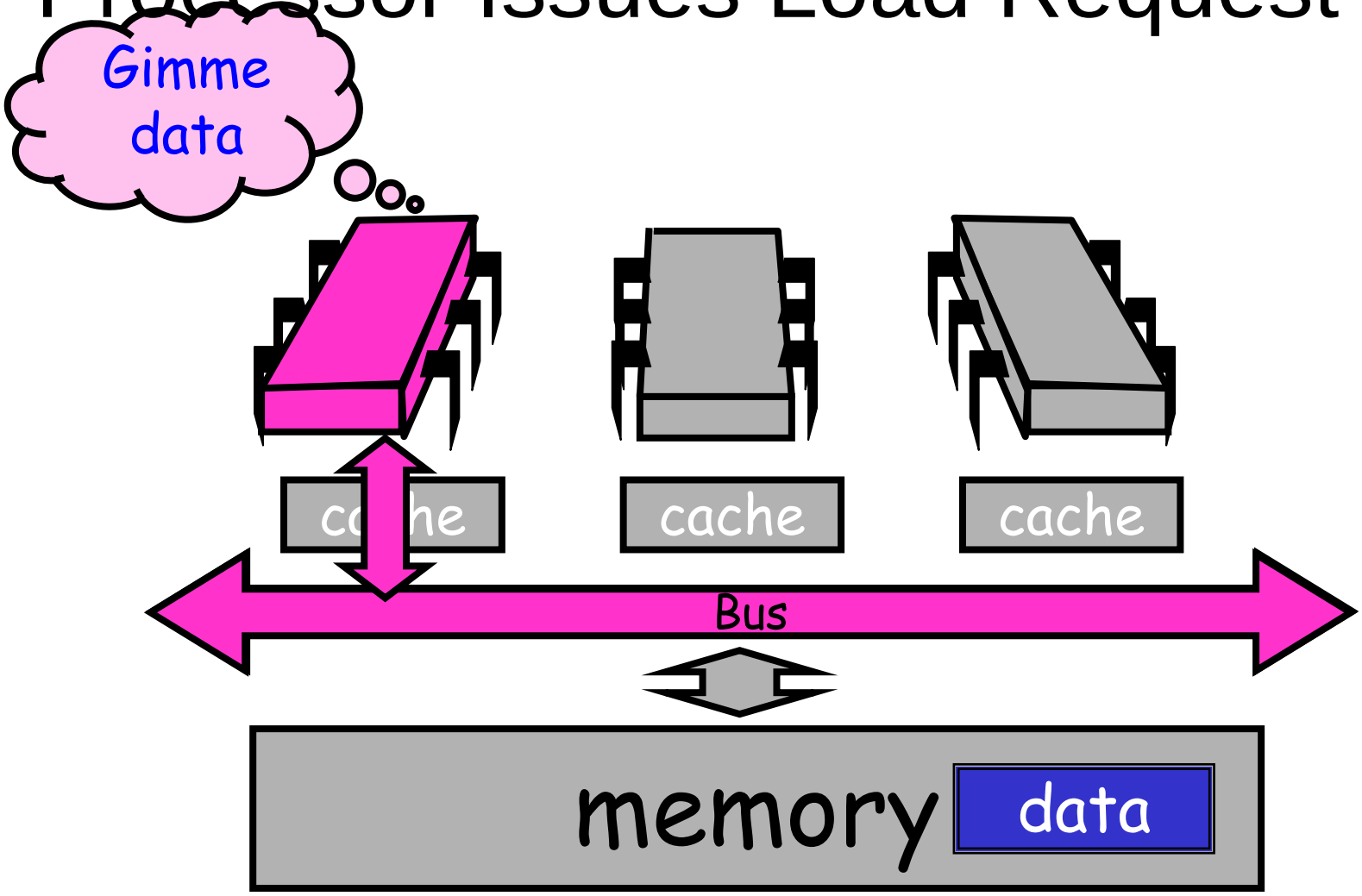
Cave Canem

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

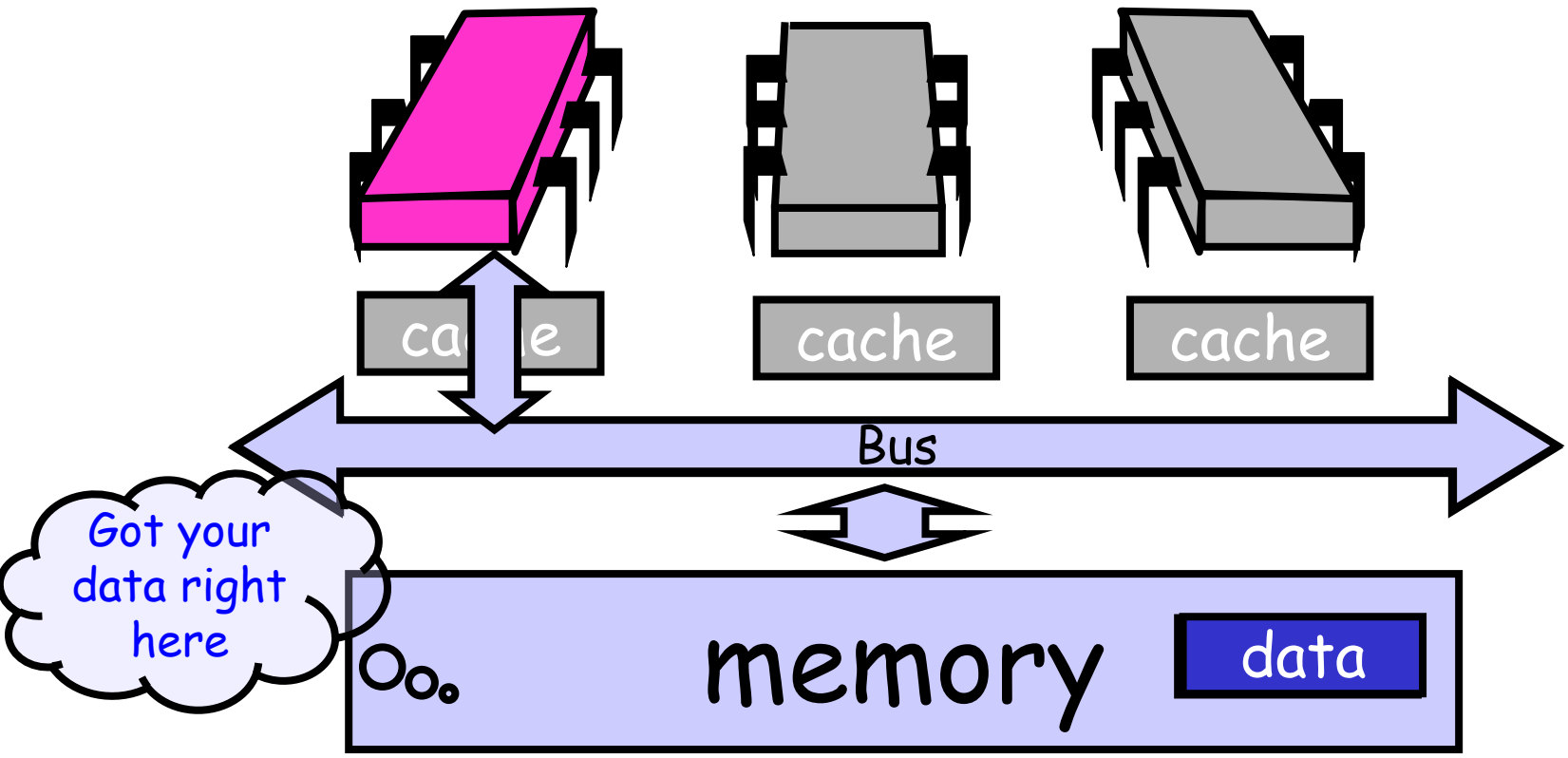
Processor Issues Load Request



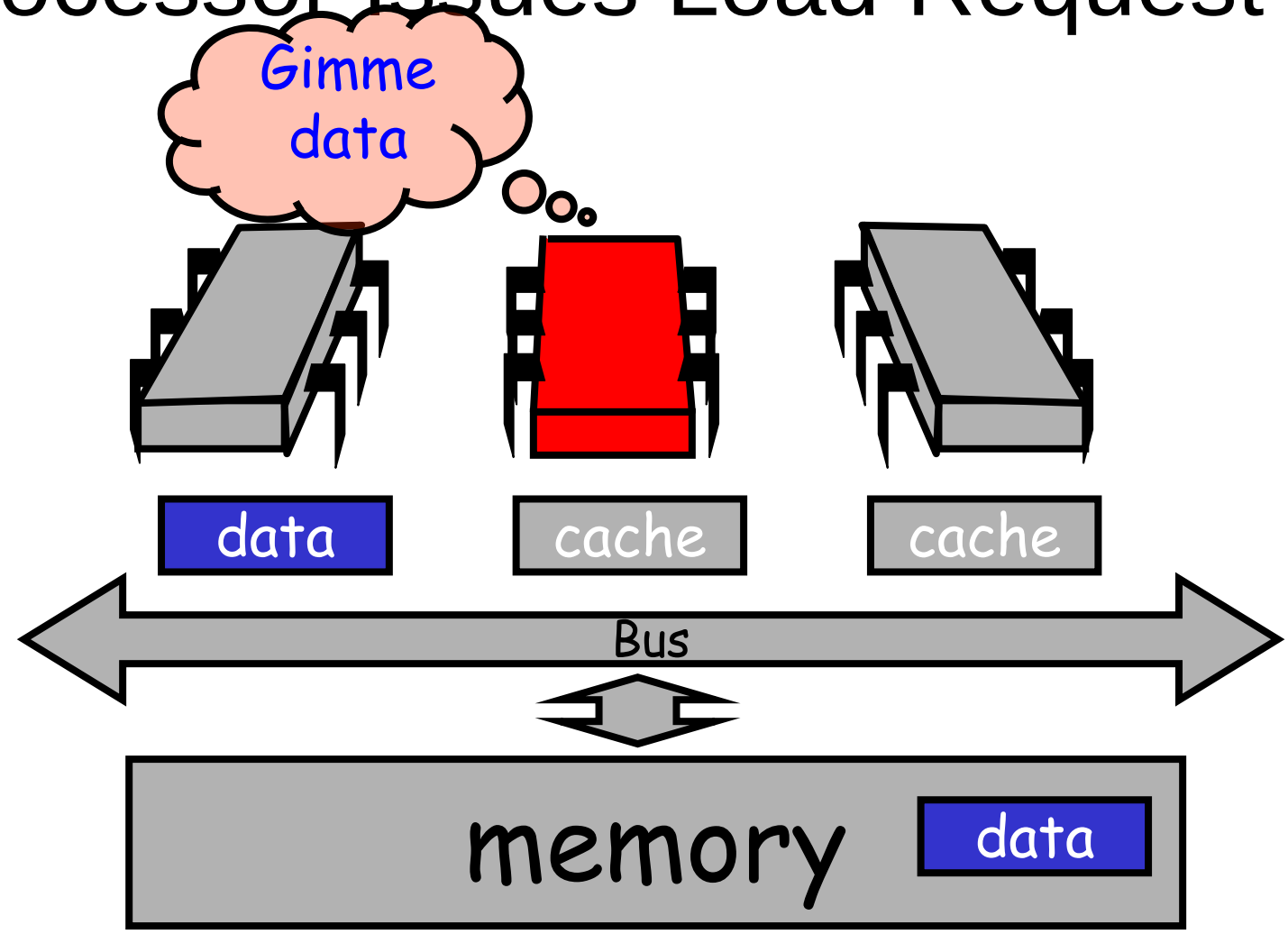
Processor Issues Load Request



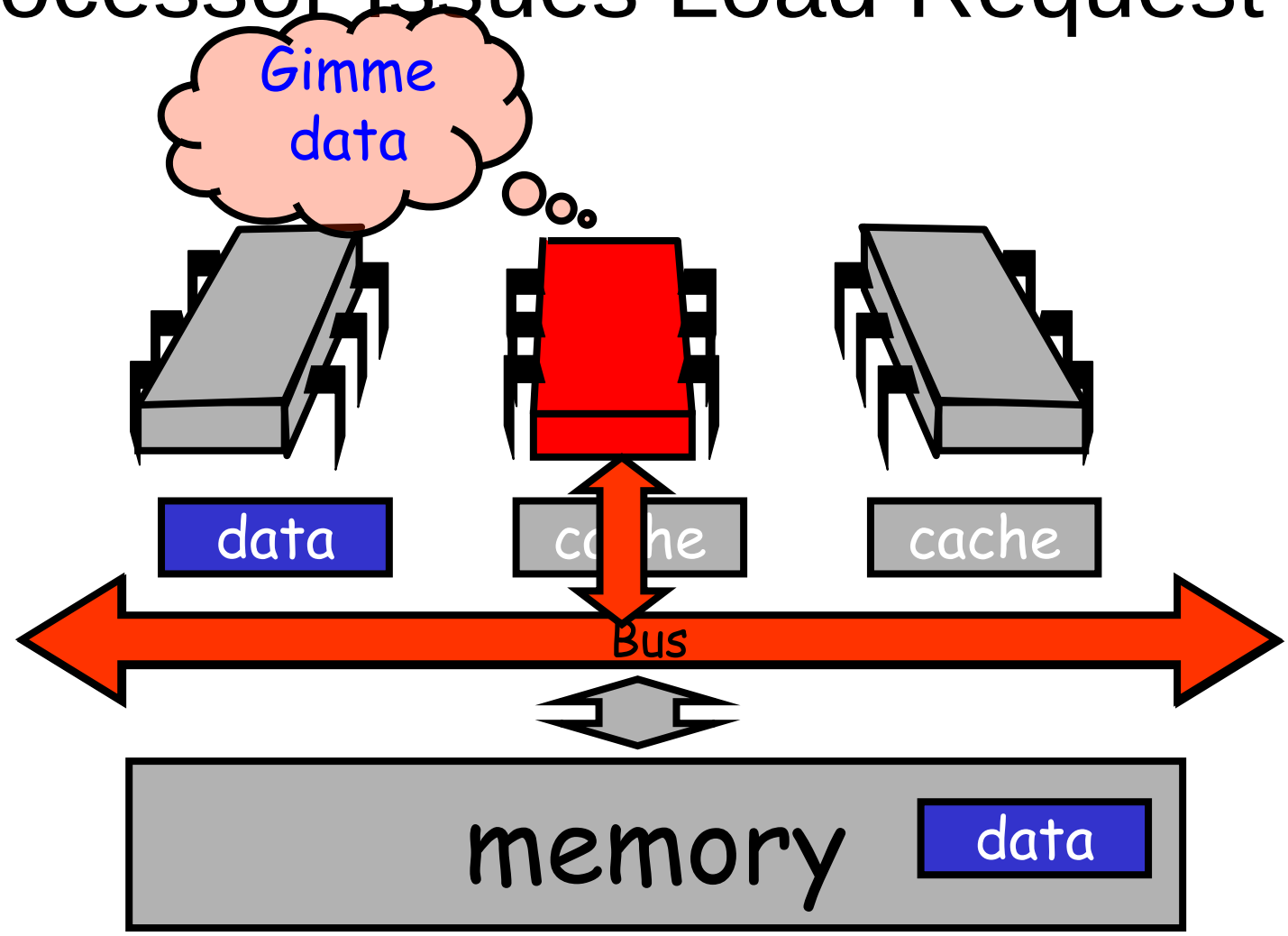
Memory Responds



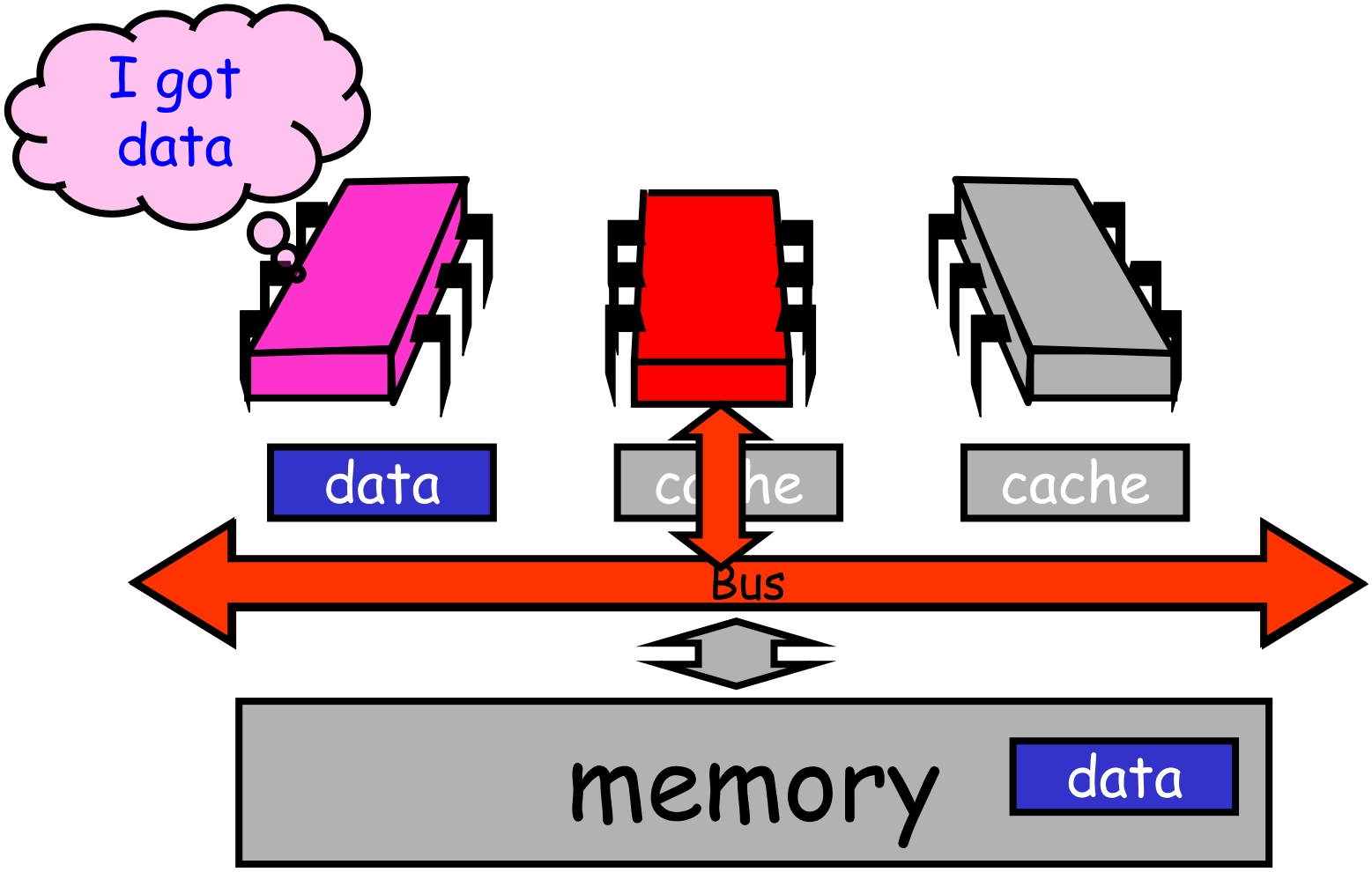
Processor Issues Load Request



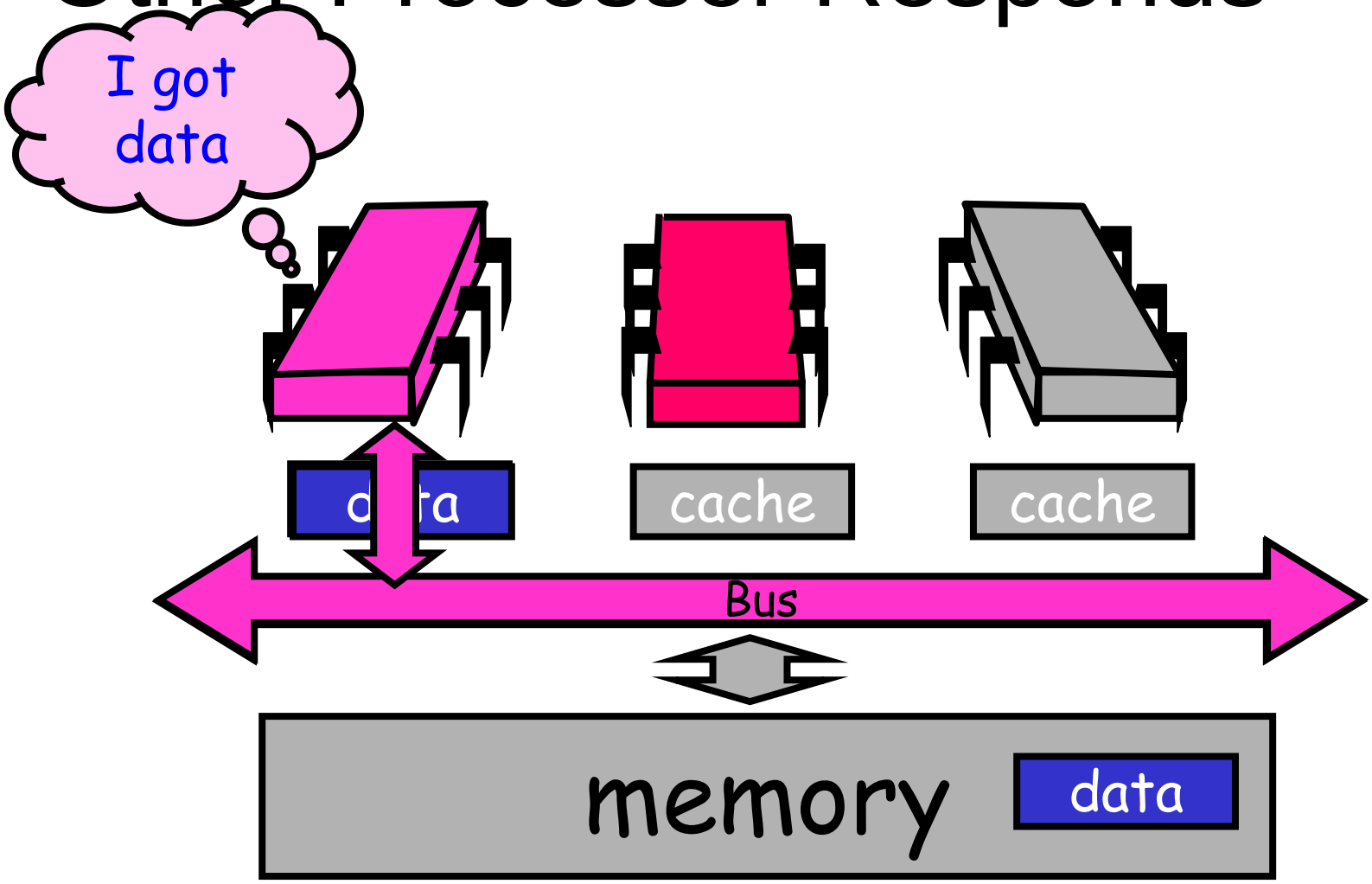
Processor Issues Load Request



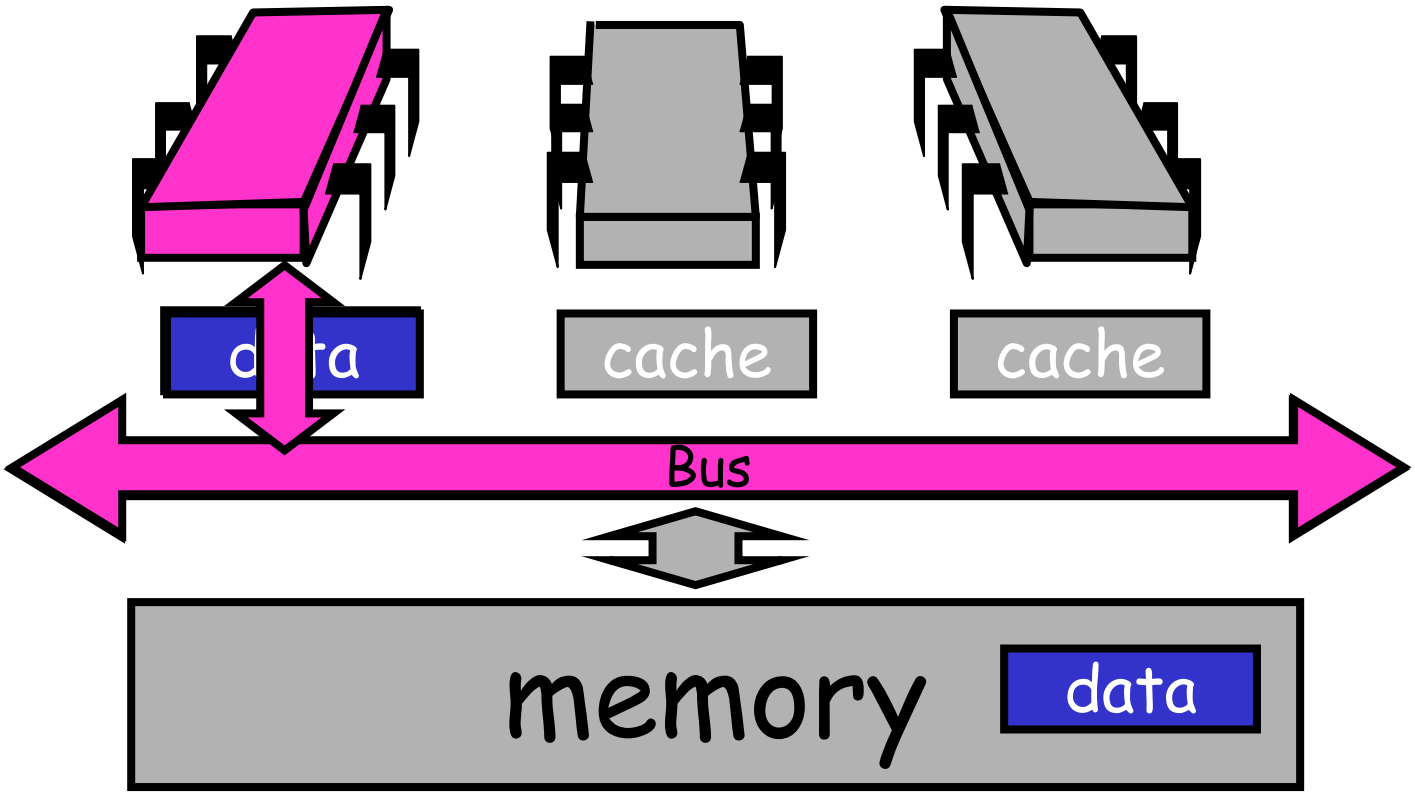
Processor Issues Load Request



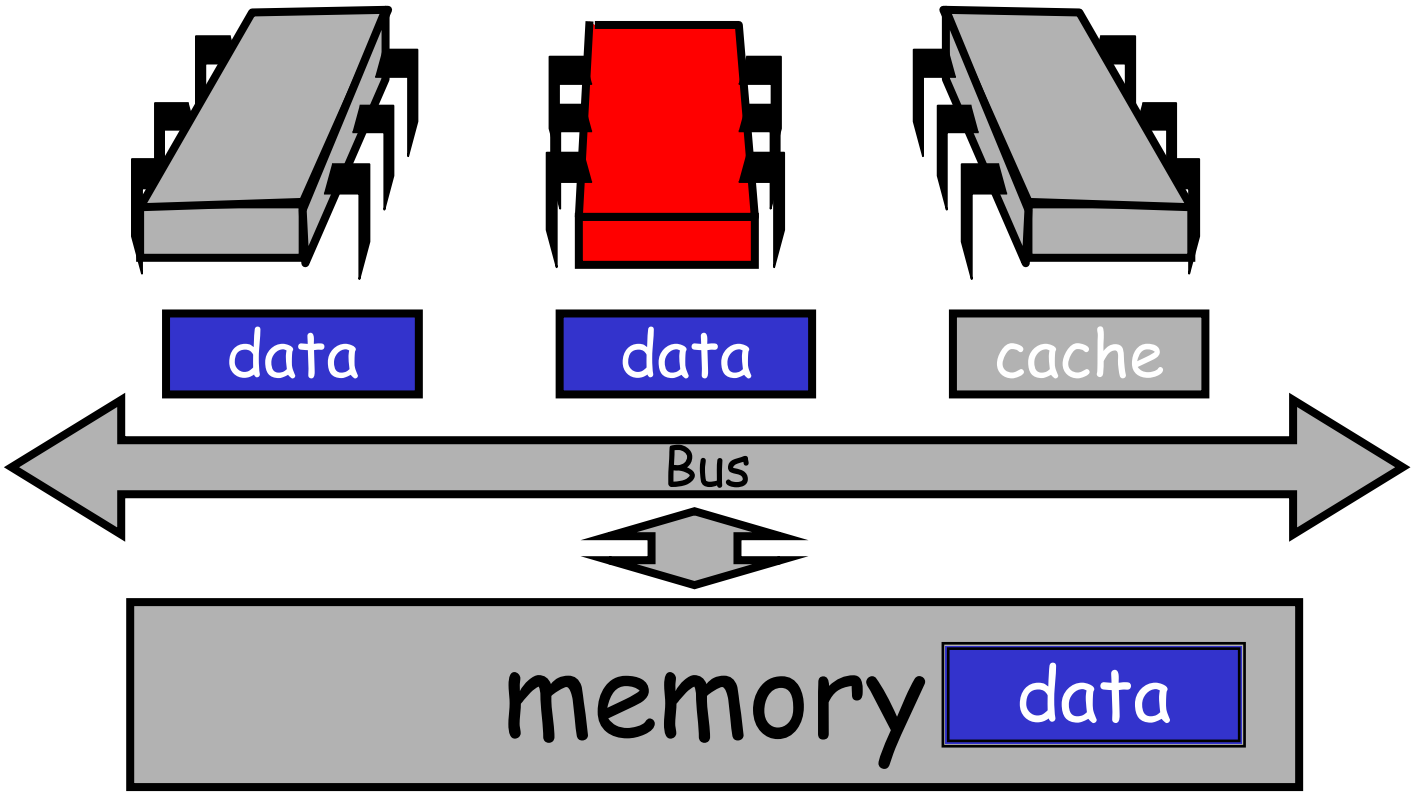
Other Processor Responds



Other Processor Responds



Modify Cached Data



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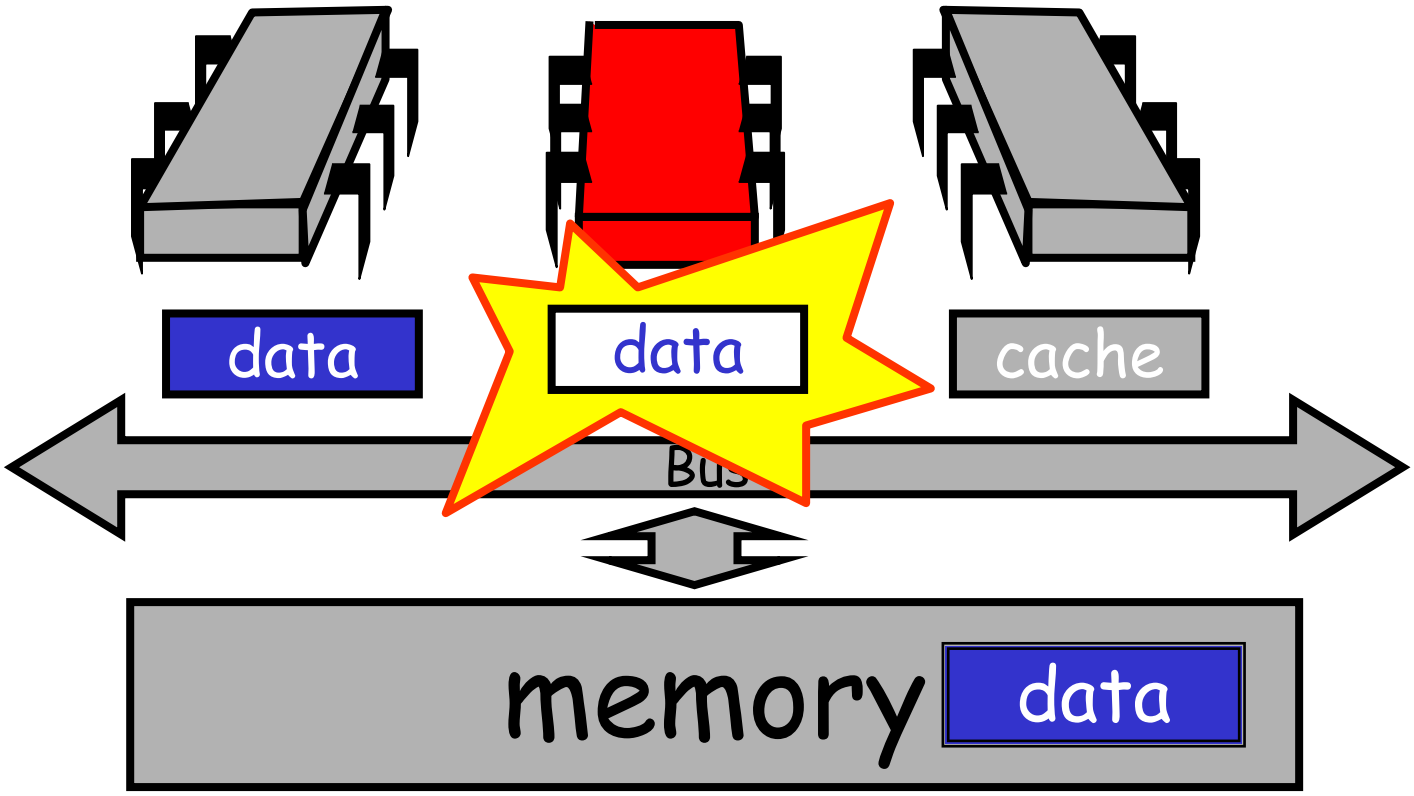
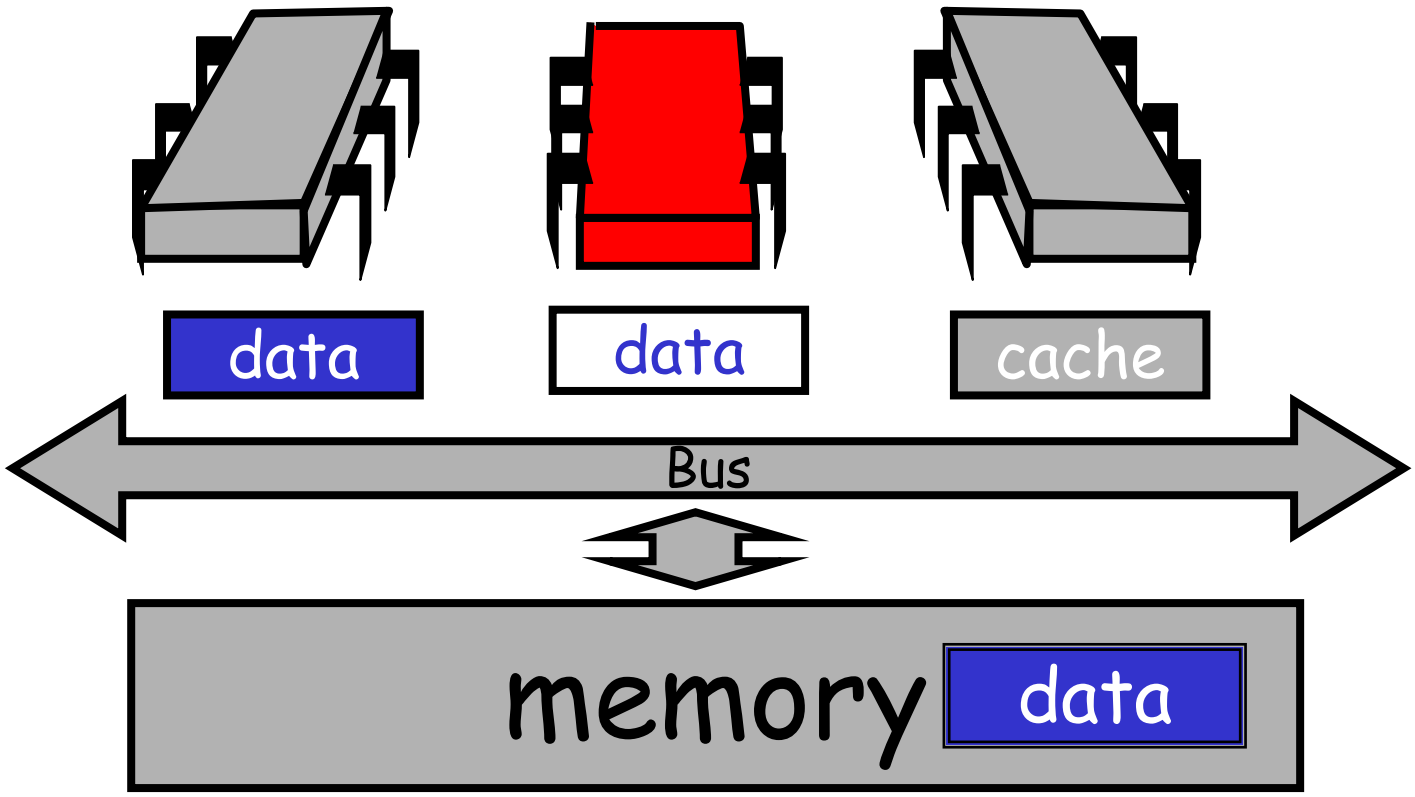
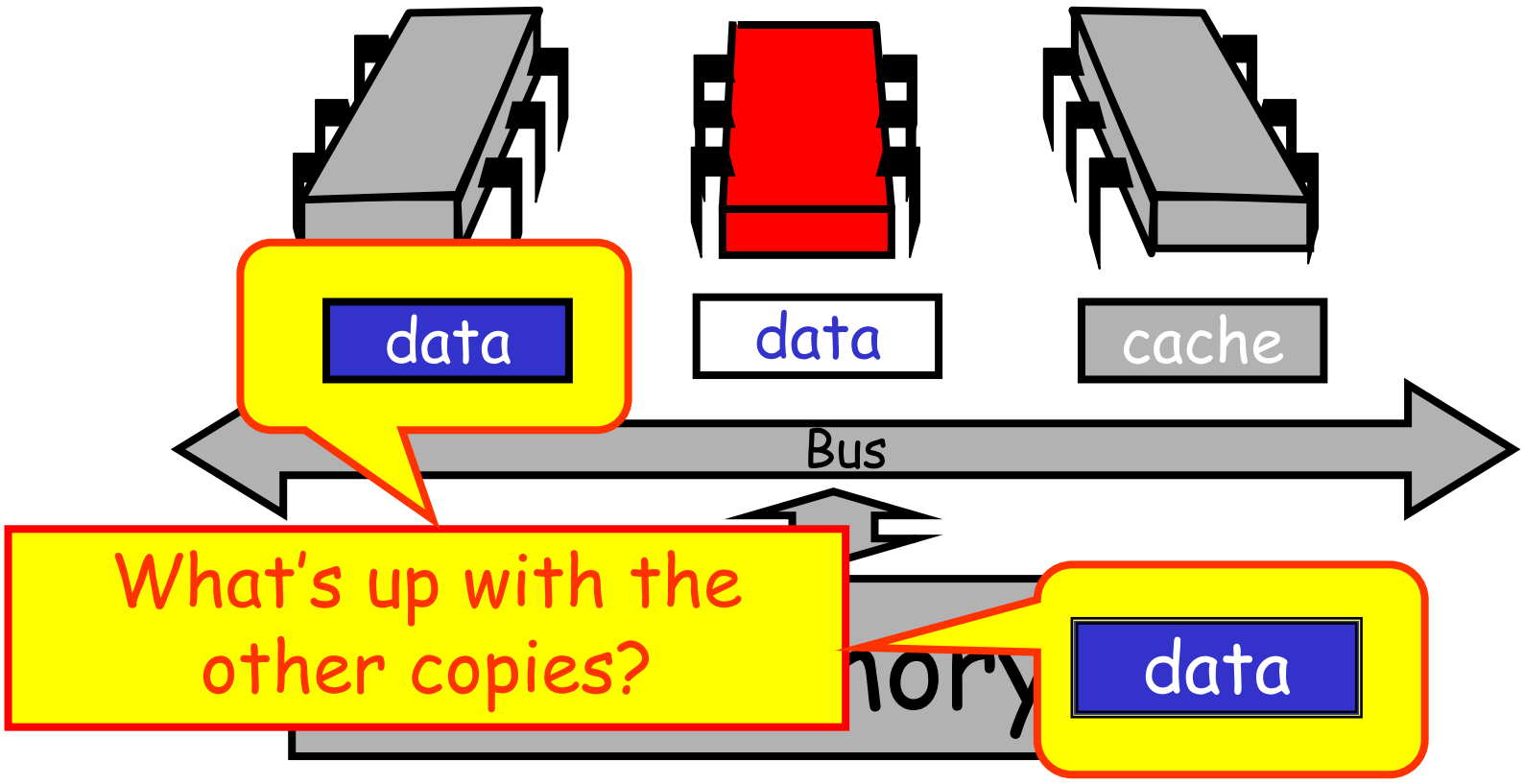


Modify Cached Data



Modify Cached Data



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?

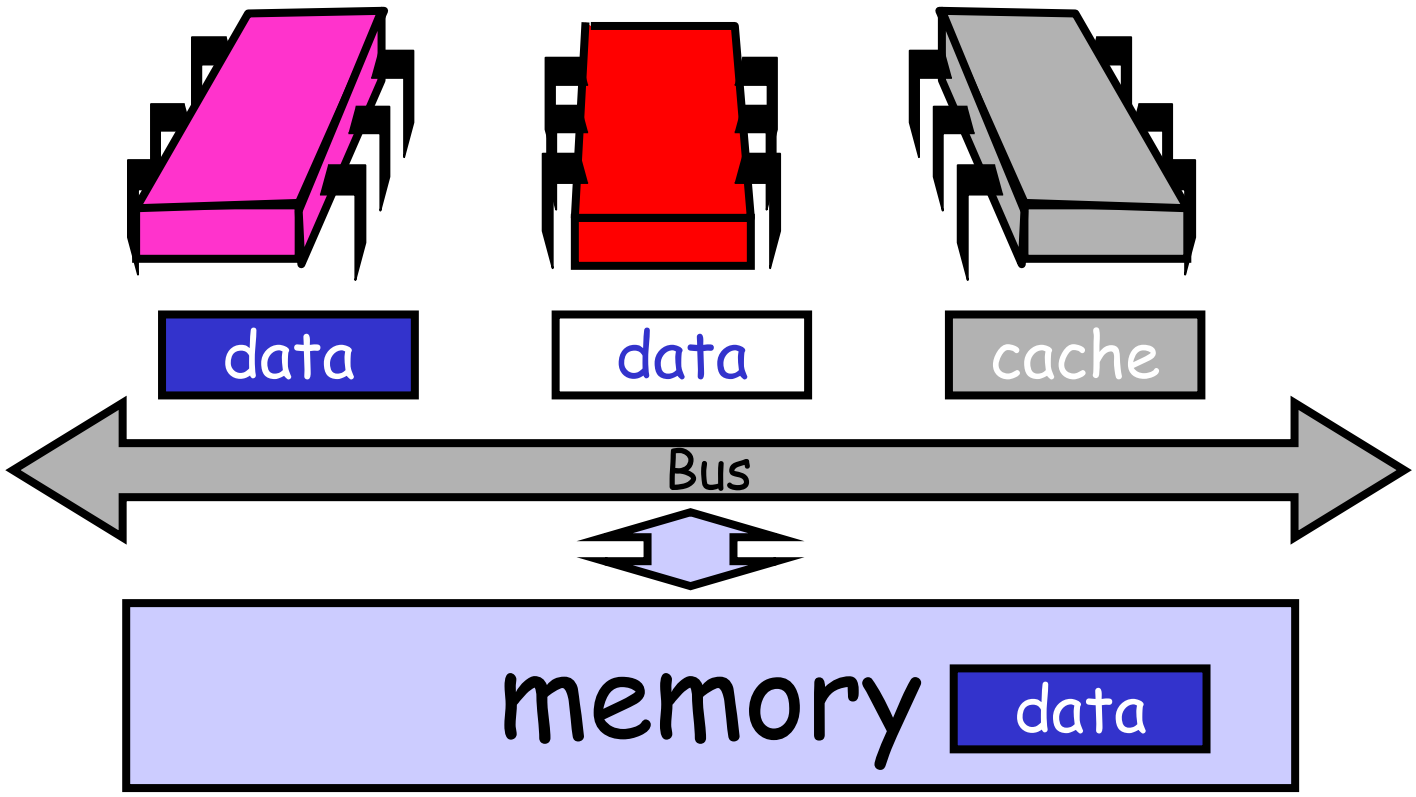
Write-Back Cache Coherence Protocol

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

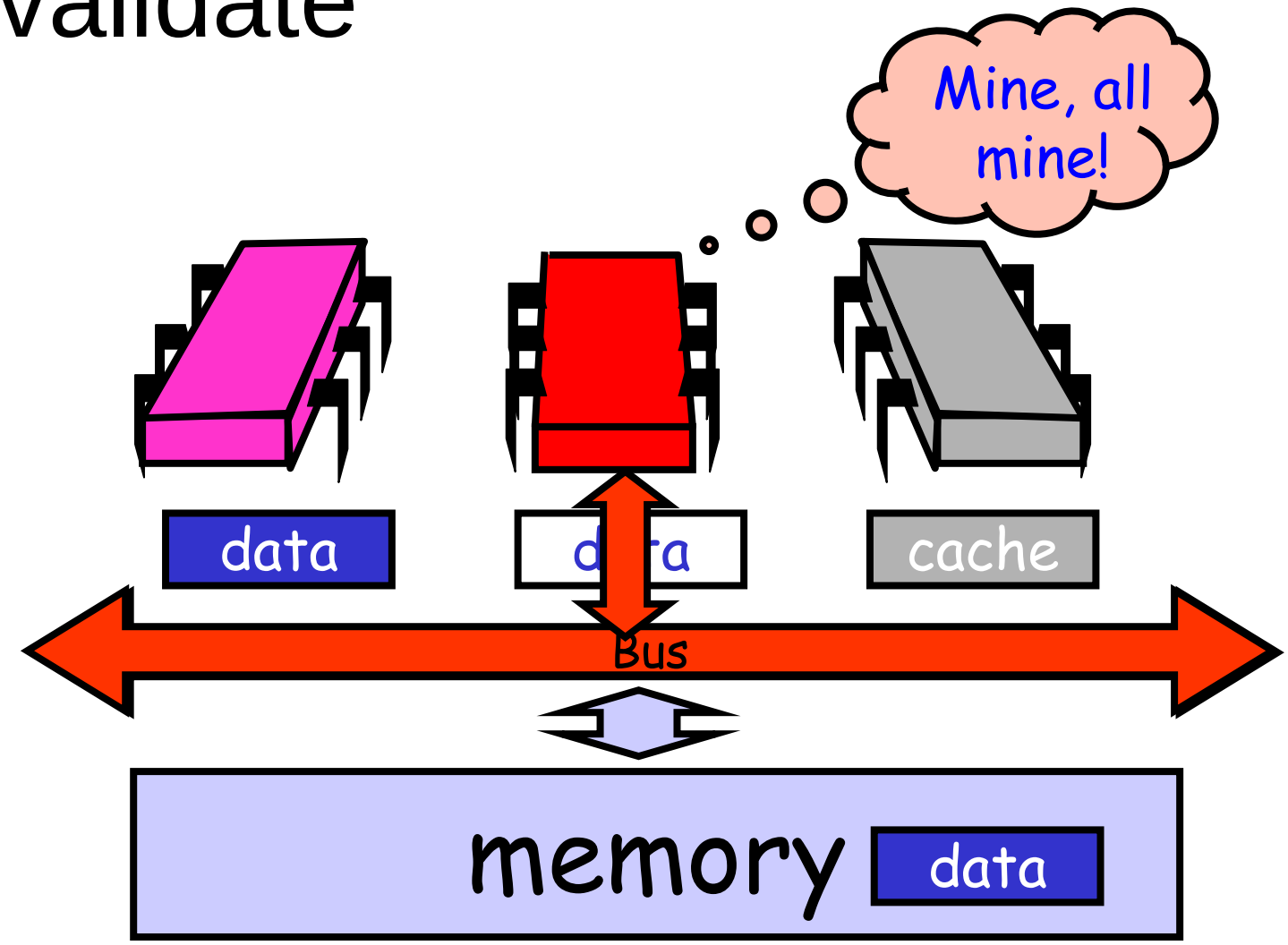
Write-Back Caches

- Cache entry has three states
  - Invalid: contains raw seething bits (meaningless)
  - Valid: I can read but I can't write because it may be cached elsewhere
  - Dirty: Data has been modified
    - Intercept other load requests
    - Write back to memory before using cache

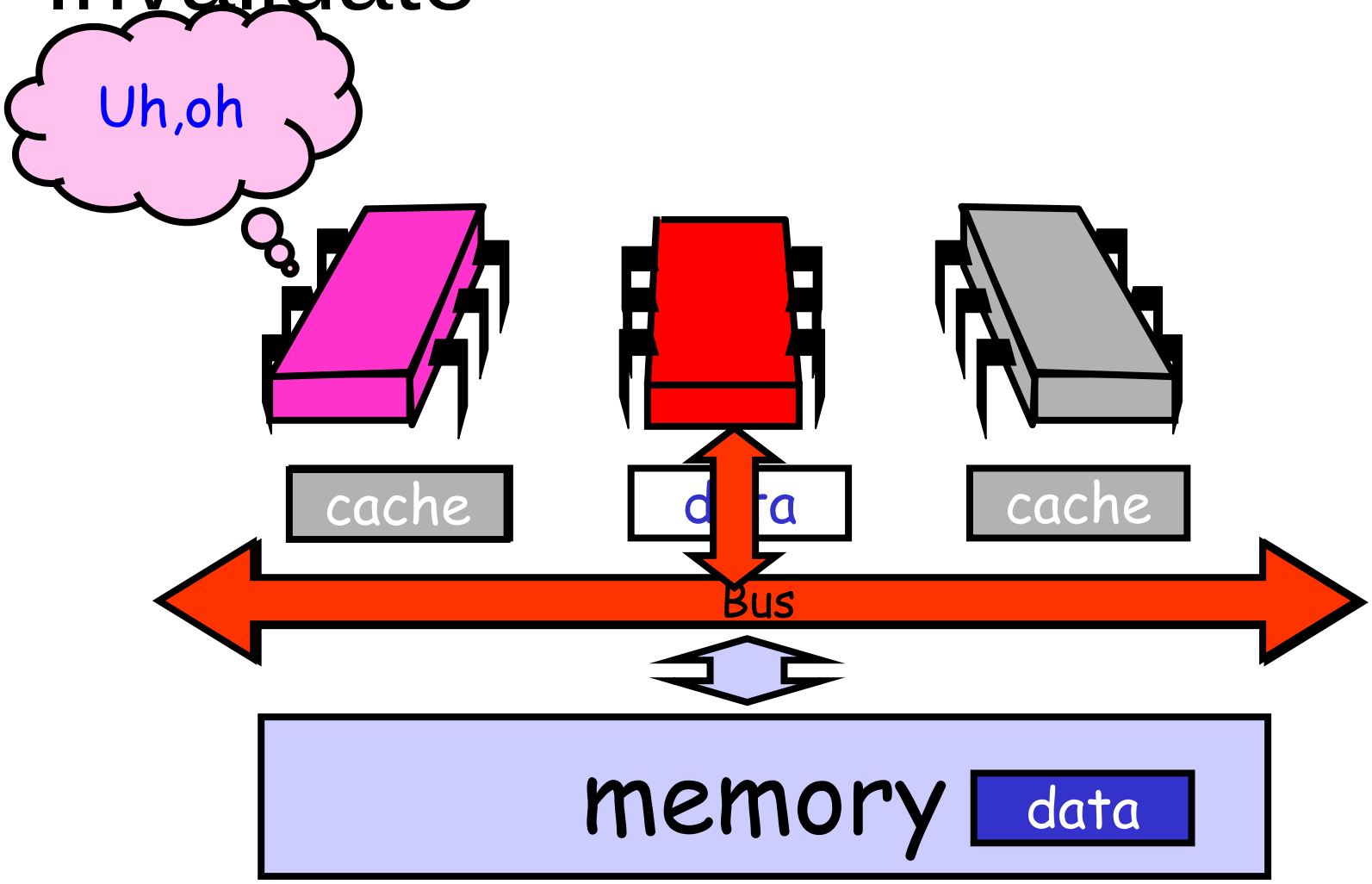
Invalidate



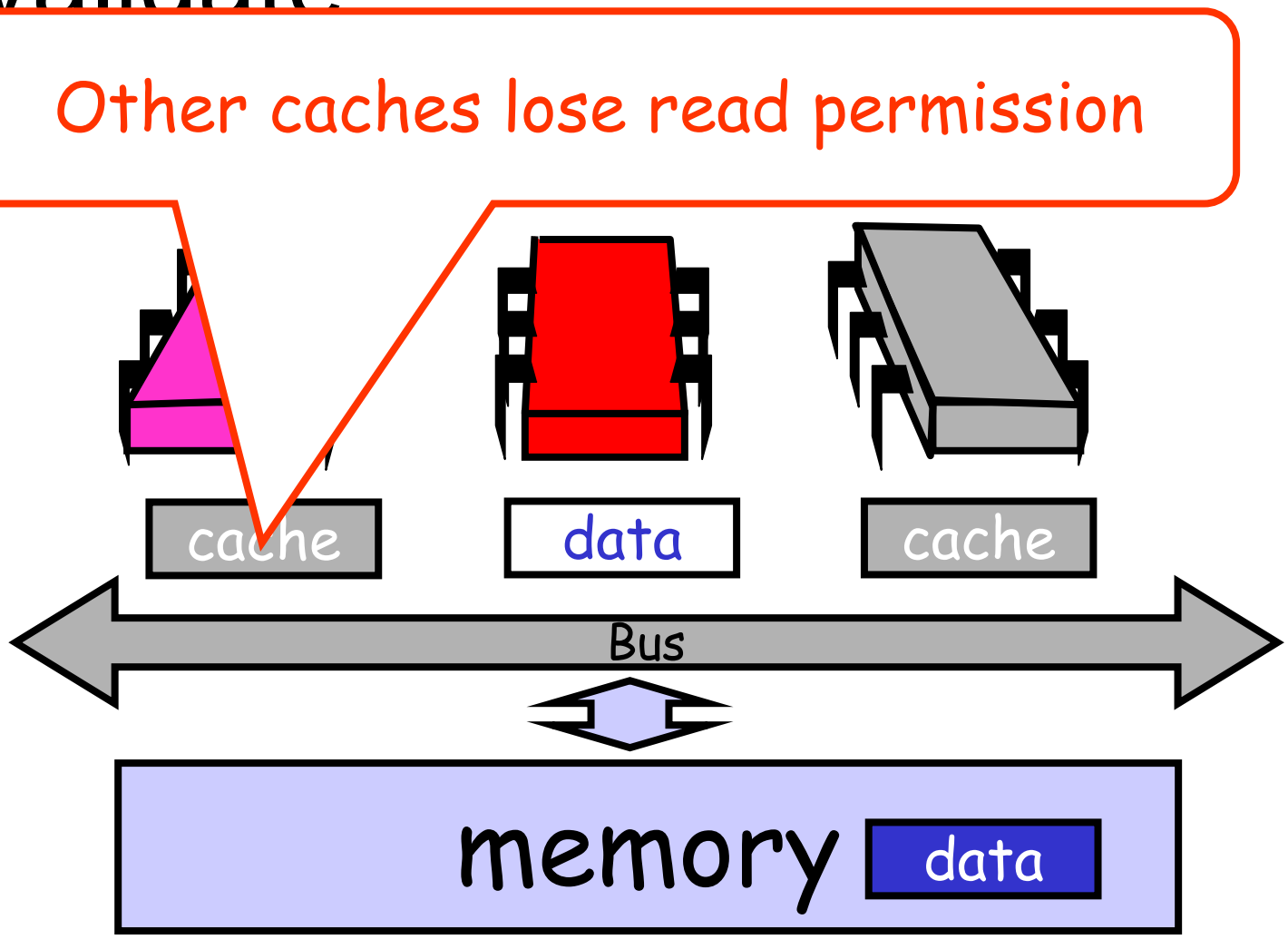
Invalidate



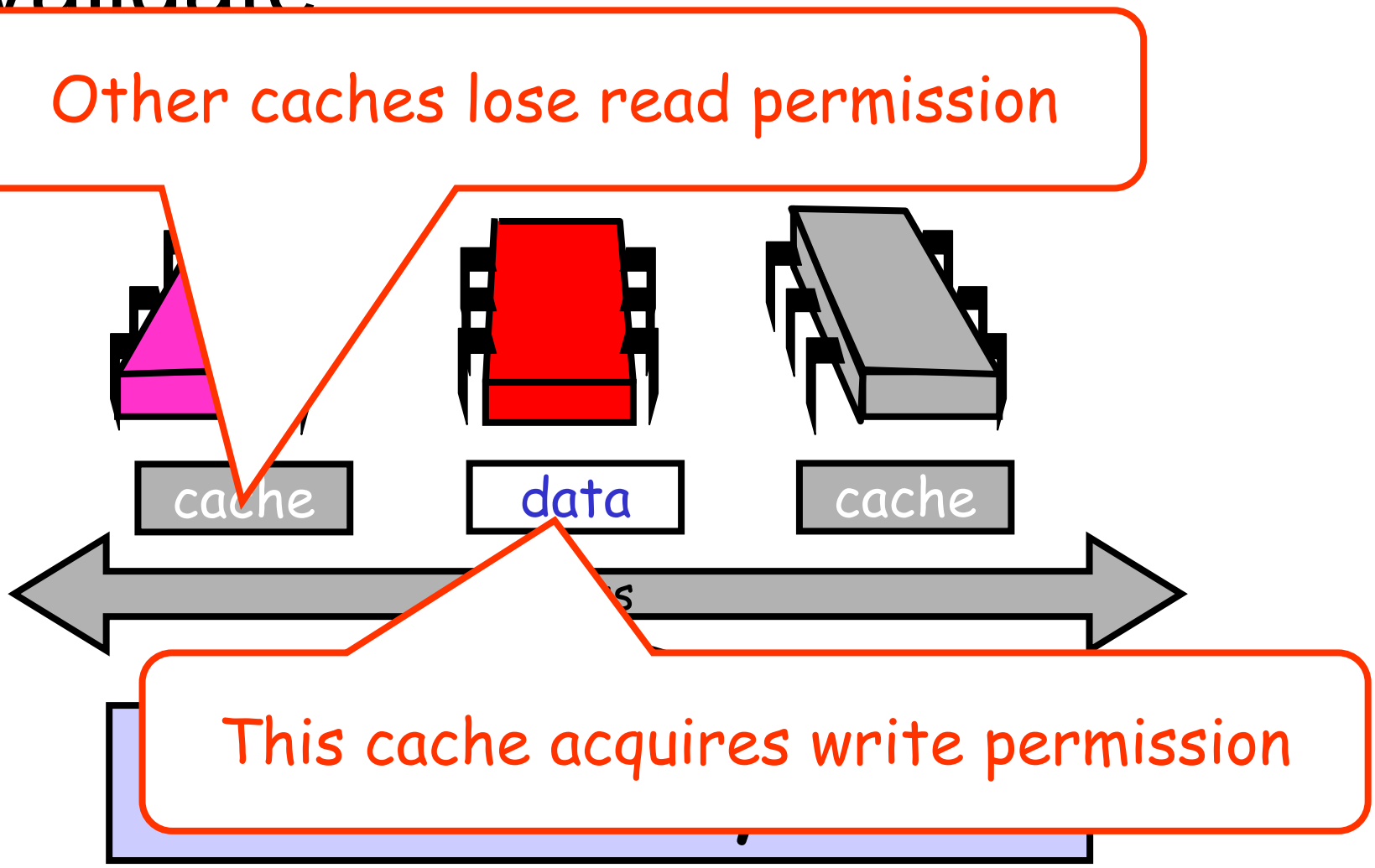
Invalidate



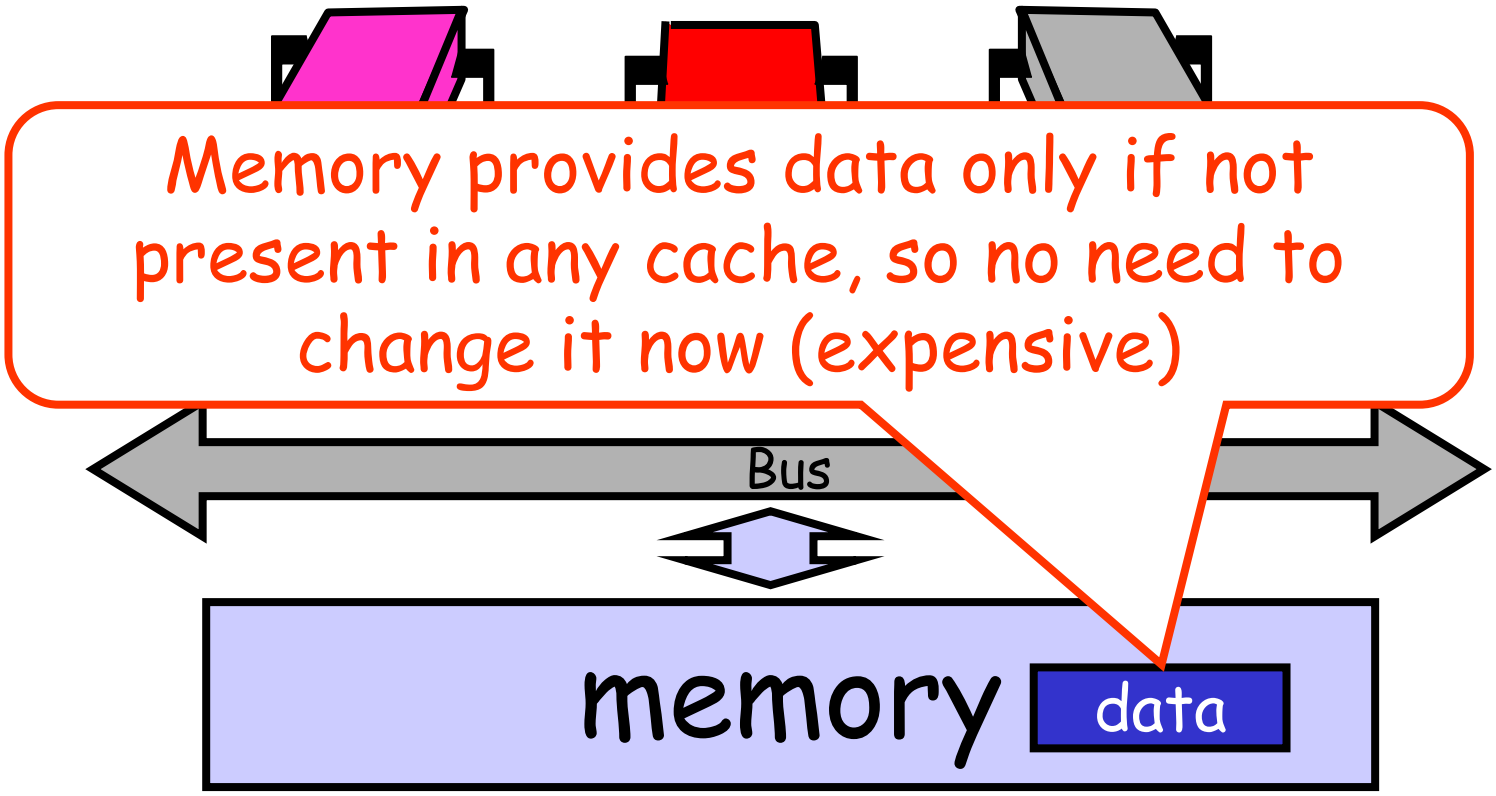
Invalidate


Other caches lose read permission
cache
data
cache
Bus
memory
data

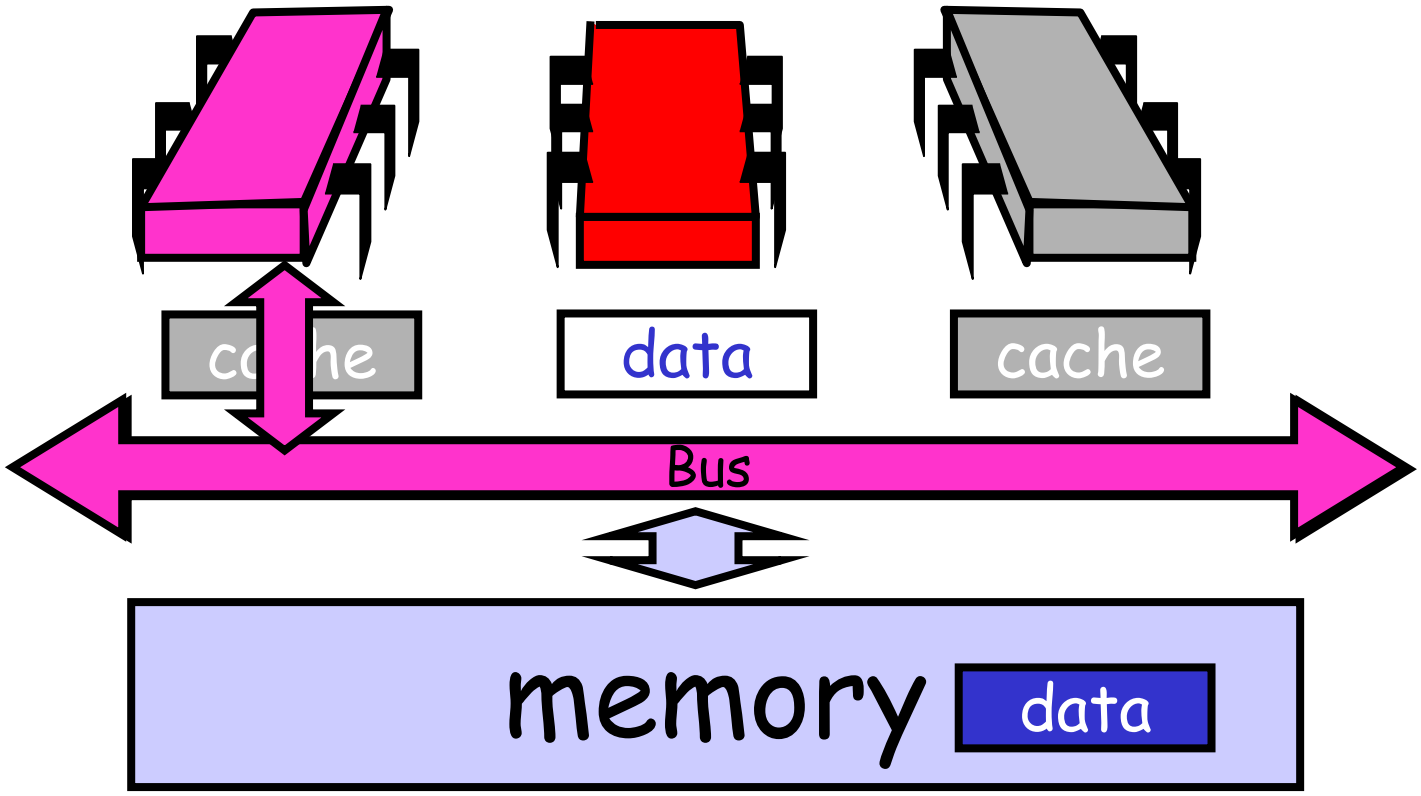
Invalidate


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

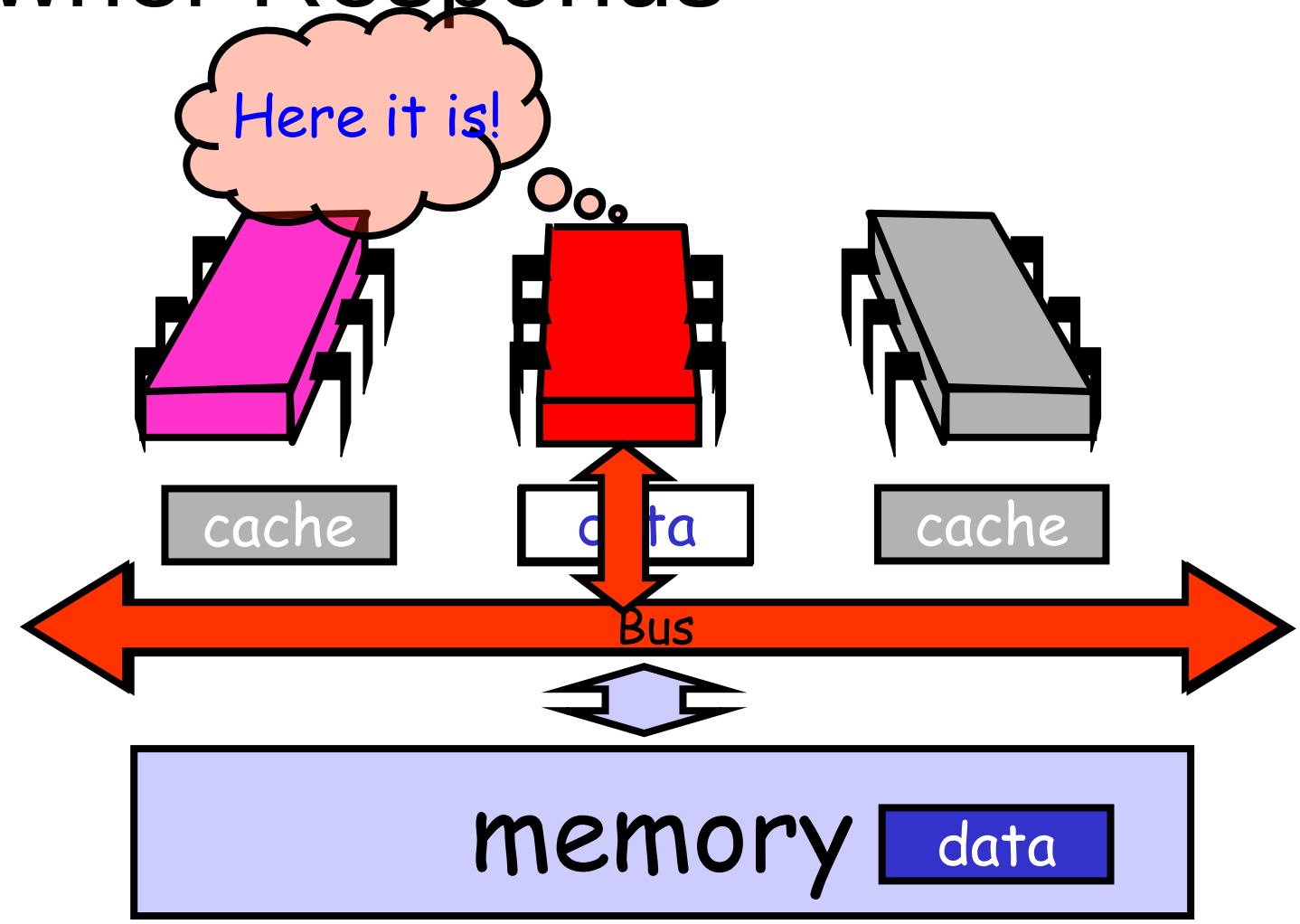
Invalidate


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

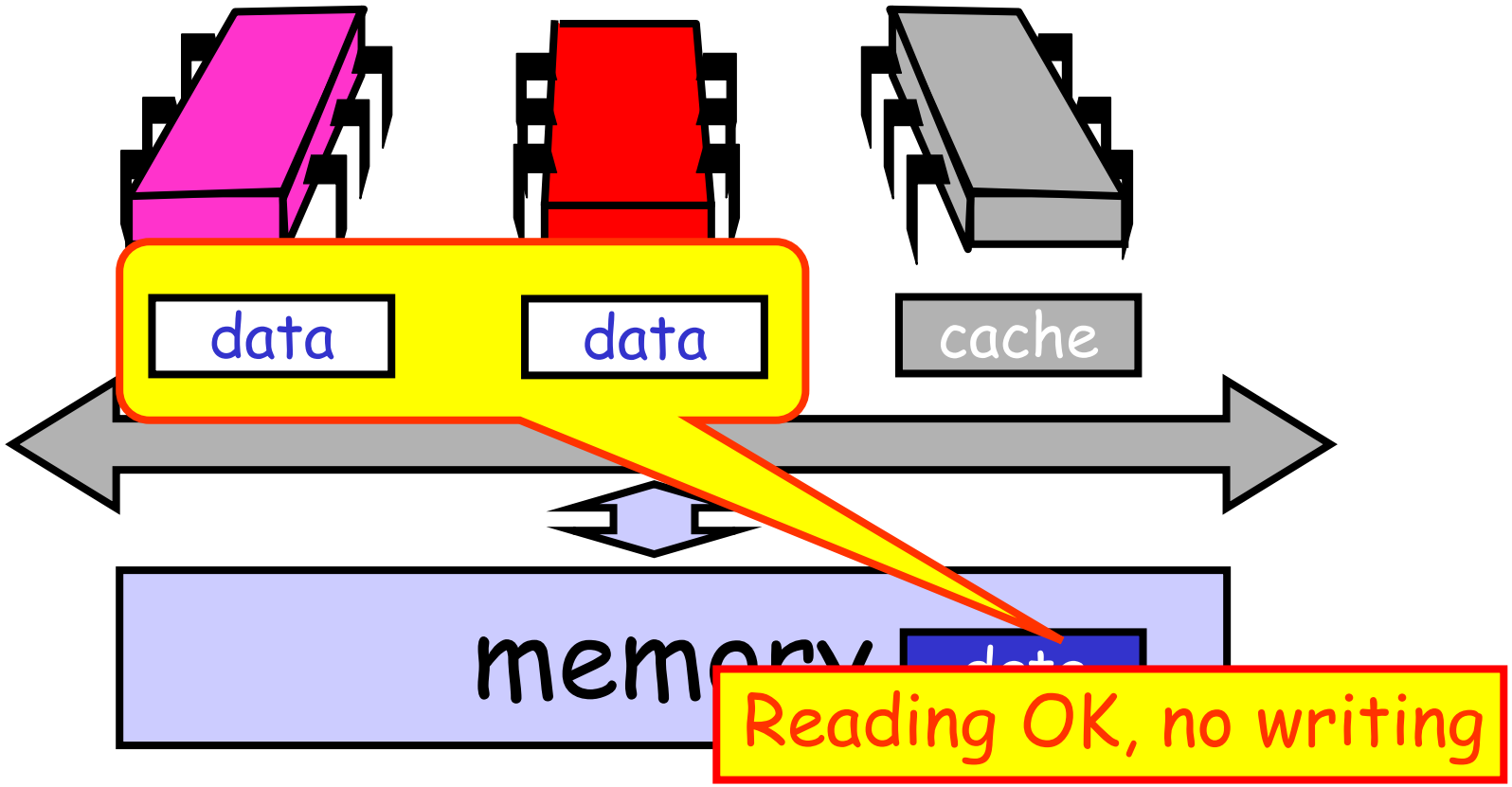
Another Processor Asks for Data



Owner Responds



End of the Day …



Test-and-set Lock

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

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

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

Has to change to current value while spinning

Back to TASLocks

- How does a TASLock perform on a write-back shared-bus architecture?
  - Because it uses the bus, each getAndSet() call delays all the other threads
    - Even those not waiting for the lock
  - The getAndSet() call forces the other processors to discard their own cached copies – resulting in a cache miss every time
  - They must then use the bus to fetch the new, but unchanged value

TASLock

- When the thread wants to release the lock it may be delayed because the bus is being monopolized by the spinners

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()) {}
   if (!state.getAndSet(true))
    return;
  }
}
```

Wait until lock looks free

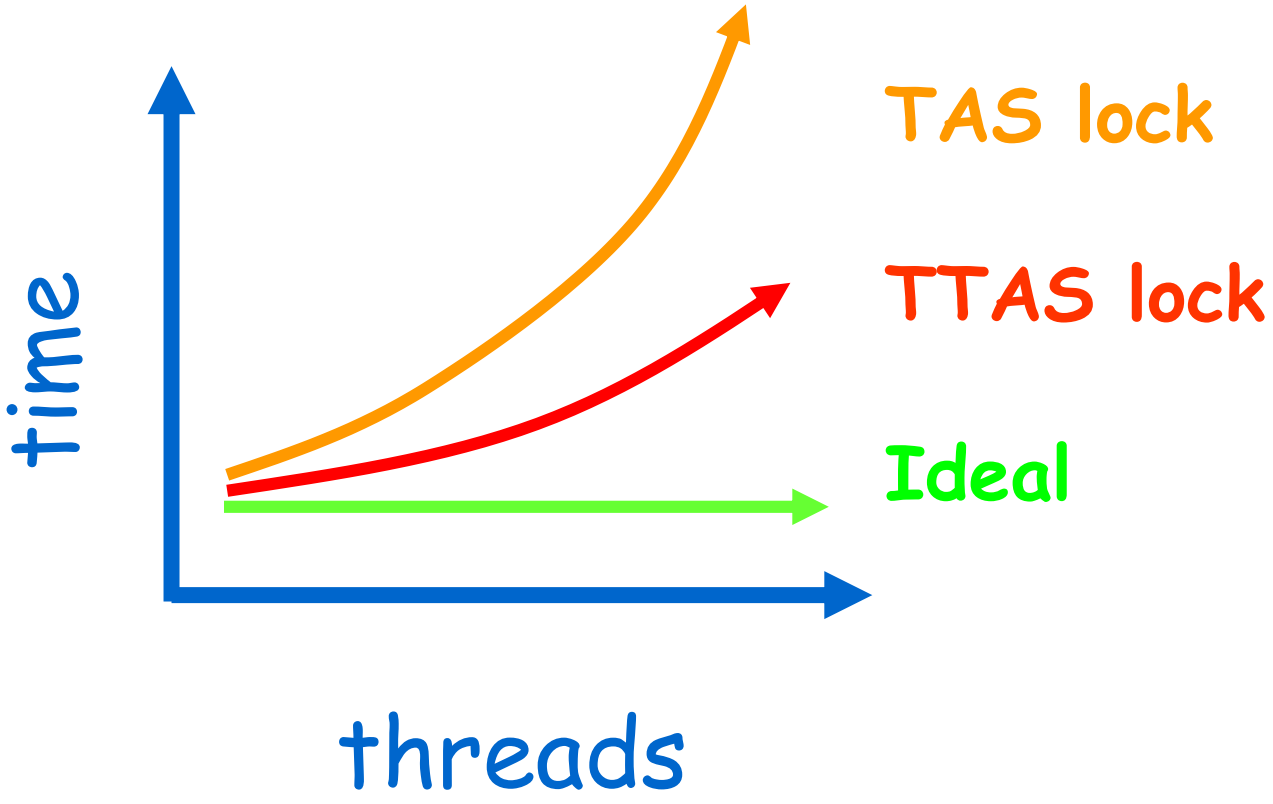
Test-and-test-and-set Lock

```
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



What about the TTASLock?

- Suppose thread A acquires the lock.
- The first time thread B reads the lock it takes a cache miss and has to use the bus to fetch the new value
- As long as A holds the lock however, B repeatedly rereads the value – resulting in a cache hit every time
- B thus produces no extra traffic

What about the TTASLock?

- However when A releases the lock:
  - A writes false to the lock variable
  - The spinner's cached copies are invalidated
  - Each one takes a cache miss
  - They all use the bus to read a new value
  - They all call getAndSet() to acquire the lock
  - The first one to acquire the lock invalidates the others who must then reread the value
  - Storm of traffic

Local spinning

- Threads repeatedly reread cached values instead of repeatedly using the bus

Exponential Backoff

- Recall that in the TTASLock, the thread first reads the lock and if it appears to be free it attempts to acquire the lock
- “If I see that the lock is free, but then another thread acquires it before I can, then there must be high contention for that lock”
- Better to back off and try again later

For how long should a thread back off?

- Rule of thumb:
  - The larger number of unsuccessful tries, the higher the contention, the longer the thread should back off.
- Approach:
  - Whenever the thread sees the lock has become free, but fails to acquire it, it backs of before retrying

What about lock-step?

- What happens if all the threads backs off the same amount of time?
- Instead the threads should back off for a random amount of time
- Each time the thread tries and fails to get the lock, it doubles the back-off time, up to a fixed maximum.

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 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;
 }}}
```

Otherwise back off for random duration

Exponential Backoff Lock

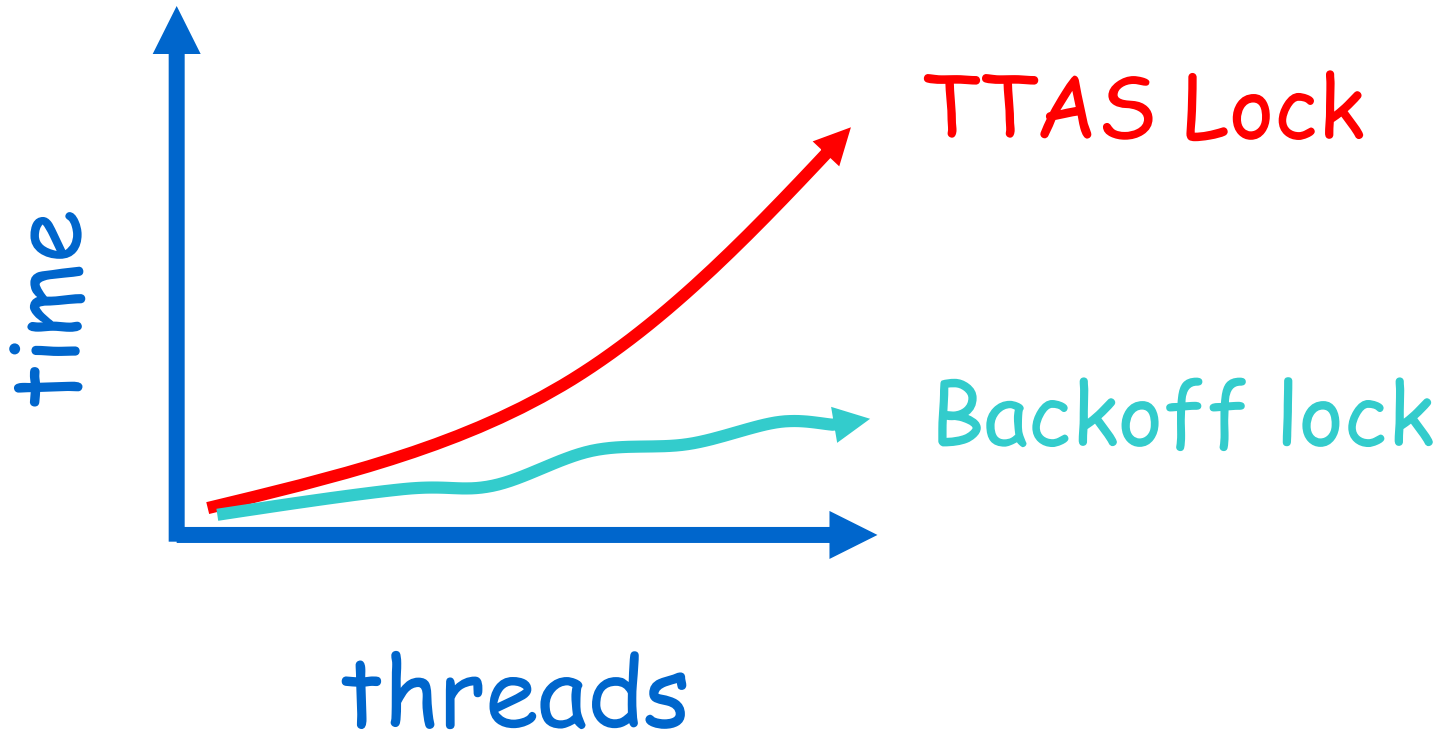
```
public class Backoff implements lock {
 public void lock() {
  int delay = MIN_DELAY;
  while (true) {
   while (state.get()) {}
   if (!lock.getAndSet(true))
    return;
   sleep(random() % delay);
   if (delay < MAX_DELAY)
    delay = 2 * delay;
 }}}
```

Double max delay, within reason

Exponential Backoff Lock

- Important to note that a thread backs off only when it fails to acquire a lock that was just available, but is not available anymore
- Observing that a lock is held by another thread does not imply backoff

Spin-Waiting Overhead



Backoff: Other Issues

- Good
  - Easy to implement
  - Beats TTAS lock
- Bad
  - Must choose parameters carefully
    - Sensitive to choice of minimum and maximum delays
  - Sensitive to number of processors and their speed
    - Cannot have a general solution for all platforms and machines

BackoffLock drawbacks

- Cache-coherence Traffic:
  - All threads spin on the same location
- Critical Section Underutilization:
  - Threads delay longer than necessary

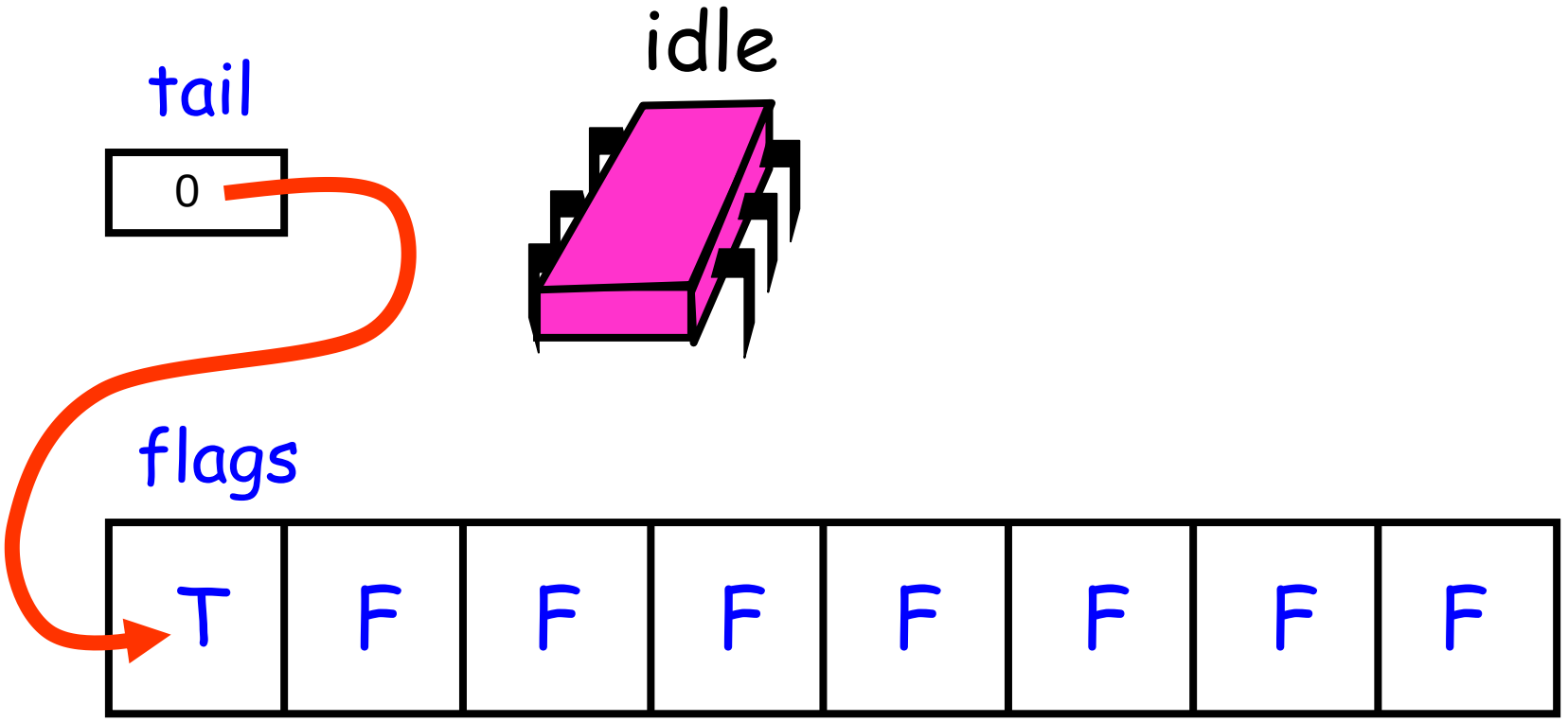
Idea

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

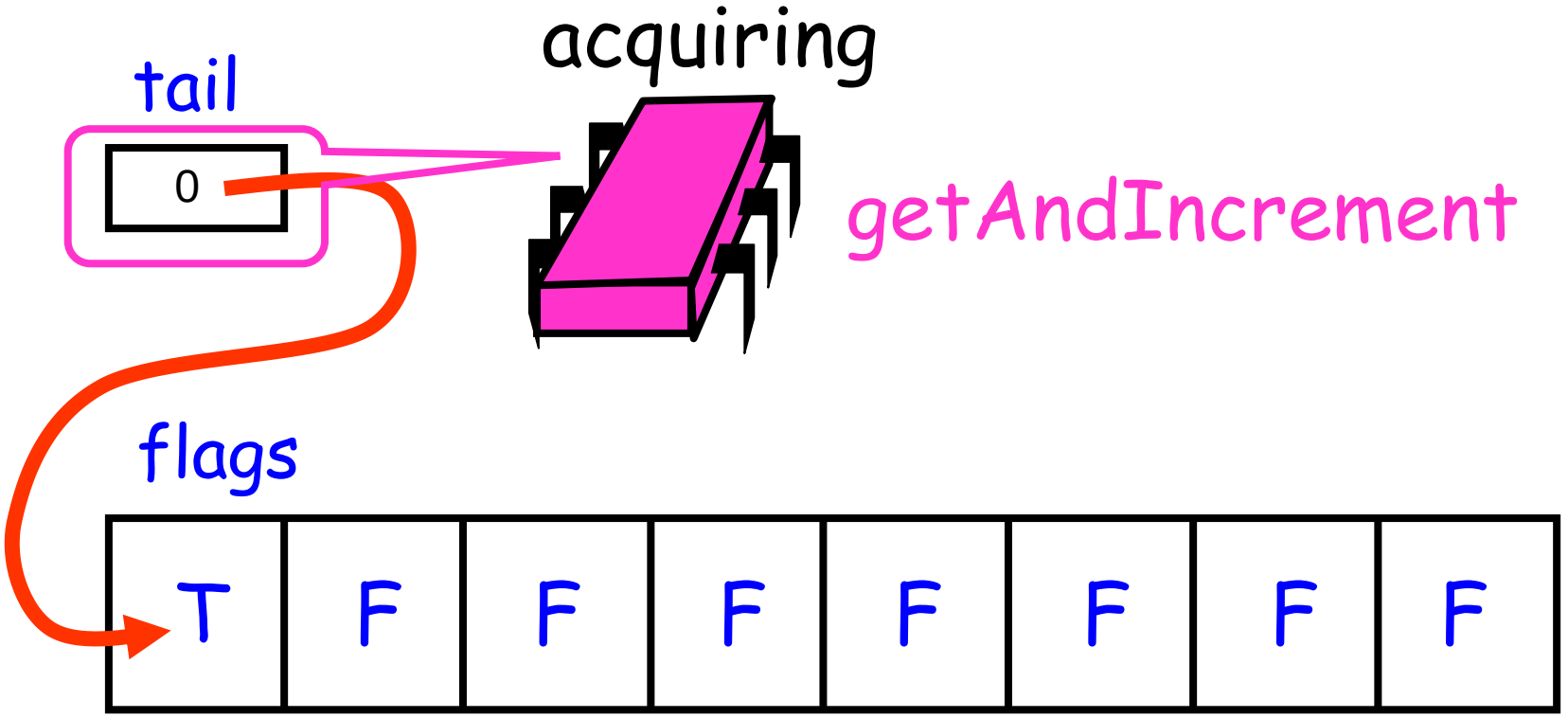
Queue Locks

- Cache-coherence traffic is reduced since each thread spins on a different location
- No need to guess when to attempt to access lock – increase critical section utilization
- First-come-first-served fairness

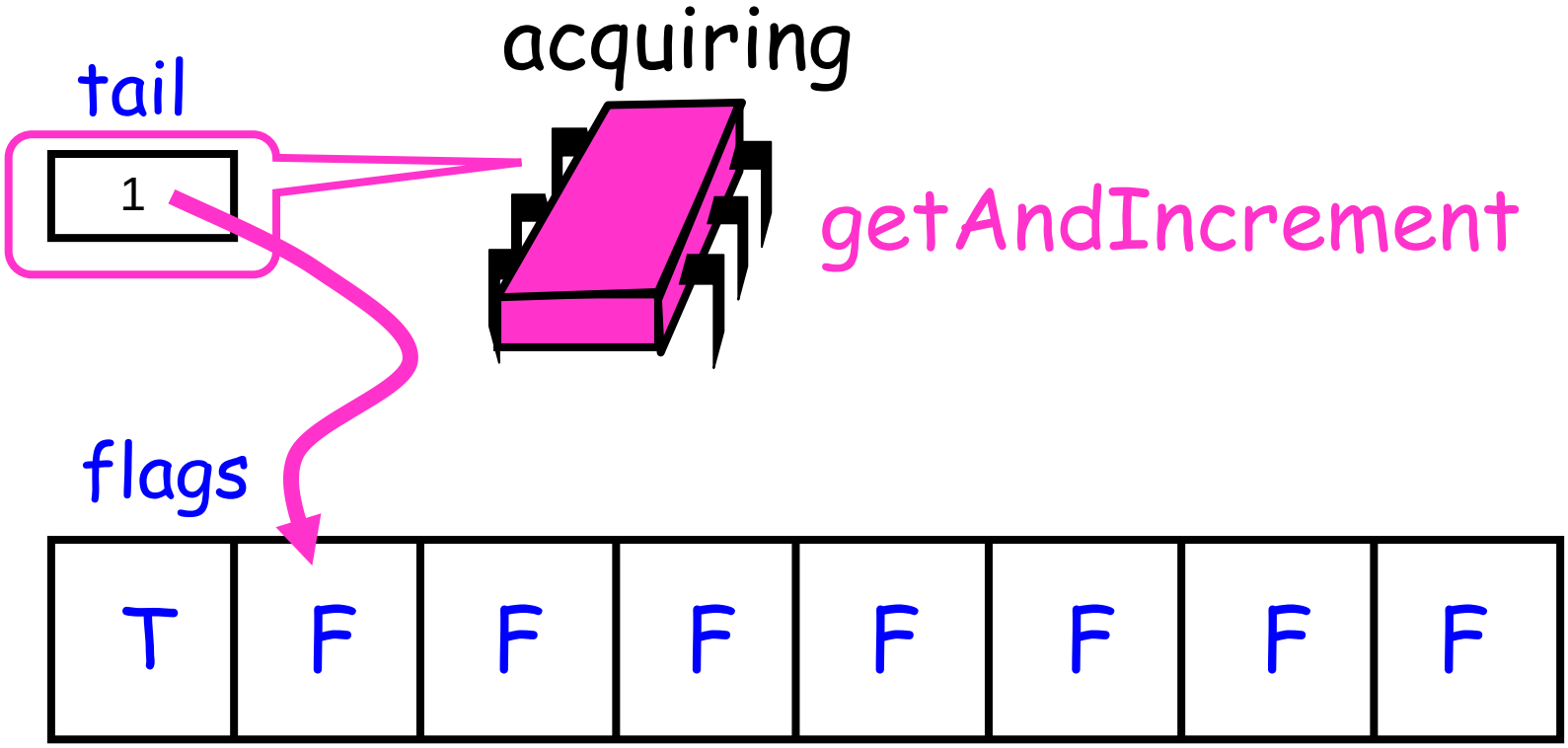
Anderson Queue Lock



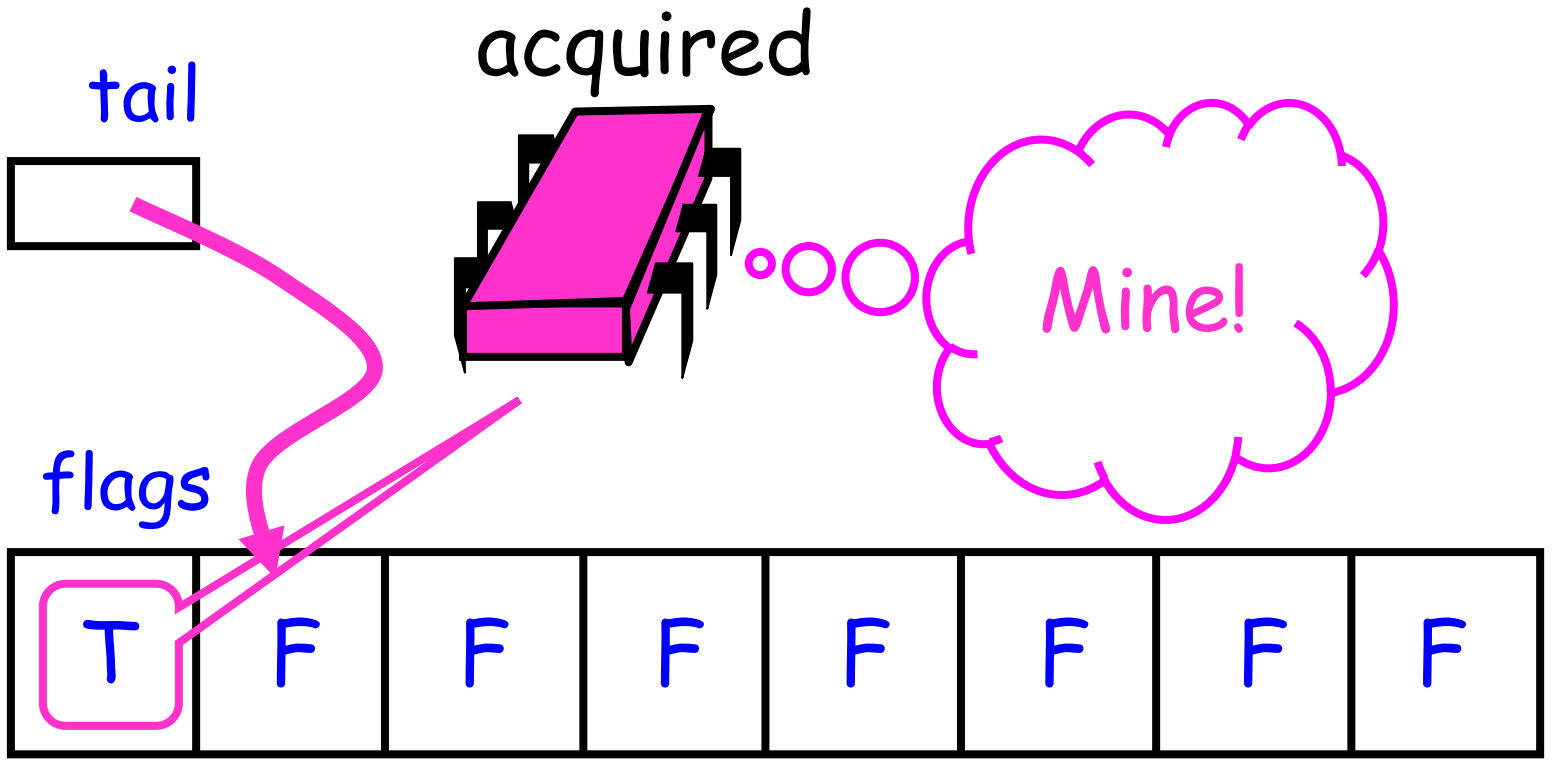
Anderson Queue Lock



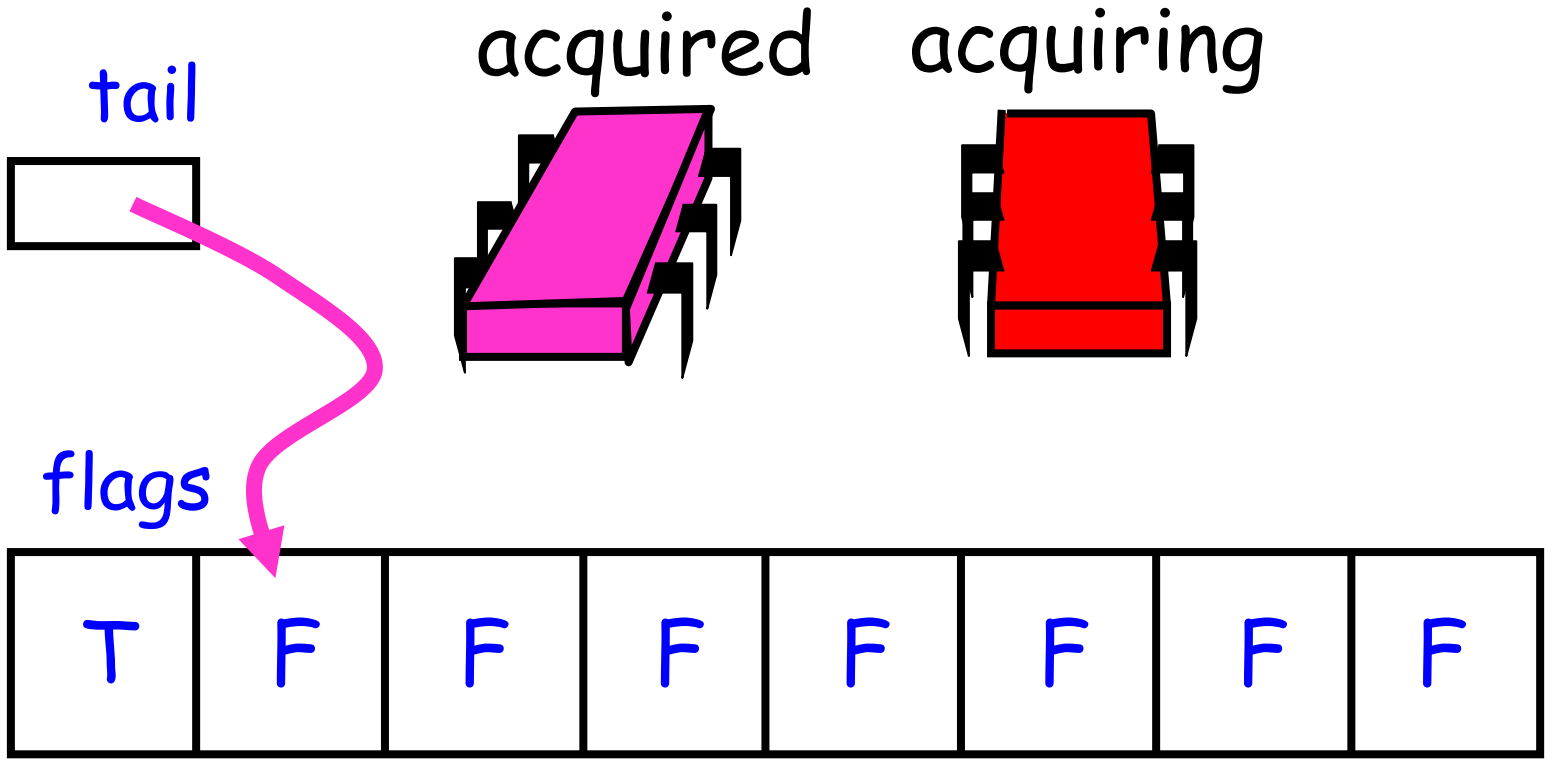
Anderson Queue Lock



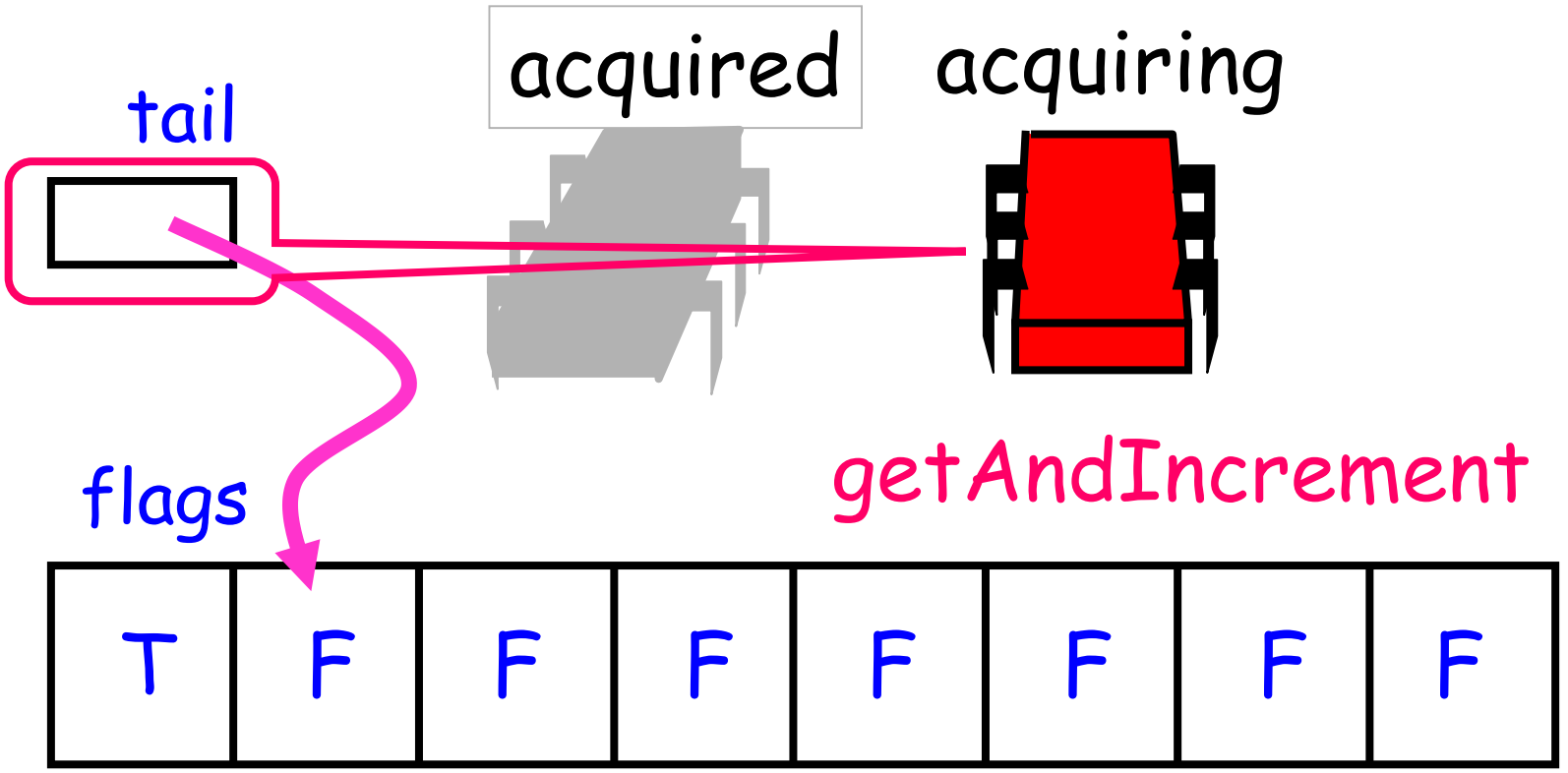
Anderson Queue Lock



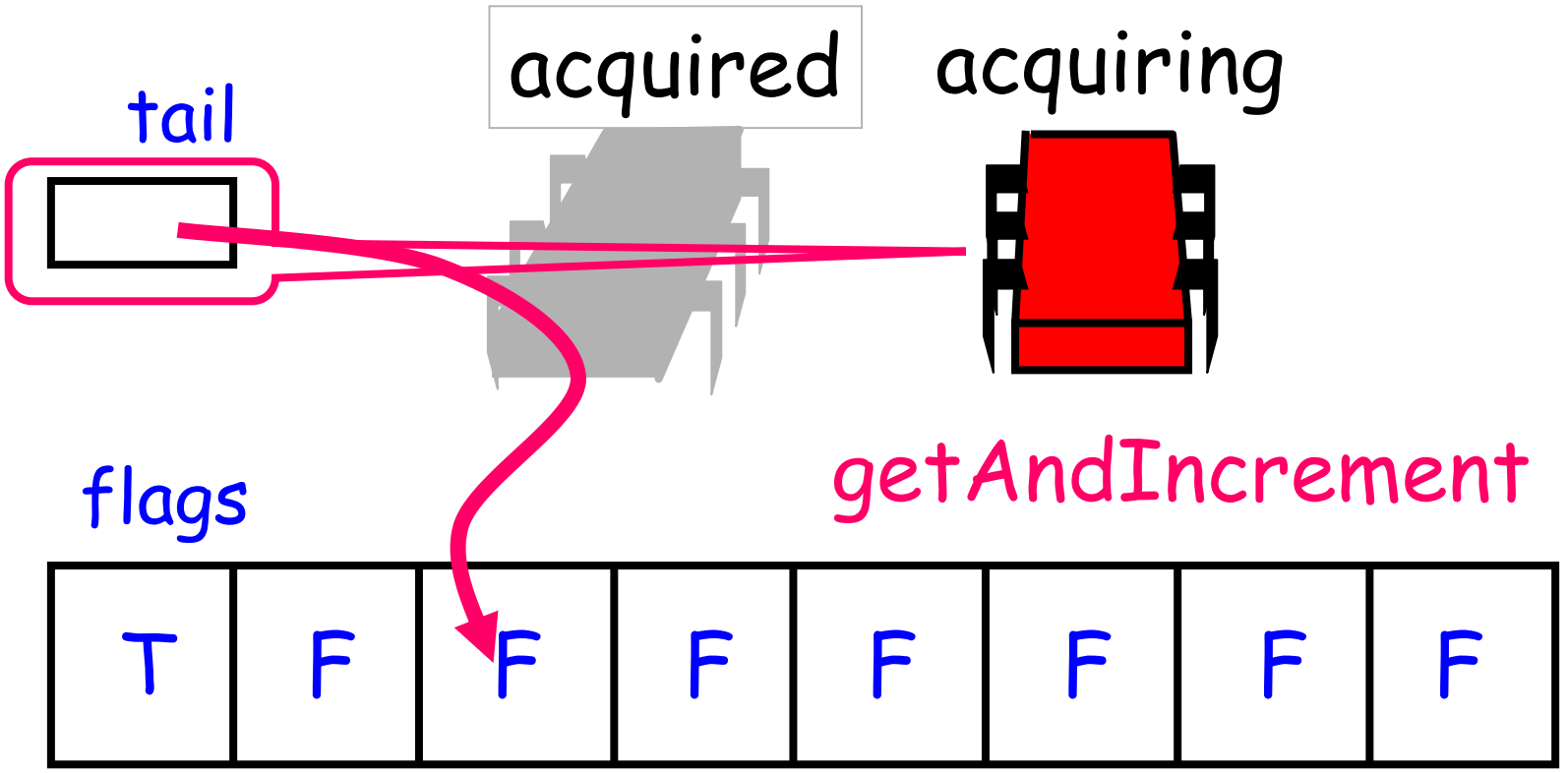
Anderson Queue Lock



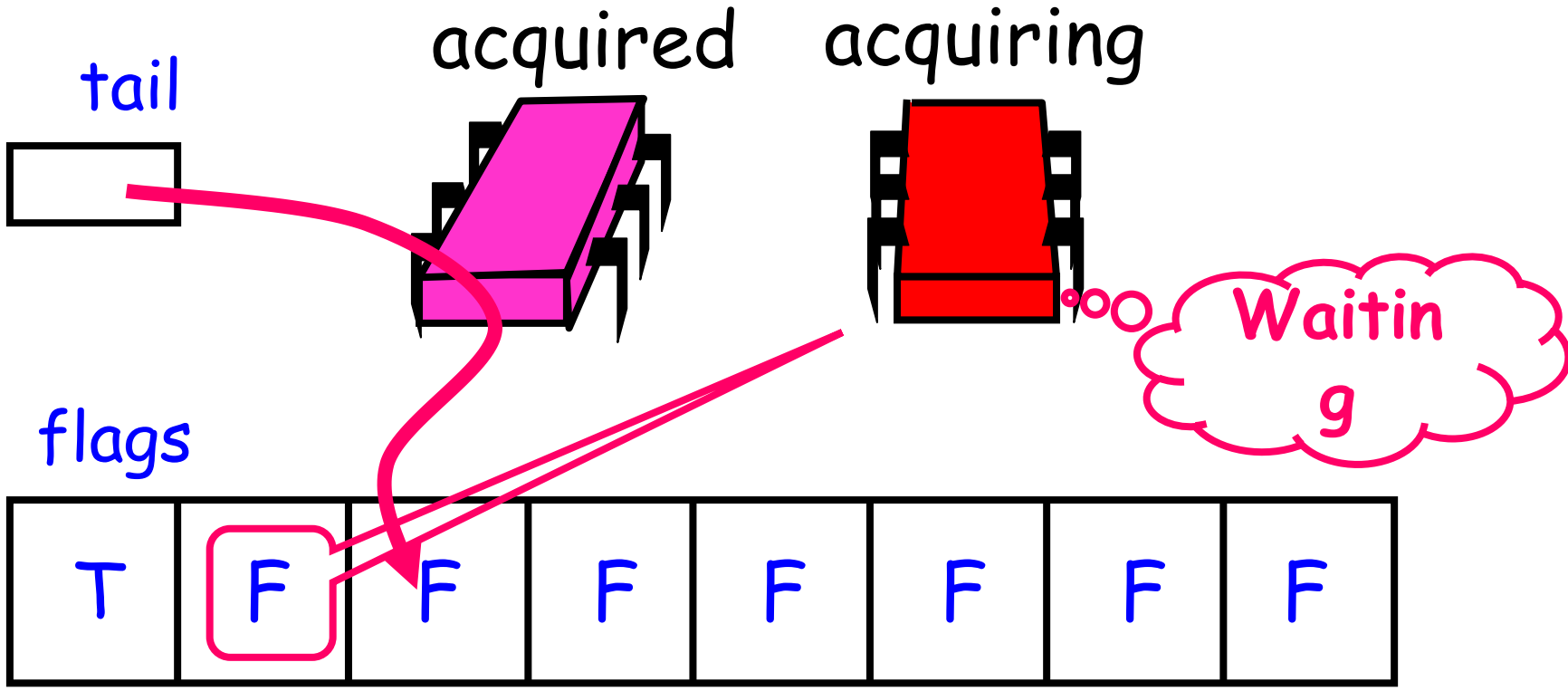
Anderson Queue Lock



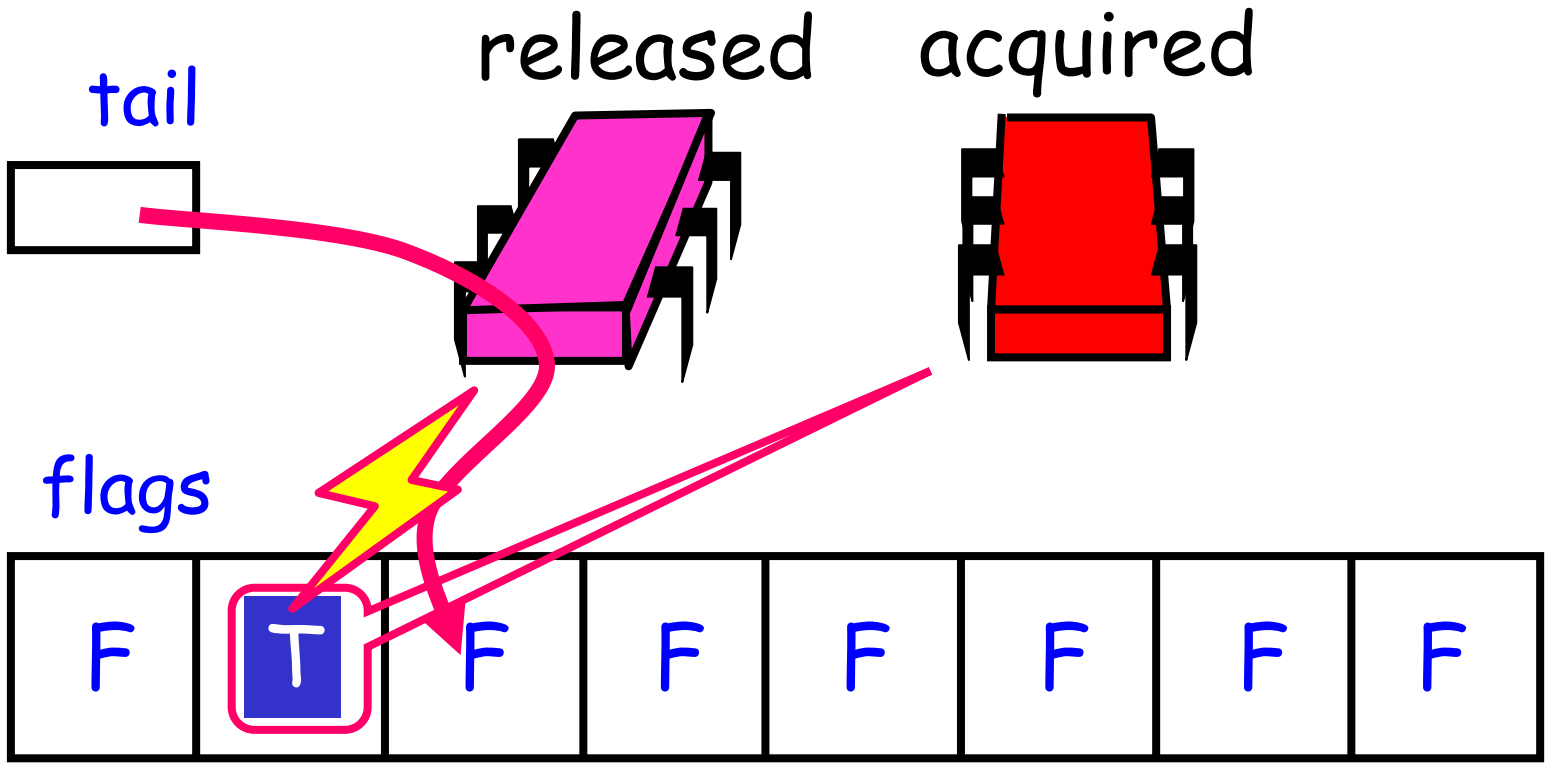
Anderson Queue Lock



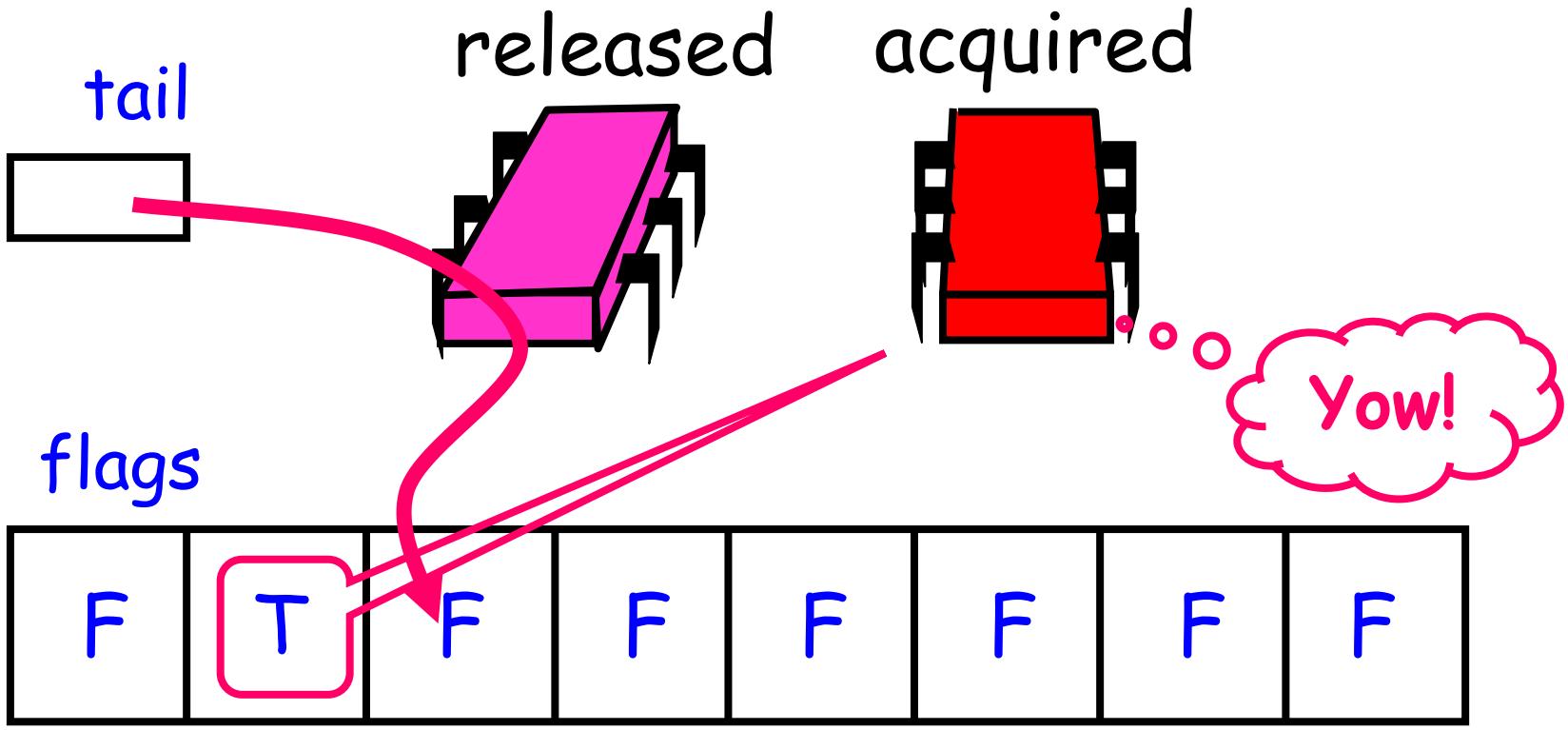
Anderson Queue Lock



Anderson Queue Lock



Anderson Queue Lock



Anderson Queue Lock

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

Anderson Queue Lock

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

One flag per thread

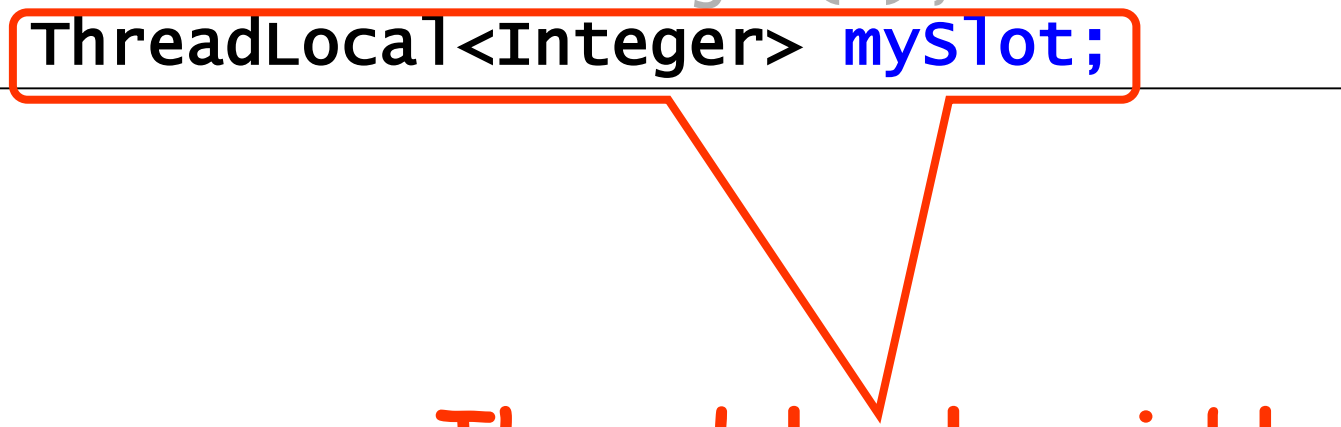
Anderson Queue Lock

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

Next flag to use

Anderson Queue Lock

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



Anderson Queue Lock

```
public lock() {
 mySlot = tail.getAndIncrement();
 while (!flags[mySlot]) {};
}

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

Anderson Queue Lock

```
public lock() {
 mySlot = tail.getAndIncrement();
 while (!flags[mySlot]) {};
}

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

Take next slot

Anderson Queue Lock

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

public unlock() {
 flags[mySlot] = false:
 flags[(mySlot+
}
```

Spin until told to go

Anderson Queue Lock

```
public lock() {
 myslot = next.getAndIncrement();
 while (!flags[myslot]) {};
}

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

Prepare slot for re-use

Anderson Queue Lock

```
public lock() {
 mySlot = ne
 while (!flags[mySlot]) {};
}

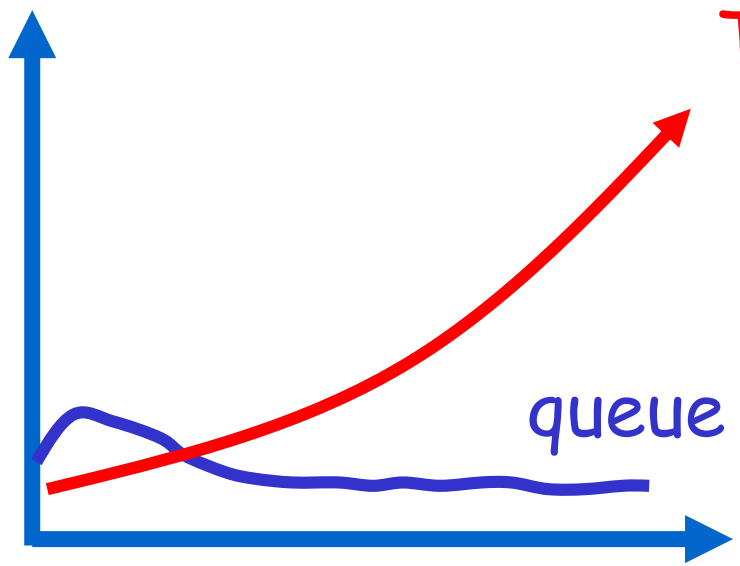
public unlock() {
 flags[mySlot] = false;
 flags[(mySlot+1)] = true;
}
```

Tell next thread to go

Anderson Queue Lock

- Although the flags [] array is shared, contention on the array locations are minimised since each thread spins on its own locally cached copy of a single array location

Performance



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

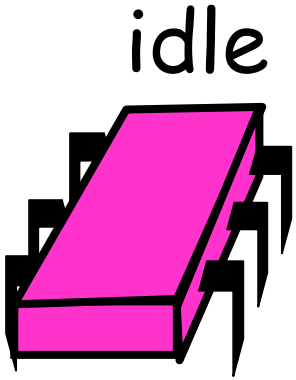
Anderson Queue Lock

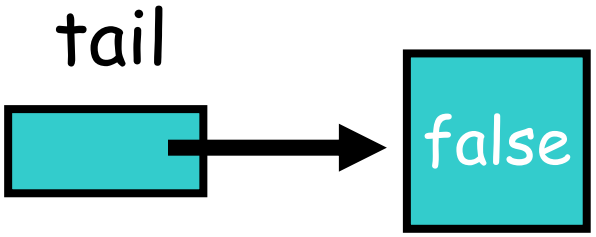
- Good
  - First truly scalable lock
  - Simple, easy to implement
- Bad
  - Not space efficient
  - One bit per thread
    - Unknown number of threads?
    - Small number of actual contenders?

CLH Queue Lock

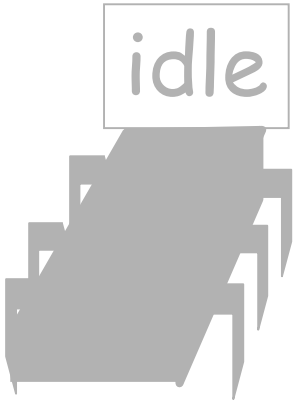
- Virtual Linked List keeps track of the queue
- Each thread's status is saved in its node:
  - True – has acquired the lock or wants to acquire the lock
  - False – is finished with the lock and has released it
- Each node keeps track of its predecessors status

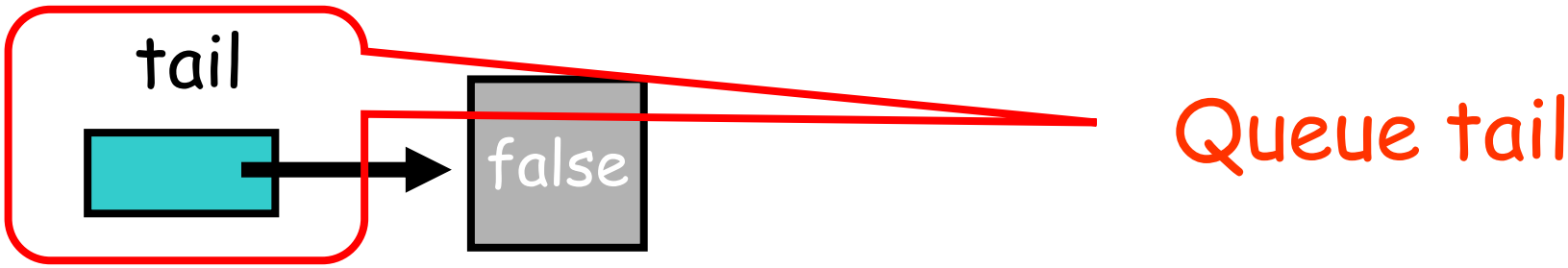
Initially





Initially





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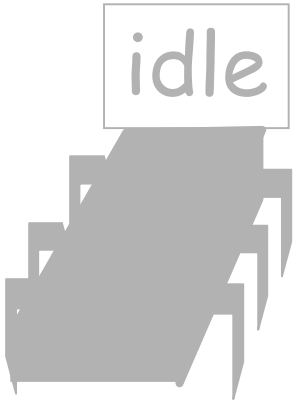

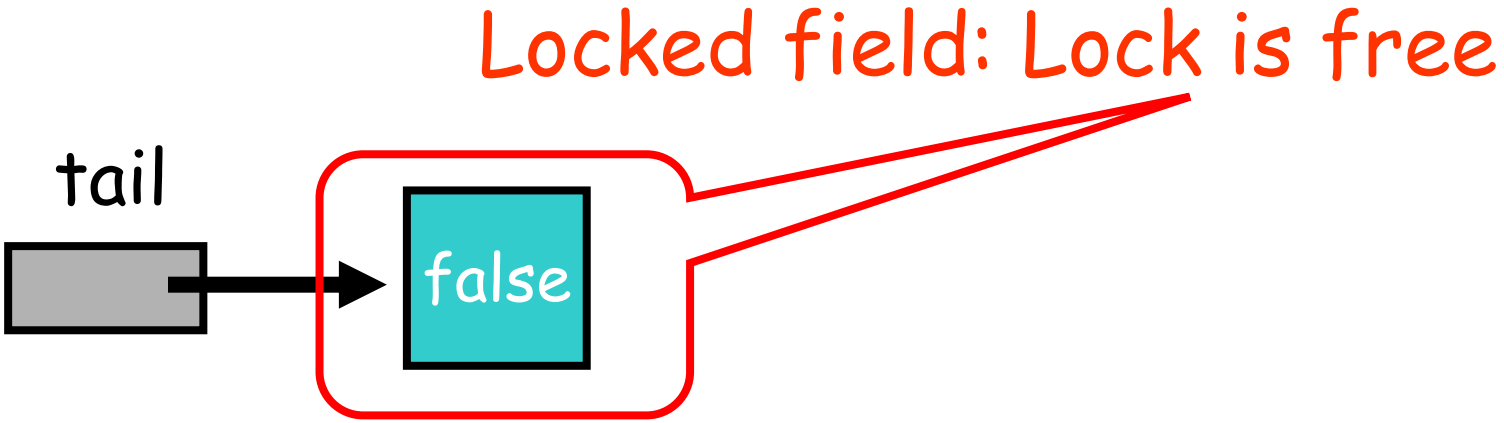

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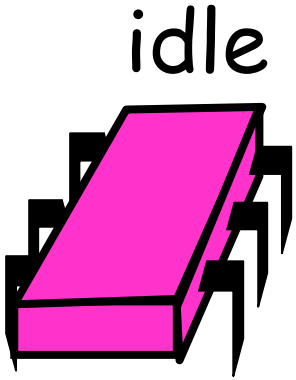
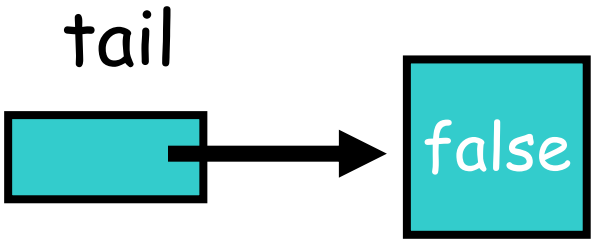
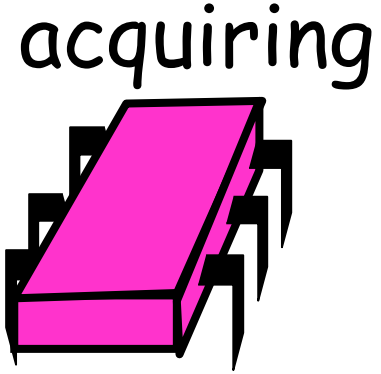
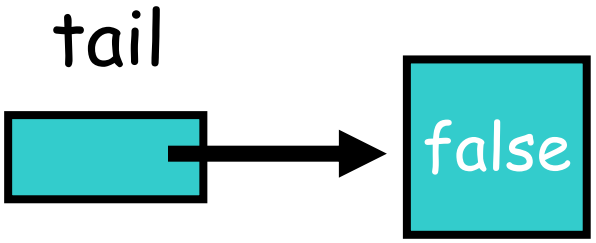




Purple Wants the Lock





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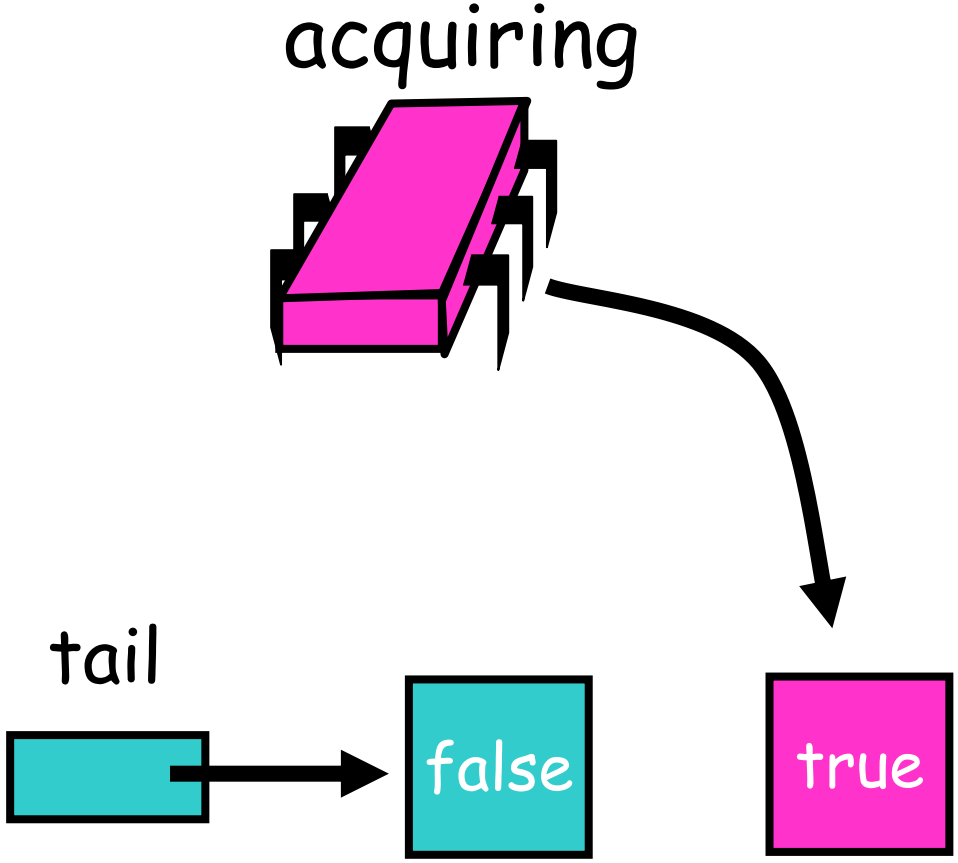

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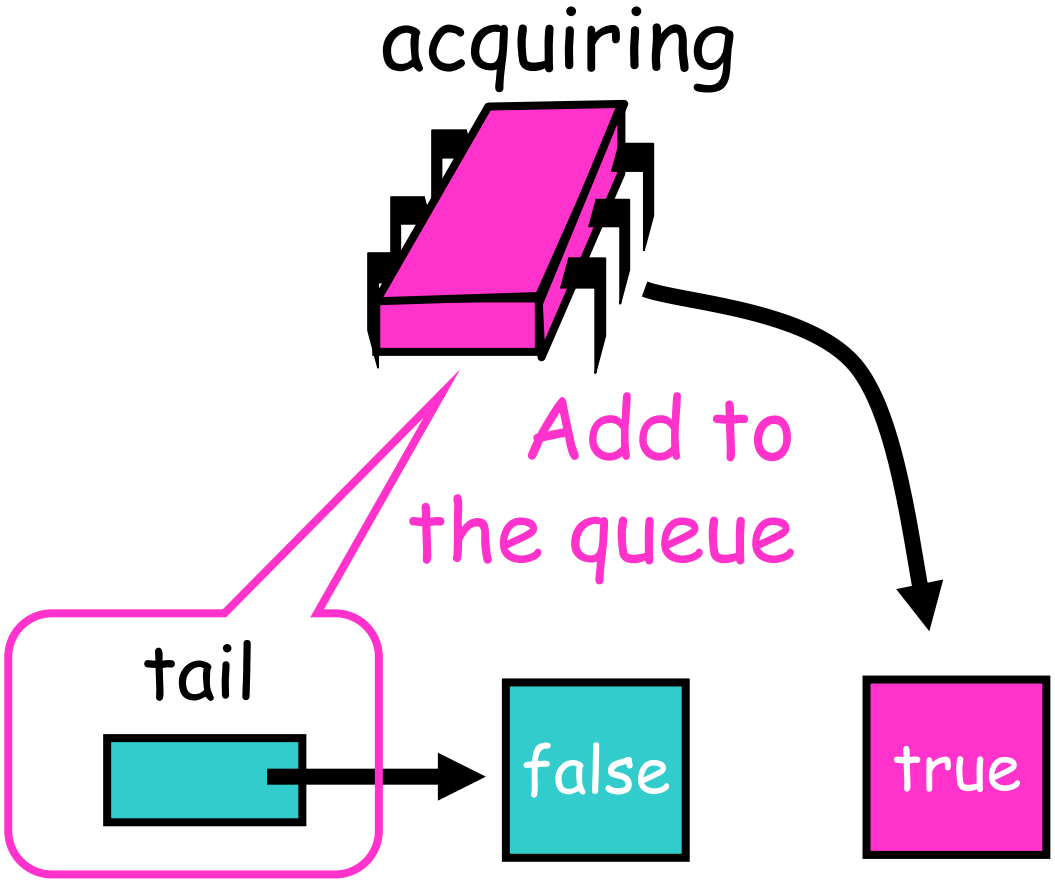
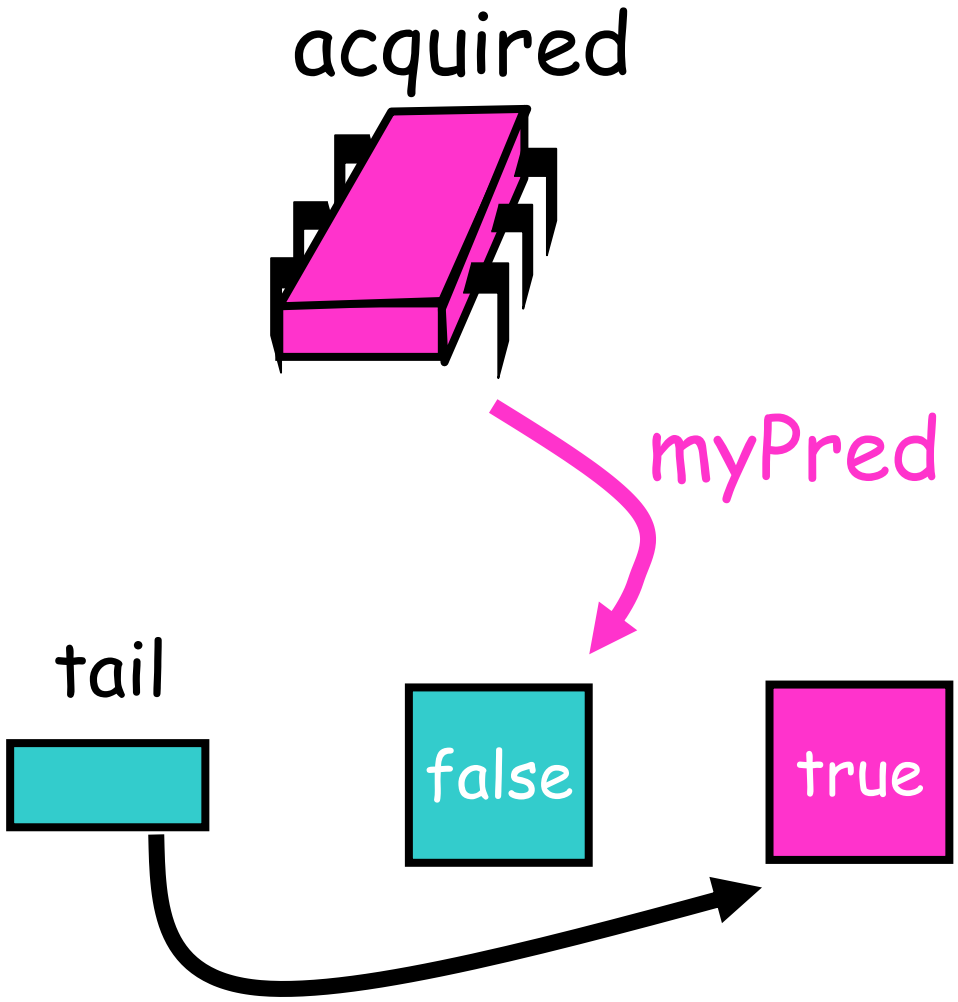
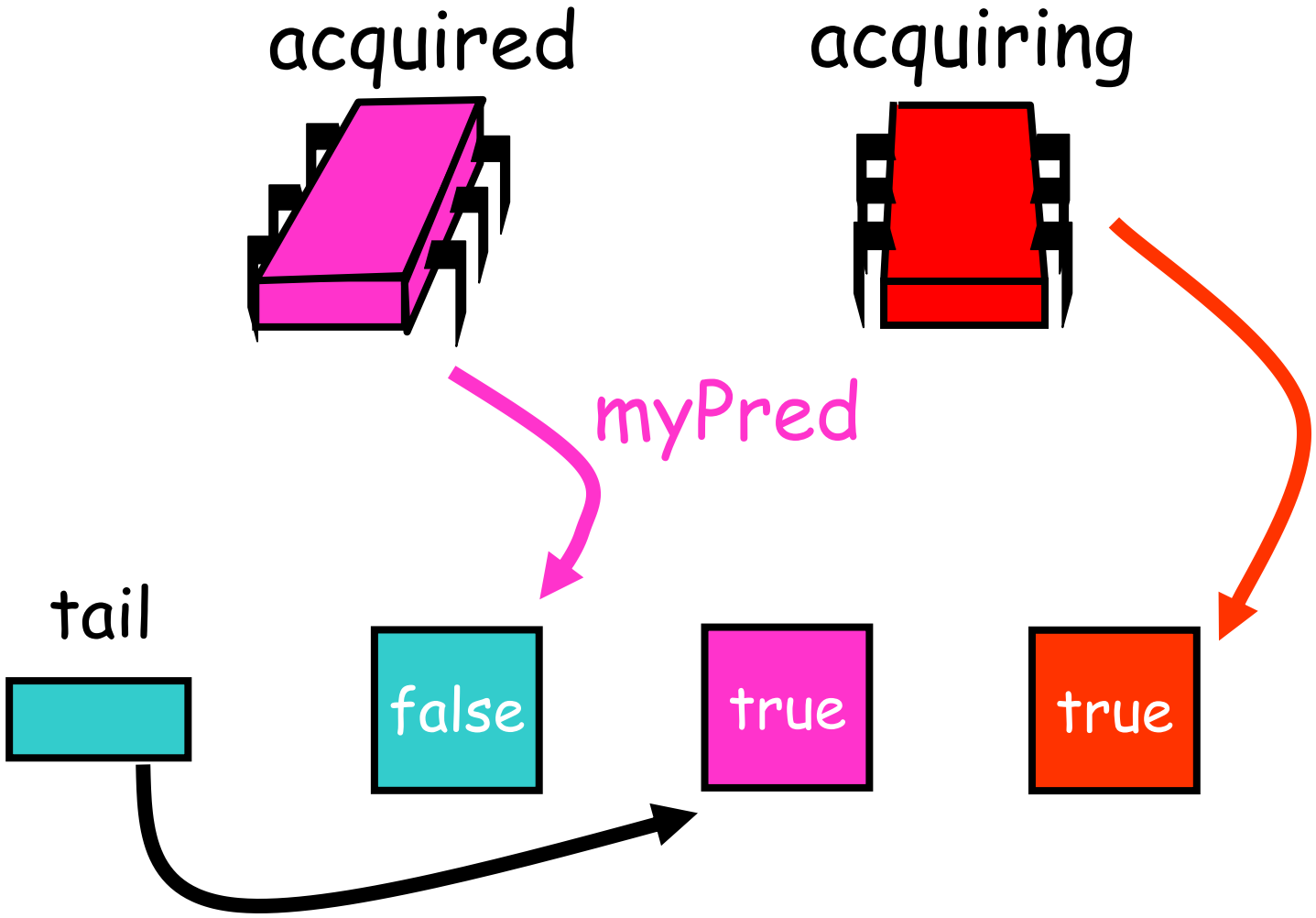


Purple Has the Lock



Red Wants the Lock



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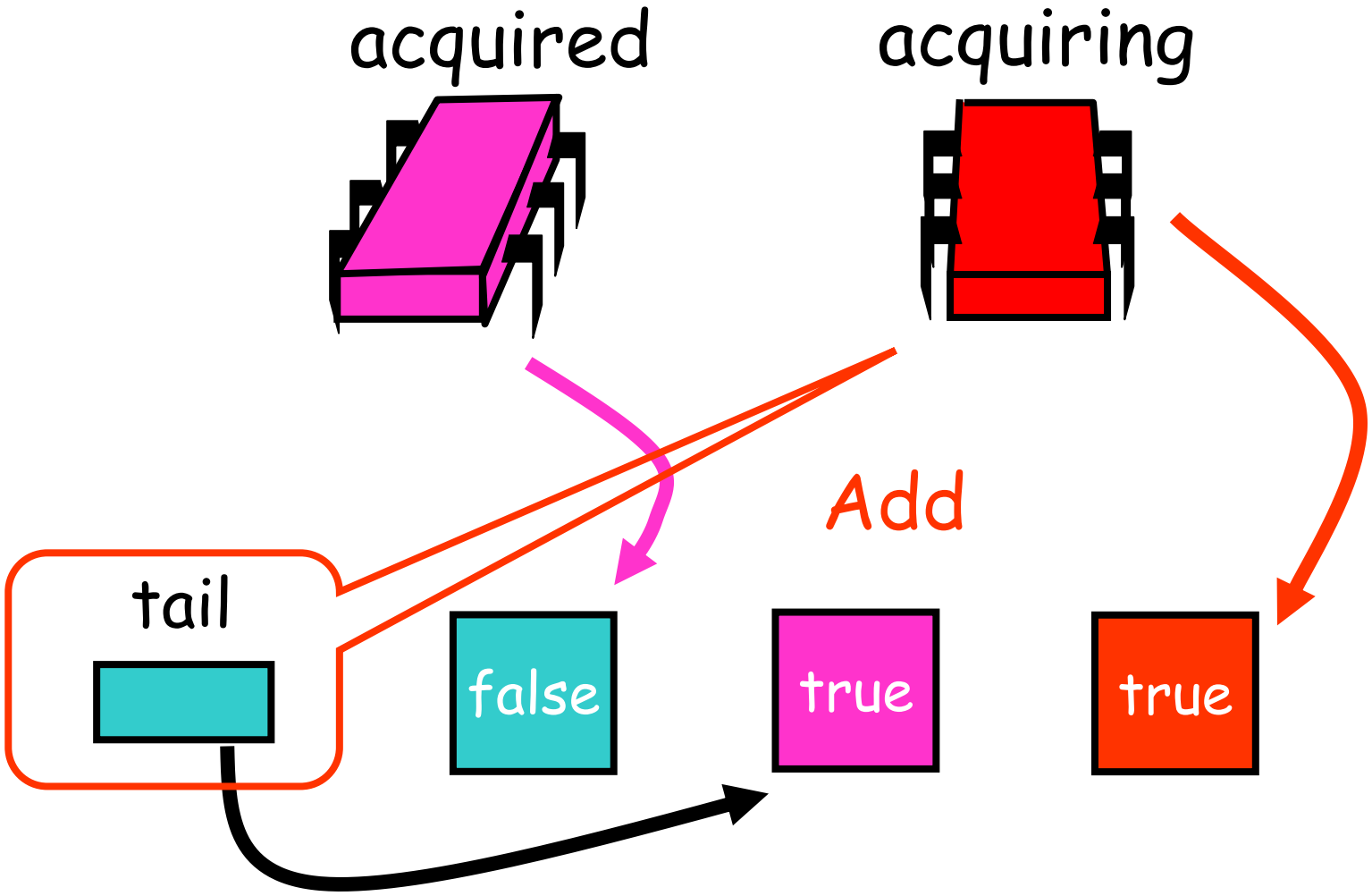

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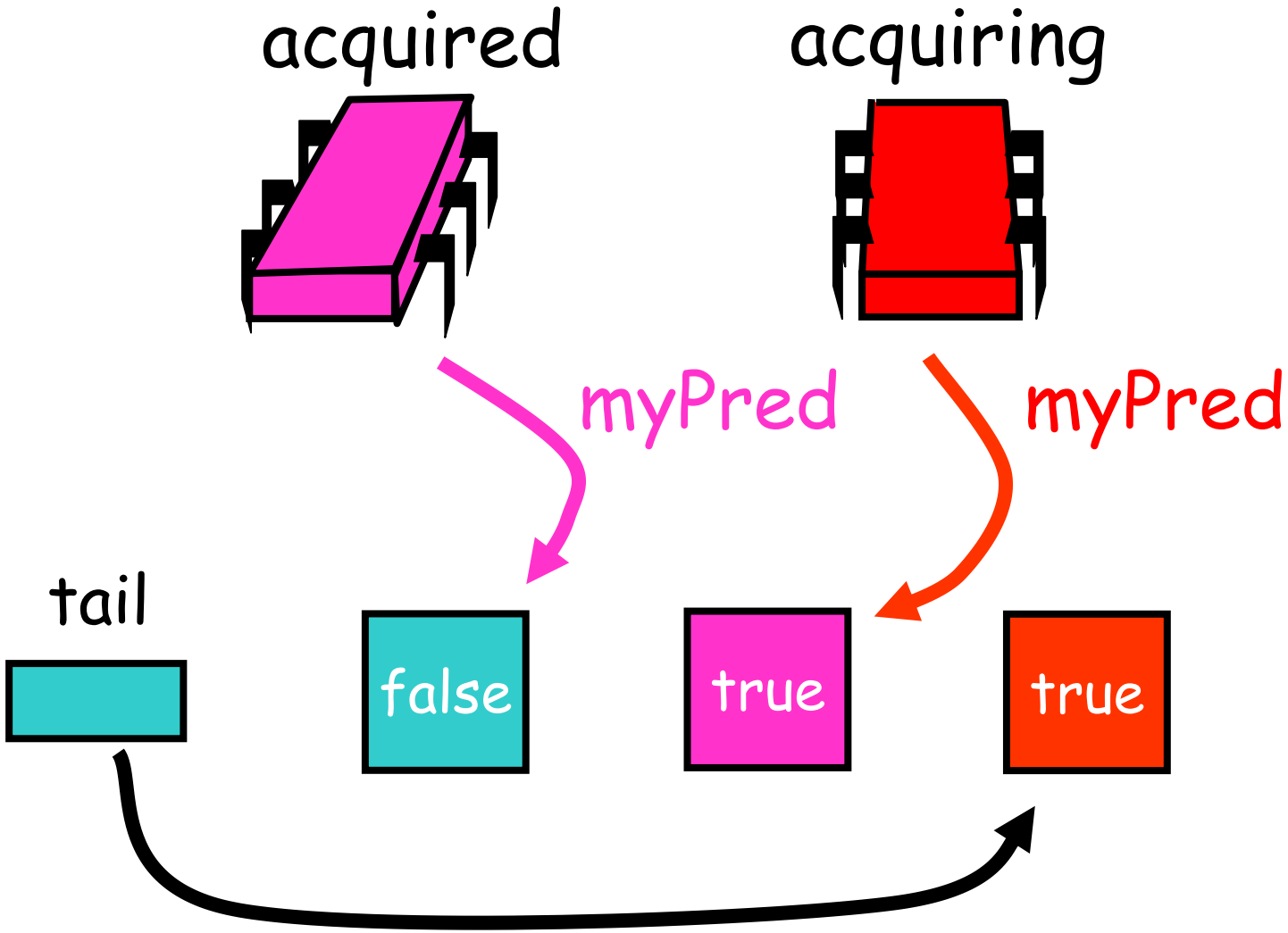

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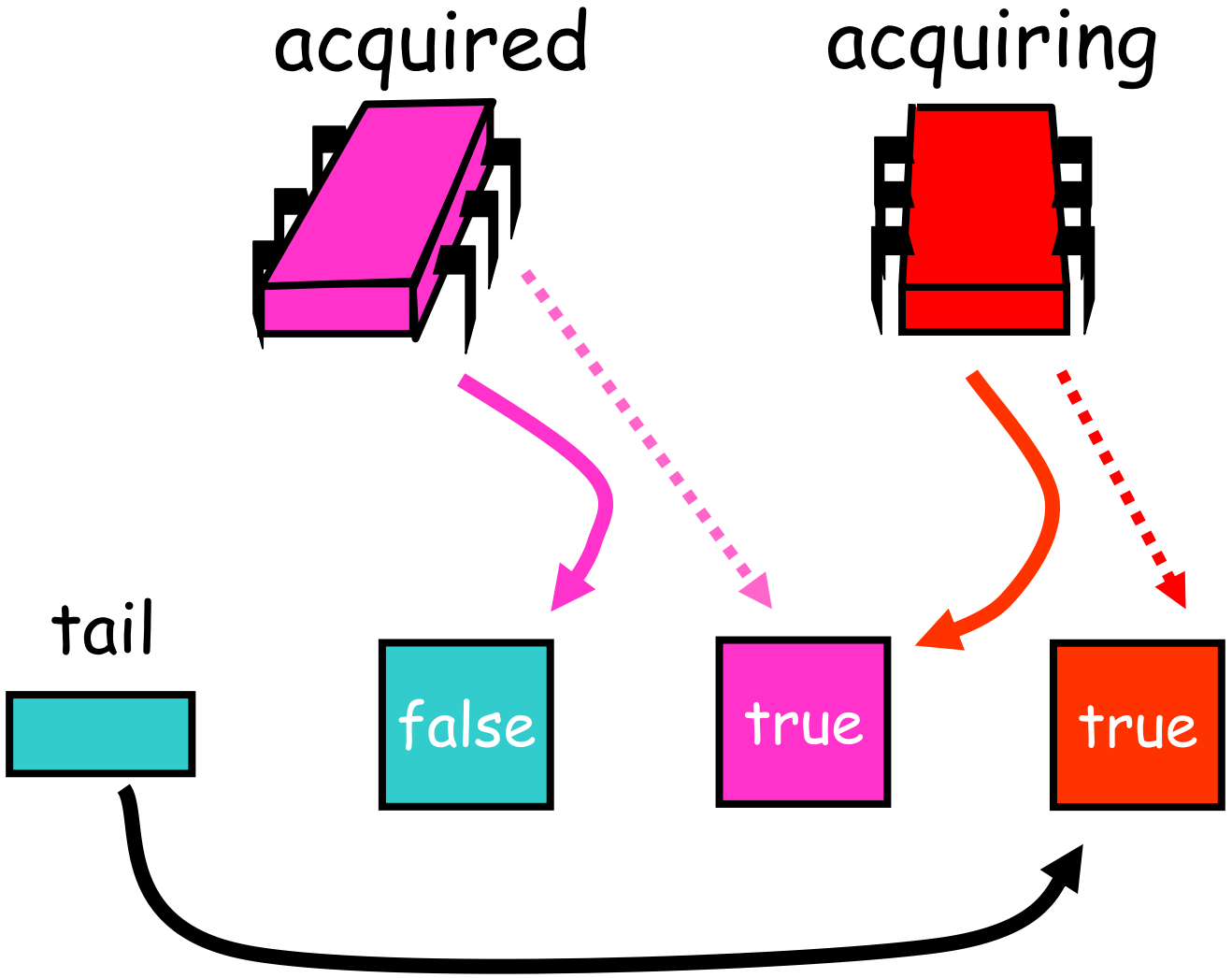

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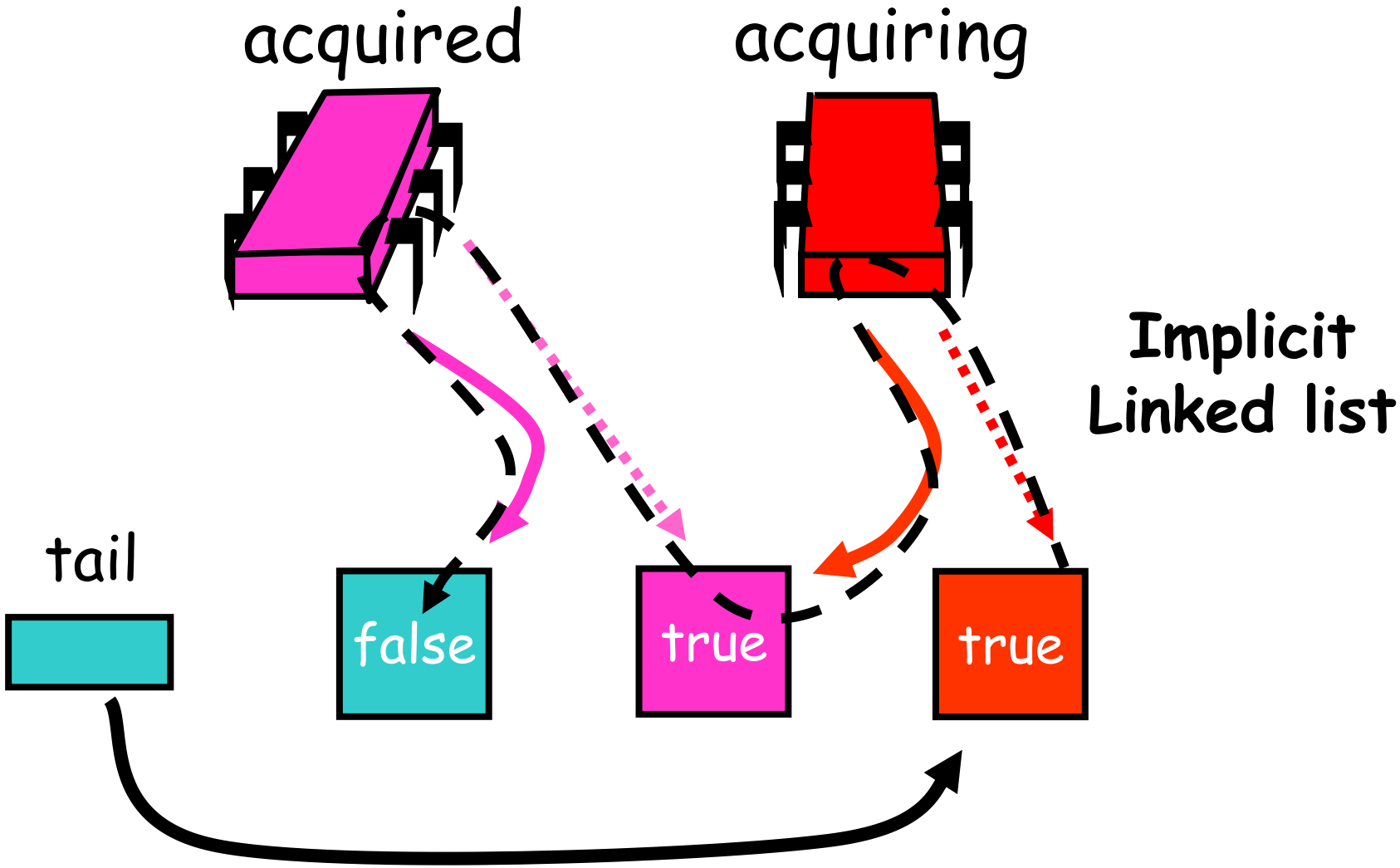

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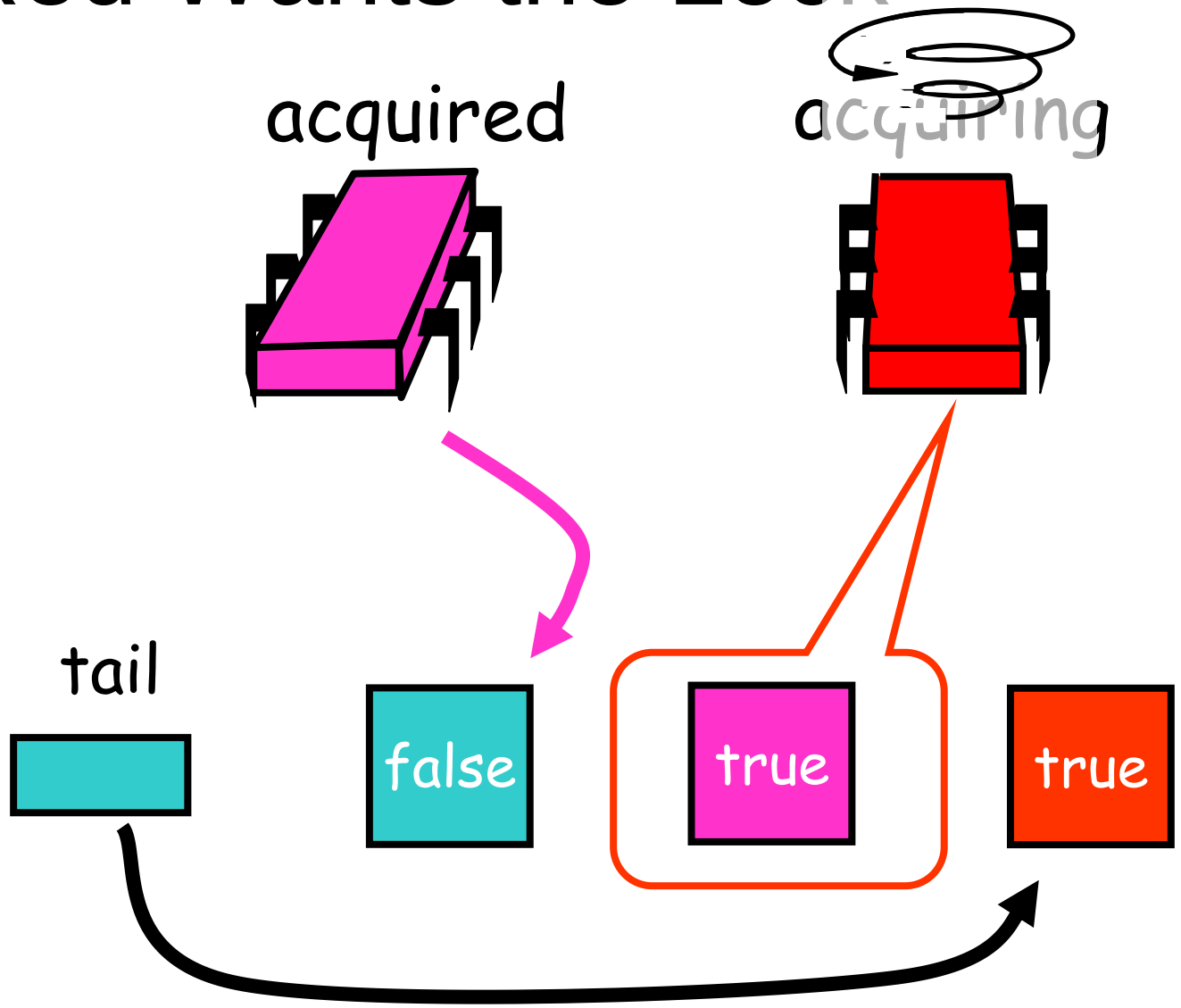

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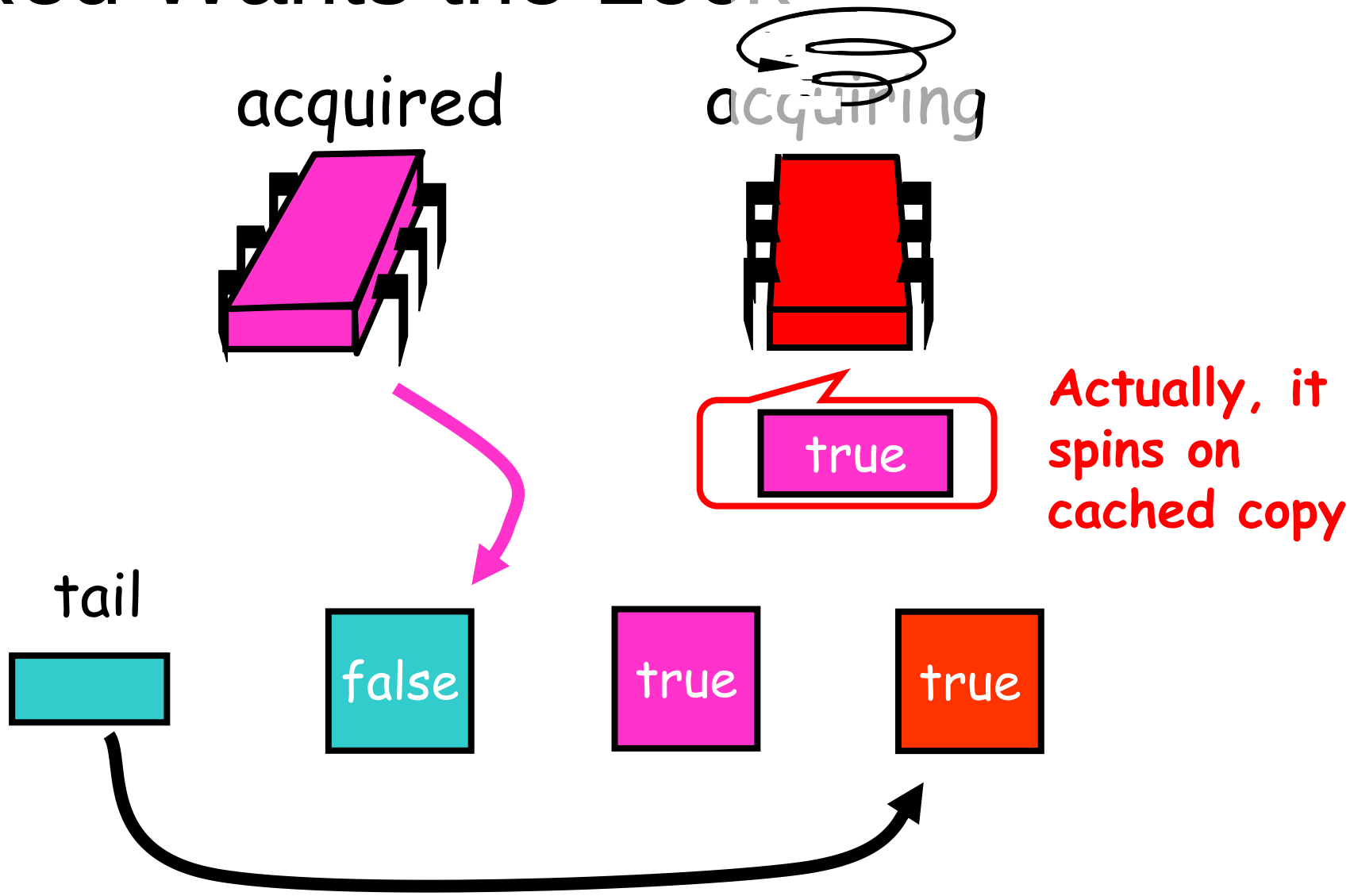
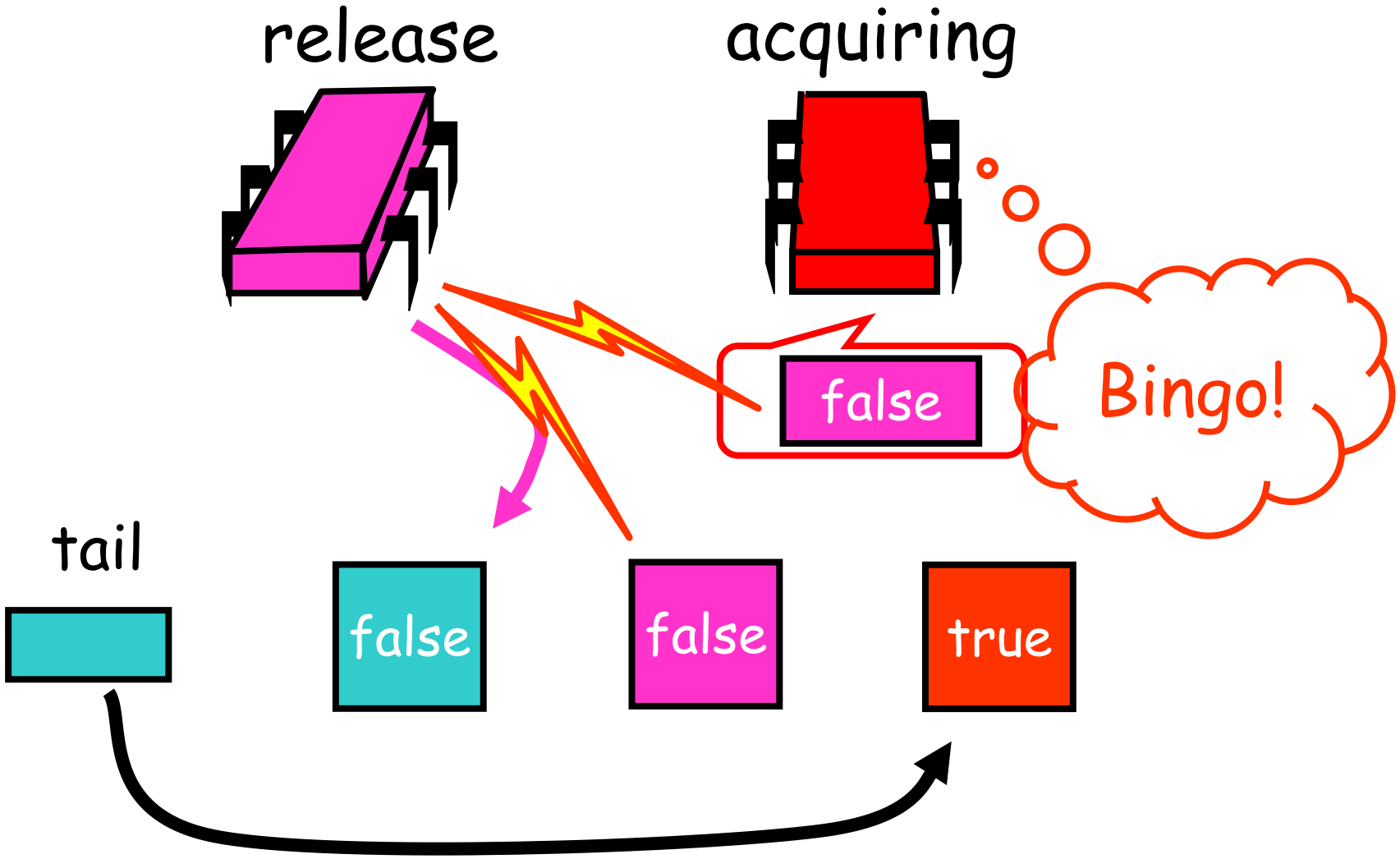
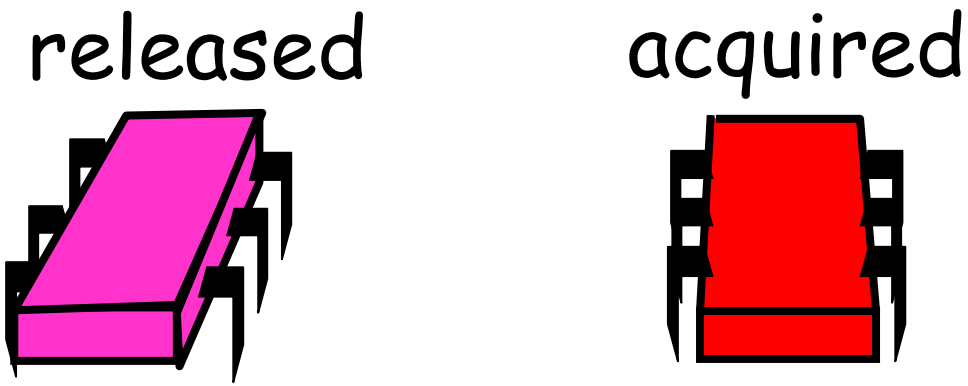
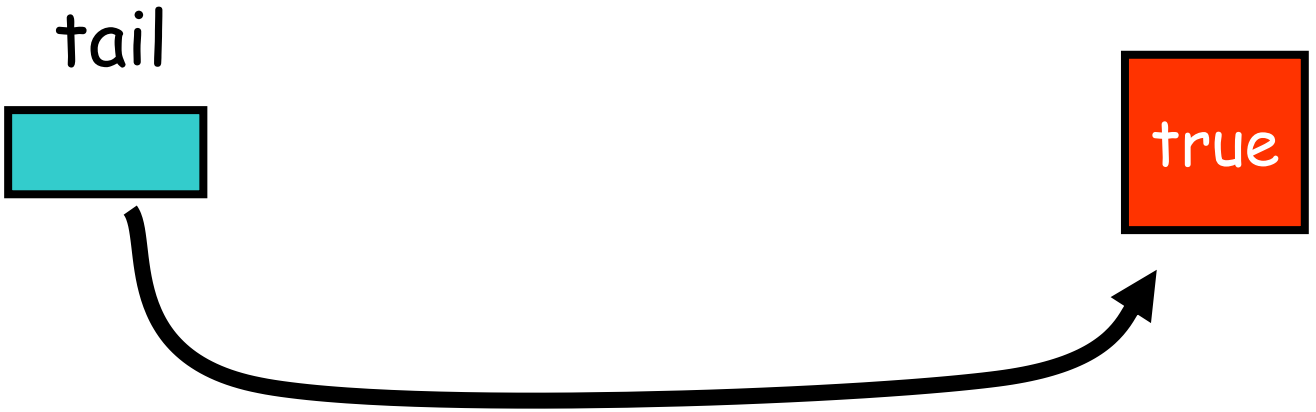


Purple Releases



Purple Releases





CLH Queue Lock

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

CLH Queue Lock

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  while (pred.locked) {}
 }}
```

Queue tail

CLH Queue Lock

```
class CLHLock implements Lock {
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 public void lock() {
  myNode.locked = true;
  Qnode pred
     = tail.getAndSet(myNode);
  while (pred.lo
 }}
```

Thread-local Qnode

CLH Queue Lock

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 AtomicReference<Qnode> tail;
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     = new Qnode();
 public void lock() {
  myNode.locked = true;
  Qnode pred
     = tail.getAndSet(myNode);
  while (pred.locked) {}
 }}
```

Add my node

CLH Queue Lock

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

- Good
  - Lock release affects predecessor only
  - Small, constant-sized space

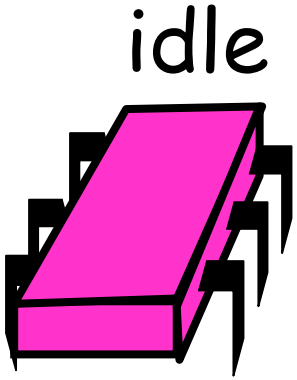
MCS Lock

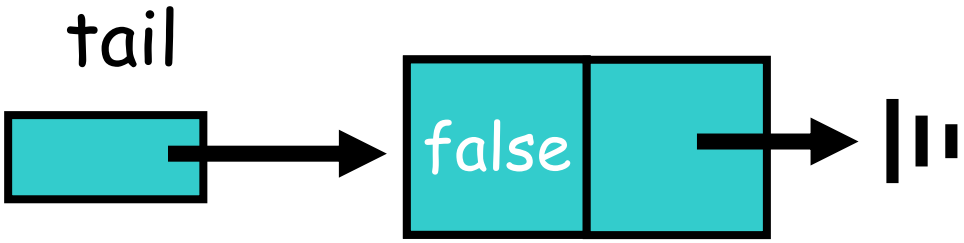
- FIFO order
- Spin on local memory only
- Small, Constant-size overhead

MCS Queue Lock

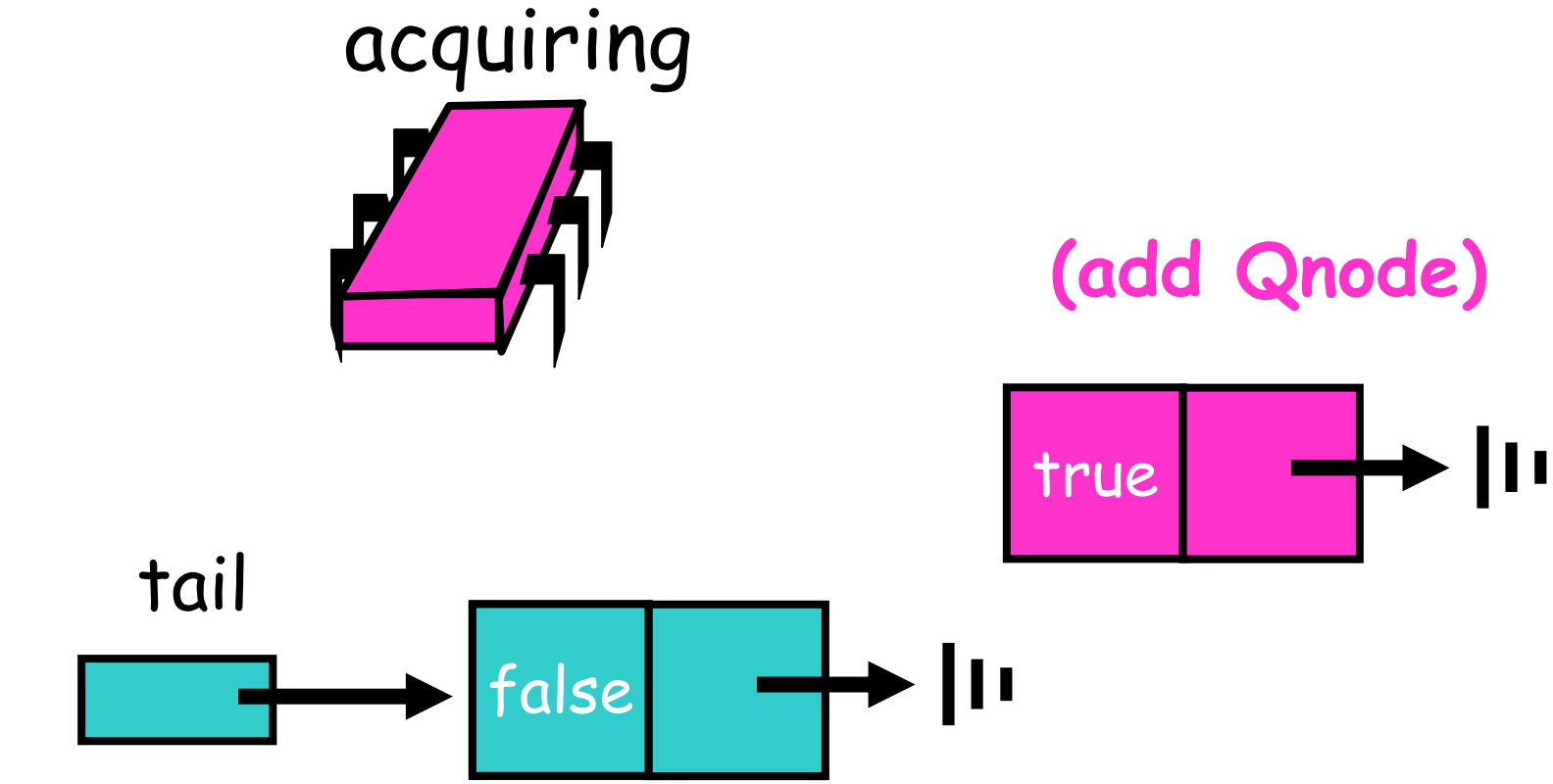
- Similar to CLHLock, but the linked list is explicit instead of implicit
- Each node in the Queue has a next field

Initially





Acquiring



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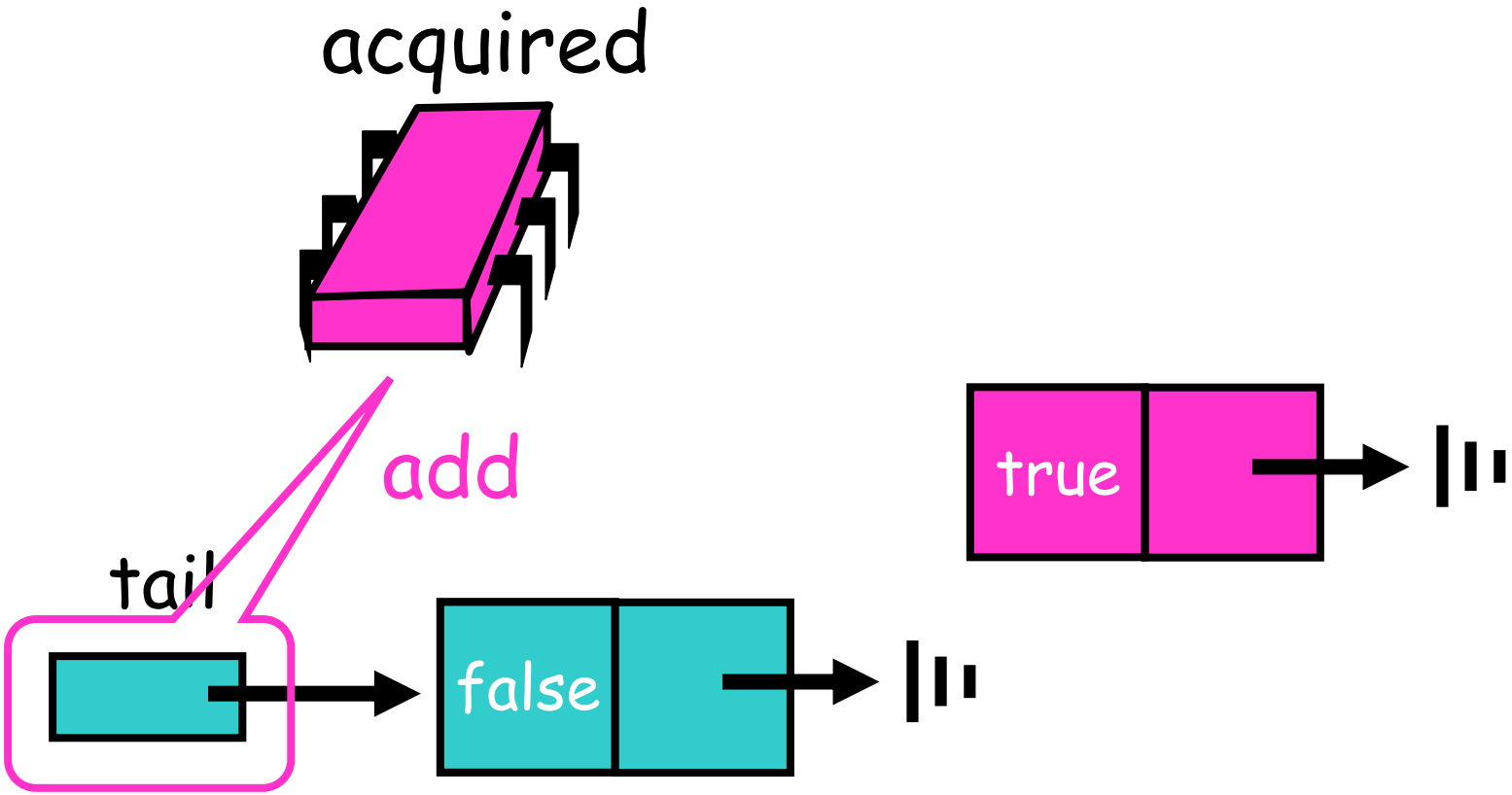

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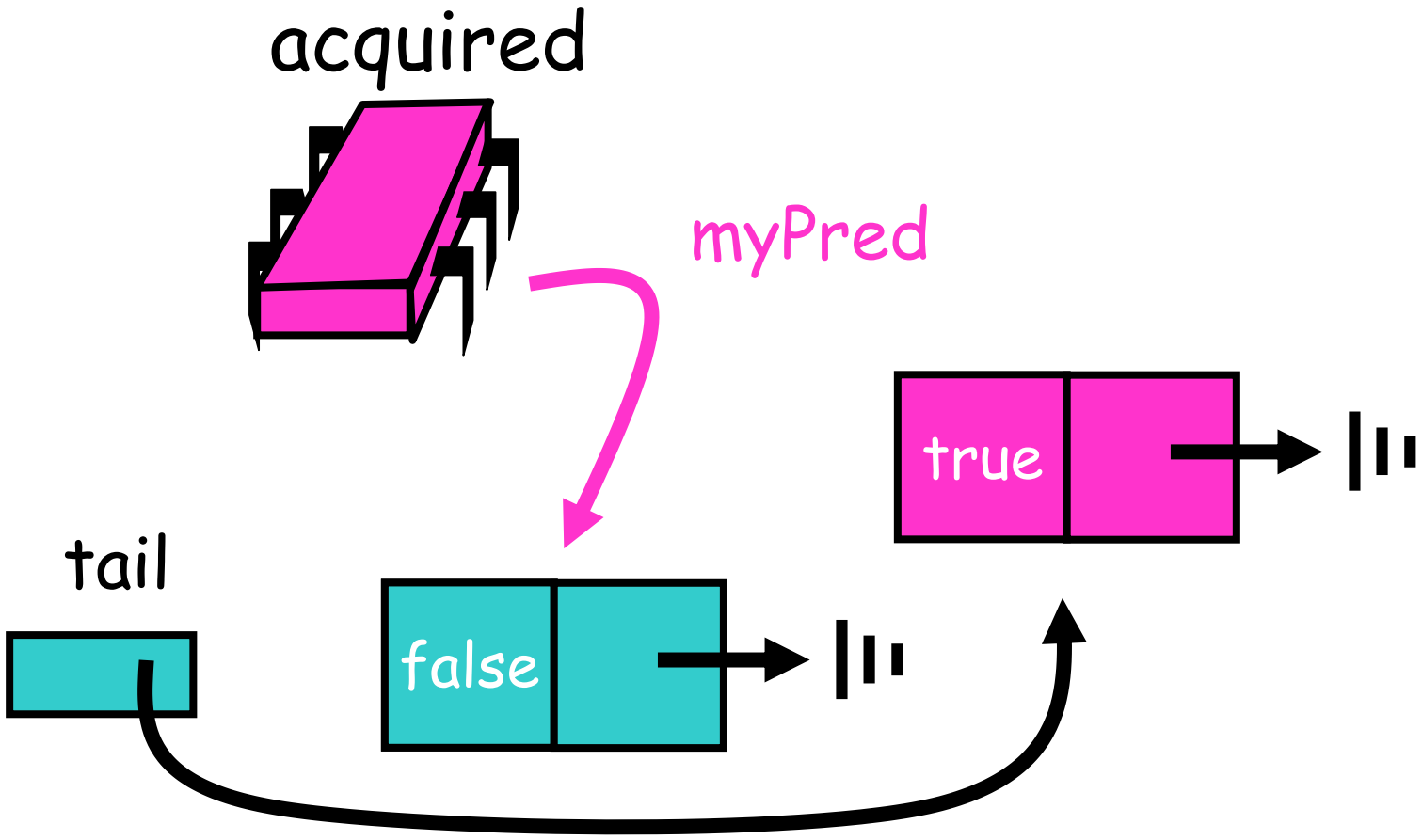

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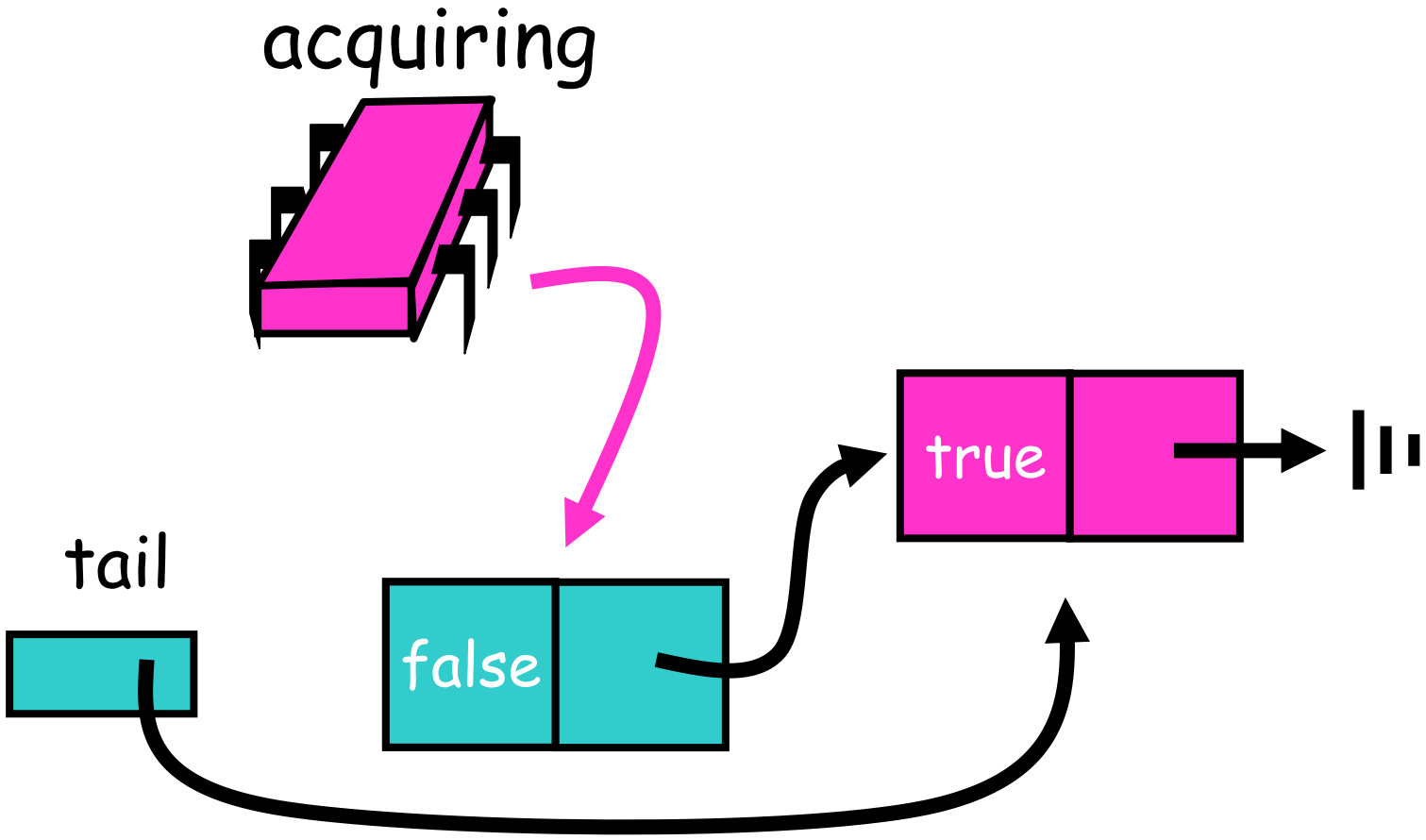

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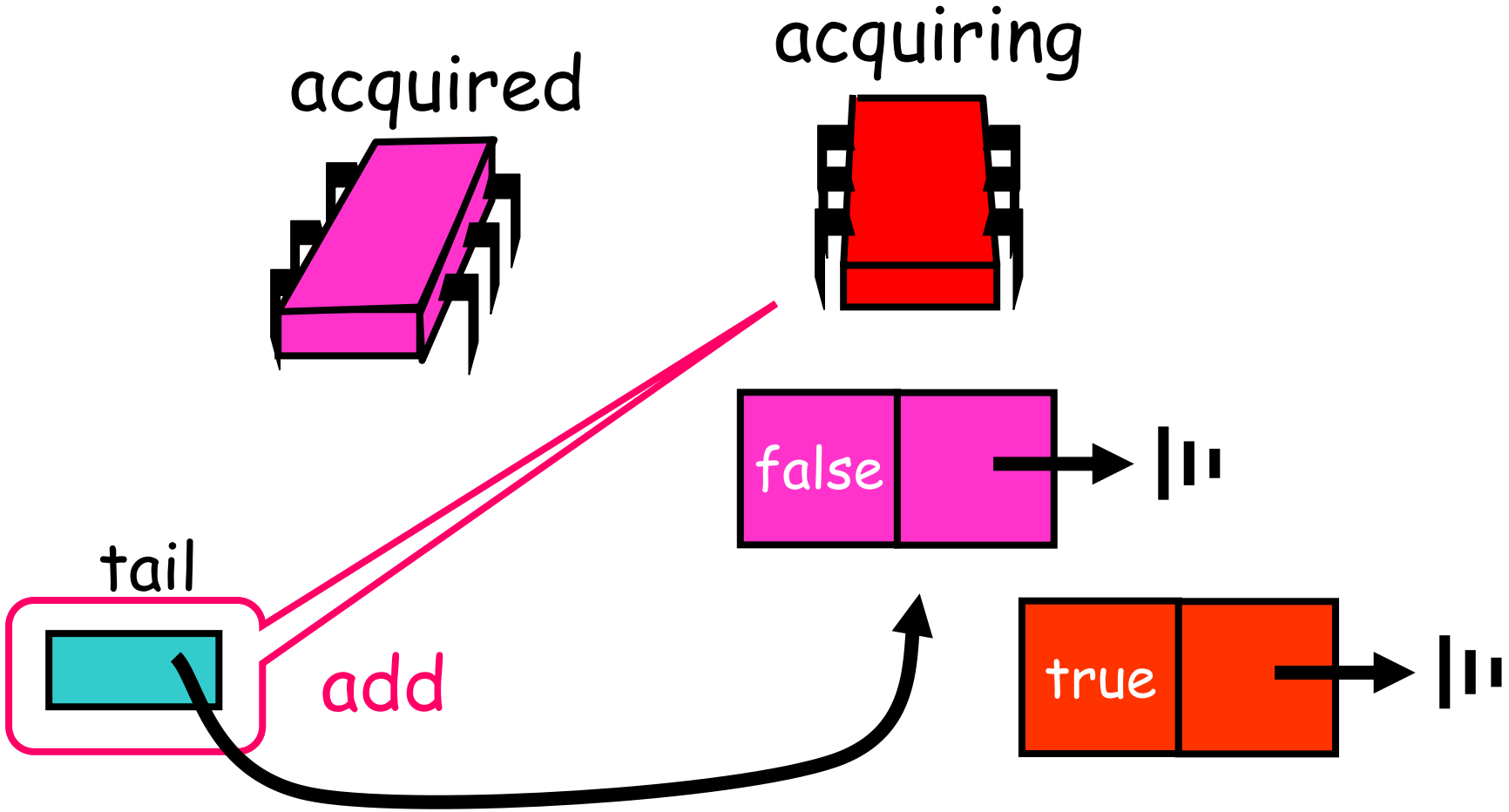

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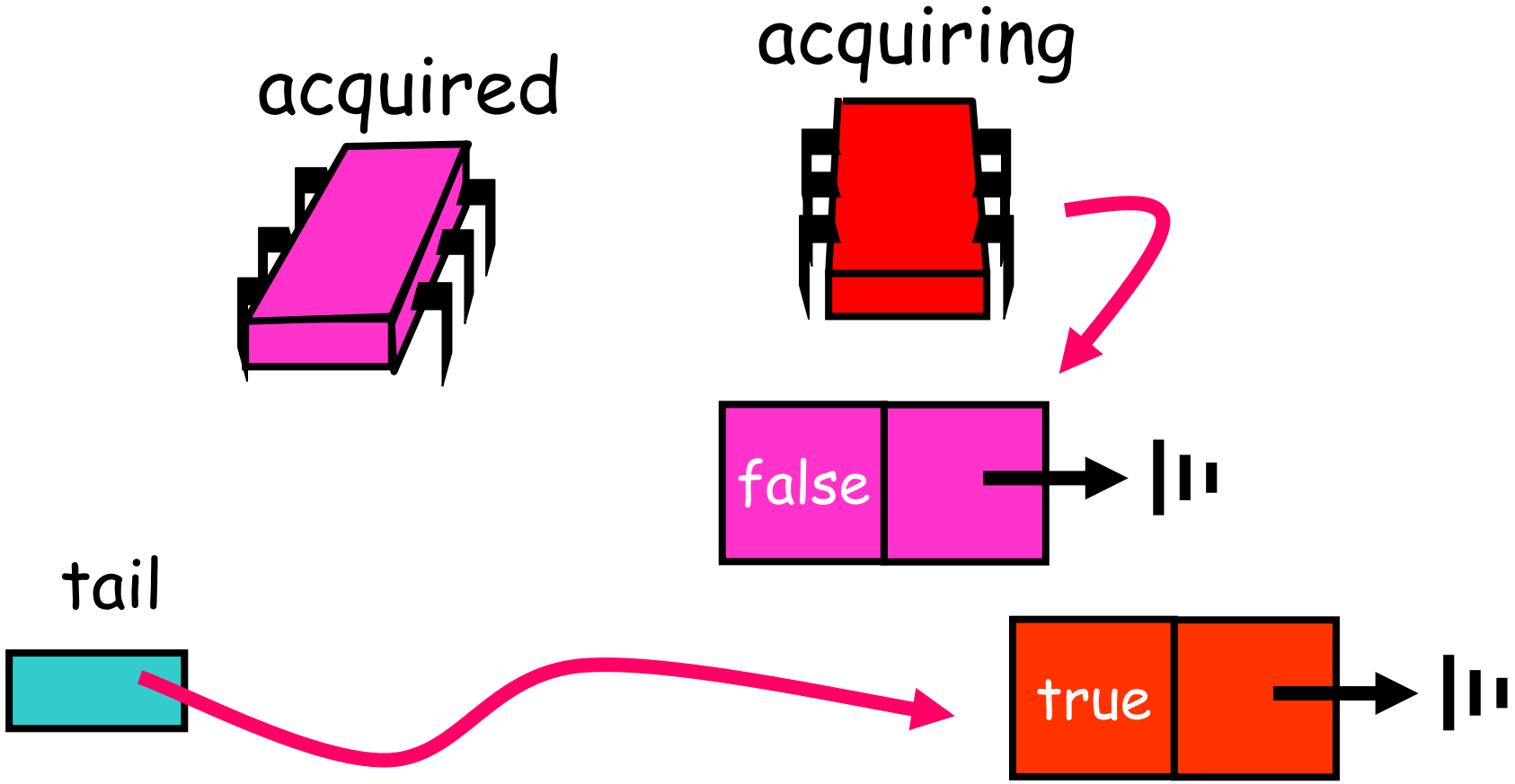

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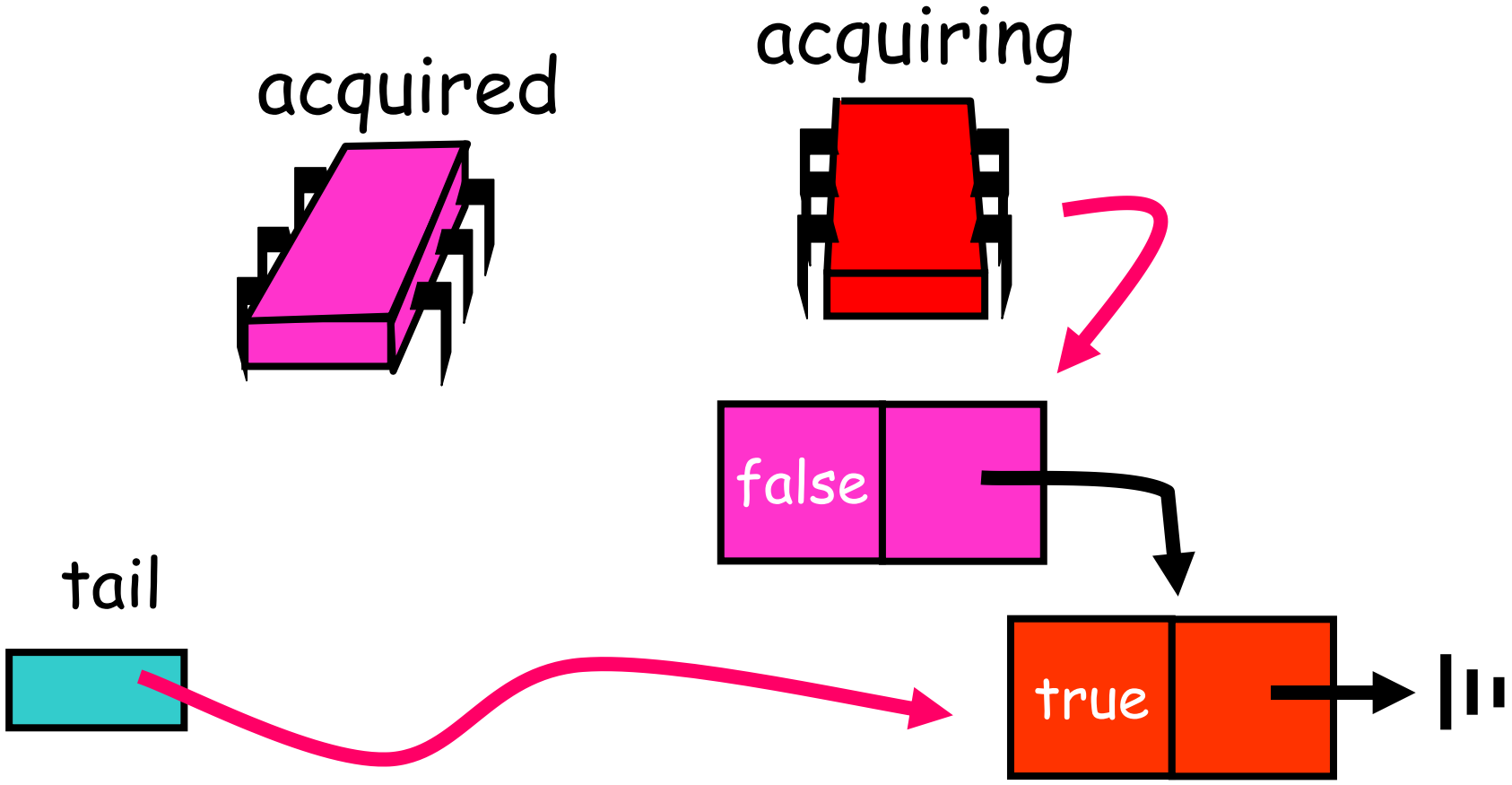
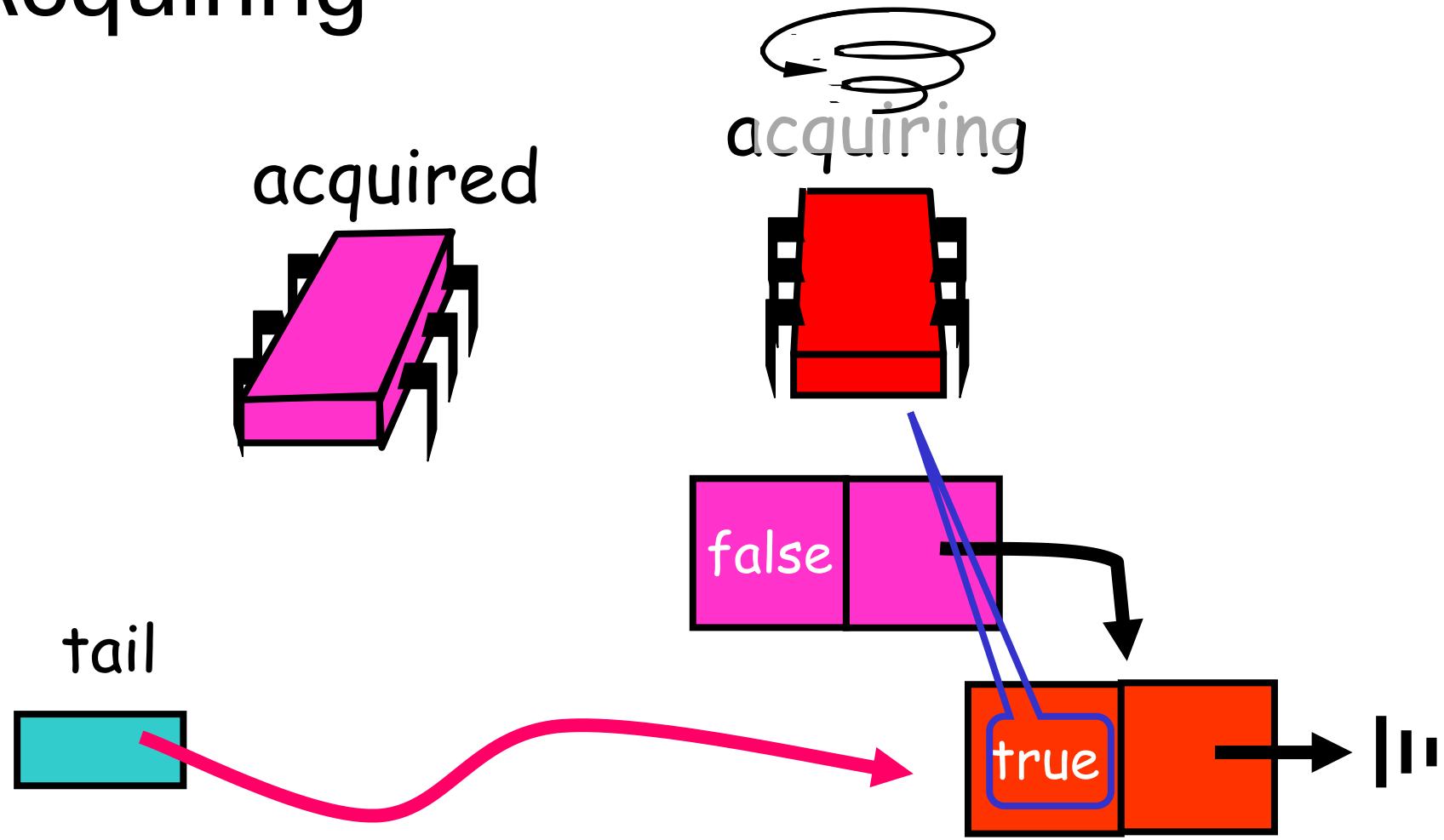
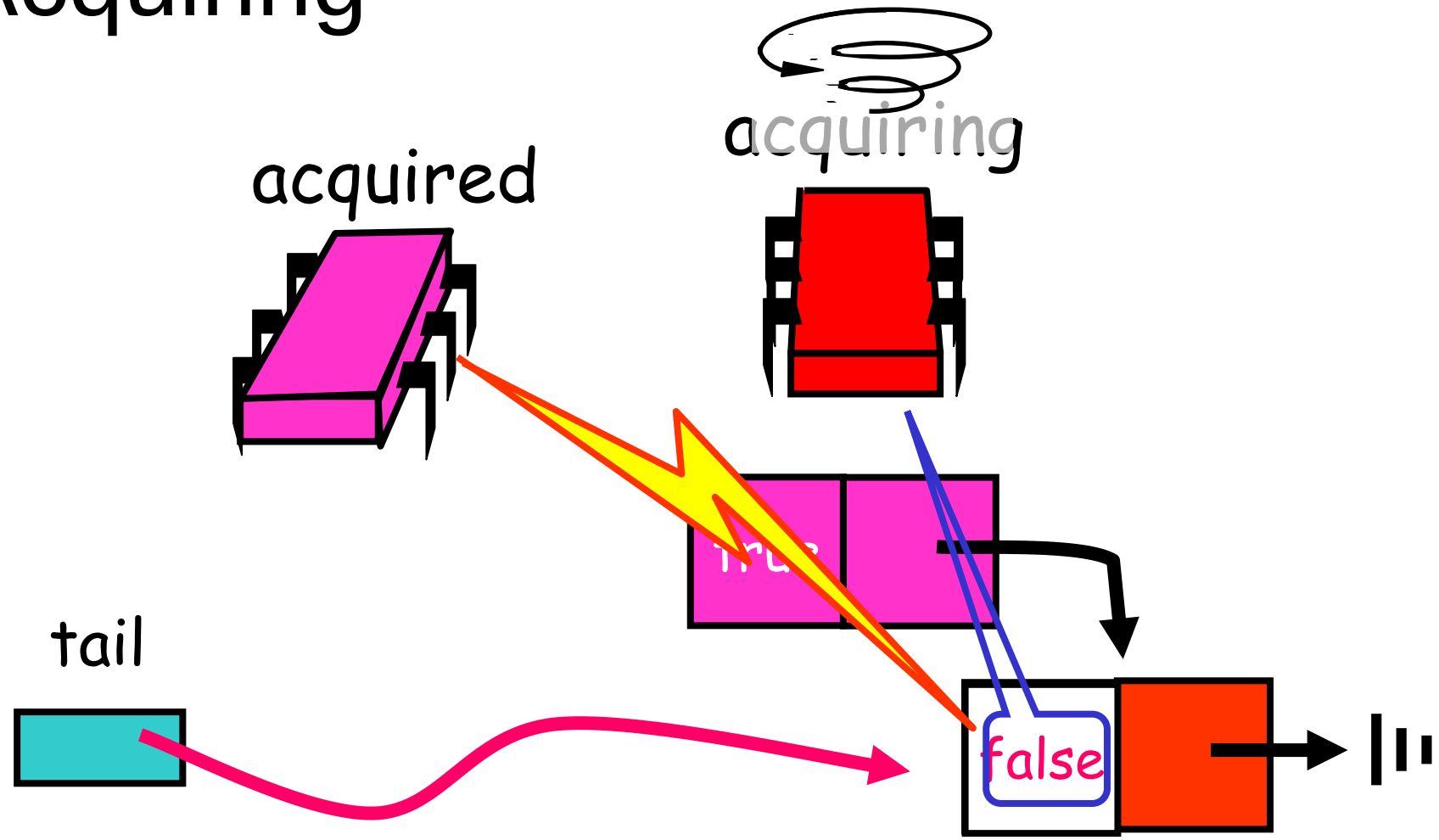


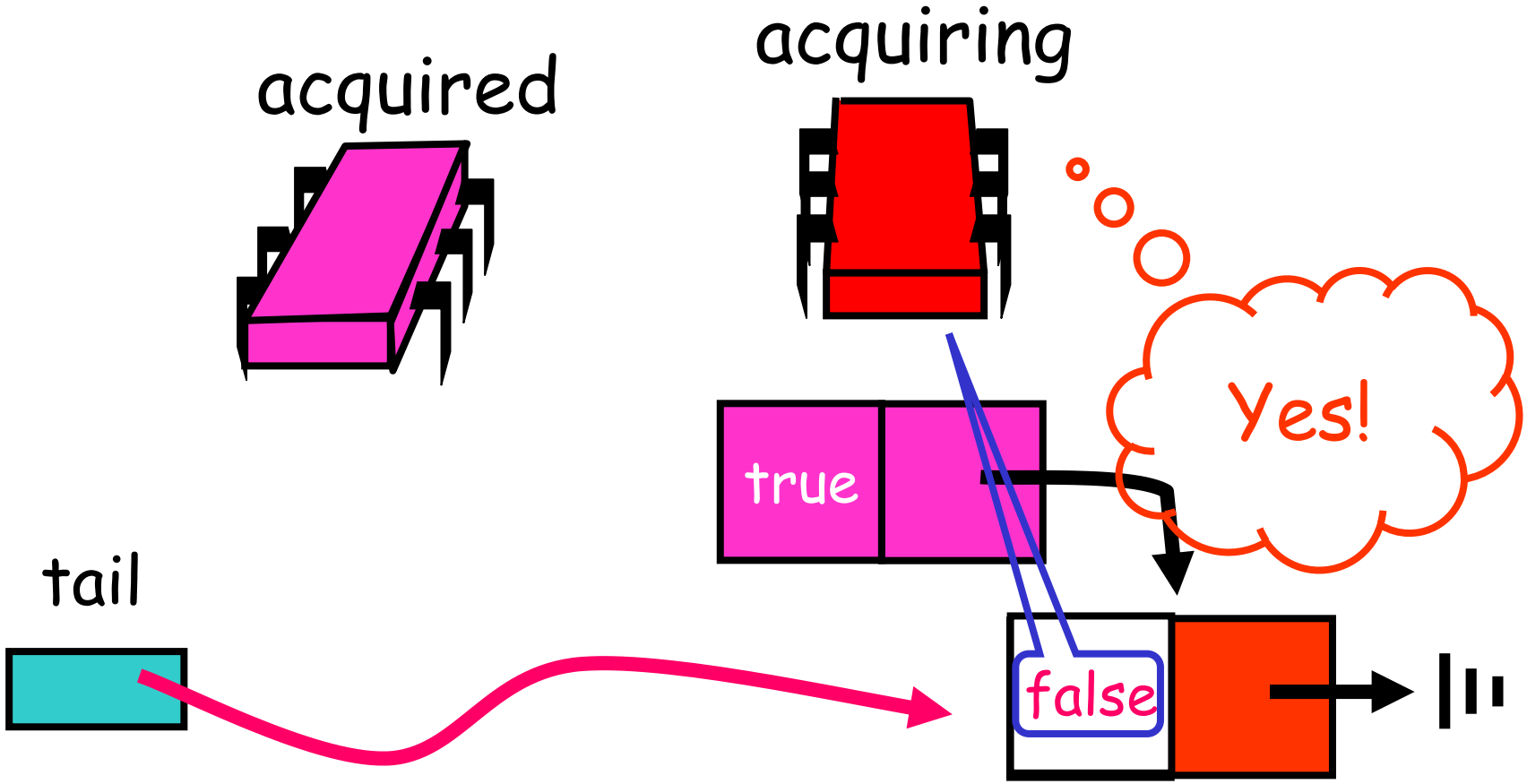
Acquiring



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

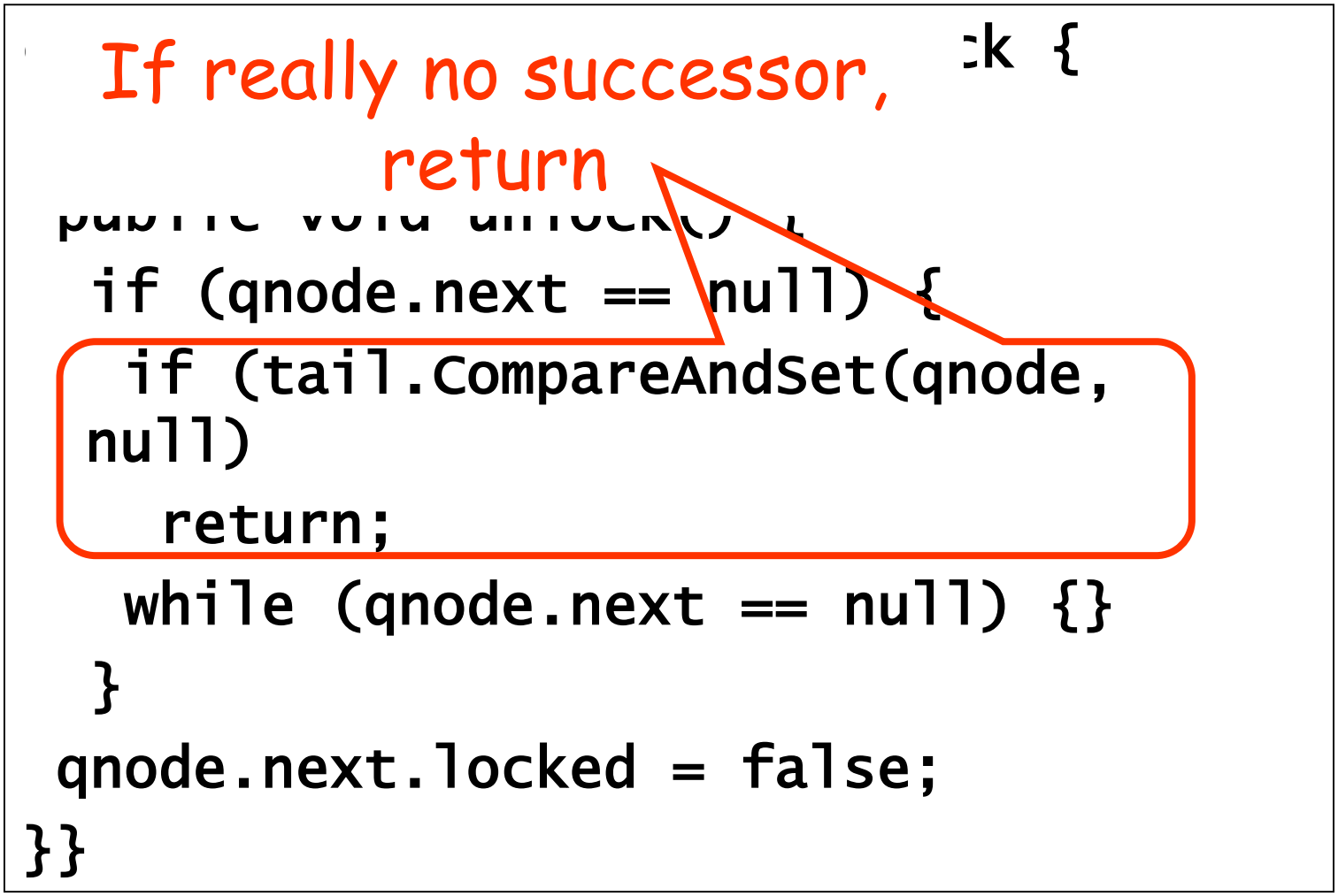
```
class MCSLock implements Lock {
 AtomicReference tail;
 public void unlock() {
  if (qnode.next == null) {
   if (tail.CAS(qnode, null)
    return;
   while (qnode.next == null) {}
  }
 qnode.next.locked = false;
}}
```

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



MCS Queue Lock

Otherwise wait for successor to catch up

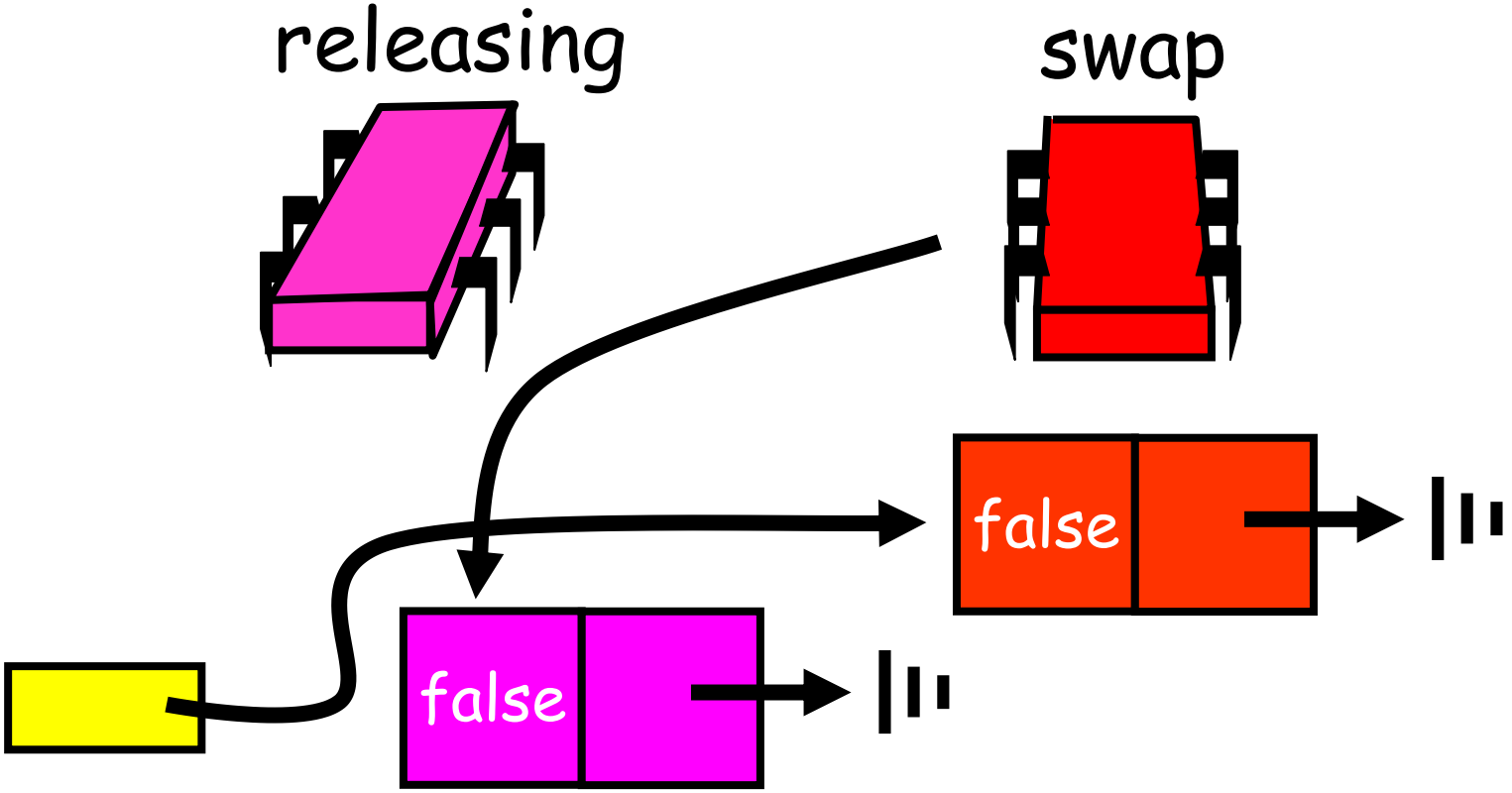
```
:k {
 public void unlock() {
  if (qnode.next == null) {
   if (tail.CAS(qnode, null)
    return;
   while (qnode.next == null) {}
  }
 qnode.next.locked = false;
}}
```

MCS Queue Lock

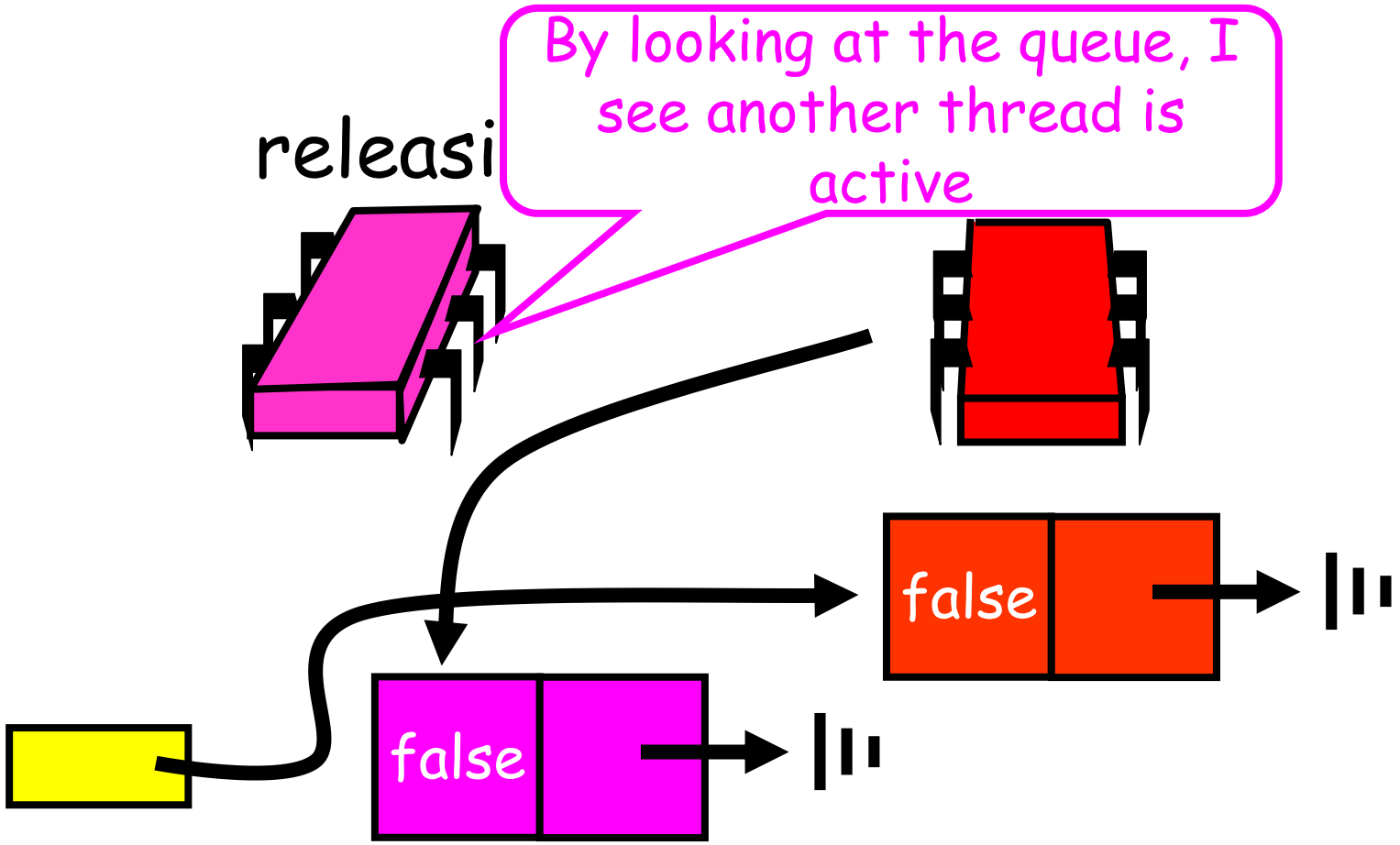
```
class MCSLock implements Lock {
 AtomicRef
 public vo
  if (qnode.next == null) {
   if (tail.CAS(qnode, null)
    return;
   while (qnode.next == null) {}
  }
 qnode.next.locked = false;
}}
```

Pass lock to successor

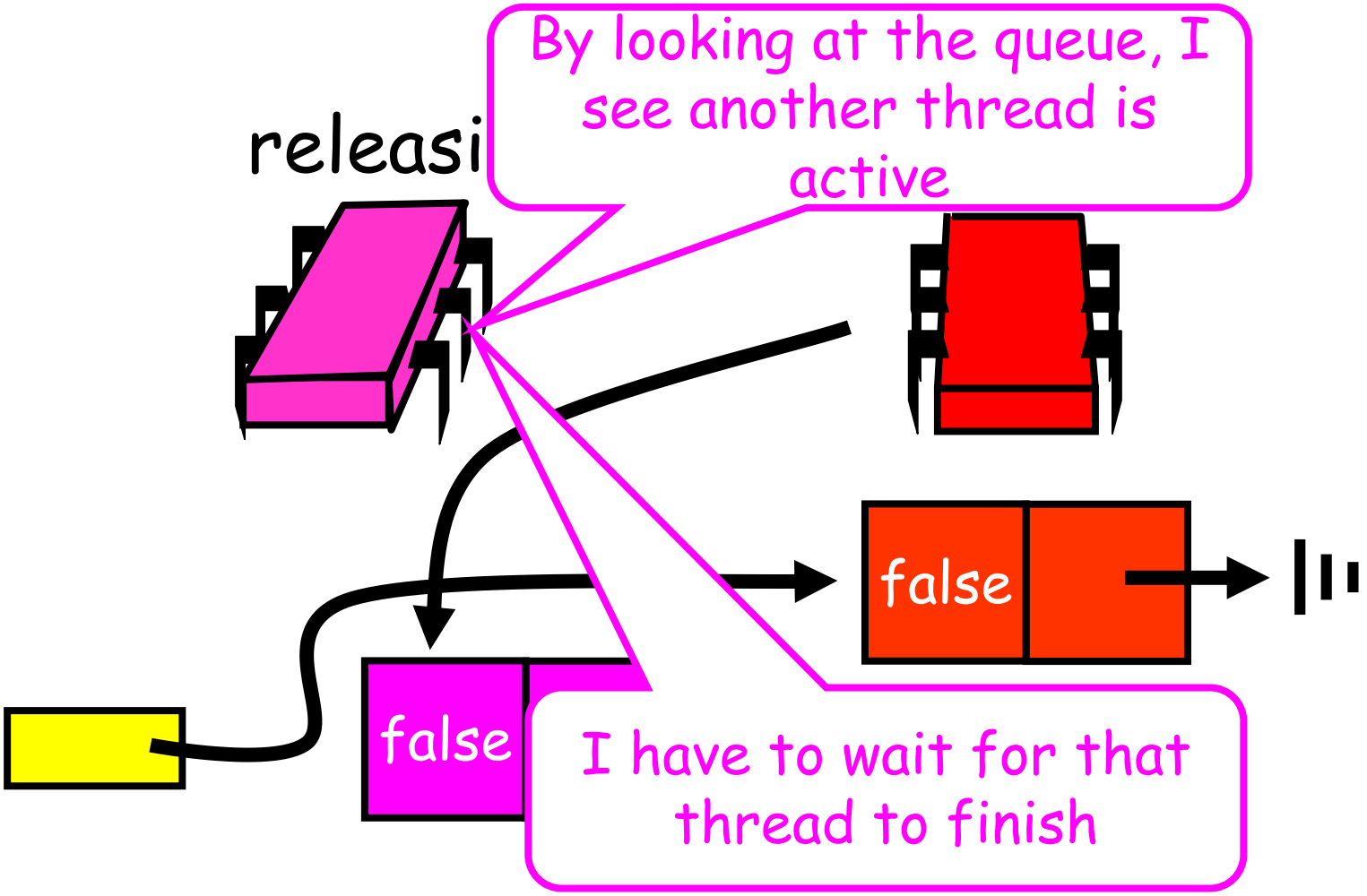
Purple Release



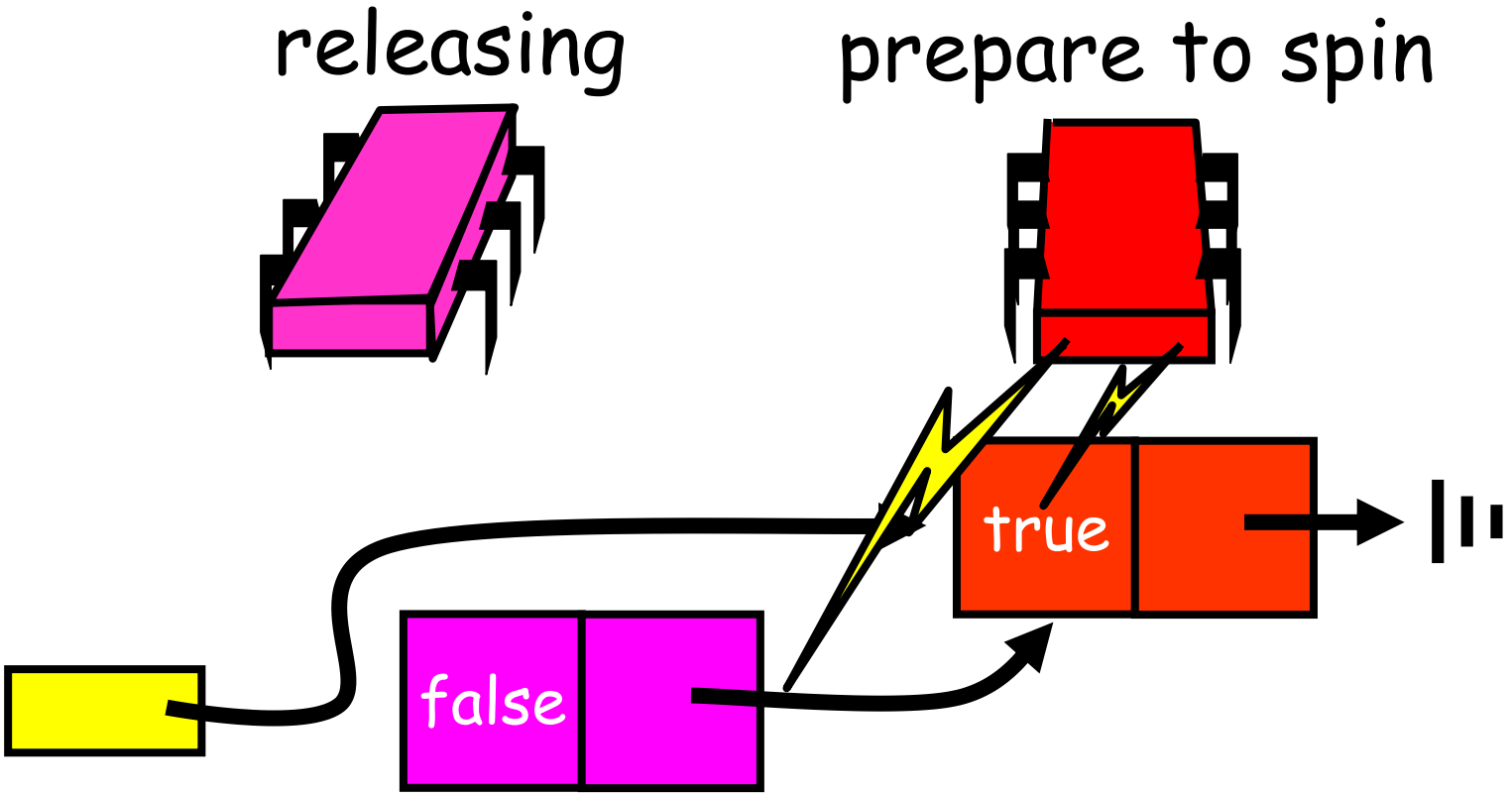
Purple Release



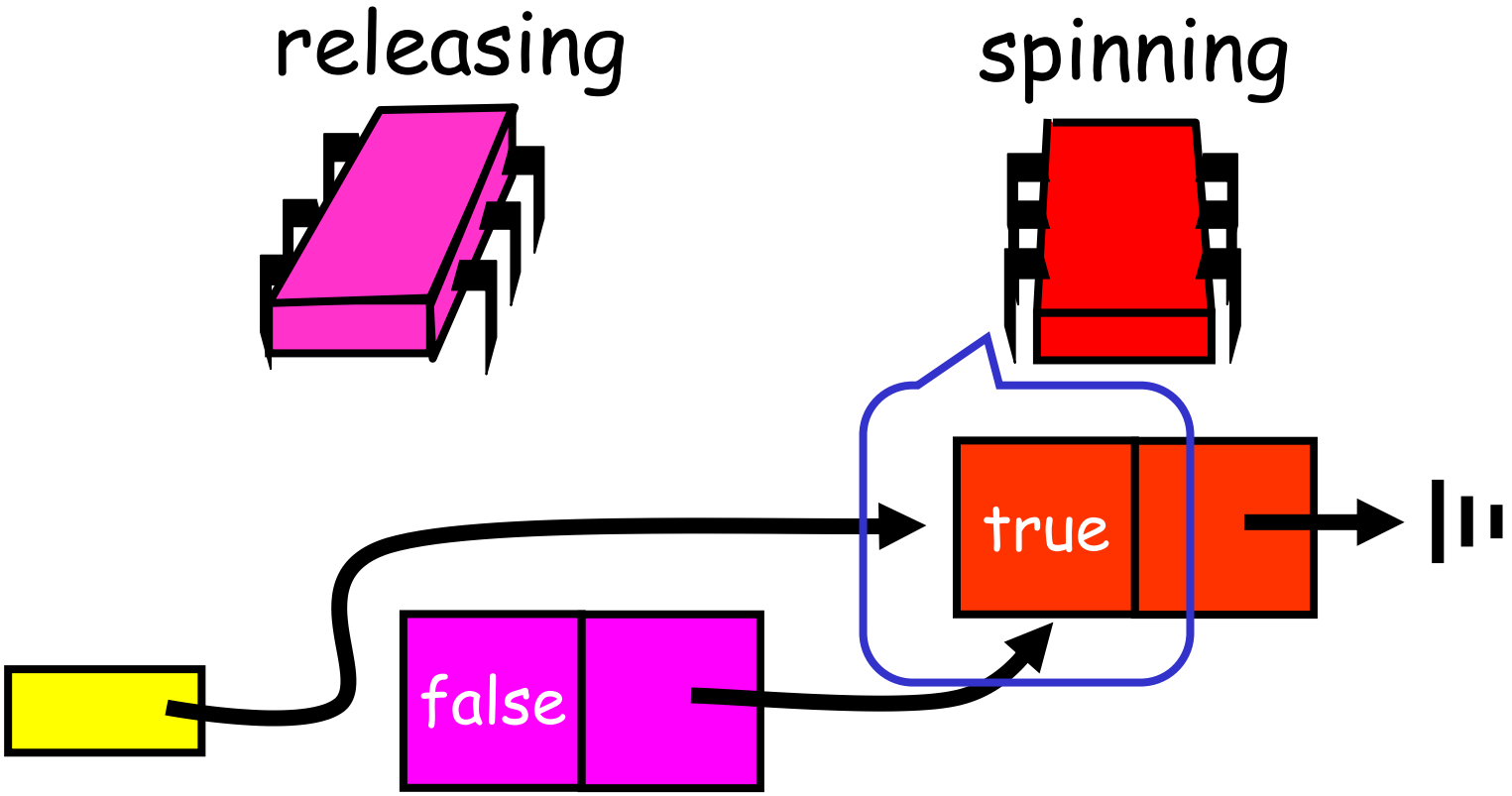
Purple Release



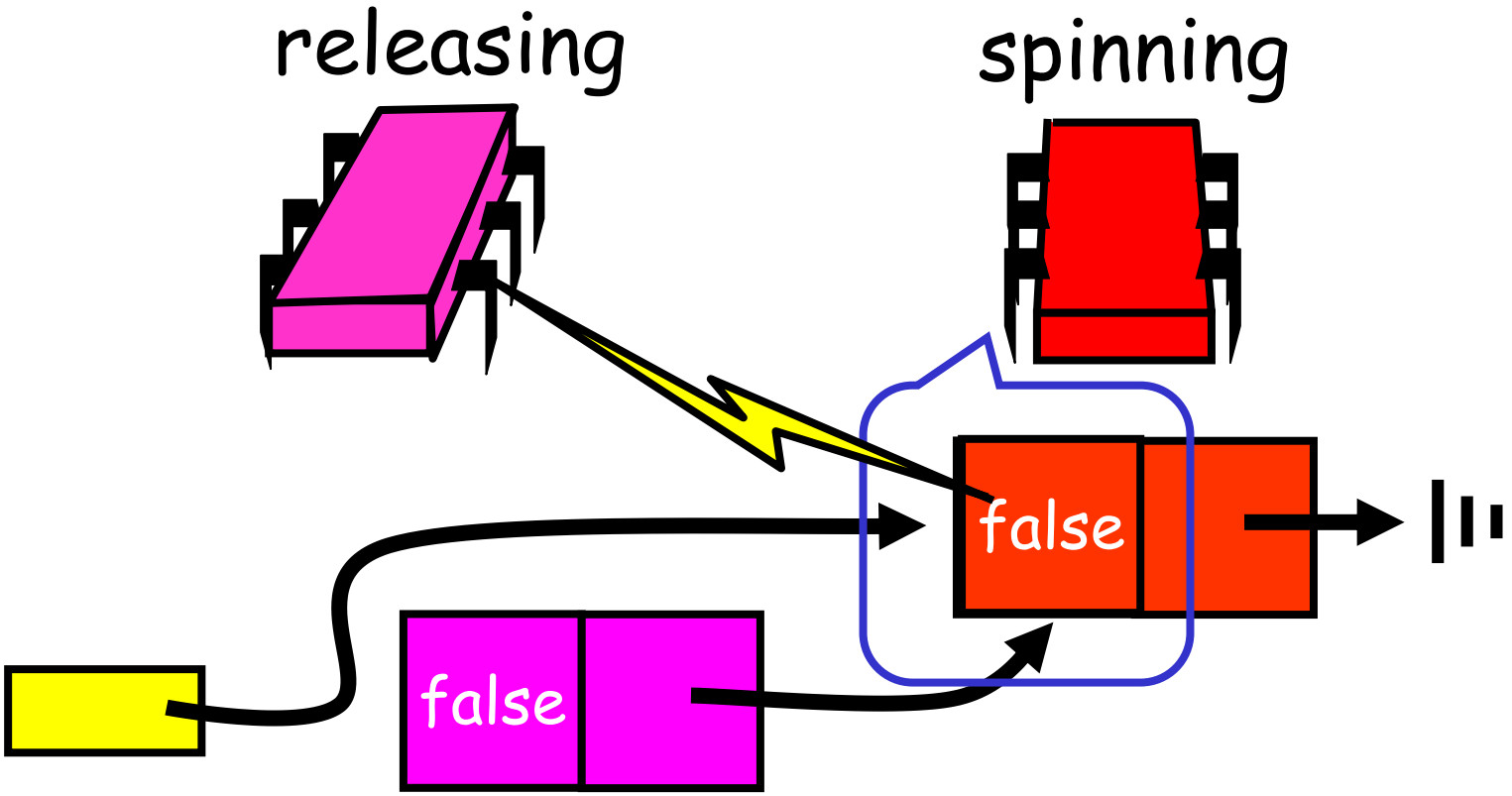
Purple Release



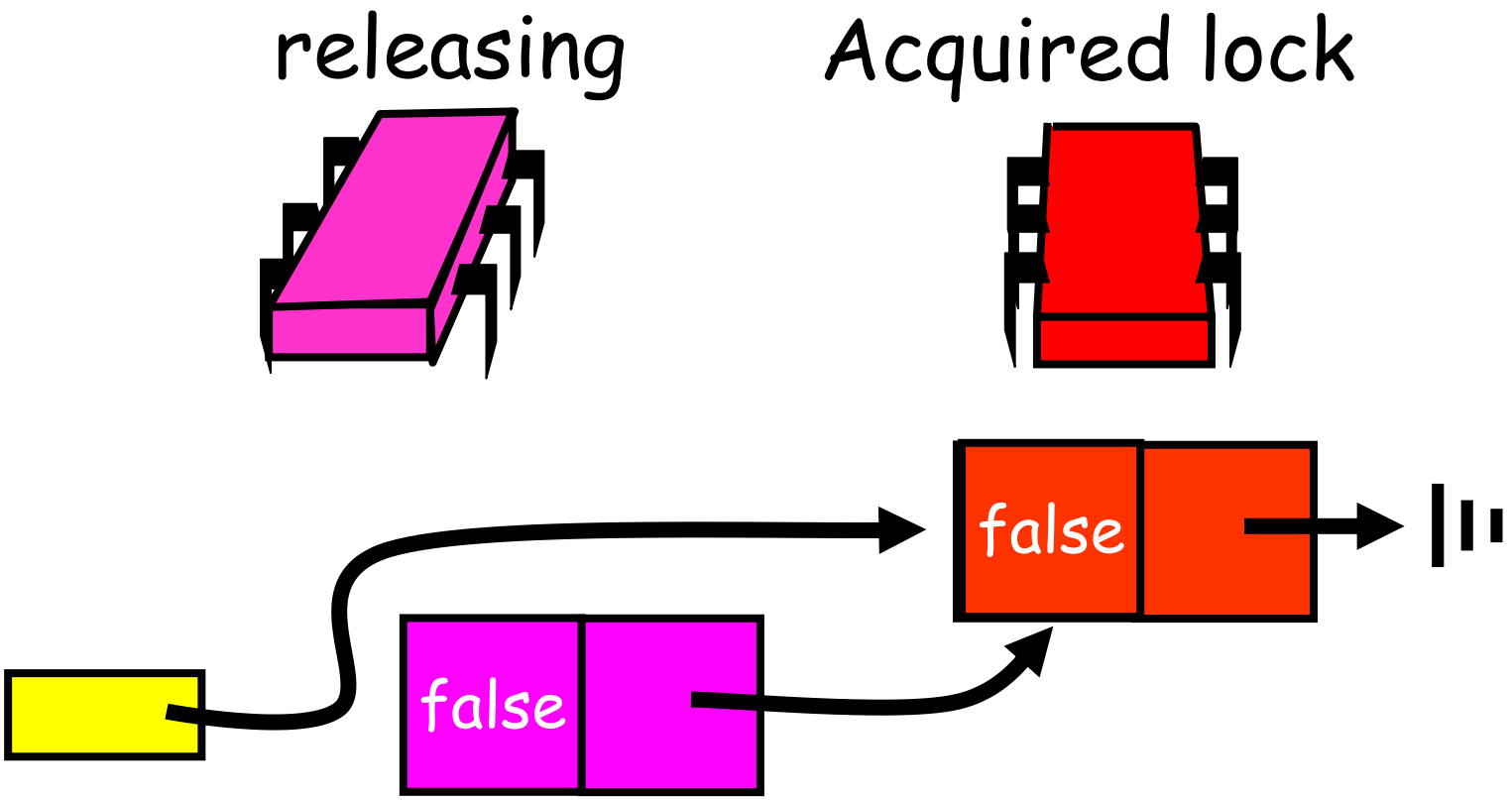
Purple Release



Purple Release



Purple Release



Lock with timeout

- Java interface includes a tryLock() method to specify a maximum duration the thread is willing to wait to acquire the lock
- Should the thread not acquire the lock in the designated time, the thread will timeout

Abortable Locks

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

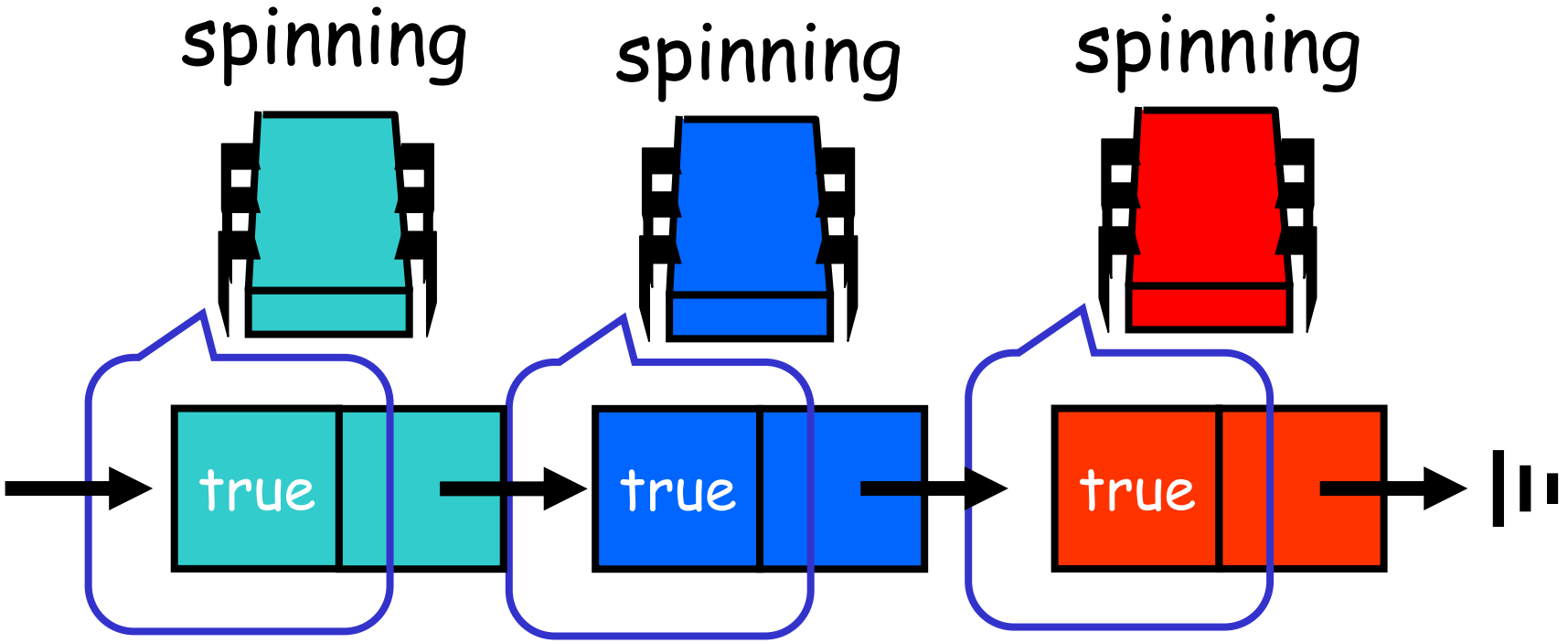
Lock with timeout

- What happens to other threads when you timeout?

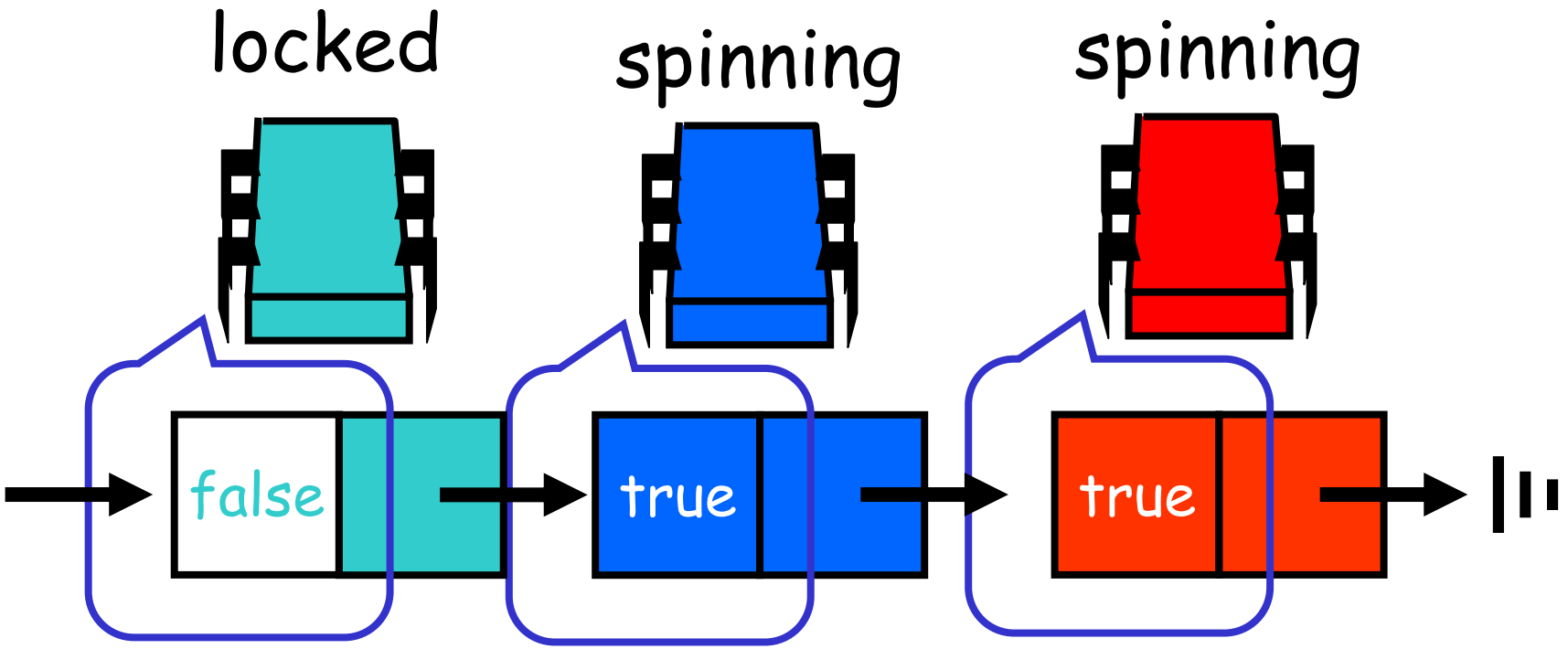
Back-off Lock

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

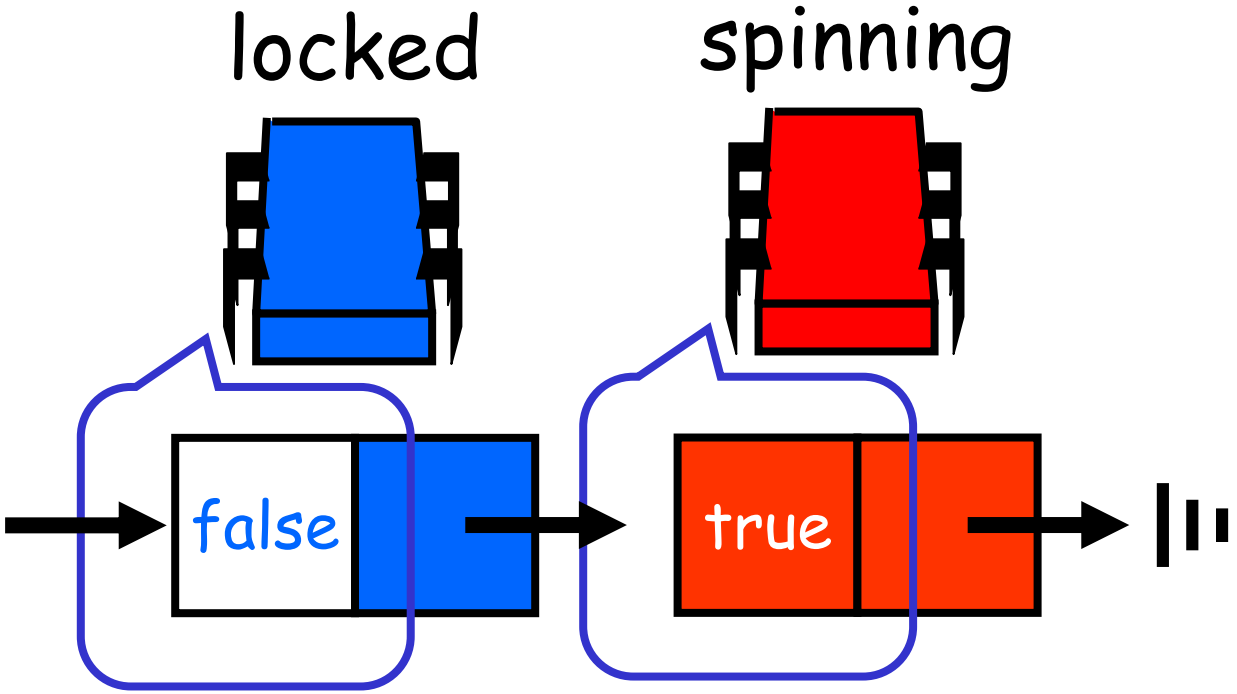
MCS Queue Locks



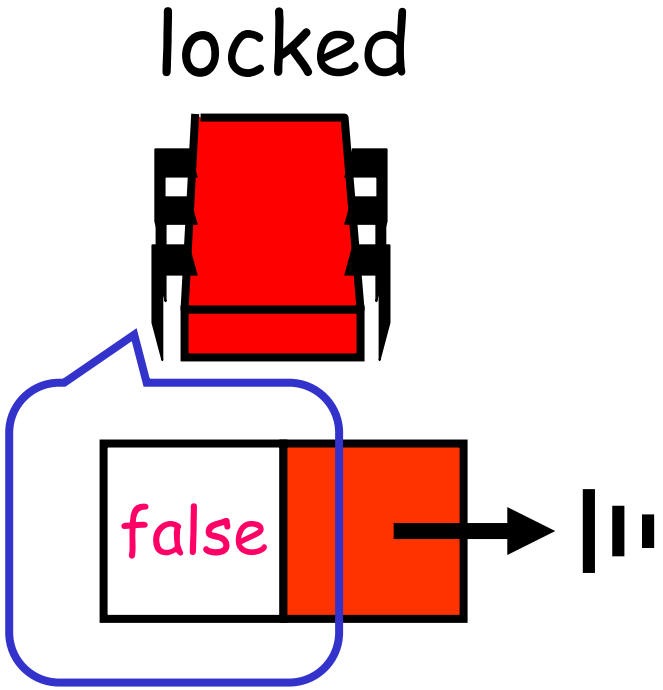
MCS Queue Locks



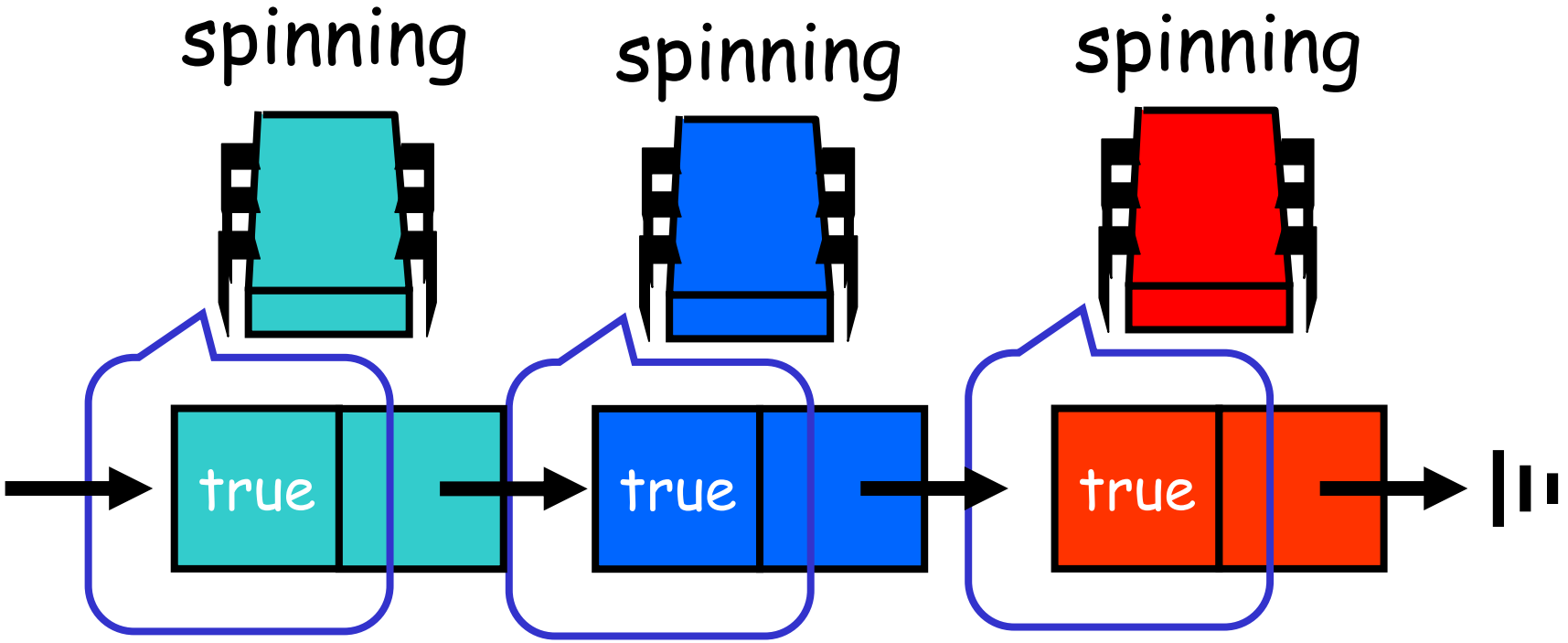
MCS Queue Locks



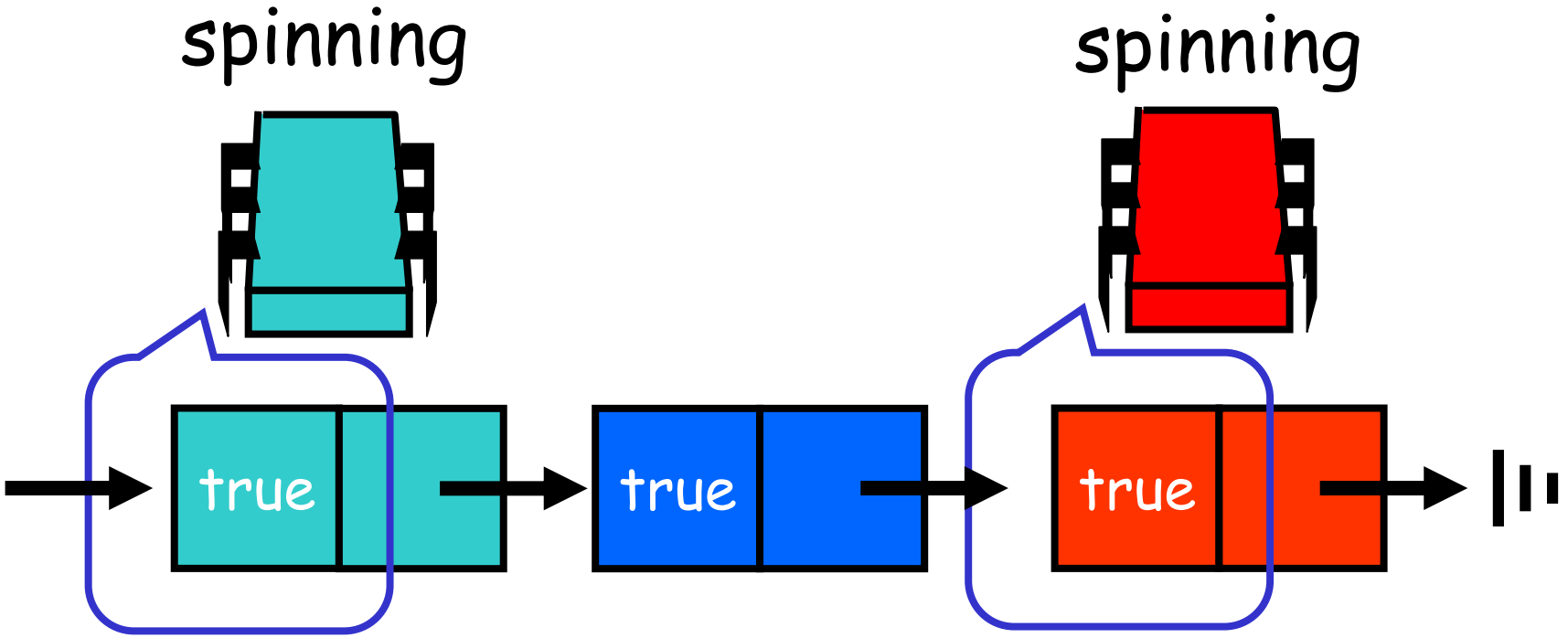
MCS Queue Locks



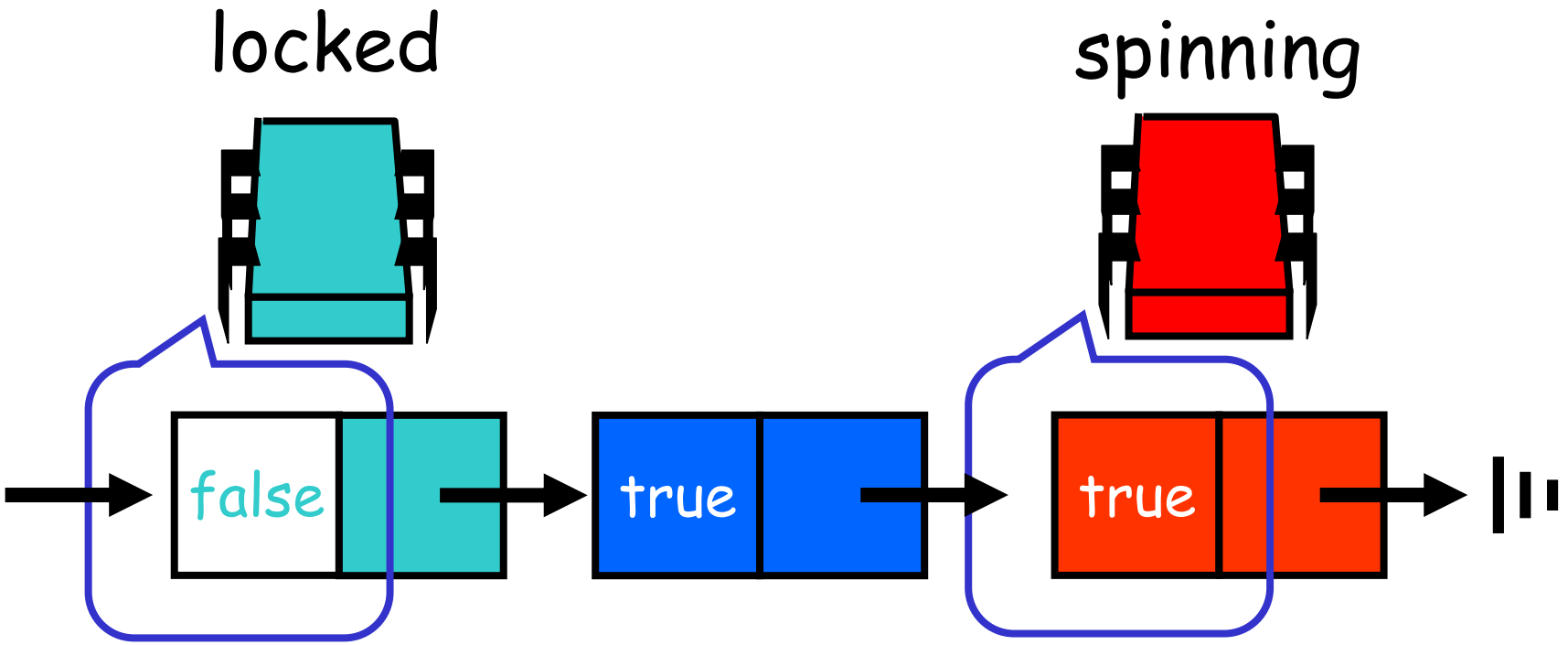
MCS Queue Locks



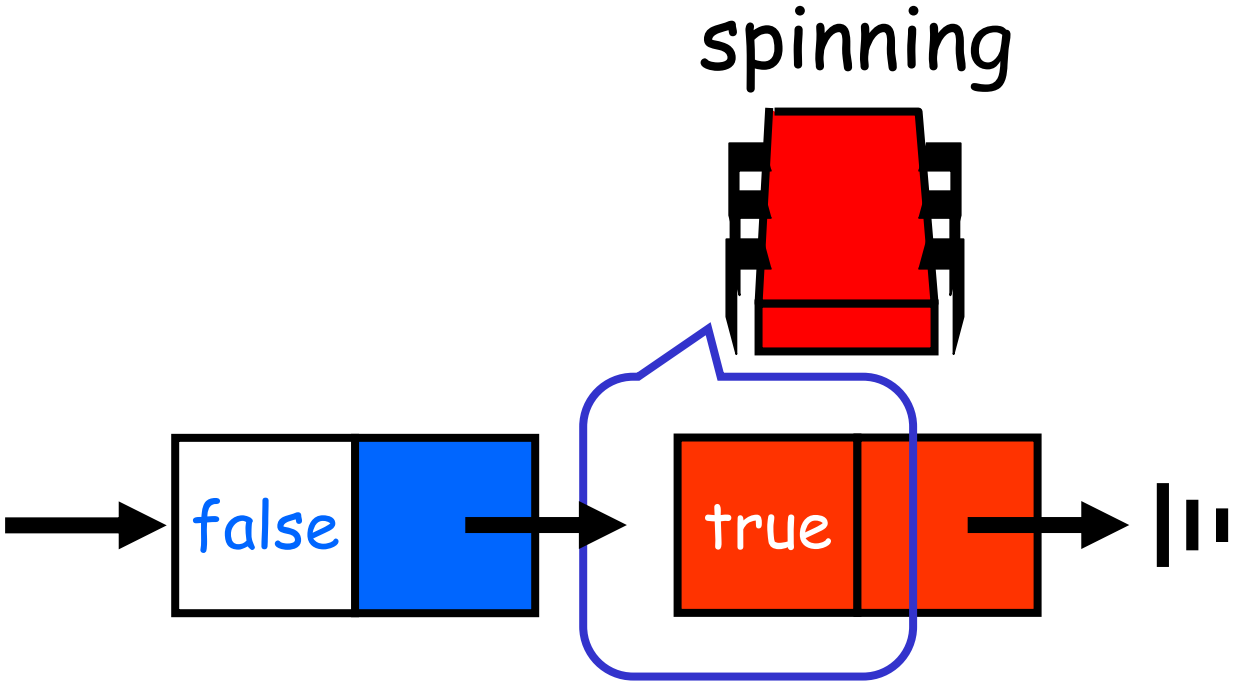
MCS Queue Locks



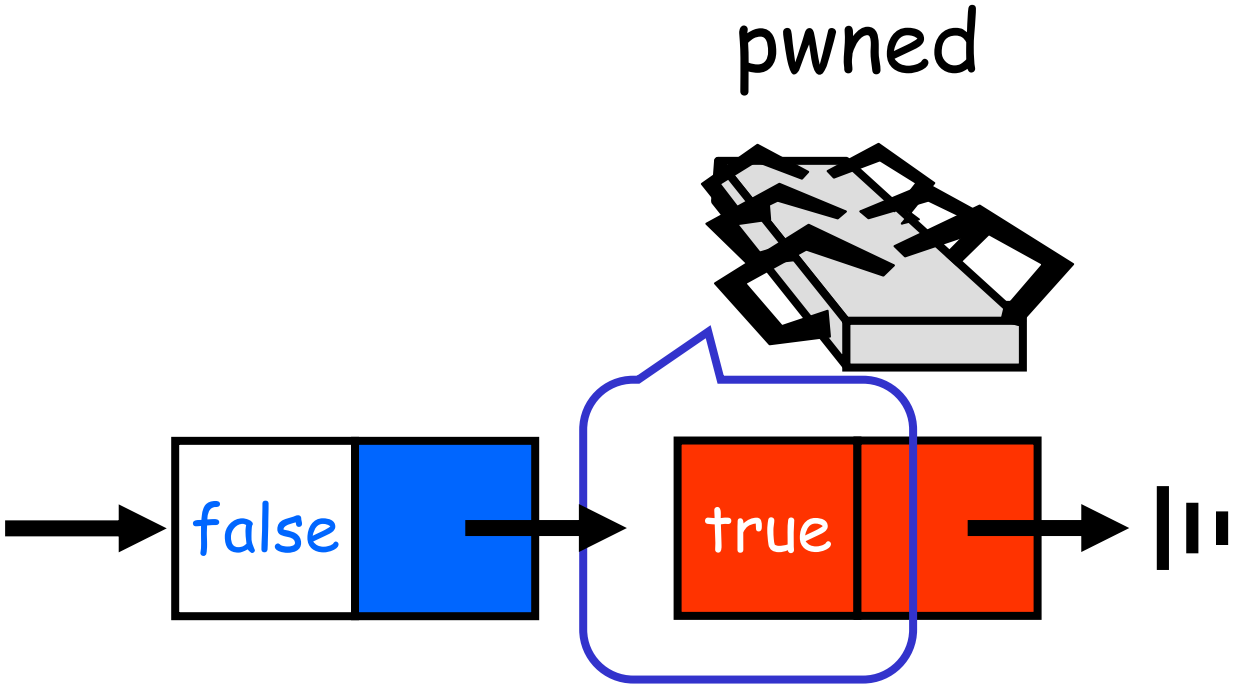
MCS Queue Locks



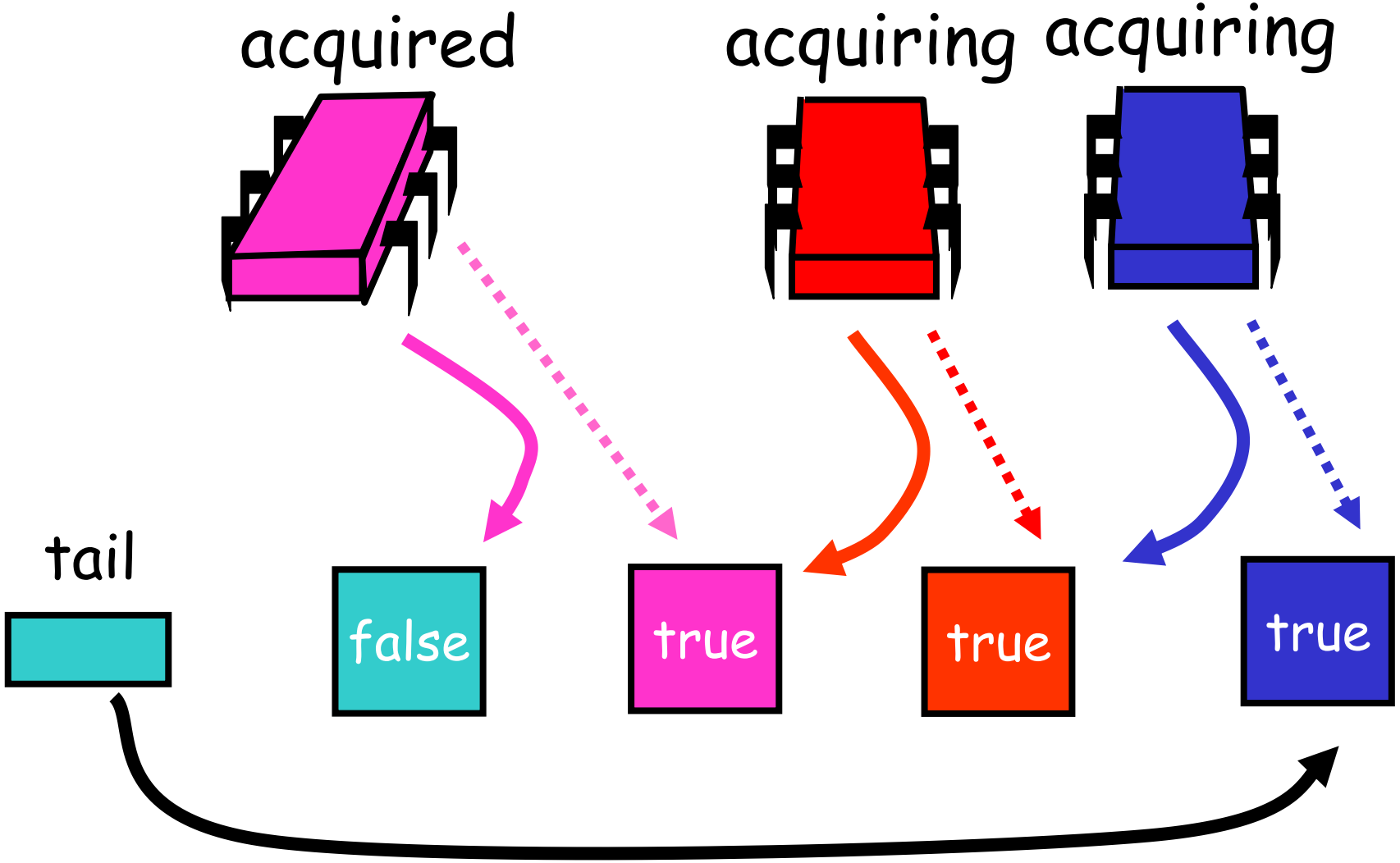
MCS Queue Locks

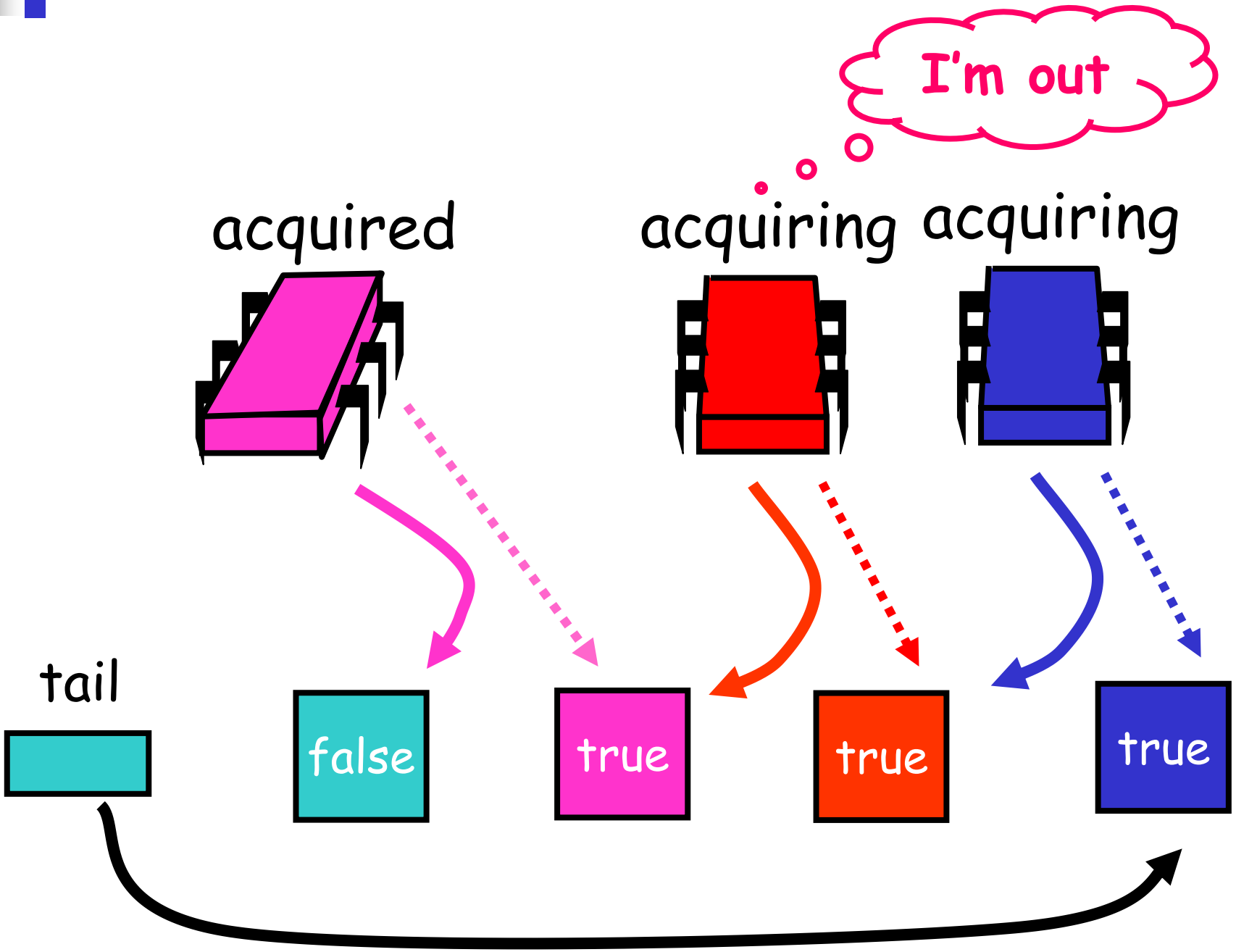


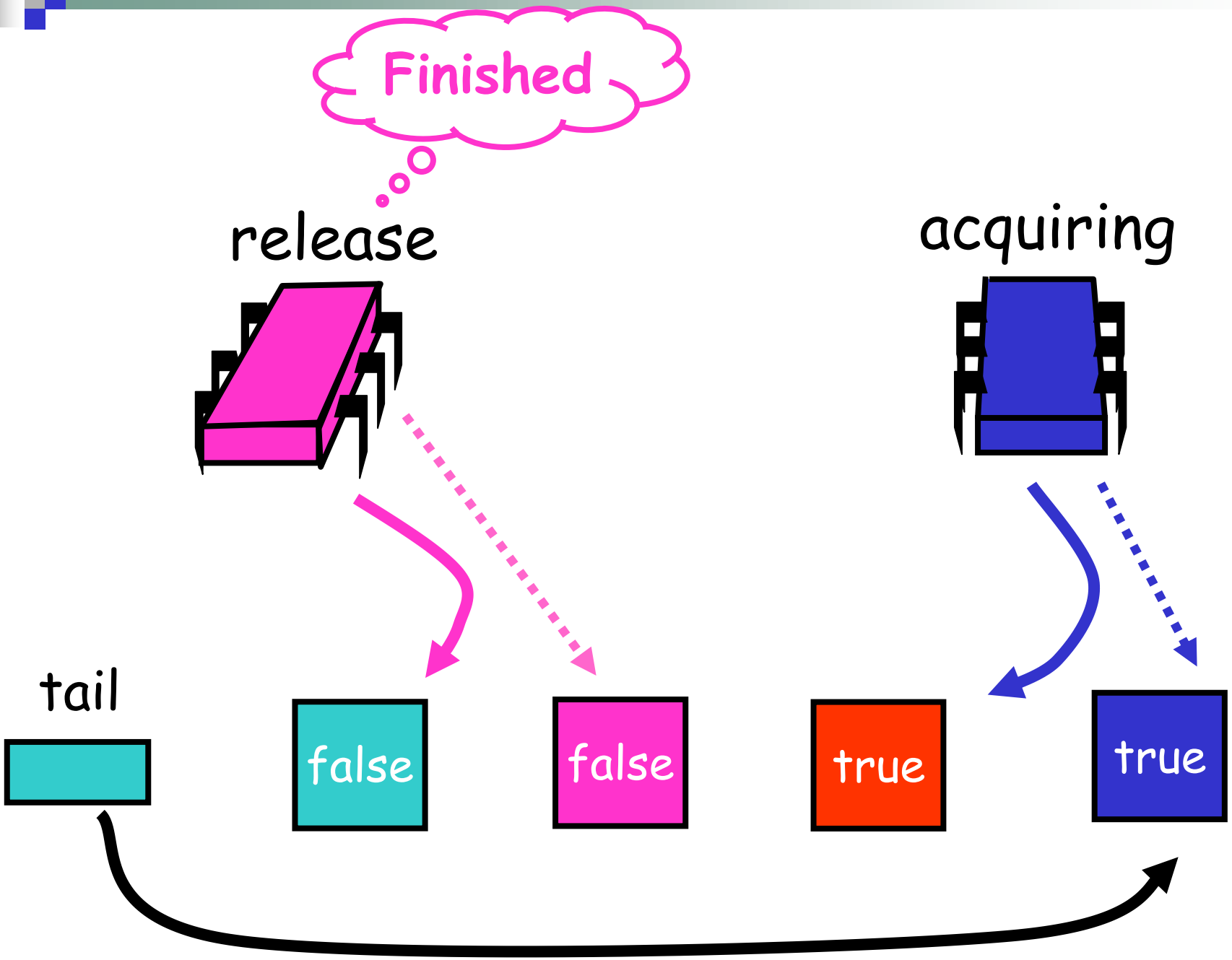
MCS Queue Locks



CLH Queue Lock




I'm out
acquired
acquiring
acquiring
tail
false
true
true
true


Finished
release
acquiring
tail
false
false
true
true

Queue Locks

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

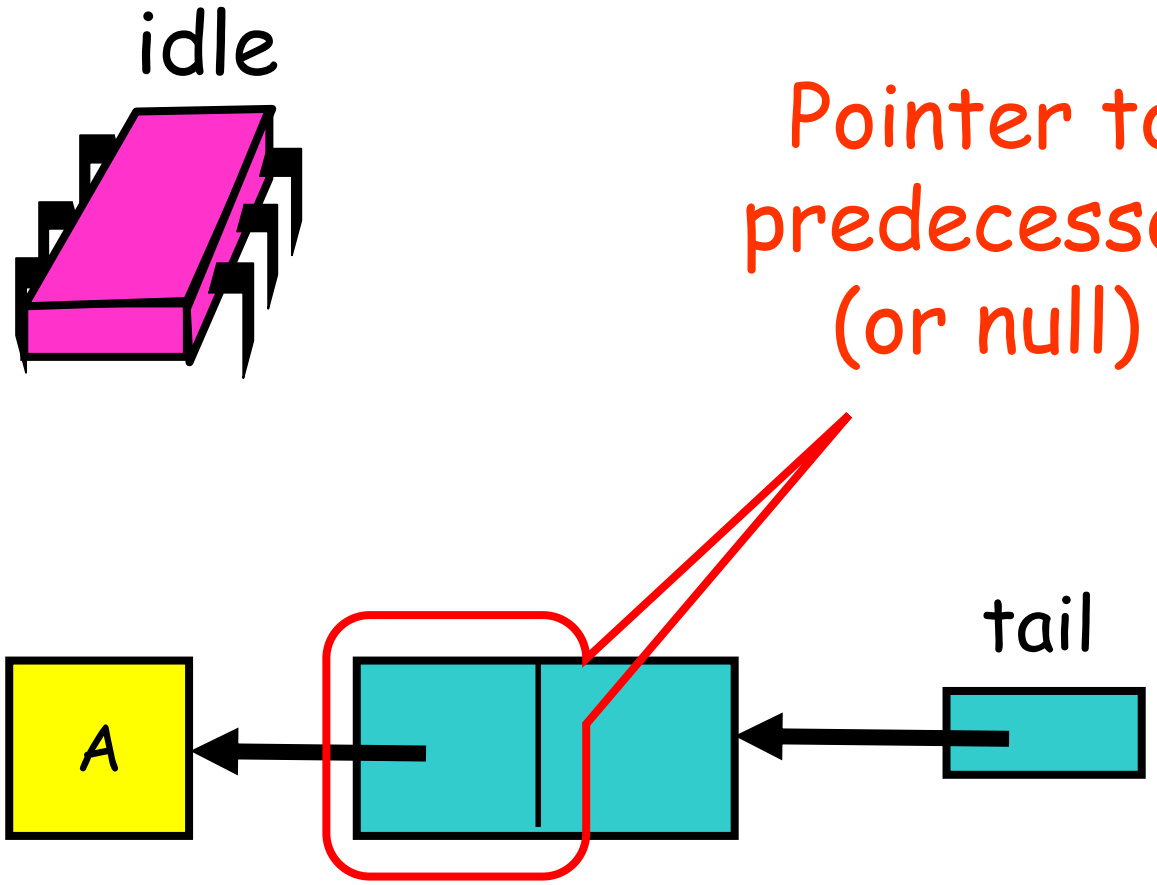
Abortable CLH Lock

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

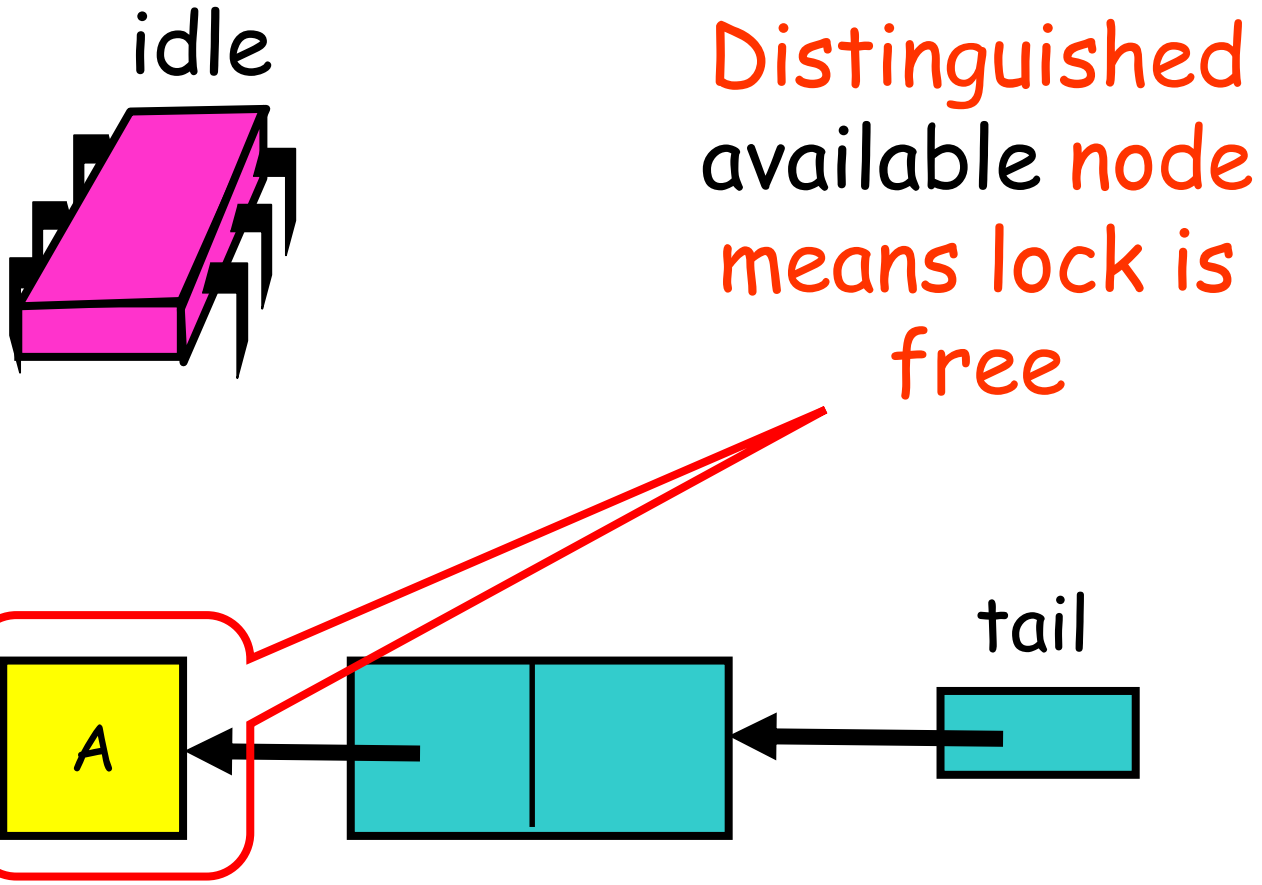
A queue lock with timeouts

- When a thread times out, it marks it node as abandoned
- The successor in the queue notices that the node has been abandoned
- Successor starts spinning on the abandoned node’s predecessors

Initially

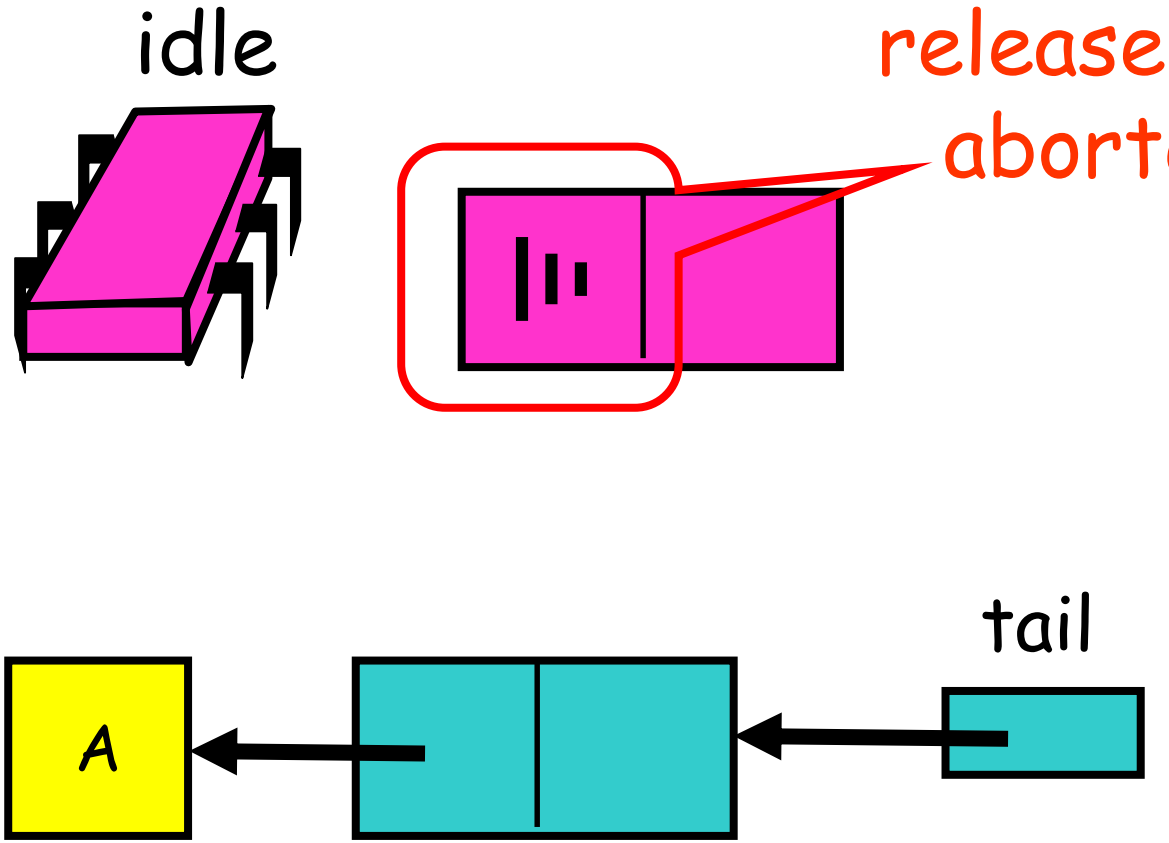


Acquiring

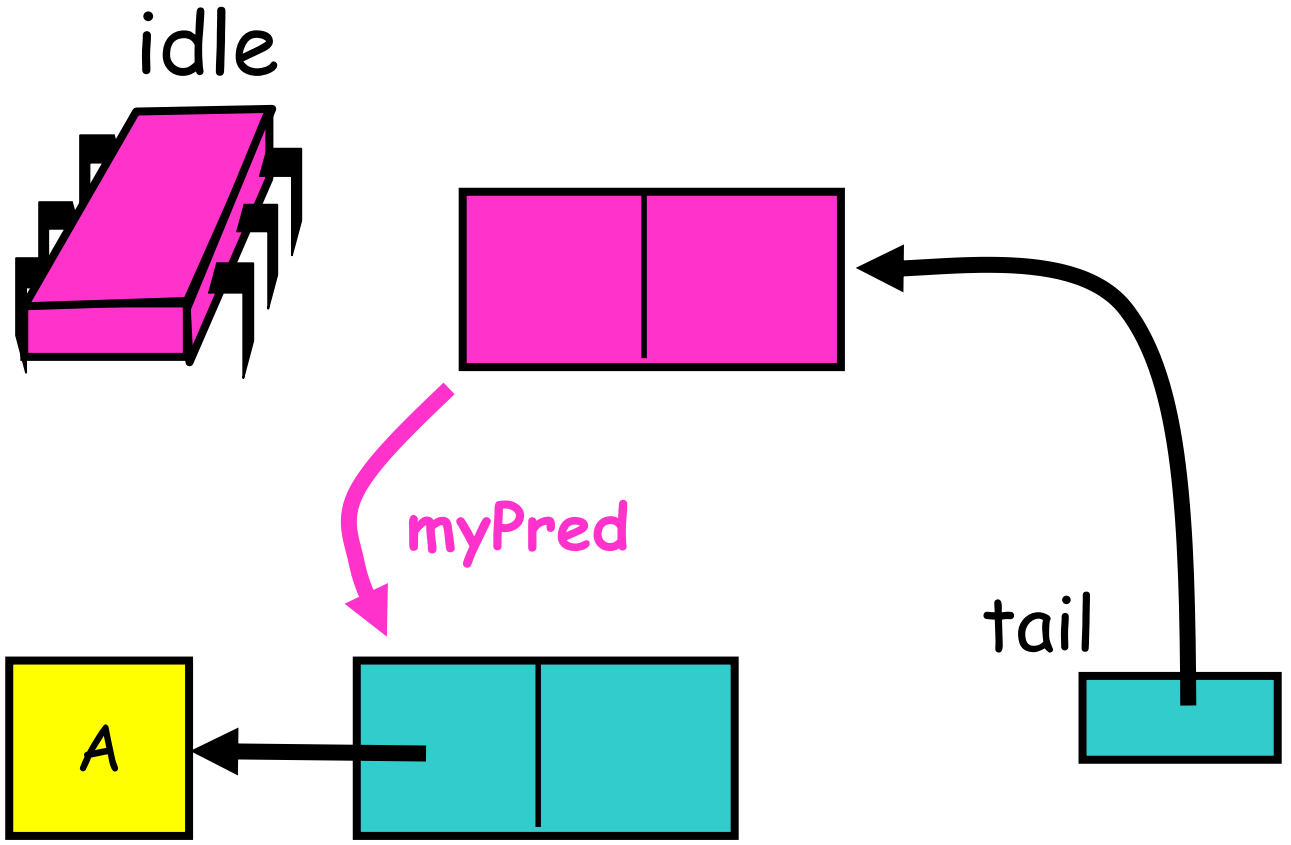

idle
Distinguished
available node
means lock is
free
tail
A

Acquiring

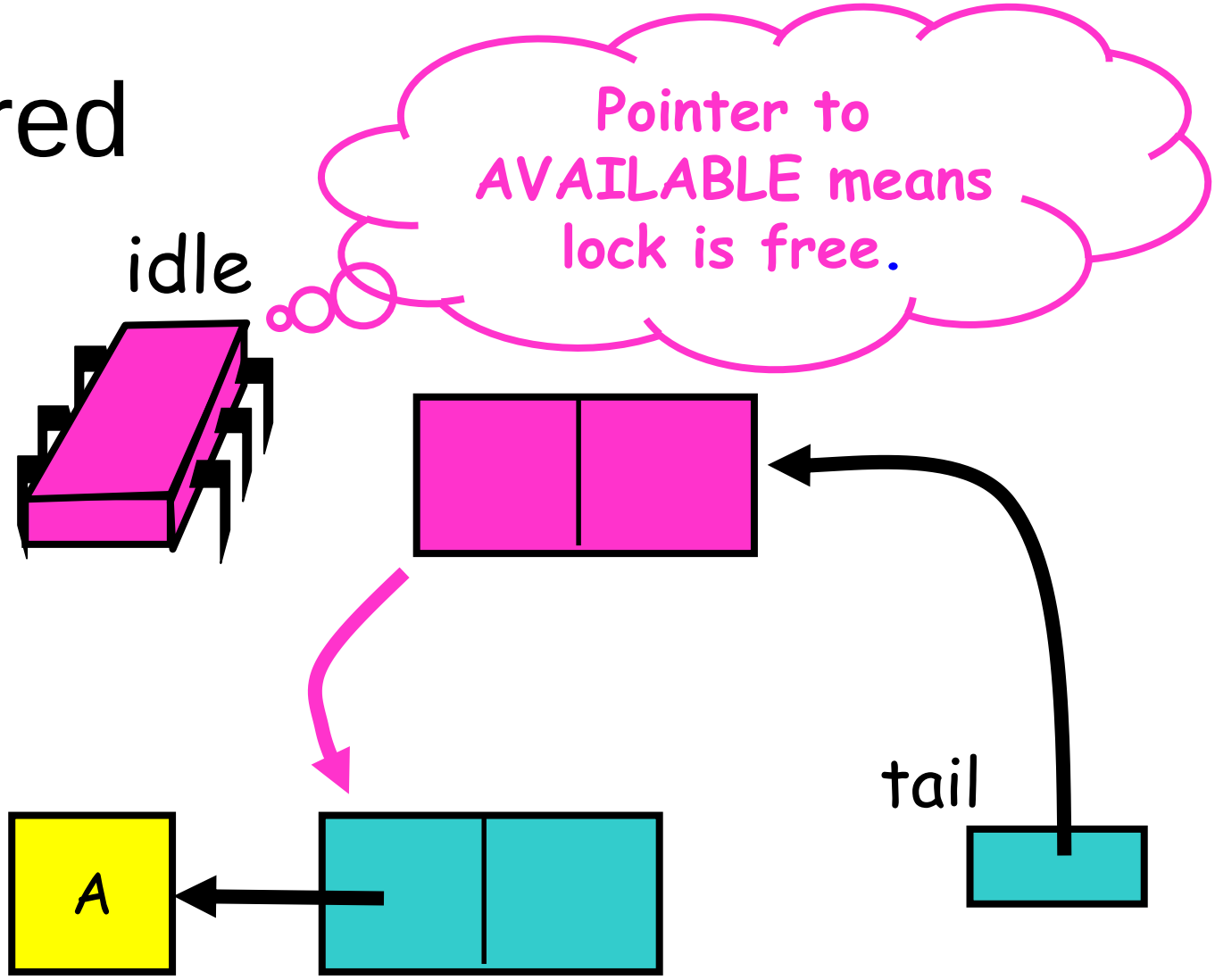
Null predecessor means lock not released or aborted



Acquiring



Acquired



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;
   }
```

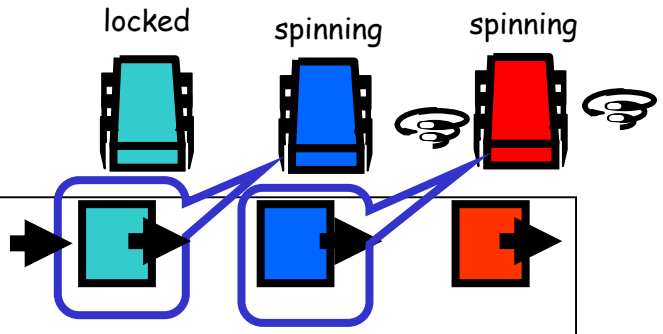
Swap with tail

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;
  }
}
```

What do I do when I time out?

Time-out Lock

```
…
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 Lock

```
…
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

Composite Locks

- Spin lock algorithms impose trade-offs
- Most spin locks have advantages and disadvantages

Composite Locks

- Backoff Lock:
  - \+ provide trivial timeout protocols
  - \- are not scalable
  - \- may have critical section underutilization if timeout parameters are not well-tuned.

Composite Locks

- Queue locks:
  - \+ provide first-come-first-served fairness
  - \+ fast lock release
  - \- nontrivial protocols for abandoned nodes

Composite Locks

- Composite locks combine the best of both approached

Composite Locks

- Idea:
  - In a queue only the threads at the front of the queue require lock handoffs
- Solution:
  - Keep a small number of waiting threads in a queue and have the rest use exponential backoff

Composite Locks

- Keep a short, fixed-sized array of lock nodes
- Each thread that tries to acquire the lock selects a node in the array at random
- If the node is in use, the thread backs off and tries again

Composite Locks

- Once the thread acquires a node, it enqueues that node in a TOLock-style queue
- The thread spins on the preceding node and when that node's owner signals it is done, the thread enters the critical section

Composite Locks

- Every node in the array has a state:
  - FREE, WAITING, RELEASED, ABORTED
- Actions depend on the state of the randomly selected node

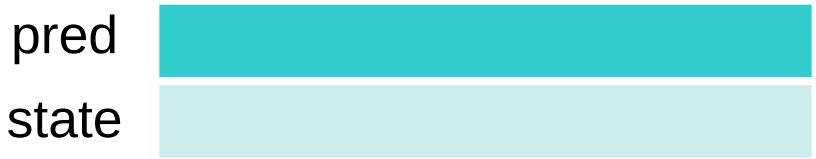
Composite Lock

- A FREE node is available for other threads to acquire
- A WAITING node is linked into the queue and either in the critical section or waiting to enter
- A node becomes RELEASED when the owner leaves the critical section
- If a node is enqueued but the owner has quit, the node is ABORTED

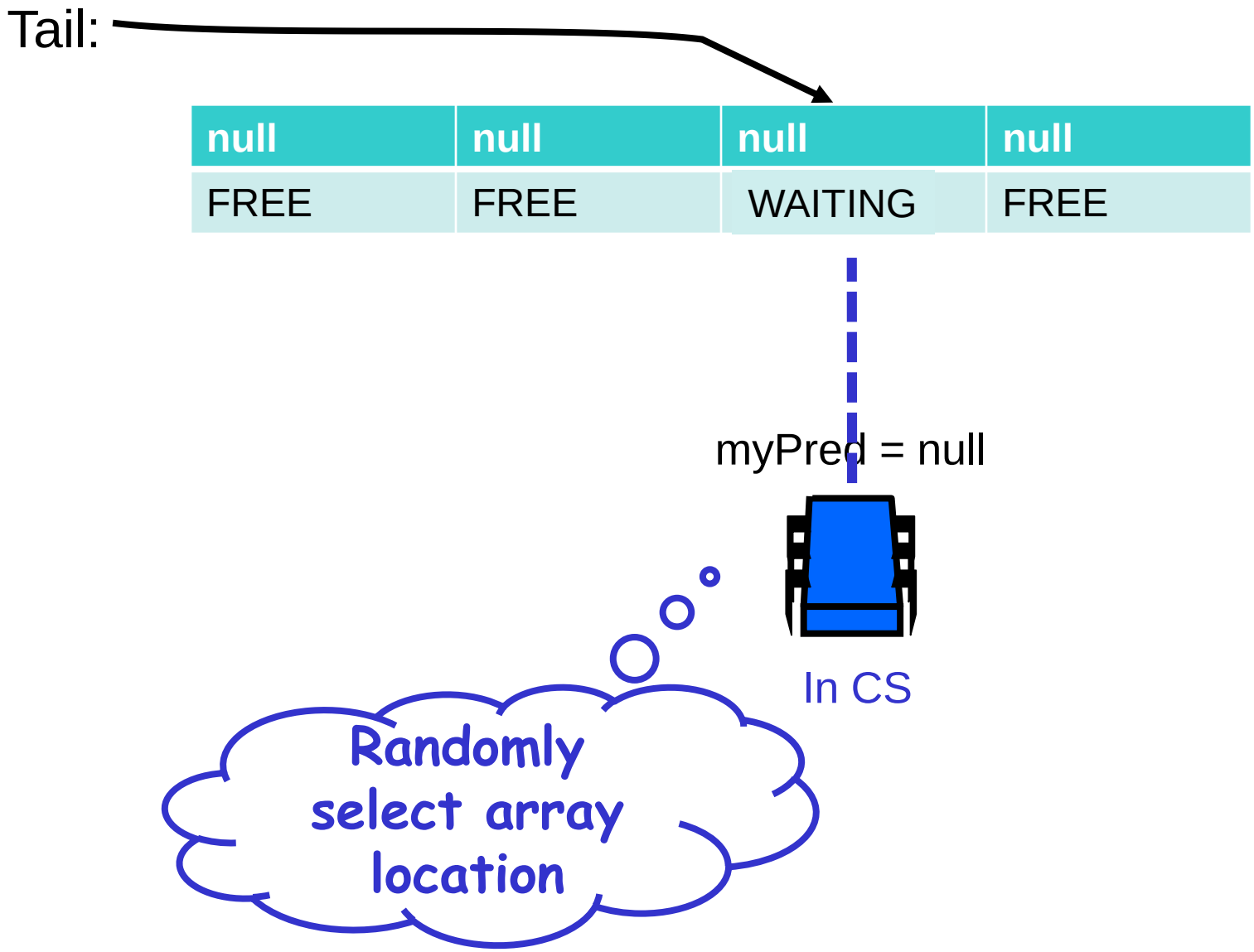
Composite Lock

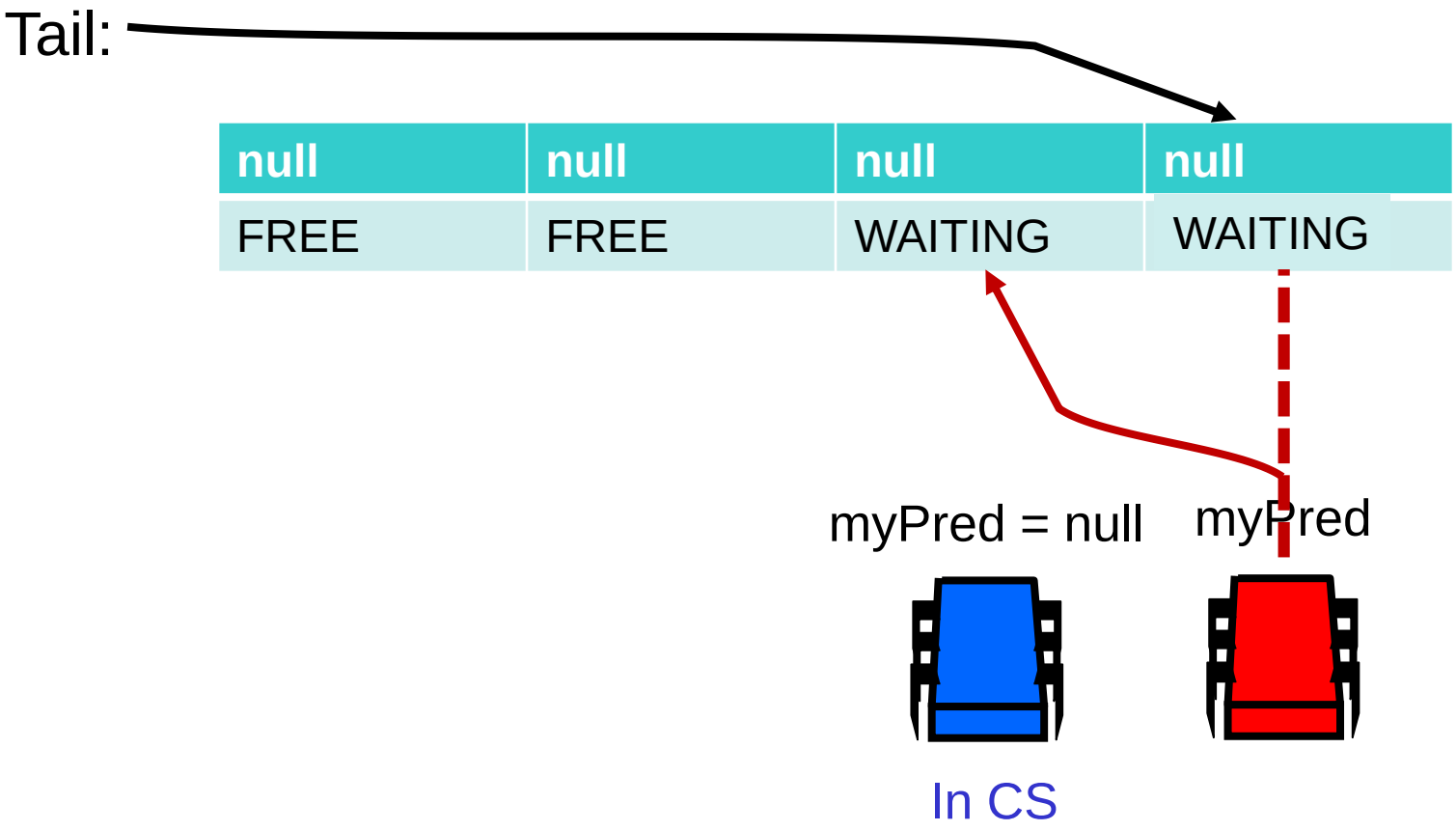
- A thread acquires the lock in three steps:
  - Acquires a node in the waiting array
  - Enqueues the node in the queue
  - Waits until the node reaches the head of the queue

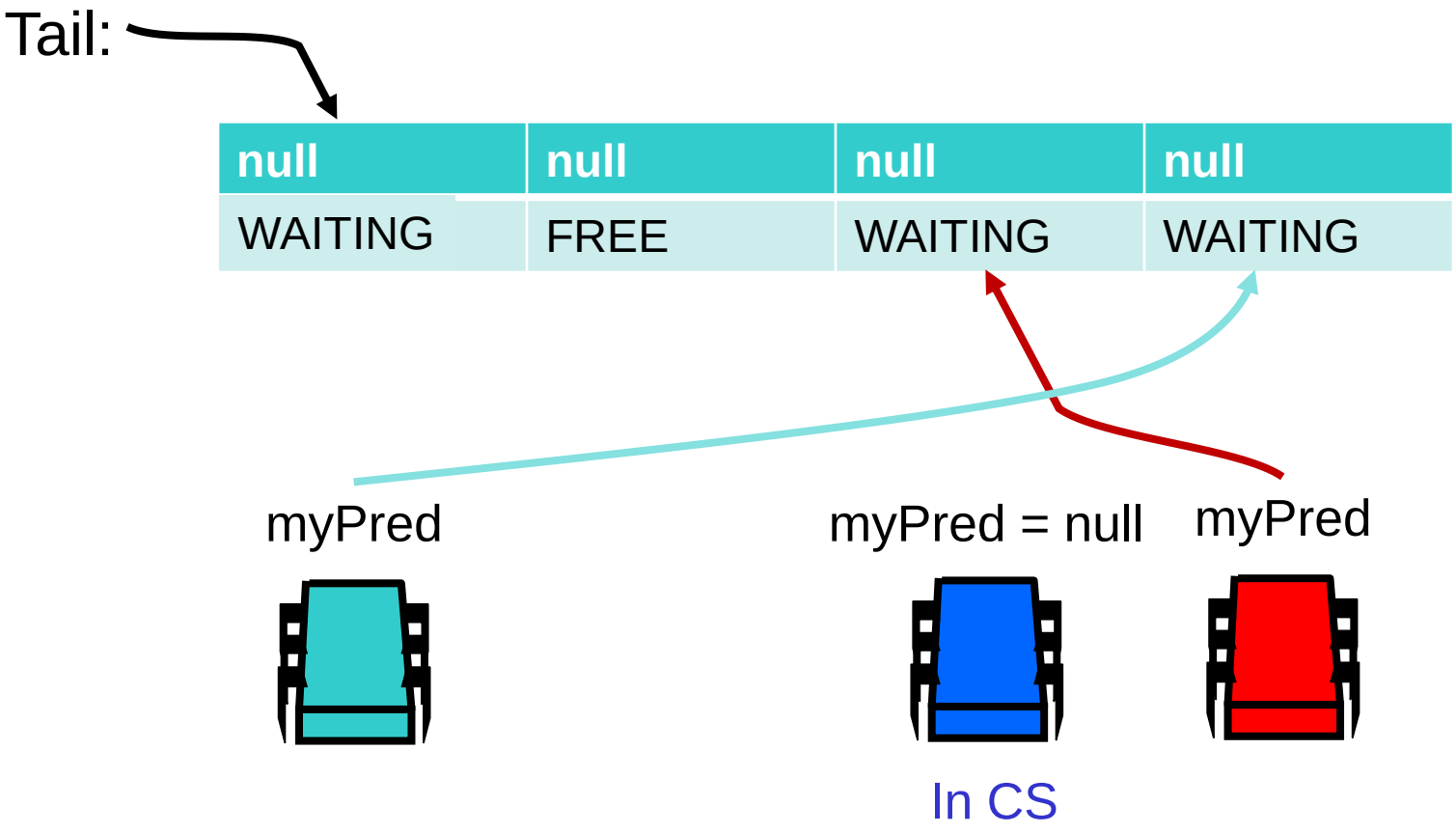
Qnode:

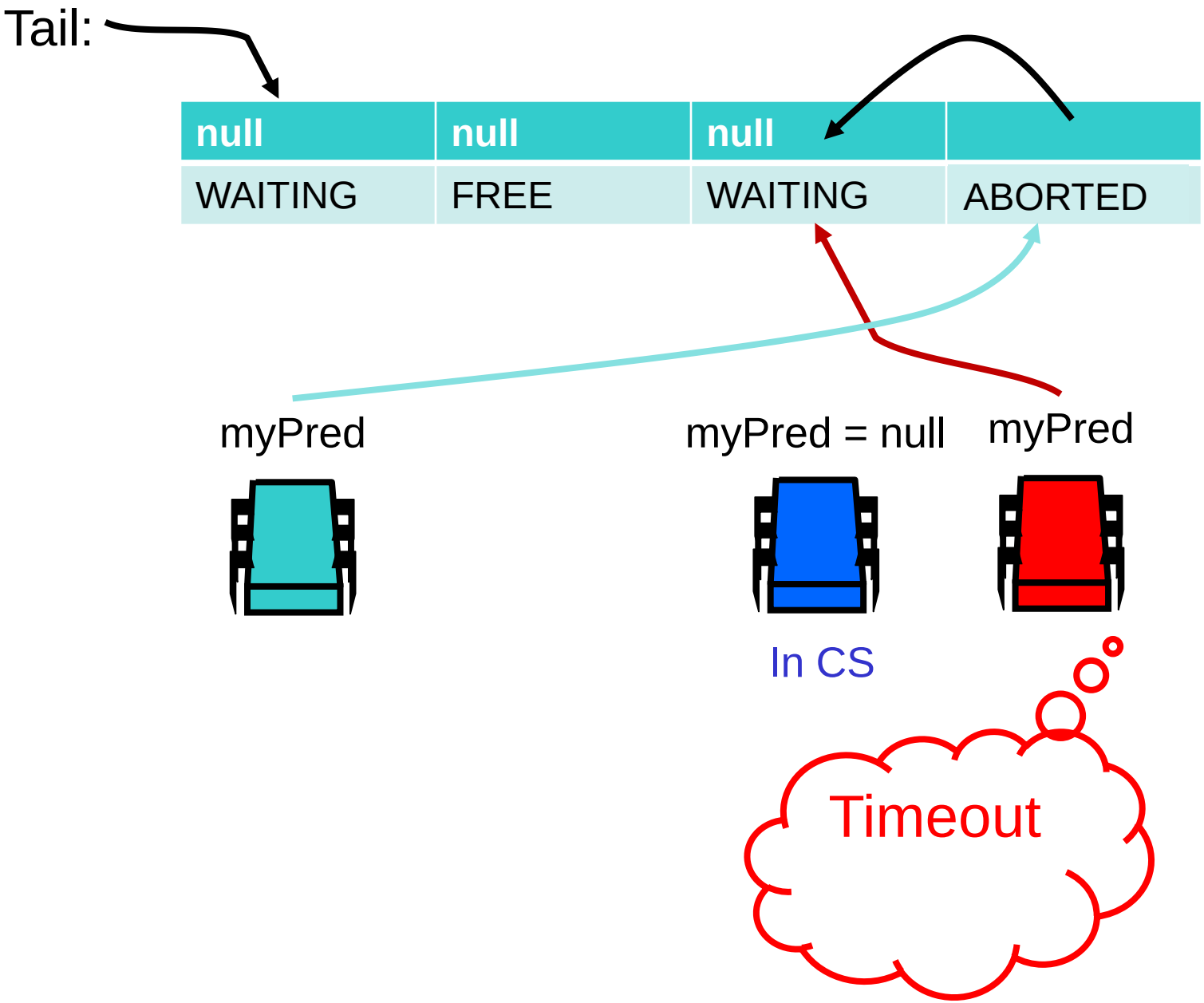


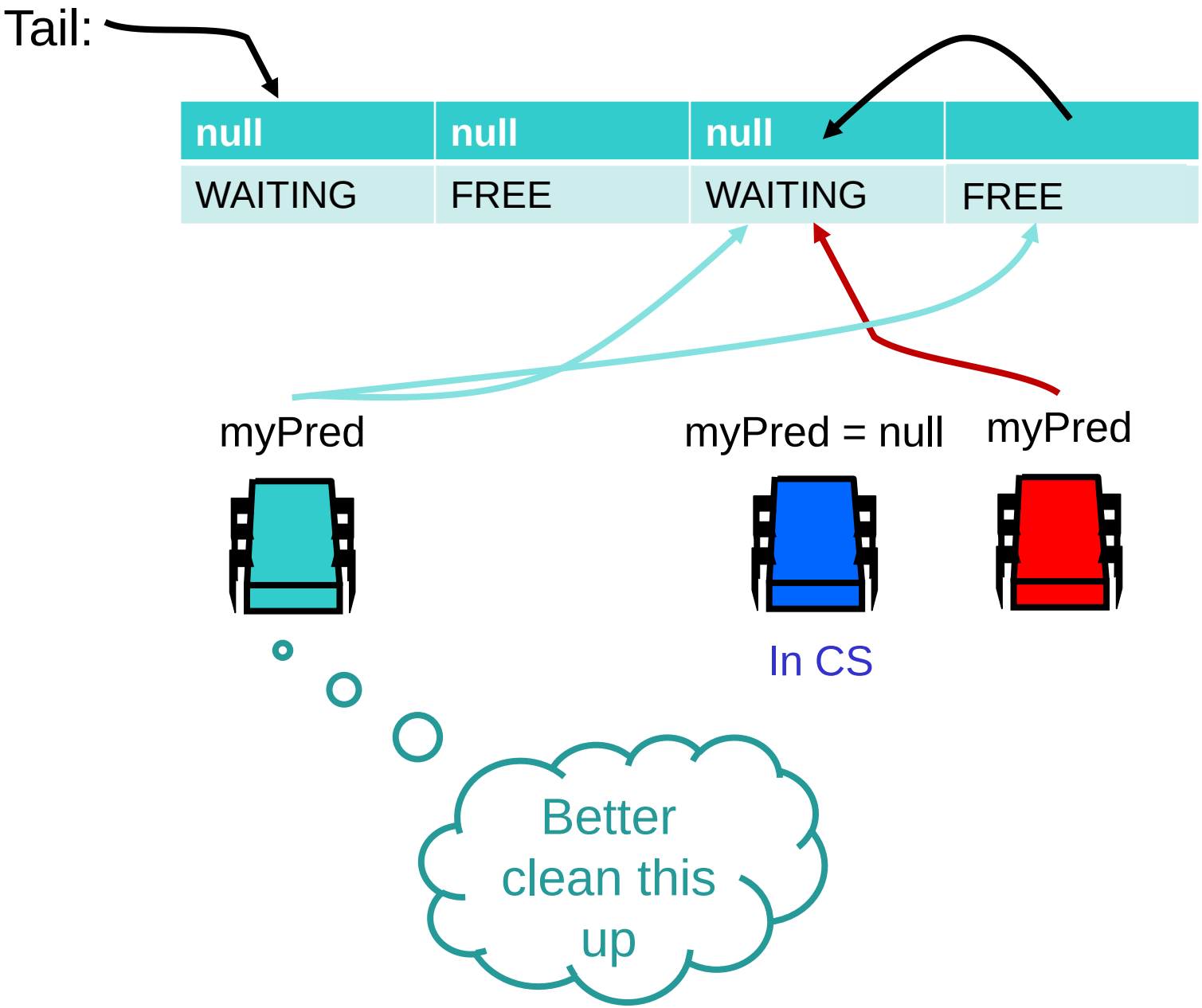
myPred


Tail:
null
null
null
null
FREE
FREE
WAITING
FREE
myPred = null
In CS
Randomly select array location


Tail:
null
null
null
null
FREE
FREE
WAITING
WAITING
myPred = null
myPred
In CS


Tail:
null
null
null
null
WAITING
FREE
WAITING
WAITING
myPred
myPred = null
myPred
In CS


Tail:
null
null
null
WAITING
FREE
WAITING
ABORTED
myPred
myPred = null
myPred
In CS
Timeout


Tail:
null
null
null
WAITING
FREE
WAITING
FREE
myPred
myPred = null
myPred
In CS
Better clean this up

Composite Lock

```
public class CompositeLock implements
  Lock {
  AtomicReference<Qnode> tail;
  Qnode [] waiting;
…
```

Tail field is either null or points to last value entered into queue (waiting array)

Composite Lock

```
public class CompositeLock implements
  Lock {
  AtomicReference<Qnode> tail;
  Qnode [] waiting;
…
```

Short queue of waiting threads – implemented as array

Composite Lock

```
enum State {FREE, WAITING, RELEASED,
  ABORTED}
class Qnode {
  AtomicReference<State> state;
  Qnode pred;

  public Qnode() {
      state = new
  AtomicReference<State>
  (State.FREE);
}
```

Composite Lock

```
enum State {FREE, WAITING, RELEASED,
  ABORTED}
class Qnode {
  AtomicReference<State> state;
  Qnode pred;

  public Qnode() {
      state = new
  AtomicReference<State>
  (State.FREE);
}
```

Starting states for all threads is FREE

Composite Lock

```
public boolean tryLock() {
   Qnode node = acquireNode();
   Qnode pred = spliceNode(node);
   waitForPredecessor(pred, node);
}
```

Composite Lock

```
public boolean tryLock() {
  Qnode node = acquireNode();
  Qnode pred = spliceNode(node);
  waitForPredecessor(pred, node);
}
```

Randomly select node from waiting array and return available node

Composite Lock

```
public boolean tryLock() {
  Qnode node = acquireNode();
  Qnode pred = spliceNode(node);
  waitForPredecessor(pred, node);
}
```

Add selected node to queue

Composite Lock

```
public boolean tryLock() {
   Qnode node = acquireNode();
   Qnode pred = spliceNode(node);
   waitForPredecessor(pred, node);
}
```

Add selected node to queue

acquireNode()

- Thread selects a node at random
- Tries to acquire the node by setting its state from FREE to WAITING
- If it fails it examines the state
  - If ABORTED or RELEASED it recycles the node

Composite Lock

```
private Qnode acquireNode() {
   Qnode node = waiting[random.nextInt()];
   while (true) {
       if (state.compareAndSet(FREE, WAITING))
       return node;
```

Composite Lock

Choose random location in waiting array

```
private Qnode acquireNode() {
  Qnode node = waiting[random.nextInt()];
  while (true) {
      if (state.compareAndSet(FREE, WAITING))
      return node;
```

Composite Lock

If state was FREE then no problem

```
private Qnode acquireNode() {
   Qnode node = waiting[random.nextInt()];
   while (true) {
      if (state.compareAndSet(FREE, WAITING))
      return node;
```

Composite Lock

If state ABORTED or RELEASED

```
currTail = tail;
if (state == ABORTED || state ==
RELEASED) {
      if (node == currTail) {
         Qnode myPred = null;
         if (state == ABORTED)
            myPred = node.pred;
         if (tail.compareAndSet(
           currTail, myPred)
         node.state.set(WAITING);
         return node;
      }
}
```

Composite Lock

Can only be recycled if last node in queue

```
currTail = tail;
if (state == ABORTED || state ==
RELEASED) {
    if (node == currTail) {
        Qnode myPred = null;
        if (state == ABORTED)
            myPred = node.pred;
        if (tail.compareAndSet(
            currTail, myPred)
        node.state.set(WAITING);
        return node;
    }
}
```

Composite Lock

If last node is ABORTED tail is set to predecessor otherwise null

```
currTail = tail;
if (state == ABORTED || state ==
RELEASED) {
      if (node == currTail) {
         Qnode myPred = null;
         if (state == ABORTED)
            myPred = node.pred;
         if (tail.compareAndSet(
           currTail, myPred)
         node.state.set(WAITING);
         return node;
      }
}
```

Composite Lock

Successfully recycle node and set to WAITING

```
currTail = tail;
if (state == ABORTED || state ==
RELEASED) {
      if (node == currTail) {
         Qnode myPred = null;
         if (state == ABORTED)
            myPred = node.pred;
         if (tail.compareAndSet(
           currTail, myPred)
            node.state.set(WAITING);
         return node;
      }
}
```

spliceNode()

- Once node is acquired, the node is spliced into the queue
- Thread tries to set tail to node
- If timeout, set node to FREE and throw TimeoutException
- If succeeds return prior value of tail (node’s predecessor)

Composite Lock

```
private Qnode spliceNode(Qnode node) {
  Qnode currTail;
  do {
      currTail = tail;
      if (timeout()) {
        node.state.set(FREE);
        throw new TimeoutException();
      }
  } while (!tail.compareAndSet(currTail,
  node);
  return currTail;
}
```

If waited too long…

Composite Lock

```
private Qnode spliceNode(Qnode node) {
   Qnode currTail;
   do {
       currTail = tail;
       if (timeout()) {
         node.state.set(FREE);
         throw new TimeoutException();
       }
   } while (!tail.compareAndSet(currTail,
   node);
   return currTail;
}
```

Composite Lock

```
private Qnode spliceNode(Qnode node) {
  Qnode currTail;
  do {
      currTail = tail;
      if (timeout()) {
        node.state.set(FREE);
        throw new TimeoutException();
      }
  } while (!tail.compareAndSet(currTail,
  node);
  return currTail;
}
```

Try to set tail to new node

Composite Lock

- Finally thread has to wait its turn
- If predecessor is null thread can enter CS
- If predecessor is not RELEASED, check if it is ABORTED
  - If so, mark as FREE and get ABORTED node's predecessor
- If predecessor is RELEASED enter CS

Composite Lock

```
private void waitforPredecessor {
   if (pred == null)
       return;
   State predState = pred.state.get();
   while (predState != RELEASED) {
       if (predState == ABORTED) {
             Qnode temp = pred;
             pred = pred.pred;
             temp.state.set(FREE);
       }
```

Composite Lock

```
private void waitforPredecessor {
   if (pred == null)
       return;
   State predState = pred.state.get();
   while (predState != RELEASED) {
       if (predState == ABORTED) {
             Qnode temp = pred;
             pred = pred.pred;
             temp.state.set(FREE);
       }
```

If I am first in line

Composite Lock

```
private void waitforPredecessor {
  if (pred == null)
      return;
  State predState = pred.state.get();
  while (predState != RELEASED) {
      if (predState == ABORTED) {
            Qnode temp = pred;
            pred = pred.pred;
            temp.state.set(FREE);
      }
```

Spin on predecessor's state

Composite Lock

```
private void waitforPredecessor {
   if (pred == null)
       return;
   State predState = pred.state.get();
   while (predState != RELEASED) {
       if (predState == ABORTED) {
           Qnode temp = pred;
           pred = pred.pred;
           temp.state.set(FREE);
       }
```

If predecessor ABORTED set to FREE and spin on predecessors predecessor

Composite Lock

```
        if (timeout()) {
              node.pred = pred;
              node.state.set(ABORTED);
        } throw new TimeoutException();
        predState = pred.state.get();
    }
    pred.state.set(FREE);
    return;
}
```

If I have waited long enough…

Composite Lock

```
        if (timeout()) {
              node.pred = pred;
              node.state.set(ABORTED);
        } throw new TimeoutException();
        predState = pred.state.get();
    }
    pred.state.set(FREE);
    return;
}
```

When predecessor RELEASED

Composite Lock

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