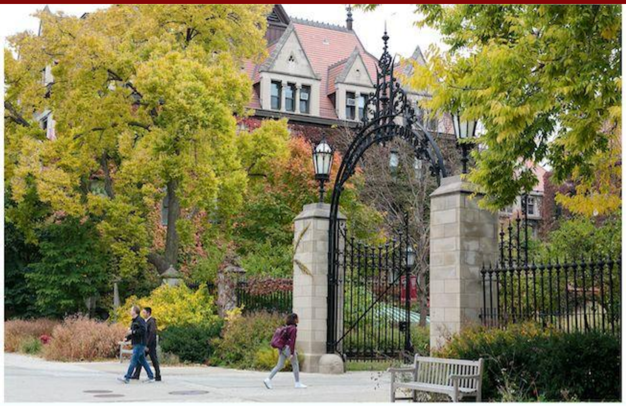
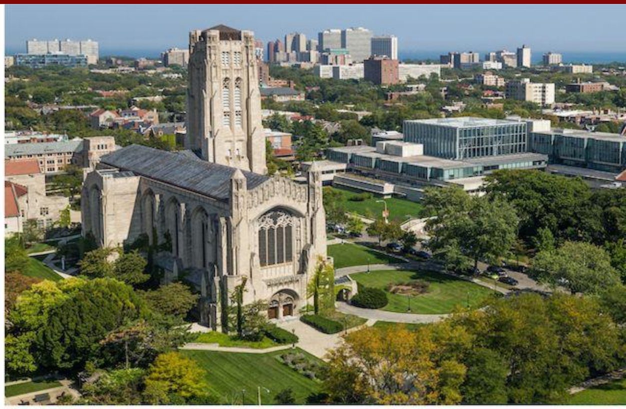
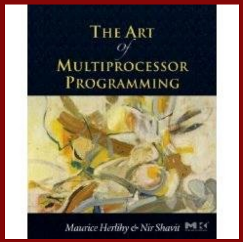
MPCS 52060 - Parallel Programming
M3: Principles of Mutual Exclusion



Original slides from "The Art of Multiprocessor Programming" by
Maurice Herlihy & Nir Shavit with modifications by Lamont Samuels

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Memory Models

Memory Models

- Different architectures (Intel, ARM/POWER PC, etc.) allow the reordering of instructions such that code running on multicore processes can have different results depending on the architecture
- Additionally, compilers can also perform optimizations, where these optimizations can also reorder the read/write operations to shared variables.

```
// Assuming x and y are zeroed out (i.e. x = y = 0)
// at the start of the program.
// Can this program see r1 = 1, r2 = 0 at the end
// of running this program?

// Thread 1      //Thread 2
x = 1            r1 = y
y = 1            r2 = x
```

On x86 (i.e., Intel): **No**

On ARM/POWER: **Yes**

Most modern compiled language using ordinary variables: **Yes**

- A memory model provides a specification for how threads interact with memory and the visibility and consistency of changes to data stored in memory.
    - It helps programmers write data-race free concurrent code as long as they adhere to the memory model.
    - Both architectures and programming languages specify memory models.
        - Hardware architectures do so since it could be the case you write a program directly in assembly language by-passing using a compiler.

Sequential Consistency

- The gold standard memory model is to have sequential consistency
  - "The result of any execution is the same as if the operations of all the processors were executed in some sequential order, and the operations of each individual processor appear in this sequence in the order specified by its program" - Leslie Lamport 1979

```
// Thread 1      //Thread 2
x = 1            r1 = y
y = 1            r2 = x
```

There are 6 possible interleavings for the execution of this program using a sequential consistent model.

```
x = 1
        r1 = y (0)
        r2 = x (1)
y = 1
```

```
        r1 = y (0)
x = 1
y = 1
        r2 = x (1)
```

```
        r1 = y (0)
        r2 = x (0)
x = 1
y = 1
```

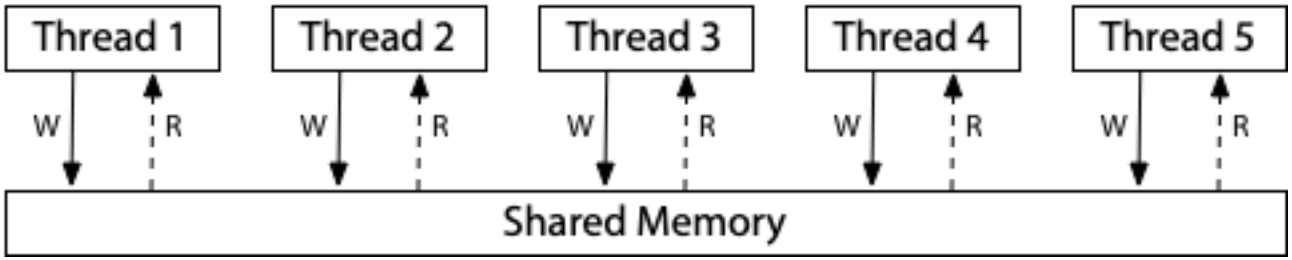
```
        r1 = y (0)
x = 1
        r2 = x (1)
y = 1
```

```
x = 1
y = 1
        r1 = y (1)
        r2 = x (1)
```

```
x = 1
        r1 = y (0)
y = 1
        r2 = x (1)
```

Sequential Consistency

- A visual model of how a sequential consistency machine works is as follows



- All processors share the same shared memory, where the machine can only process a single read or write operation from one thread at a time.
  - The single use at a time imposes a sequential order on the execution all the memory accesses.
- Sequential consistency is a great from a programmers perspective because it makes easier to reason about the execution of concurrent programs.
- However, the downside of sequential consistency is that it limits the ability for the hardware/compilers to perform optimizations that would result in faster execution of programs.
  - Thus, no modern architecture/programming memory model implements this model.

Diagram Source: https://research.swtch.com/hwmm

DRF-SC

- Since most processors cannot guaranteed sequential consistency, processors today guarantee a property called data race-free sequential-consistency (DRF-SC or sometimes SC-DRF).
  - A system guaranteeing DRF-SC provides specific synchronizing instructions that coordinate threads
  - These instructions create "happens-before" relationships between code executing on processor and code running on another.

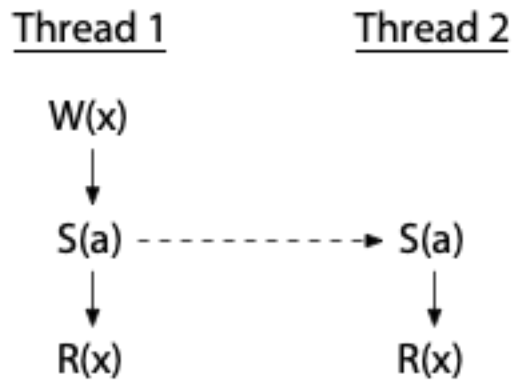


Diagram Source: https://research.swtch.com/hwmm

DRF-SC

- Processors implementing a DRF-SC model guarantee that programs without data races behave as if they were running on a sequentially consistent machines
- Also modern languages have adopted DRF-SC to make it possible to write correct multithreaded programs in programming languages.
  - Java memory model with locks, and volatile variables implement DRF-SC
  - C/C++ memory model us atomics with various degrees of guaranteeing DRF-SC via its synchronization operations.
  - Go uses atomics, mutexes, and channels, etc that guarantees DRF-SC

Aside: Memory Barriers (or Fences)

```
// Assuming x and y are zeroed out (i.e. x = y = 0)
// at the start of the program.
// Can this program see r1 = 0, r2 = 0?
// Thread 1          // Thread 2
x = 1                y = 1
r1 = y               r2 = x
```

On sequentially consistent hardware: **No**

On almost every other memory model: **Yes**

- **How do we fix the above problem?** Hardware provides explicit instructions called memory barriers(or fences) for algorithms requiring stronger memory ordering.

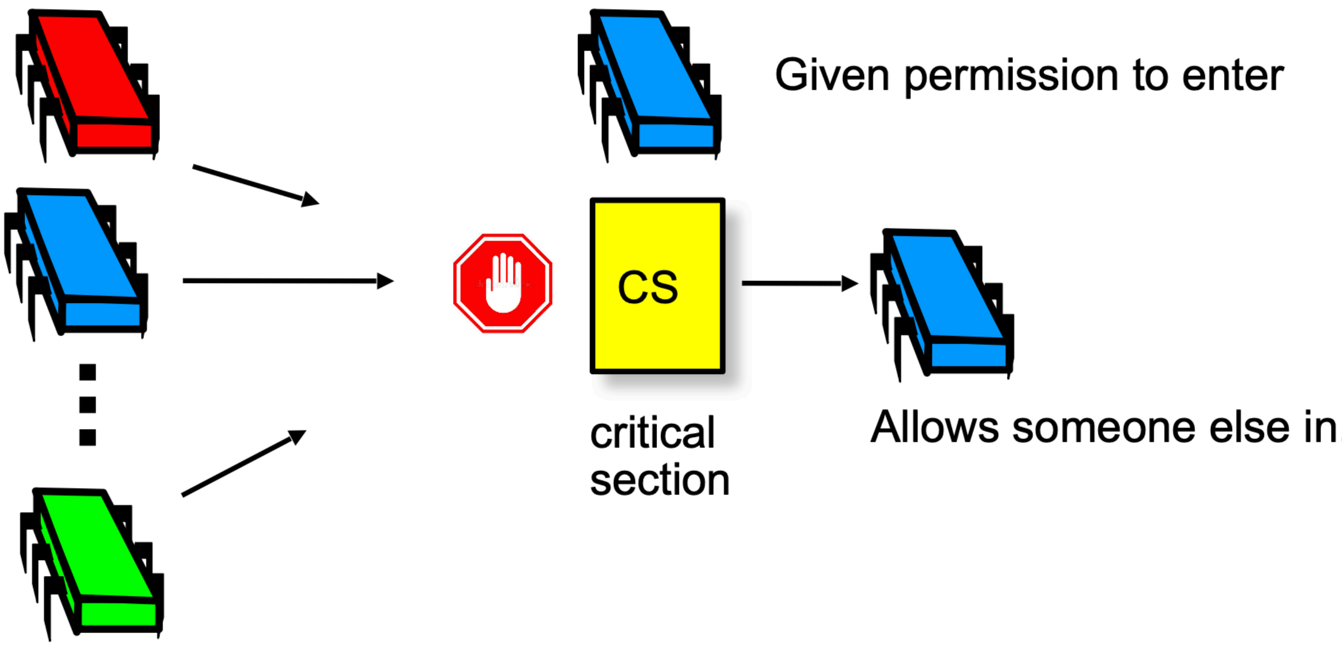
```
// Thread 1          // Thread 2
x = 1                y = 1
barrier              barrier
r1 = y               r2 = x
```

  - The barrier will make sure each thread flushes its previous write to memory before starting its read. ***r1=0 and r2= 0 is no longer possible after adding the barrier.***
  - How these barriers get implemented to enforce this requirement is beyond the scope of this class.
  - When using atomic operations memory barriers are explicitly used in the implementation to ensure strong ordering.

Principles of Mutual Exclusion

M3 Objective

- How we are going to ensure determinism when threads want to enter in the critical section?



Formalizing Concurrent Computation

- Two types of formal properties in asynchronous computation:

- Safety Properties:
  - Nothing bad happens ever
  - For example - a traffic light never displays green in all directions, even if power fails.
- Liveness Properties:
  - States that a particular “good” thing will happen.
  - For example - a red light will eventually turn green.

Formalizing Critical Sections

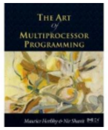
- Synchronization primitives need to adhere to the following properties and principles about critical sections in order to be correct:
  - Mutual Exclusion Property:
    - Critical sections of different threads do not overlap. Only one thread is executing a critical section at a time
    - Guarantees that a computation's results are correct.
    - This is a safety property.
  - Deadlock-freedom property:
    - If multiple threads simultaneously request to enter a critical section, then it must allow one to proceed
    - Threads outside the critical section have no say in which thread can proceed into the critical section, only those currently waiting have influence.
    - It implies the system never "freezes".
    - This is a liveness property.

Formalizing Critical Sections

- Starvation-freedom property:
  - Every thread that attempts to acquire the lock eventually succeeds.
  - Many mutual exclusive algorithms in practice are not starvation free because its less likely starvation will occur in those algorithms.
  - There is no guarantee on how long thread will wait to acquire the lock.
  - Also known as lockout freedom or bounded-waiting
  - This is a liveness property.
- Fairness Principle:
  - A thread who just left the critical section cannot immediately re-enter the critical section if other threads have already requested to enter the critical section.
  - Some algorithms place bounds on how long a thread can wait.

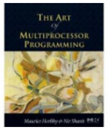
Implementing Locks
Two-Thread vs *n*-Thread Solutions

- 2-thread solutions first
  - Illustrate most basic ideas
- Then *n*-thread solution
- You will never use these protocols
- You are advised to understand them
  - The same issues show up everywhere
  - Except hidden and more complex



Two-Thread Conventions

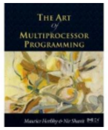
```
class … implements Lock {
  …
  // thread-local index, 0 or 1
  public void lock() {
    int i = ThreadID.get();
    int j = 1 - i;
  …
  }
}
```



Two-Thread Conventions

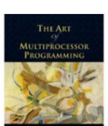
```
class … implements Lock {
  …
  // thread-local index, 0 or 1
  public void lock() {
    int i = ThreadID.get();
    int j = 1 - i;
  …
  }
}
```

Henceforth: i is current thread, j is other thread



LockOne

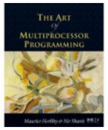
```
class LockOne implements Lock {
private boolean[] flag = new boolean[2];
public void lock() {
  int i = ThreadID.get();
  int j = 1 - i;
  flag[i] = true;
  while (flag[j]) {}
 }
public void unlock() {
  int i = ThreadID.get();
  flag[i] = false;


}
```



LockOne

```
class LockOne implements Lock {
private boolean[] flag = new boolean[2];
public void lock() {
  flag[i] = true;
  while (flag[j]) {}
 }
```

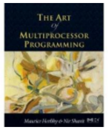
Each thread has flag



LockOne

```
class LockOne implements Lock {
private boolean[] flag = new boolean[2];
public void lock() {
  flag[i] = true;
  while (flag[j]) {}
 }
```

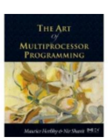
Set my flag



LockOne

```
class LockOne implements Lock {
private boolean[] flag = new boolean[2];
public void lock() {
   flag[i] = true;
   while (flag[j]) {}
  }
```

Wait for other flag to become false

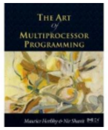


Deadlock Freedom

- LockOne Fails deadlock-freedom
  - Concurrent execution can deadlock

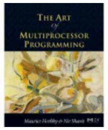
```
flag[i] = true;     flag[j] = true;
while (flag[j]){}   while (flag[i]){}
```

  - Sequential executions OK



LockTwo

```
public class LockTwo implements Lock {
 private int victim;
 public void lock() {
   int i = ThreadID.get();
   int j = 1 - i;
  victim = i;
  while (victim == i) {};
 }

 public void unlock() {}
}
```



LockTwo

```
public class LockTwo implements Lock {
 private int victim;
 public void lock() {
  victim = i;
  while (victim == i) {};
 }

 public void unlock() {}
}
```

Let other go first

LockTwo

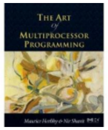
```
public class LockTwo implements Lock {
 private int victim;
 public void lock() {
  victim = i;
  while (victim == i) {};
 }

 public void unlock() {}
}
```

Wait for permission

LockTwo

```
public class Lock2 implements Lock {
 private int victim;
 public void lock() {
  victim = i;
  while (victim == i) {};
 }

 public void unlock() {}
}
```

Nothing to do



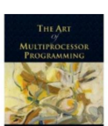
LockTwo Claims

- Satisfies mutual exclusion
  - If thread **`i`** in critical section
  - Then **`victim == j`**
  - Cannot be both 0 and 1
- Not deadlock free
  - Sequential execution deadlocks
  - Concurrent execution does not

```
public void LockTwo() {
   victim = i;
   while (victim == i) {};
  }
```

Peterson’s Algorithm

```
public void lock() {
  int i = ThreadID.get();
  int j = 1 - i;
  flag[i] = true;
  victim  = i;
  while (flag[j] && victim == i) {};
}
public void unlock() {
 flag[i] = false;
}
```



Peterson's Algorithm

Announce I'm interested

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

Peterson’s Algorithm

Announce I’m interested

Defer to other

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

Peterson’s Algorithm

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

Announce I’m interested

Defer to other

Wait while other interested & I’m the victim

Peterson's Algorithm

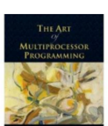
```
public void lock() {
  flag[i] = true;
  victim  = i;
  while (flag[j] && victim == i) {};
  }
public void unlock() {
  flag[i] = false;
}
```

Announce I'm interested

Defer to other

Wait while other interested & I'm the victim

No longer interested



Peterson's Algorithm

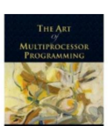
- Satisfies mutual exclusion & deadlock freedom properties
  - Uses both lock-one and lock-two strategies
- Downside: only works for two threads

Bakery Algorithm

- N-threaded locking algorithm
- Provides First-Come-First-Served
- How?
  - Take a “number”
  - Wait until lower numbers have been served
- Lexicographic order
  - $(a,i) > (b,j)$
    - If $a > b$, or $a = b$ and $i > j$

Bakery Algorithm

```
class Bakery implements Lock {
   boolean[] flag;
   Label[] label;
  public Bakery (int n) {
    flag  = new boolean[n];
    label = new Label[n];
    for (int i = 0; i < n; i++) {
       flag[i] = false; label[i] = 0;
    }
  }
 …
```



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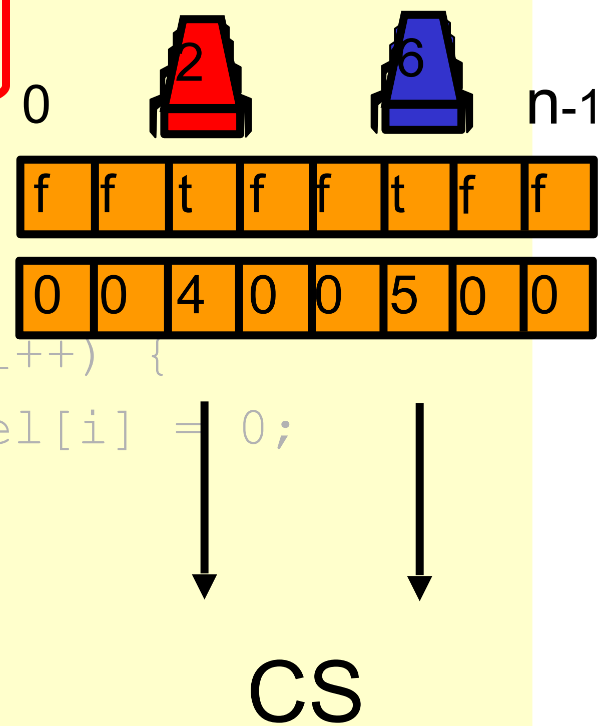
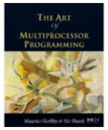
       flag[i] = false; label[i] = 0;
    }
  }
 …
```





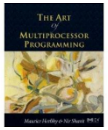
Bakery Algorithm

```
class Bakery implements Lock {
   …
  public void lock() {
   flag[i]  = true;
   label[i] = max(label[0], …,label[n-1])+1;
   while (∃k flag[k]
                  && (label[i],i) > (label[k],k));
  }
```

Bakery Algorithm

```
class Bakery implements Lock {
  …
 public void lock() {
  flag[i]  = true;
  label[i] = max(label[0], …,label[n-1])+1;
  while (∃k flag[k]
             && (label[i],i) > (label[k],k));
 }
```

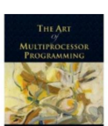
I'm interested



Bakery Algorithm

Take increasing label (read labels in some arbitrary order)

```
class Bakery implements Lock {
  …
 public void lock() {
  flag[i]  = true;
  label[i] = max(label[0], …,label[n-1])+1;
  while (∃k flag[k]
           && (label[i],i) > (label[k],k));
 }
```



Bakery Algorithm

```
class Bakery implements Lock {
  …
 public void lock() {
  flag[i]  = true;
  label[i] = max(label[0], …,label[n-1])+1;
  while (∃k flag[k]
                 && (label[i],i) > (label[k],k));
 }
```

Someone is interested

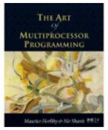
Bakery Algorithm

```
class Bakery implements Lock {
  boolean flag[n];
  int label[n];

 public void lock() {
  flag[i]  = true;
  label[i] = max(label[0], …,label[n-1])+1;
  while (∃k flag[k]
           && (label[i],i) > (label[k],k));
 }
```

Someone is interested …

… whose (label,i) in lexicographic order is lower

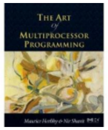


Bakery Algorithm

```
class Bakery implements Lock {

    …

 public void unlock() {
   flag[i] = false;
 }
}
```



Bakery Algorithm

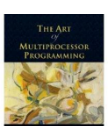
```
class Bakery implements Lock {

    …

 public void unlock() {
   flag[i] = false;
 }
}
```

No longer interested

labels are always increasing

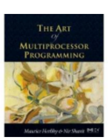


Bakery Algorithm

- Has no deadlock and adheres to mutual exclusion property
- There is always one thread with earliest label

Deep Philosophical Question

- The Bakery Algorithm is
  - Succinct,
  - Elegant, and
  - Fair.
- Q: So why isn't it practical?
- A: Well, you have to read N distinct variables



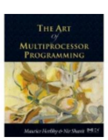
Principles of Mutual Exclusion

Mutex in Go

- Go has a package called sync that provides basic synchronization primitives such as mutual exclusion locks.
  - The sync package Go's provides mutual exclusion with sync.Mutex and its two methods:
  - m.Lock(): locks m. If the lock is already in use, the calling goroutine blocks until the mutex is available.
  - m.Unlock(): Unlock unlocks m. It is a run-time error if m is not locked on entry to Unlock.
- Now let's take a look at how locks are implemented behind the scenes.

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

- Keep trying
  - "spin" or "busy-wait"
    - When spinning, a thread repeatedly tests a condition, but, effectively, does no useful work until the condition has the appropriate value.
    - Can be very wasteful of CPU cycles.
    - Can also be unreliable if compiler optimization is turned on.
  - Good if delays are short
- Give up the processor
  - Good if delays are long
  - Always good on uniprocessor



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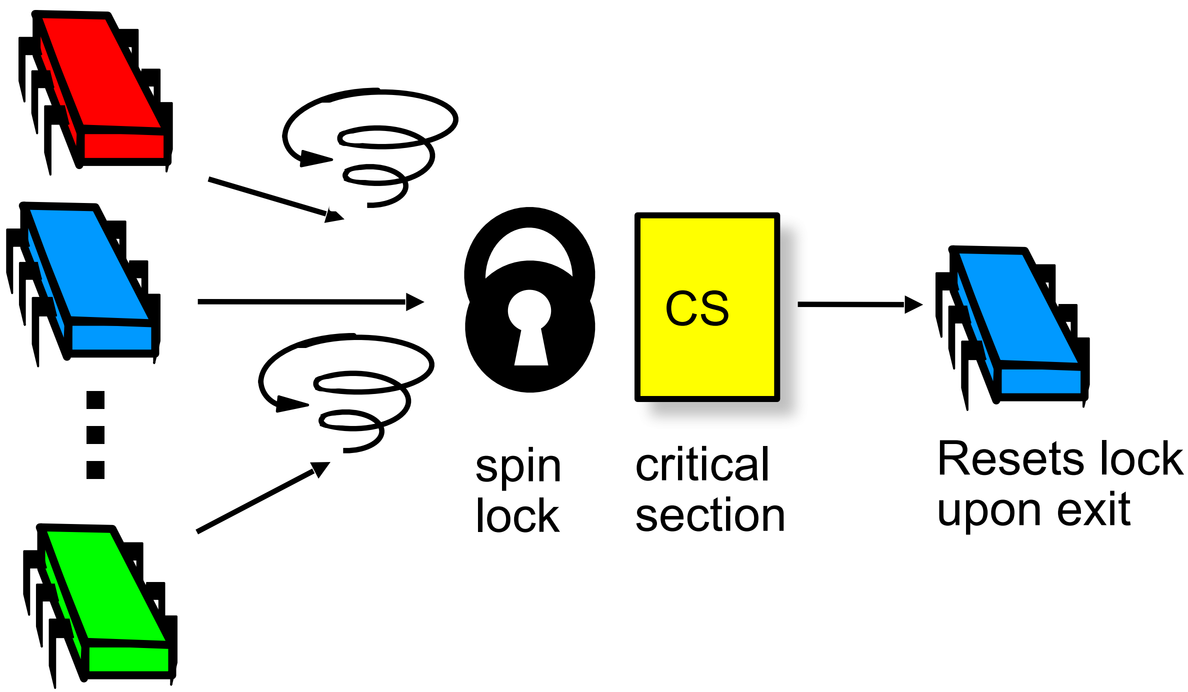
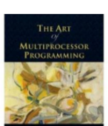
our focus

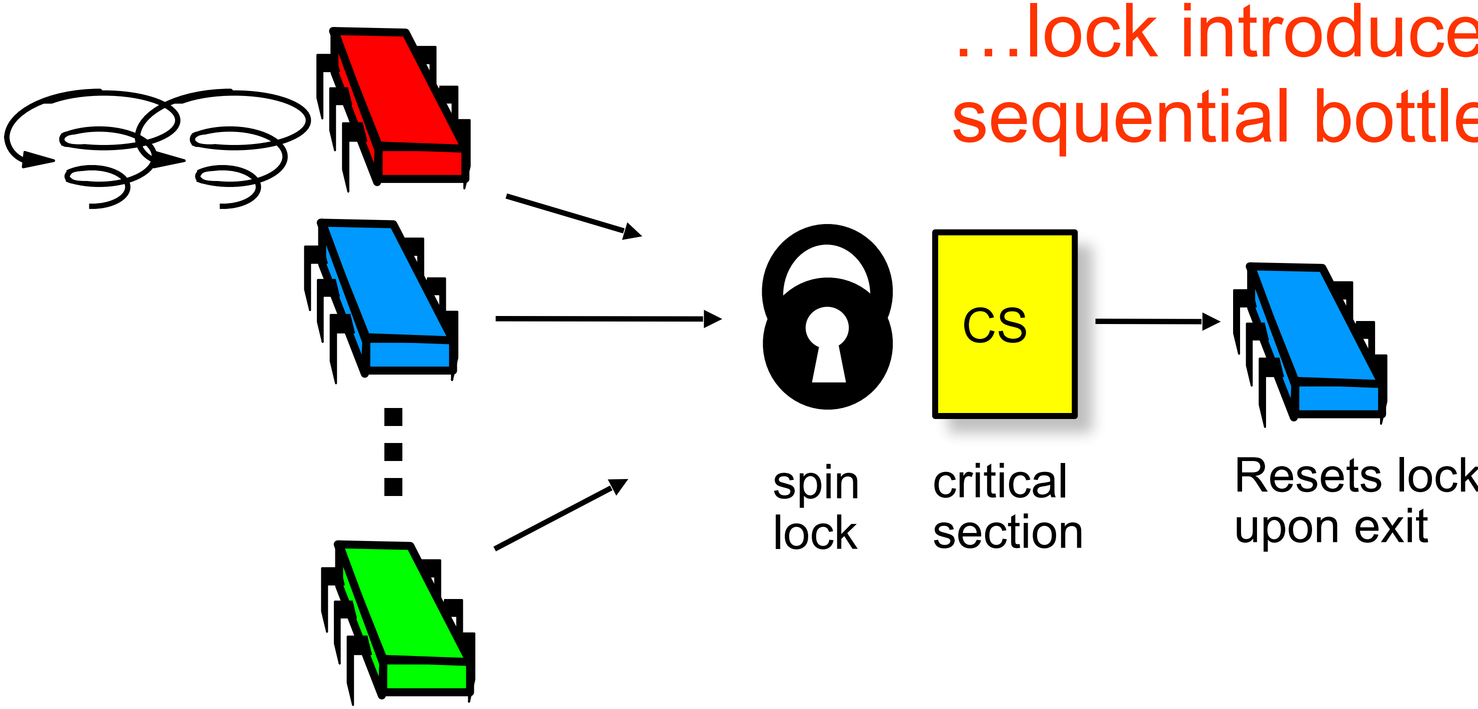
Basic Spin-Lock



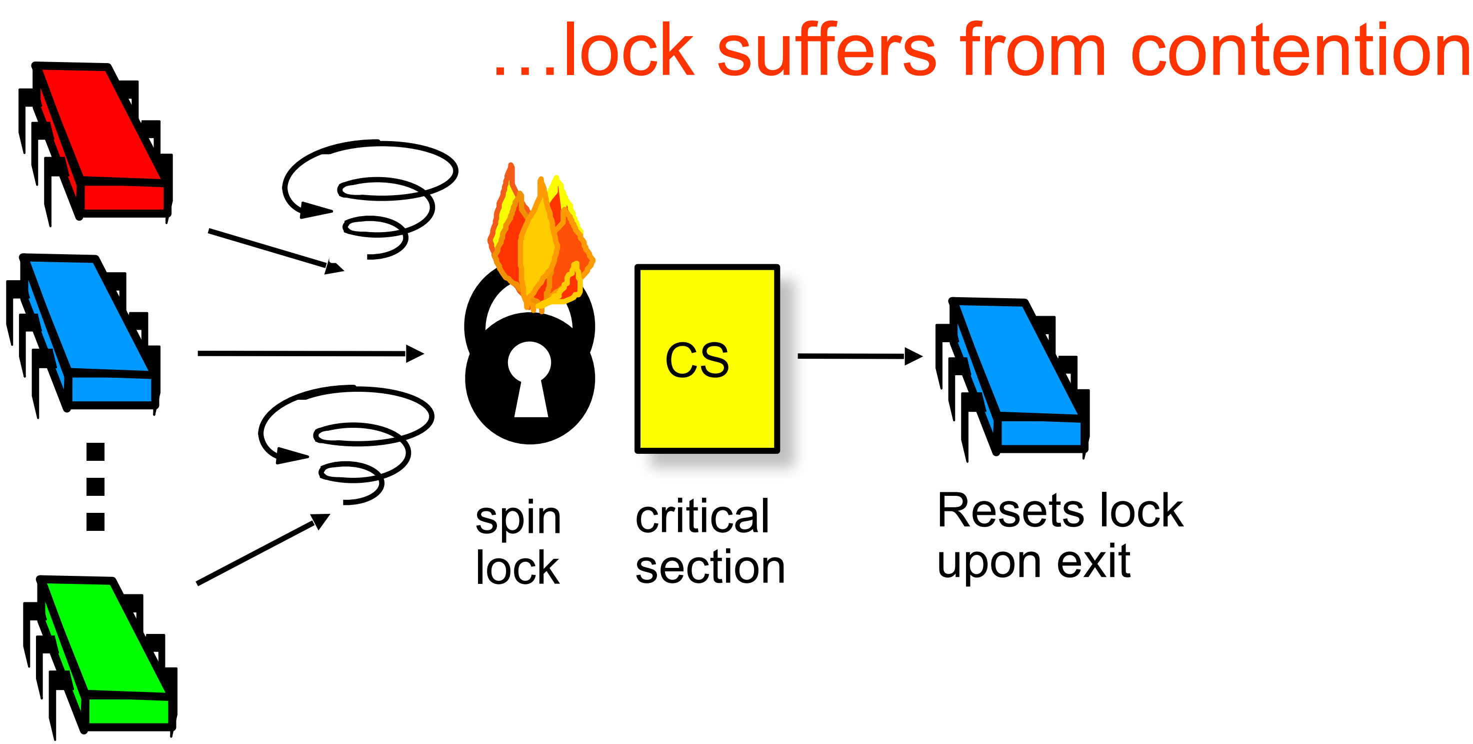


Basic Spin-Lock

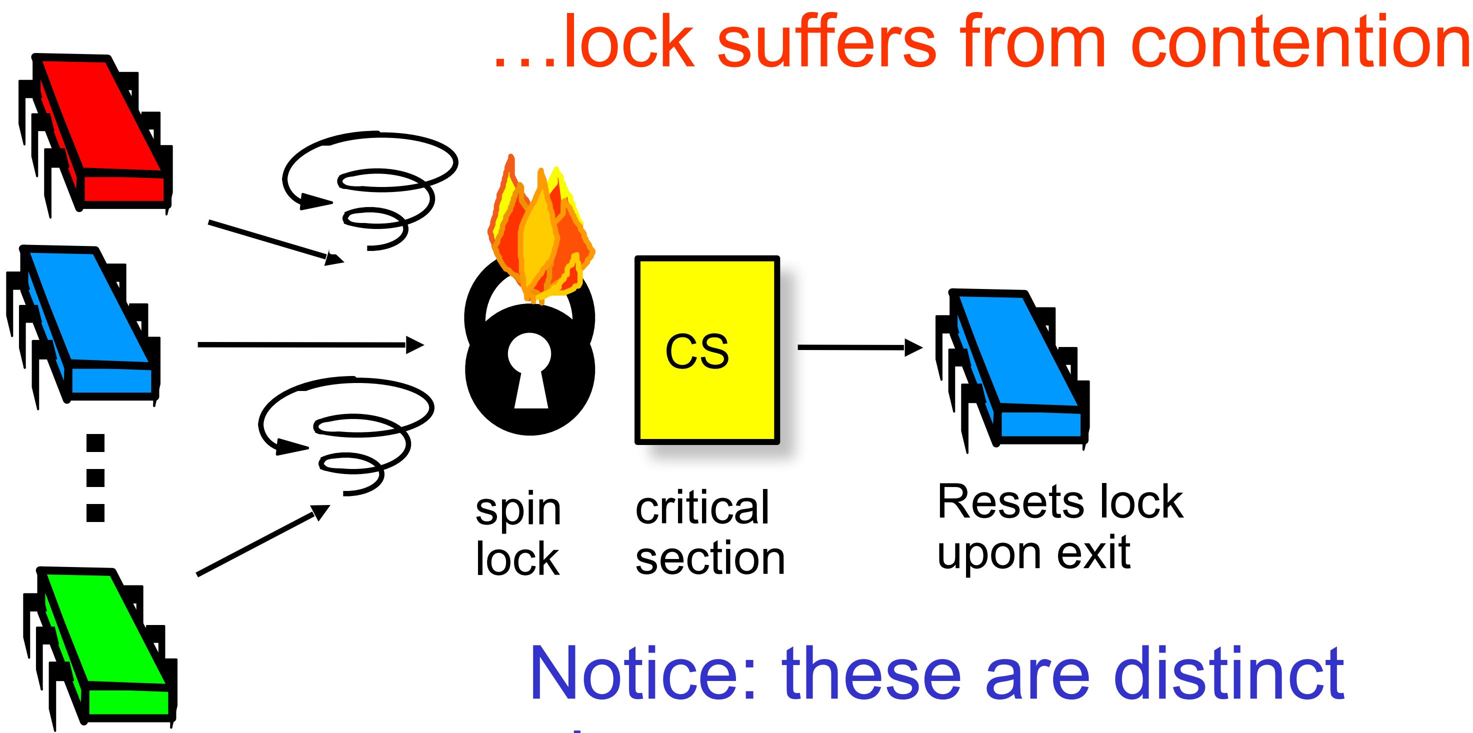
…lock introduces sequential bottleneck



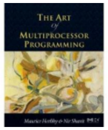
Basic Spin-Lock



Basic Spin-Lock

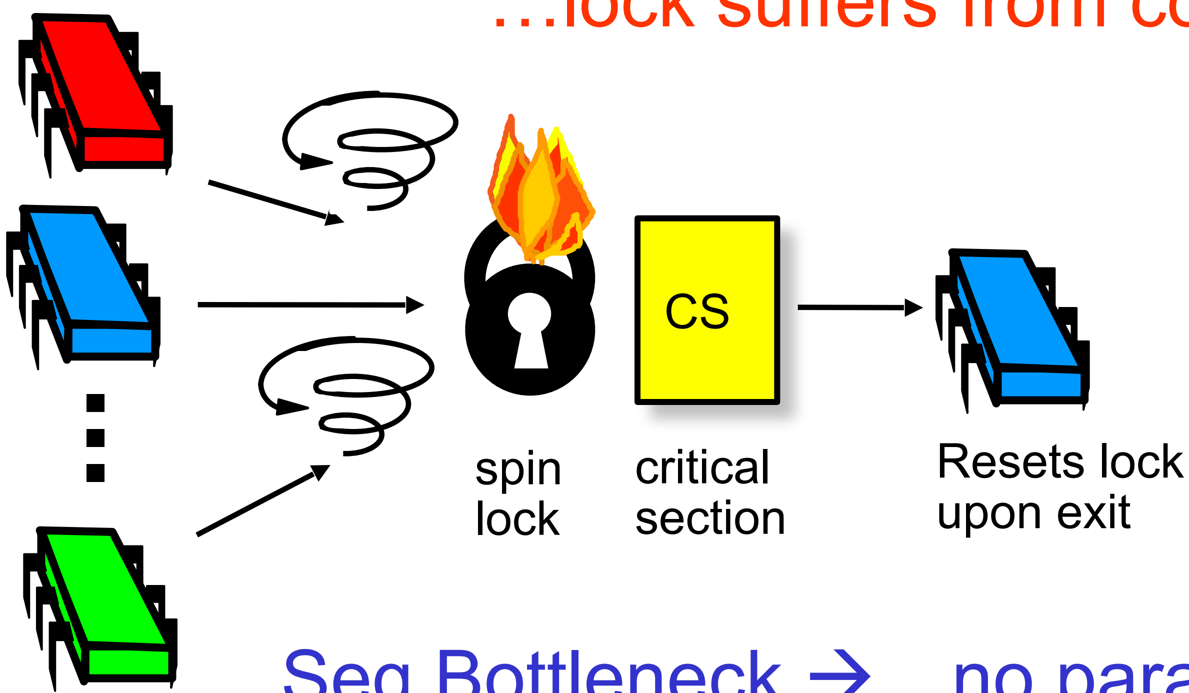


Notice: these are distinct phenomena

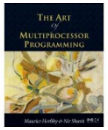


Basic Spin-Lock

…lock suffers from contention

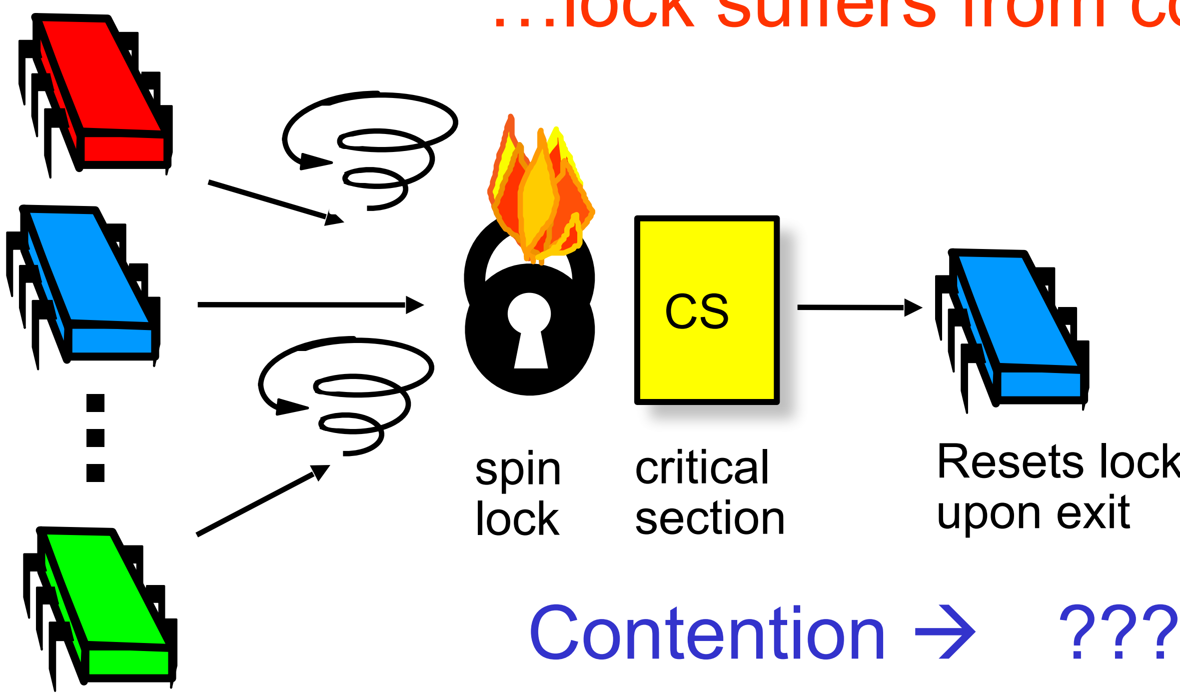


Seq Bottleneck → no parallelism



Basic Spin-Lock

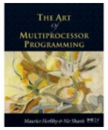
…lock suffers from contention



Contention → ???

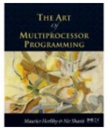
Test-and-Set

- 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"



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

```
public class AtomicBoolean {
 boolean value;

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

Test-and-Set

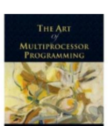
```
public class AtomicBoolean {
 boolean value;

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

Swap old and new values

Test-and-Set

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

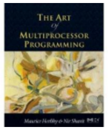


Test-and-Set

```
AtomicBoolean lock
 = new AtomicBoolean(false)

boolean prior = lock.getAndSet(true)
```

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

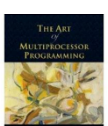


Test-and-set Lock

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

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

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



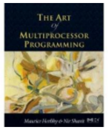
Test-and-set Lock

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

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

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

Lock state is AtomicBoolean



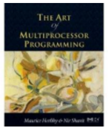
Test-and-set Lock

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

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

 void unlock() {
  sta
 }}
```

Keep trying until lock acquired



Test-and-set Lock

```
class TA
 AtomicB
  new At

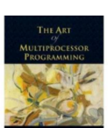
 void lock() {
  while (state.getAndSet(true)) {}
 }

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

Release lock by resetting state to false

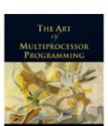
Space Complexity

- TAS spin-lock has small "footprint"
- N thread spin-lock uses O(1) space
- As opposed to O(n) Peterson/Bakery

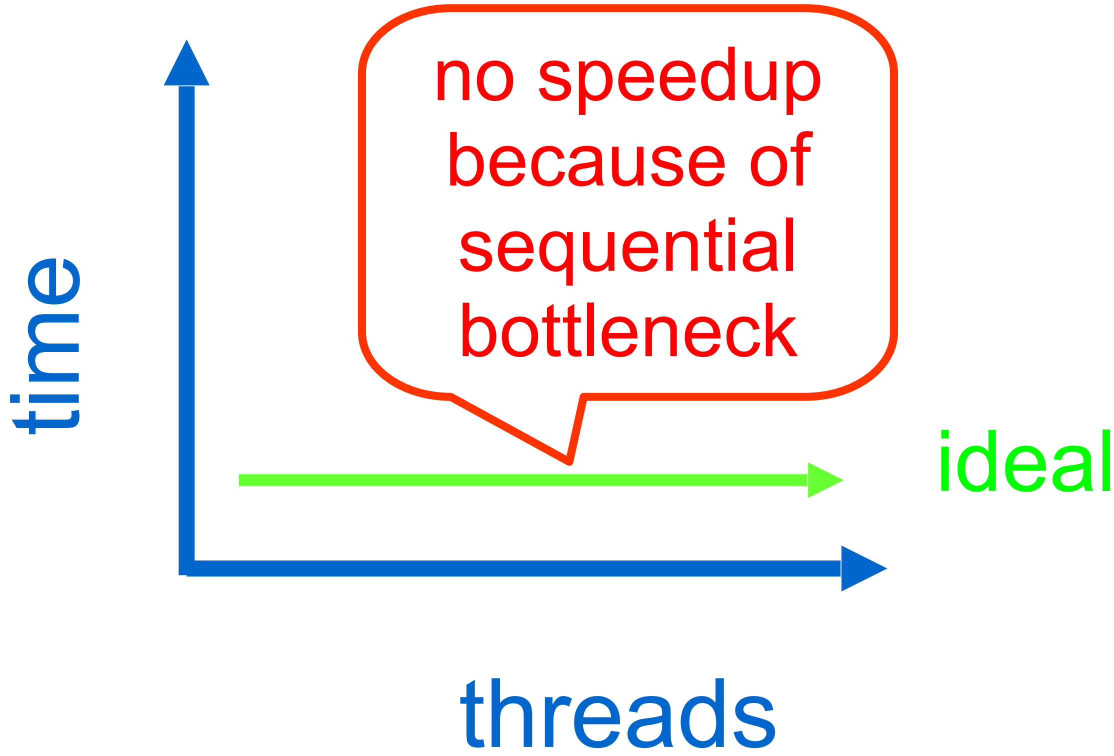


Performance

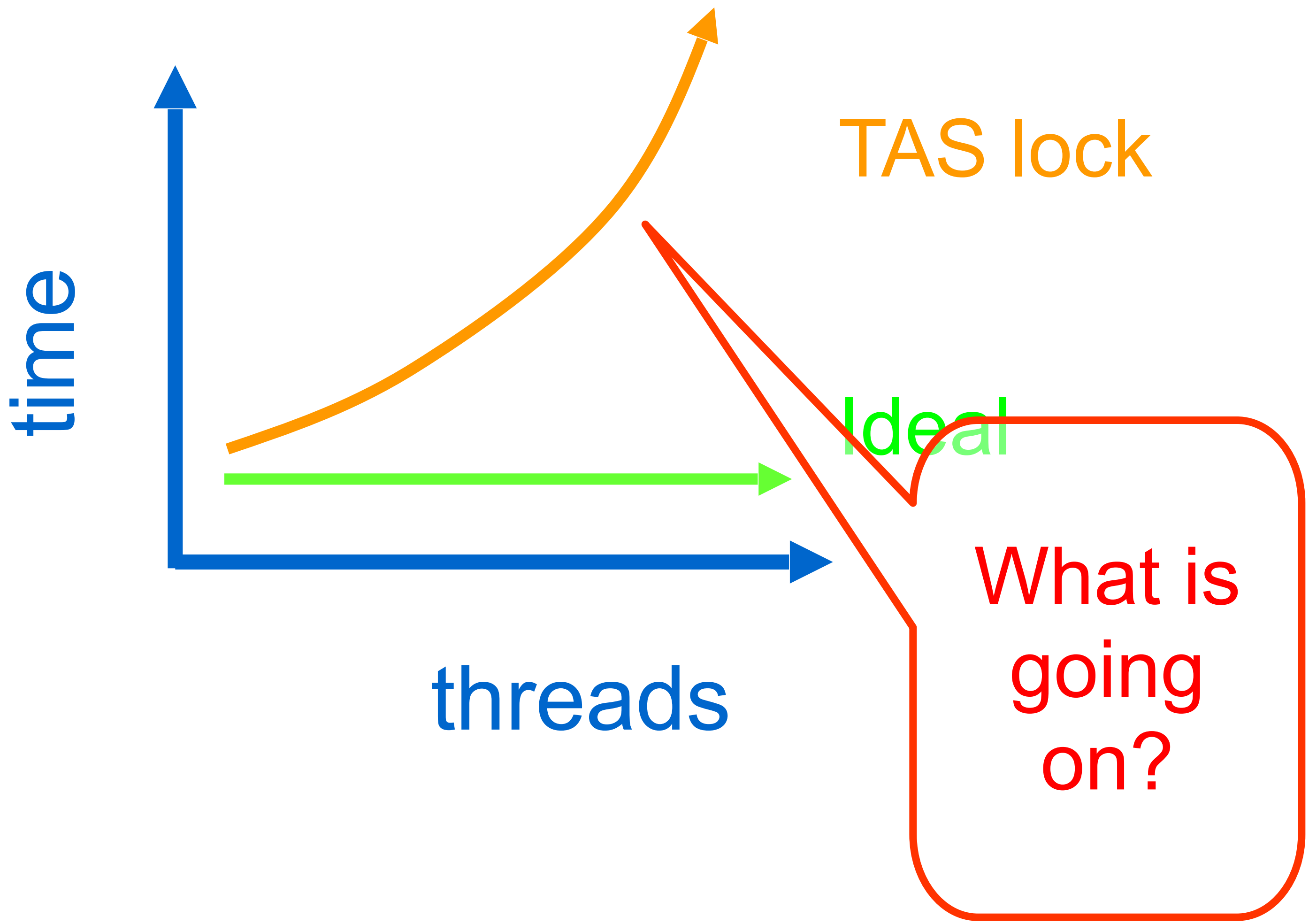
- Experiment
  - *n* threads
  - Increment shared counter 1 million times
- How long should it take?
- How long does it take?

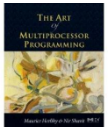


Graph


no speedup because of sequential bottleneck
ideal
time
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 =
  new AtomicBoolean(false);

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

Wait until lock looks free

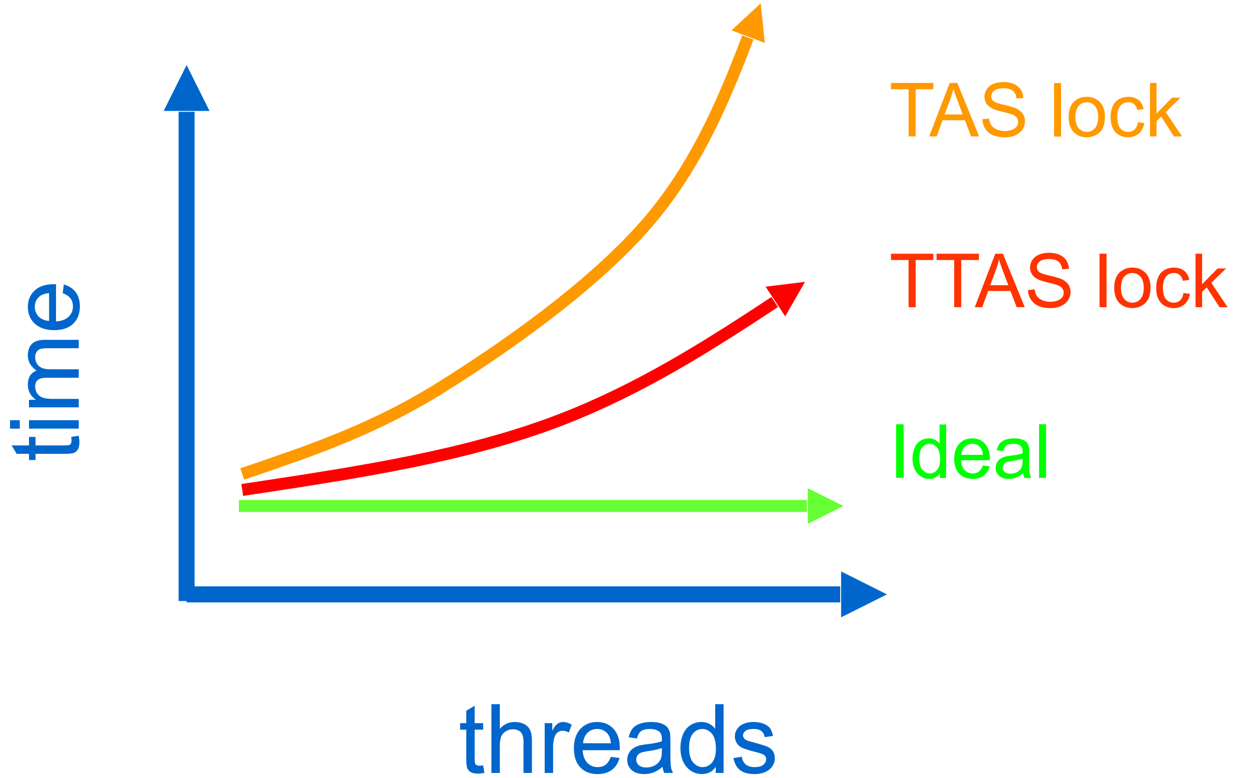
Test-and-test-and-set Lock

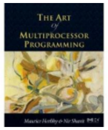
```
class TTASlock {
 AtomicBoolean state =
  new AtomicBoolean(false);

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

Then try to acquire it

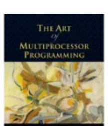
Mystery #2





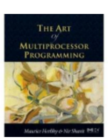
Mystery

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

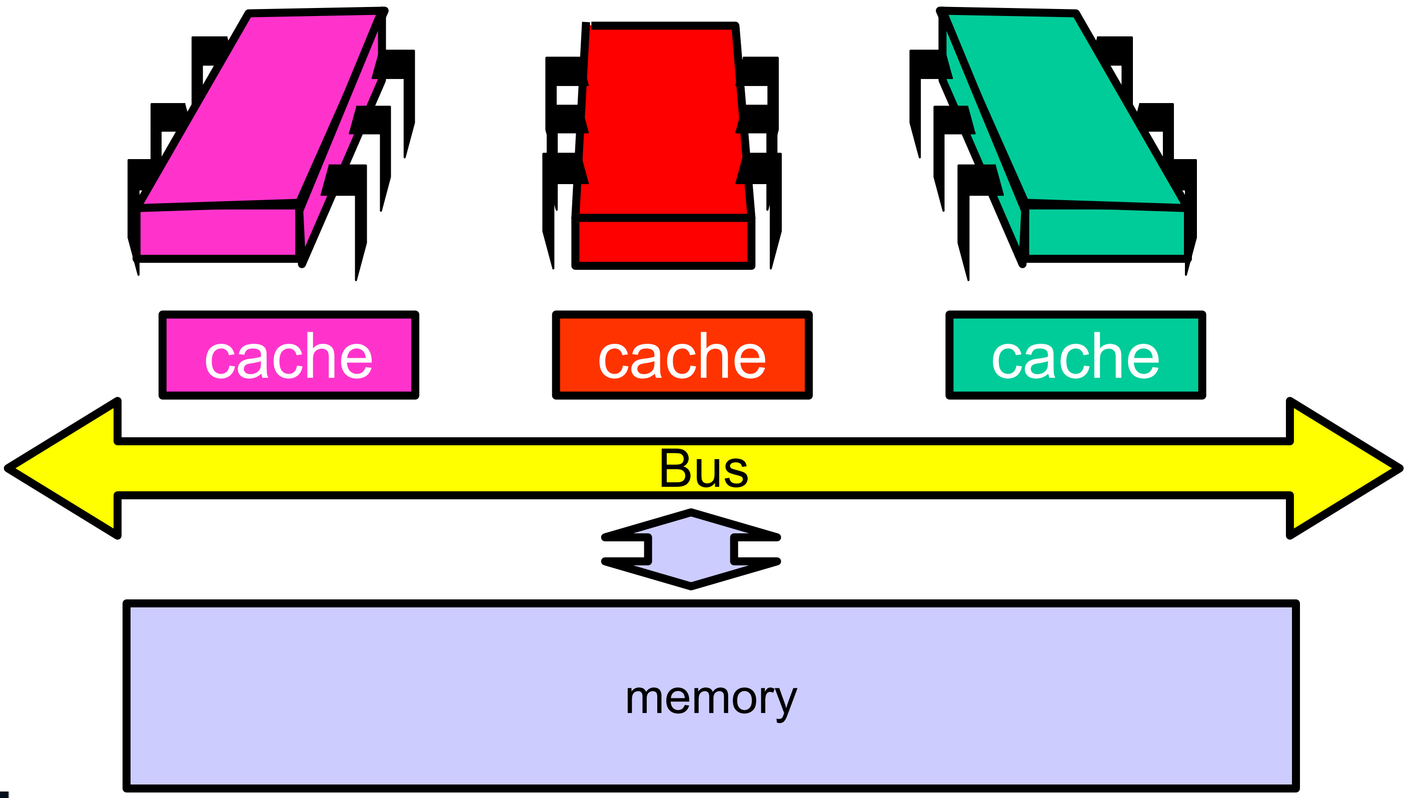


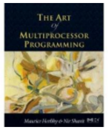
Opinion

- 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 …

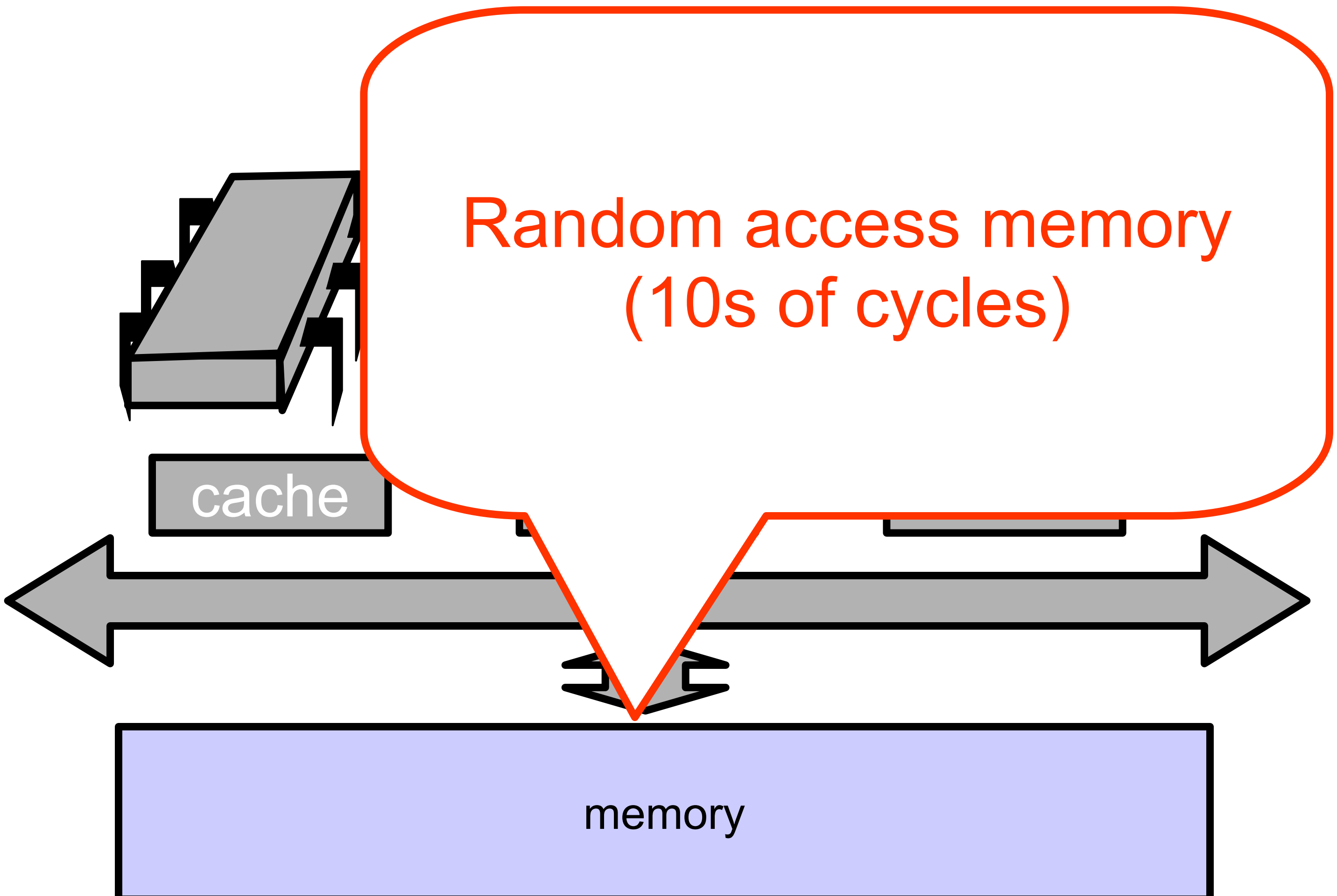


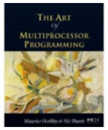
Bus-Based Architectures





Bus-Based Architectures

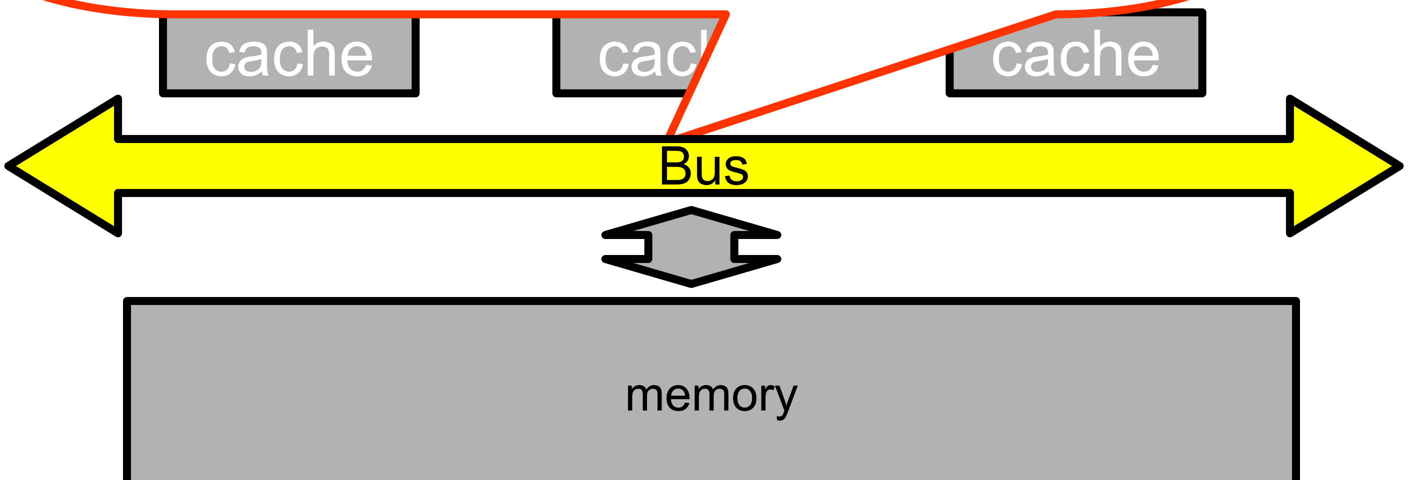




Bus-Based Architectures

Shared Bus

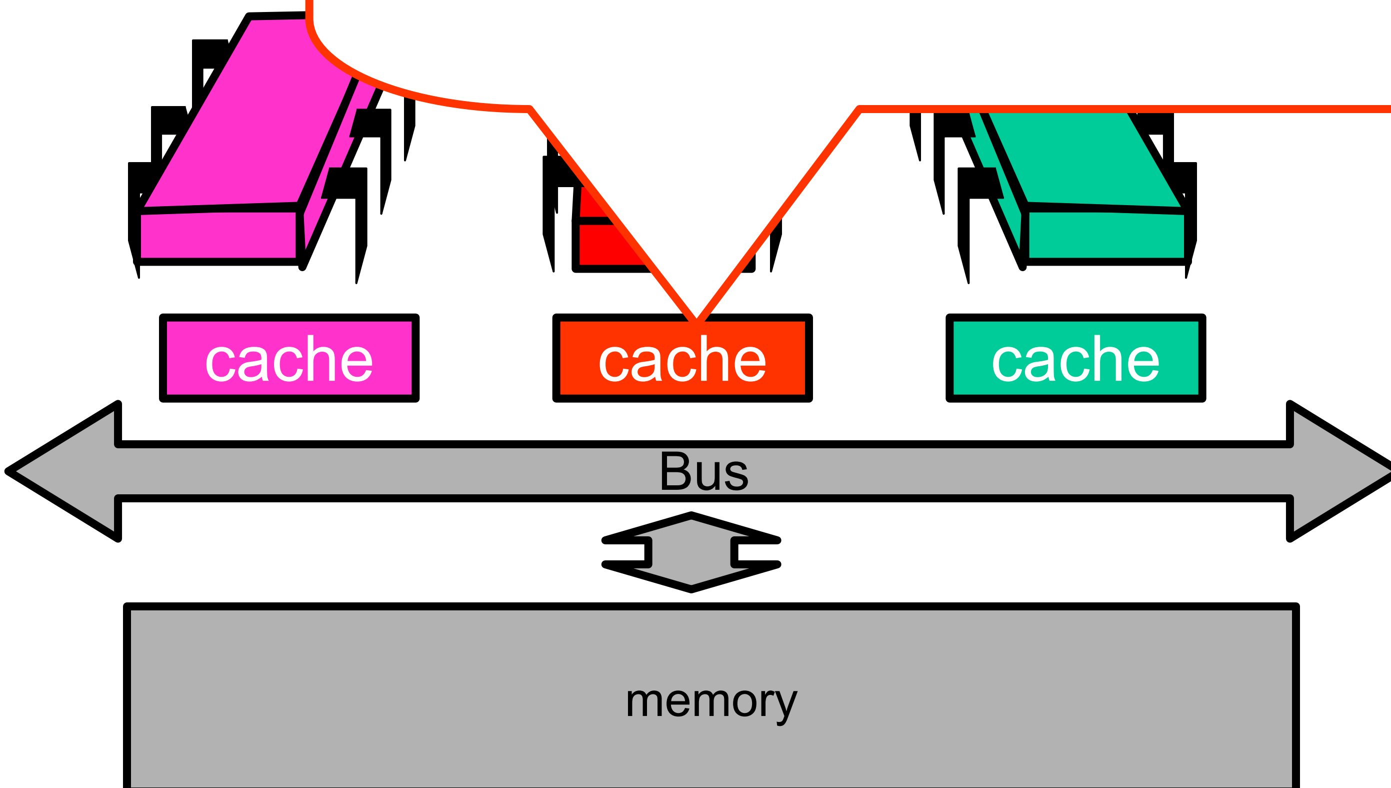
- Broadcast medium
- One broadcaster at a time
- Processors and memory all "snoop"

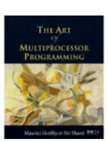


Bus-

Per-Processor Caches

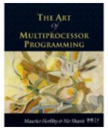
- Small
- Fast: 1 or 2 cycles
- Address & state information





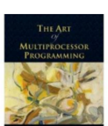
Mutual Exclusion

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



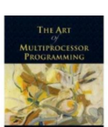
Simple TASLock

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

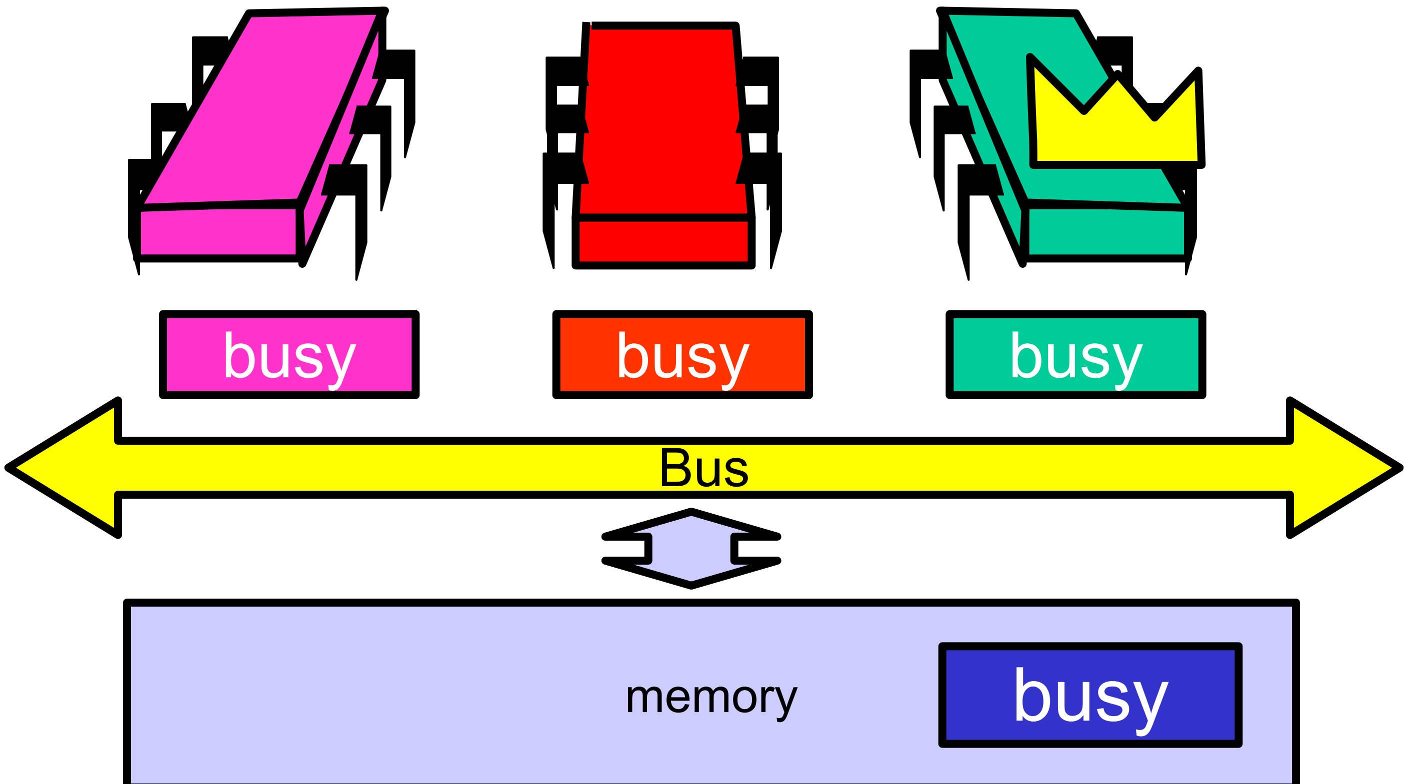


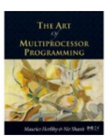
Test-and-test-and-set

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

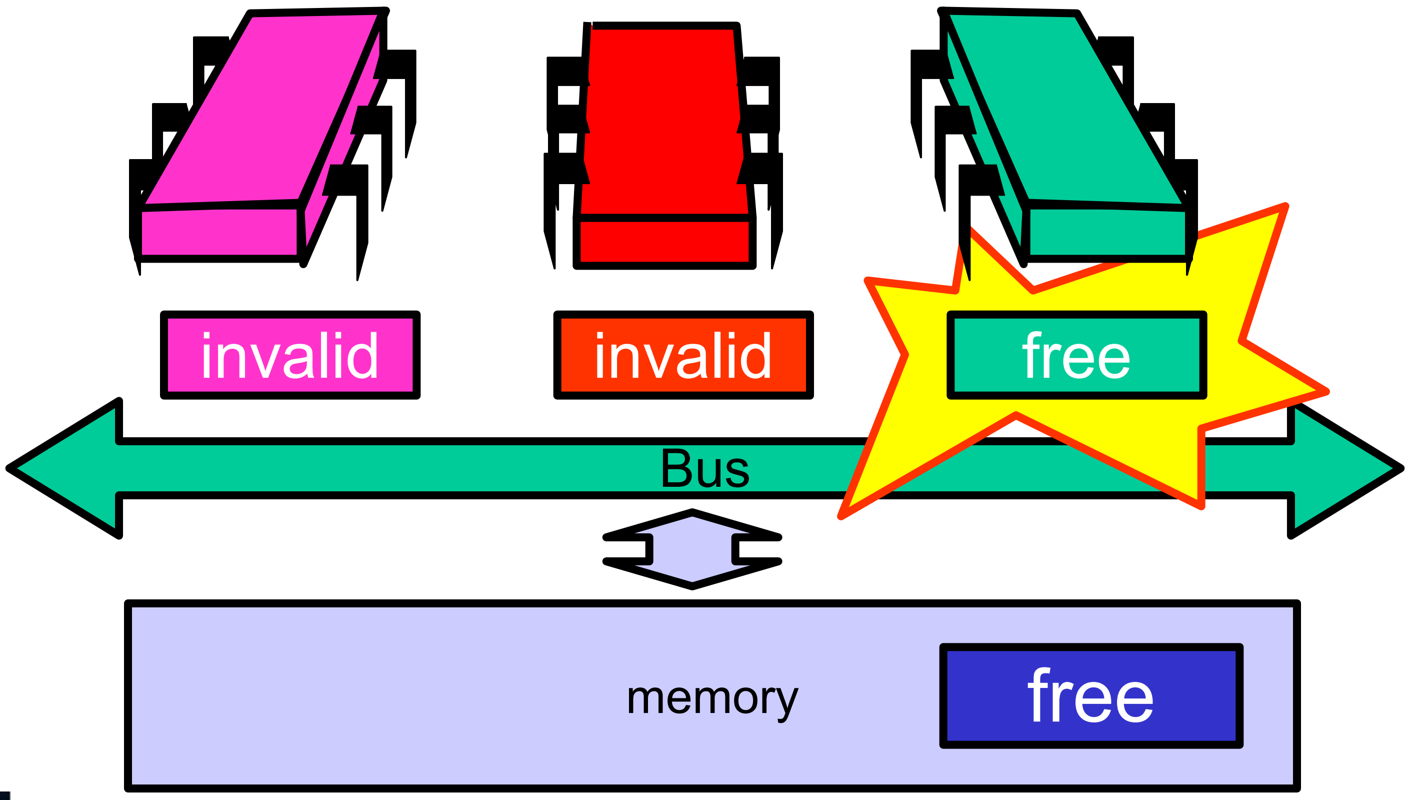


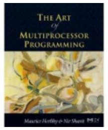
Local Spinning while Lock is Busy





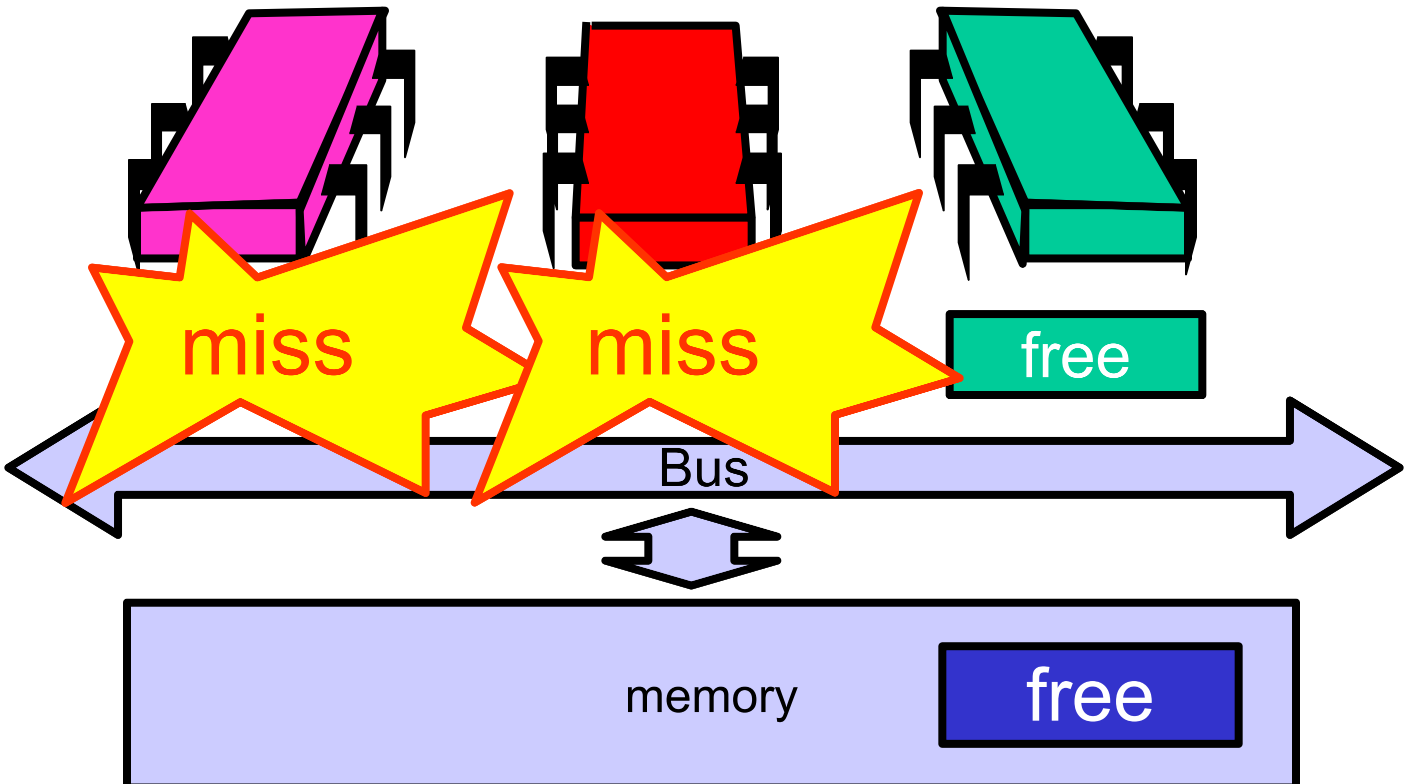
On Release

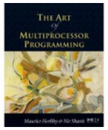




On Release

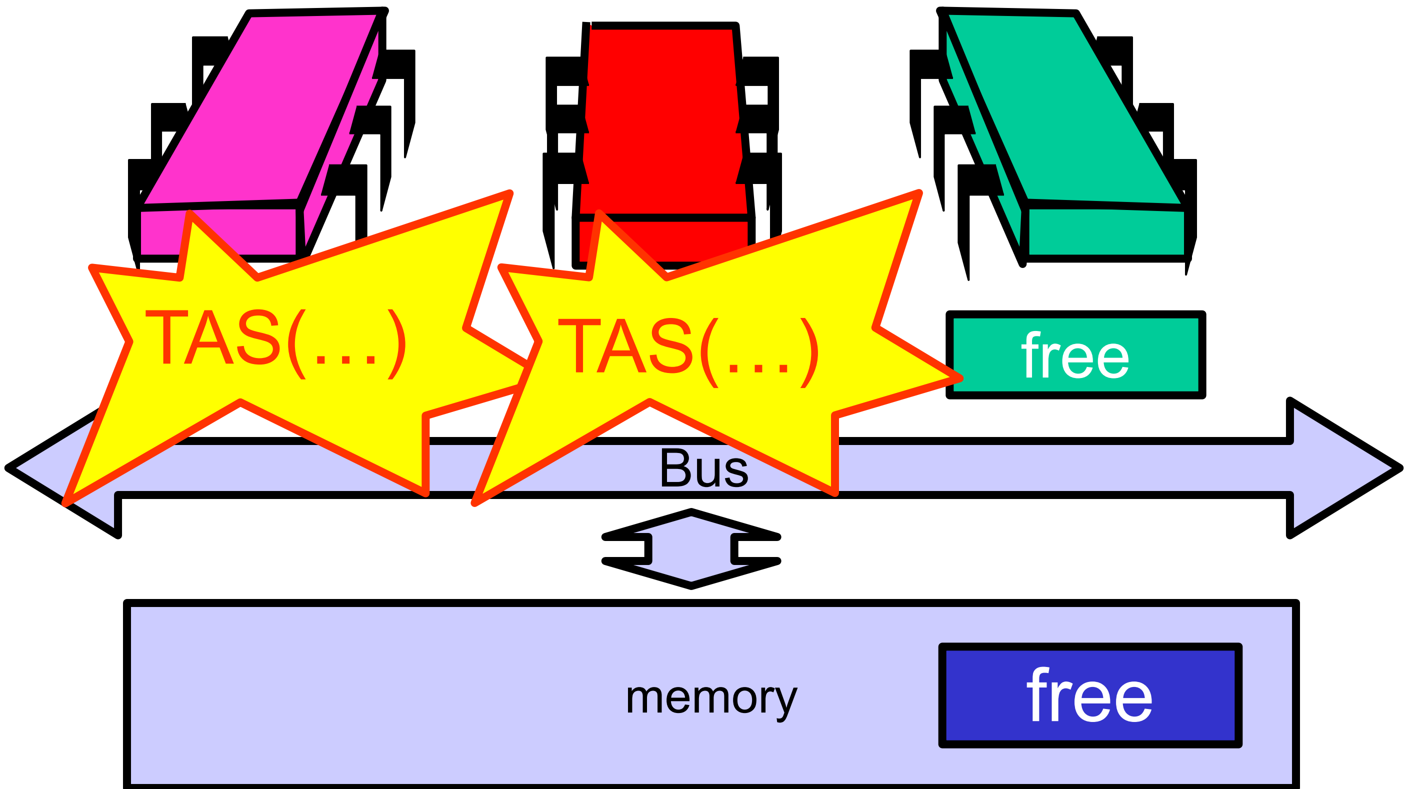
Everyone misses, rereads

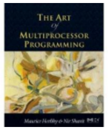




On Release

Everyone tries TAS

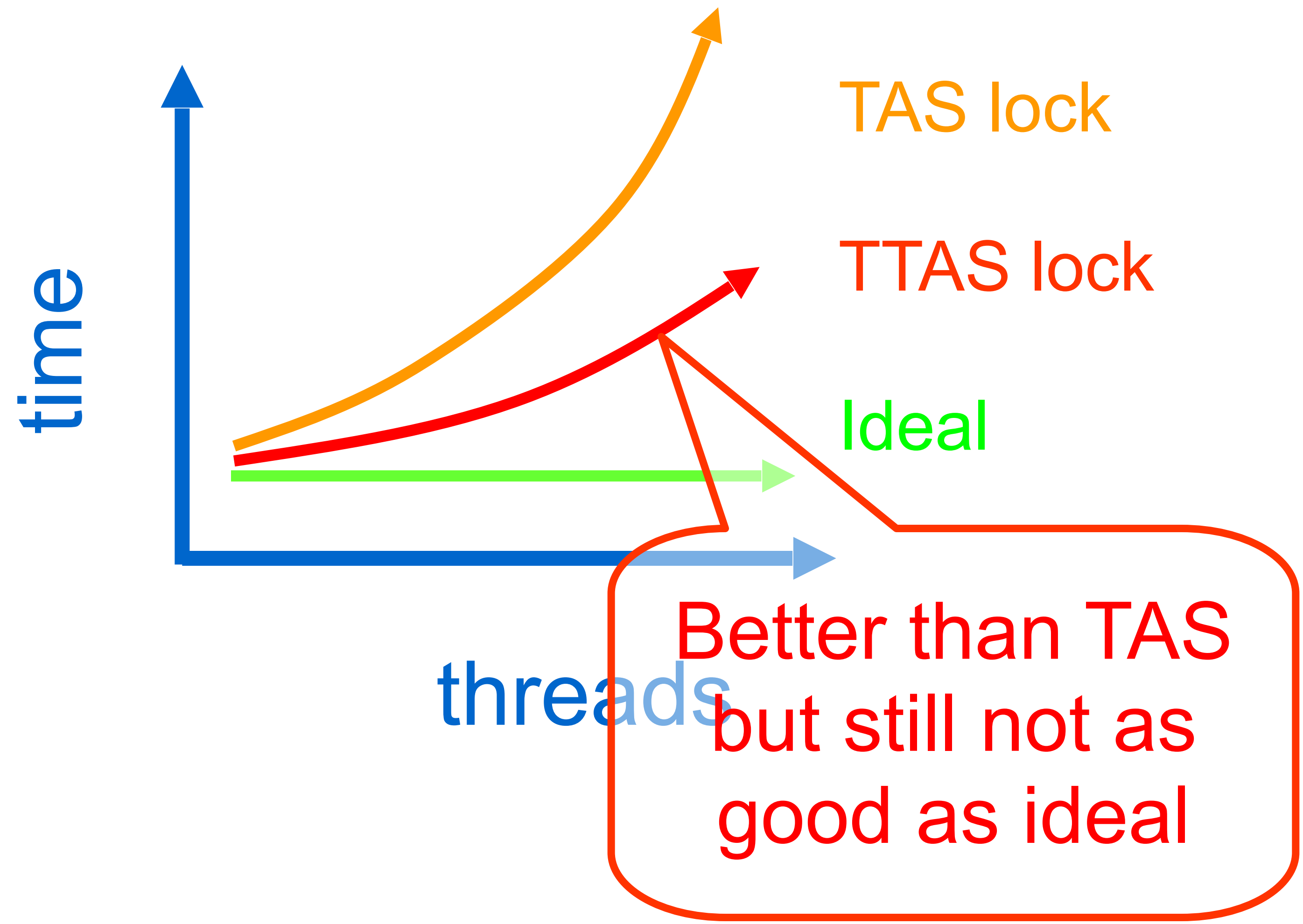




Problems

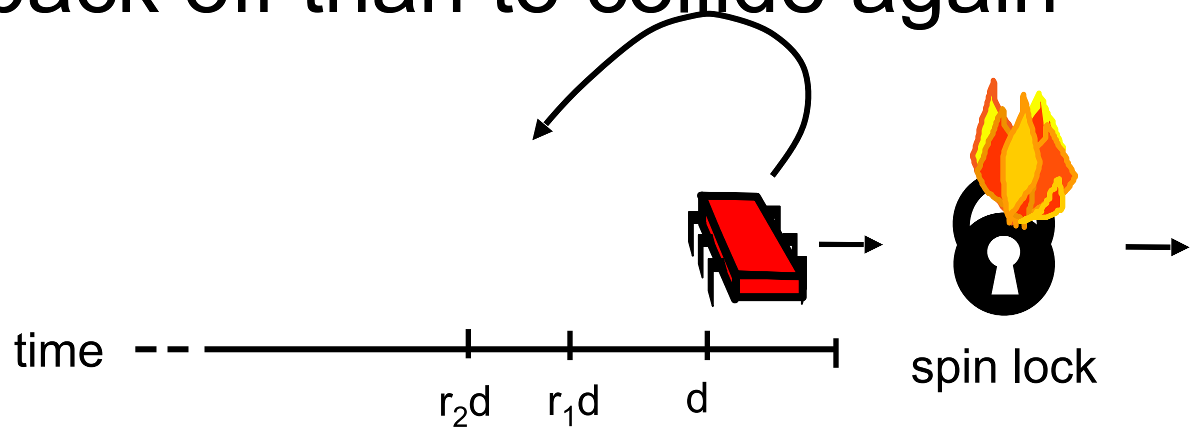
- Everyone misses
  – Reads satisfied sequentially
- Everyone does TAS
  – Invalidates others' caches

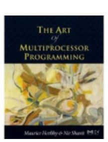
Mystery Explained



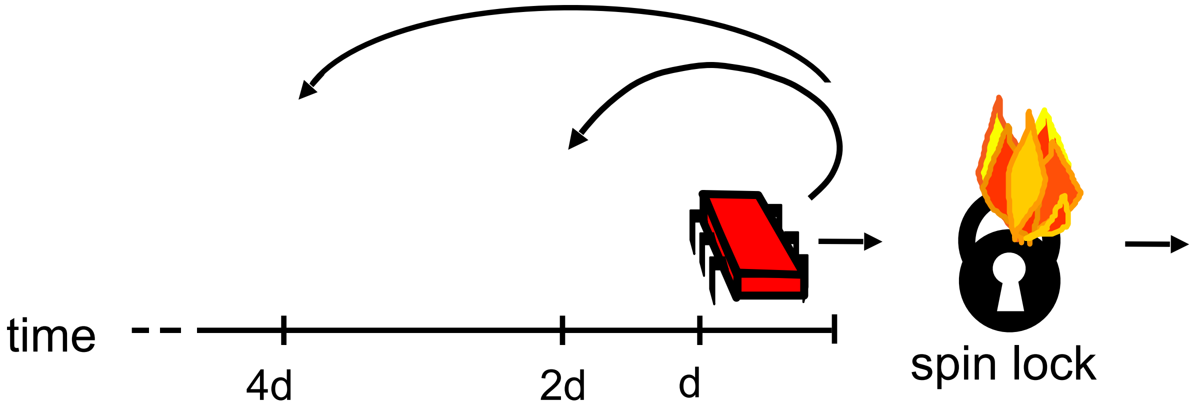
Solution: Introduce Delay

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





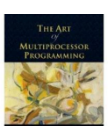
Dynamic Example: Exponential Backoff



If I fail to get lock
- wait random duration before retry
- Each subsequent failure doubles expected wait

Exponential Backoff Lock

```
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

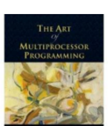
```
public class Backoff implements lock {
 public void lock() {
  int delay = MIN_DELAY;
  while (true) {
   while (state.get()) {}
   if (!lock.getAndSet(true))
    return;
   sleep(random() % delay);
   if (delay < MAX_DELAY)
    delay = 2 * delay;
 }}}
```

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 * delay;
 }}}
```

Wait until lock looks free



Exponential Backoff Lock

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

If we win, return

Exponential Backoff Lock

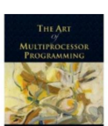
Back off for random duration

```
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;
 }}}
```

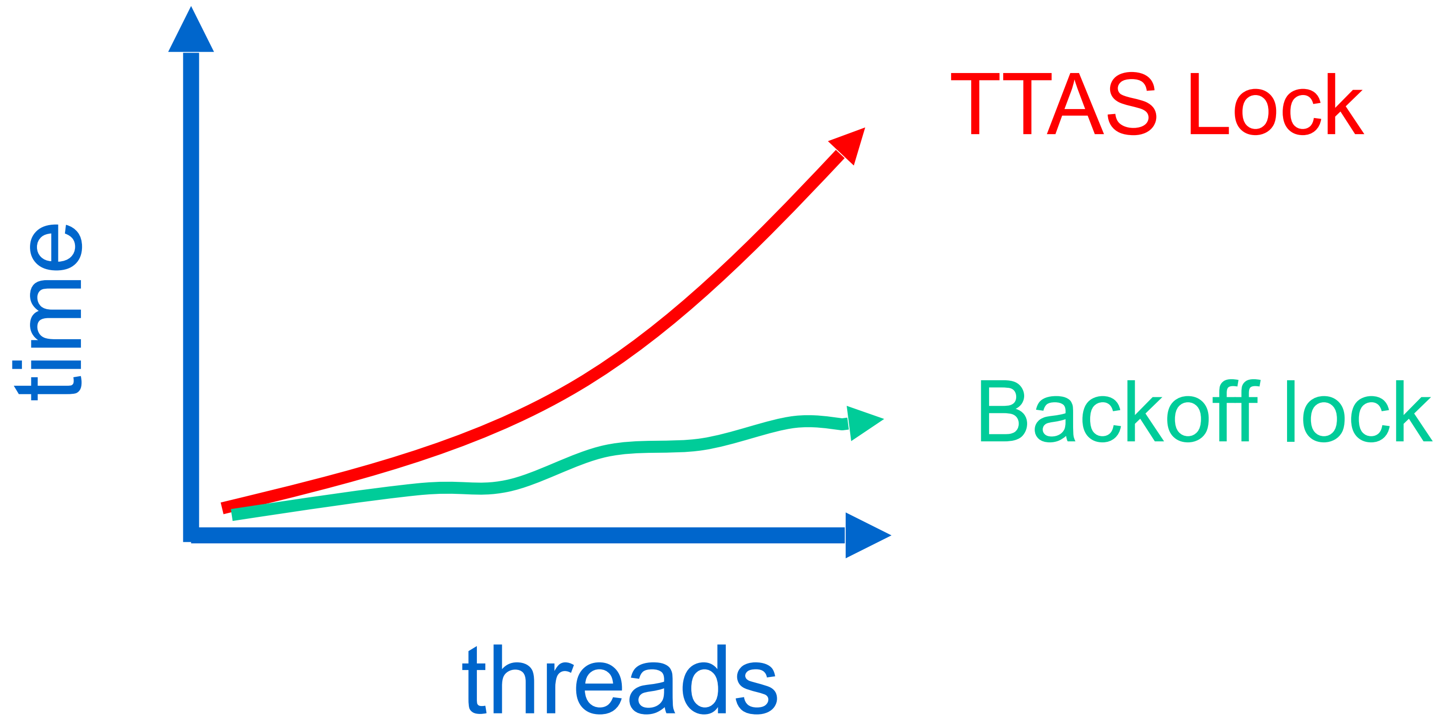
Exponential Backoff Lock

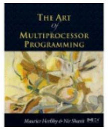
```
public class Backoff implements lock {
 pub
  int delay = MIN_DELAY;
  while (true) {
   while (state.get()) {}
   if (!lock.getAndSet(true))
    return;
   sleep(random() % delay);
   if (delay < MAX_DELAY)
    delay = 2 * delay;
 }}}
```

Double max delay, within reason



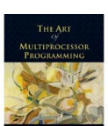
Spin-Waiting Overhead





Backoff: Other Issues

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



Parallel Performance

Performance Theory

In this course, the main goal for parallelization is to improve performance. But what does "*performance*" mean? Usually it's one of the following

- Reducing the latency, which is the total time for a program/task to compute a single result.
- Increasing throughput, which is the rate at which results are computed.
- Reducing the power consumption of a computation
- Also the distinct of reducing costs or adding resources to meet a deadline.

All of these are valid interpretations of "*performance*".

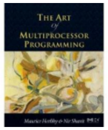
Speedup

- One important metric related to performance and parallelism is speedup
  - A ratio between the latency of solving a task with one processing unit versus solving the same problem with multiple processing units in parallel.
  - Linear speedup - a algorithm runs P times faster on P processors
    - Very rare in practice due to the extra work disturbing tasks to processors and coordinating them. (Amdahl's Law)

Amdahl's Law

- Limit on speedup - Amdahl's law sometimes called ***strong scalability*** which considers speedup as n-threads vary but the problem size stays the same.

$$\text{Speedup} = \frac{1\text{-thread execution time}}{n\text{-thread execution time}}$$



Amdahl's Law

$$\textbf{Speedup=}\ \frac{1}{1-p+\frac{p}{n}}$$

Amdahl's Law

$$\textbf{Speedup=} \frac{1}{1-p+\boxed{\frac{p}{n}}}$$

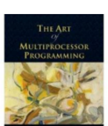
Parallel fraction

Amdahl's Law

Sequential fraction

Parallel fraction

$$\textbf{Speedup} = \frac{1}{1-p+\frac{p}{n}}$$



Amdahl's Law

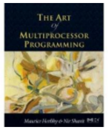
Sequential fraction

Parallel fraction

$$\text{Speedup} = \frac{1}{1 - p + \frac{p}{n}}$$

Number of threads

Amdahl's Law (in practice)



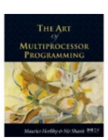
Example

- Ten processors
- 60% concurrent, 40% sequential
- How close to 10-fold speedup?

Example

- Ten processors
- 60% concurrent, 40% sequential
- How close to 10-fold speedup?

$$\text{Speedup} = 2.17 = \frac{1}{1 - 0.6 + \frac{0.6}{10}}$$



Example

- Ten processors
- 80% concurrent, 20% sequential
- How close to 10-fold speedup?

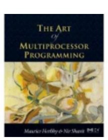
Example

- Ten processors
- 80% concurrent, 20% sequential
- How close to 10-fold speedup?

$$\text{Speedup} = 3.57 = \frac{1}{1 - 0.8 + \frac{0.8}{10}}$$

Example

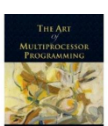
- Ten processors
- 90% concurrent, 10% sequential
- How close to 10-fold speedup?



Example

- Ten processors
- 90% concurrent, 10% sequential
- How close to 10-fold speedup?

$$\text{Speedup} = 5.26 = \frac{1}{1 - 0.9 + \frac{0.9}{10}}$$



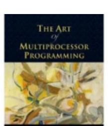
Example

- Ten processors
- 99% concurrent, 1% sequential
- How close to 10-fold speedup?

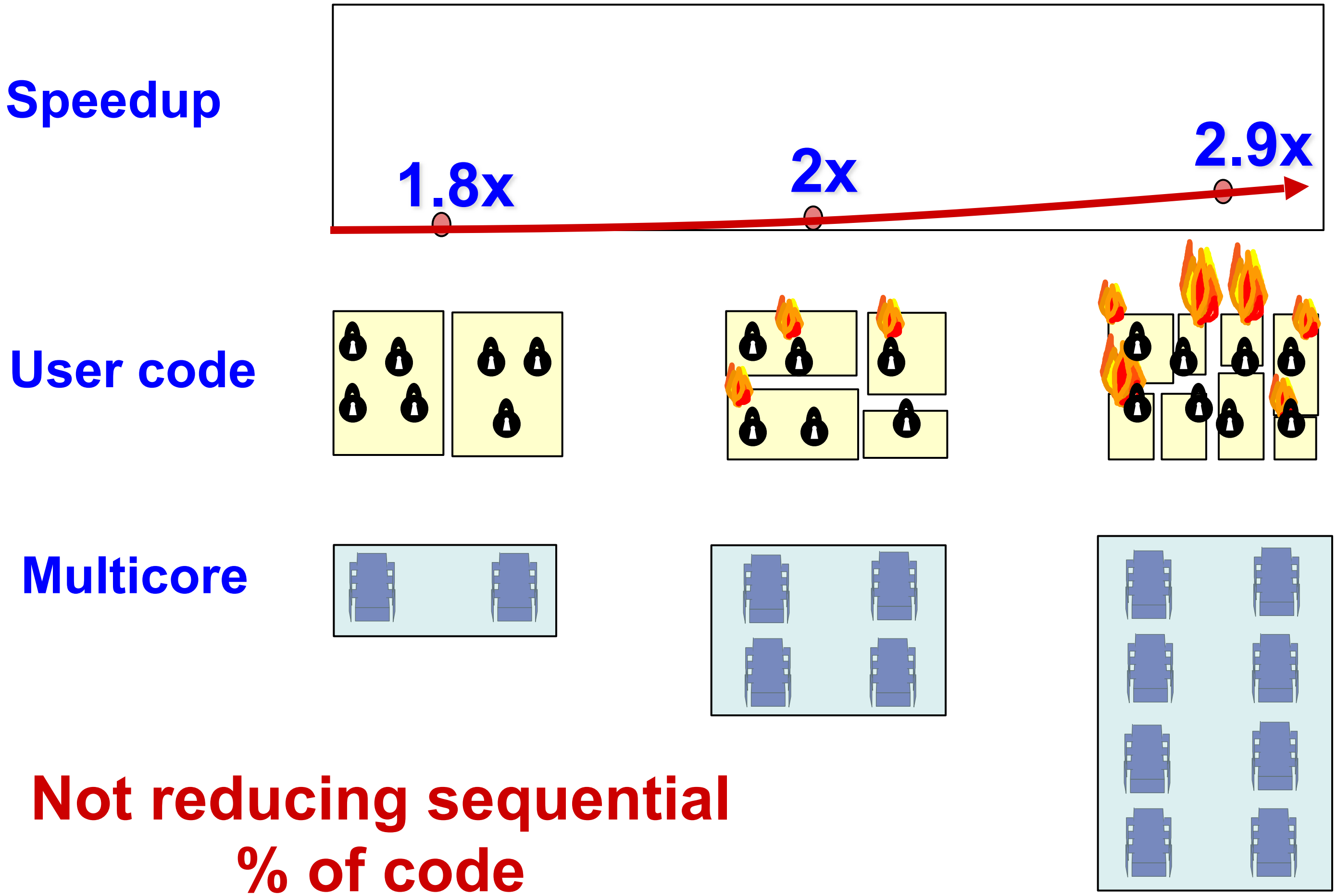
Example

- Ten processors
- 99% concurrent, 1% sequential
- How close to 10-fold speedup?

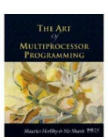
$$\text{Speedup} = 9.17 = \frac{1}{1 - 0.99 + \frac{0.99}{10}}$$



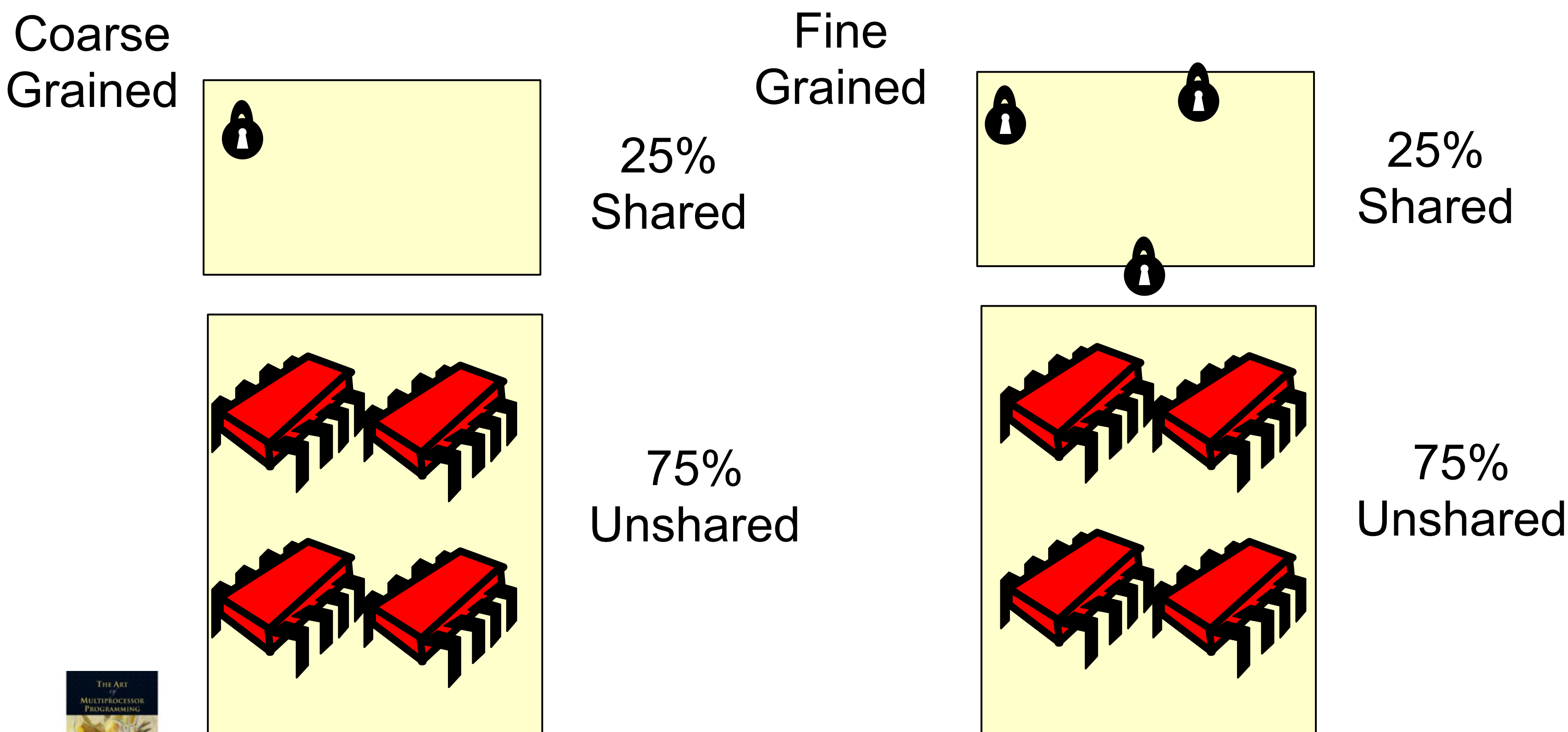
Back to Real-World Multicore Scaling



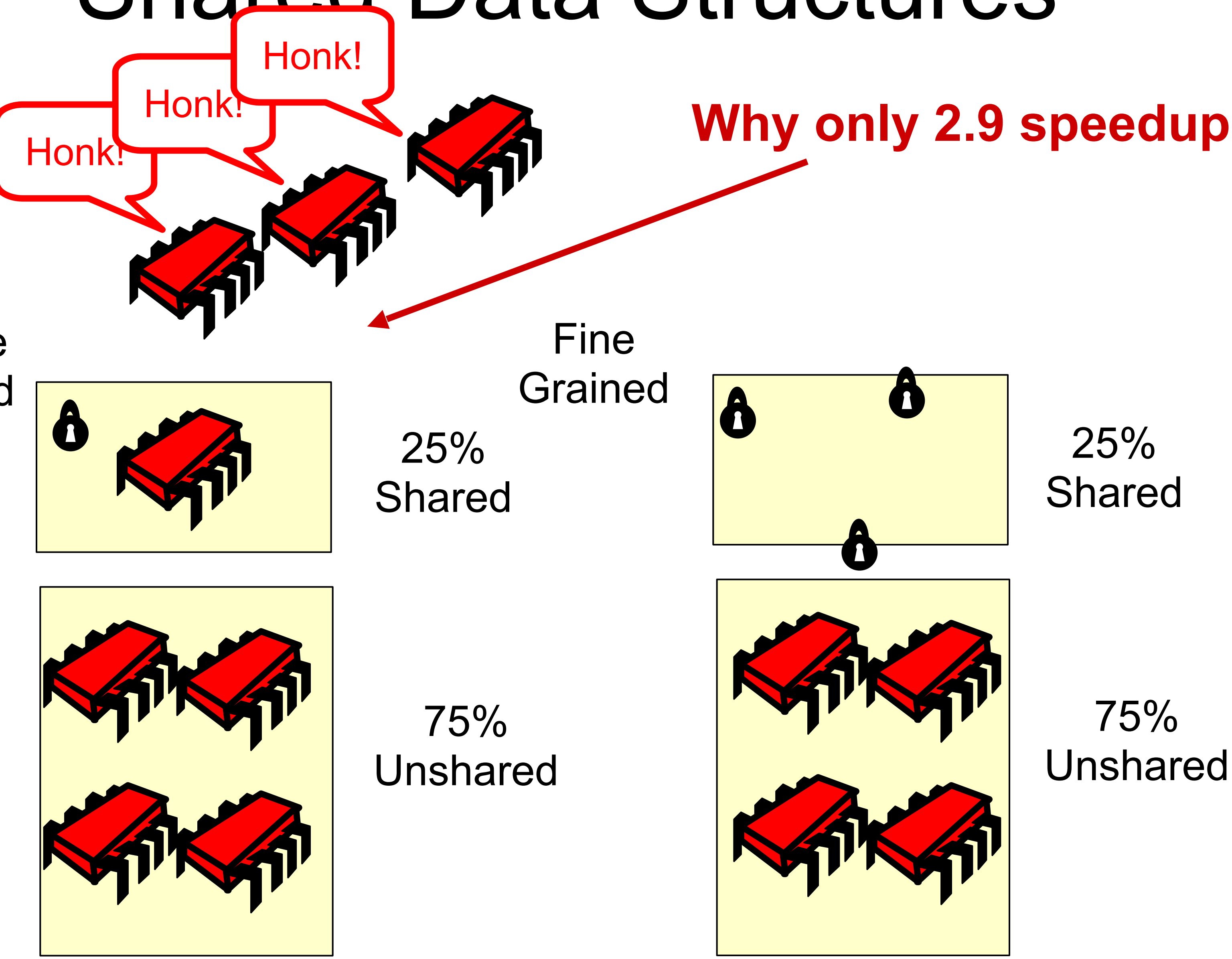
Not reducing sequential % of code

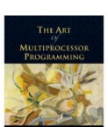


Shared Data Structures

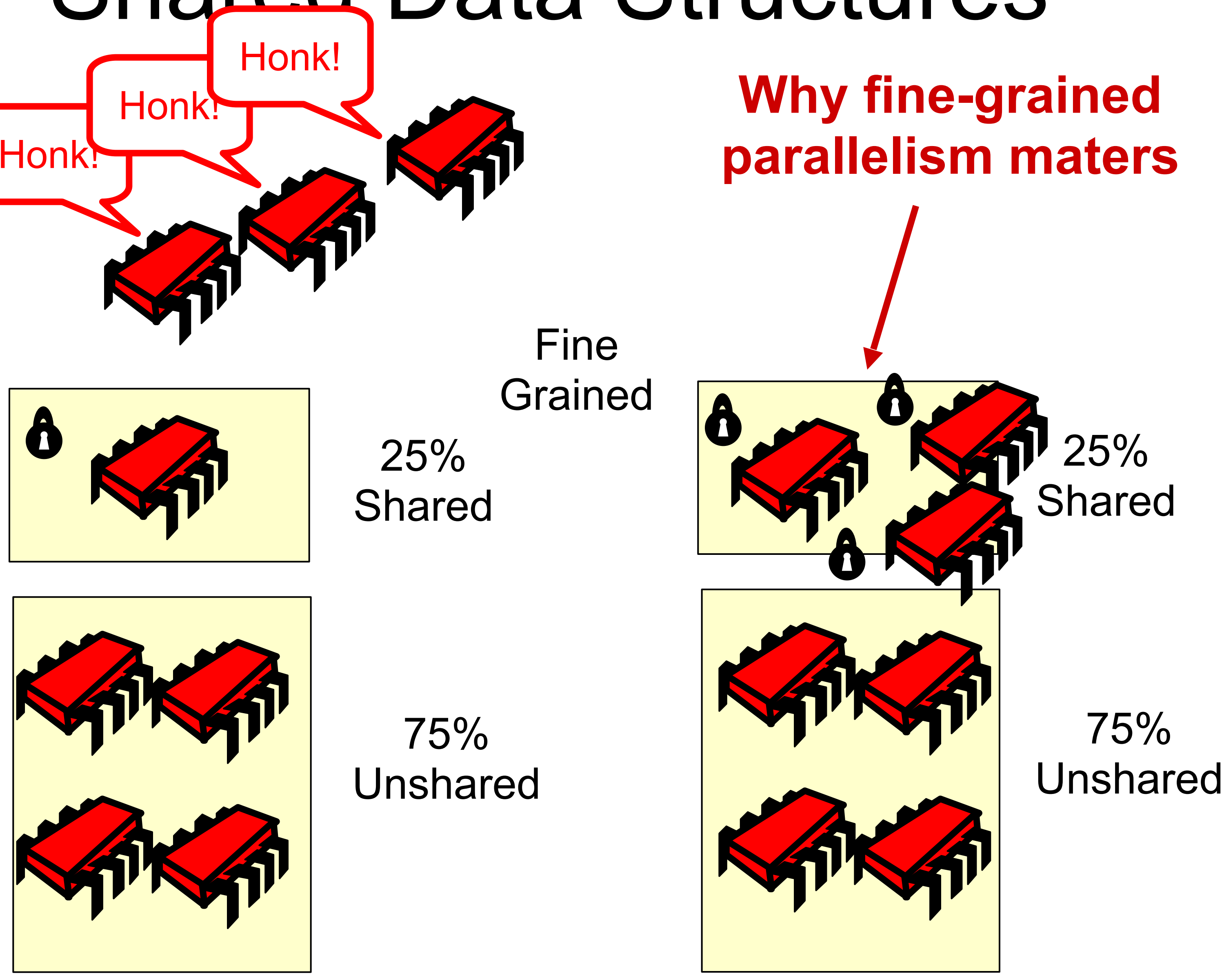


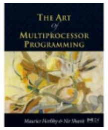
Shared Data Structures





Shared Data Structures



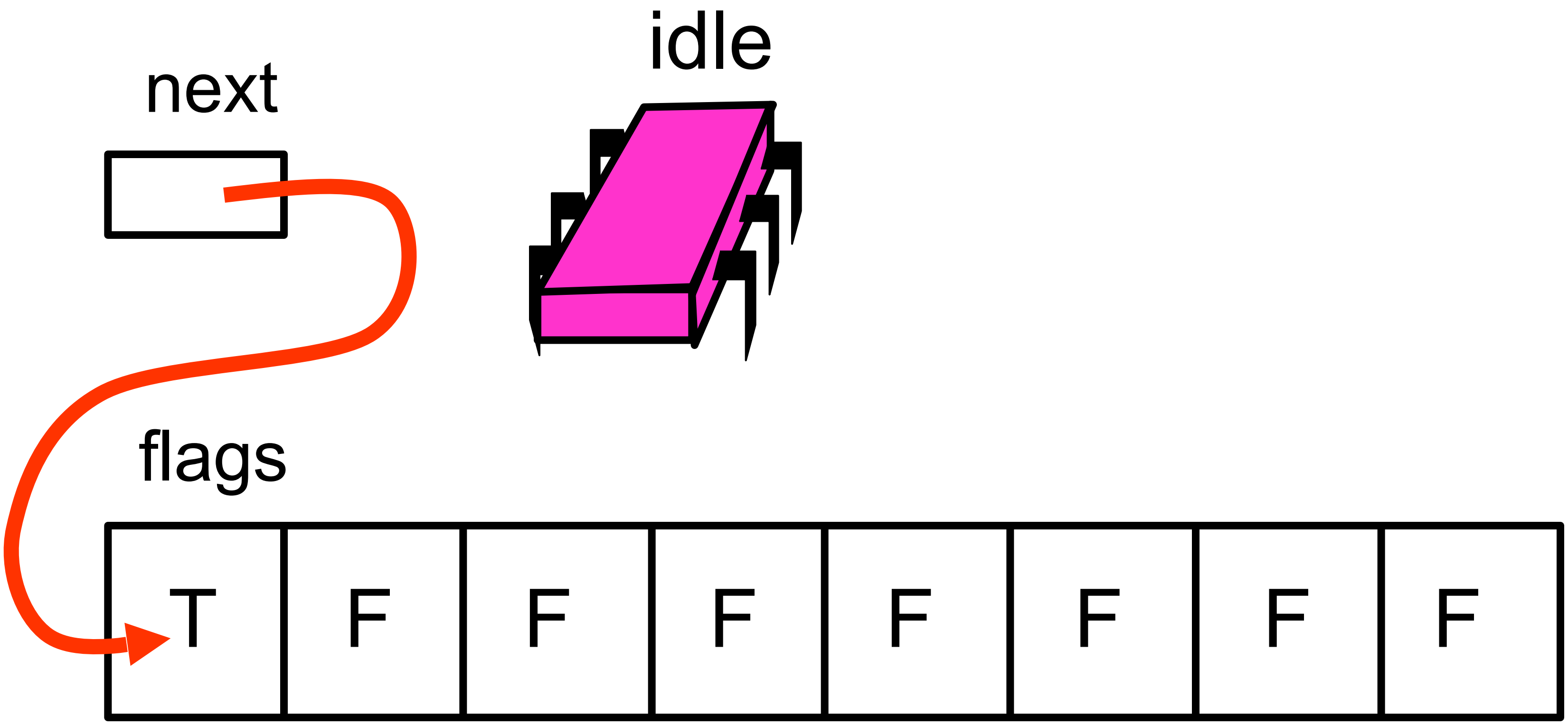


Fairness and Efficient Locks

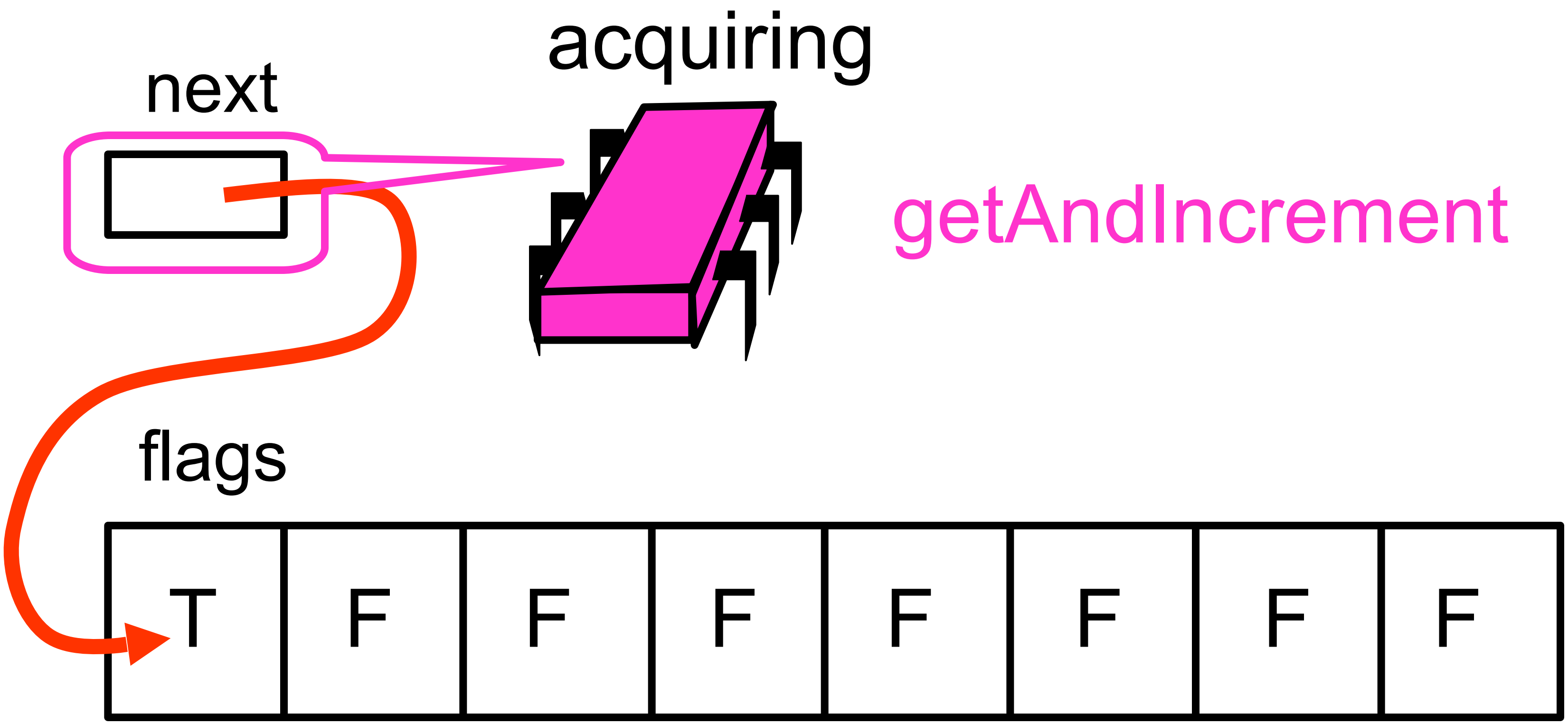
Idea

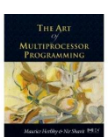
- Avoid useless invalidations
  - By keeping a queue of threads
- Each thread
  - Notifies next in line
  - Without bothering the others

Anderson Queue Lock



Anderson Queue Lock





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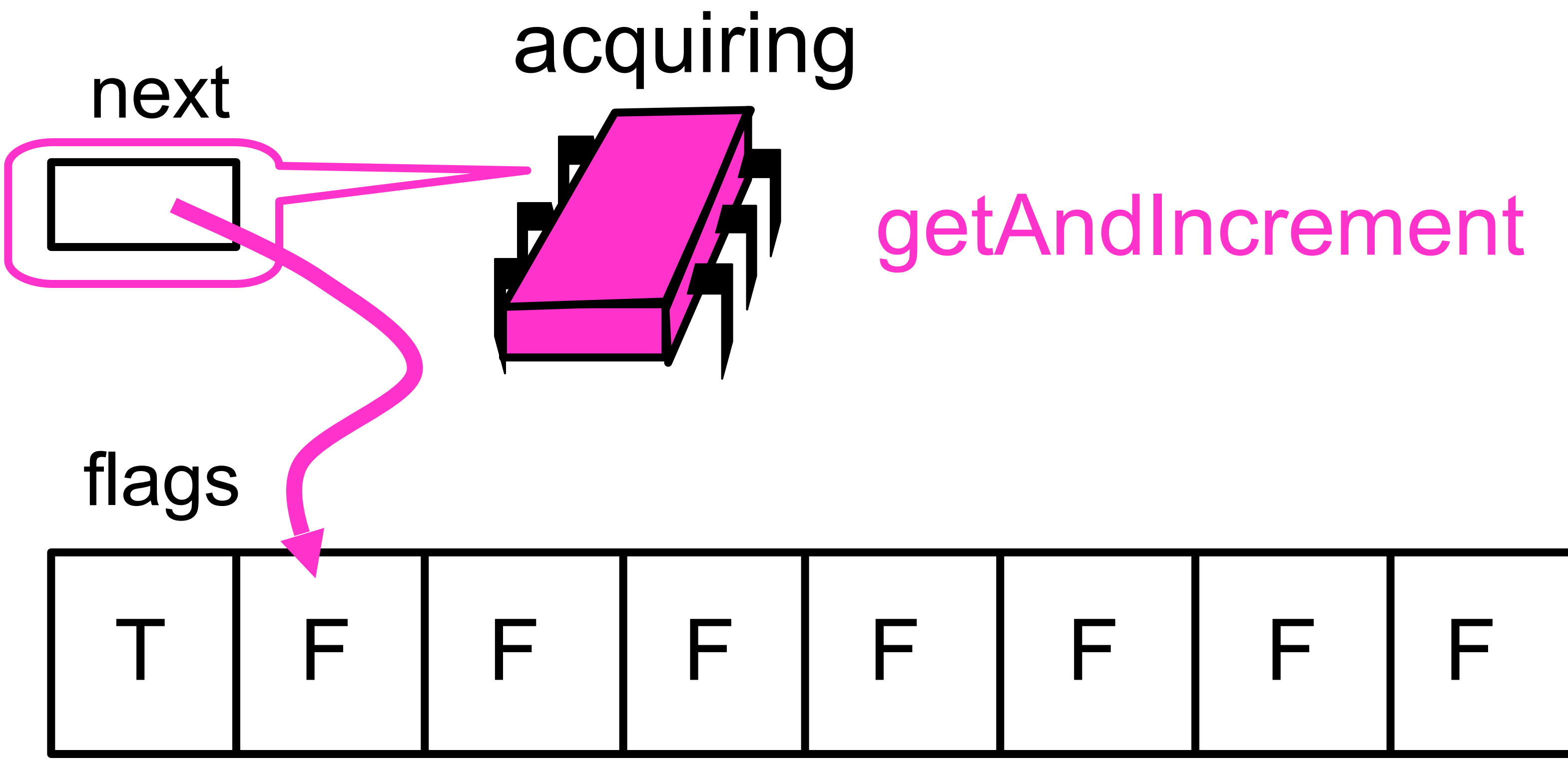

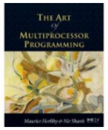

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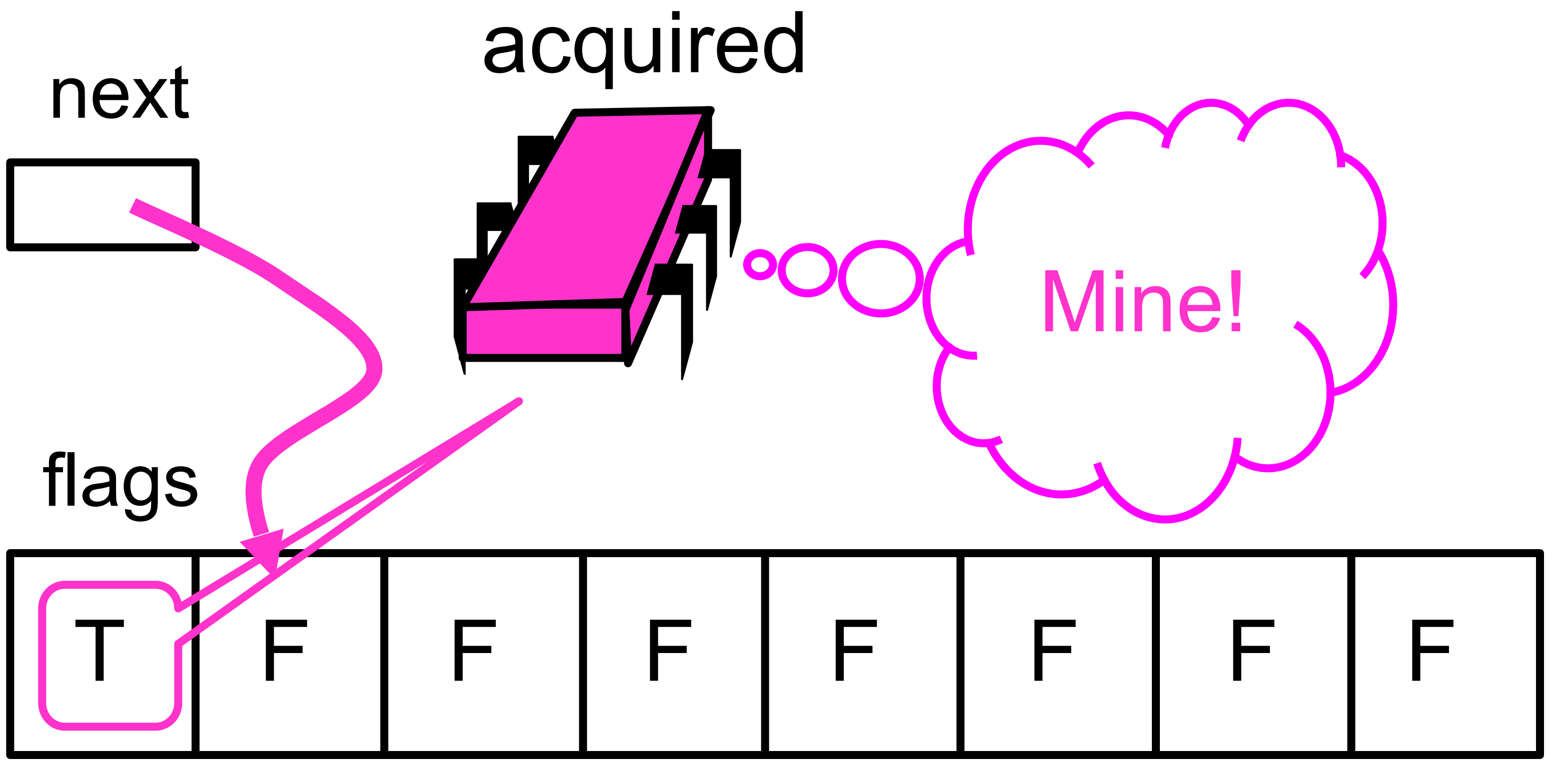

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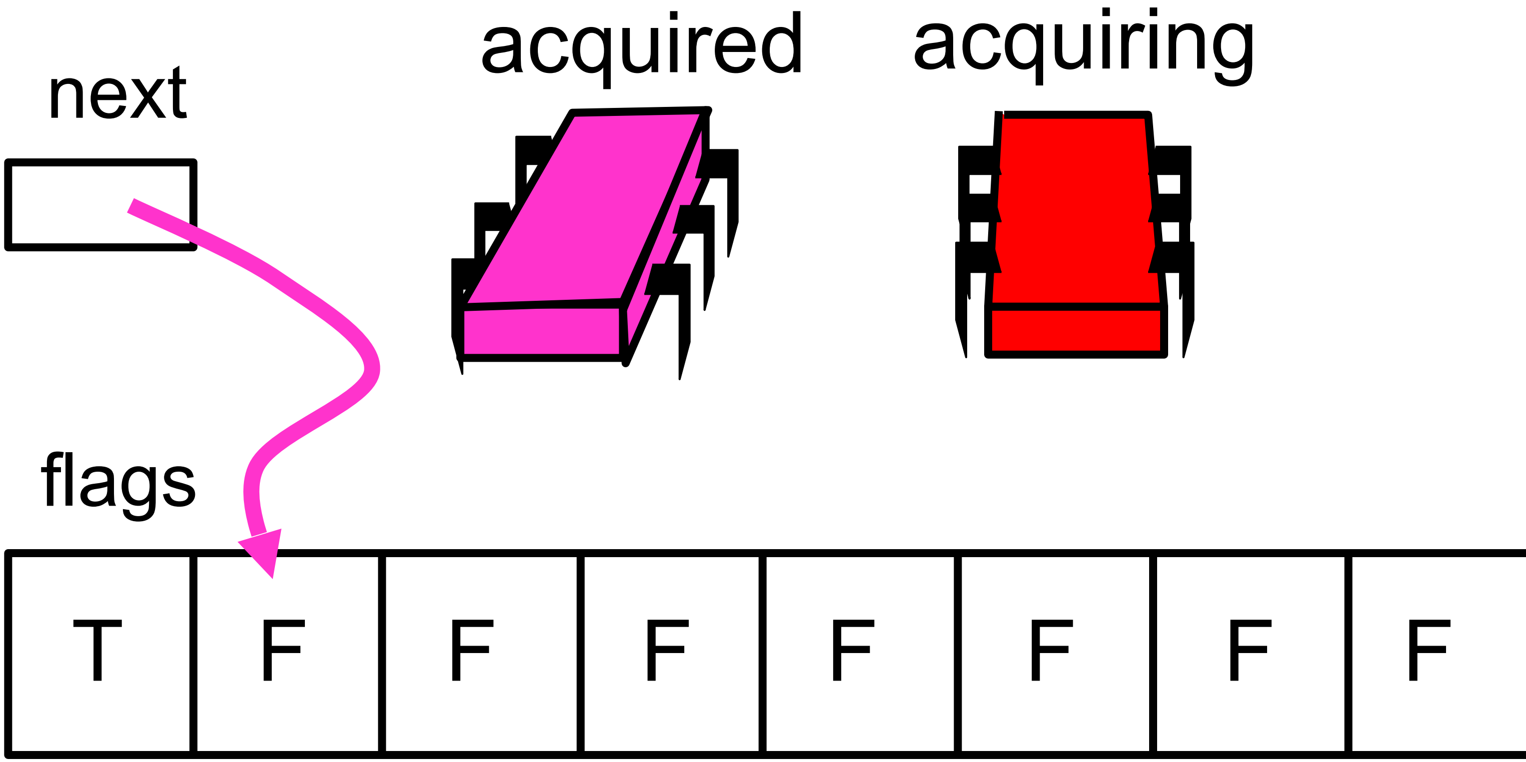

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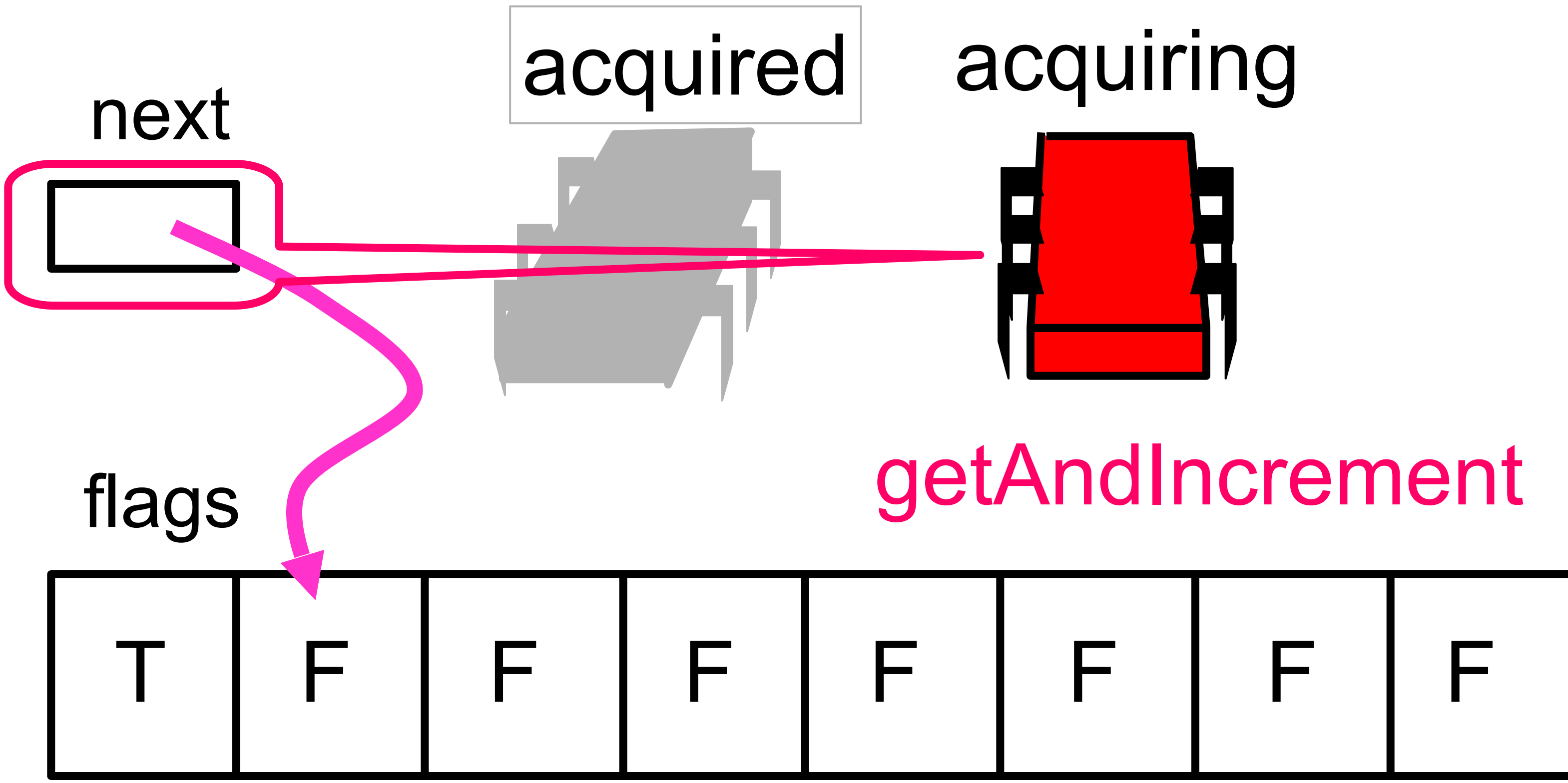
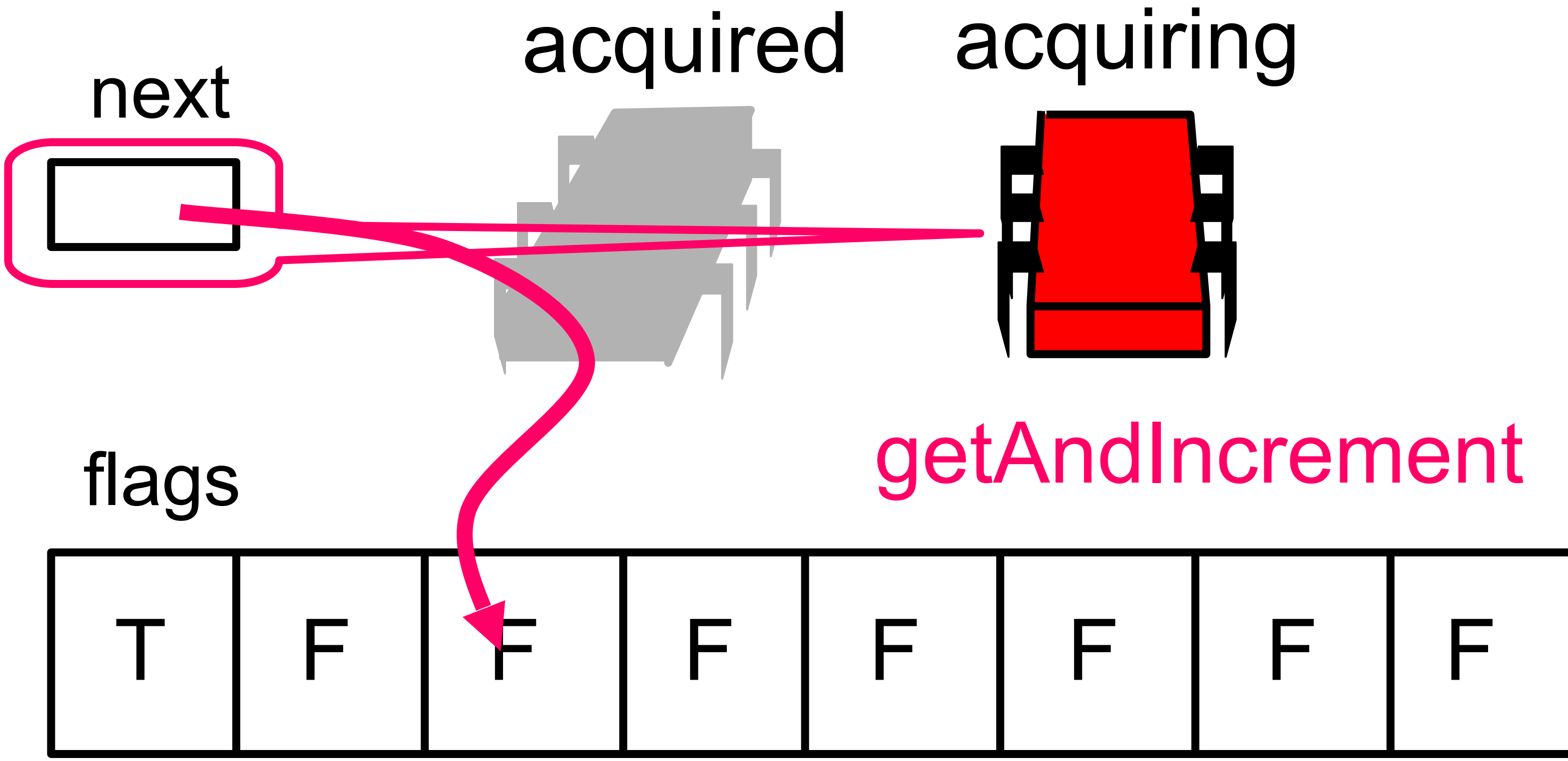
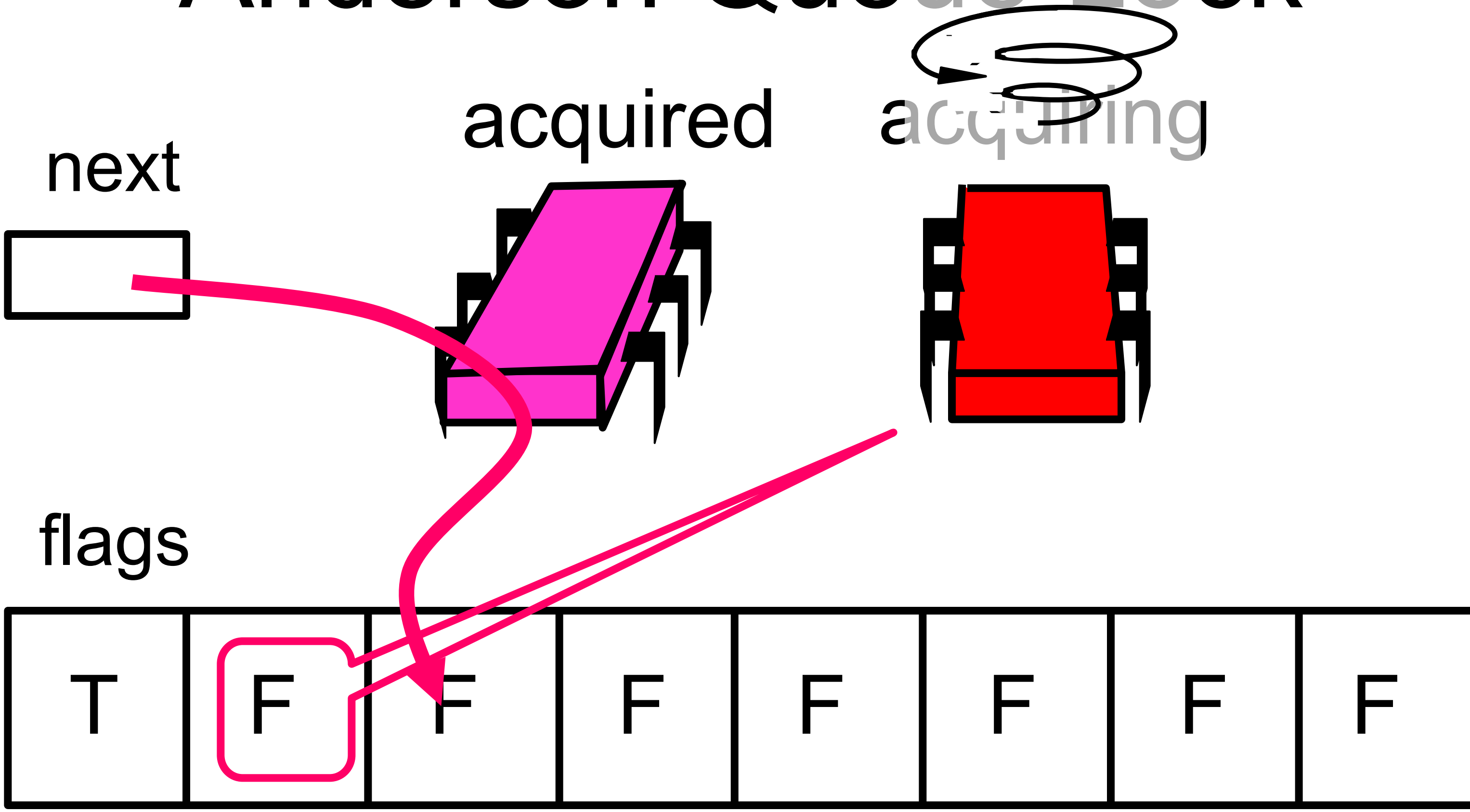


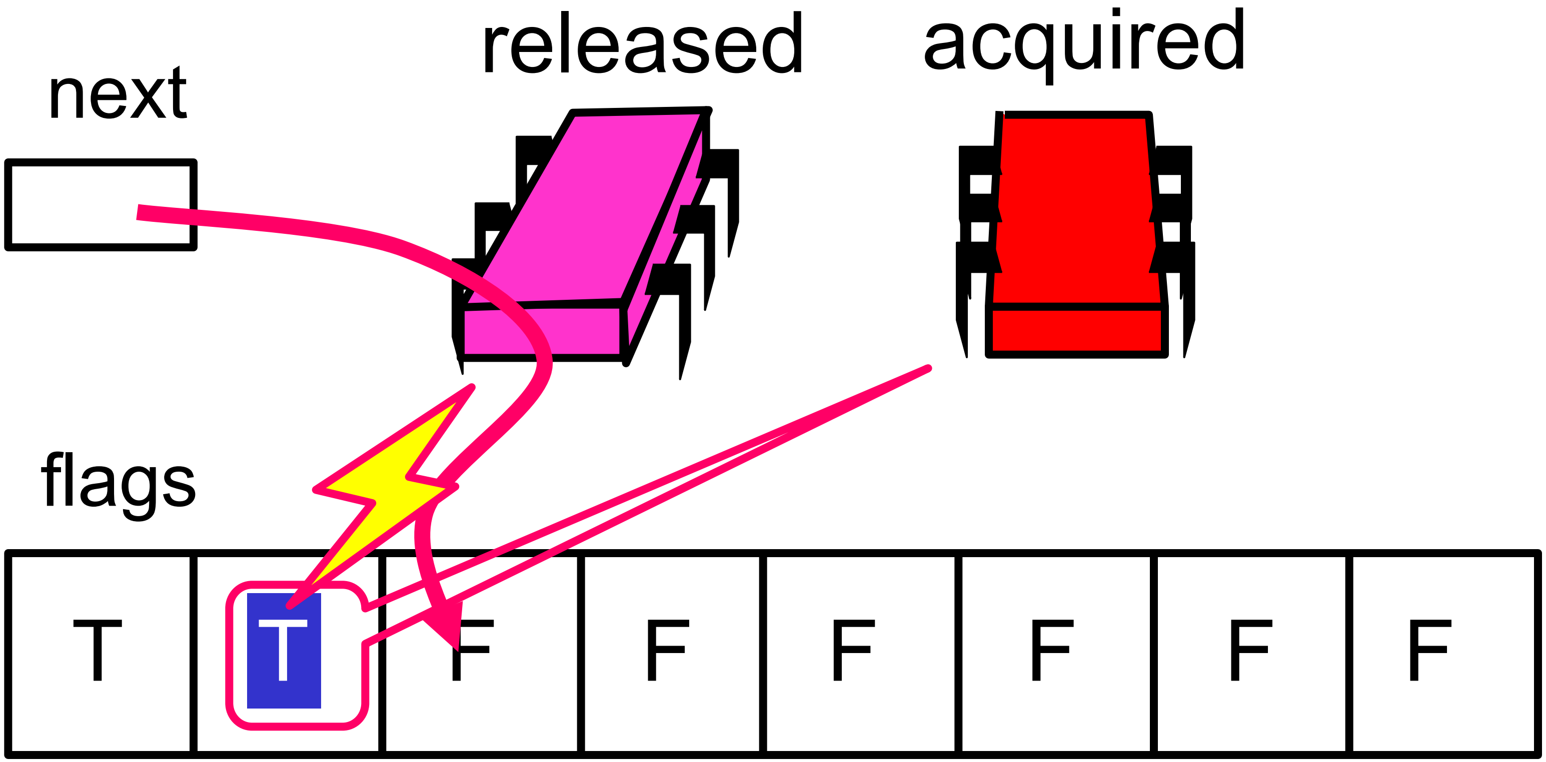
Anderson Queue Lock

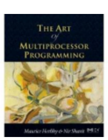


Anderson Queue Lock



Anderson Queue Lock





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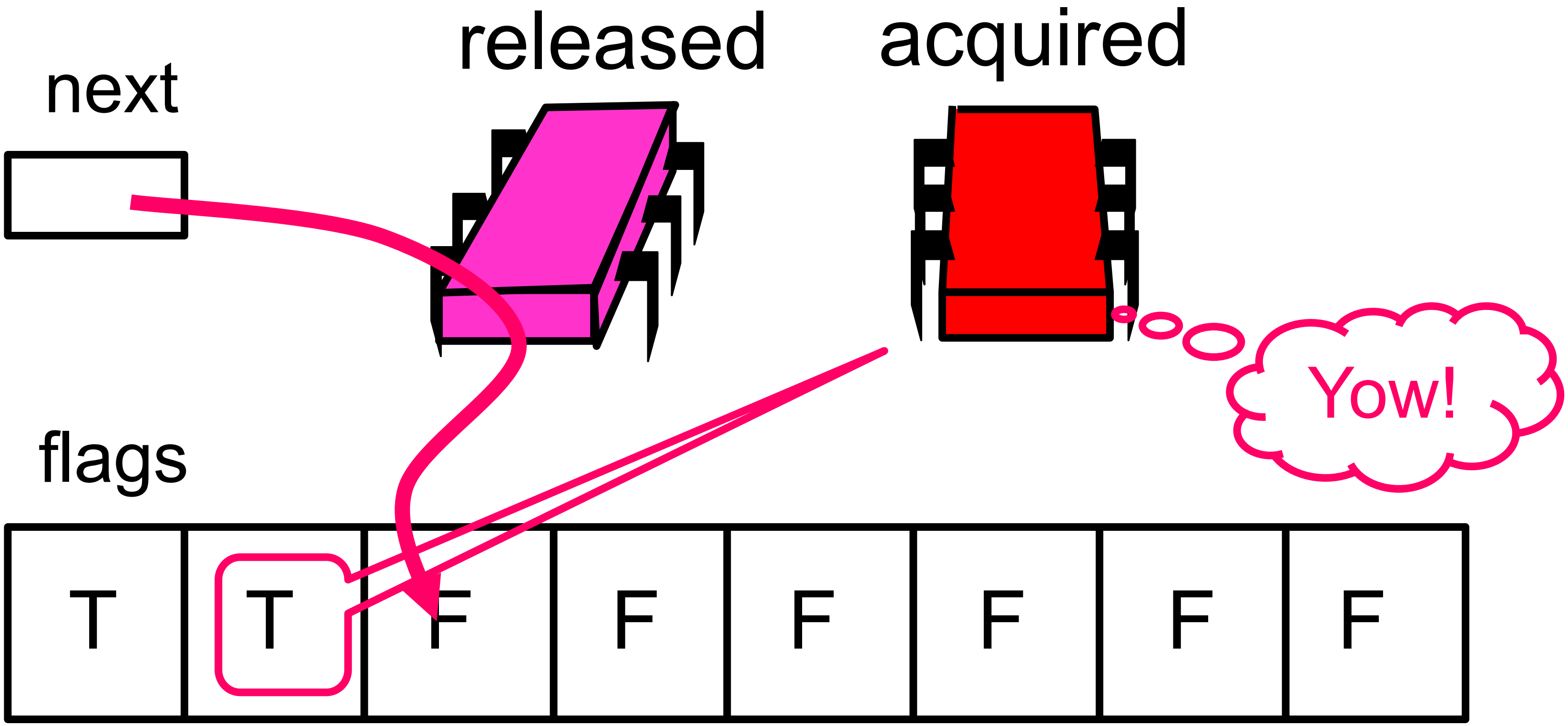

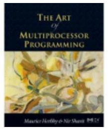

Anderson Queue Lock

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

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```

One flag per thread

Anderson Queue Lock

```
class ALock implements Lock {
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 AtomicInteger next
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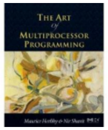
 ThreadLocal<Integer> mySlot;
```

Next flag to use



Anderson Queue Lock

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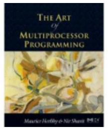
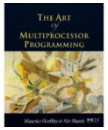
Thread-local variable



Anderson Queue Lock

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

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



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}
```

Take next slot

Anderson Queue Lock

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

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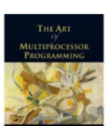

Spin until told to go



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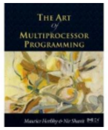
}
```

Prepare slot for re-use



Anderson Queue Lock

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}
```
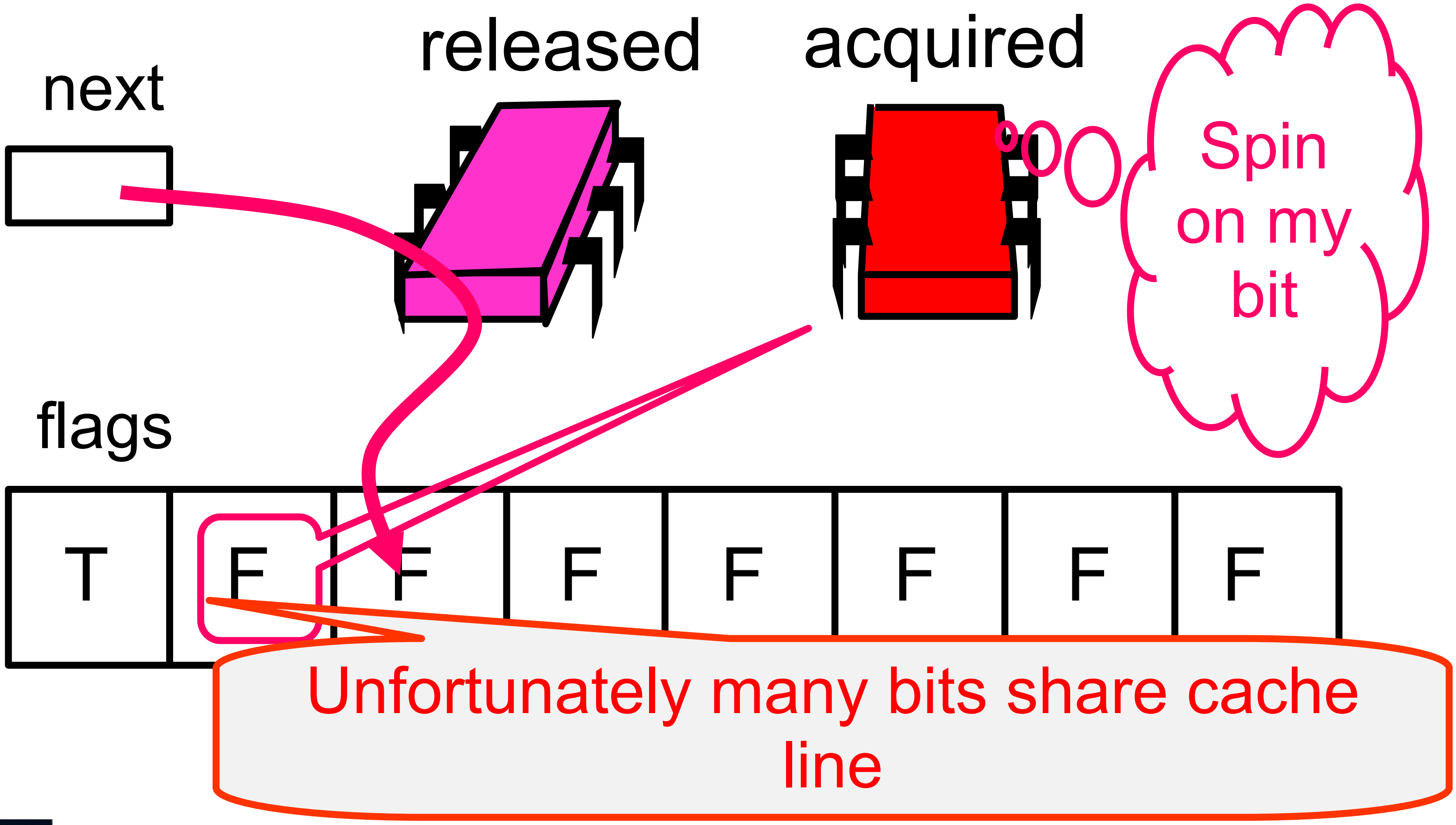
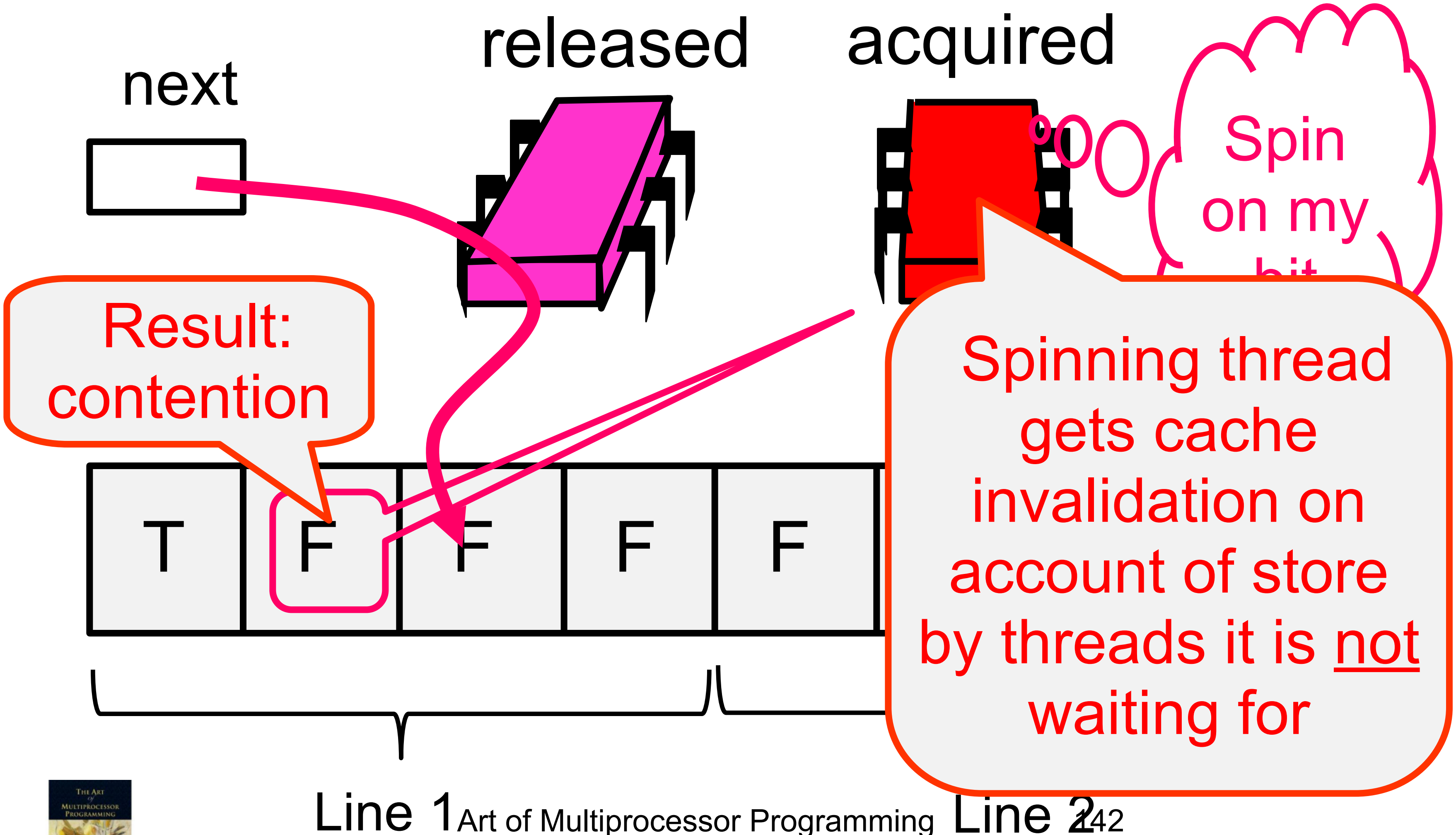

Tell next thread to go

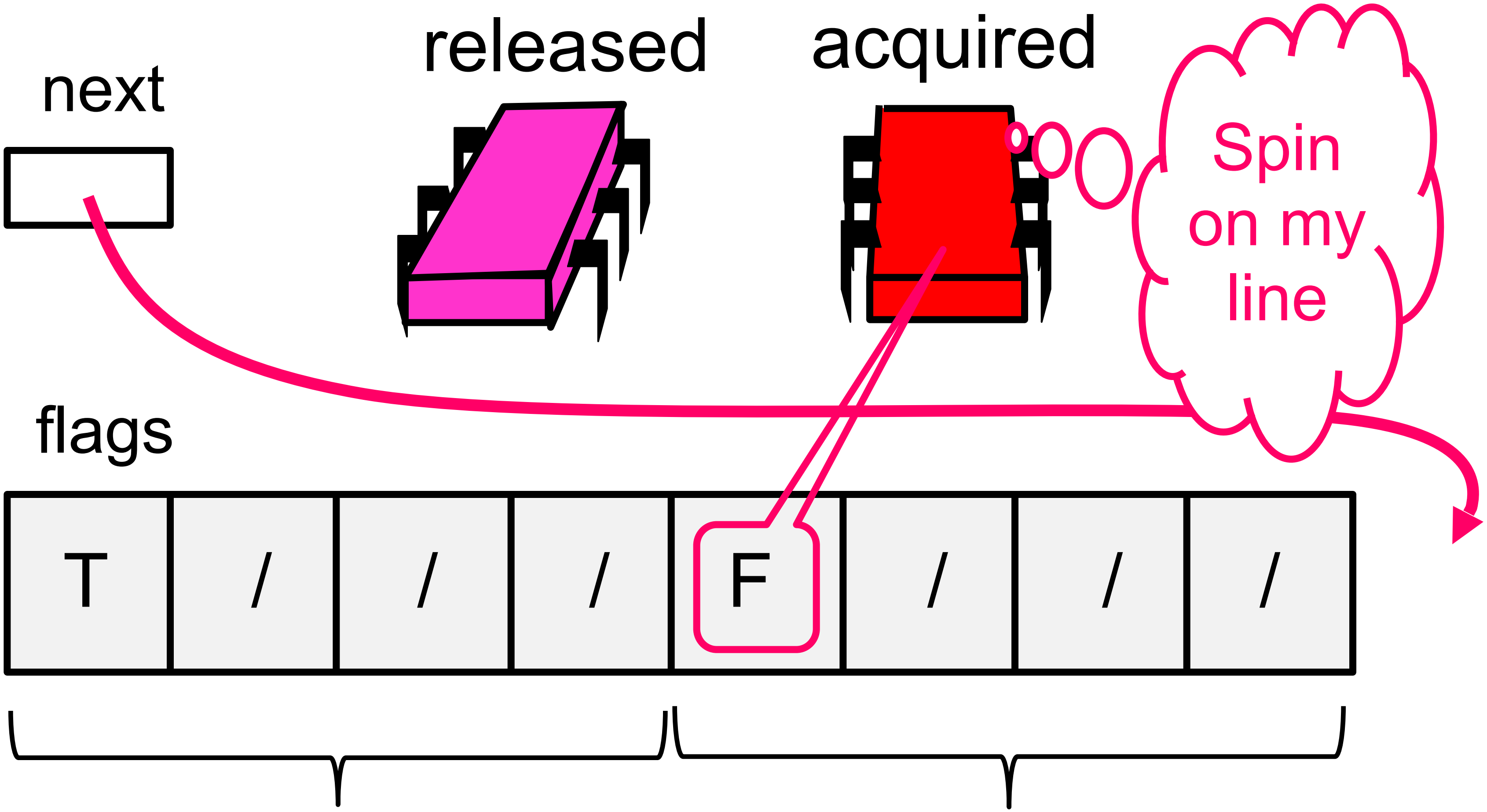
Local Spinning



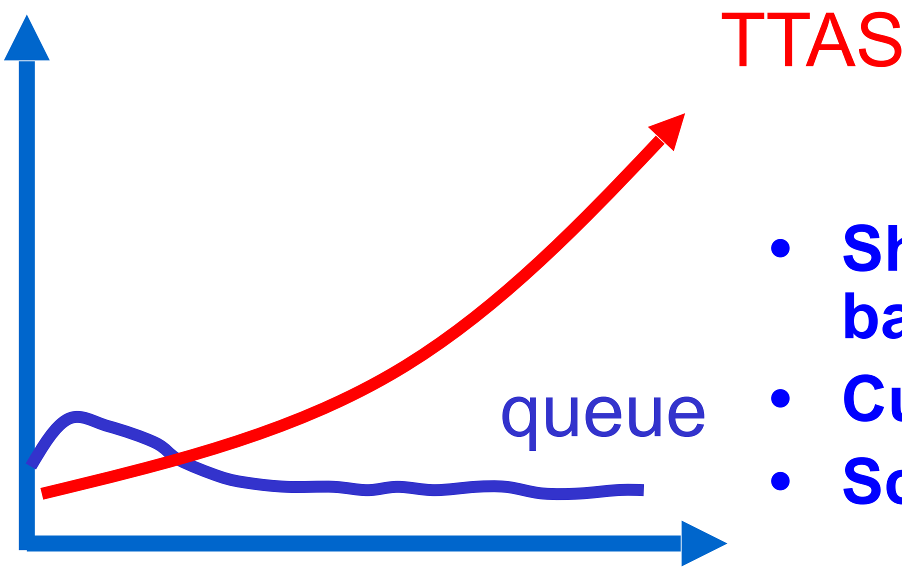
False Sharing



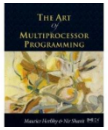
The Solution: Padding



Performance



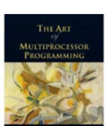
- **Shorter handover than backoff**
- **Curve is practically flat**
- **Scalable performance**



Anderson Queue Lock

Good

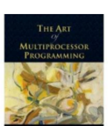
- First truly scalable lock
- Simple, easy to implement
- Back to FIFO order (like Bakery)



Anderson Queue Lock

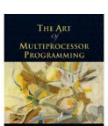
Bad

- Space hog…
- One bit per thread ➔ one cache line per thread
  - What if unknown number of threads?
  - What if small number of actual contenders?

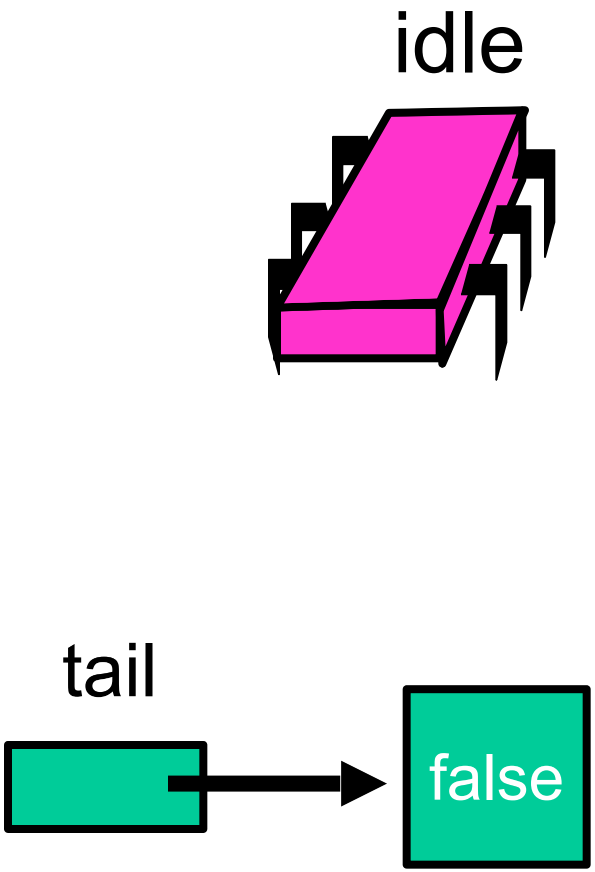


CLH Lock

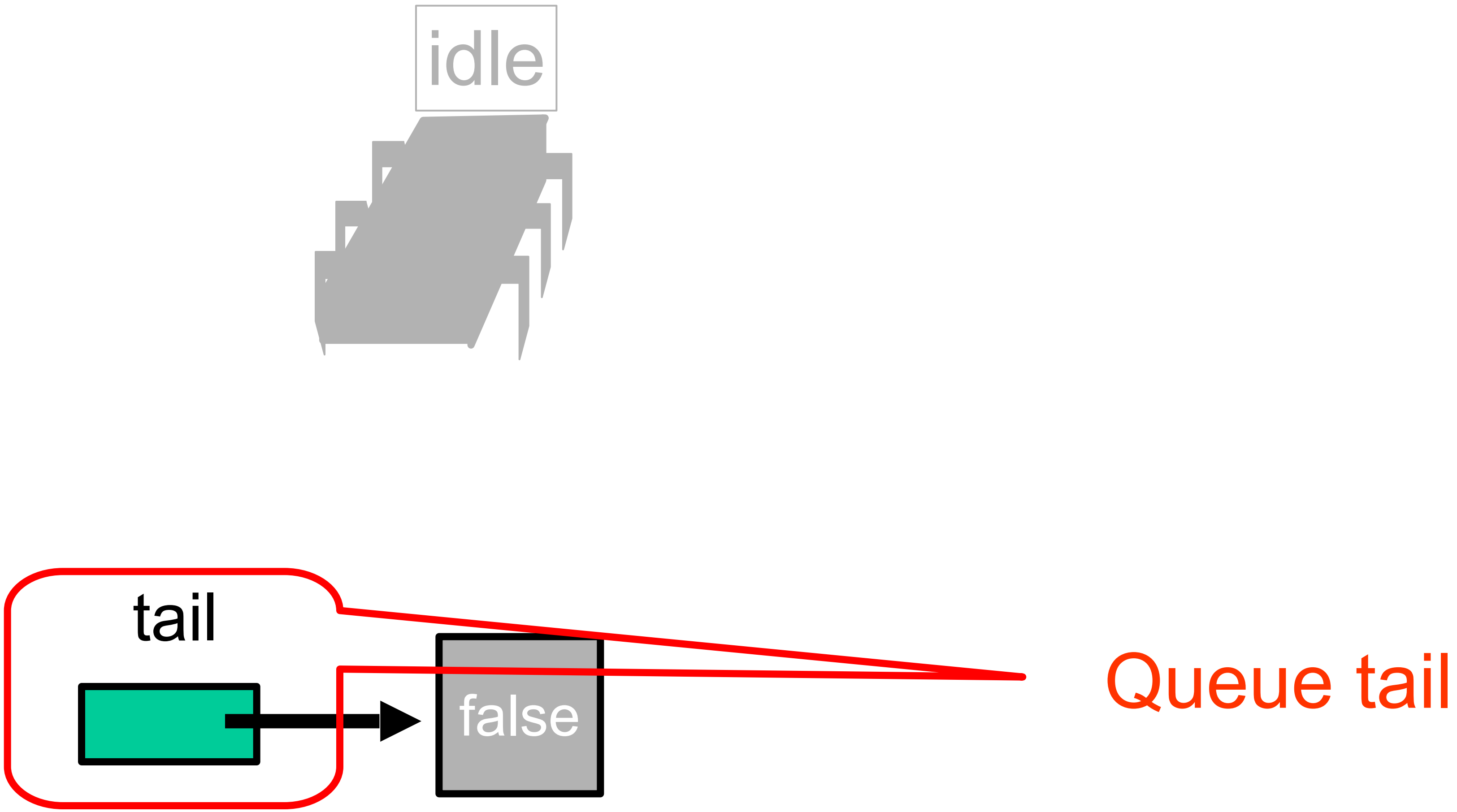
- FIFO order
- Small, constant-size overhead per thread

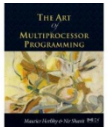


Initially

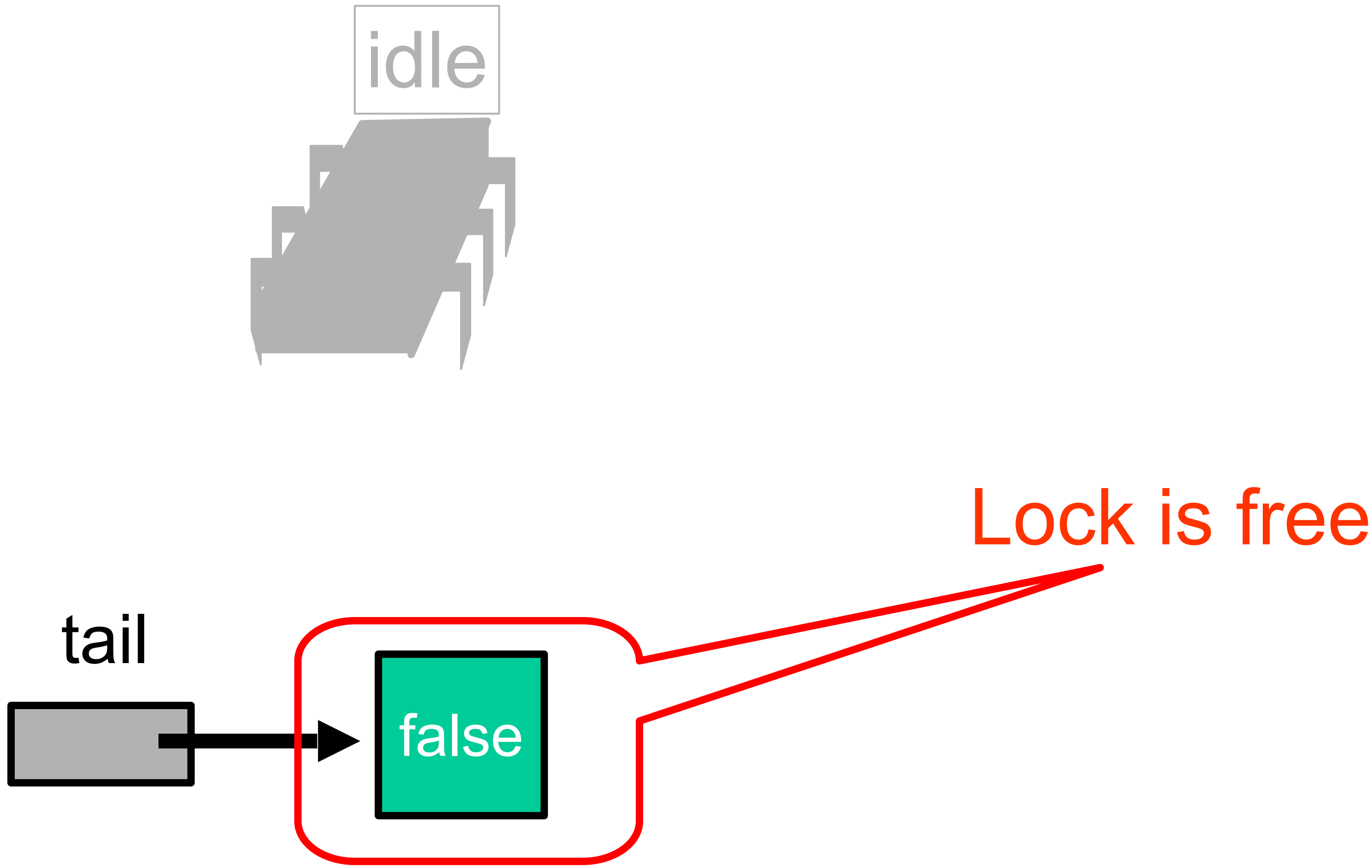


Initially

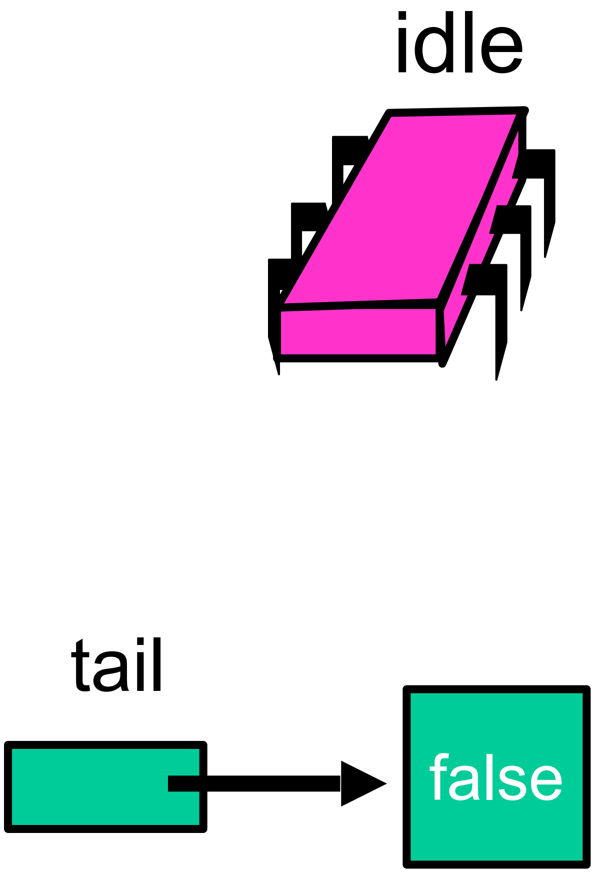




Initially

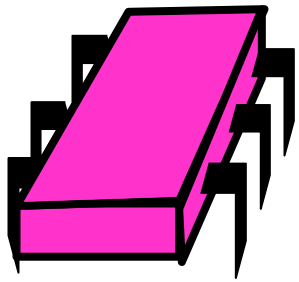


Initially

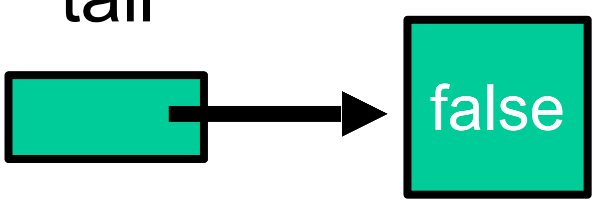


Purple Wants the Lock

acquiring



tail



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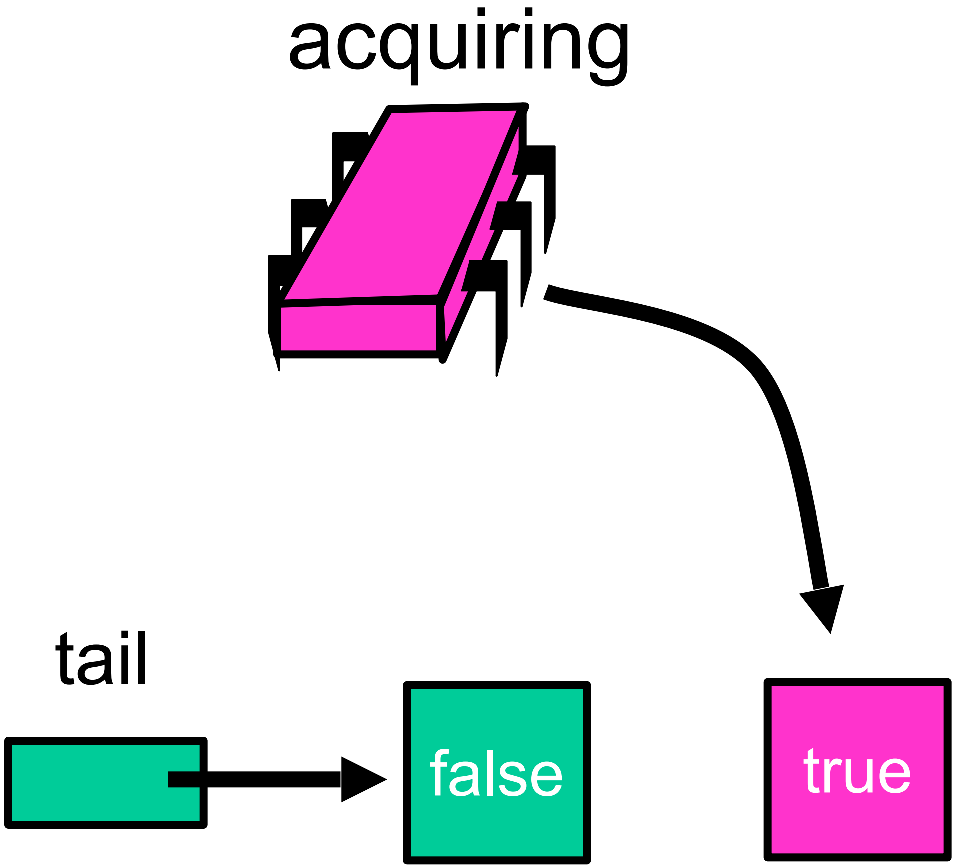

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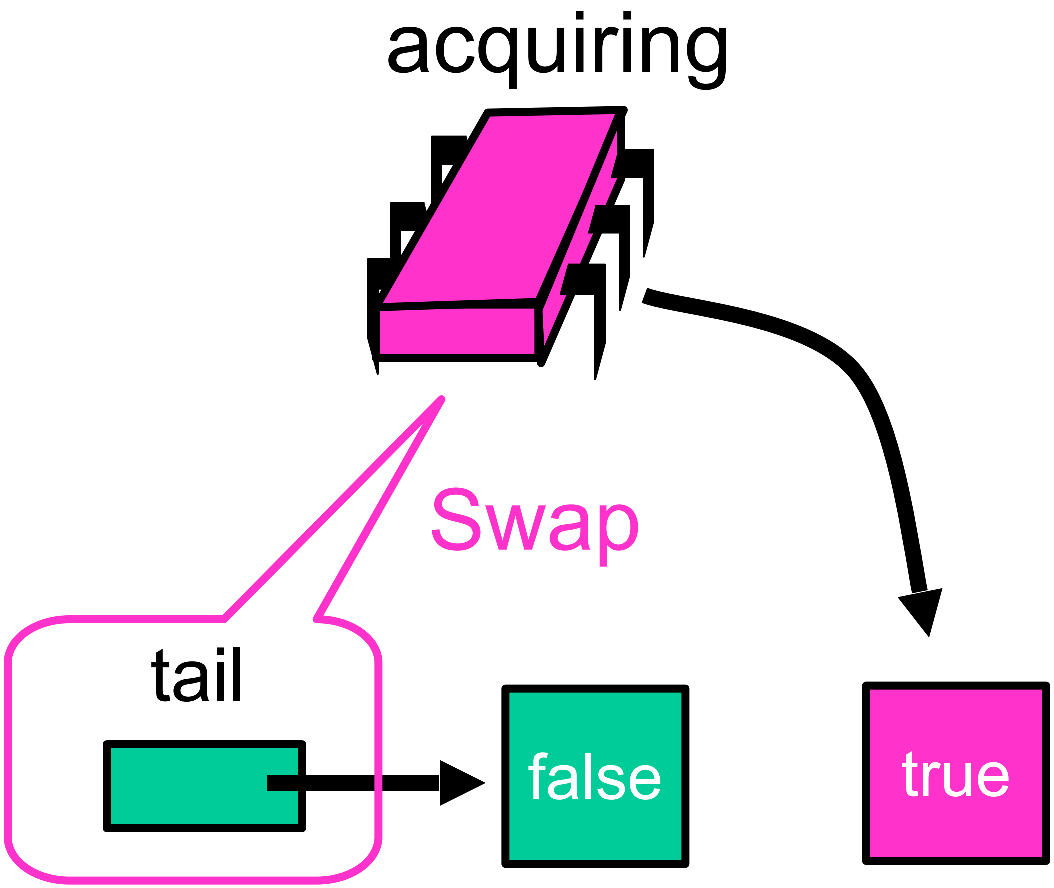
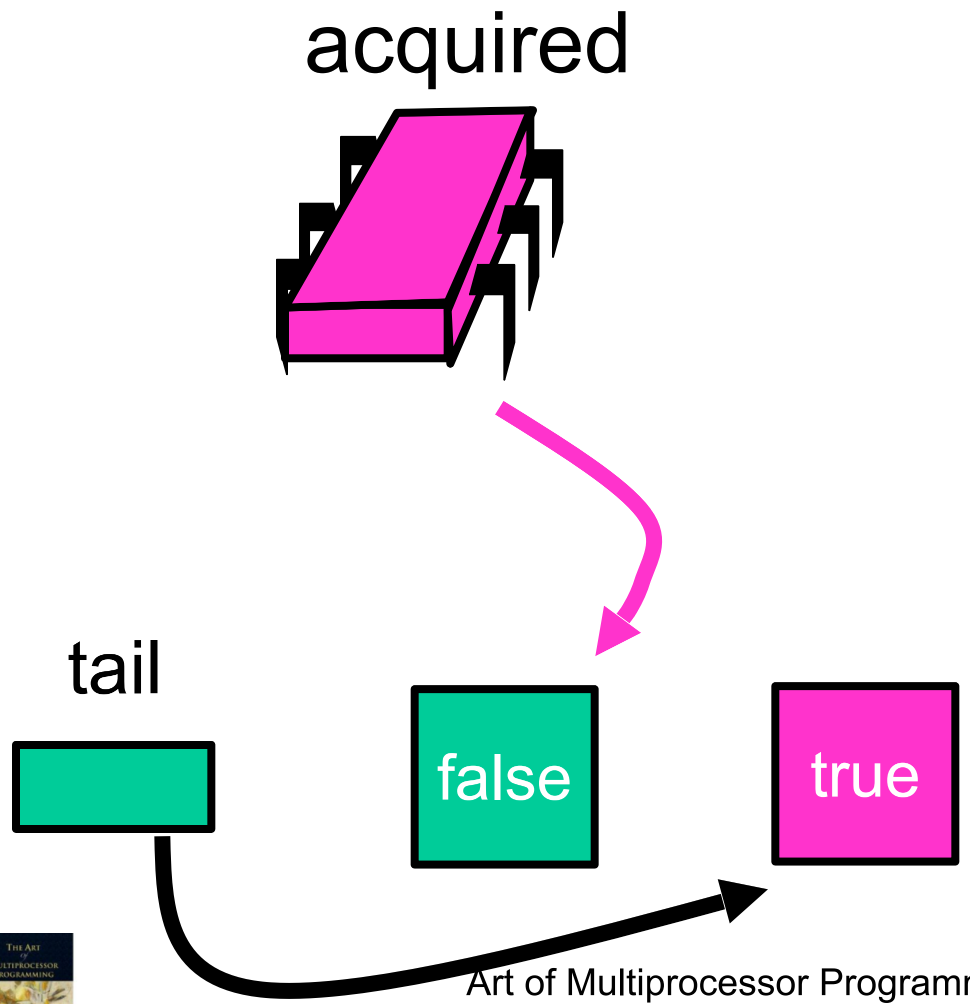
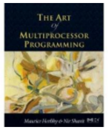
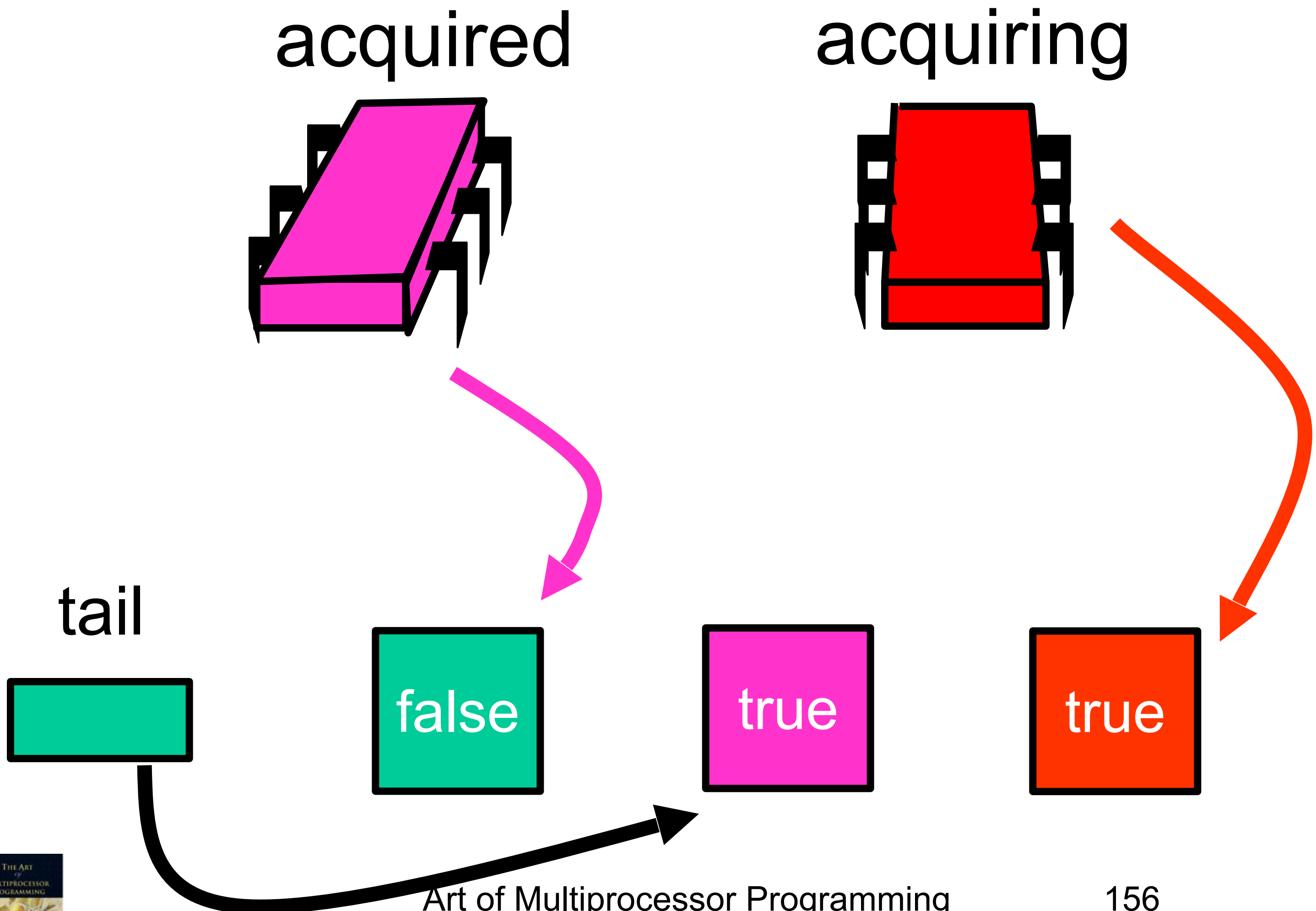


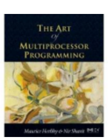
Purple Has the Lock





Red Wants the Lock





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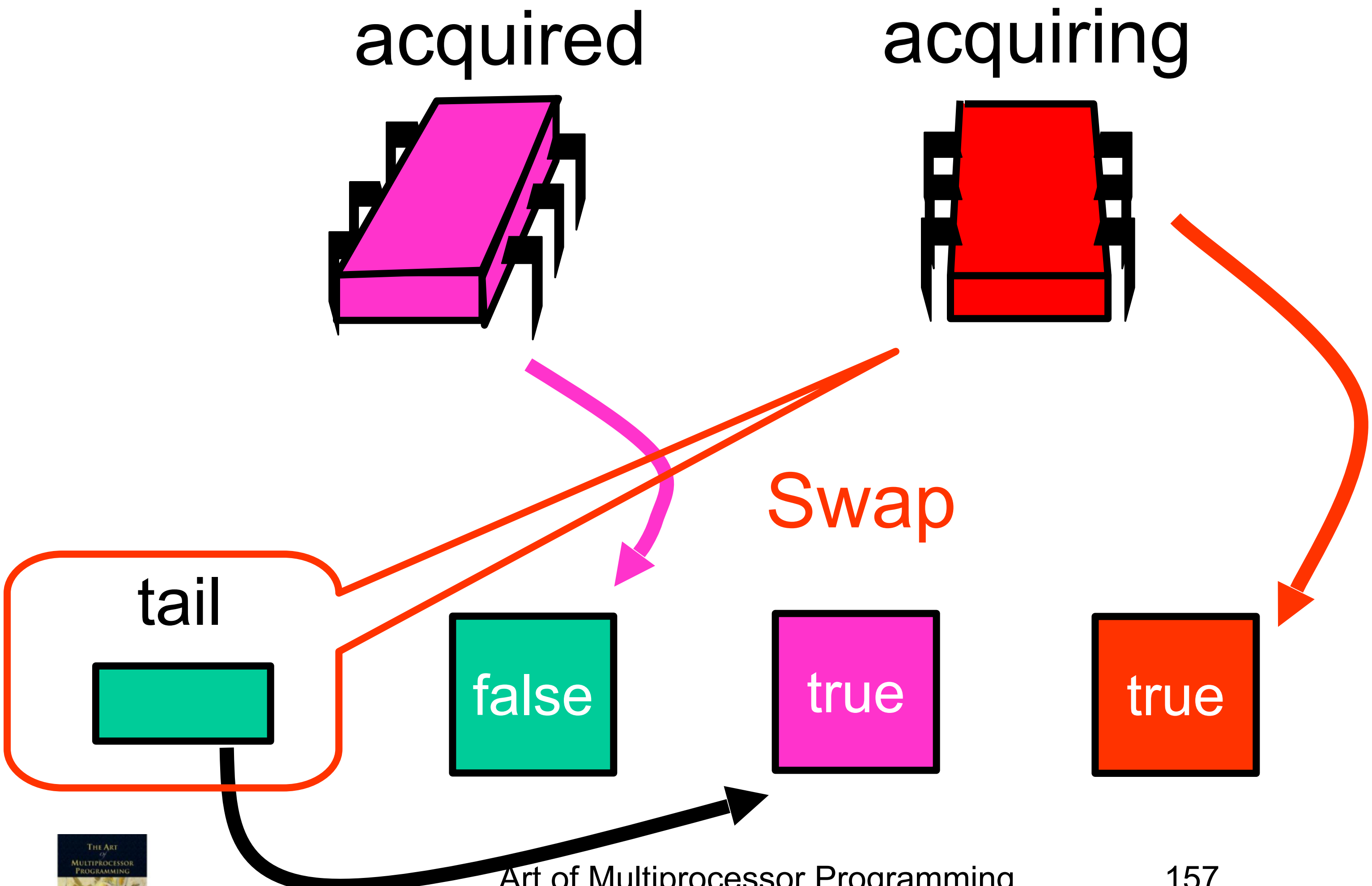

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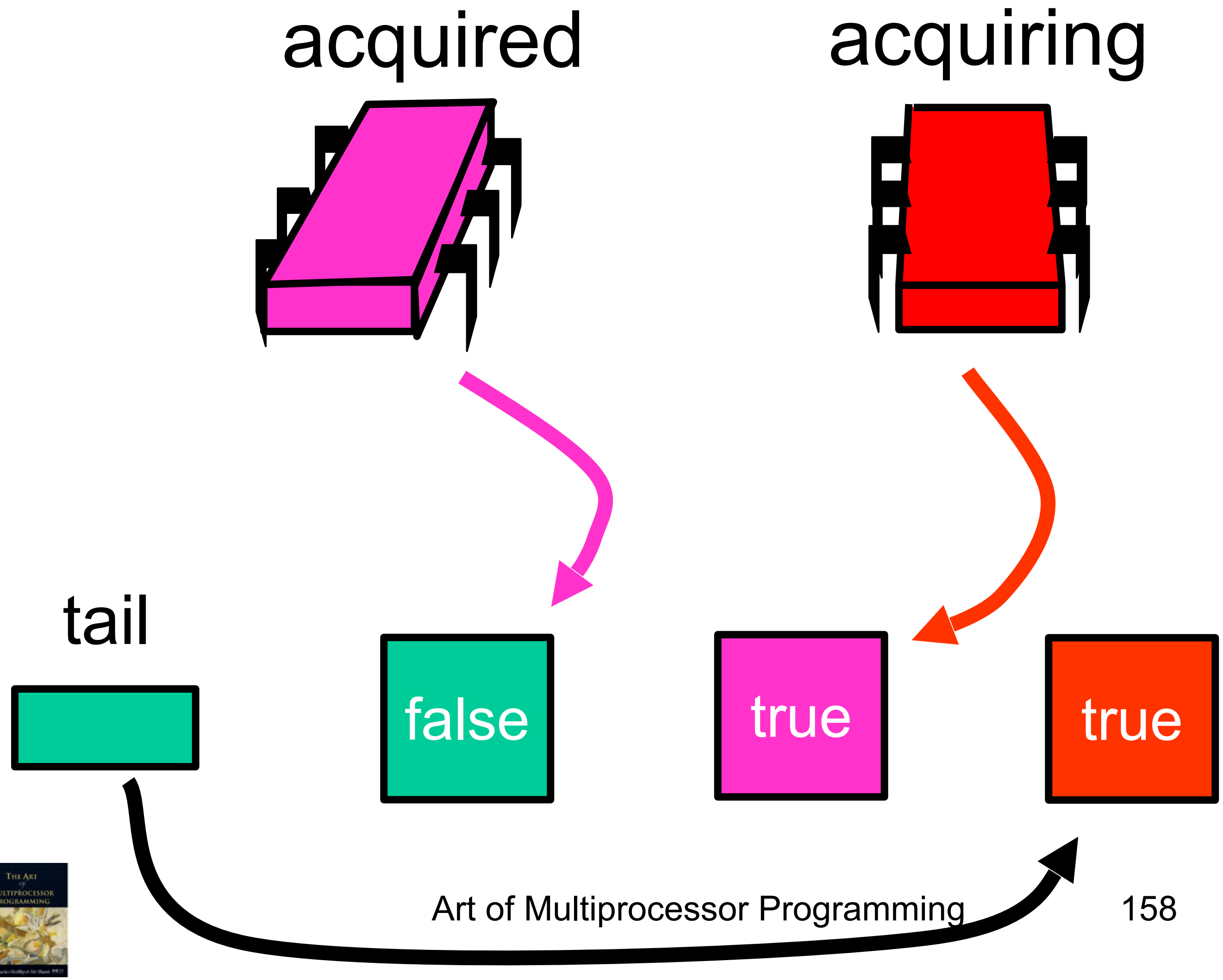

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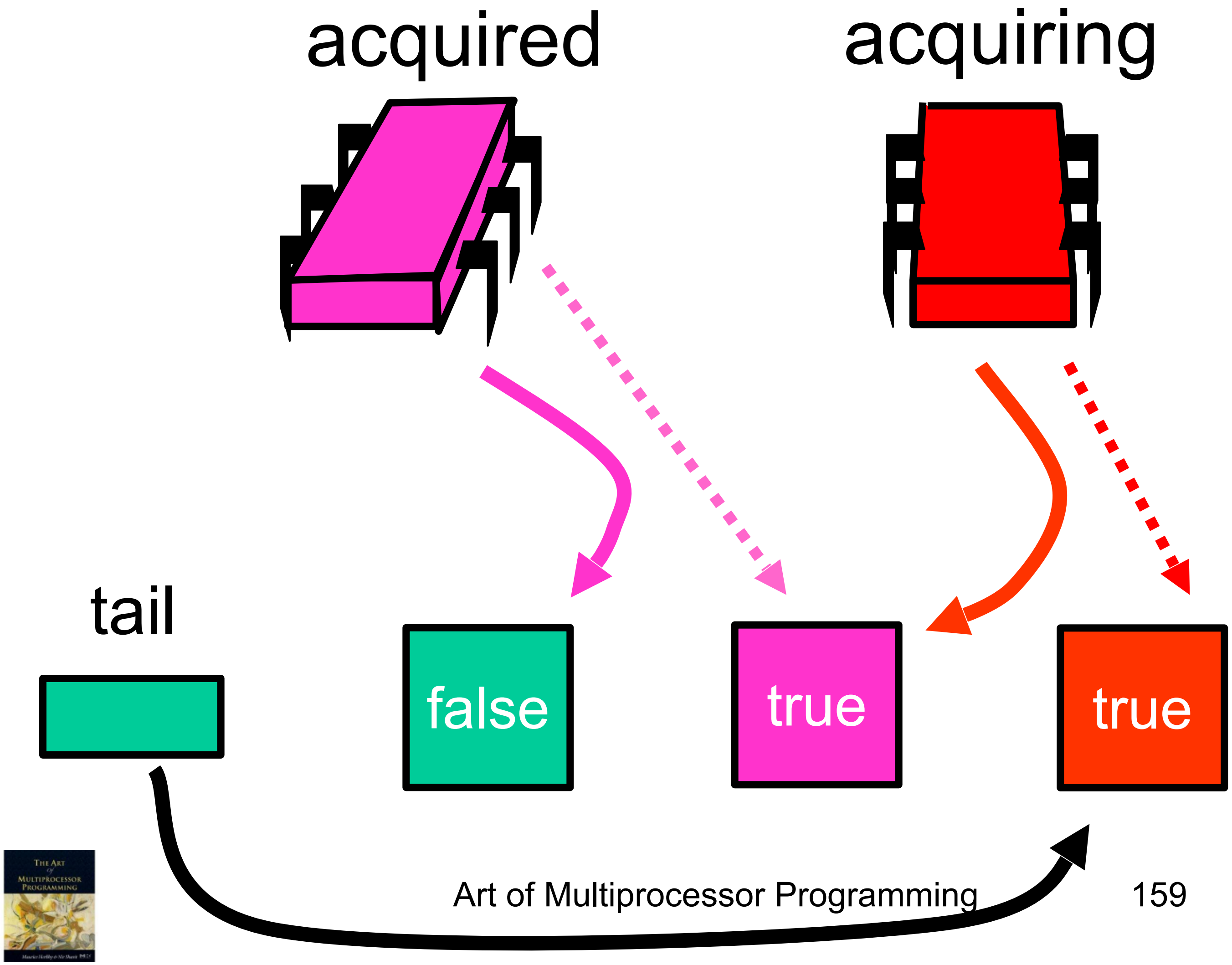

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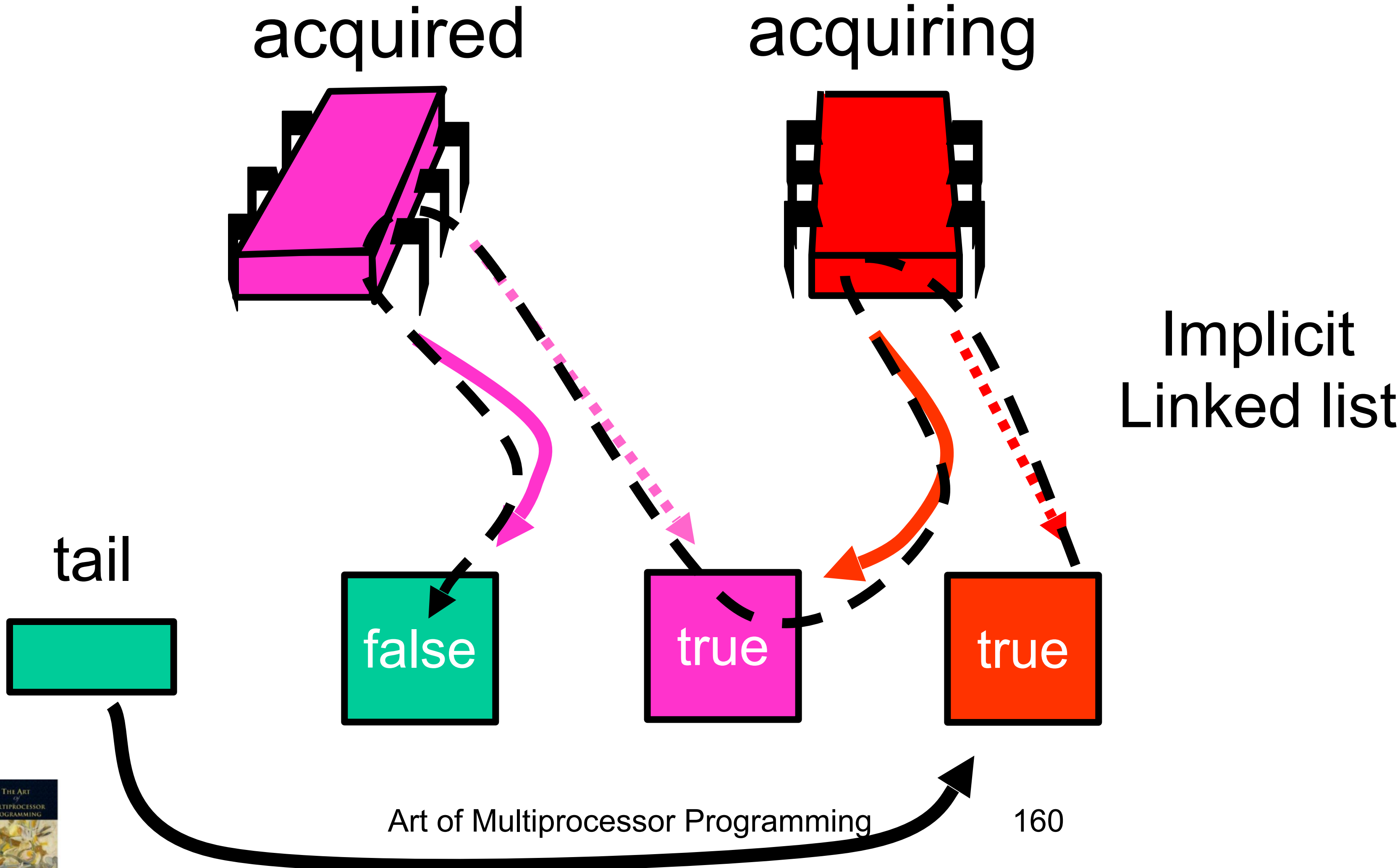

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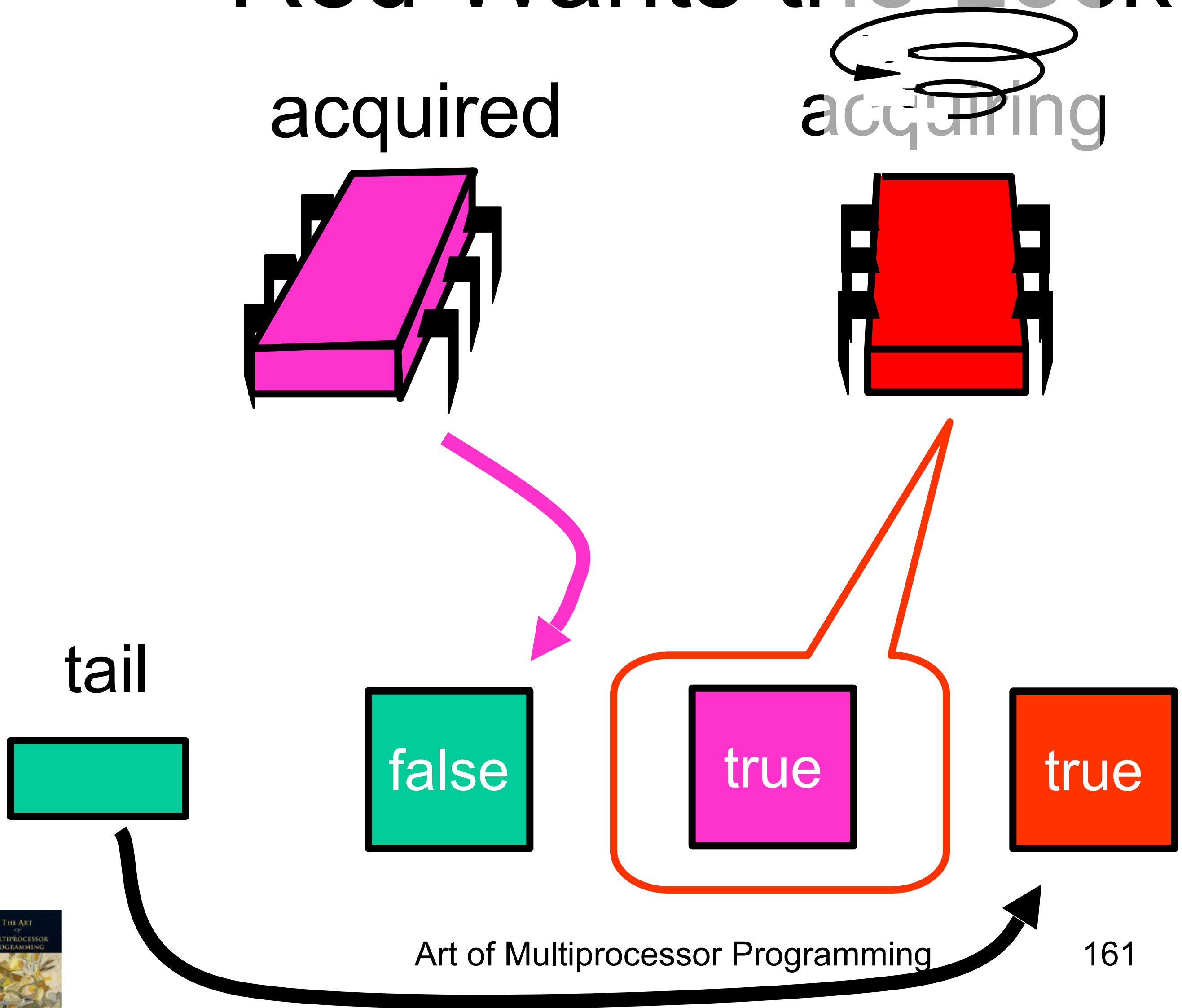

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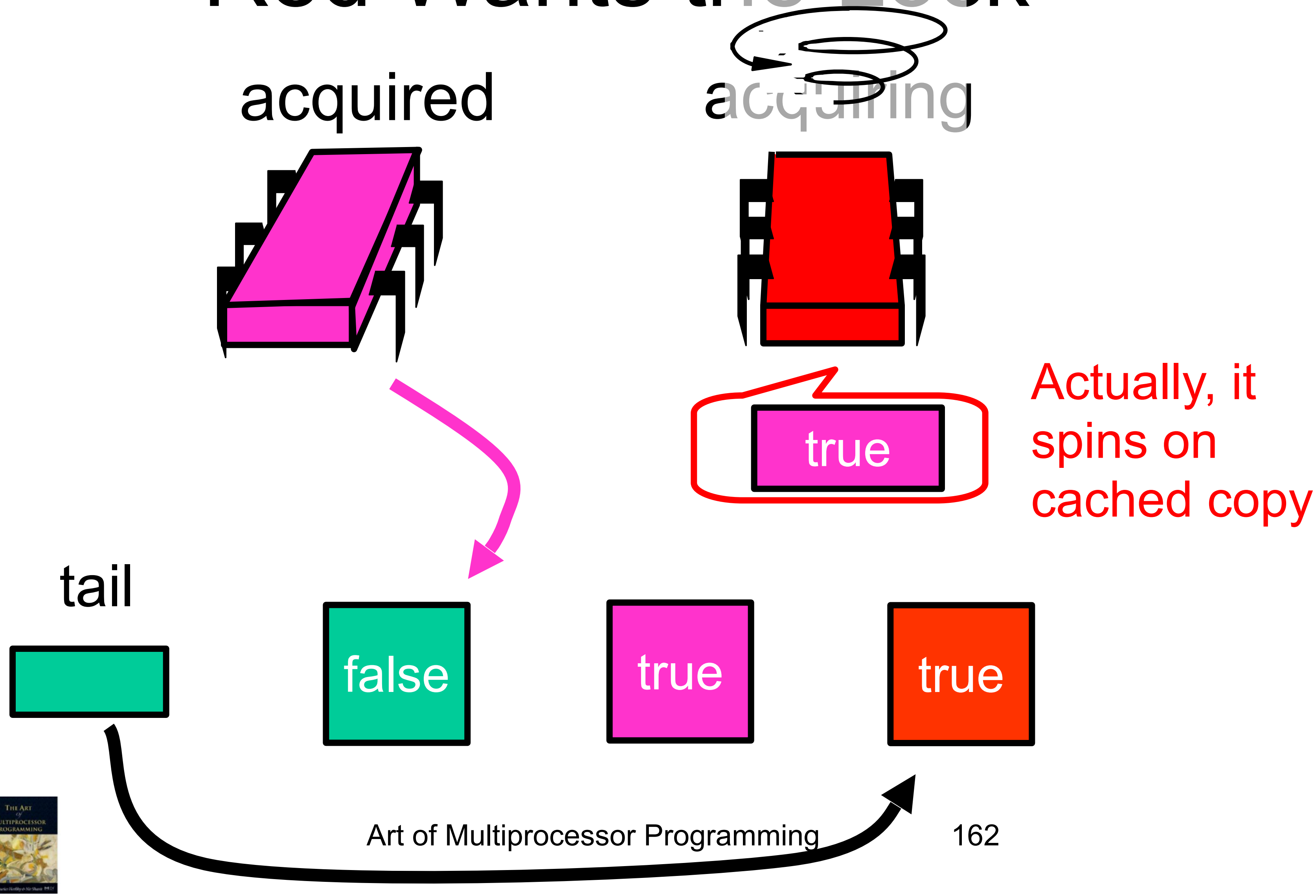
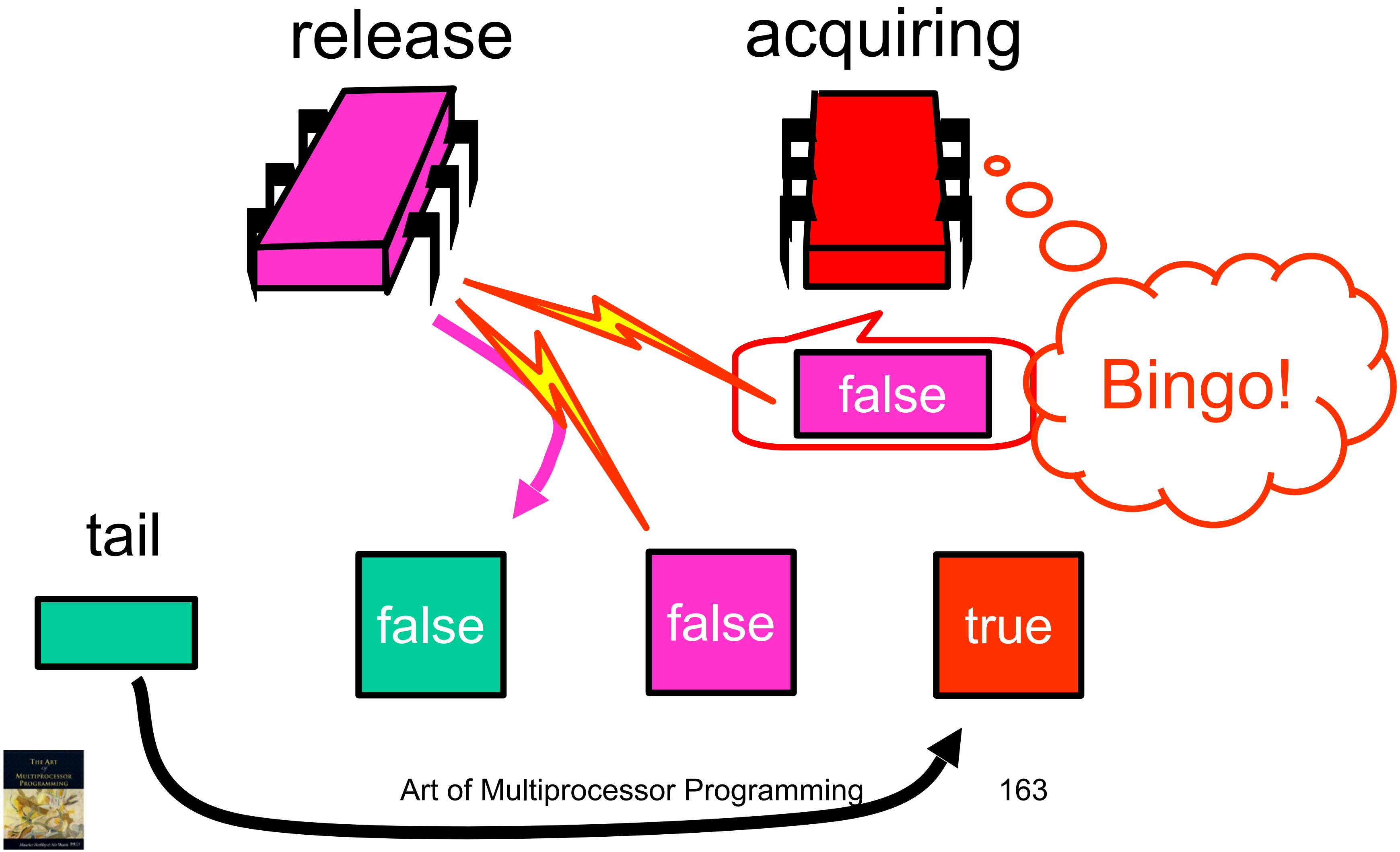
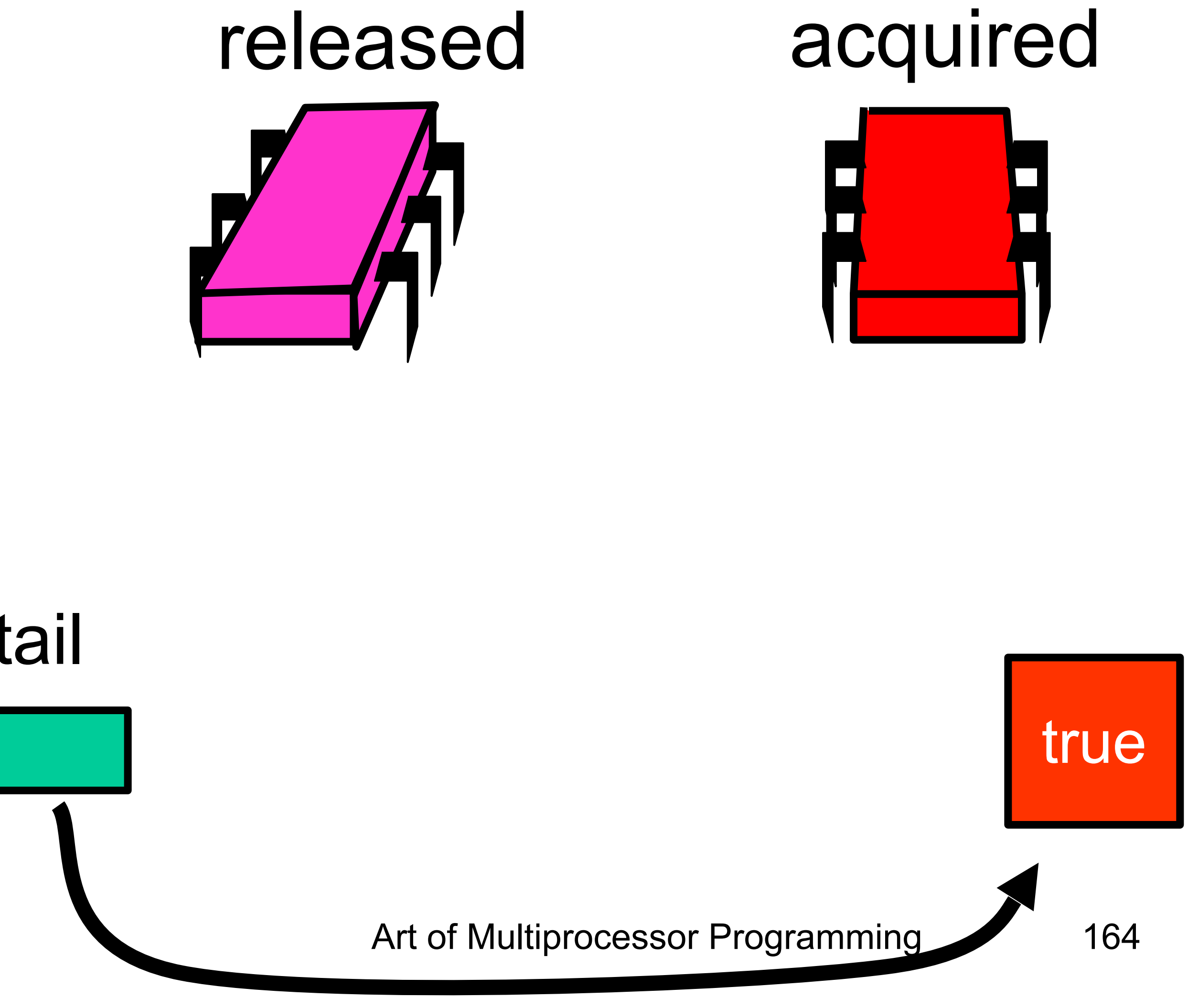
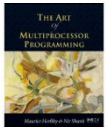


Purple Releases



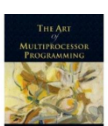
Purple Releases





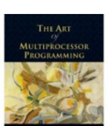
Space Usage

- 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);
}
```



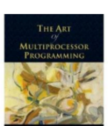
CLH Queue Lock

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

Not released yet

CLH Queue Lock

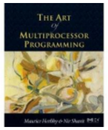
```
class CLHLock implements Lock {
 AtomicReference<Qnode> tail;
 ThreadLocal<Qnode> myNode
    = new Qnode();
 public void lock() {
  Qnode pred
    = tail.getAndSet(myNode);
  while (pred.locked) {}
 }}
```



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) {}
 }}
```

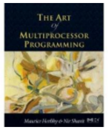
Queue tail



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) {}
 }}
```

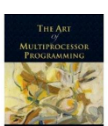
Thread-local Qnode



CLH Queue Lock

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

Swap in my node



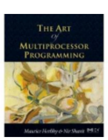
CLH Queue Lock

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

Spin until predecessor releases lock

CLH Queue Lock

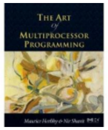
```
Class CLHLock implements Lock {
 …
 public void unlock() {
  myNode.locked.set(false);
  myNode = pred;
 }
}
```



CLH Queue Lock

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

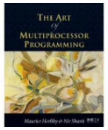
Notify successor



CLH Queue Lock

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

Recycle predecessor's node



CLH Queue Lock

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

(we don’t actually reuse myNode. Code in book shows how it’s done.)

CLH Lock

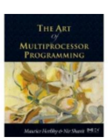
- Good
  - Lock release affects predecessor only
  - Small, constant-sized space
- Bad
  - Doesn't work for uncached NUMA architectures

CLH Lock

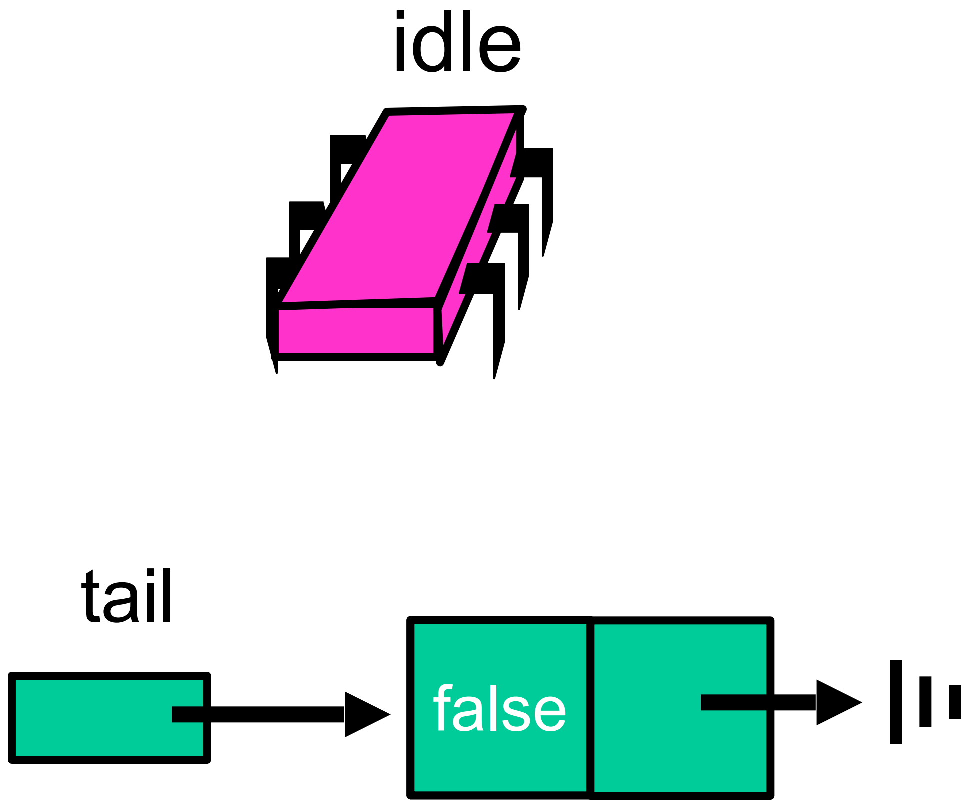
- Each thread spins on predecessor's memory
- Could be far away …

MCS Lock

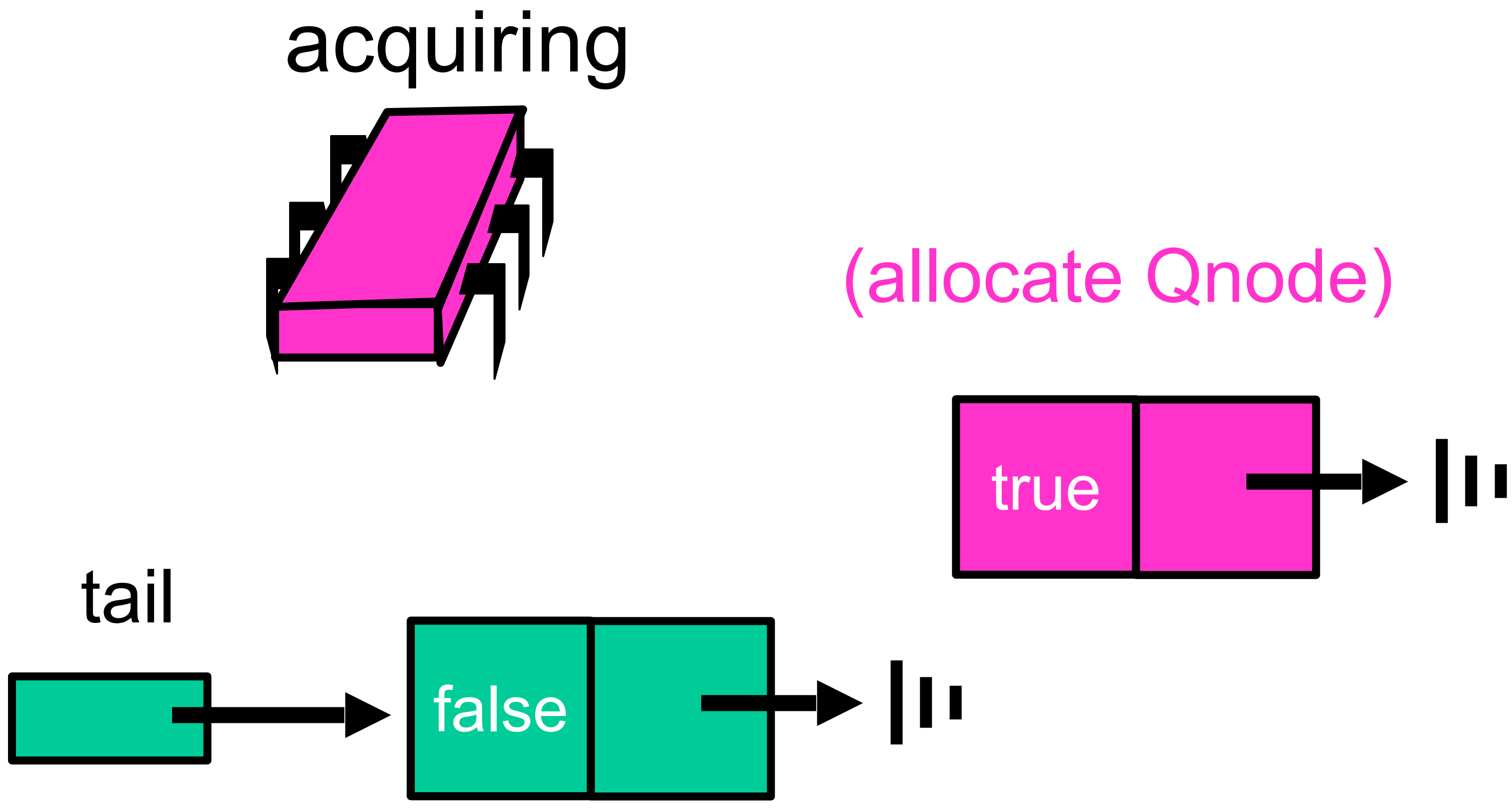
- FIFO order
- Spin on local memory only
- Small, Constant-size overhead

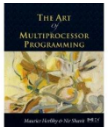


Initially

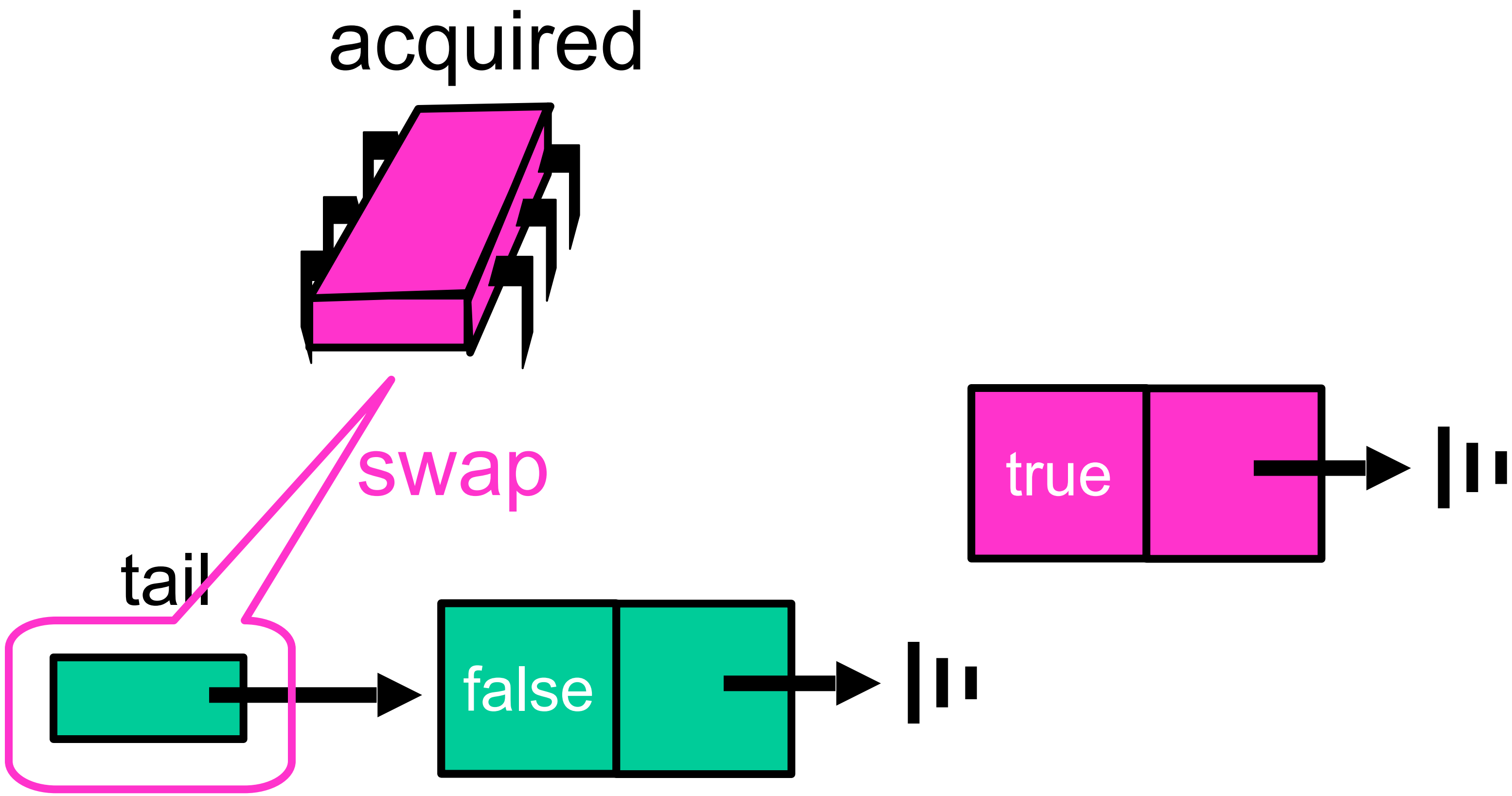


Acquiring

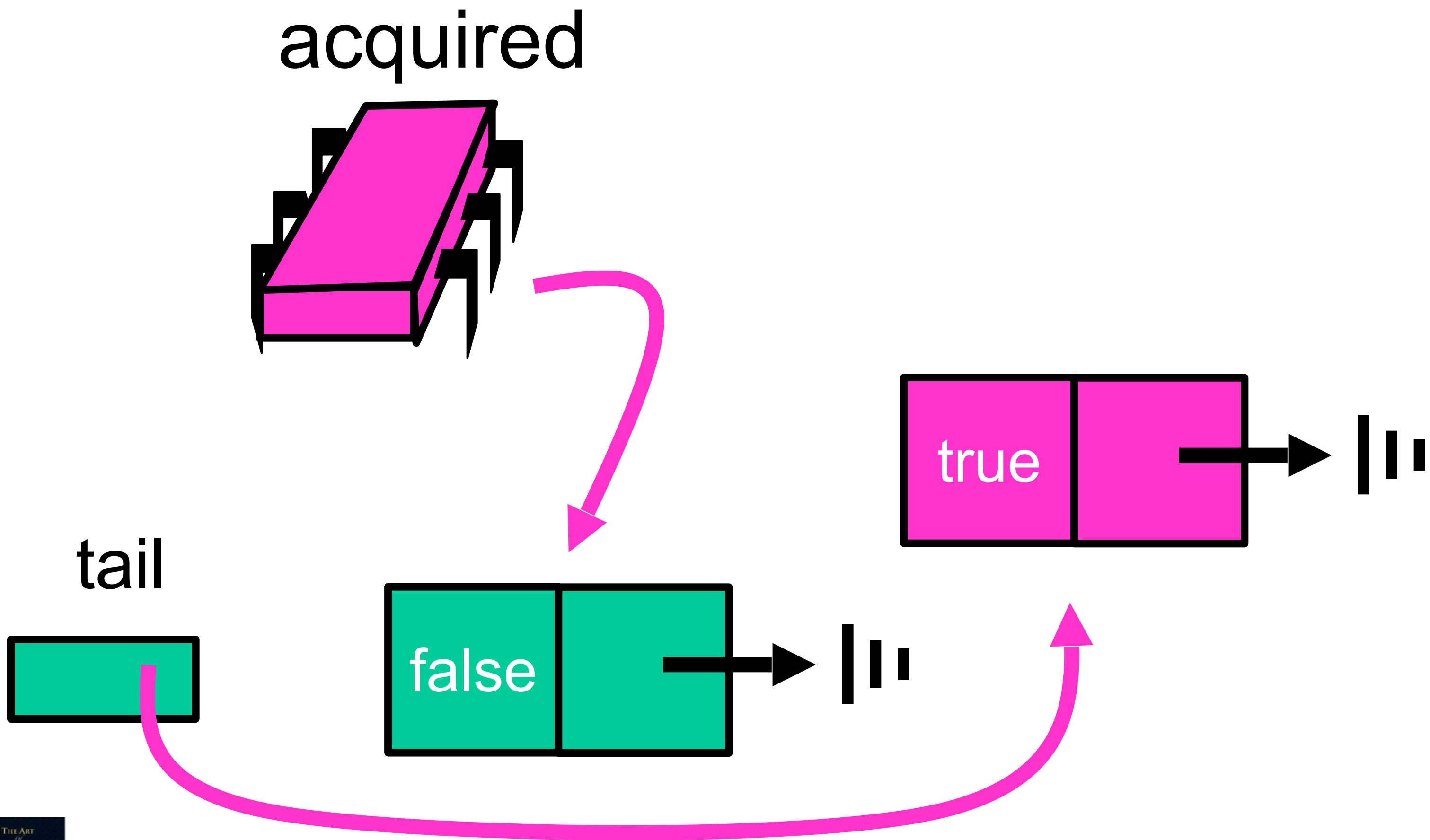


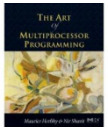


Acquiring

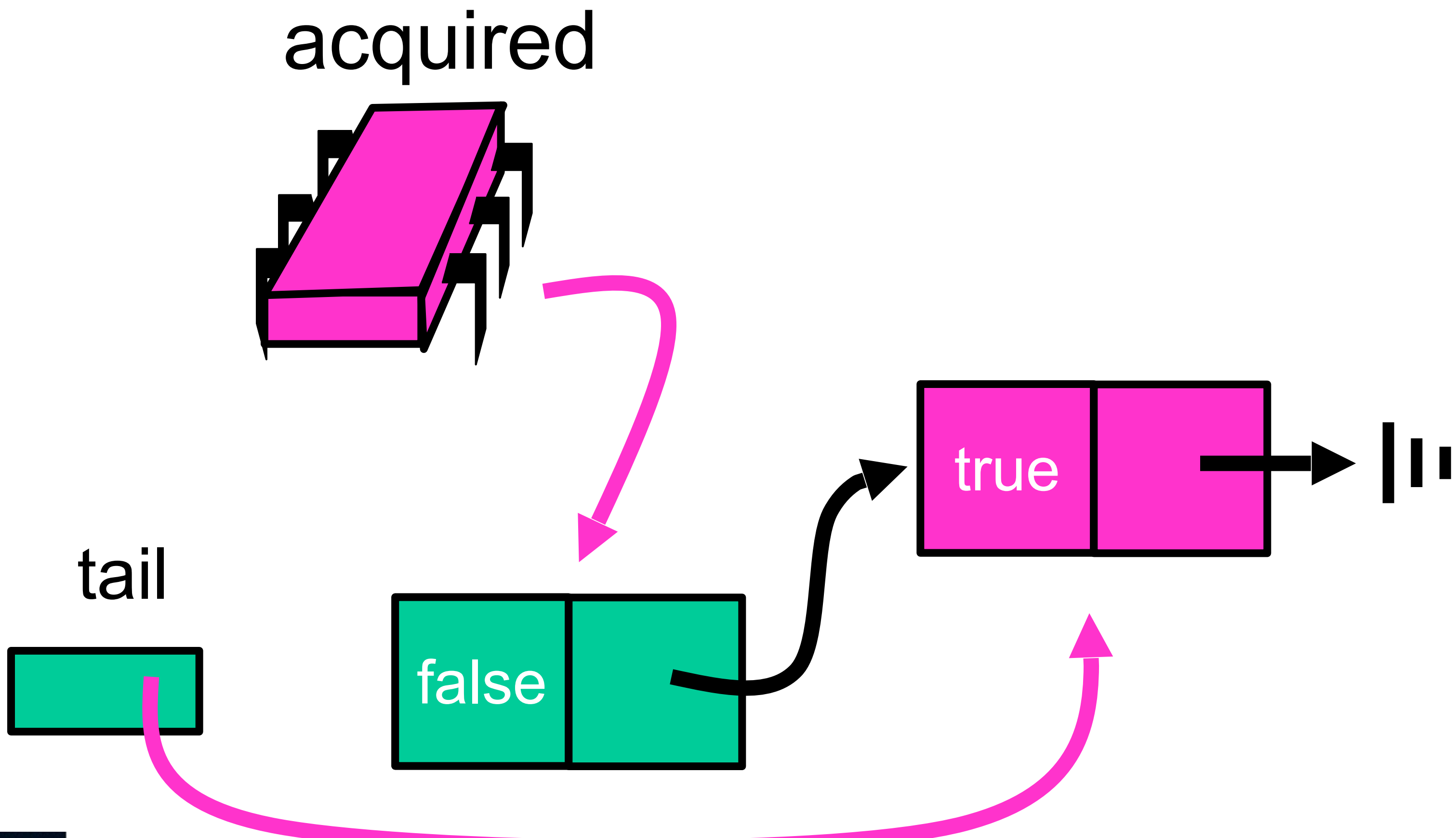


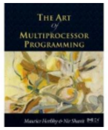
Acquiring



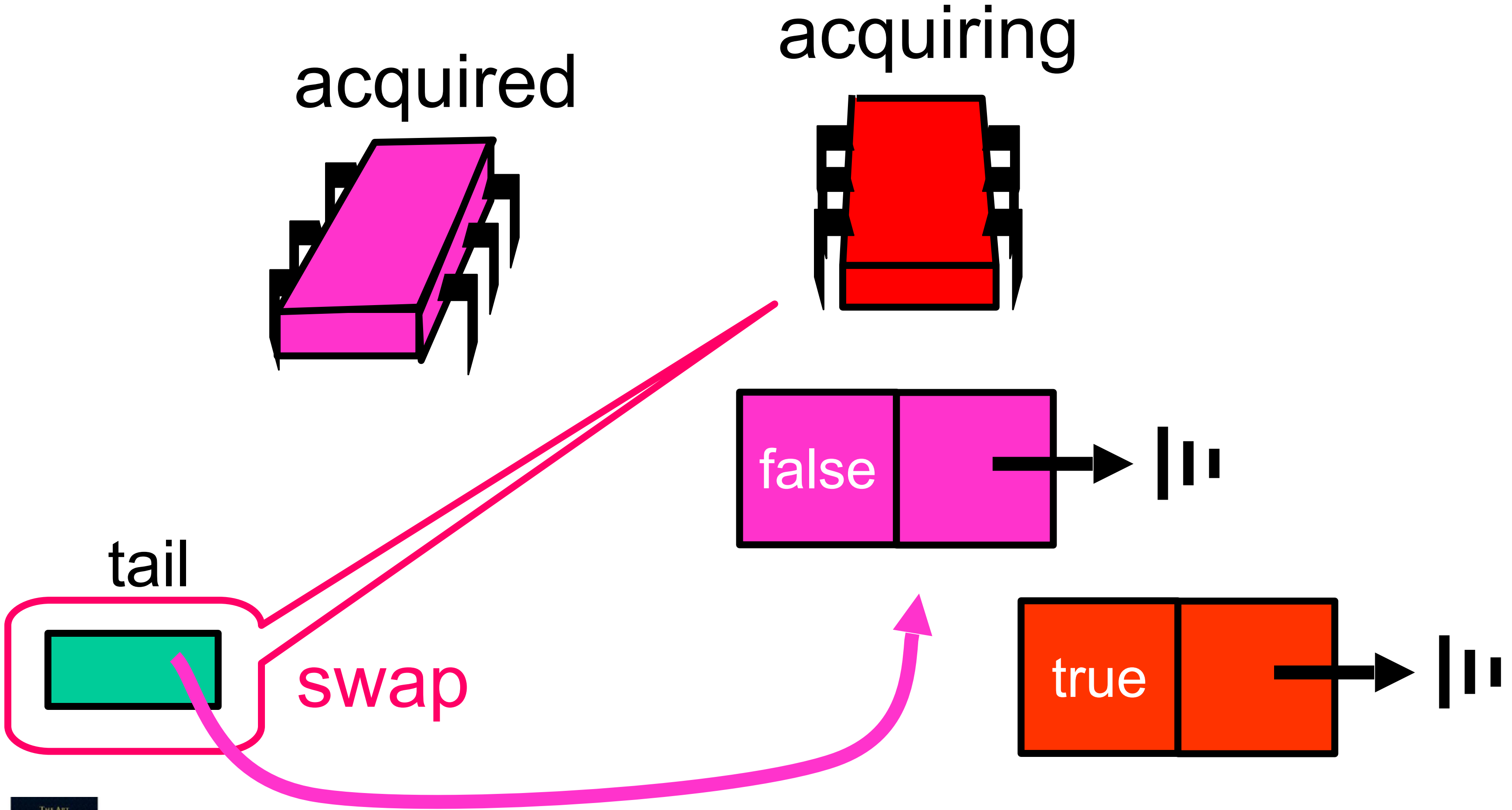


Acquired

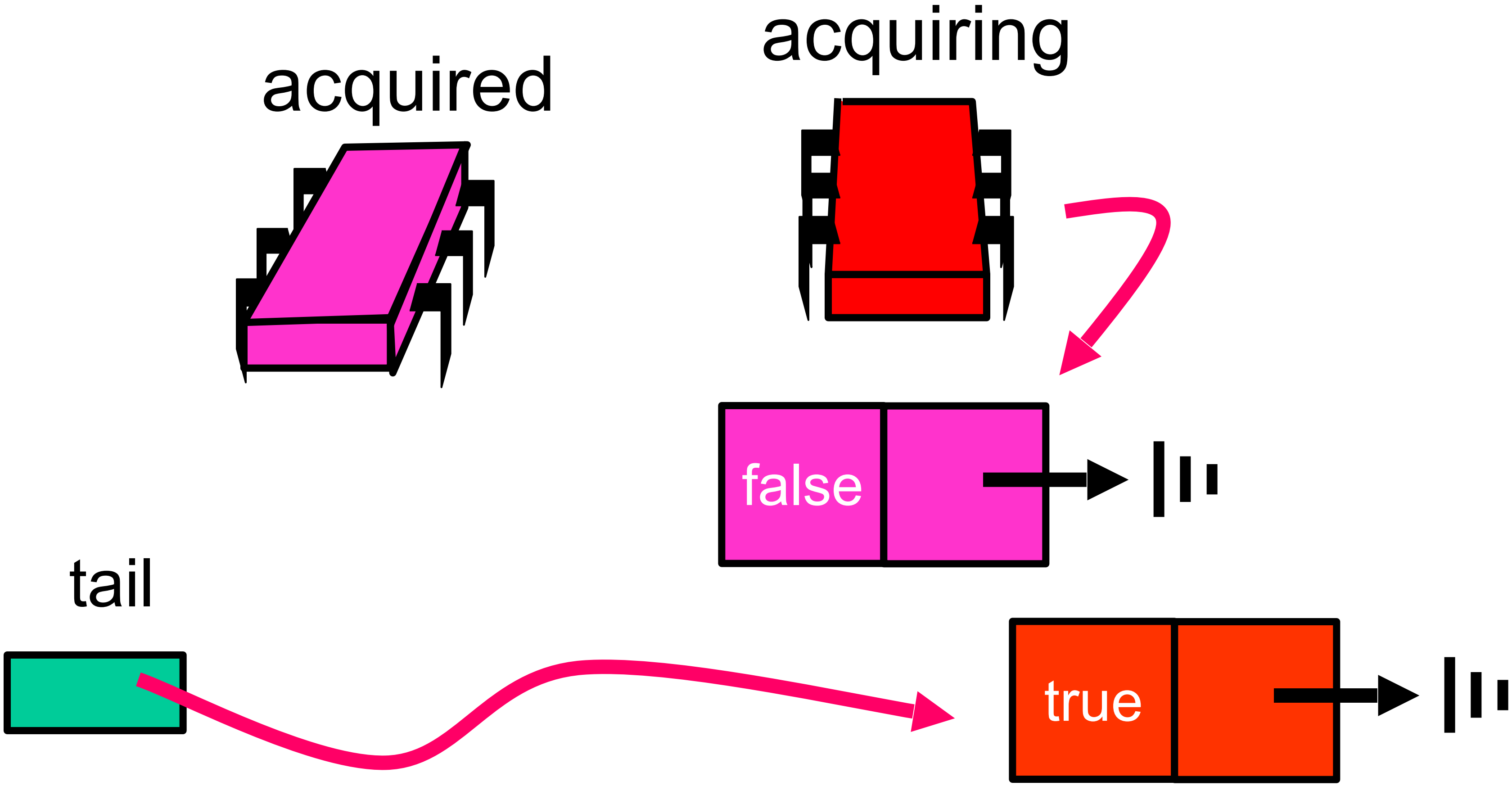




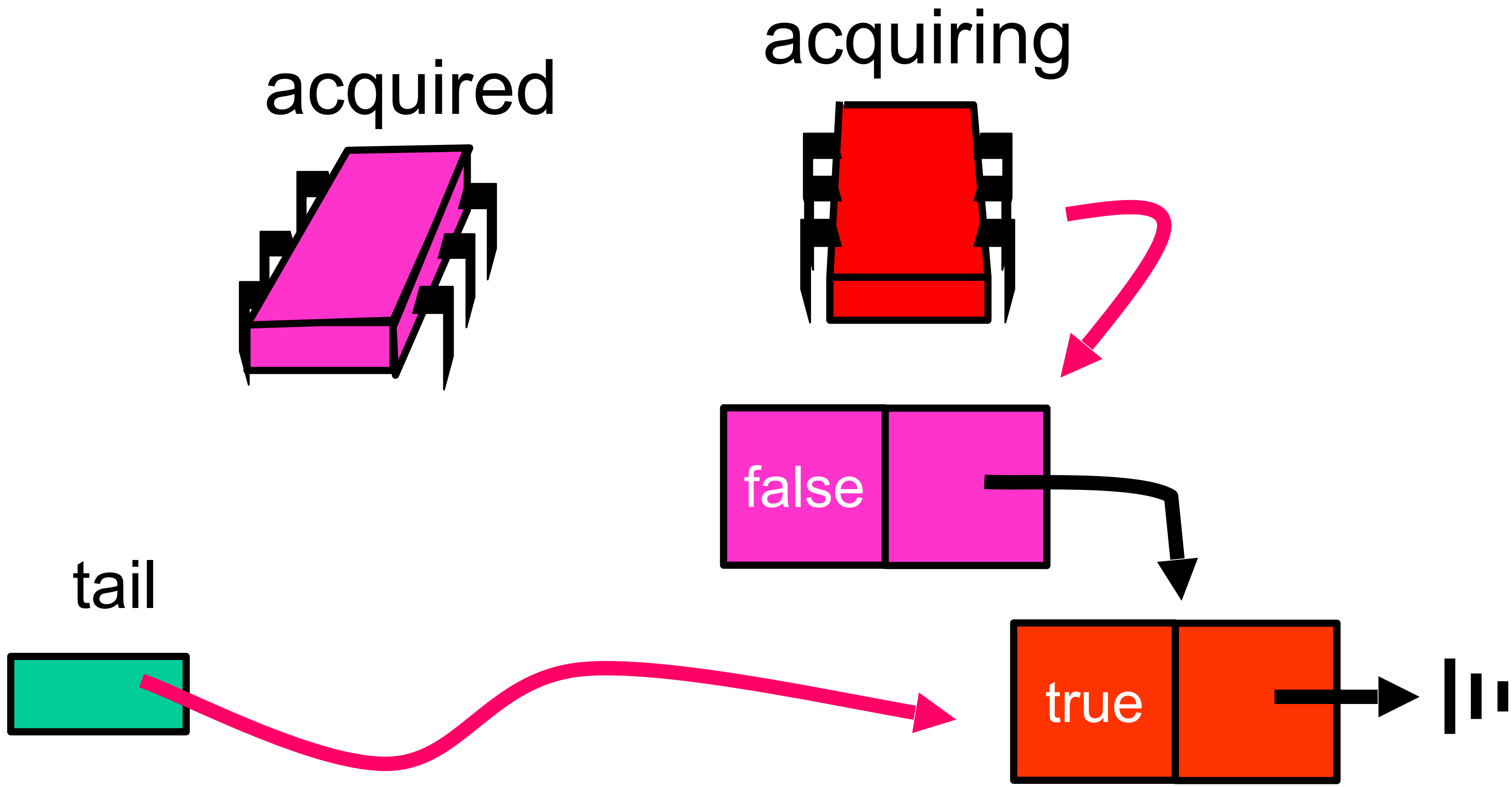
Acquiring



Acquiring



Acquiring



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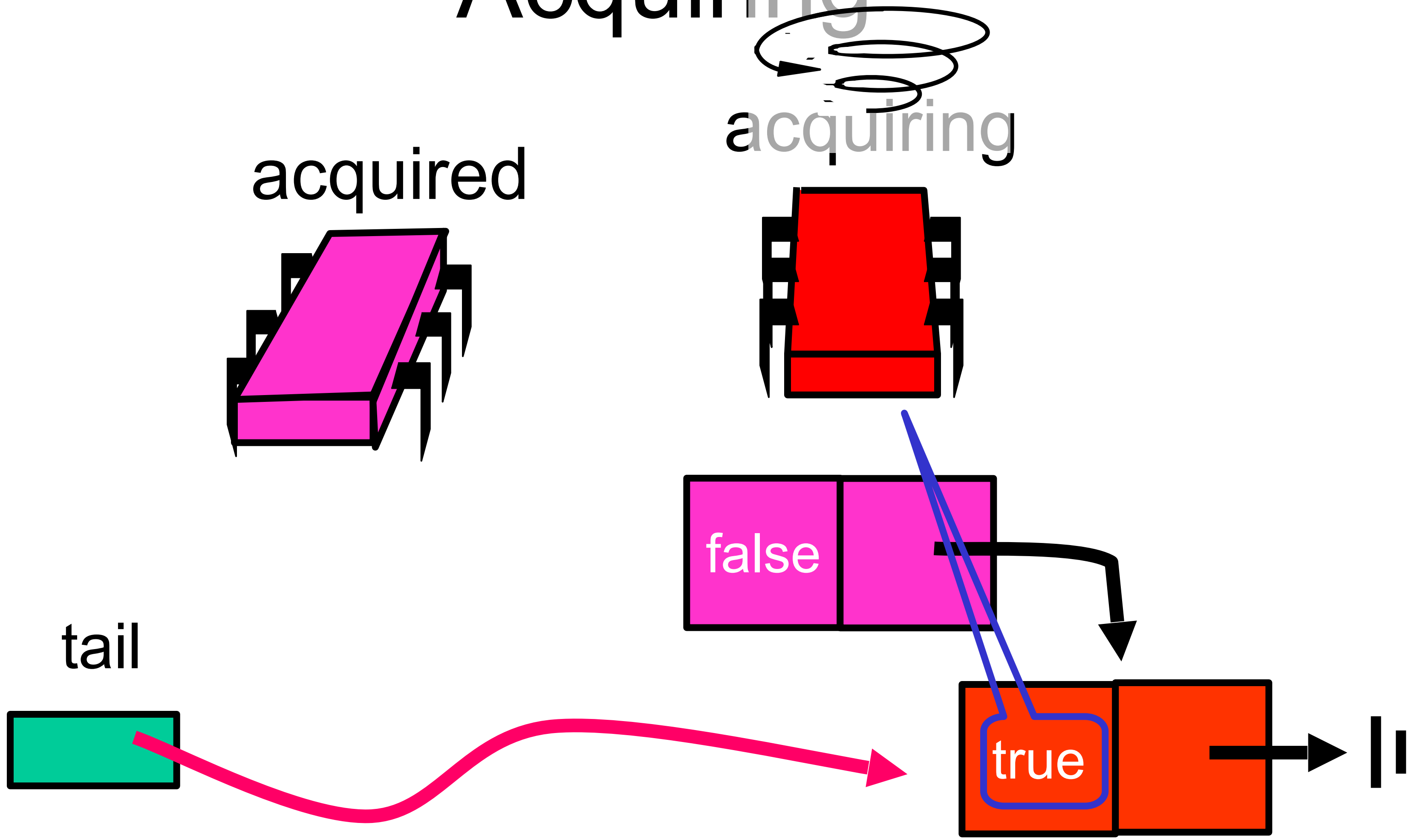

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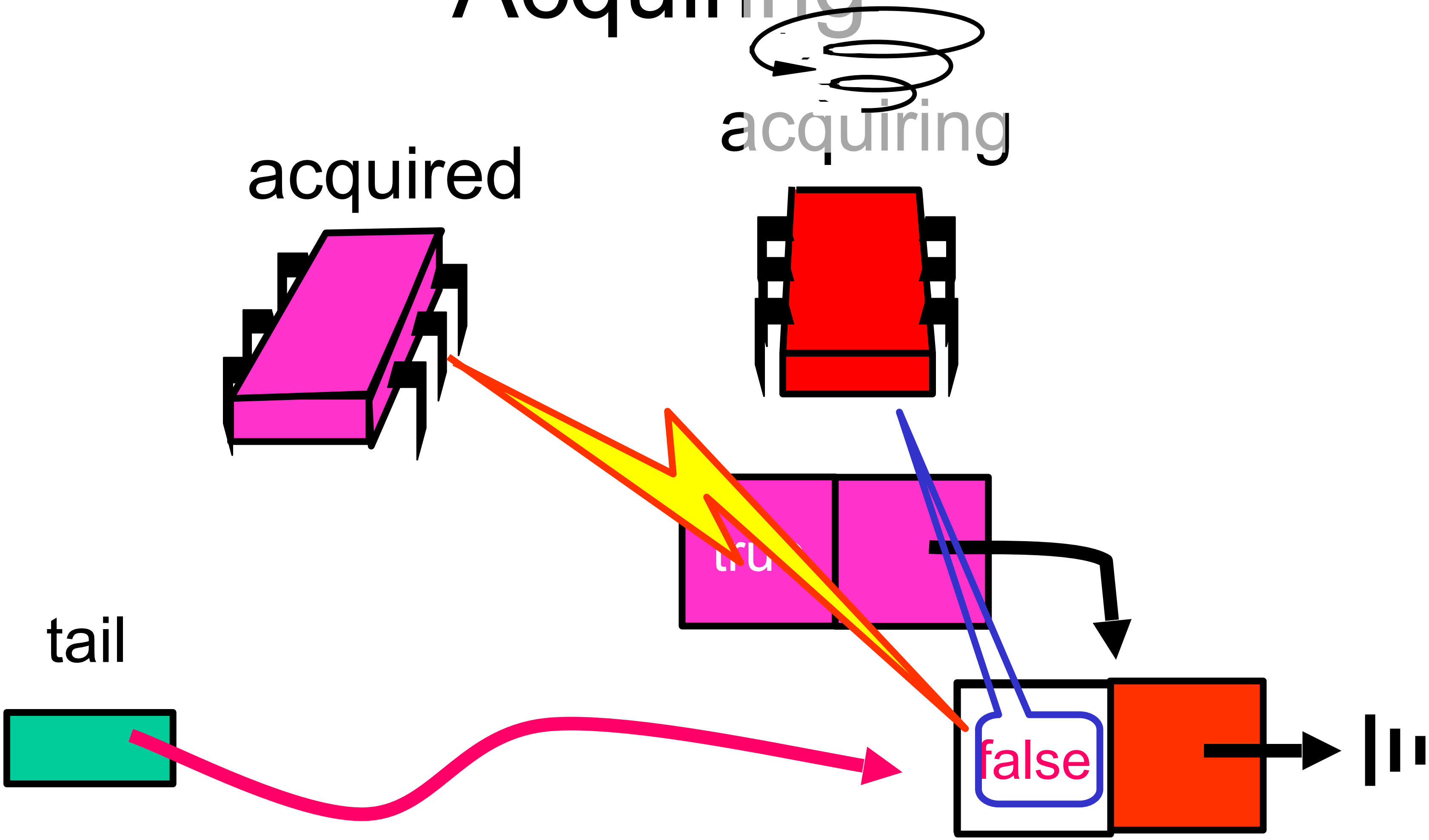
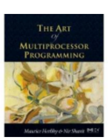
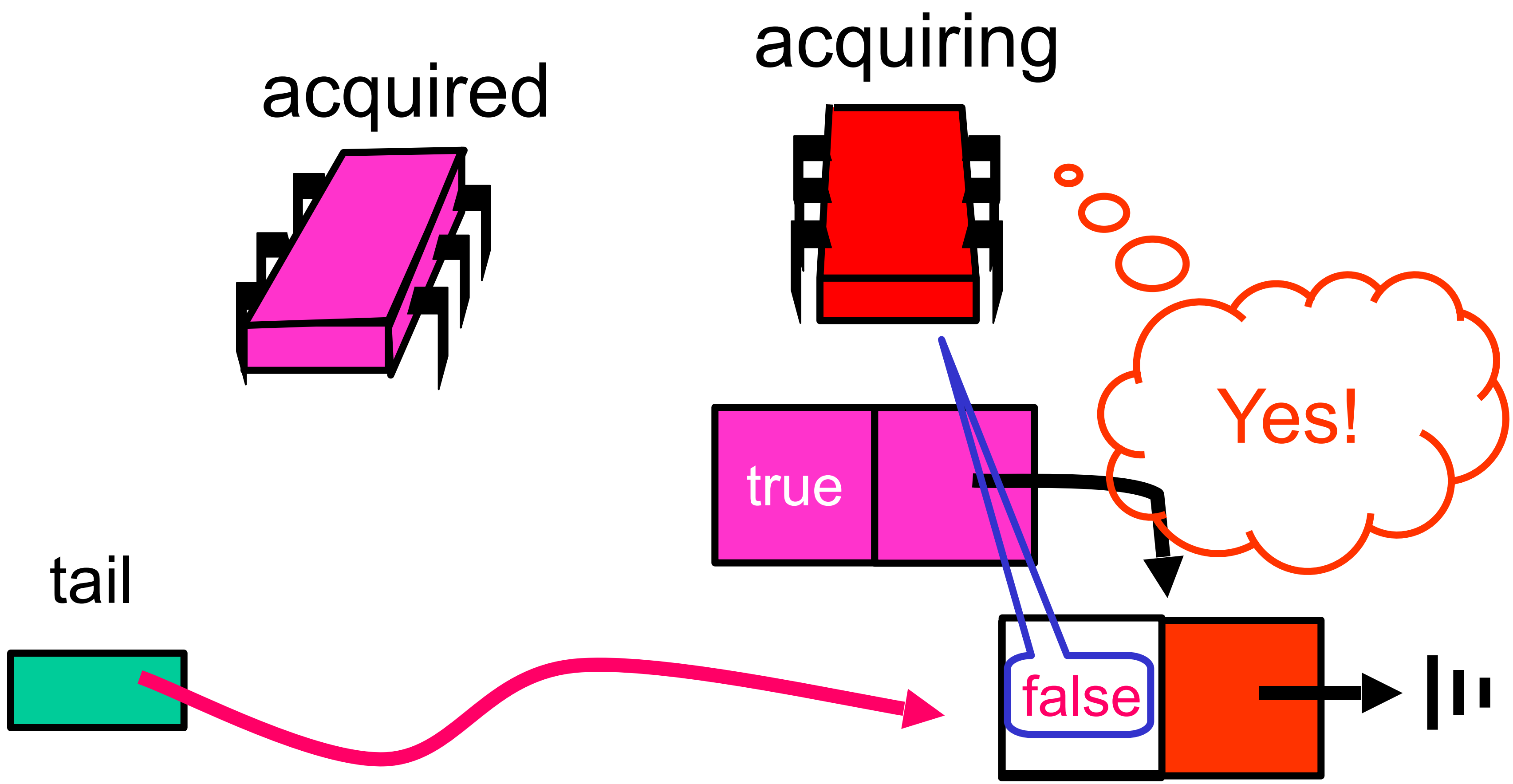
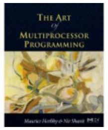




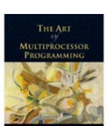
Acquiring





MCS Queue Lock

```
class Qnode {
 boolean locked = false;
 qnode   next   = null;
}
```



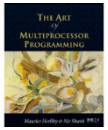
MCS Queue Lock

```
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) {}
  }}}
```

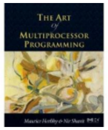
Make a QNode



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

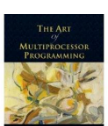
MCS Queue Lock

```
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

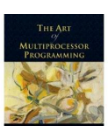
```
class MCSLock implements Lock {
 AtomicReference tail;
 public void unlock() {
  if (qnode.next == null) {
   if (tail.CAS(qnode, null)
    return;
   while (qnode.next == null) {}
  }
 qnode.next.locked = false;
}}
```

Missing successor?

MCS Queue Lock

If really no successor,
return

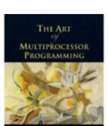
```
  public void unlock() {
    if (qnode.next == null) {
      if (tail.CAS(qnode, null)
        return;
      while (qnode.next == null) {}
    }
  qnode.next.locked = false;
}}
```



MCS Queue Lock

Otherwise wait for
successor to catch up

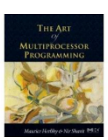
```
(                                k {
 public void unlock() {
  if (qnode.next == null) {
   if (tail.CAS(qnode, null)
    return;
   while (qnode.next == null) {}
  }
 qnode.next.locked = false;
}}
```



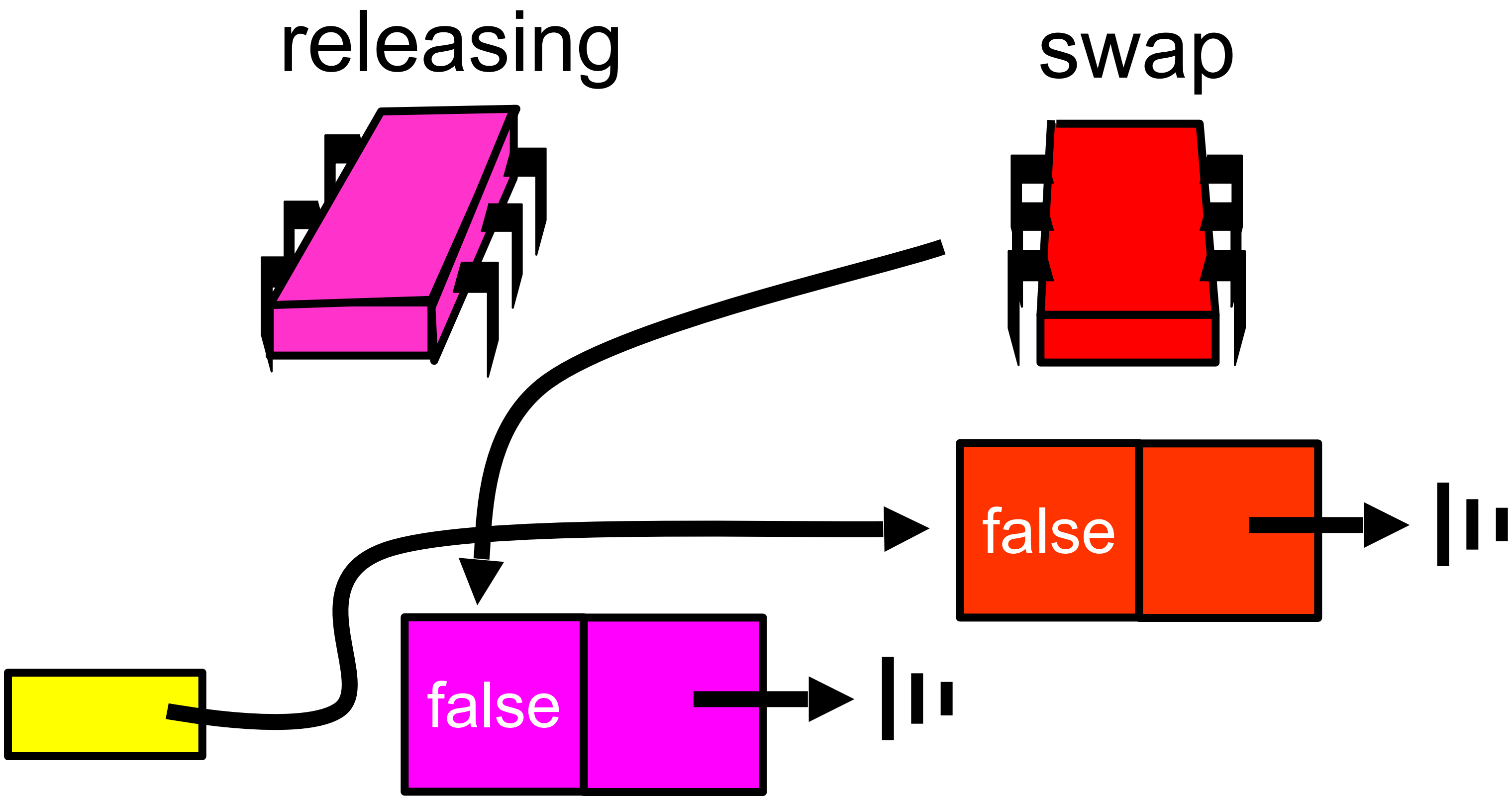
MCS Queue Lock

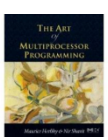
```
class MCSLock implements Lock {
 AtomicReference queue;
 public voi
  if (qnode.next == null) {
   if (tail.CAS(qnode, null)
    return;
   while (qnode.next == null) {}
  }
 qnode.next.locked = false;
}}
```

Pass lock to successor

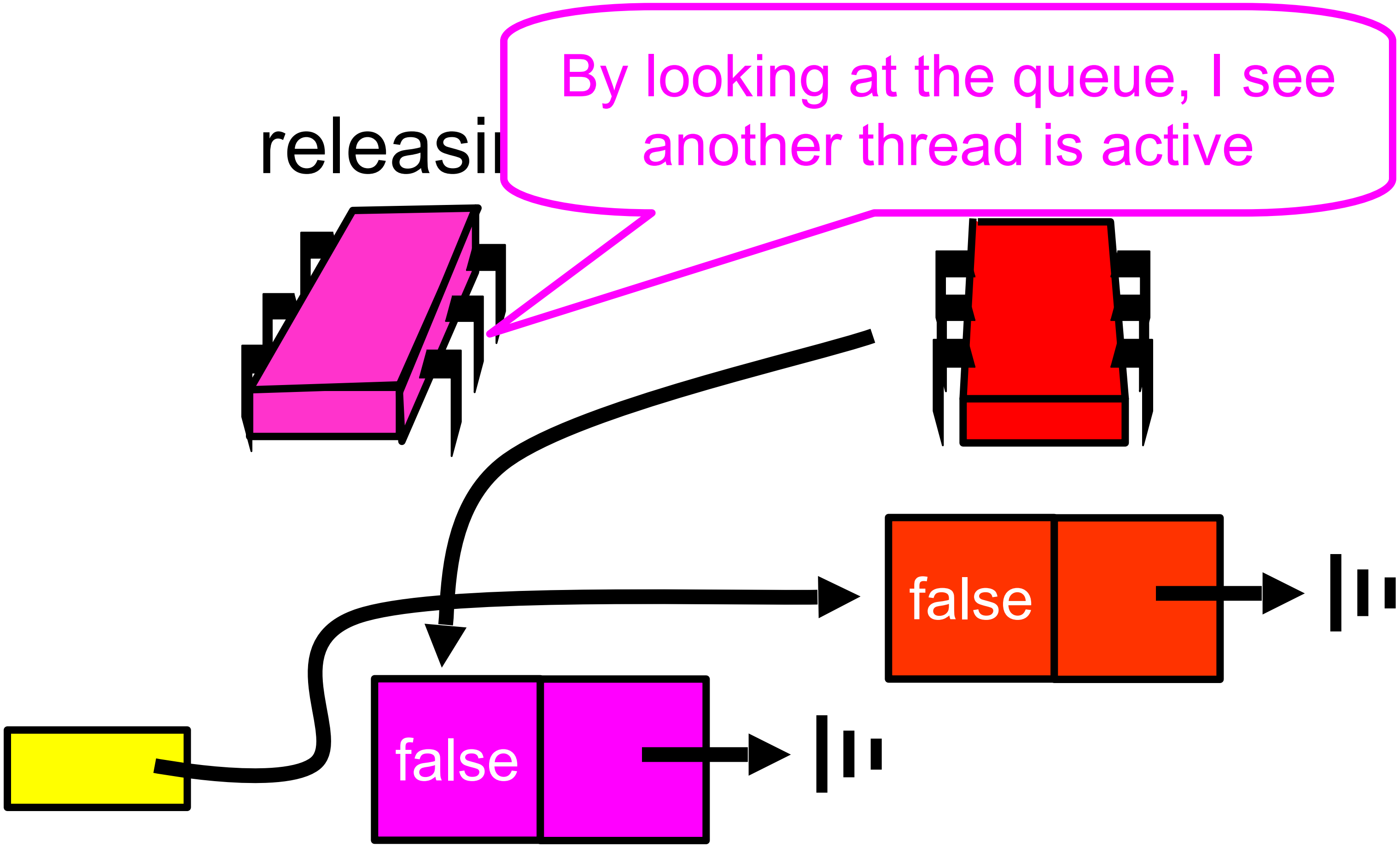


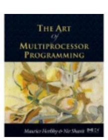
Purple Release



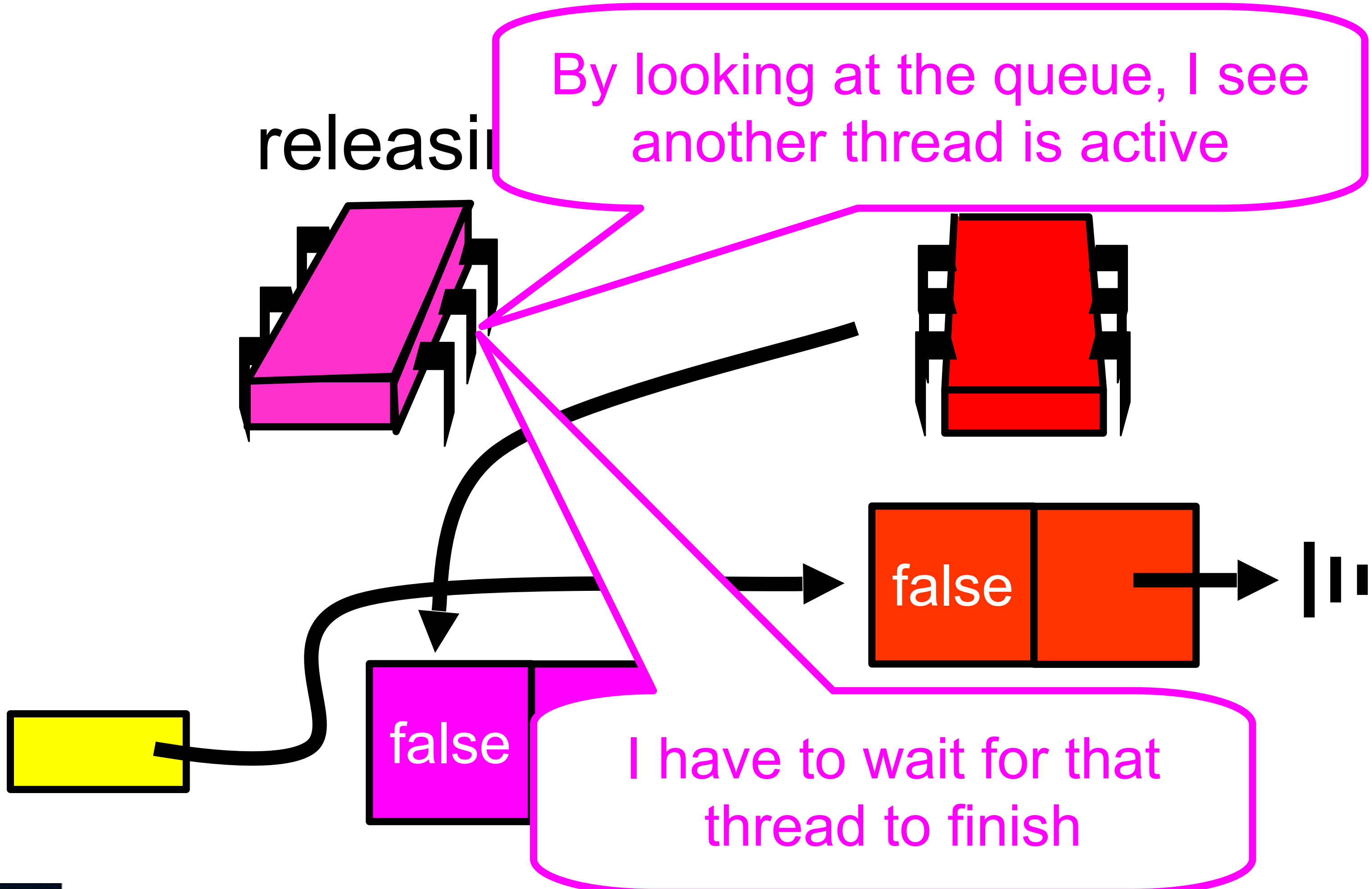


Purple Release

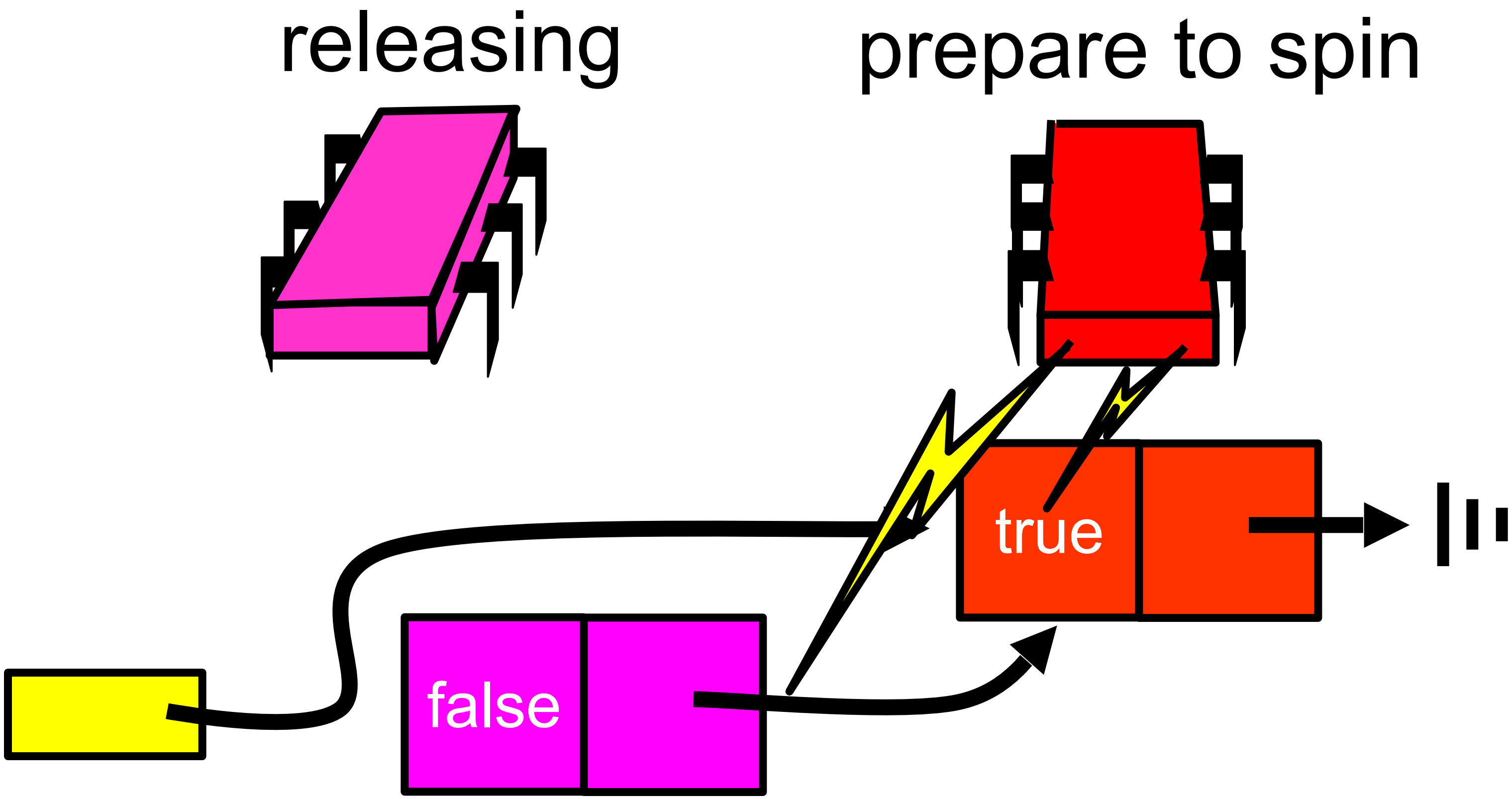




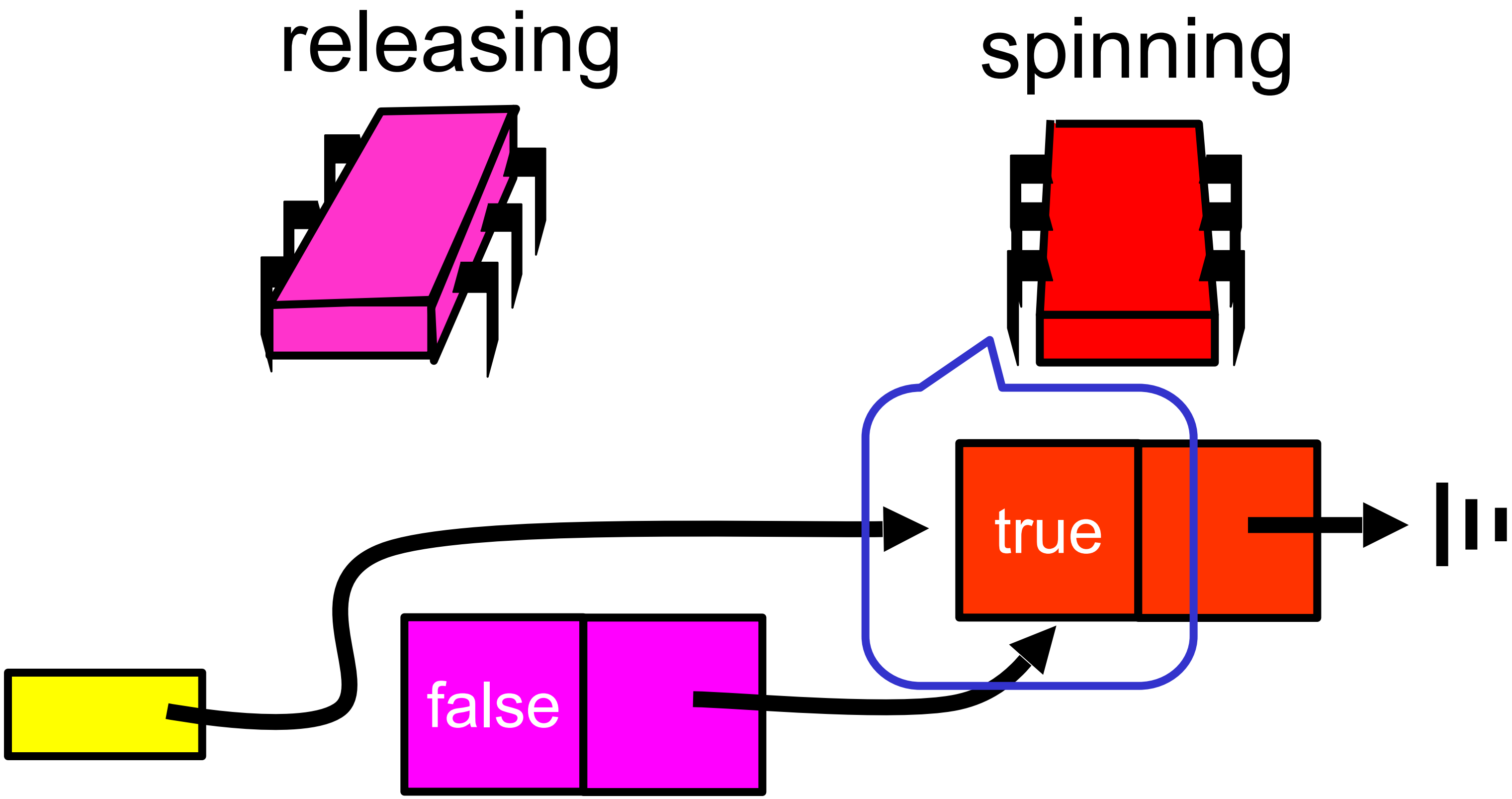
Purple Release

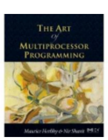


Purple Release

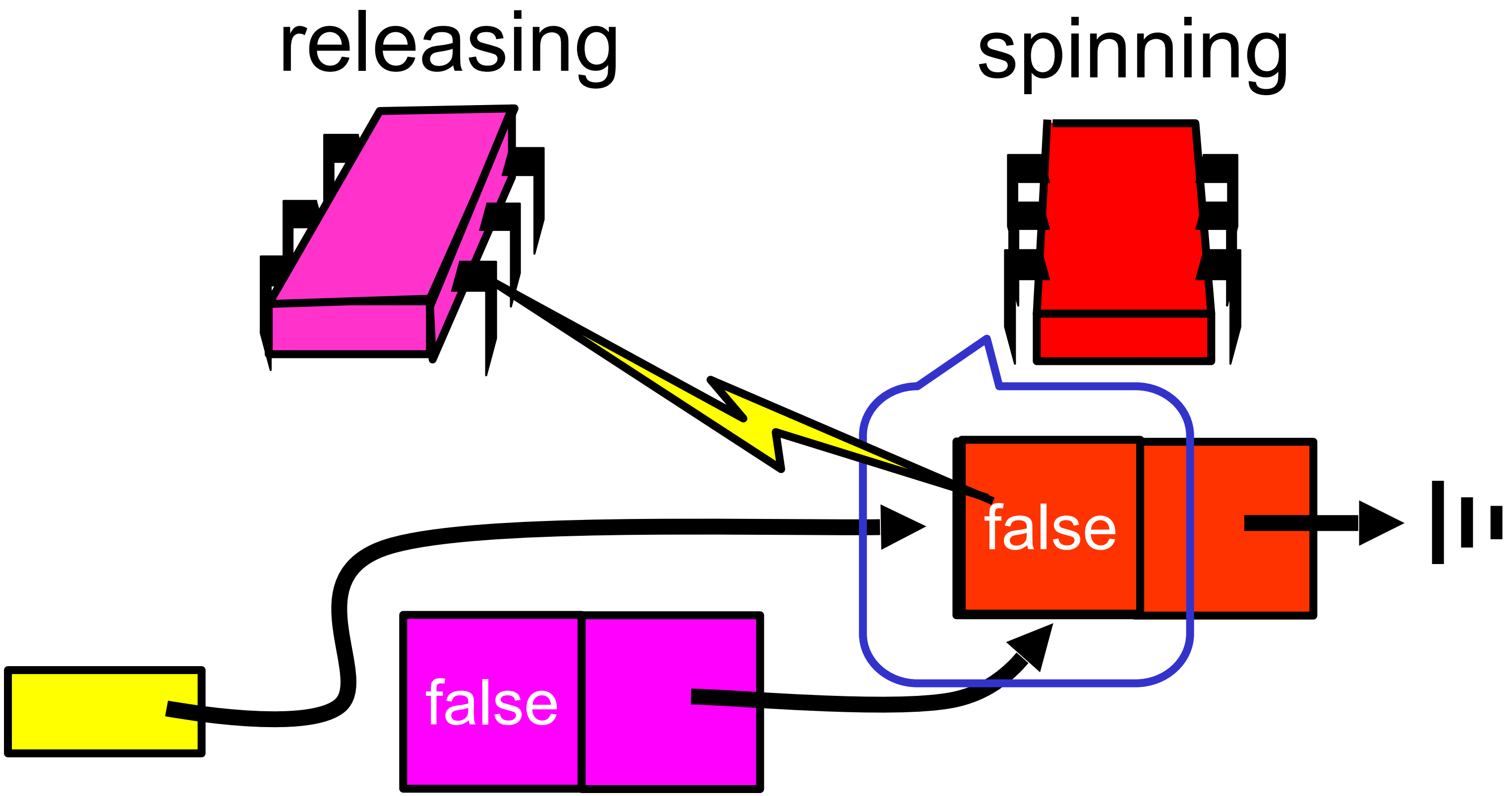


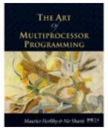
Purple Release



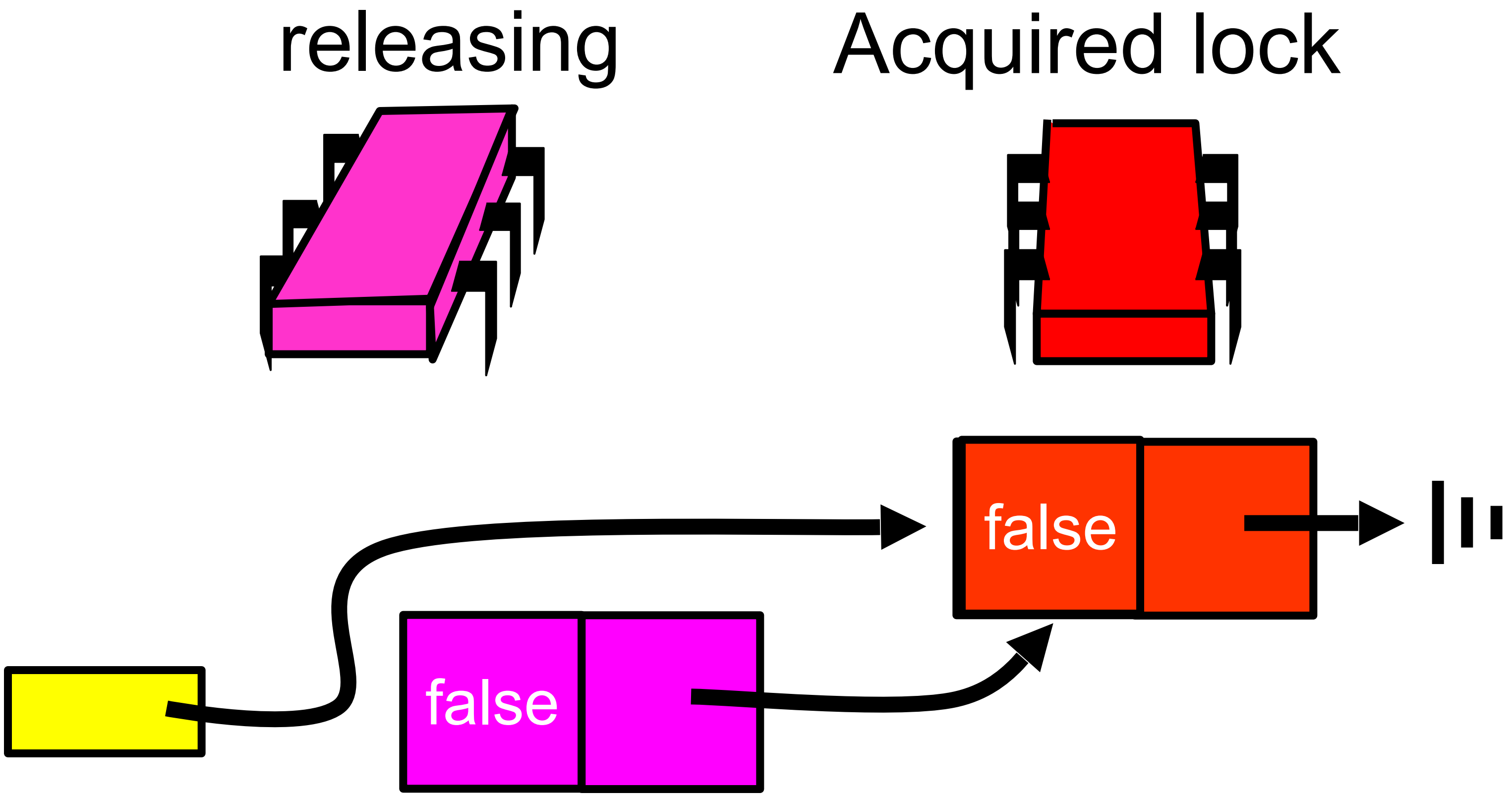


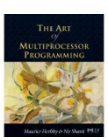
Purple Release





Purple Release



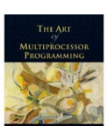


Abortable Locks

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

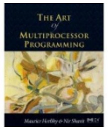
Back-off Lock

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

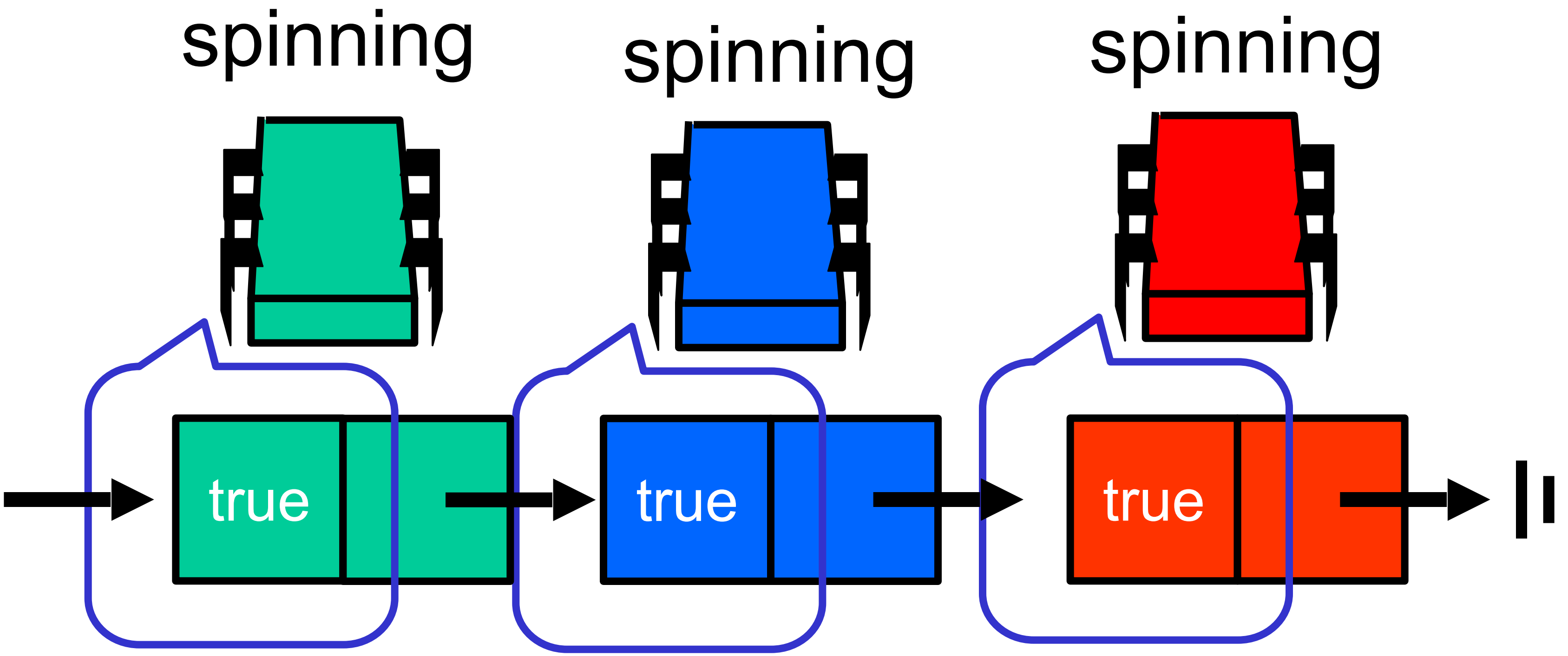


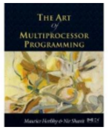
Queue Locks

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

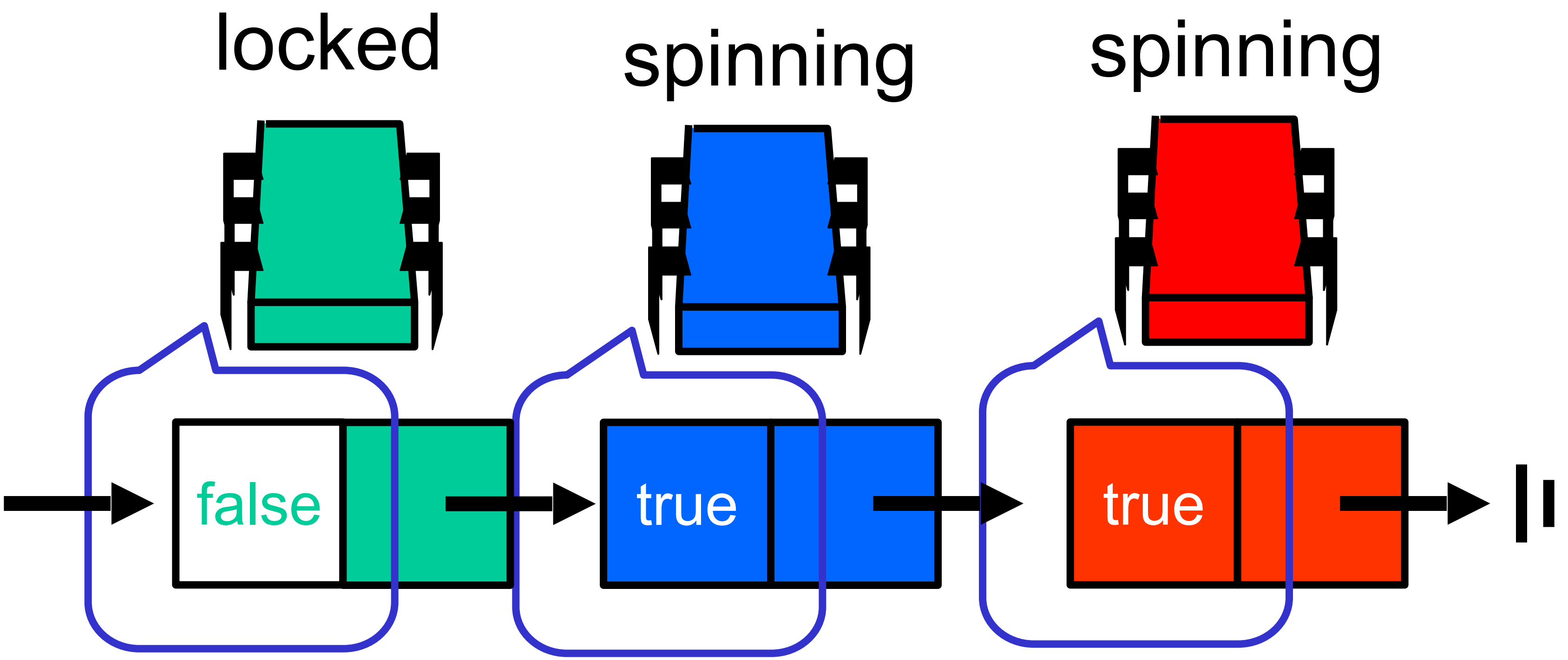


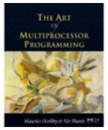
Queue Locks



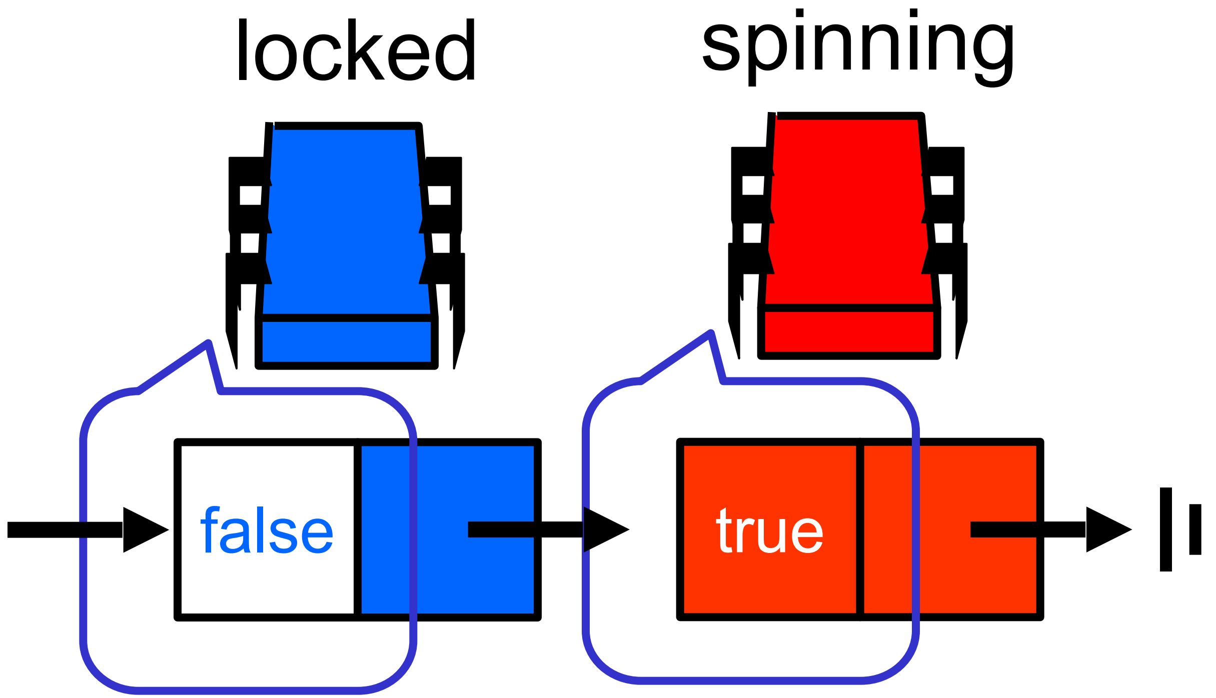


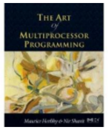
Queue Locks



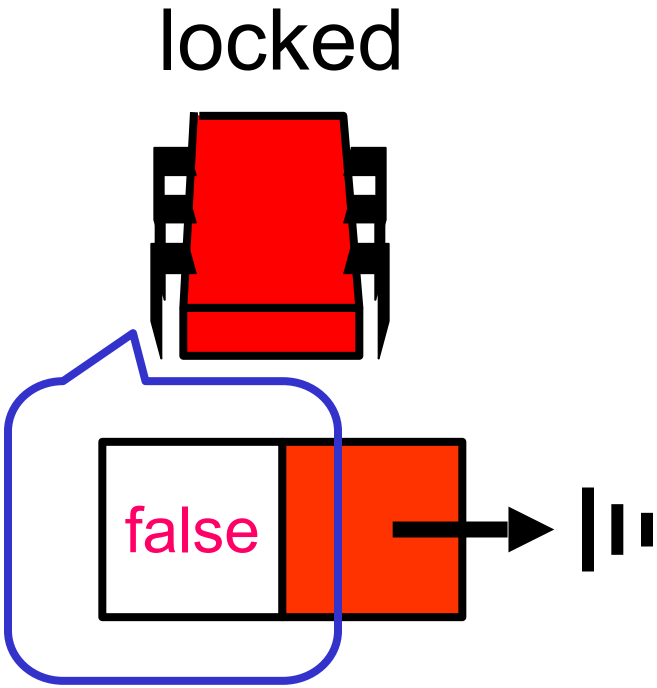


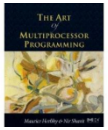
Queue Locks



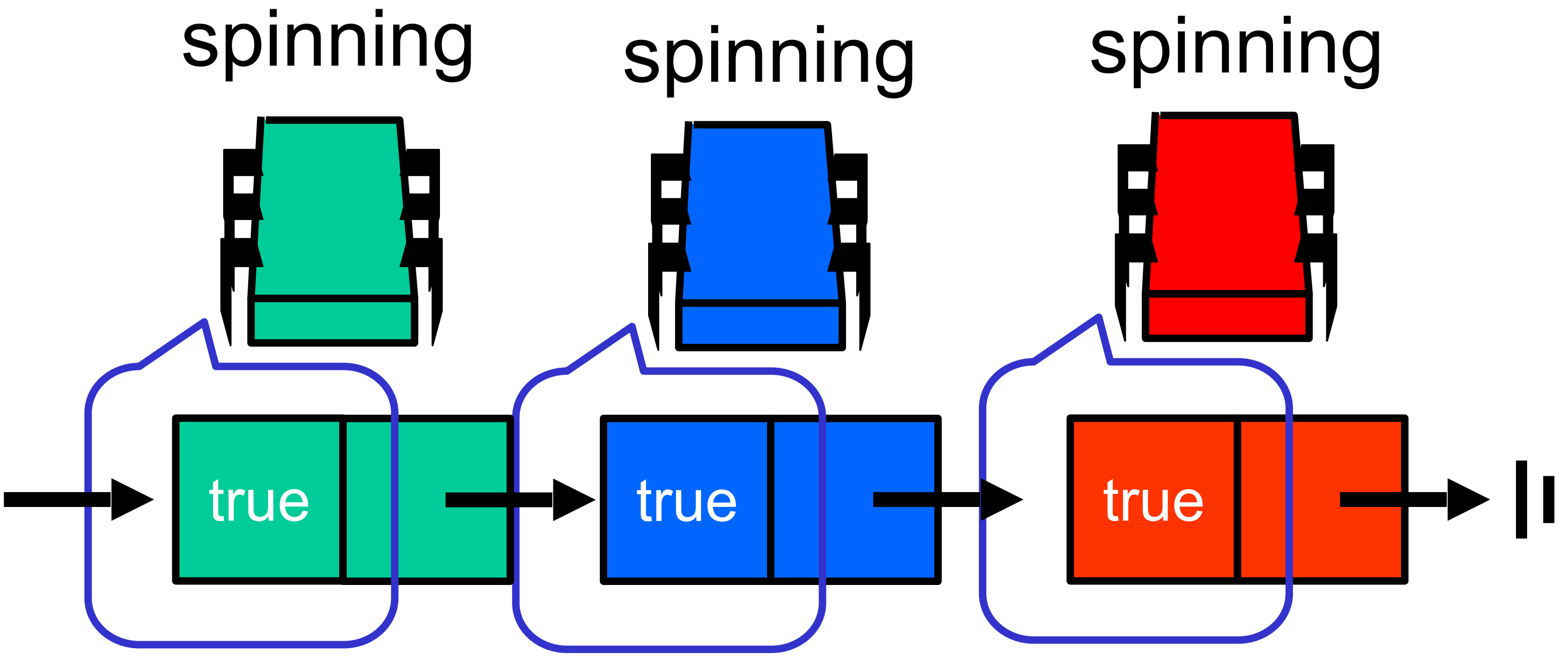


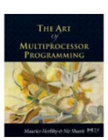
Queue Locks



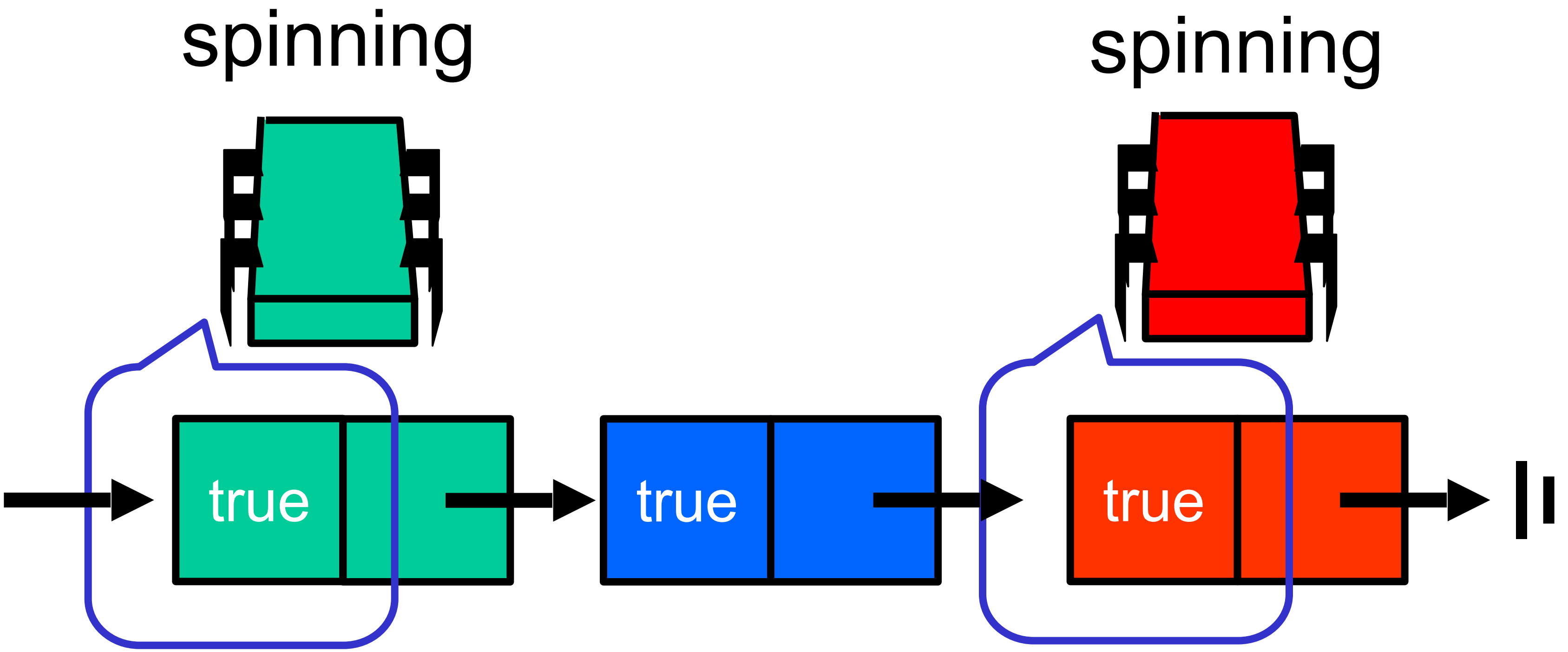


Queue Locks

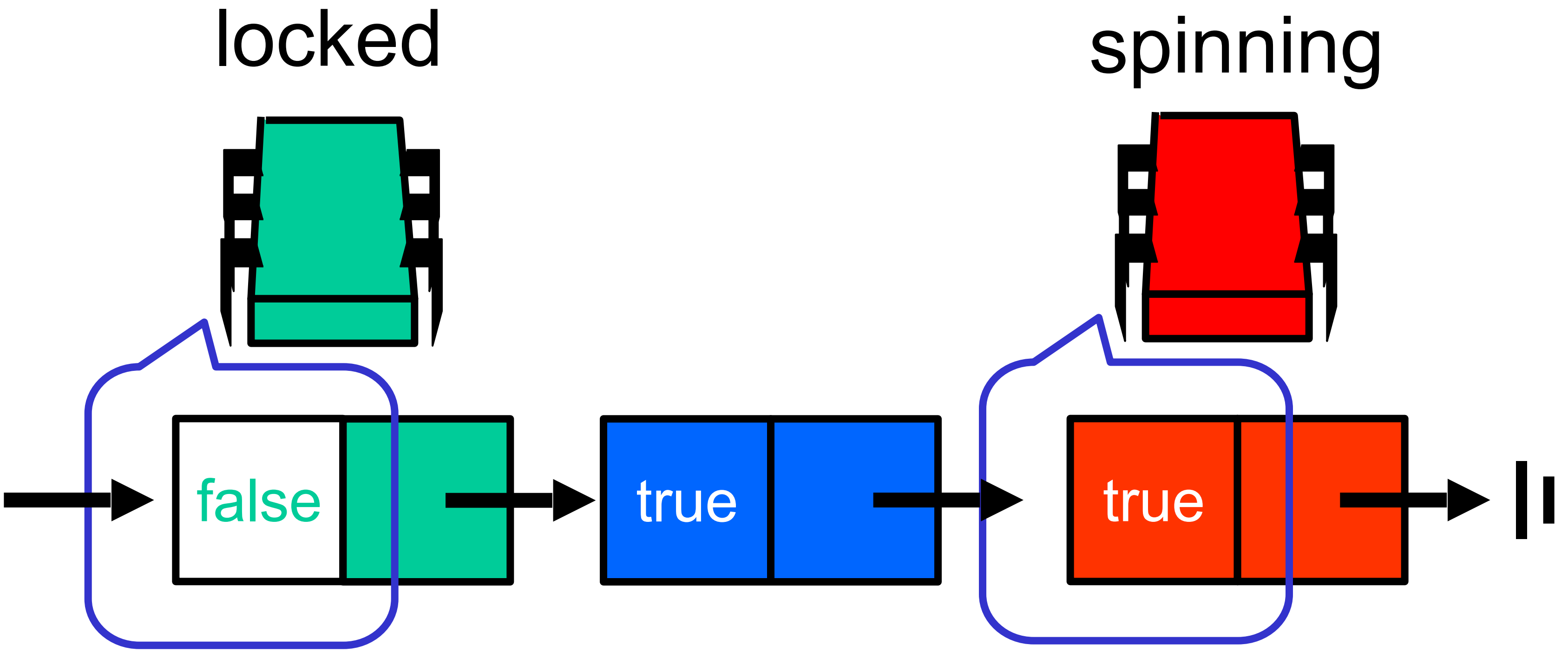


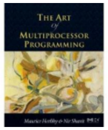


Queue Locks

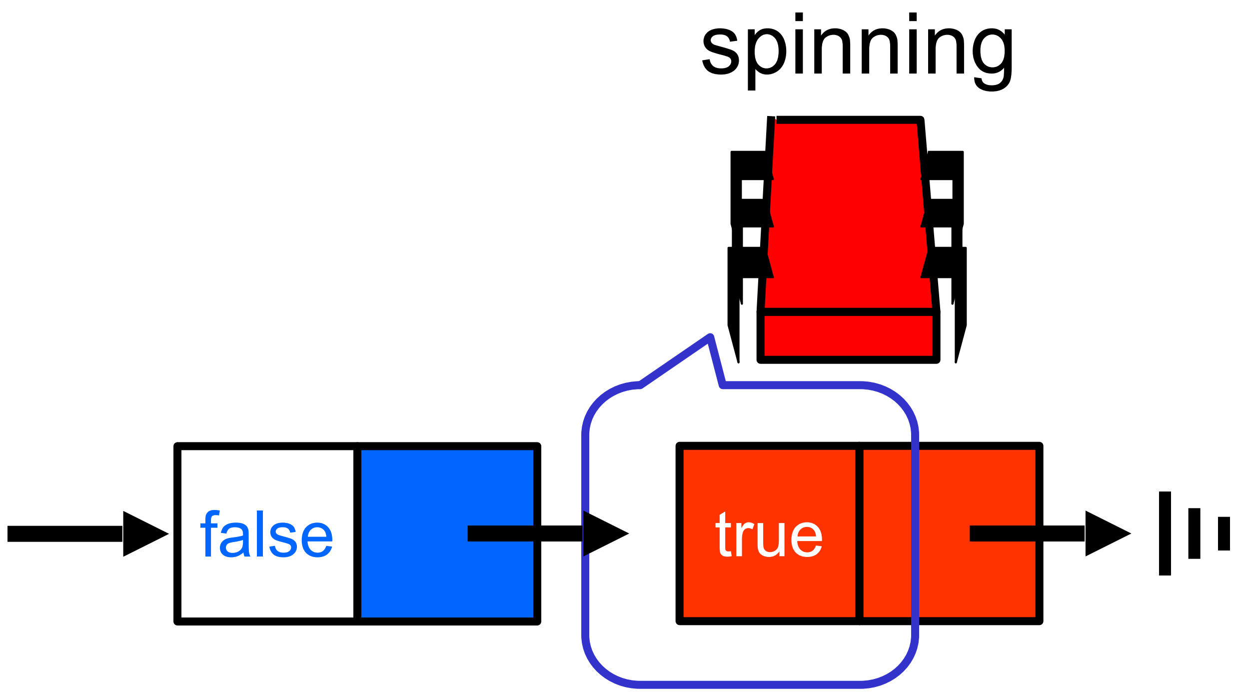


Queue Locks

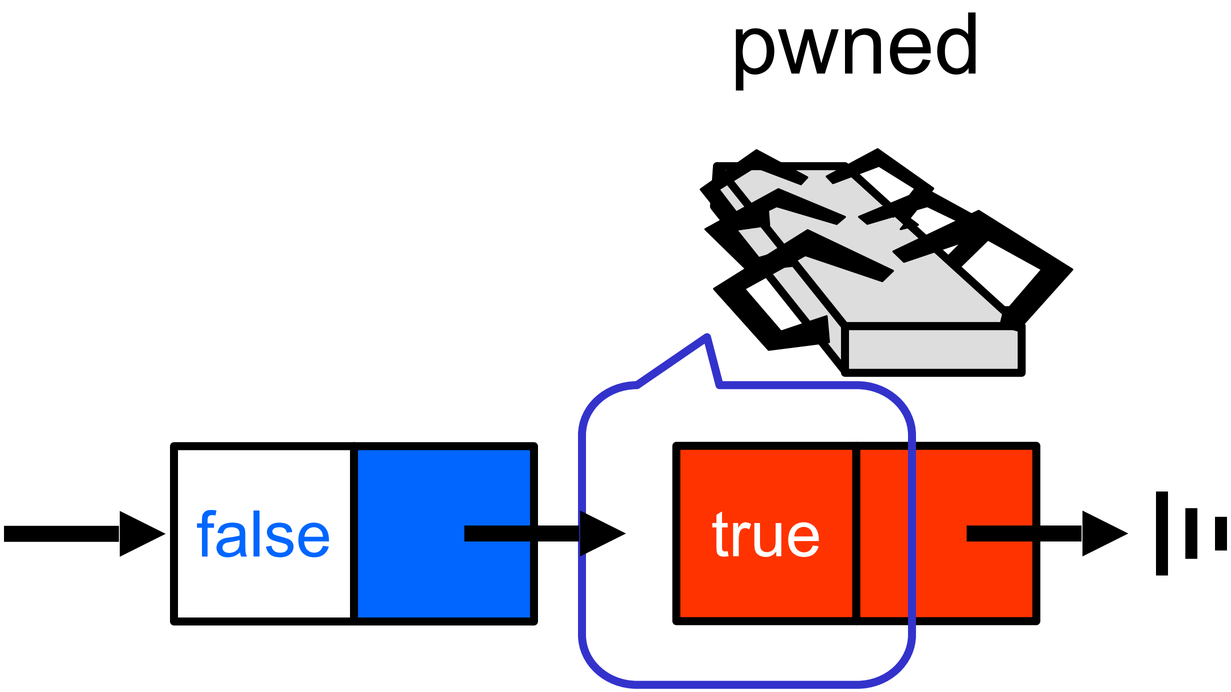


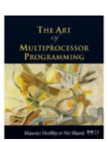


Queue Locks



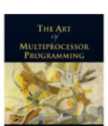
Queue Locks



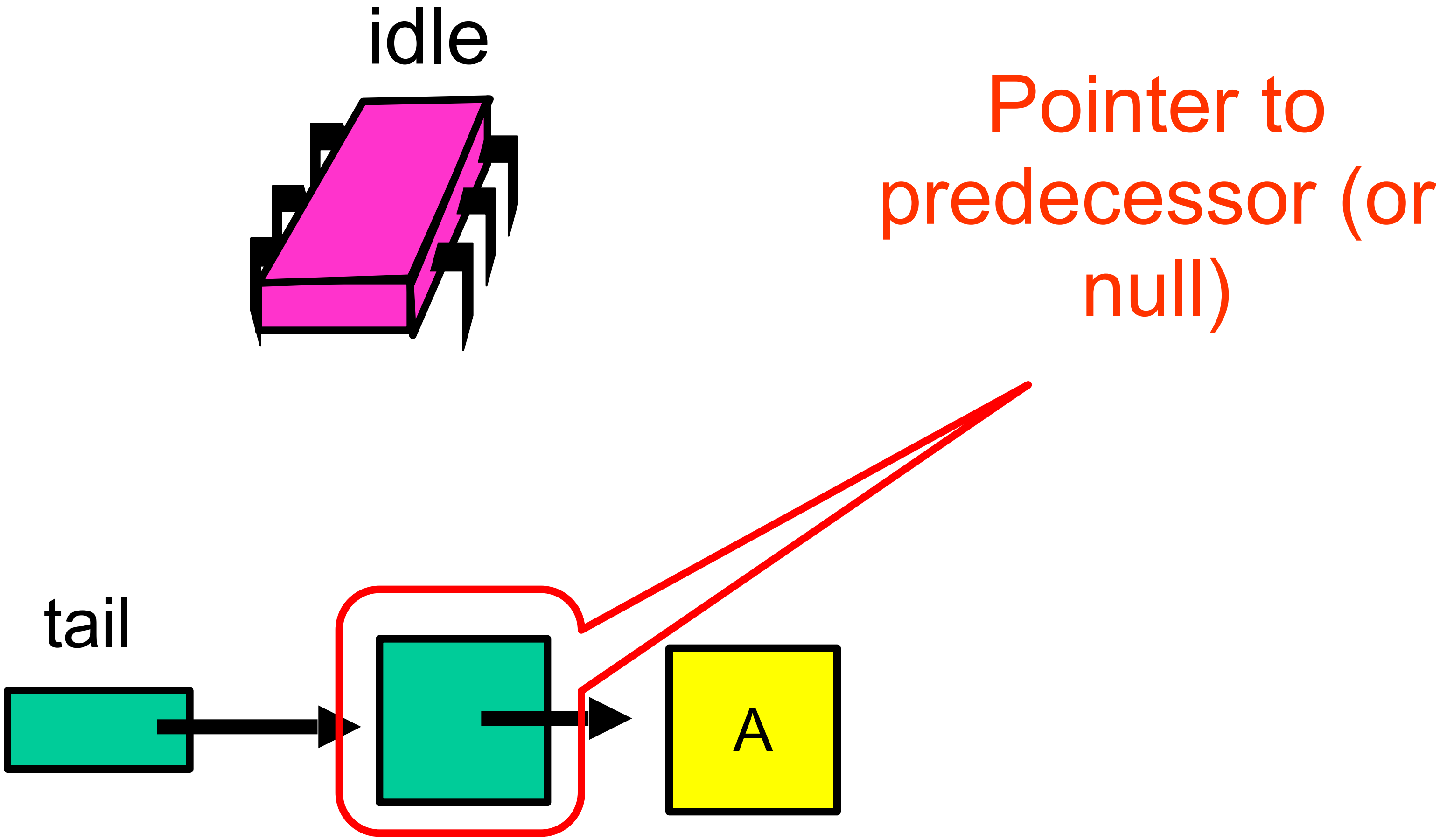


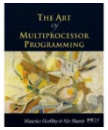
Abortable CLH Lock

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

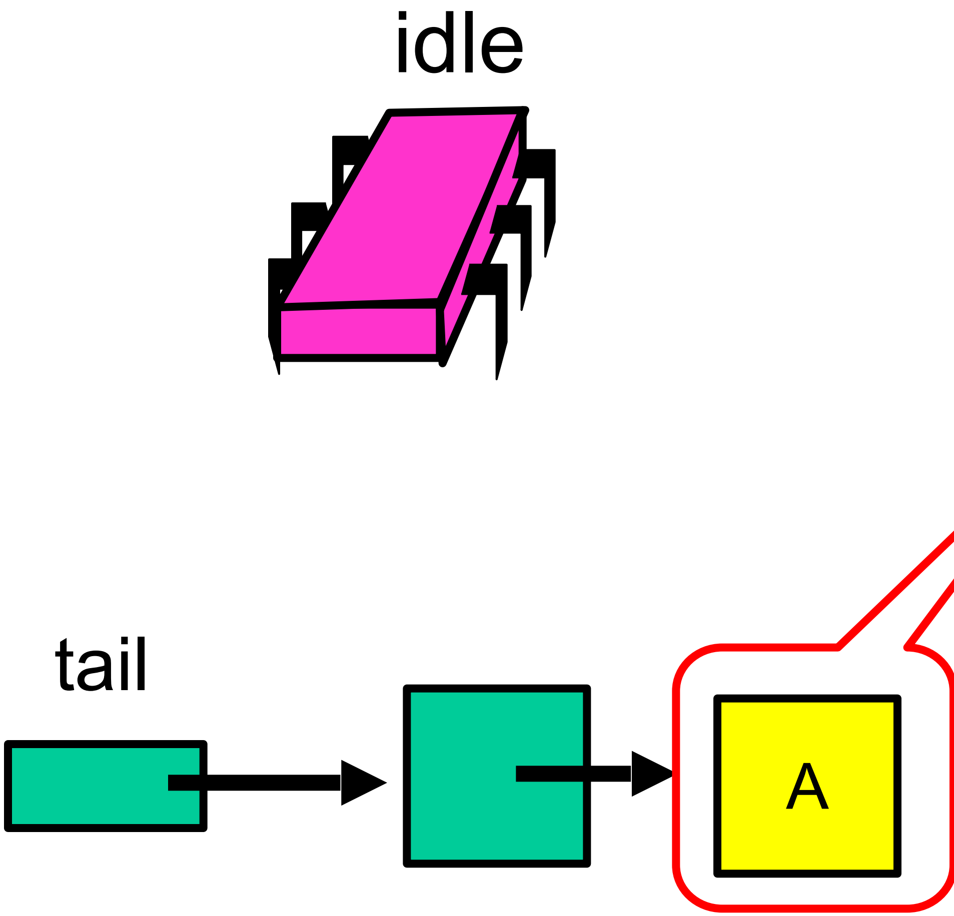


Initially

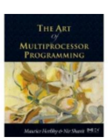




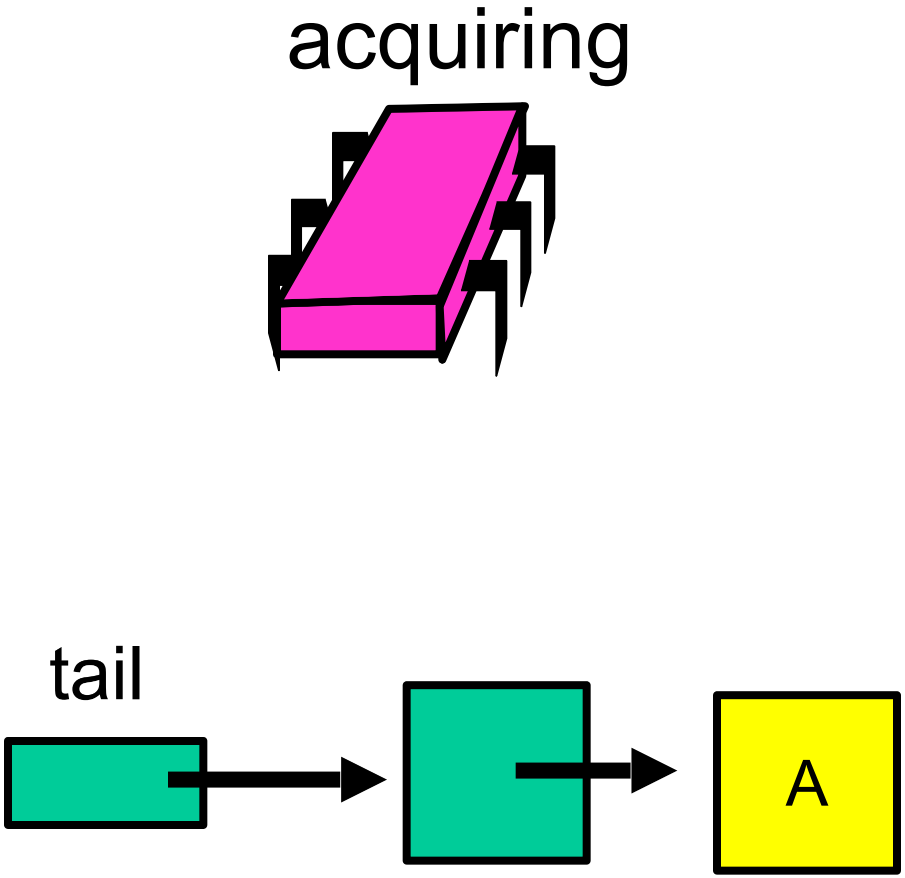
Initially



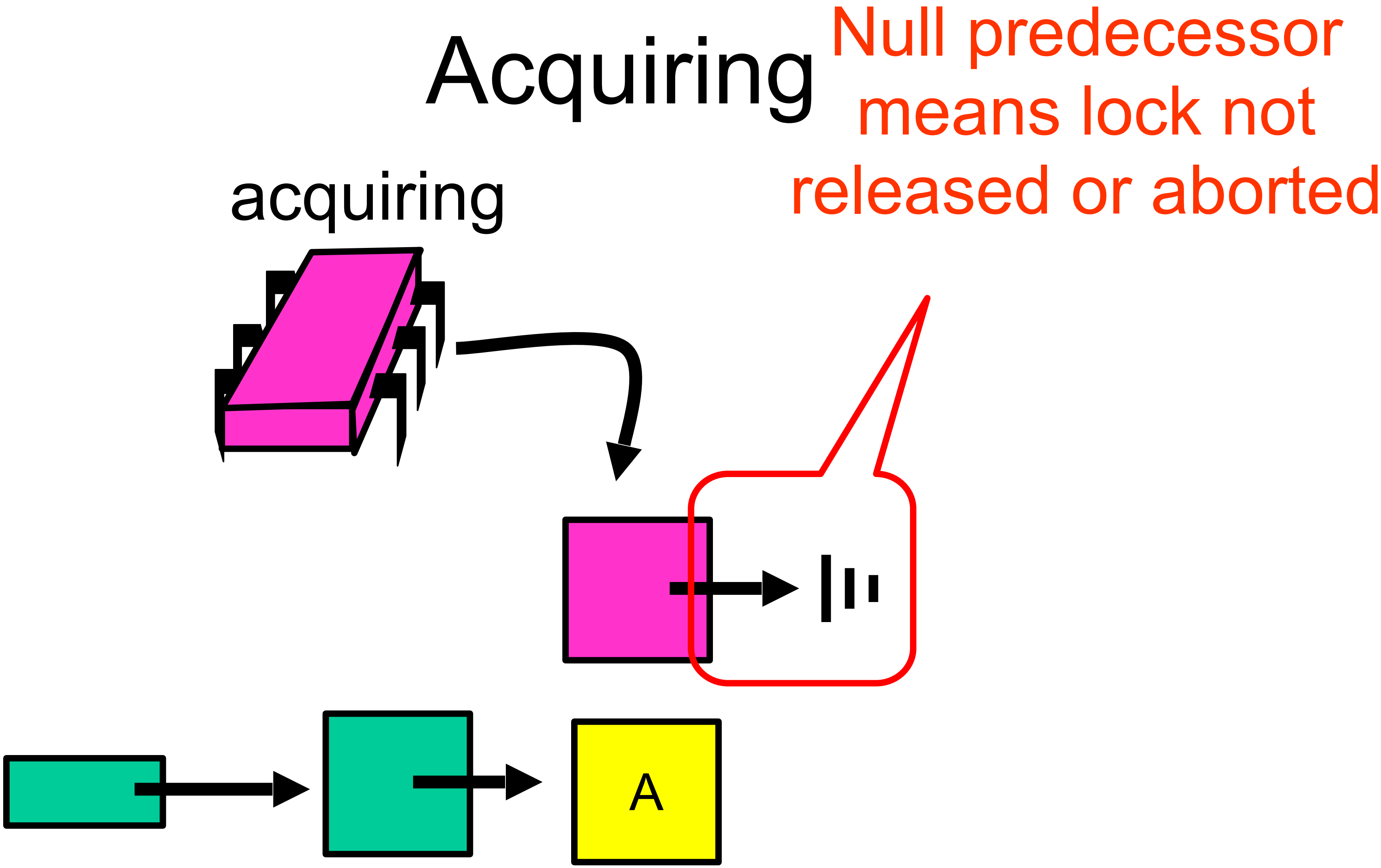
Distinguished available node means lock is free



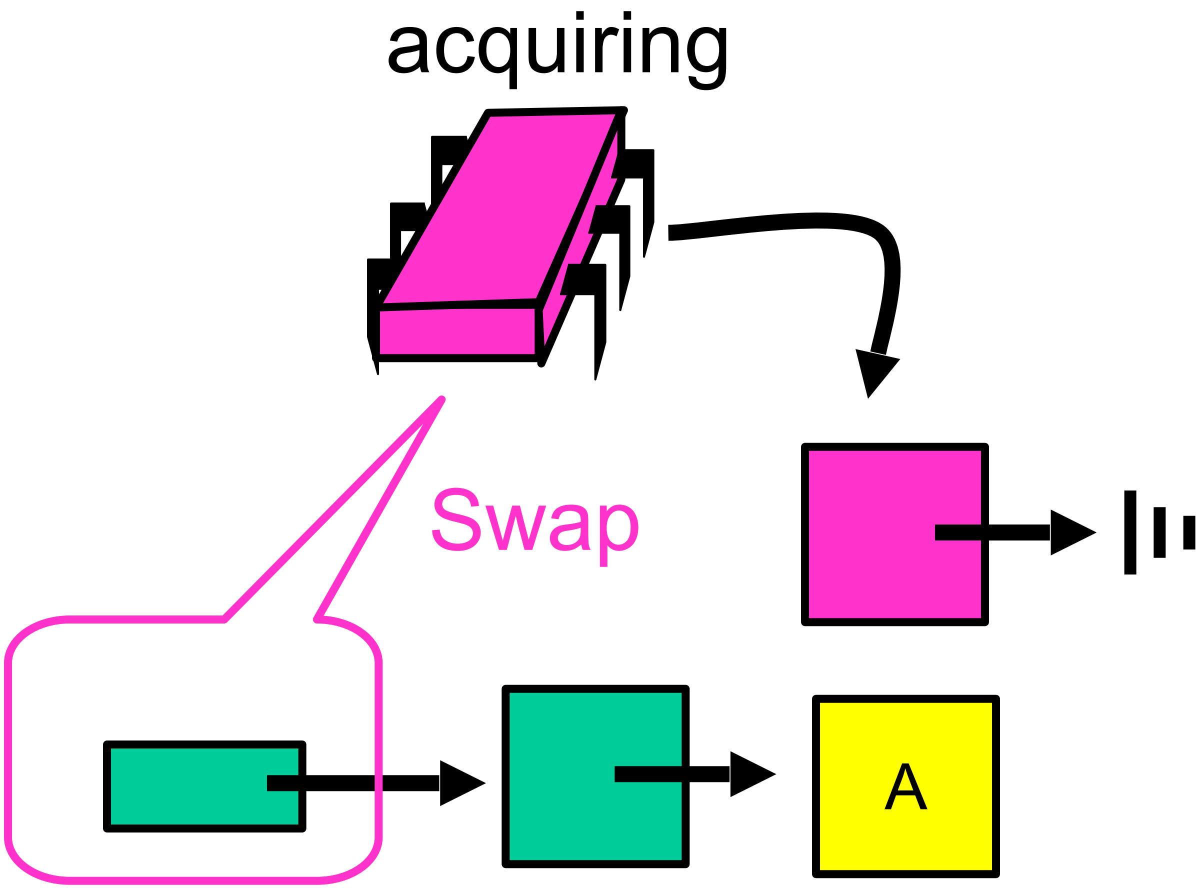
Acquiring



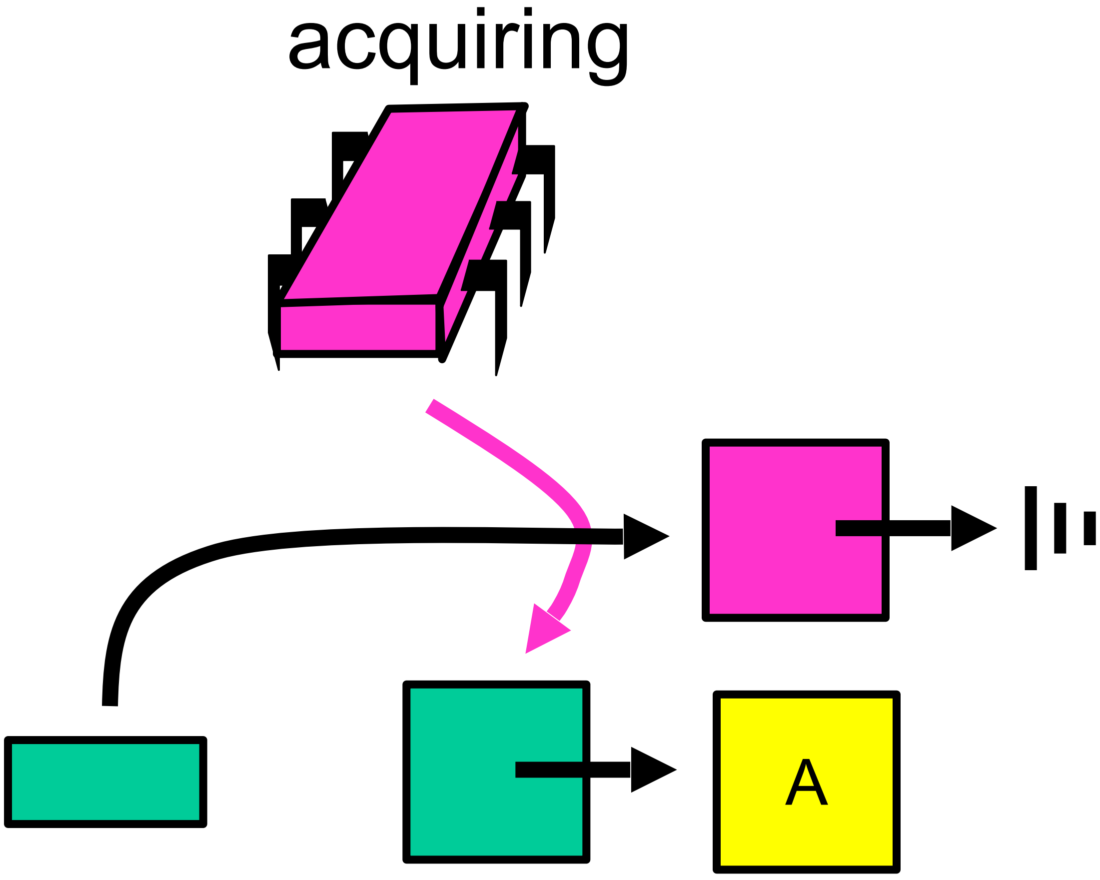
Acquiring


acquiring
Null predecessor means lock not released or aborted
A

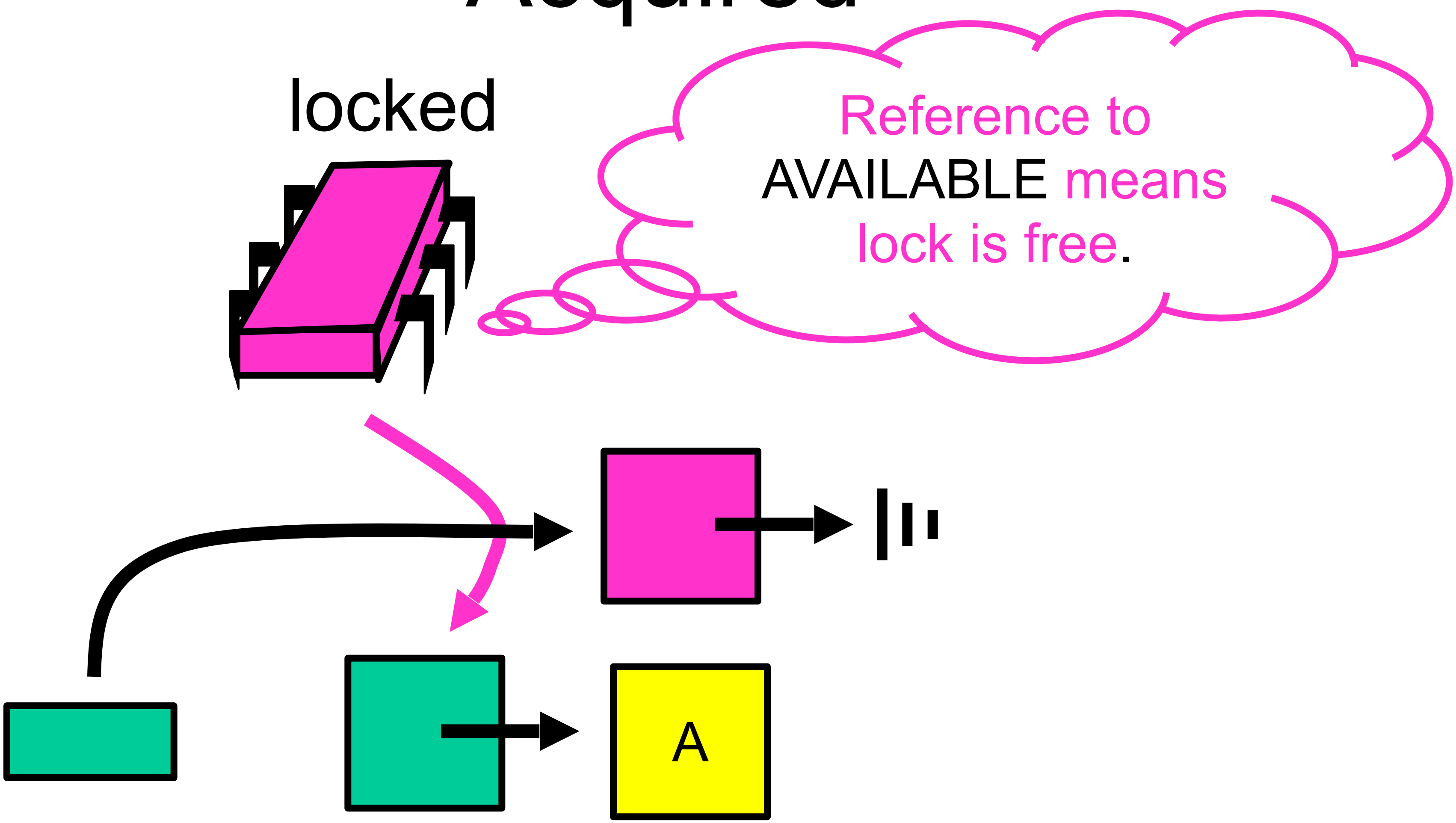
Acquiring



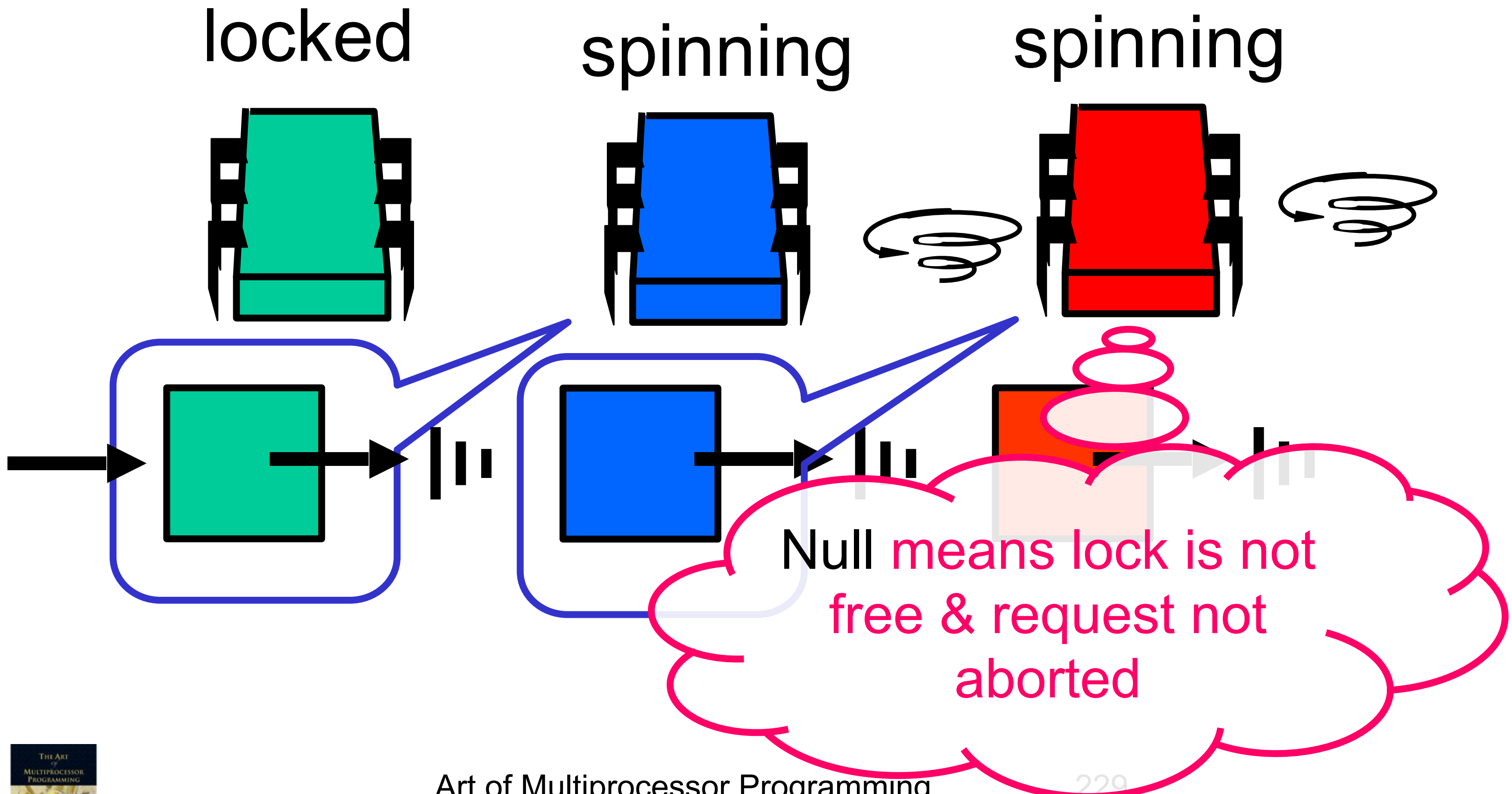
Acquiring



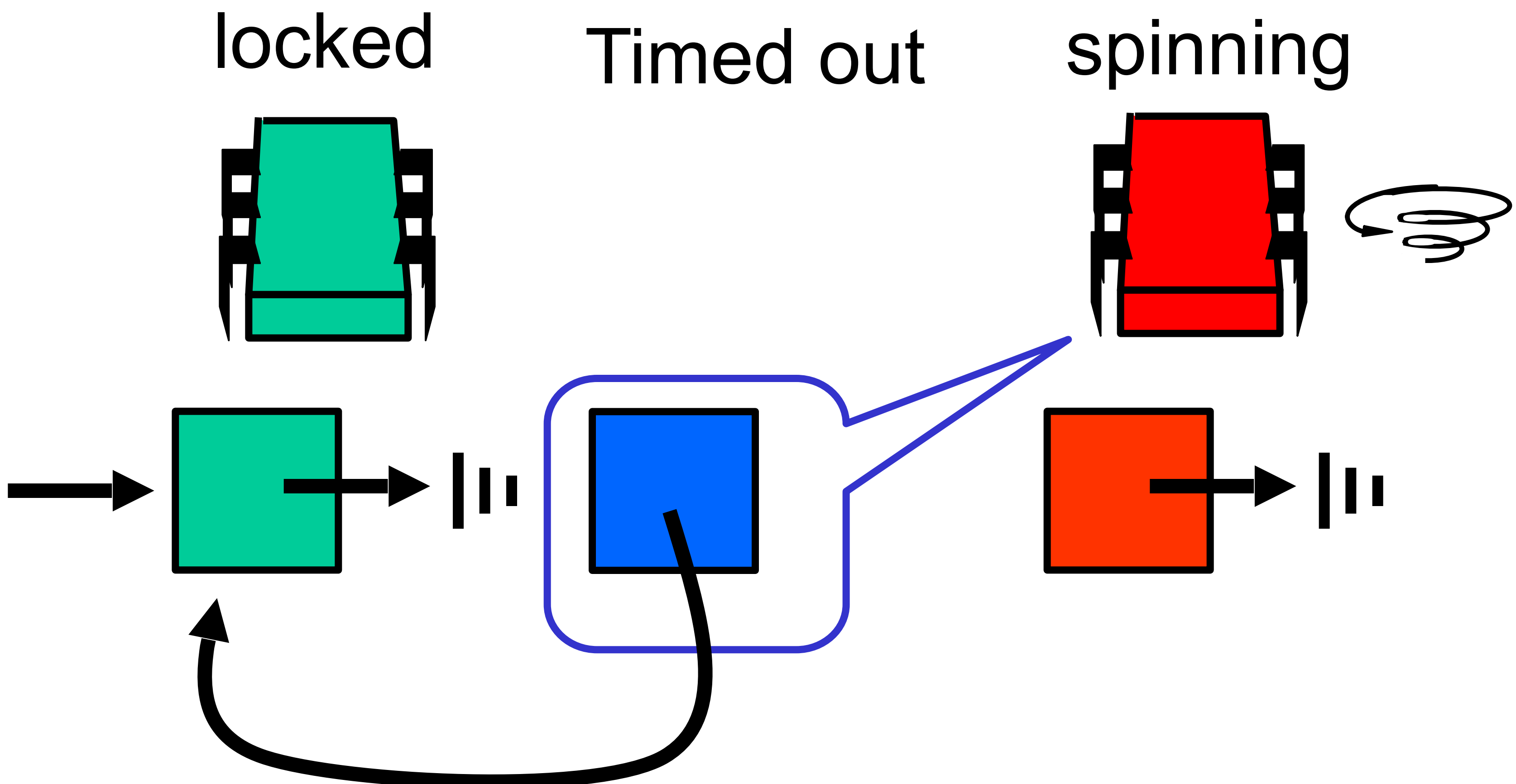
Acquired



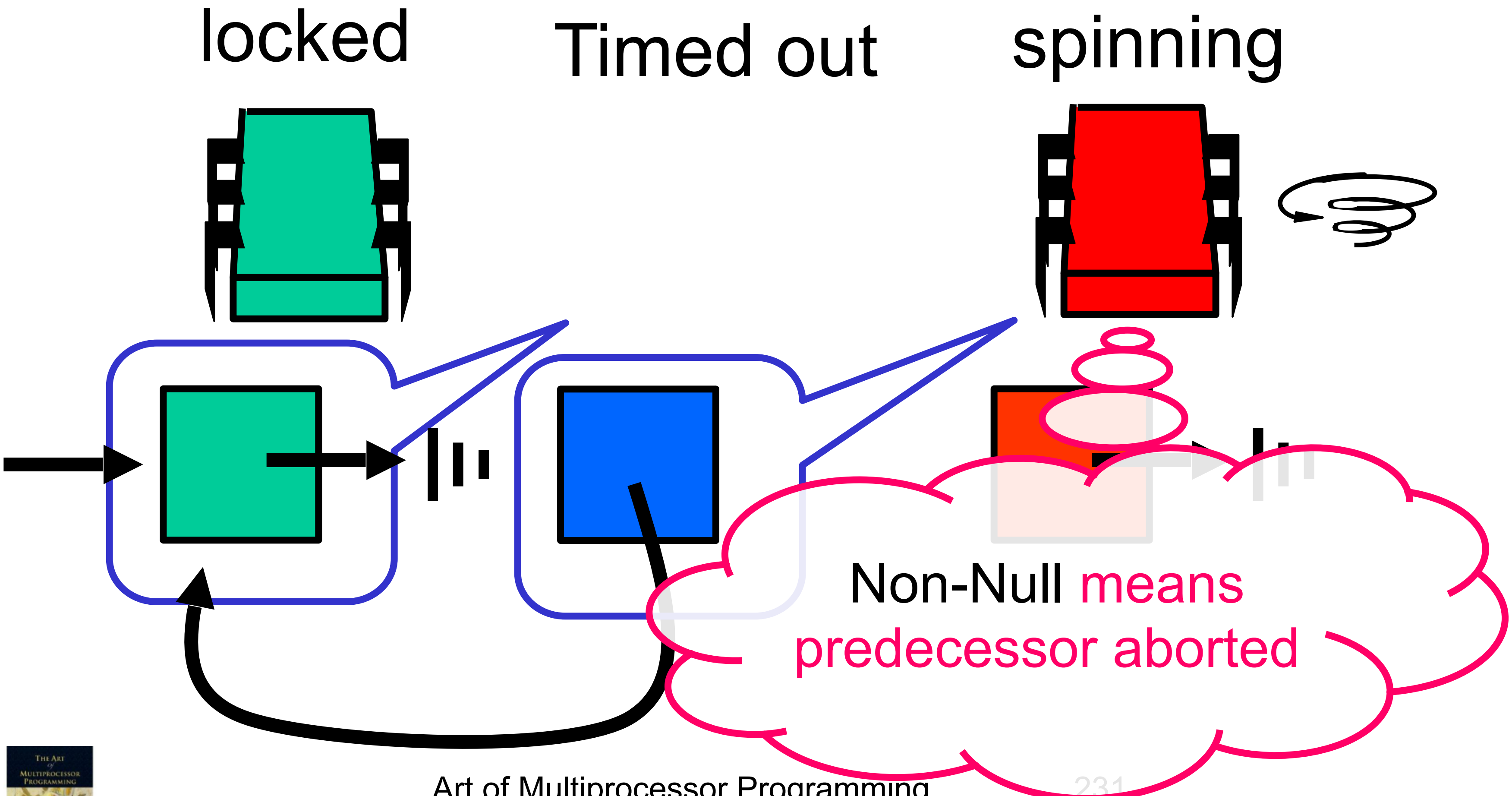
Normal Case


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

One Thread Aborts

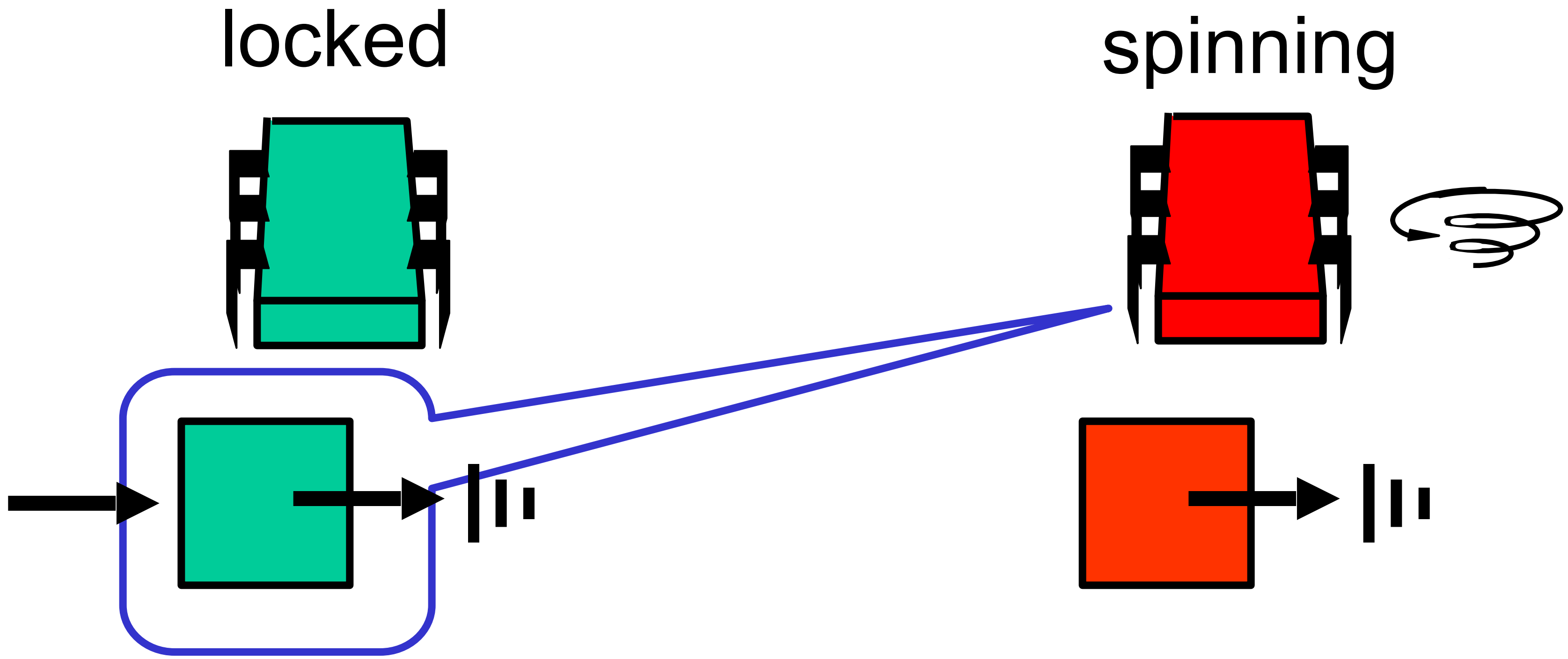


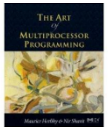
Successor Notices



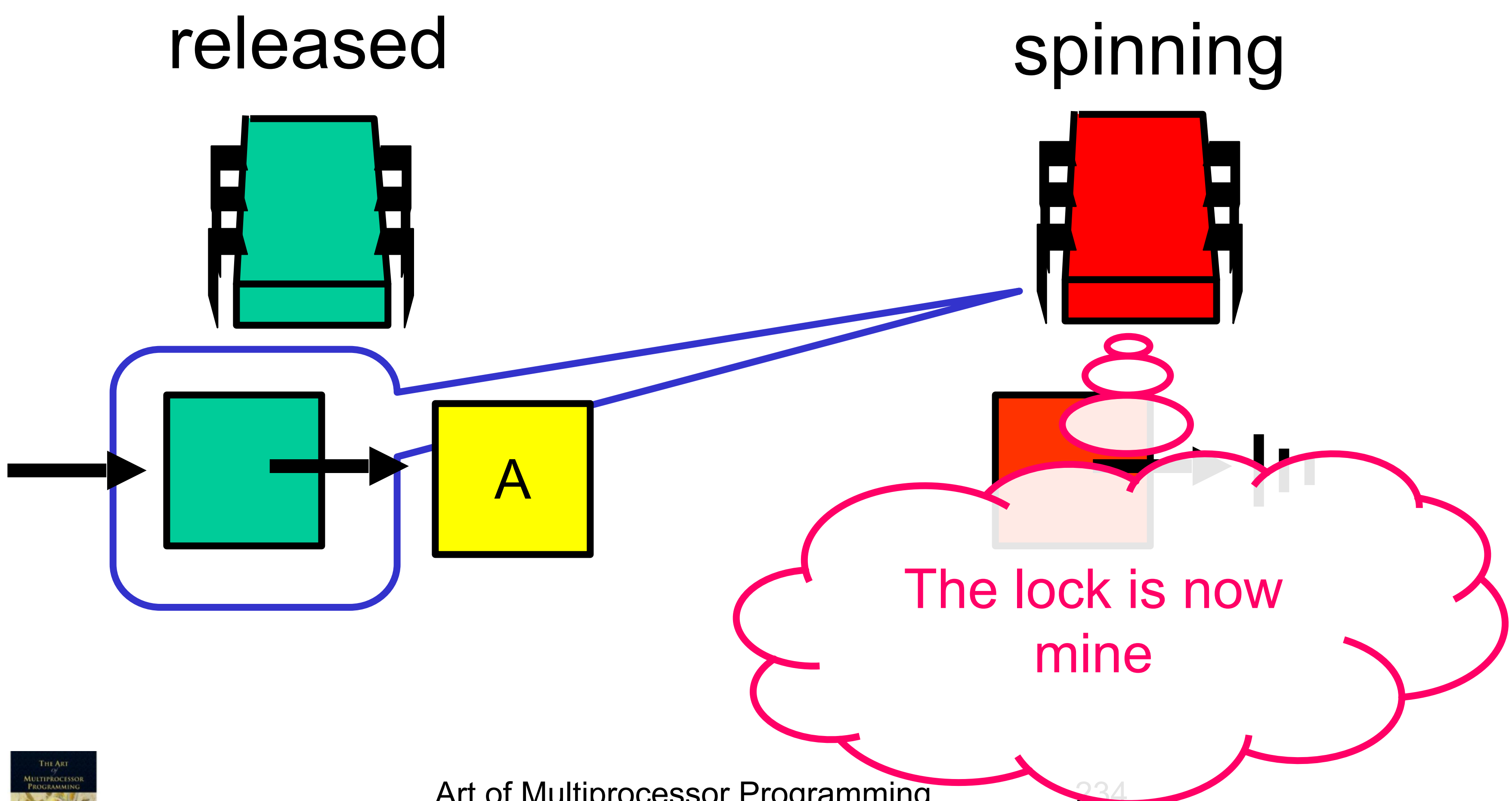
Recycle Predecessor’s Node

Spin on Earlier Node



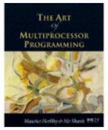


Spin on Earlier Node



Time-out Lock

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



Time-out Lock

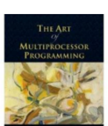
```
public class TOLock implements Lock {
  static Qnode AVAILABLE
    = new Qnode();
  AtomicReference<Qnode> tail;
  ThreadLocal<Qnode> myNode;
```

AVAILABLE node signifies free lock

Time-out Lock

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

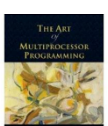
Tail of the queue



Time-out Lock

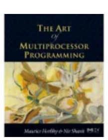
```
public class TOLock implements Lock {
  static Qnode AVAILABLE
    = new Qnode();
  AtomicReference<Qnode> tail;
  ThreadLocal<Qnode> myNode;
```

Remember my node …



Time-out Lock

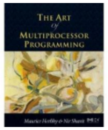
```
public boolean lock(long timeout) {
  Qnode qnode = new Qnode();
  myNode.set(qnode);
  qnode.prev = null;
  Qnode myPred = tail.getAndSet(qnode);
  if (myPred== null
      || myPred.prev == AVAILABLE) {
      return true;
   }
…
```



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;
    }
```

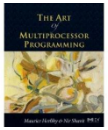
Create & initialize node



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

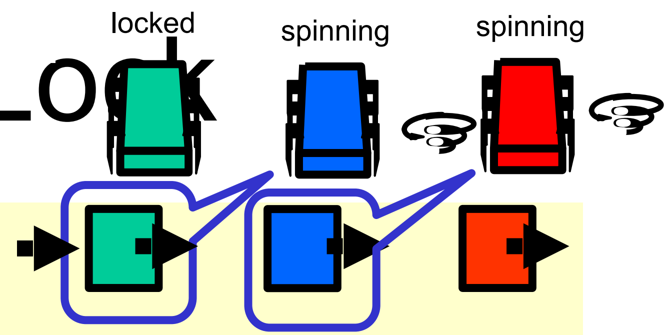


Time-out Lock

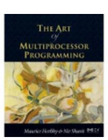
```
public boolean lock(long timeout) {
  Qnode qnode = new Qnode();
  myNode.set(qnode);
  qnode.prev = null;
  Qnode myPred = tail.getAndSet(qnode);
  if (myPred == null
      || myPred.prev == AVAILABLE) {
      return true;
   }
  ...
```

If predecessor absent or released, we are done

Time-out Lock



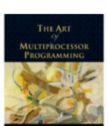

```
…
  long start = now();
  while (now()- start < timeout) {
    Qnode predPred = myPred.prev;
    if (predPred == AVAILABLE) {
      return true;
    } else if (predPred != null) {
      myPred = predPred;
    }
  }
  …
```



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;
    }
  }
  …
```

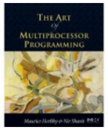
Keep trying for a while …



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

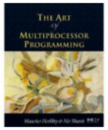
```
…
  long start = now();
  while (now()- start < timeout) {
    Qnode predPred = myPred.prev;
    if (predPred == AVAILABLE) {
      return true;
    } else if (predPred != null) {
      myPred = predPred;
    }
  }
  …
```

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.
Tell it about myPred

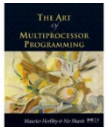
Time-out Lock

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

If CAS succeeds: no successor, simply return false

Time-Out Unlock

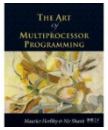
```
public void unlock() {
  Qnode qnode = myNode.get();
  if (!tail.compareAndSet(qnode, null))
    qnode.prev = AVAILABLE;
}
```



Time-out Unlock

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

If CAS failed:
successor exists,
notify 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