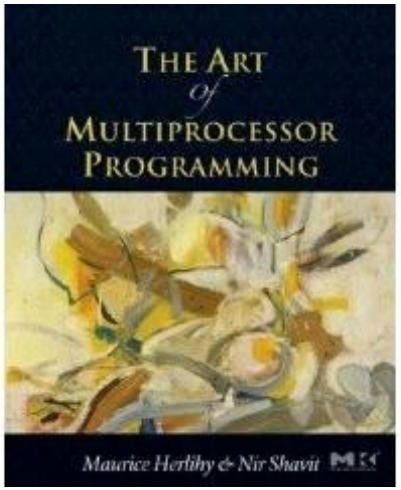
Linked Lists: Locking, Lock-Free, and Beyond …



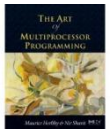
Companion slides for

The Art of Multiprocessor Programming

by Maurice Herlihy & Nir Shavit

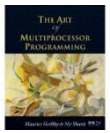
Concurrent Objects

- Adding threads should not lower throughput
  - Contention effects
  - Mostly fixed by scalable locks



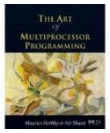
Concurrent Objects

- Adding threads should not lower throughput
  - Contention effects
  - Mostly fixed by scalable locks
- Should increase throughput
  - Not possible if inherently sequential
  - Surprising things are parallelizable



Coarse-Grained Synchronization

- Each method locks the object
  - Avoid contention using scalable locks



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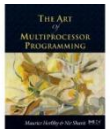
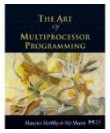
    - In simple cases



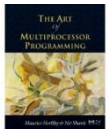
Coarse-Grained Synchronization

- Each method locks the object
  - Avoid contention using scalable locks
  - Easy to reason about
    - In simple cases
- So, are we done?



Coarse-Grained Synchronization

- Sequential bottleneck
  - Threads “stand in line”



Coarse-Grained Synchronization

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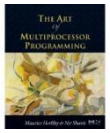
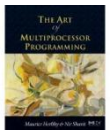
- Adding more threads
  - Does not improve throughput
  - Struggle to keep it from getting worse



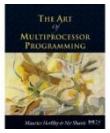
Coarse-Grained Synchronization

- Sequential bottleneck
  - Threads “stand in line”
- Adding more threads
  - Does not improve throughput
  - Struggle to keep it from getting worse
- So why even use a multiprocessor?
  - Well, some apps inherently parallel …



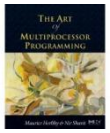
This Lecture

- Introduce four “patterns”
  - Bag of tricks …
  - Methods that work more than once …



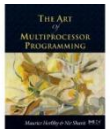
This Lecture

- Introduce four “patterns”
  - Bag of tricks …
  - Methods that work more than once …
- For highly-concurrent objects
  - Concurrent access
  - More threads, more throughput



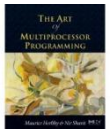
First: Fine-Grained Synchronization

- Instead of using a single lock …
- Split object into
  - Independently-synchronized components
- Methods conflict when they access
  - The same component …
  - At the same time



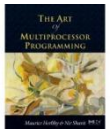
Second: Optimistic Synchronization

- Search without locking …



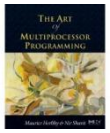
Second: Optimistic Synchronization

- Search without locking …
- If you find it, lock and check …
  - OK: we are done
  - Oops: start over



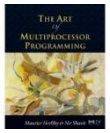
Second: Optimistic Synchronization

- Search without locking …
- If you find it, lock and check …
  - OK: we are done
  - Oops: start over
- Evaluation
  - Usually cheaper than locking, but
  - Mistakes are expensive



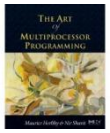
Third: Lazy Synchronization

- Postpone hard work
- Removing components is tricky
  - Logical removal
    - Mark component to be deleted
  - Physical removal
    - Do what needs to be done



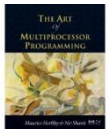
Fourth: Lock-Free Synchronization

- Don’t use locks at all
  - Use compareAndSet() & relatives …



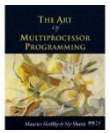
Fourth: Lock-Free Synchronization

- Don’t use locks at all
  - Use compareAndSet() & relatives …
- Advantages
  - No Scheduler Assumptions/Support



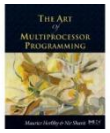
Fourth: Lock-Free Synchronization

- Don't use locks at all
  - Use compareAndSet() & relatives …
- Advantages
  - No Scheduler Assumptions/Support
- Disadvantages
  - Complex
  - Sometimes high overhead



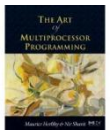
Linked List

- Illustrate these patterns …
- Using a list-based Set
  - Common application
  - Building block for other apps



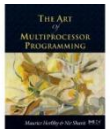
Set Interface

- Unordered collection of items



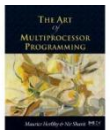
Set Interface

- Unordered collection of items
- No duplicates



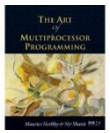
Set Interface

- Unordered collection of items
- No duplicates
- Methods
  - `add(x)` put `x` in set
  - `remove(x)` take `x` out of set
  - `contains(x)` tests if `x` in set



List-Based Sets

```
public interface Set<T> {
 public boolean add(T x);
 public boolean remove(T x);
 public boolean contains(T x);
}
```



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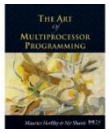

Add item to set

List-Based Sets

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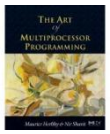
Remove item from set



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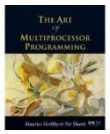
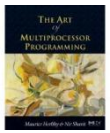
Is item in set?



List Node

```
public class Node {
 public T item;
 public int key;
 public Node next;
}
```



List Node

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public class Node {
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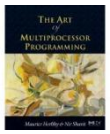
item of interest



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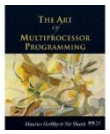
Usually hash code



List Node

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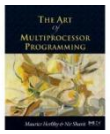
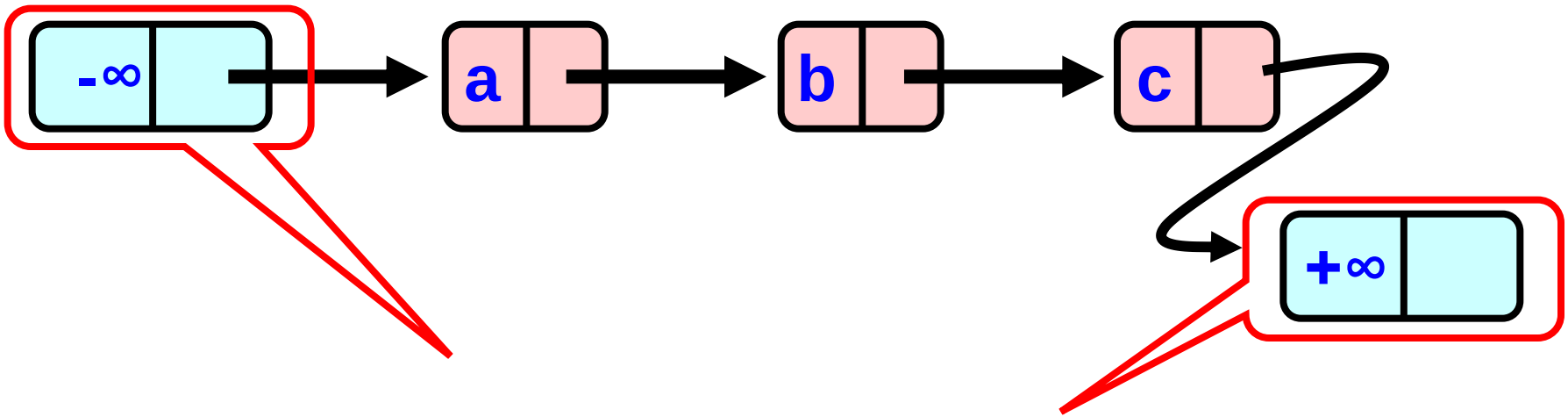
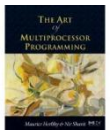
Reference to next node



The List-Based Set

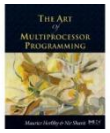


Sorted with Sentinel nodes
(min & max possible keys)



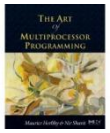
Reasoning about Concurrent Objects

- Invariant
  - Property that always holds



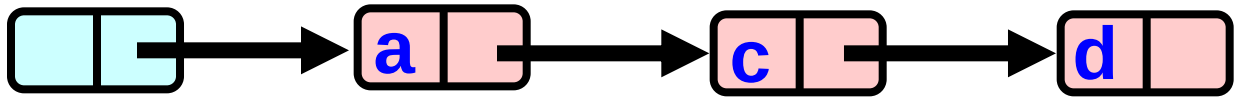
Reasoning about Concurrent Objects

- Invariant
  - Property that always holds
- Established because
  - True when object is **created**
  - Truth **preserved** by each method
    - Each **step** of each method

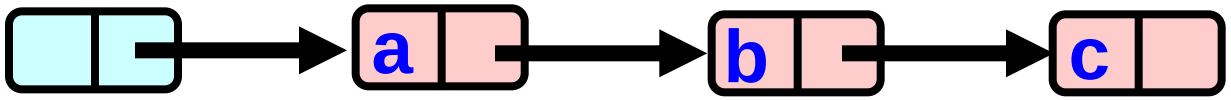


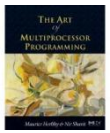
Sequential List Based Set

add()



remove()





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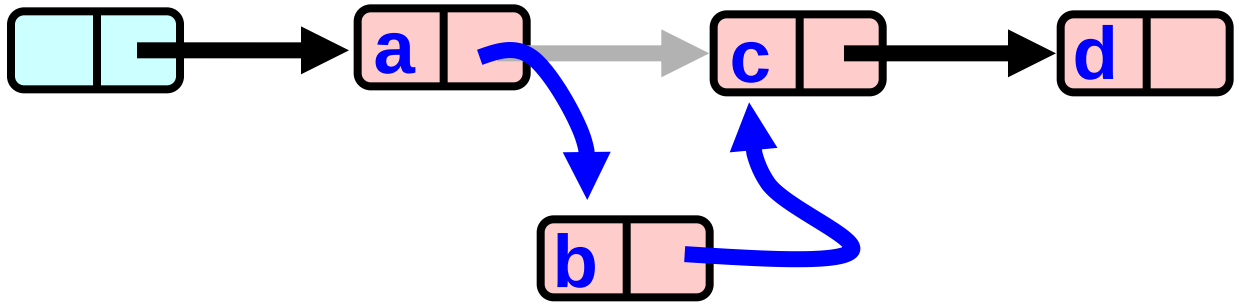
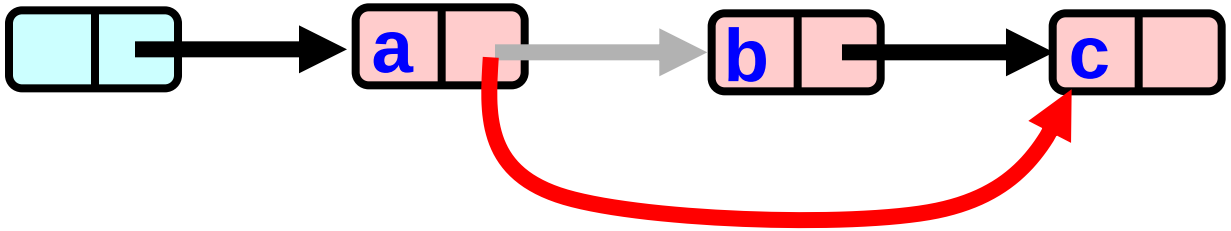
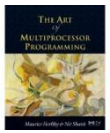
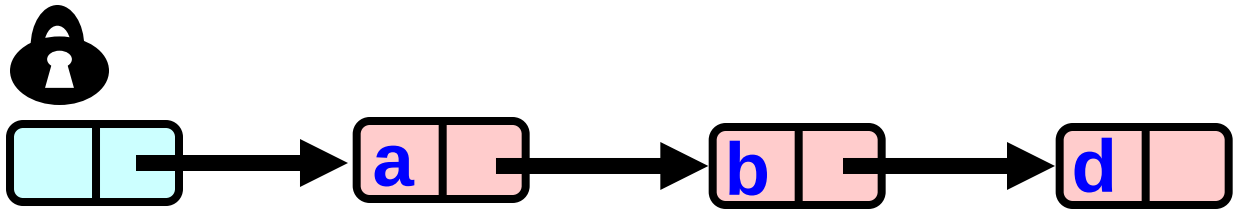


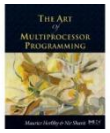
remove()





Coarse-Grained Locking





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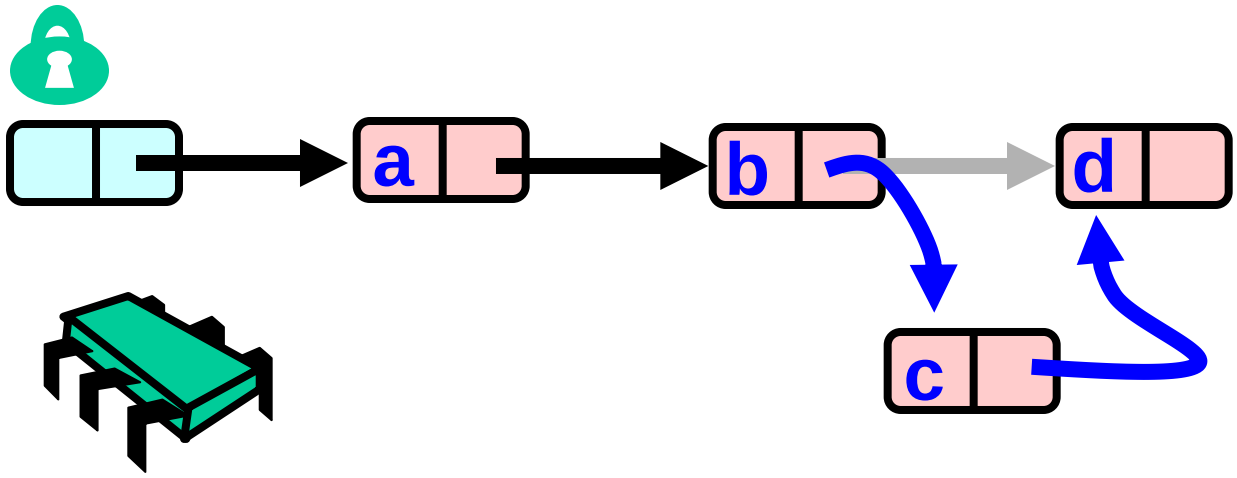

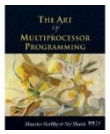

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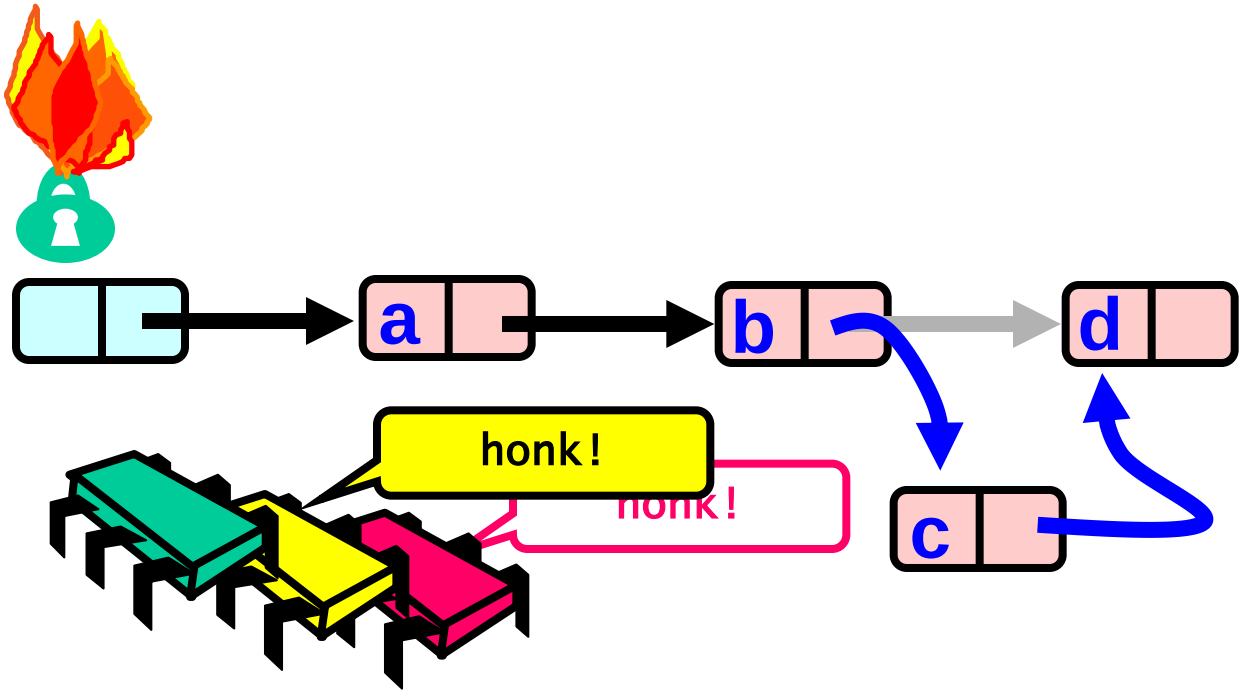
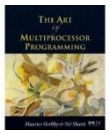
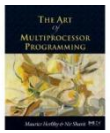


Simple but hotspot + bottleneck



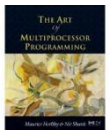
Coarse-Grained Locking

- Easy, same as synchronized methods
  - "One lock to rule them all …"



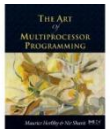
Coarse-Grained Locking

- Easy, same as synchronized methods
  - "One lock to rule them all …"
- Simple, clearly correct
  - Deserves respect!
- Works poorly with contention
  - Queue locks help
  - But bottleneck still an issue



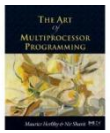
Fine-grained Locking

- Requires **careful** thought
  - "Do not meddle in the affairs of wizards, for they are subtle and quick to anger"

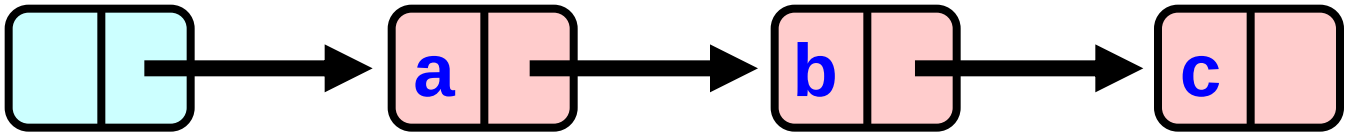


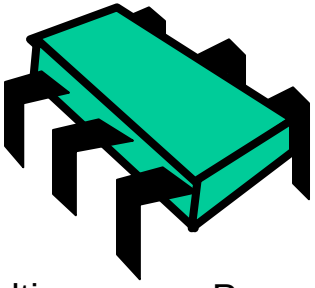
Fine-grained Locking

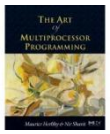
- Requires **careful** thought
  - "Do not meddle in the affairs of wizards, for they are subtle and quick to anger"
- Split object into pieces
  - Each piece has own lock
  - Methods that work on disjoint pieces need not exclude each other



Hand-over-Hand locking







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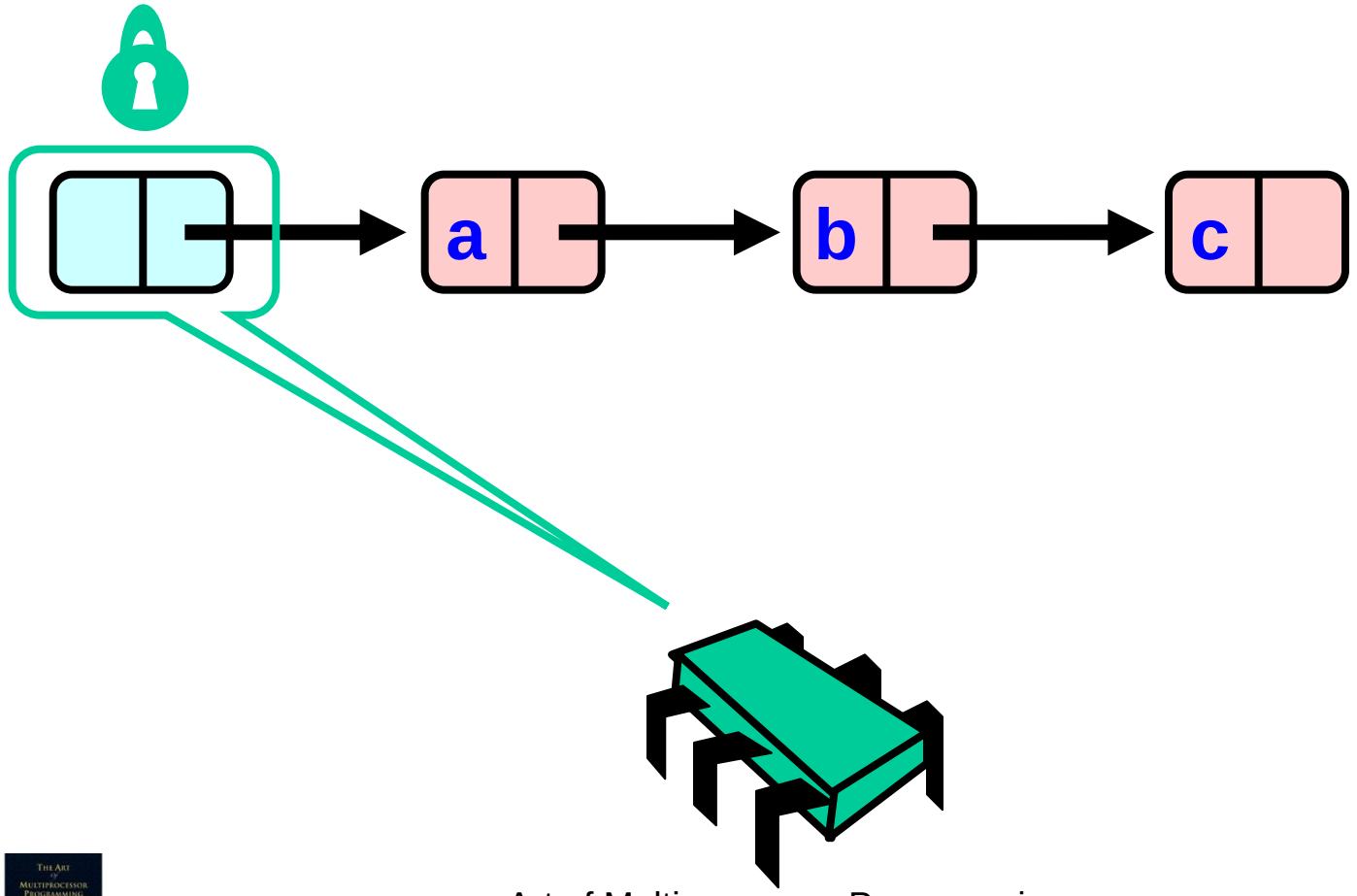

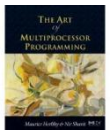

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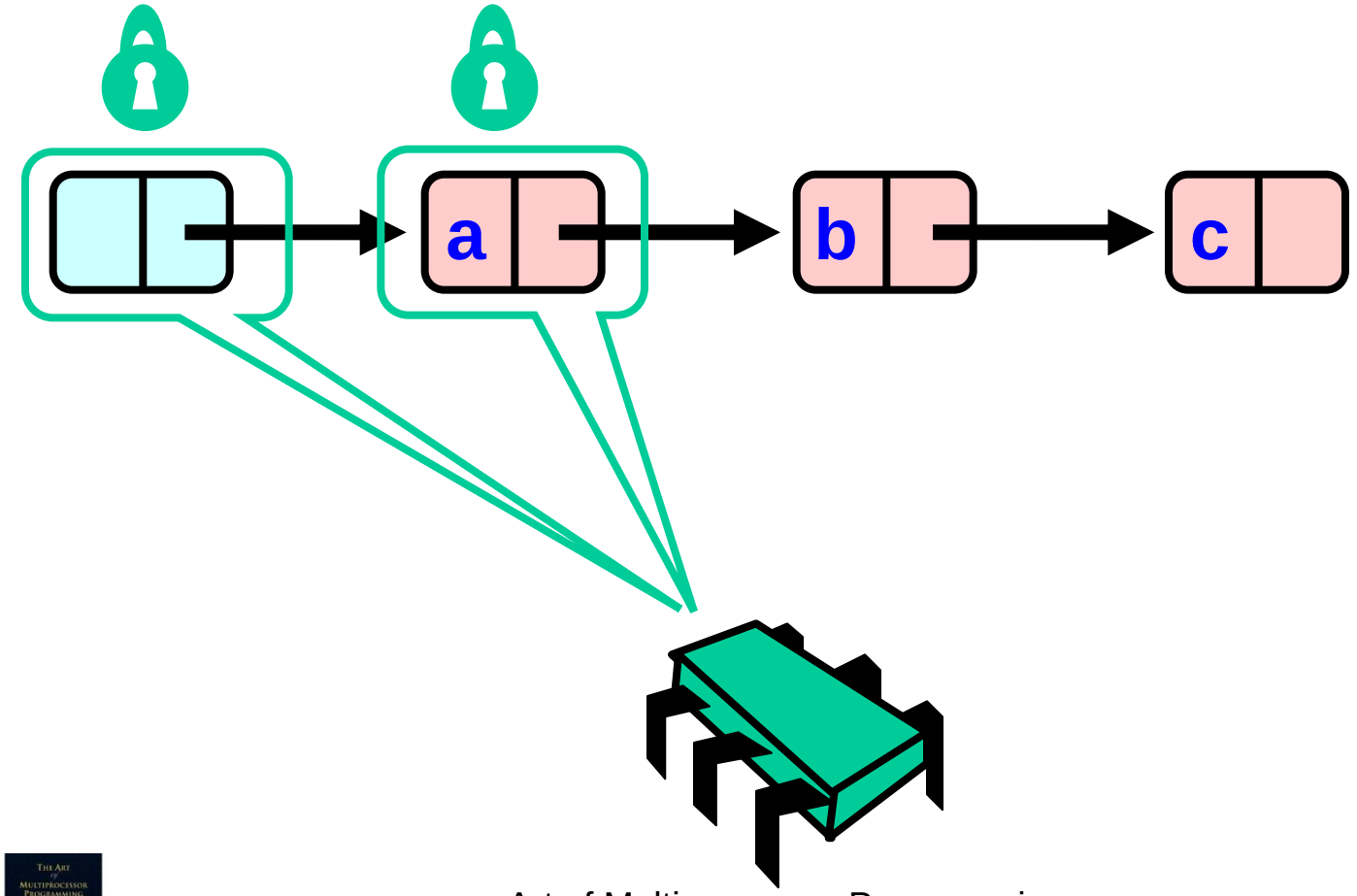

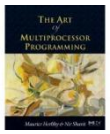

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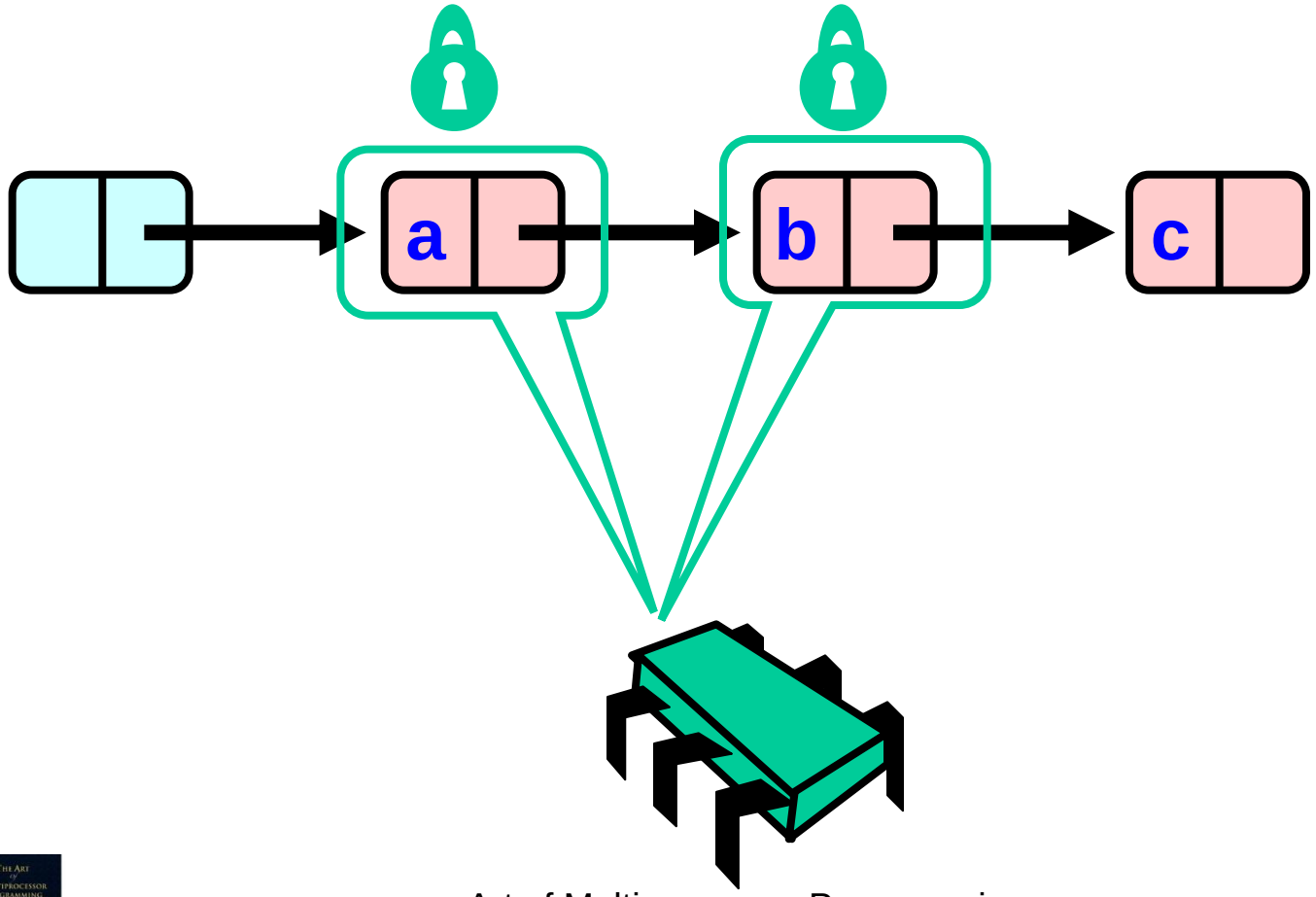

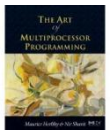

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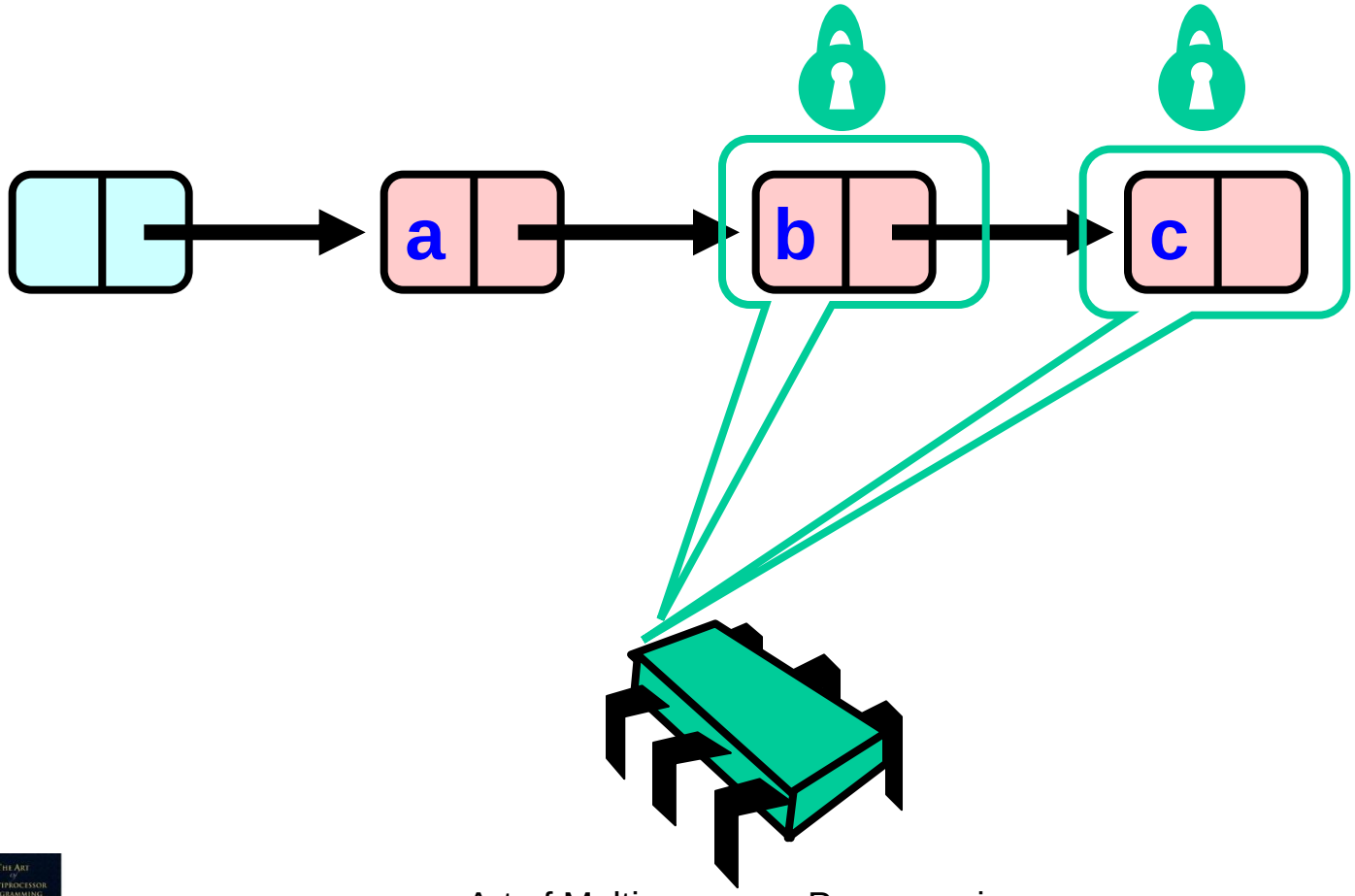
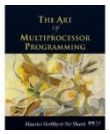
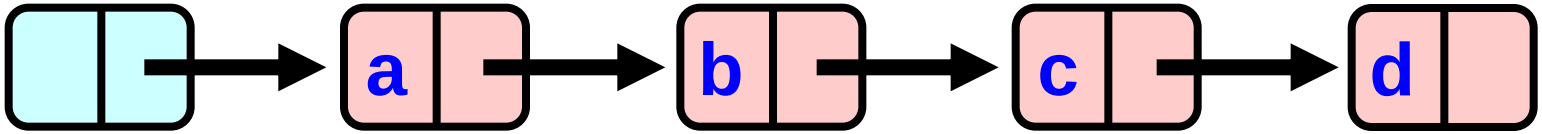
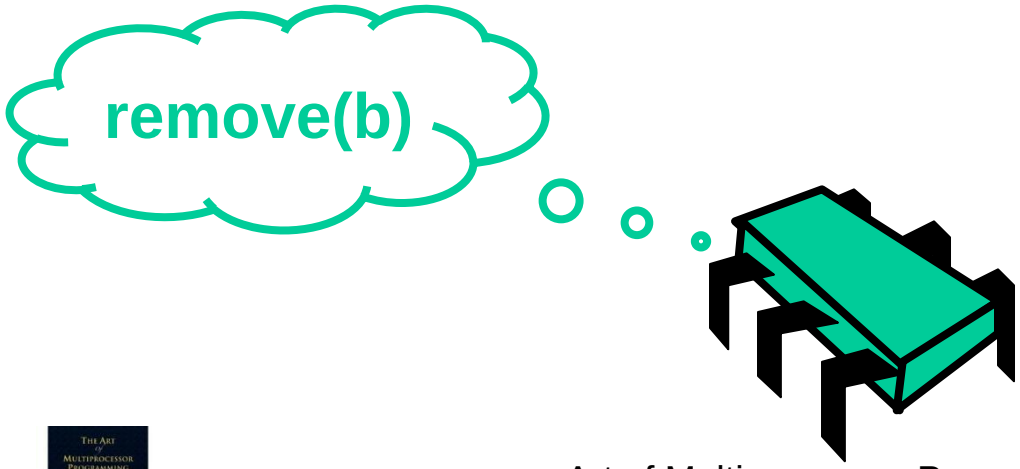
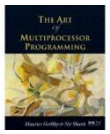




Removing a Node







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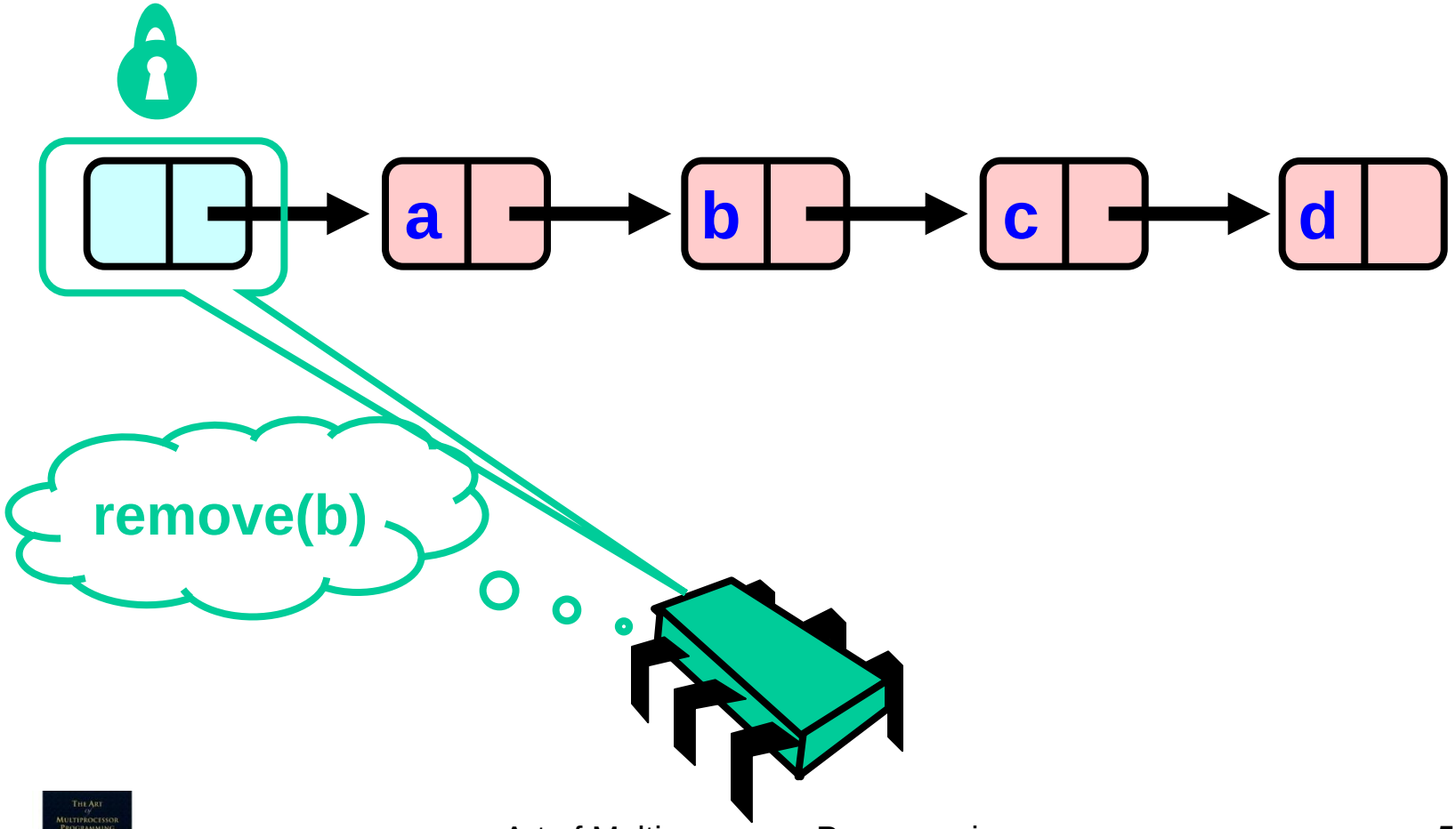
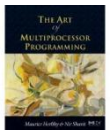
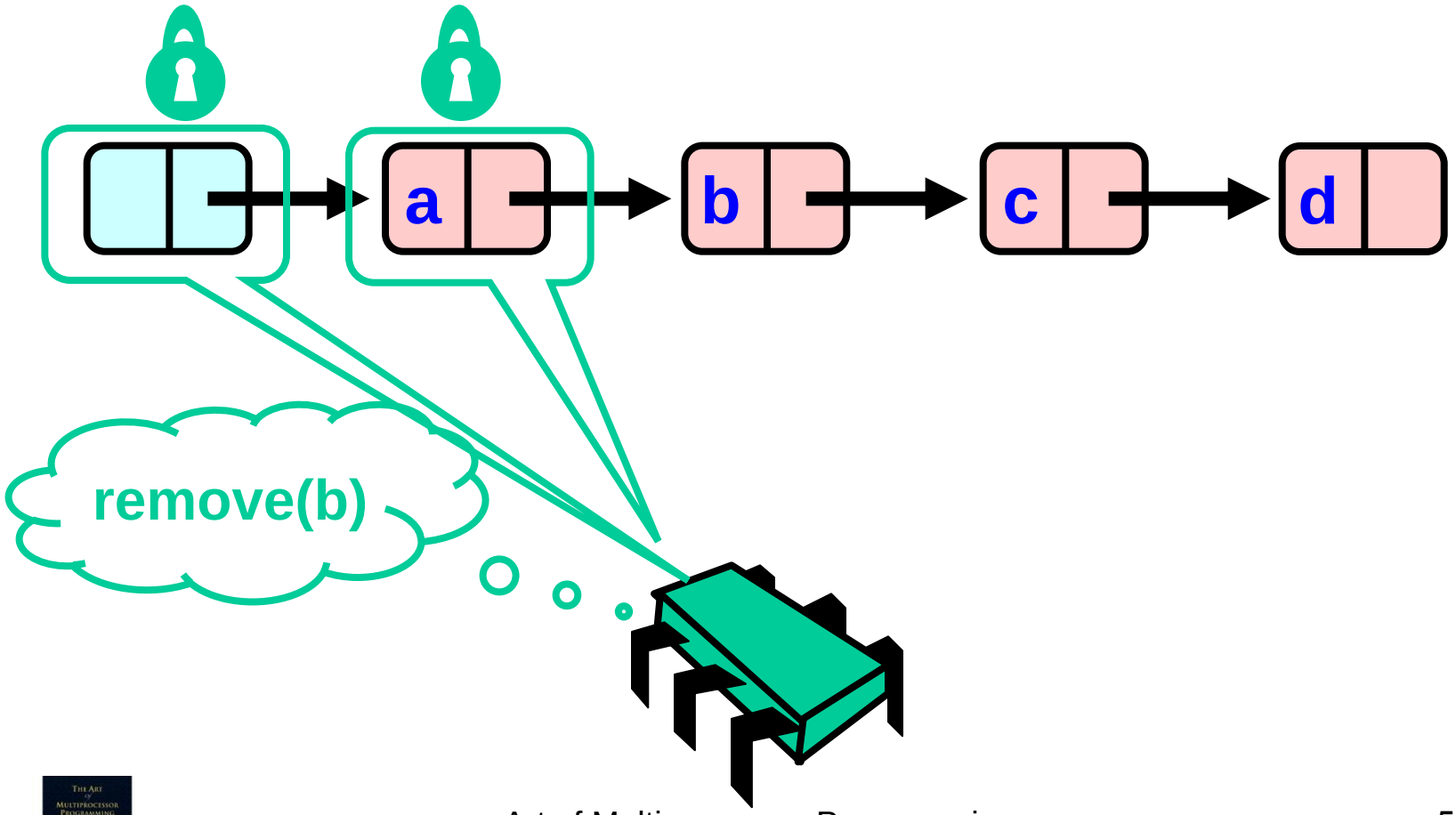
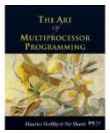


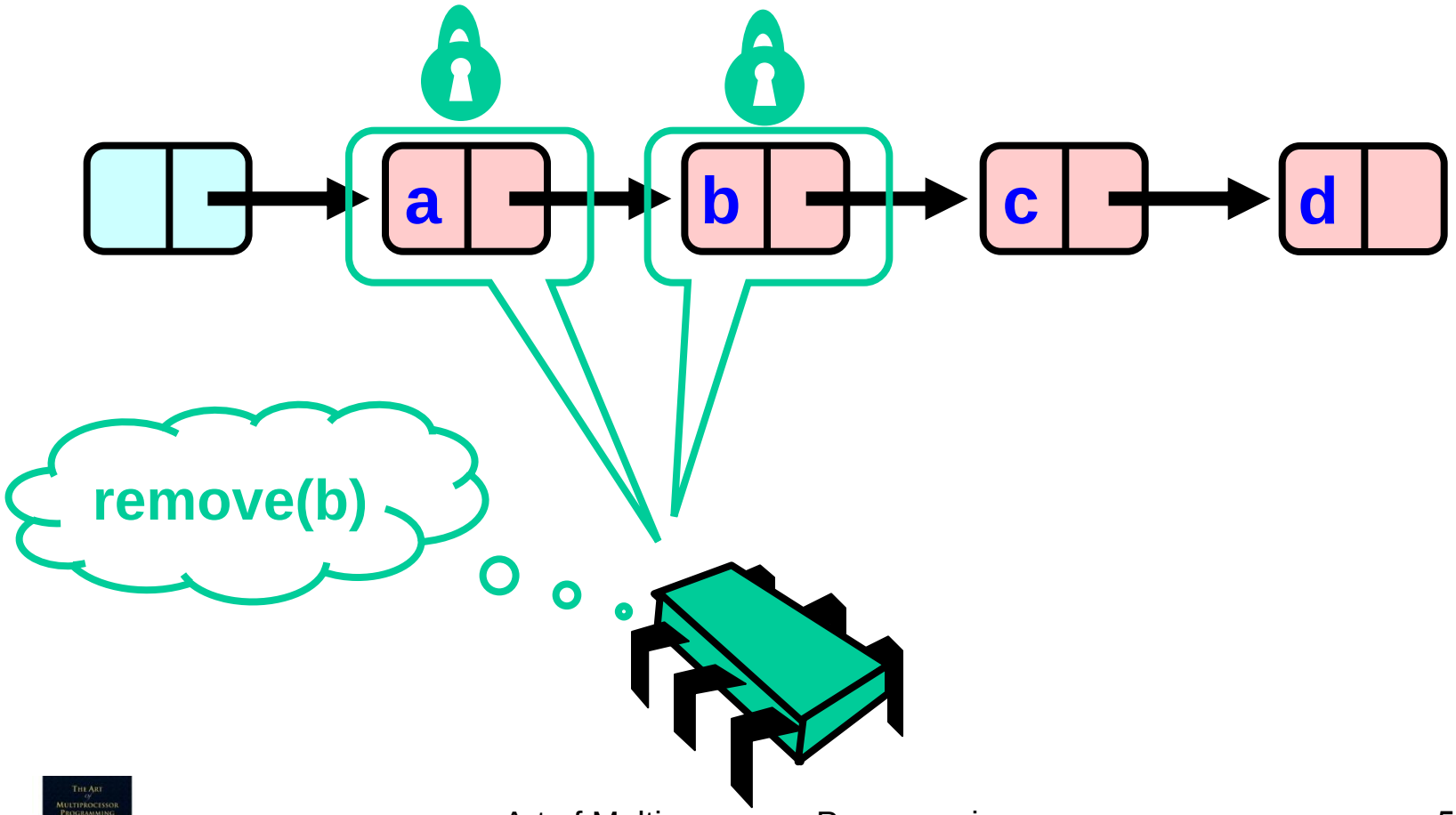


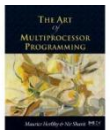
Removing a Node





Removing a Node





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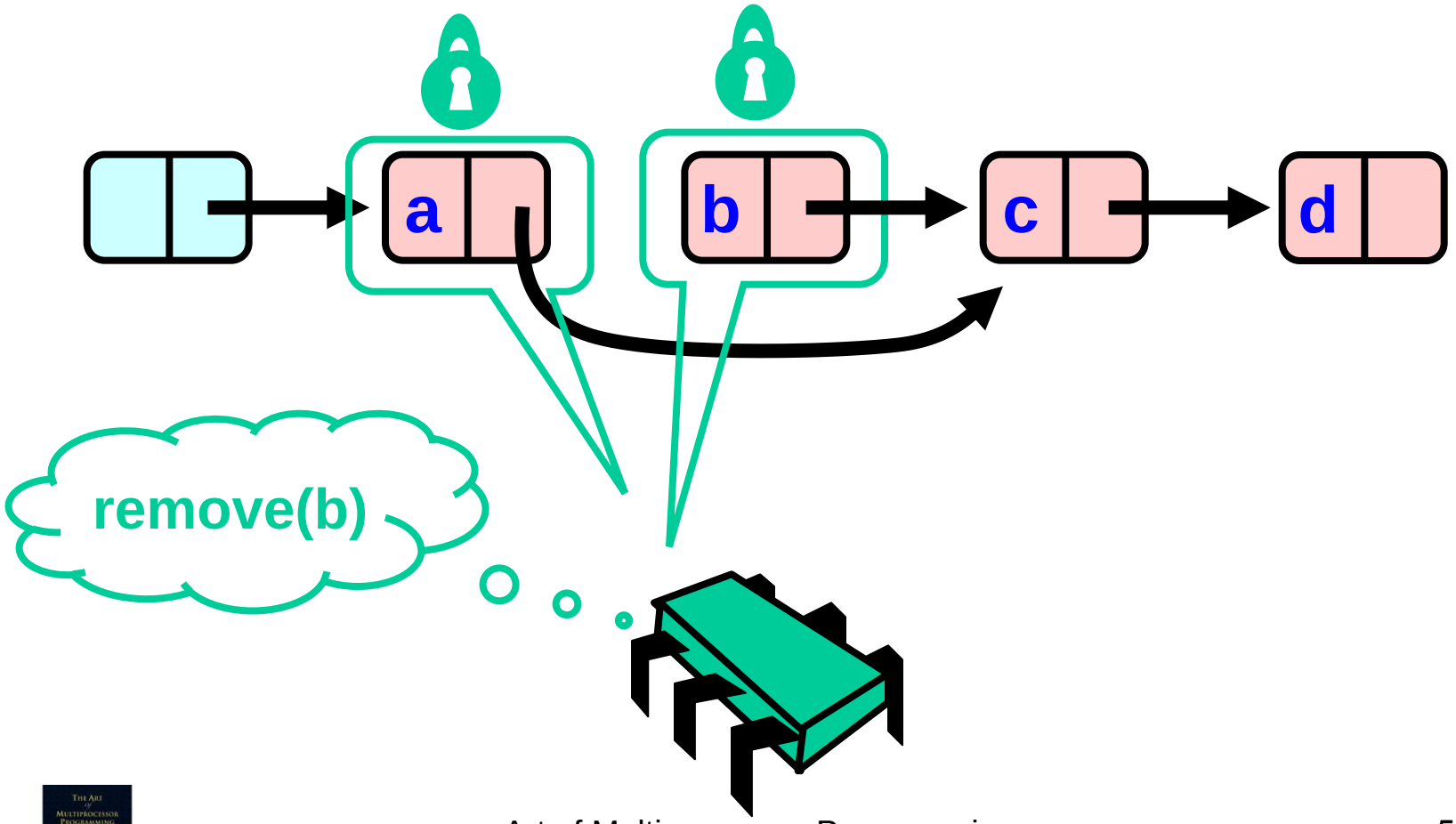

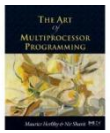

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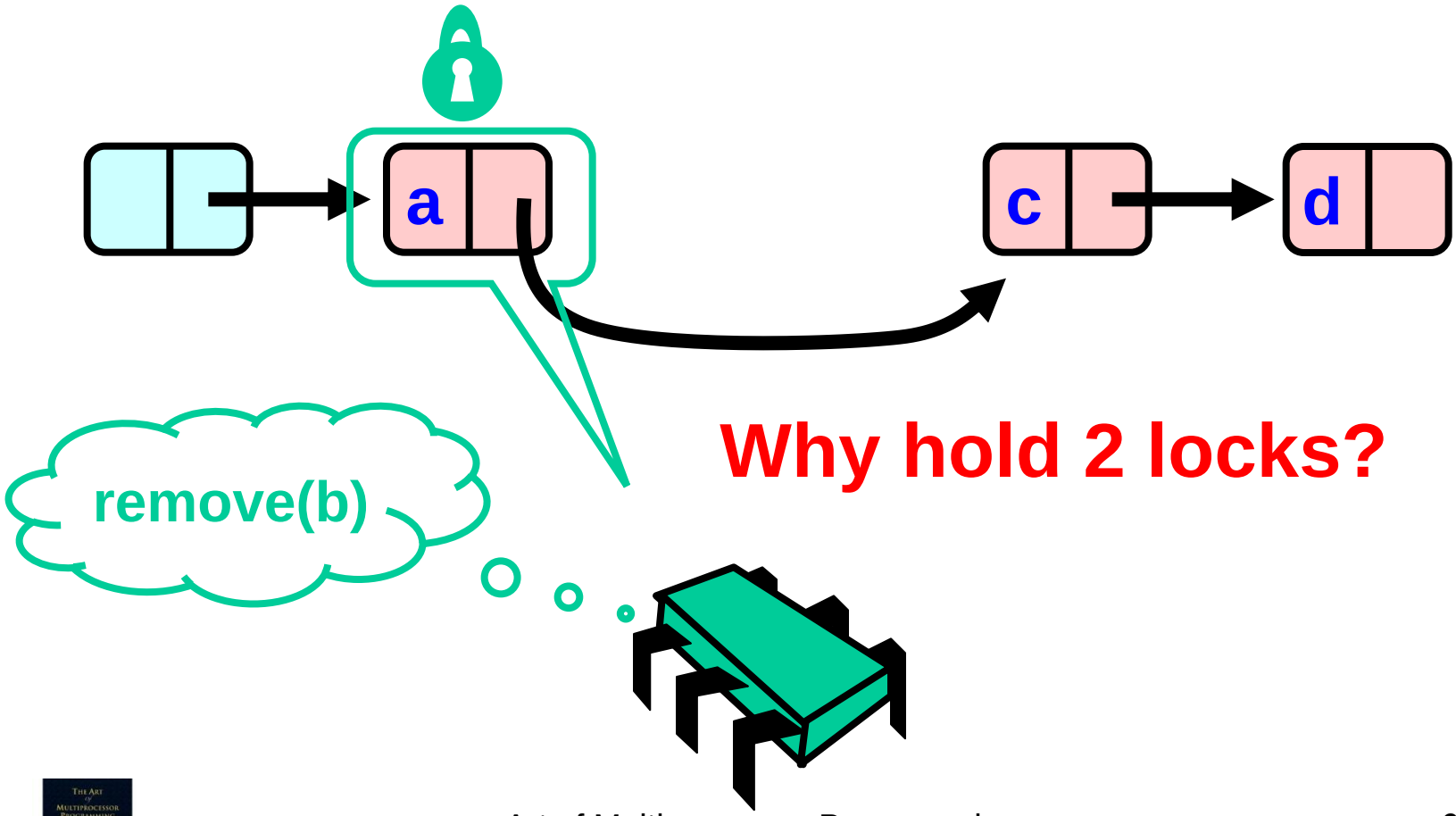
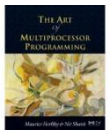
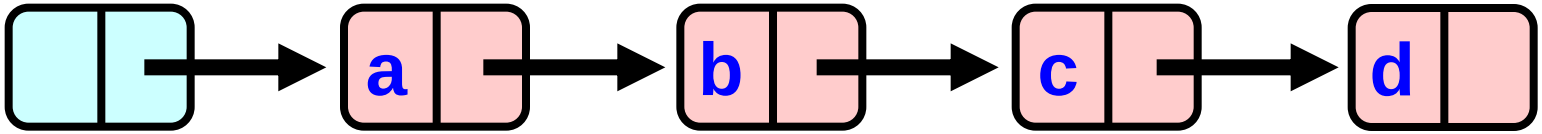
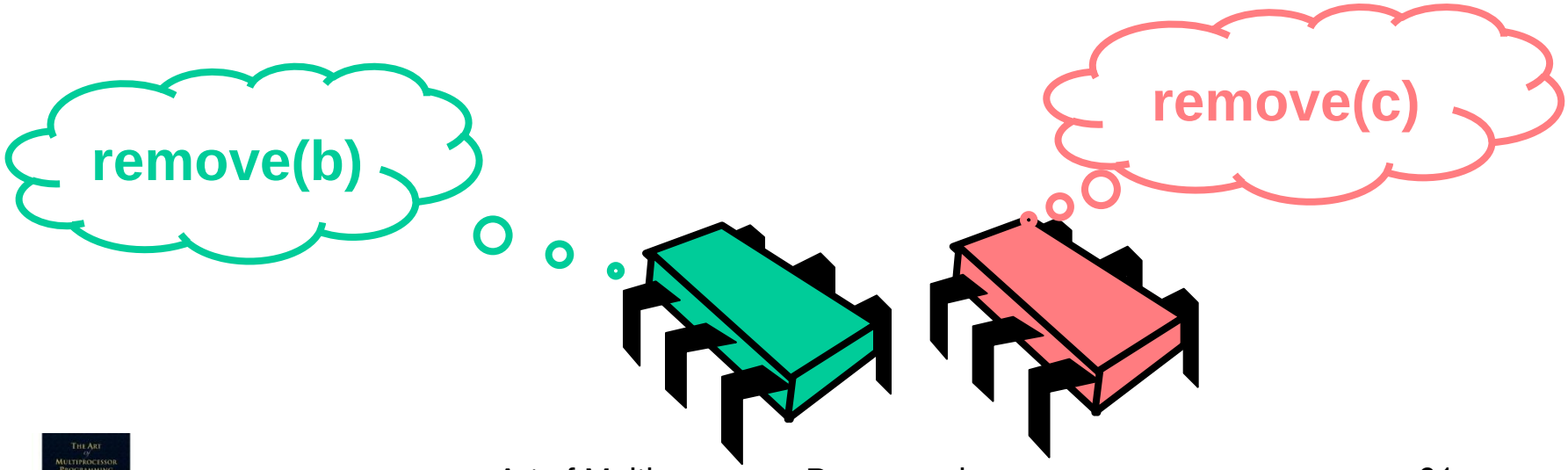
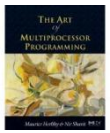




Concurrent Removes







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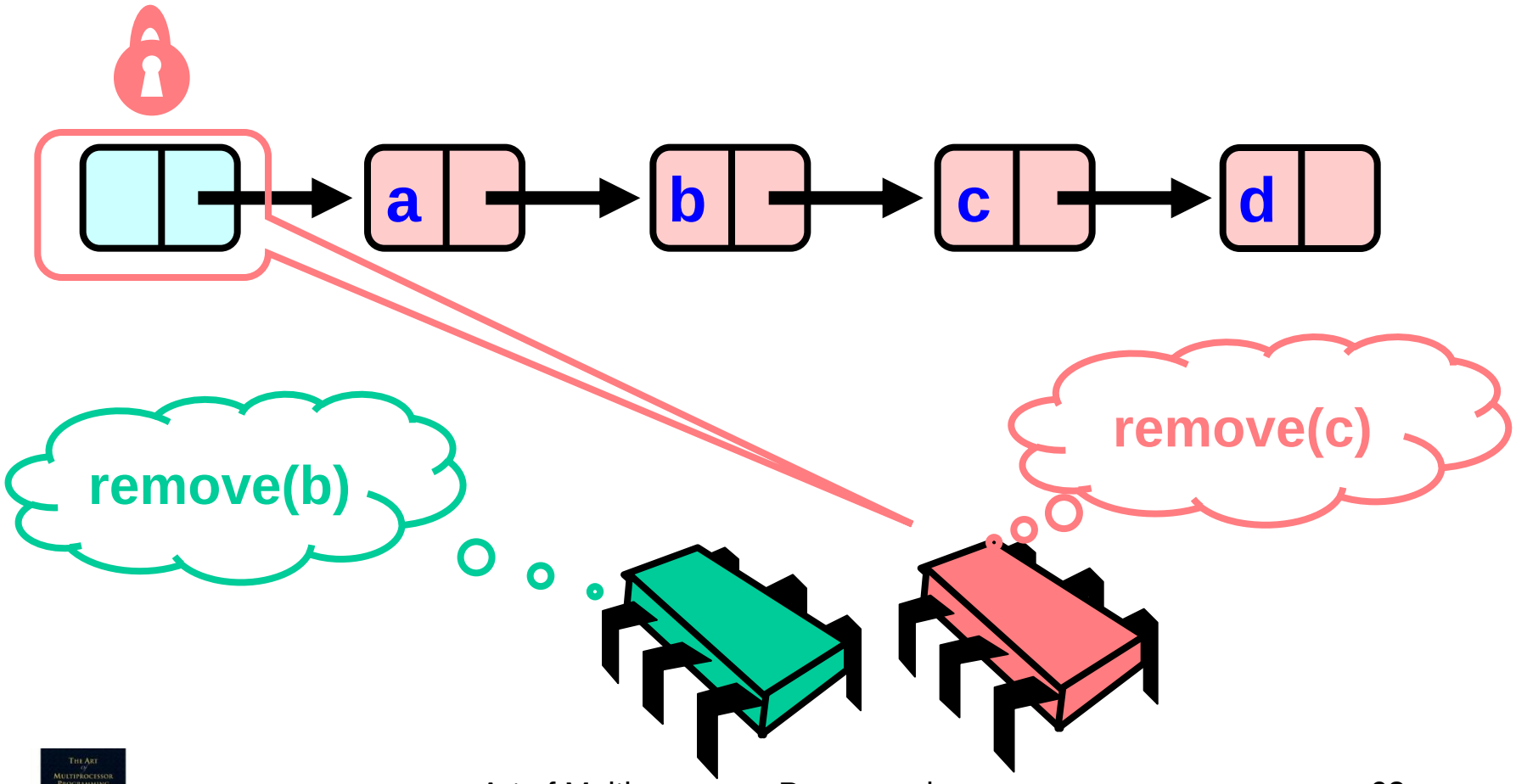

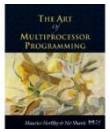

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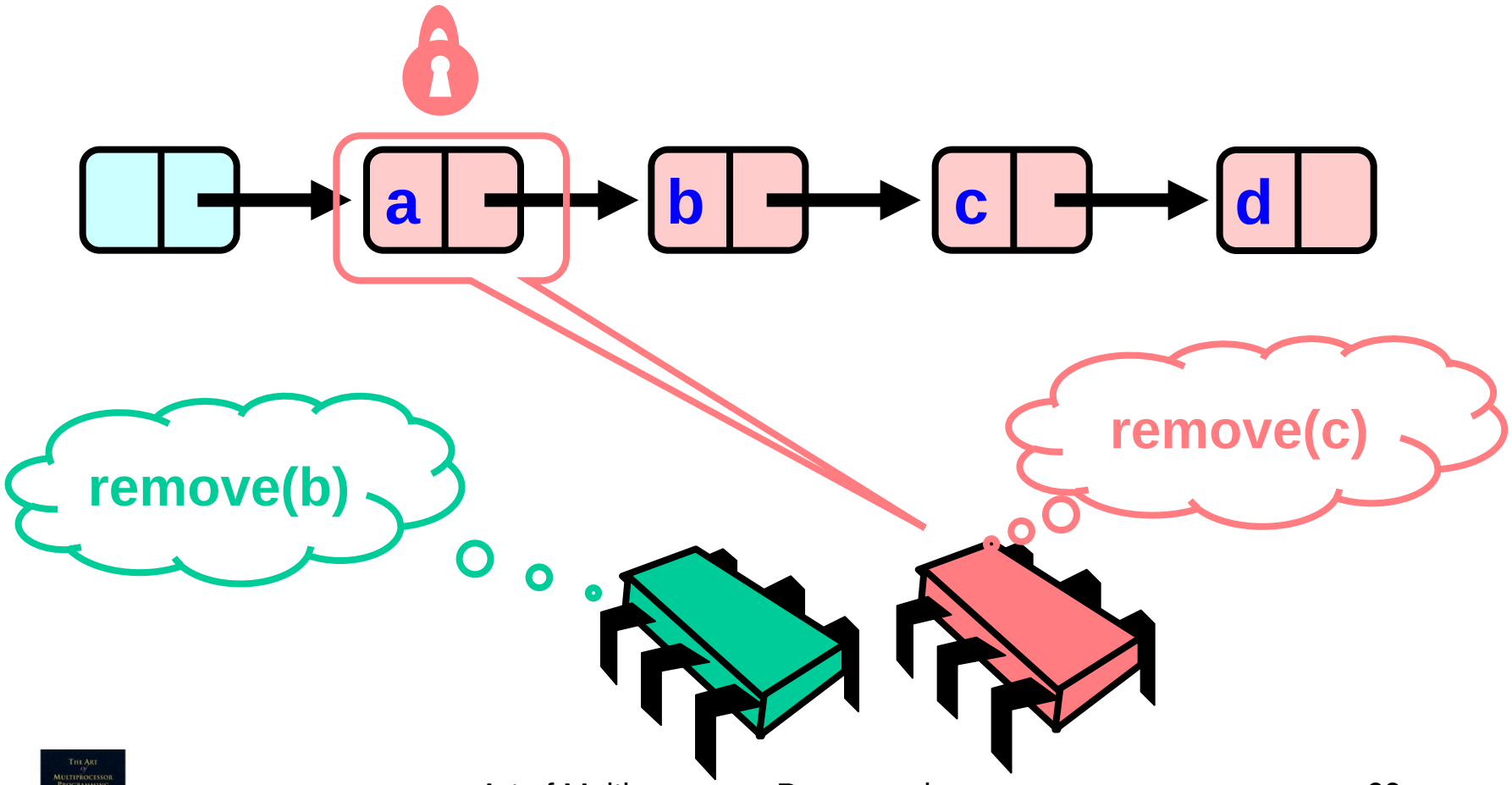

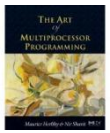

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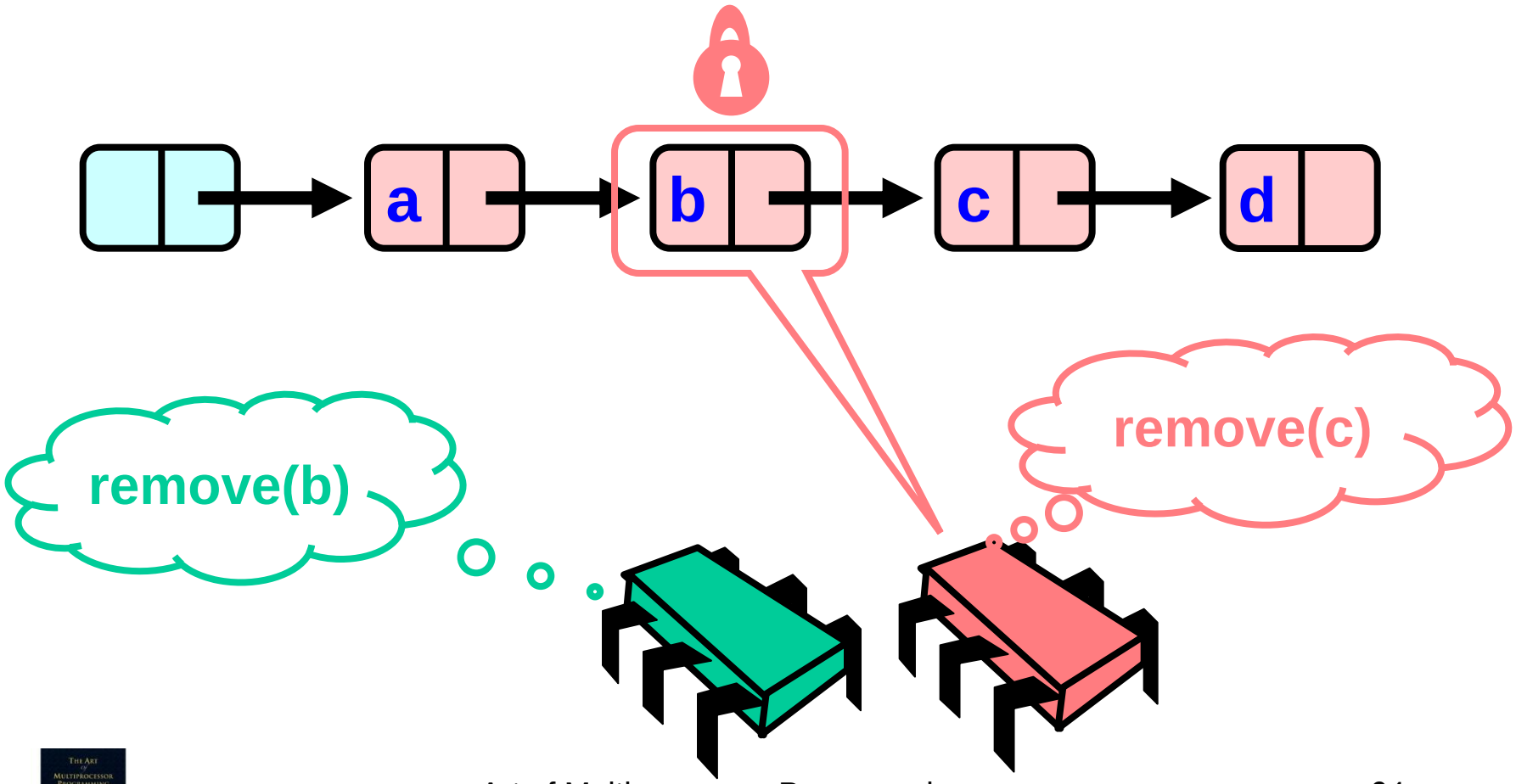

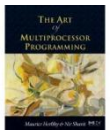

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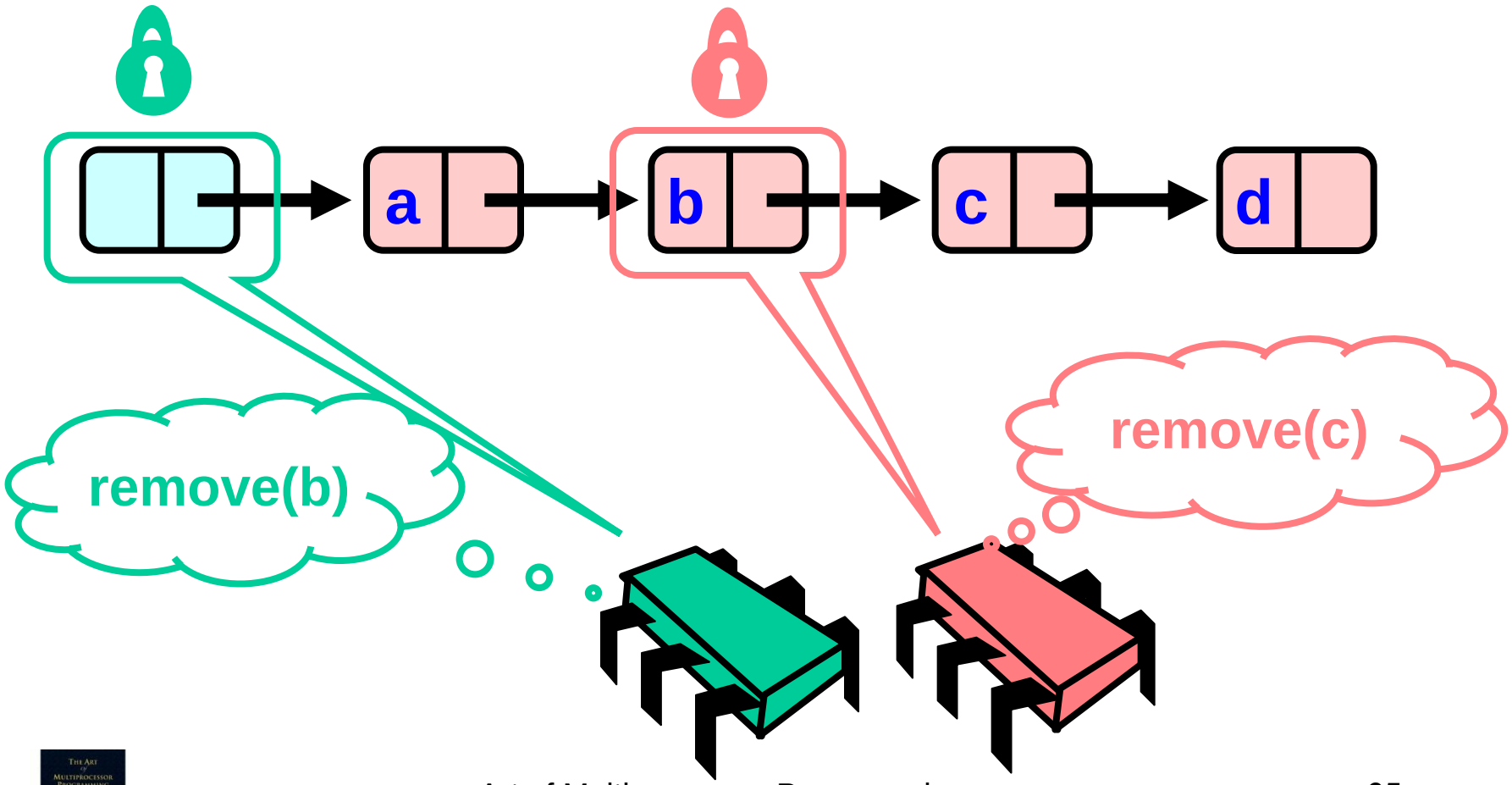

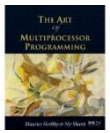

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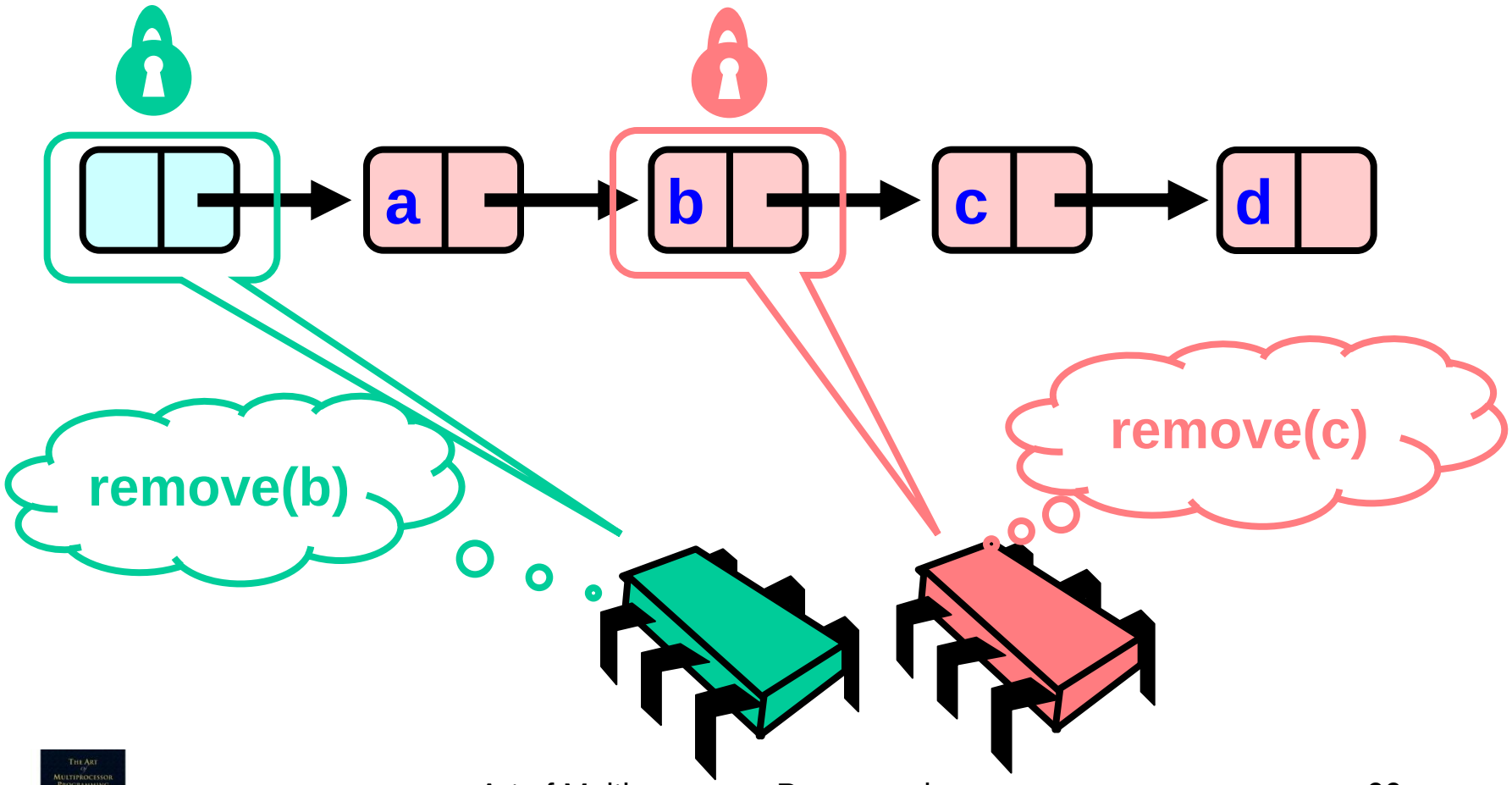
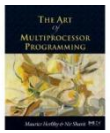
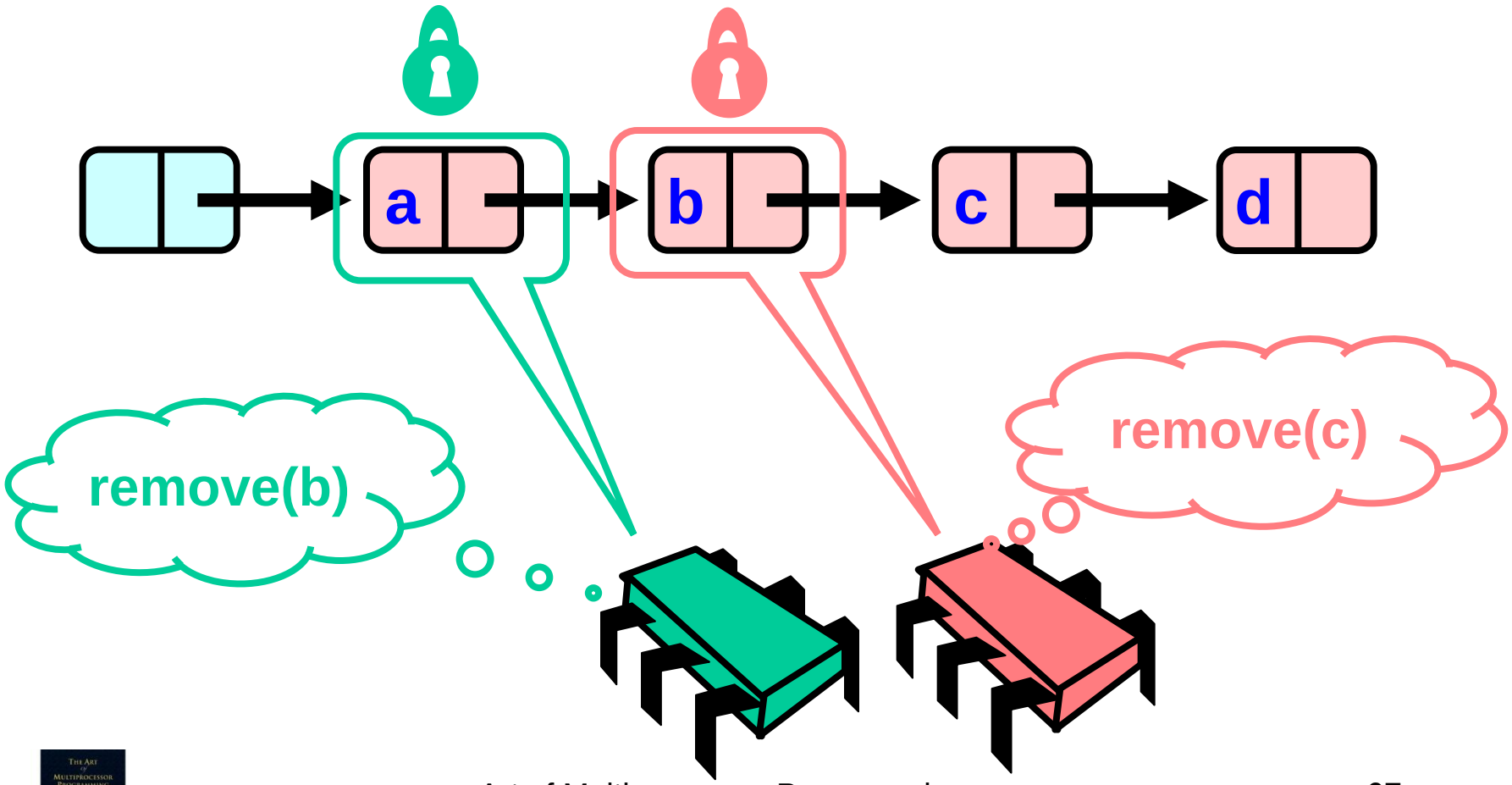
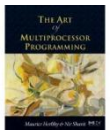


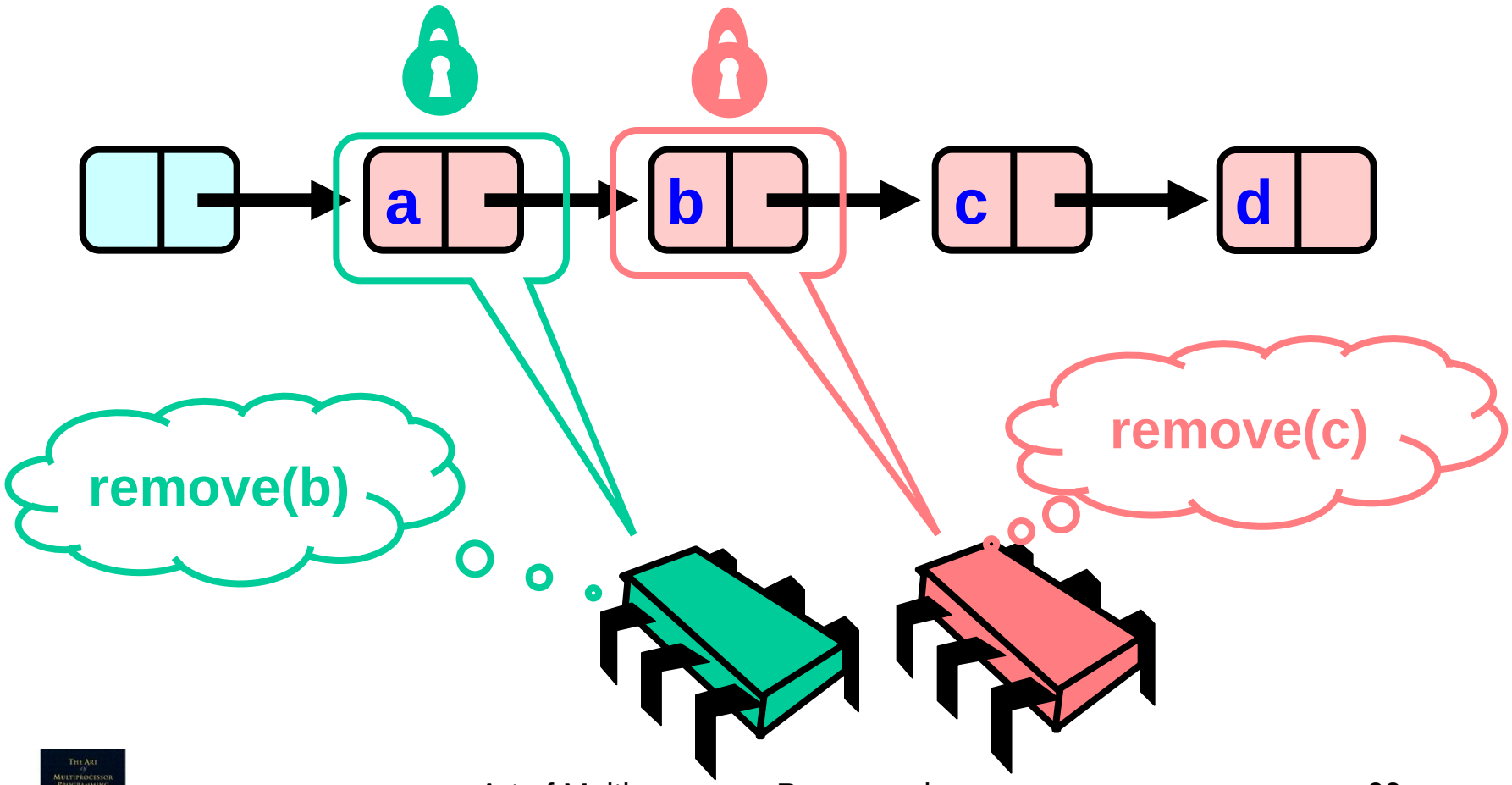


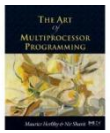
Concurrent Removes



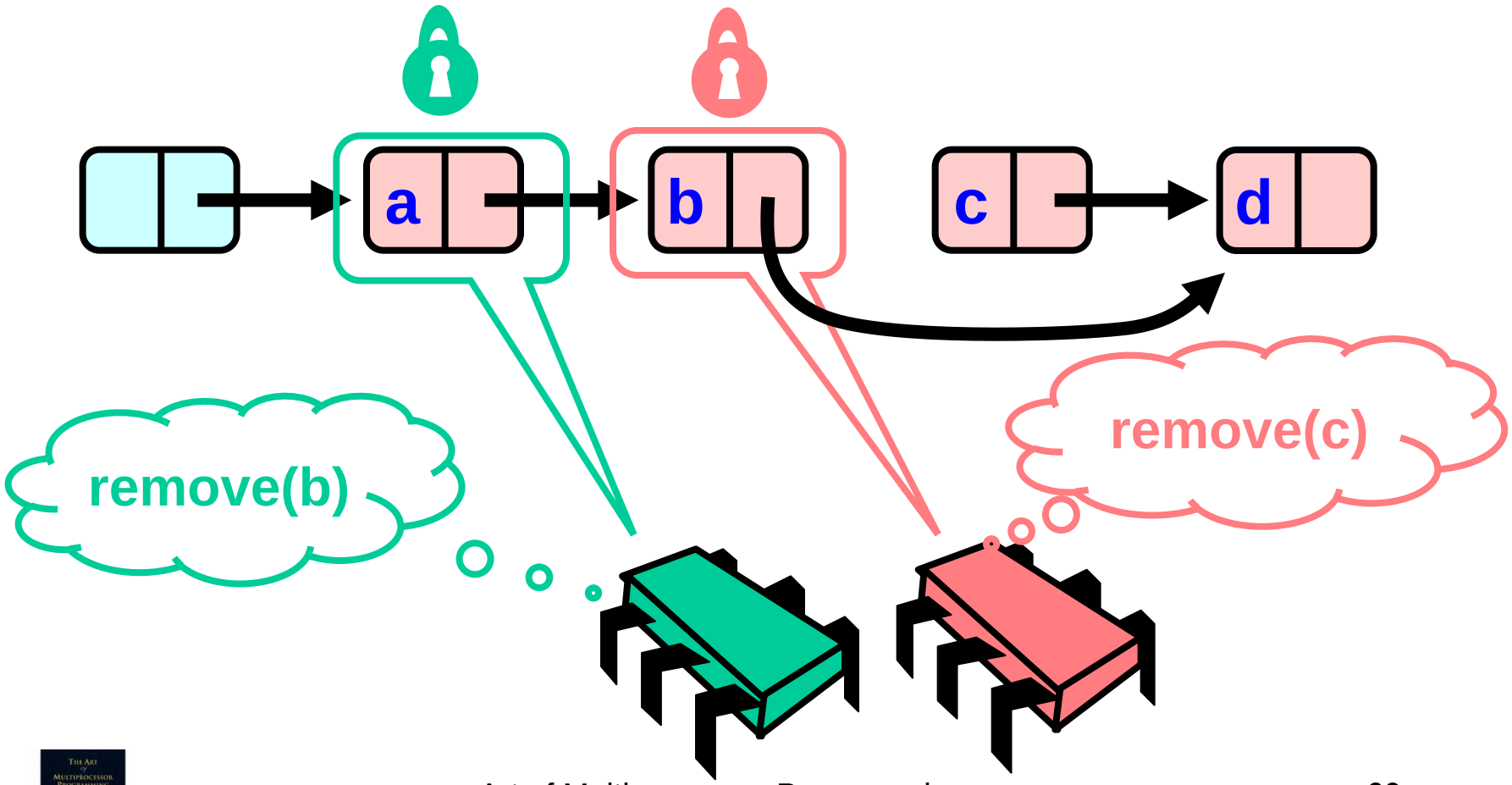


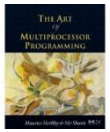
Concurrent Removes



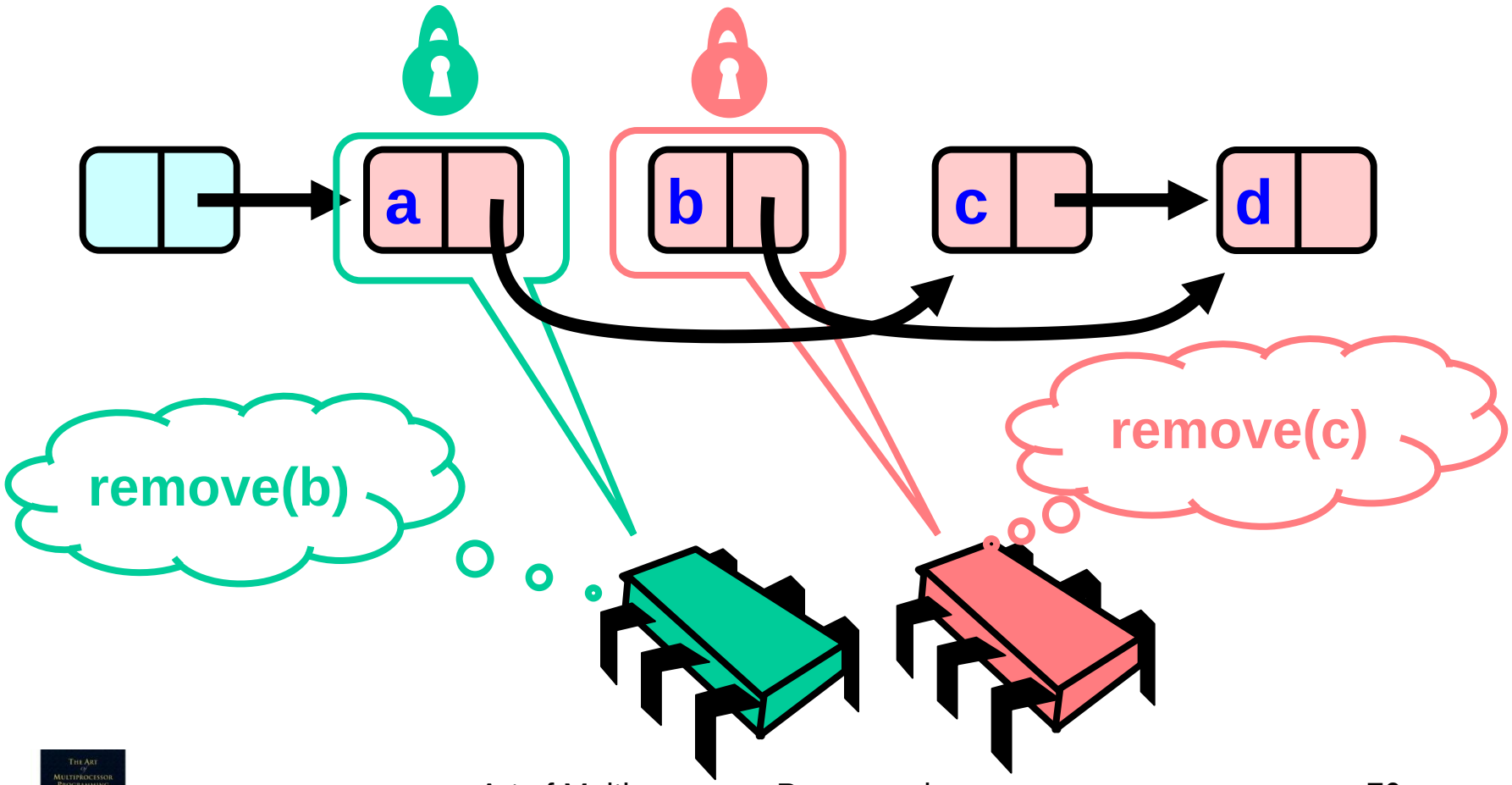


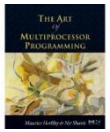
Concurrent Removes



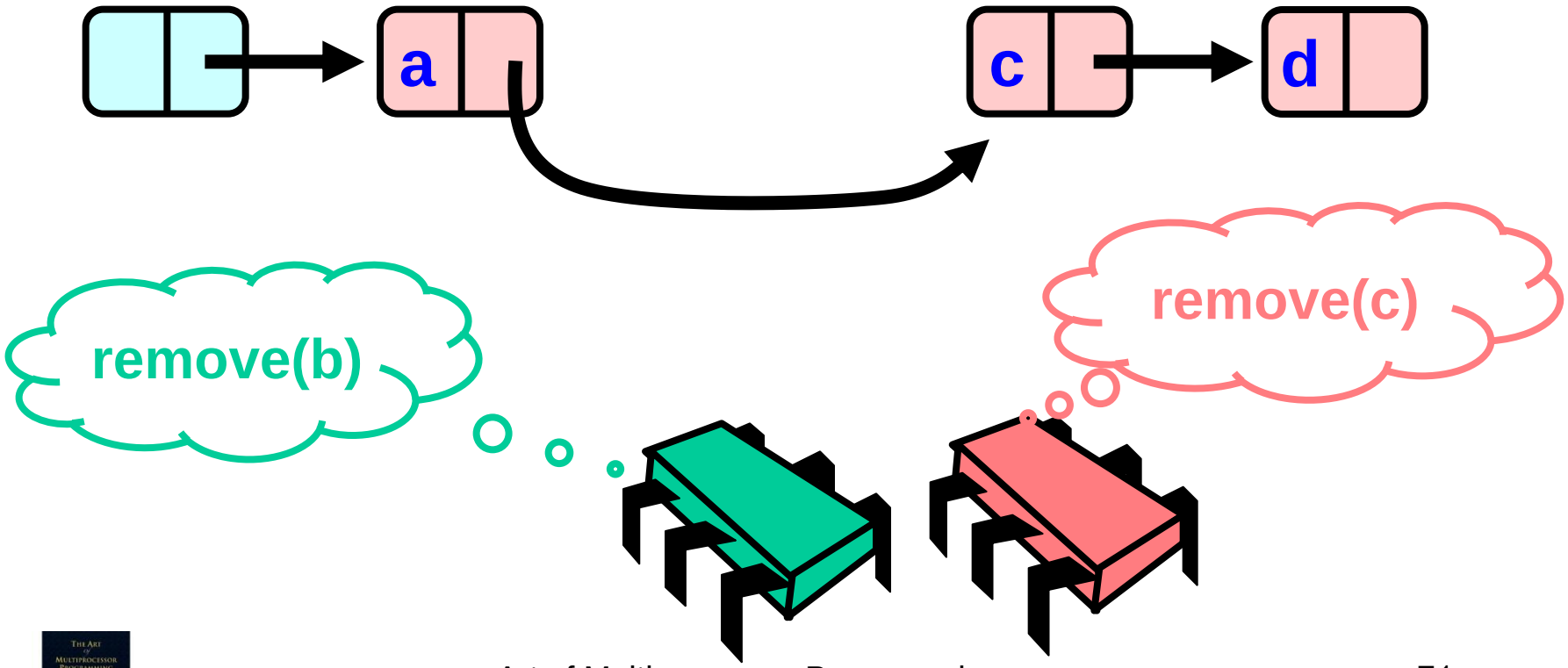


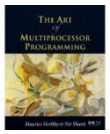
Concurrent Removes





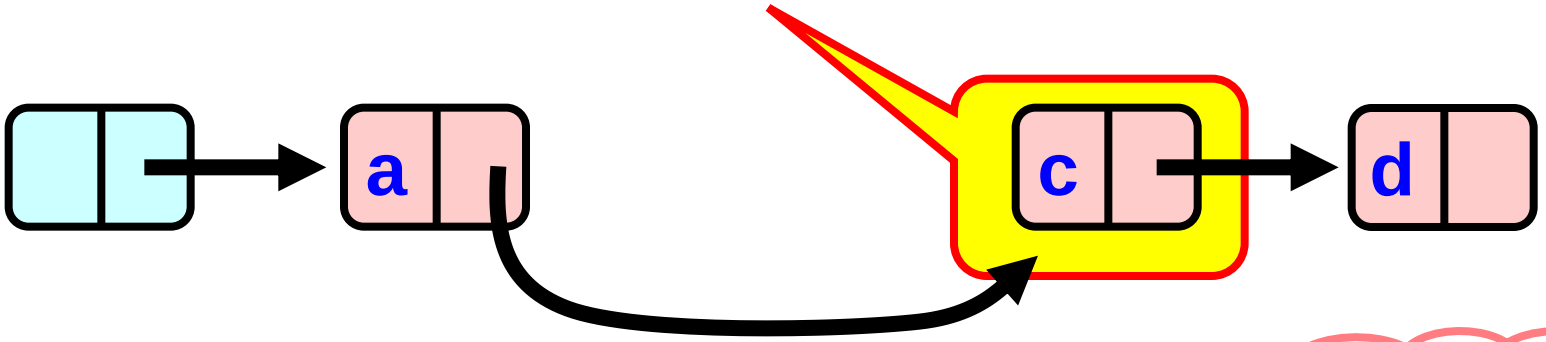
Uh, Oh

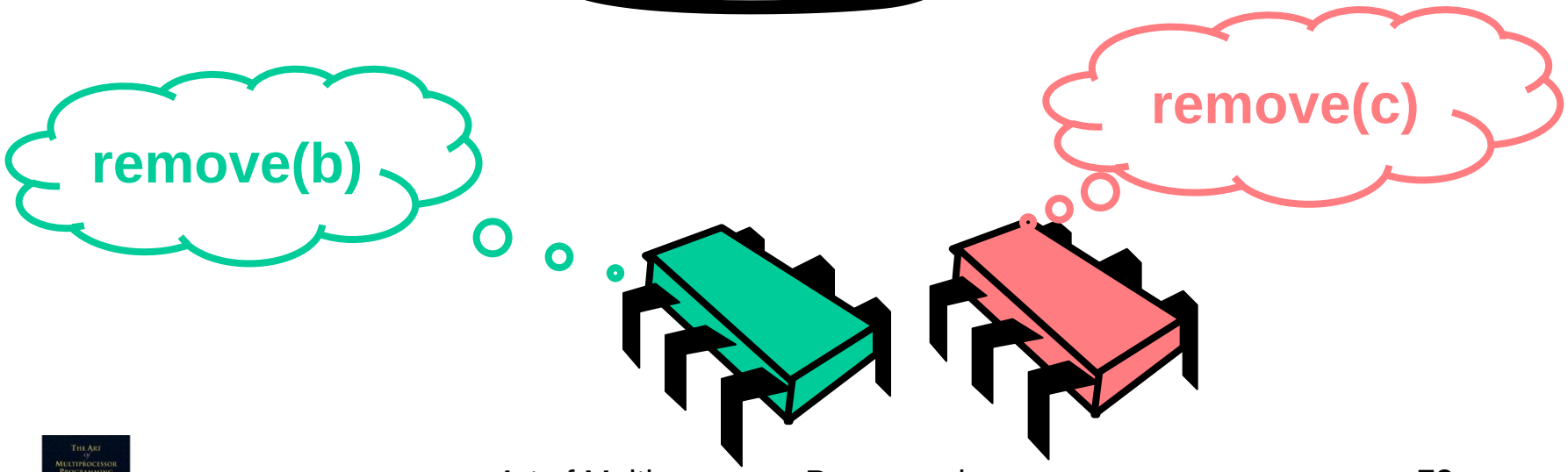


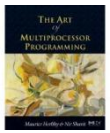


Uh, Oh

Bad news, c not removed

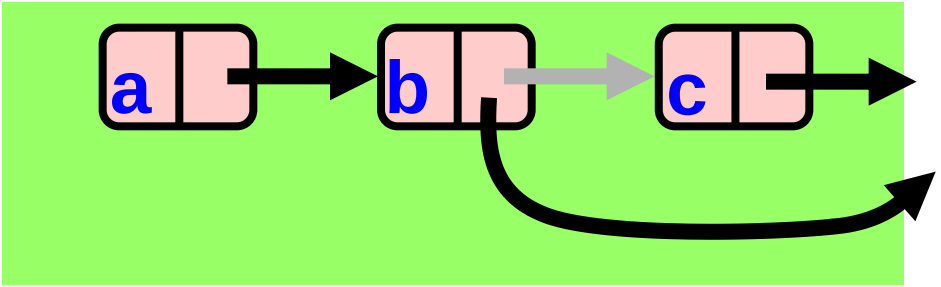




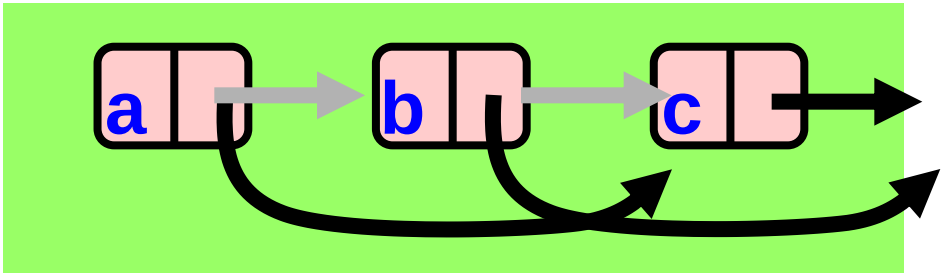


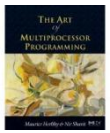
Problem

- To delete node c
  - Swing node b's next field to d



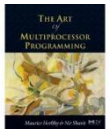
- Problem is,
  - Someone deleting b concurrently could direct a pointer to c



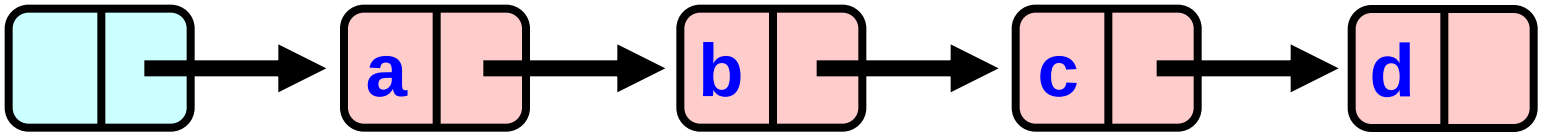


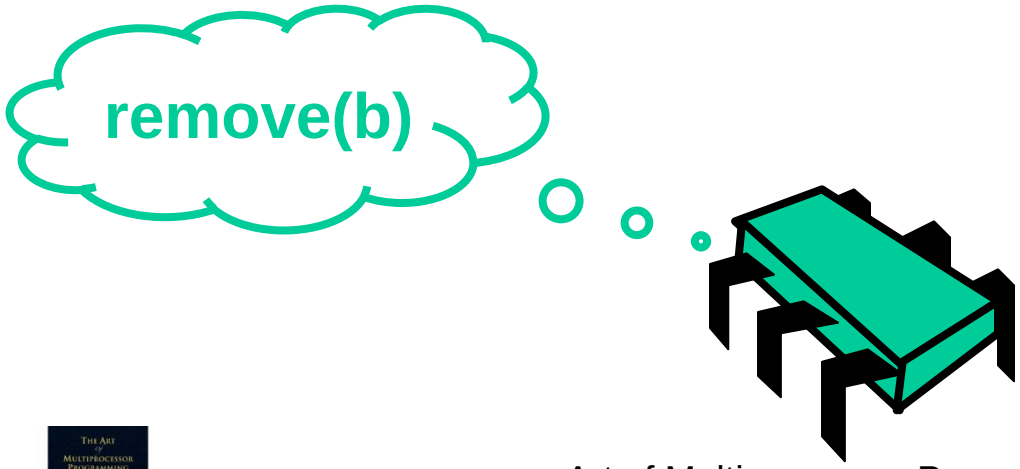
Insight

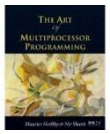
- If a node is locked
  - No one can delete node's *successor*
- If a thread locks
  - Node to be deleted
  - And its predecessor
  - Then it works



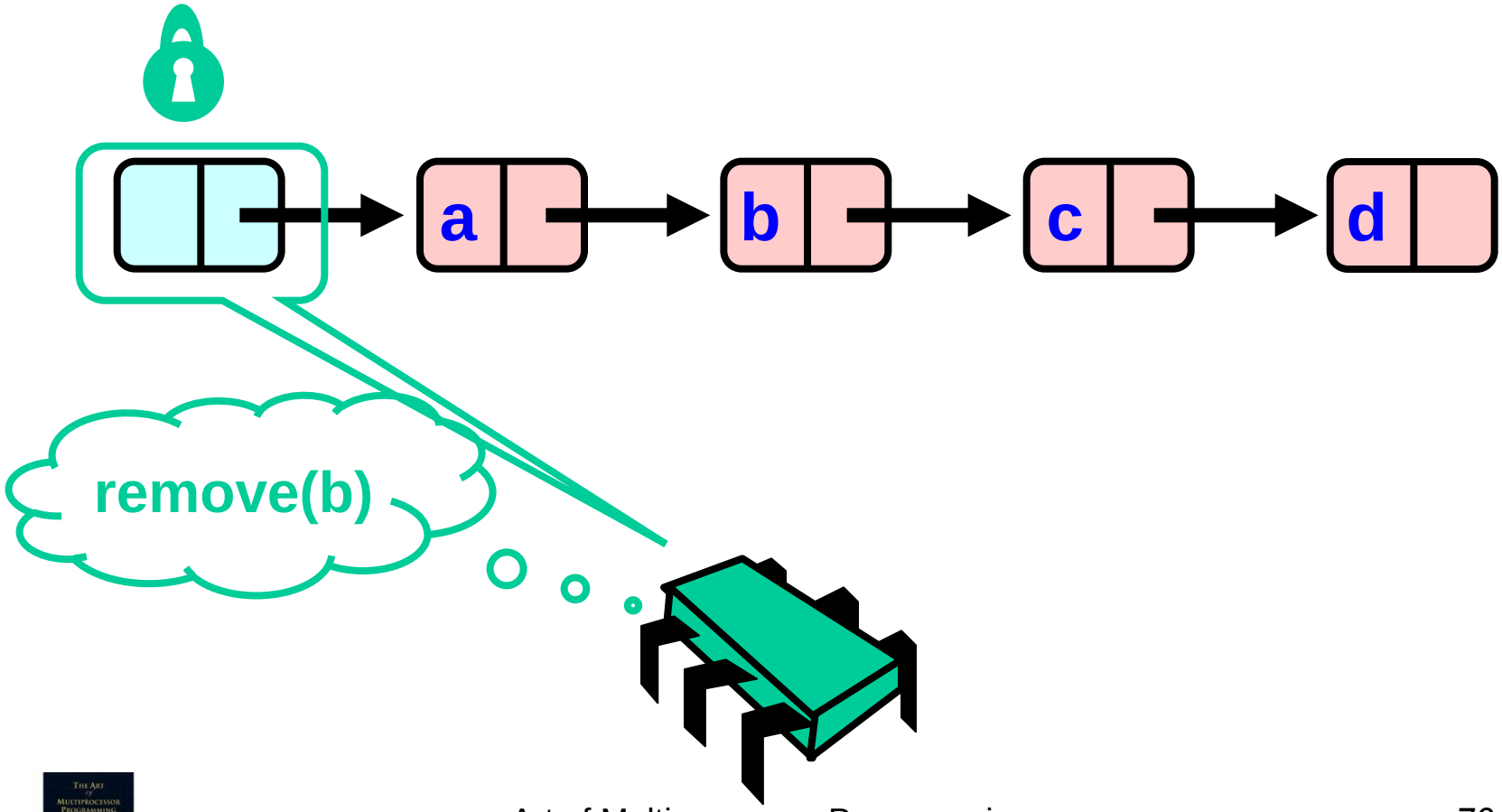
Hand-Over-Hand Again

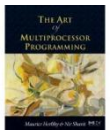




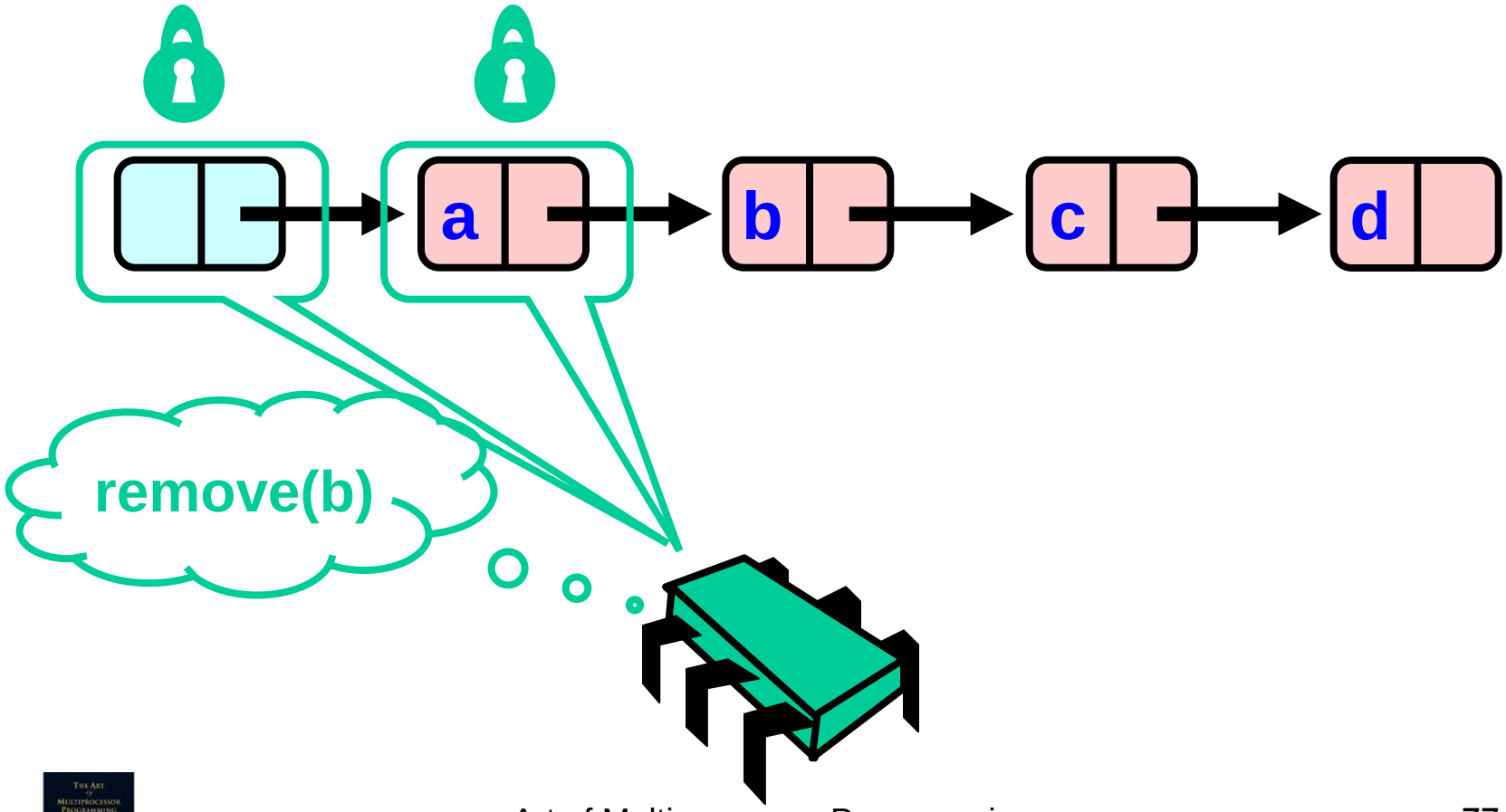


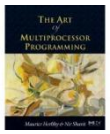
Hand-Over-Hand Again



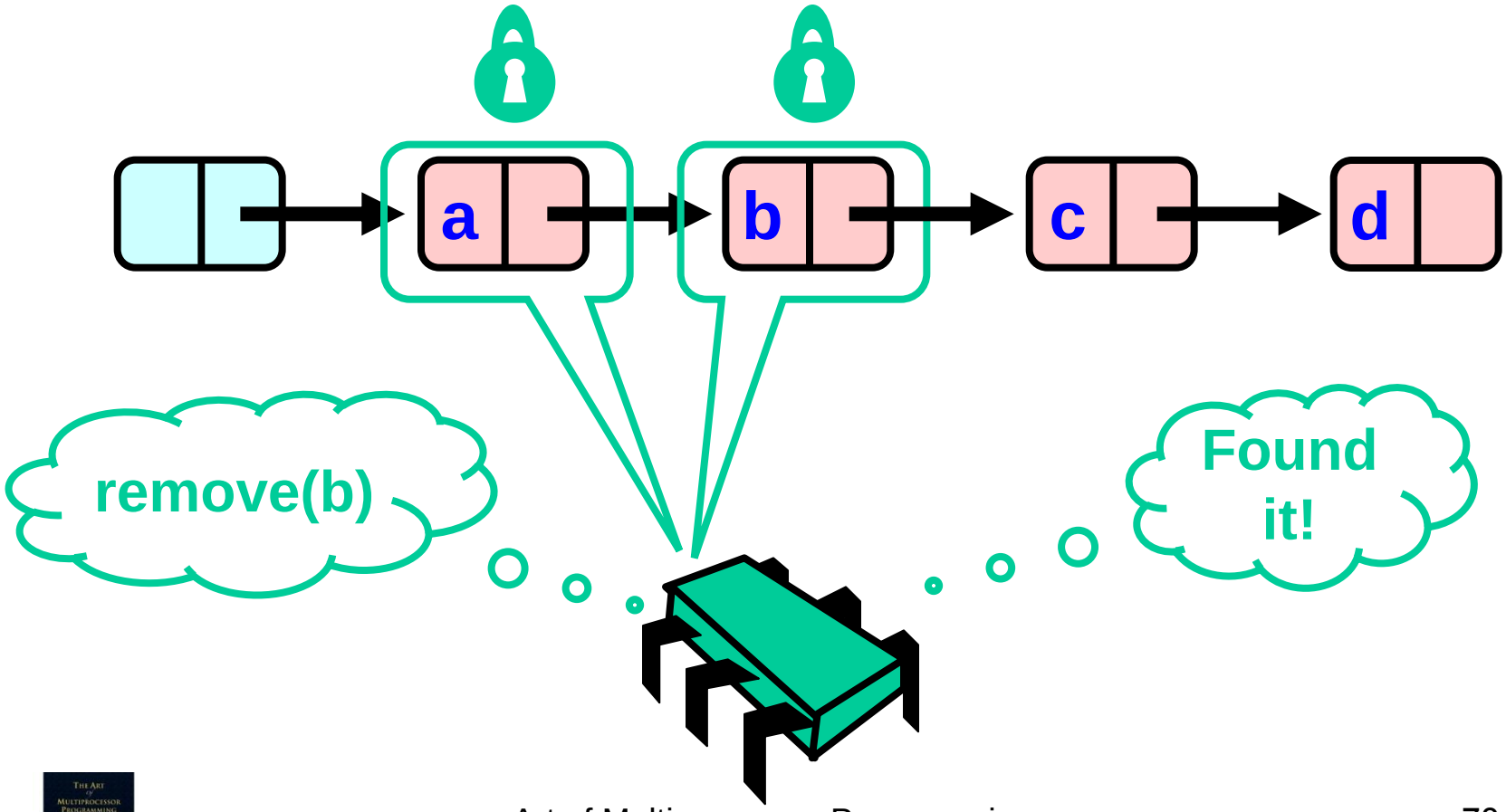


Hand-Over-Hand Again

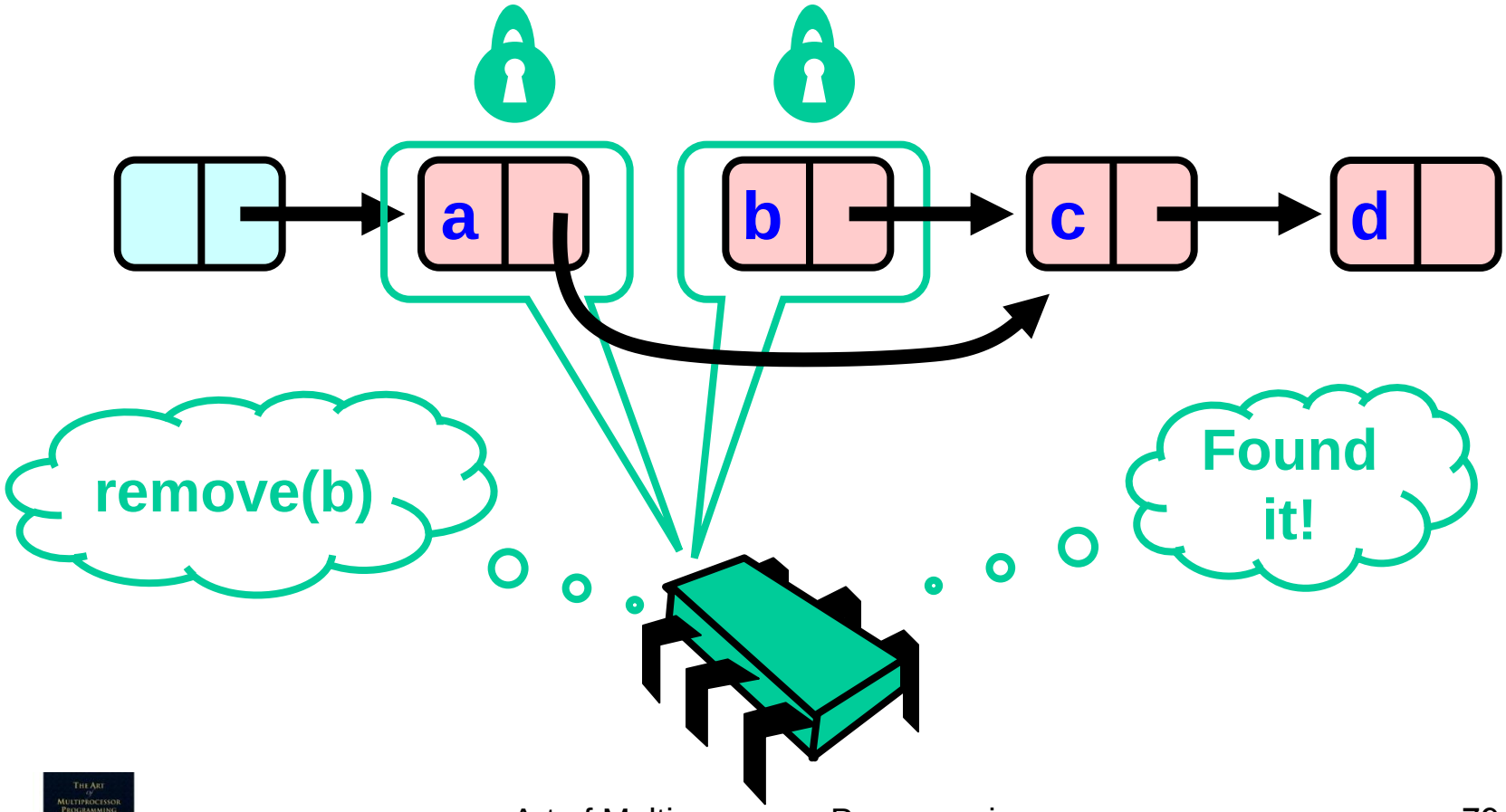




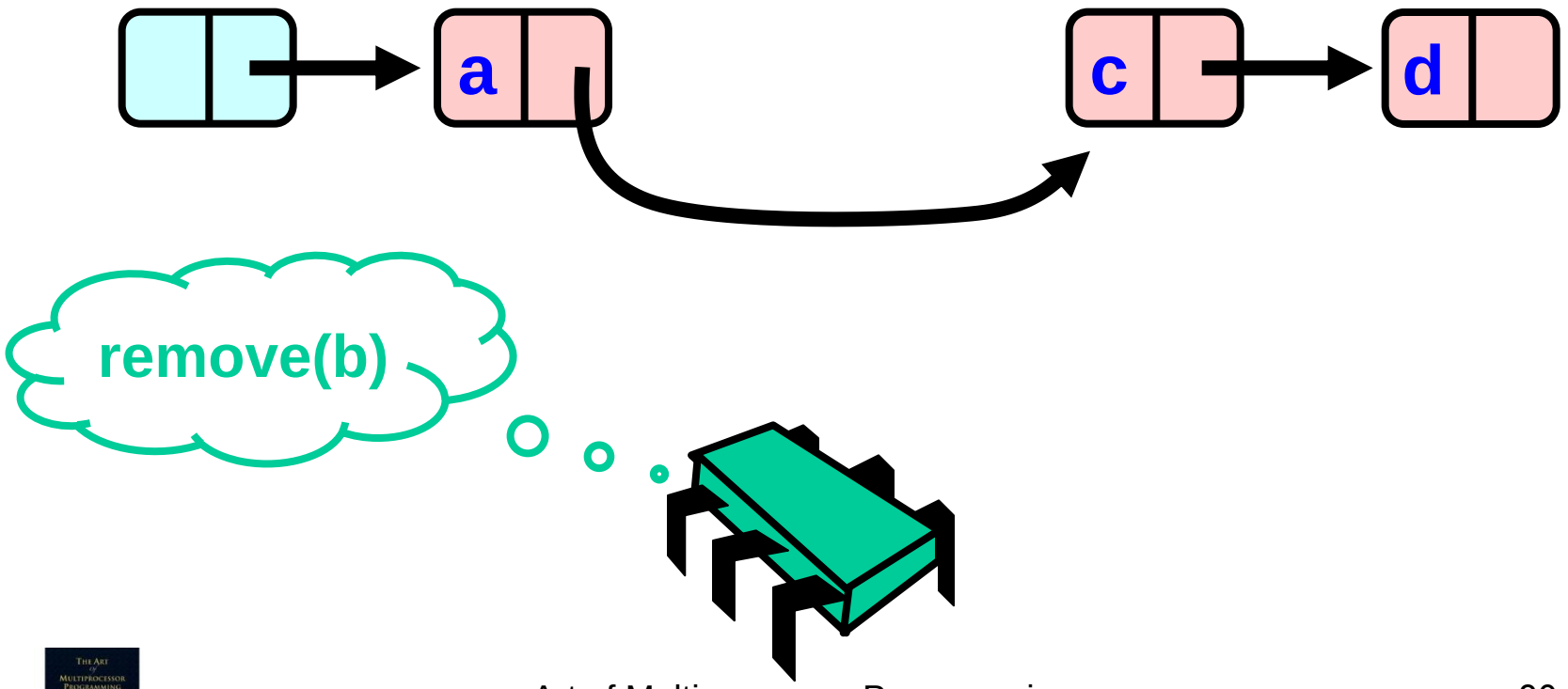
Hand-Over-Hand Again

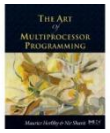


Hand-Over-Hand Again

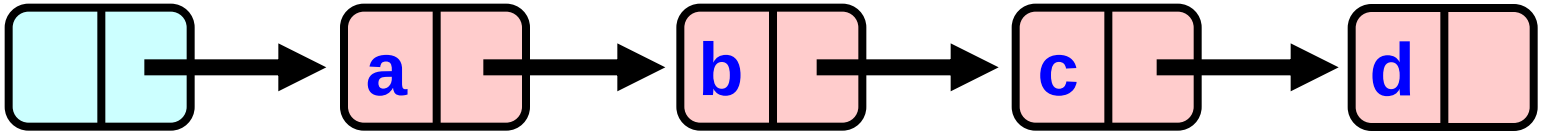


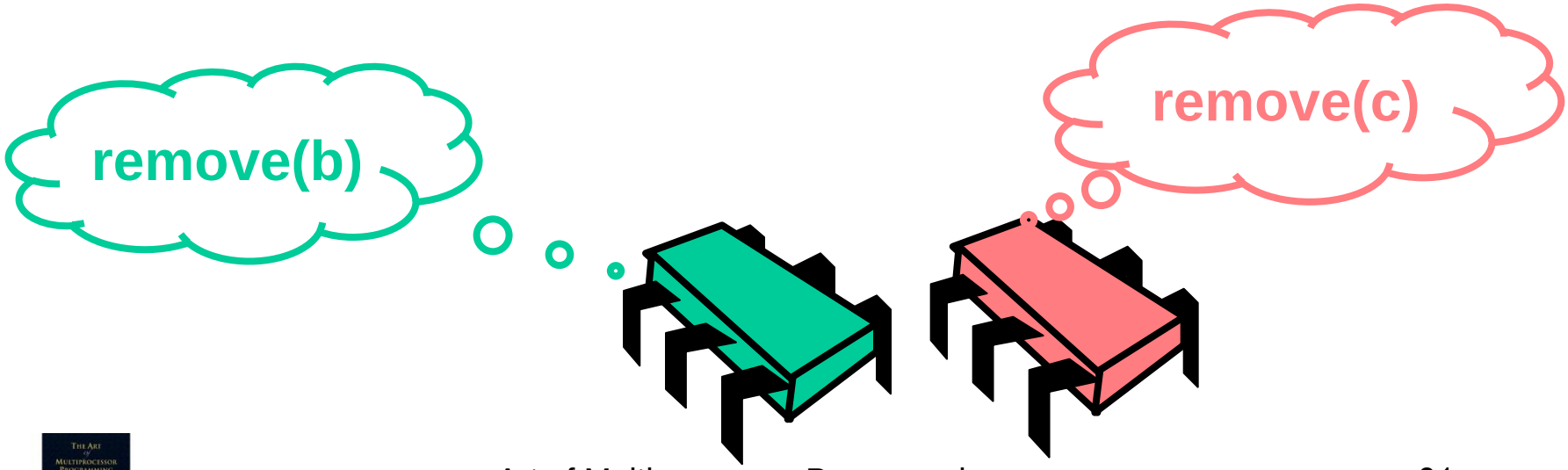
Hand-Over-Hand Again

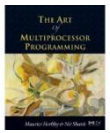




Removing a Node







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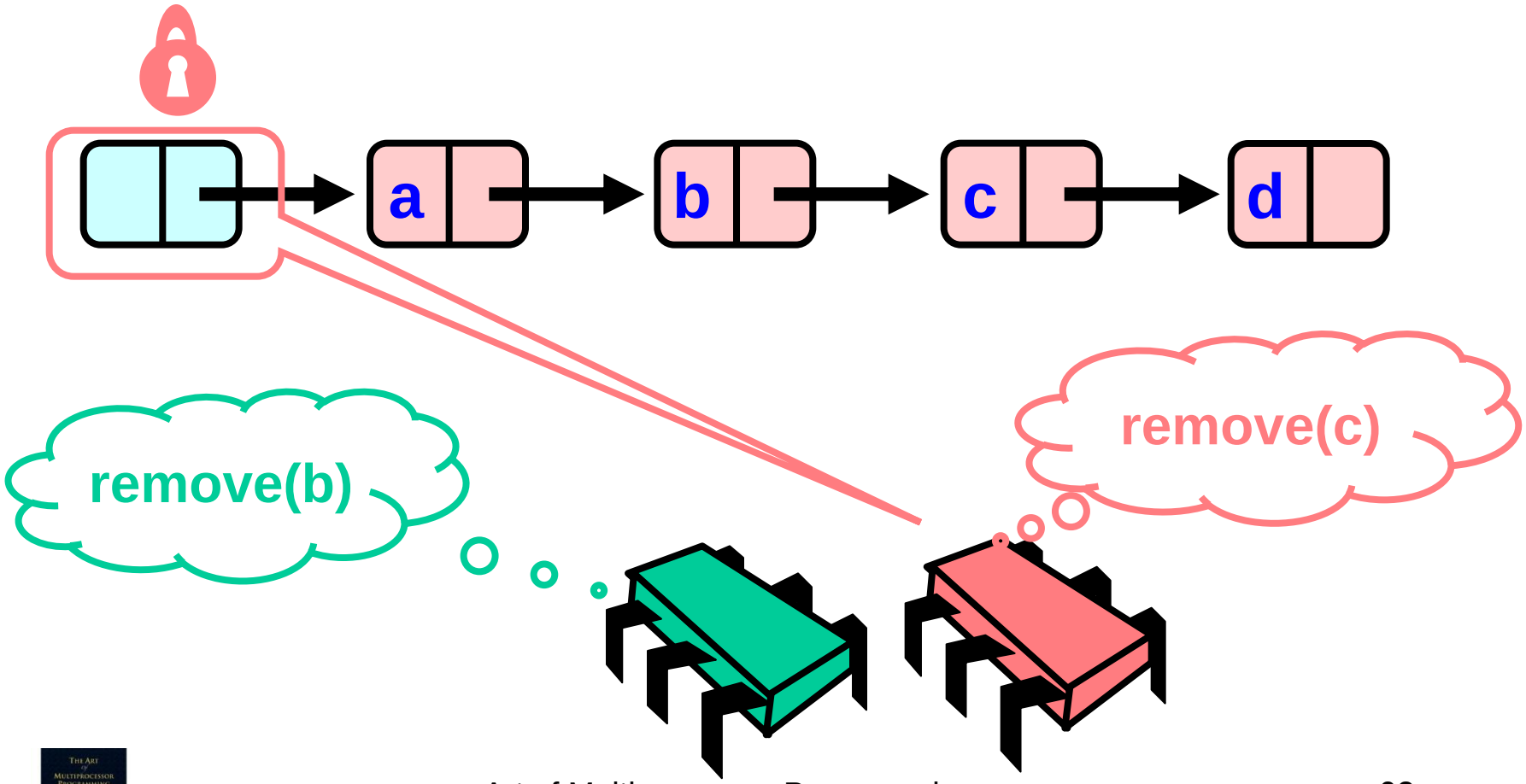

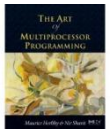

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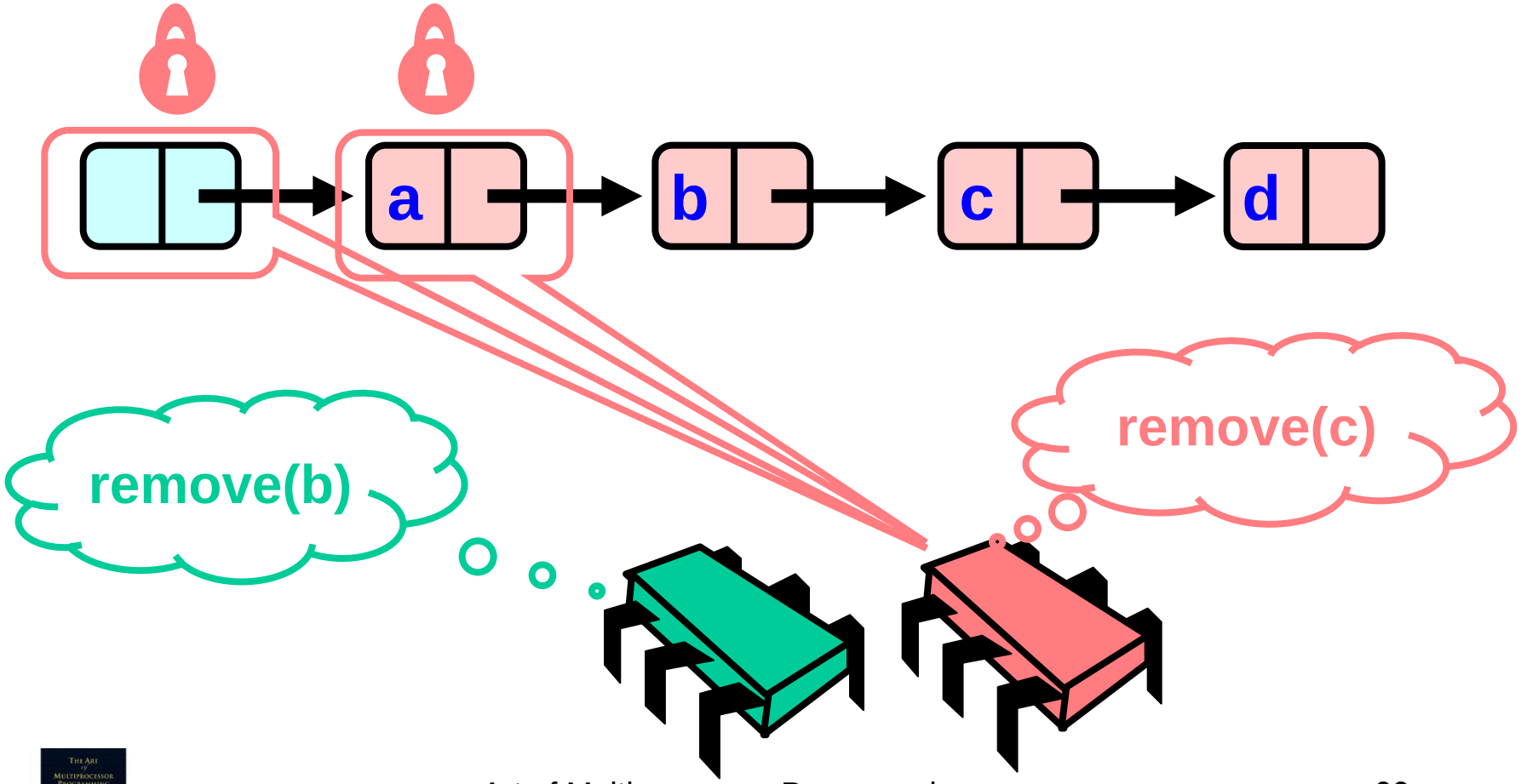

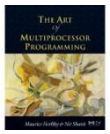

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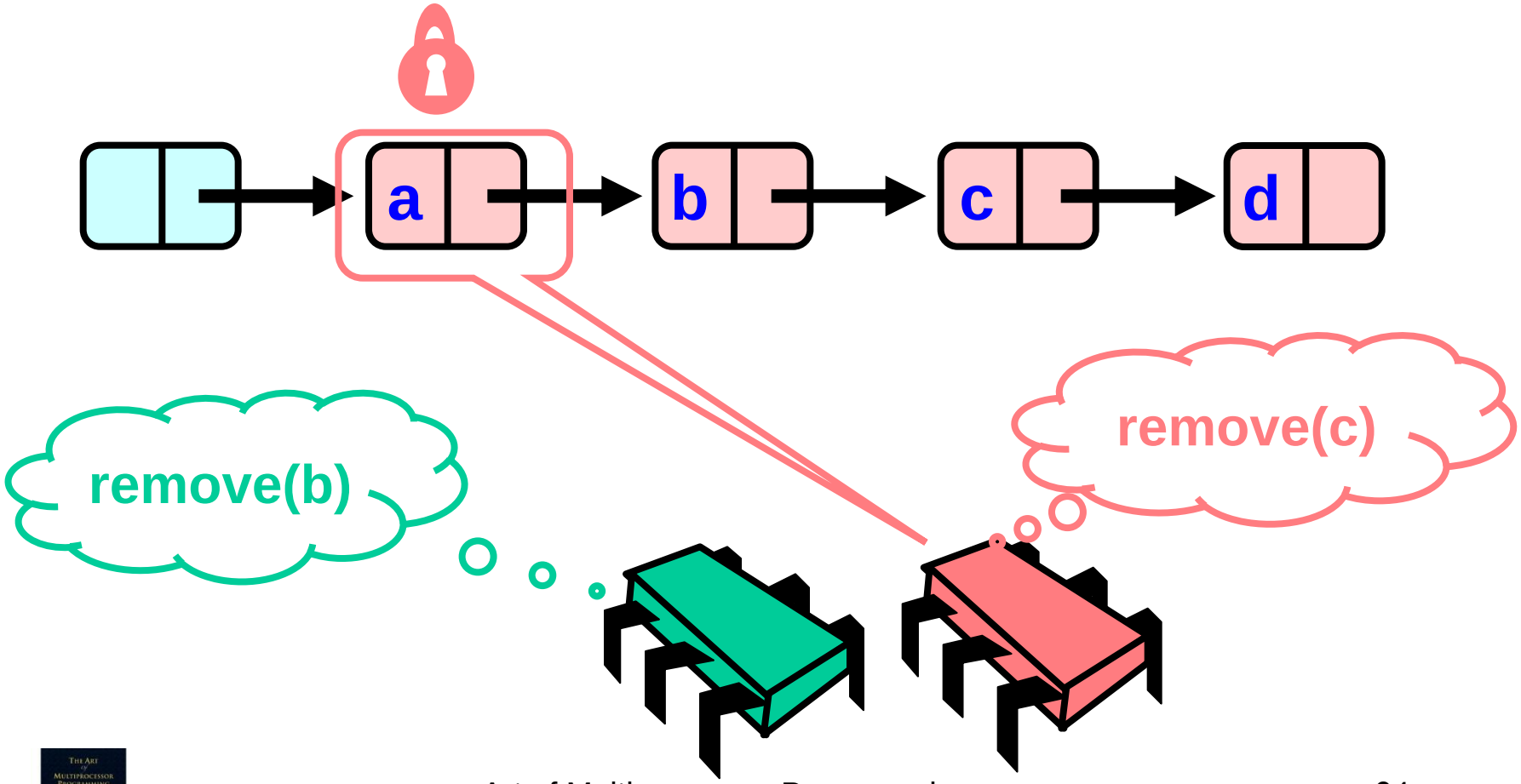

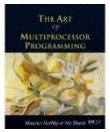

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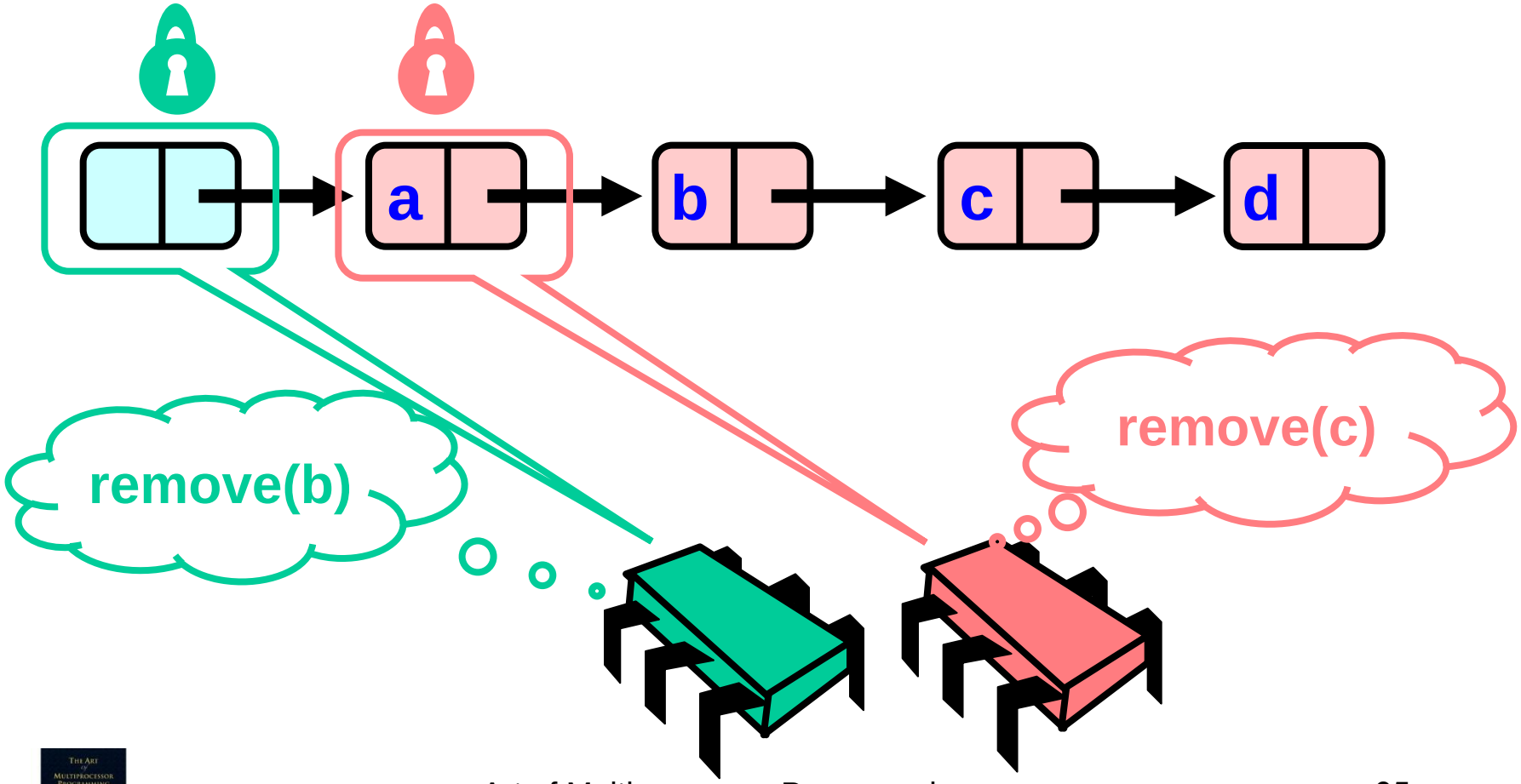

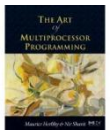

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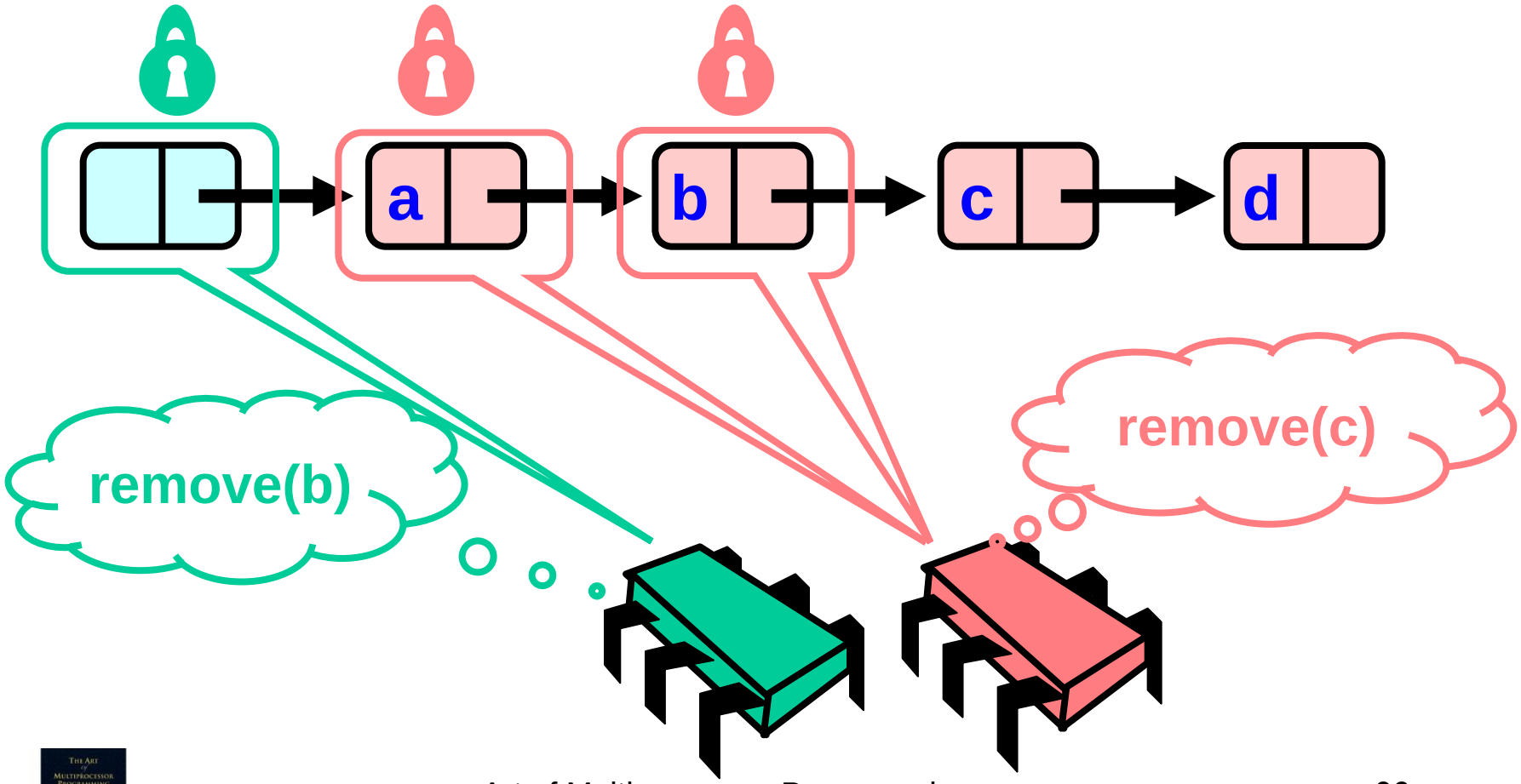

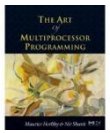

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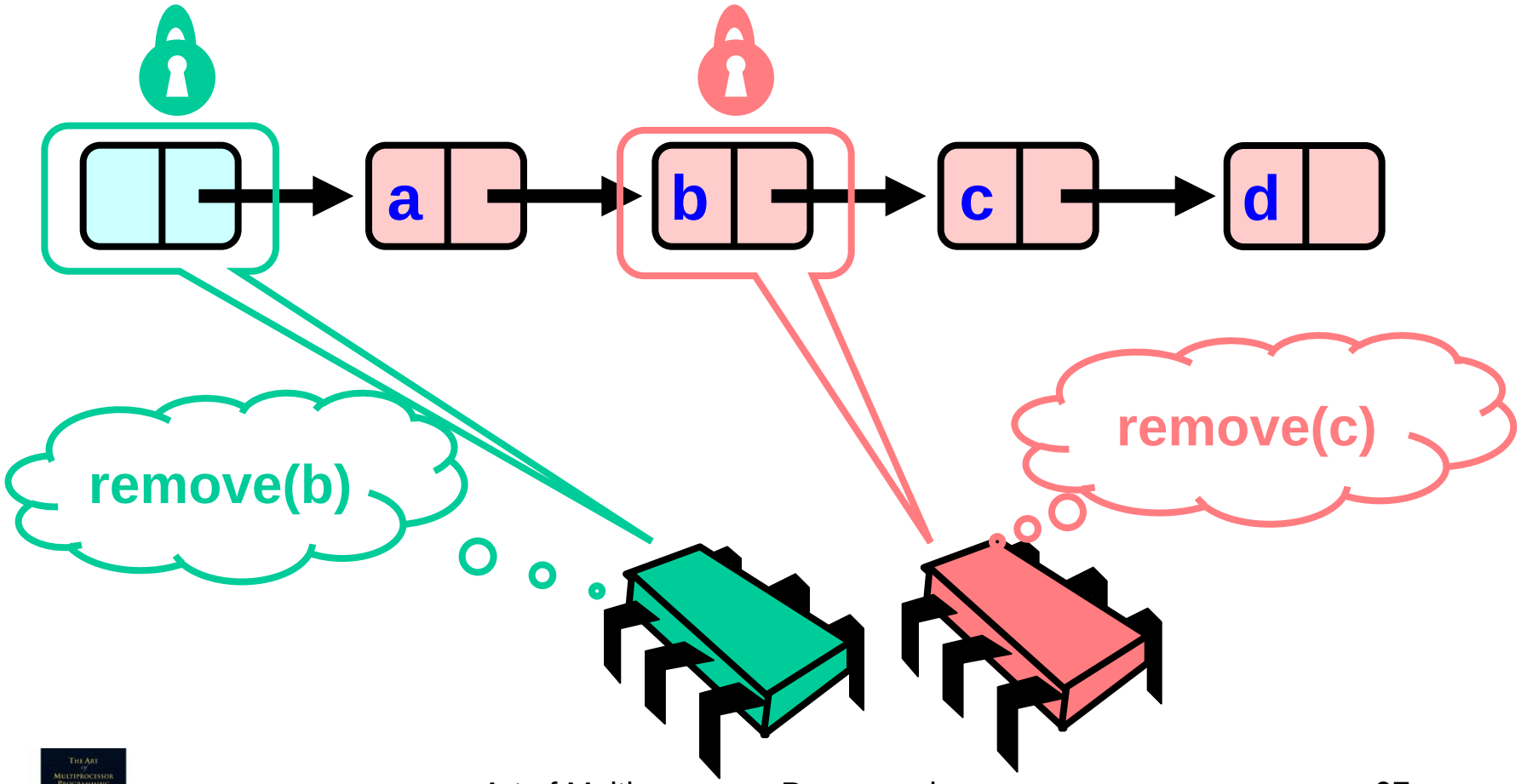

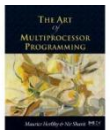

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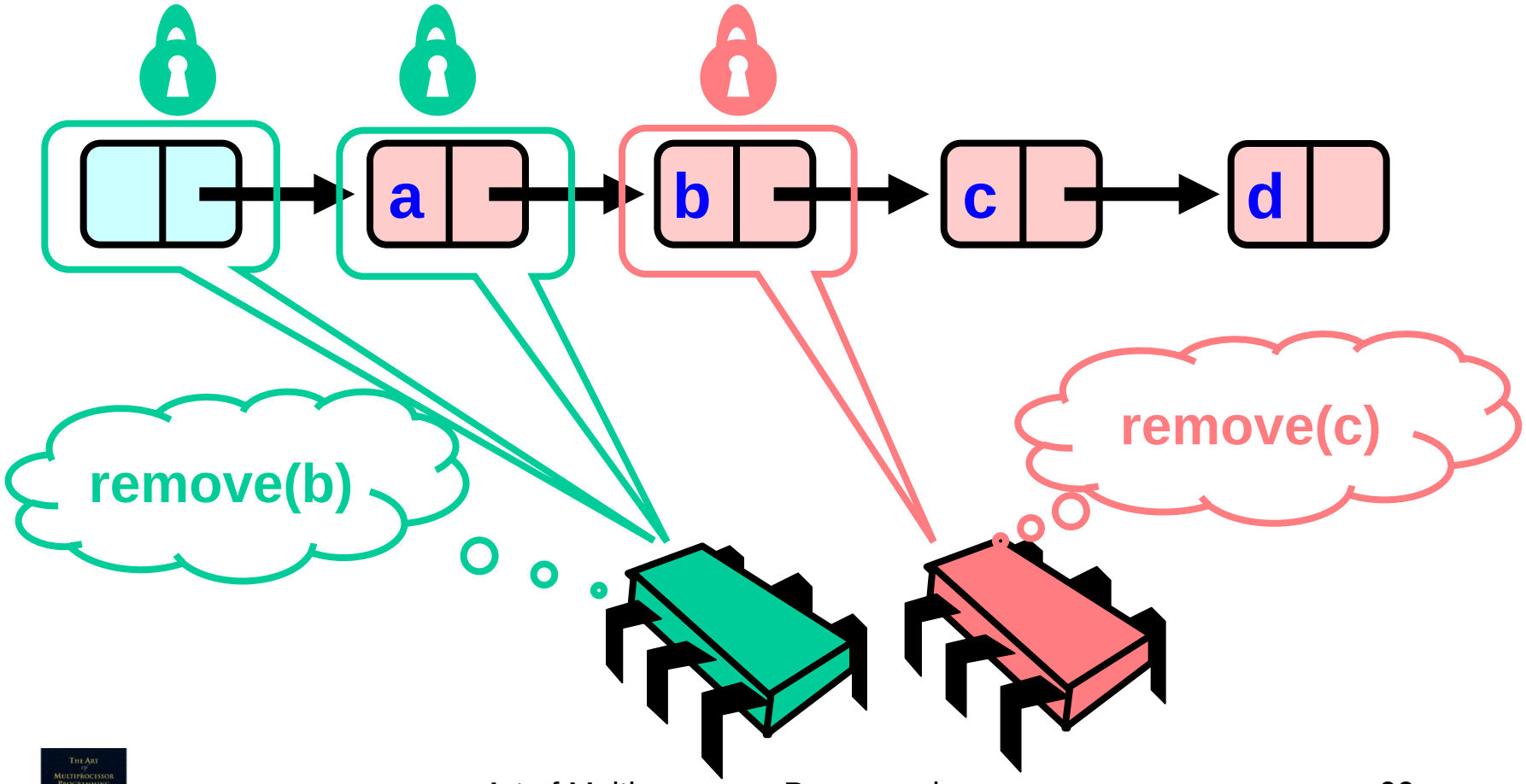

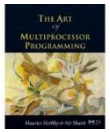

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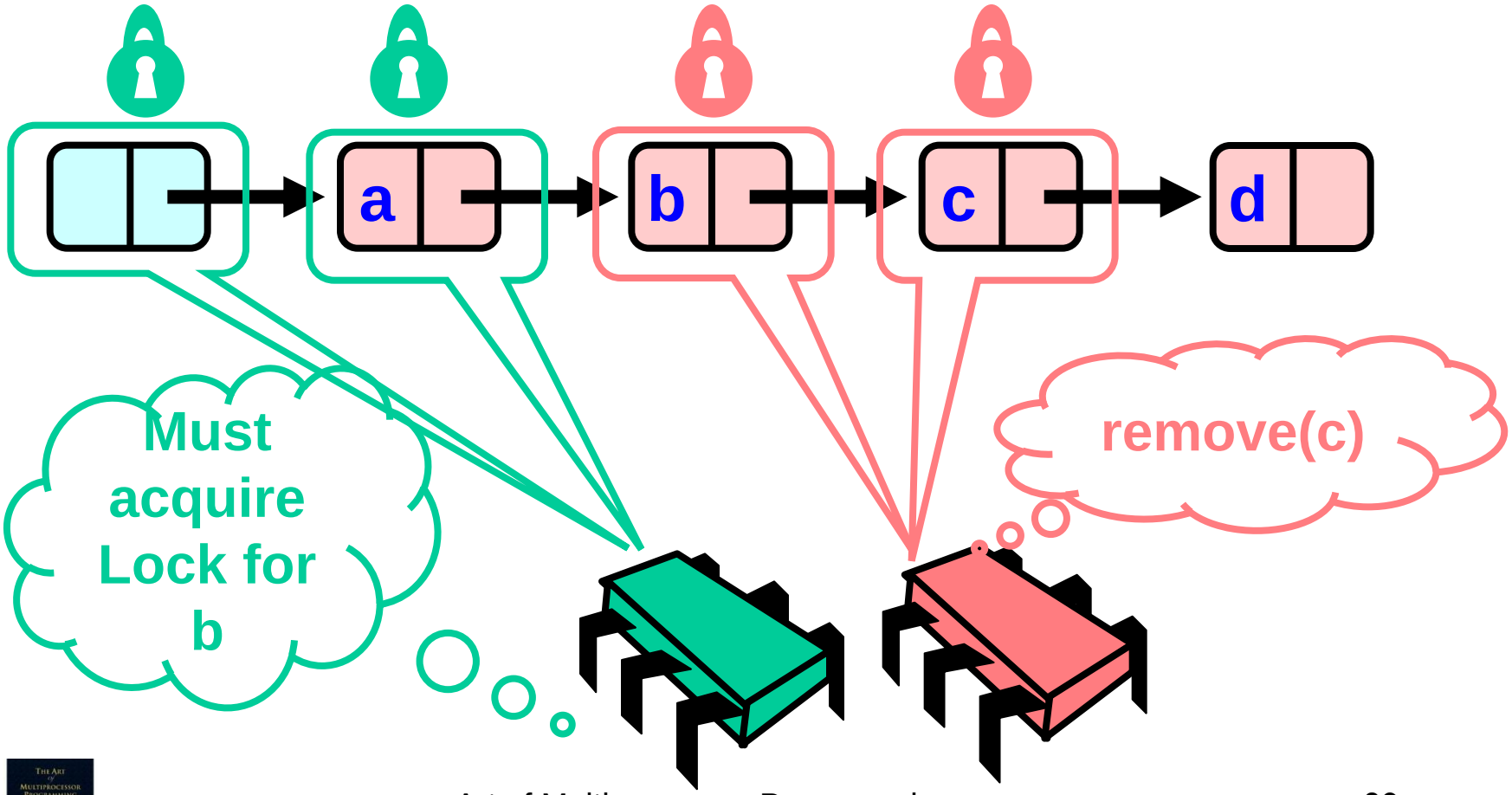

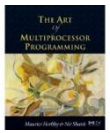

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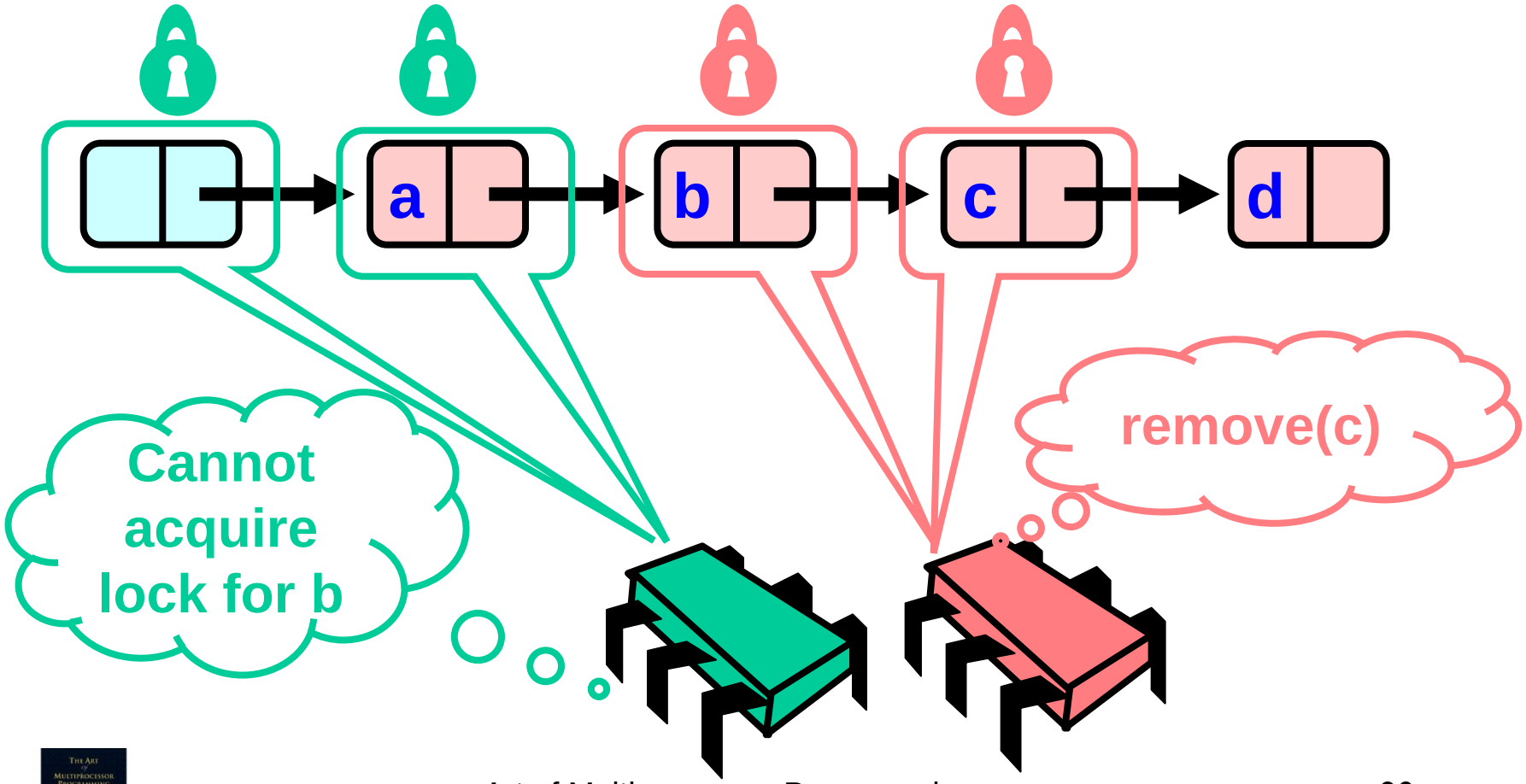

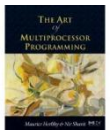

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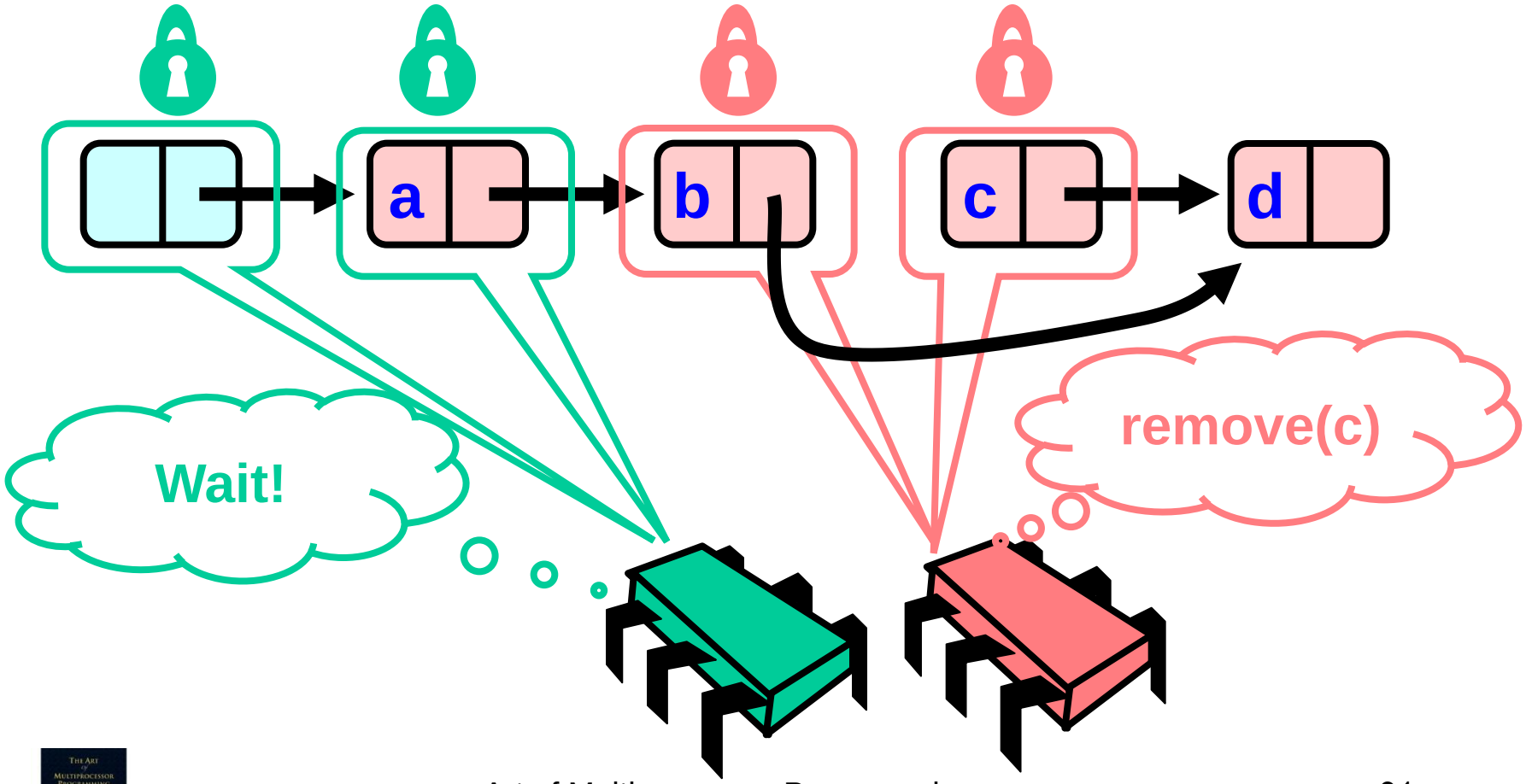

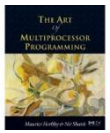

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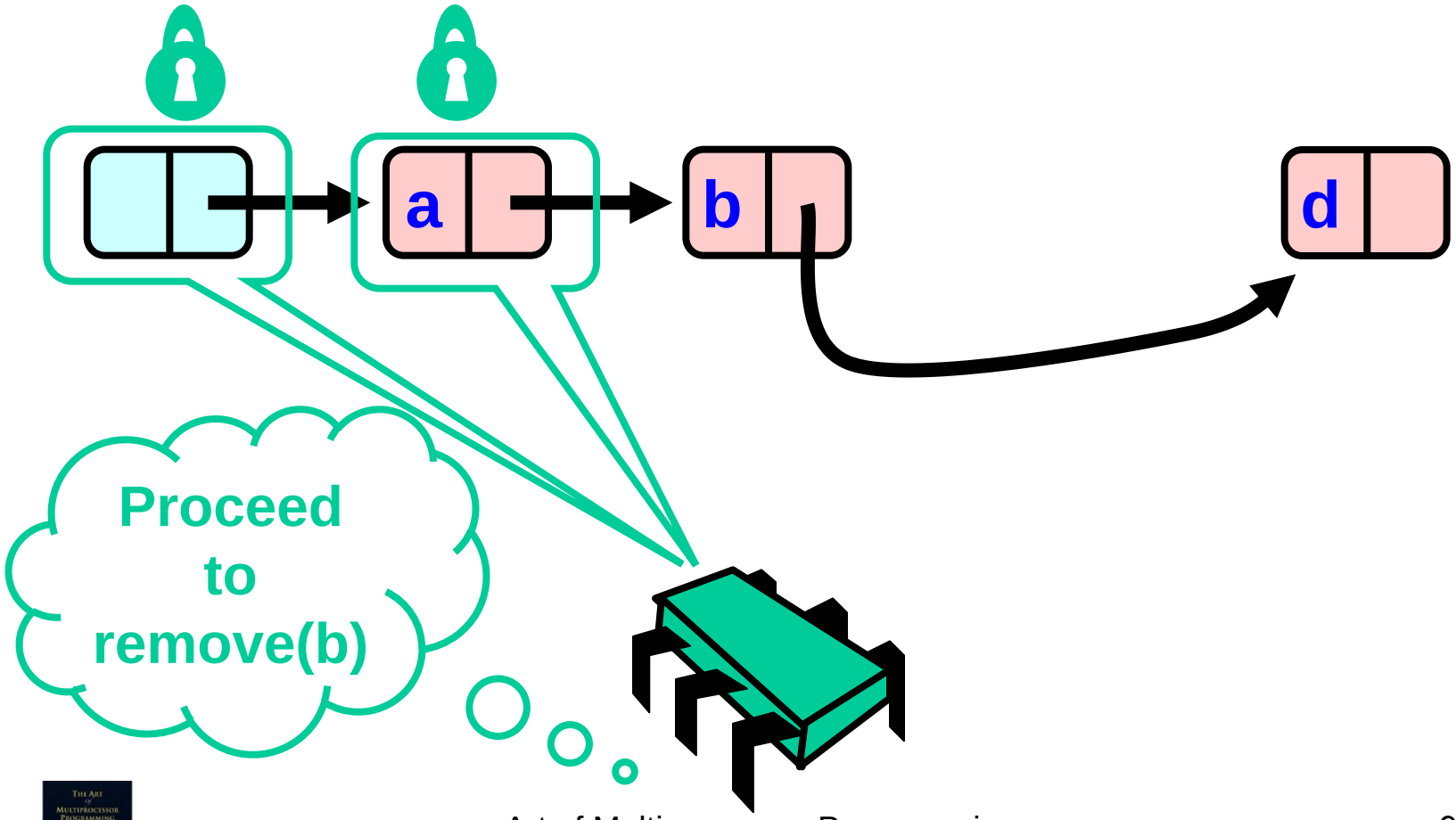

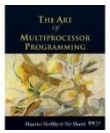

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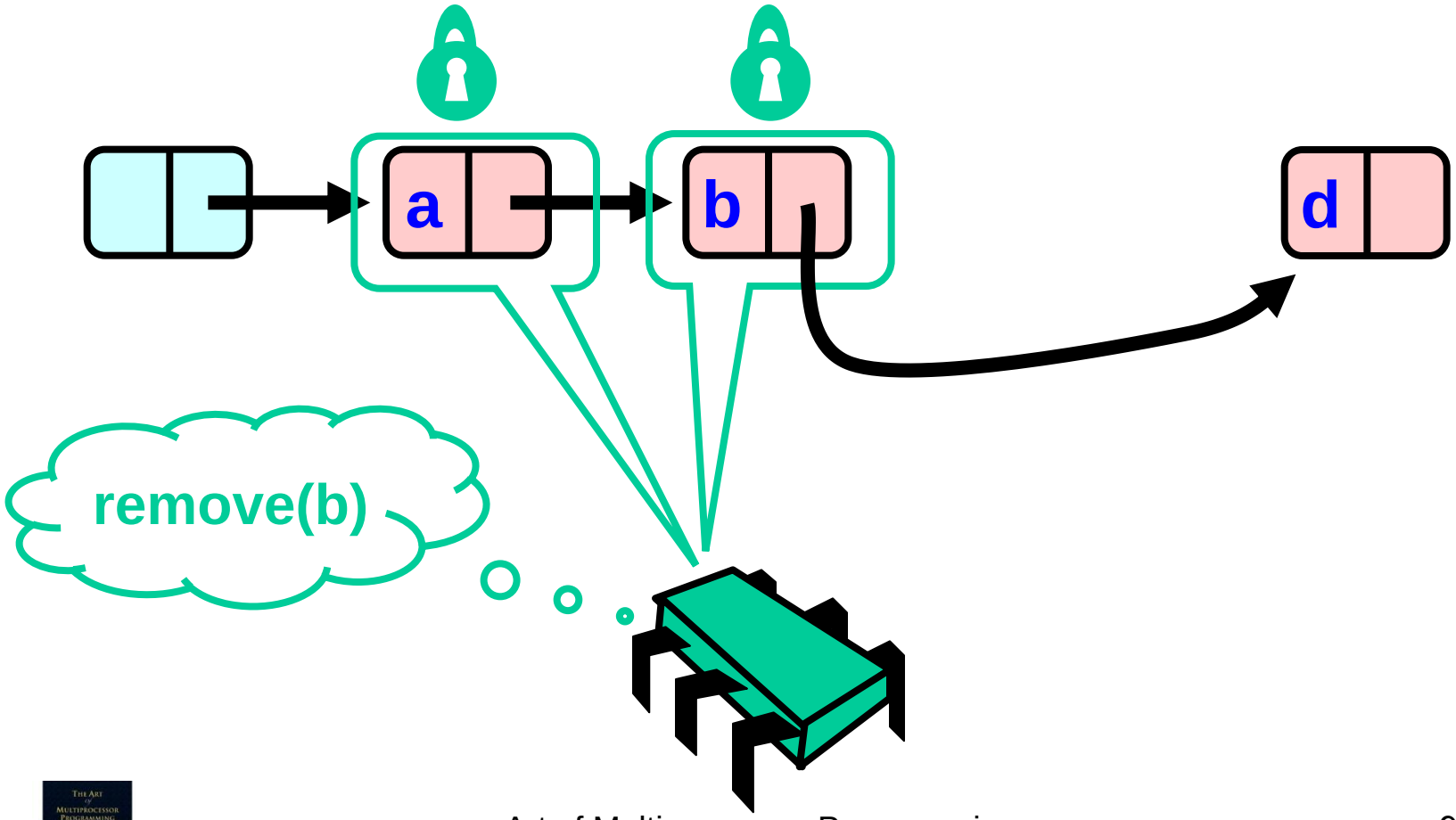

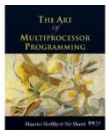

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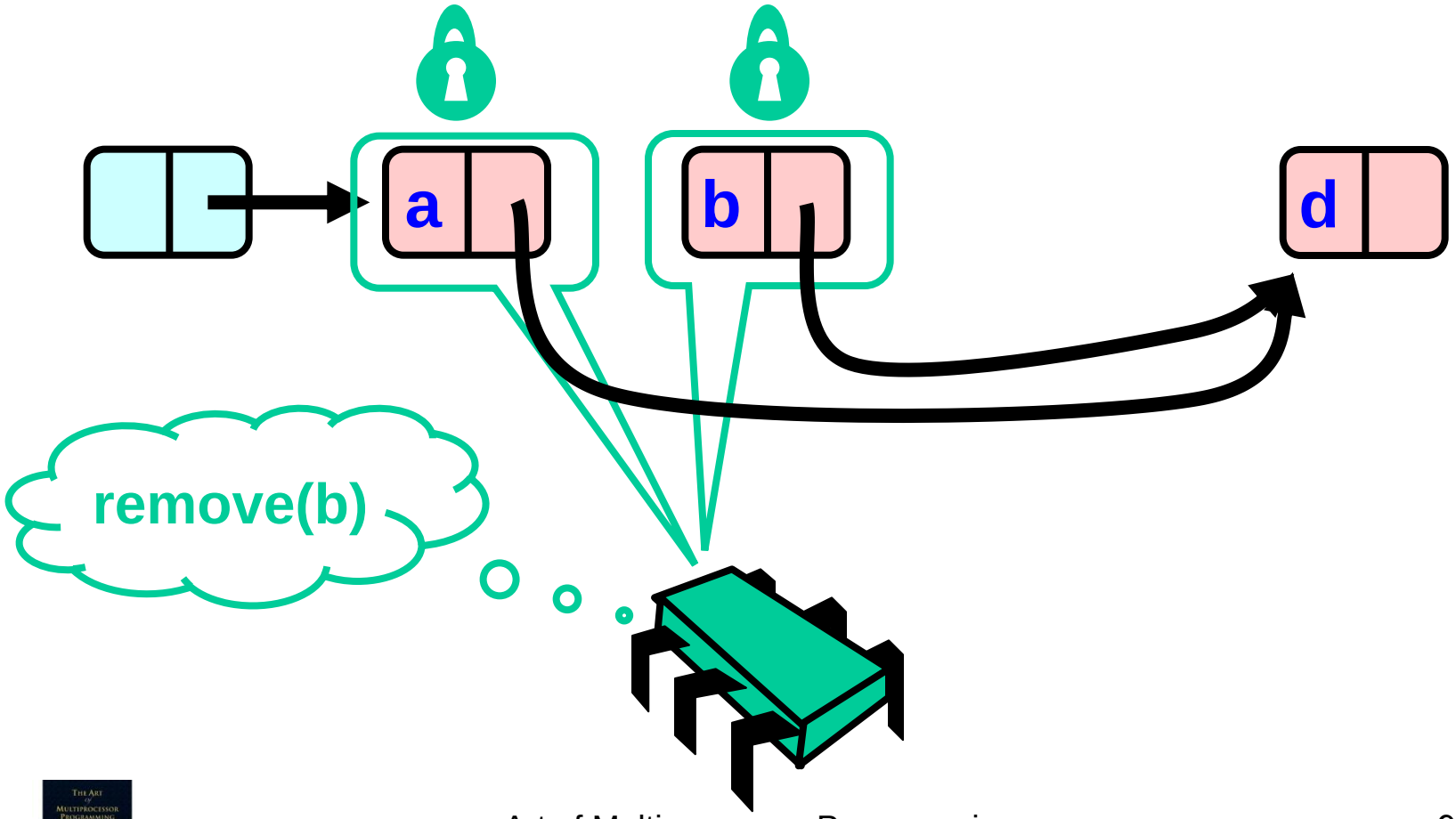

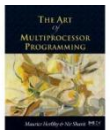

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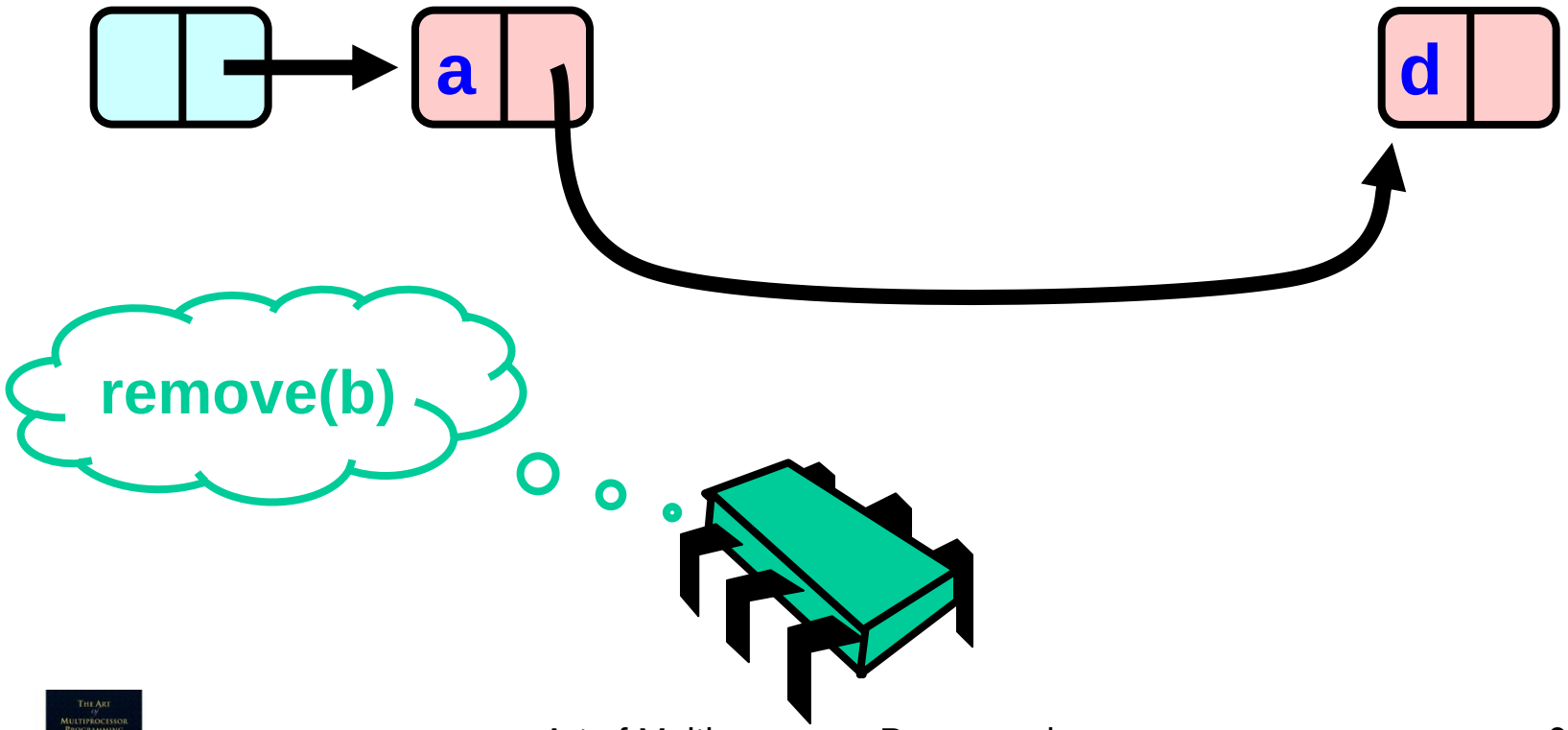

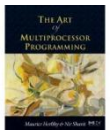

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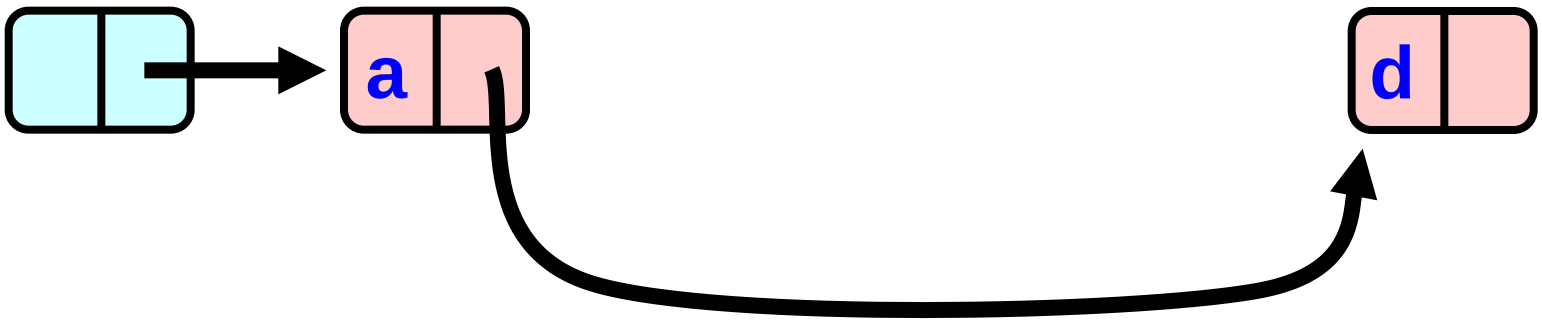
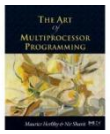
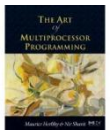




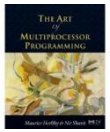
Adding Nodes

- To add node e
  - Must lock predecessor
  - Must lock successor
- Neither can be deleted
  - (Is successor lock actually required?)



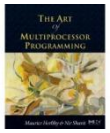
Drawbacks

- Better than coarse-grained lock
  - Threads can traverse in parallel
- Still not ideal
  - Long chain of acquire/release
  - Inefficient

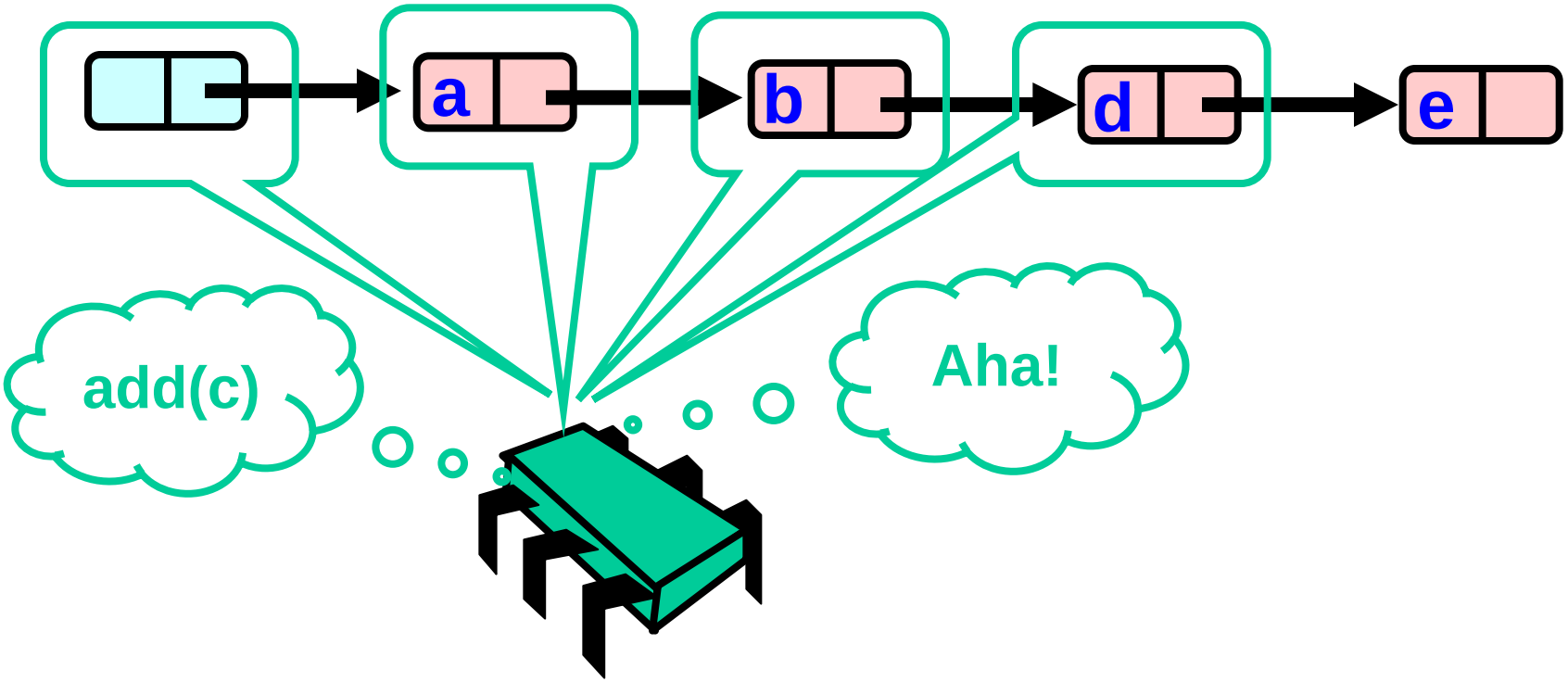


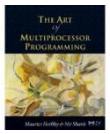
Optimistic Synchronization

- Find nodes without locking
- Lock nodes
- Check that everything is OK

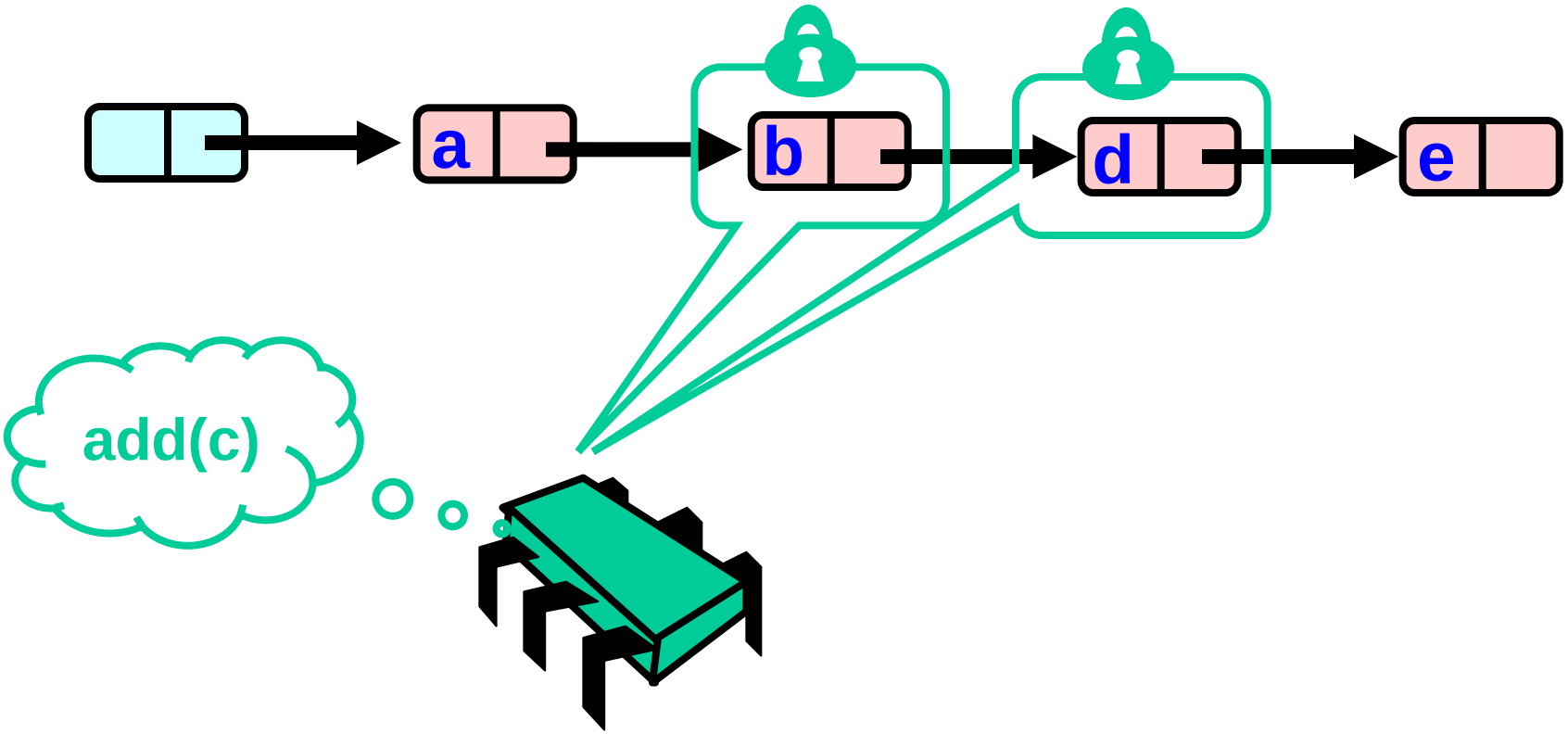


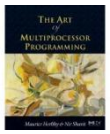
Optimistic: Traverse without Locking



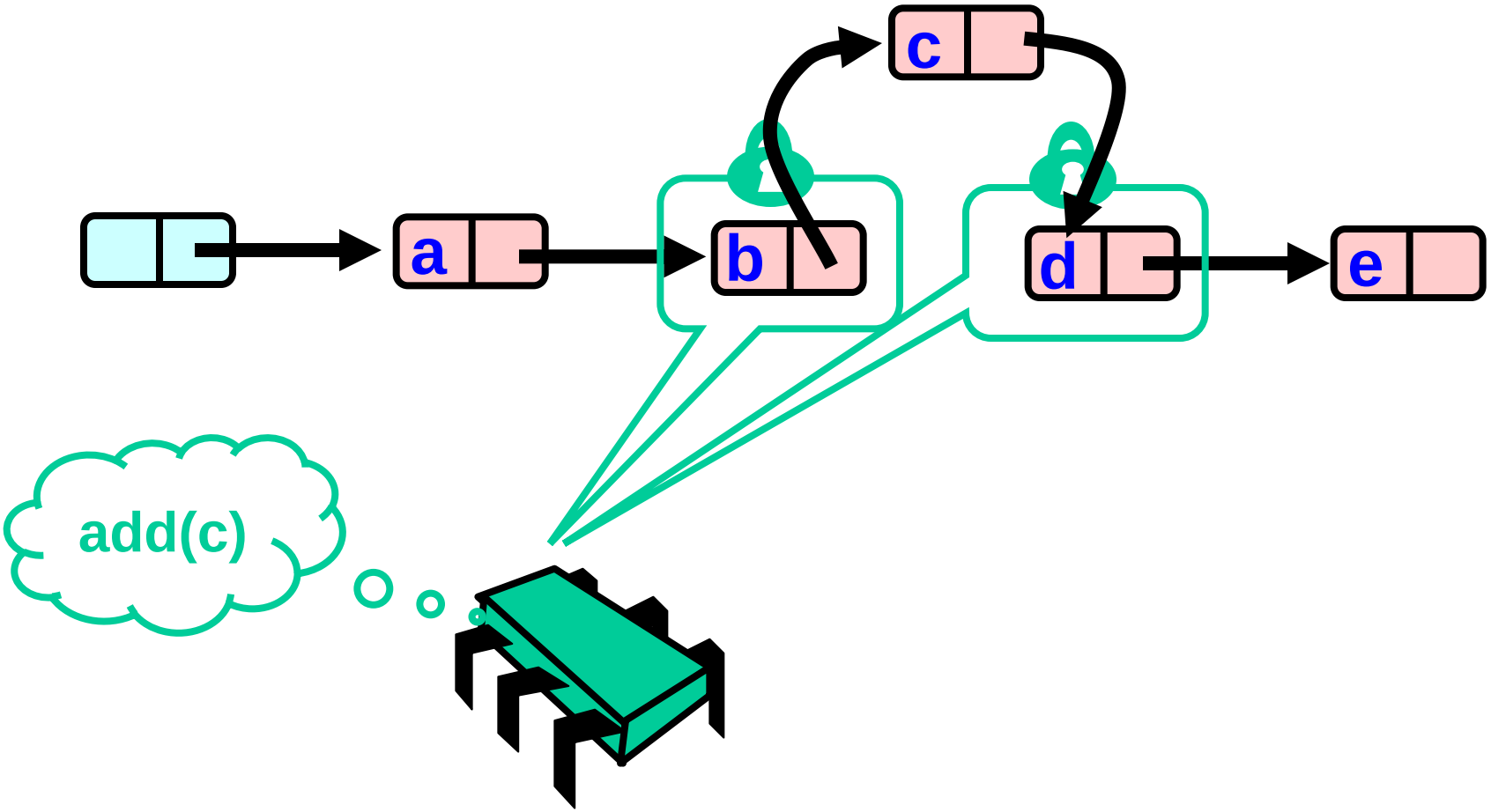


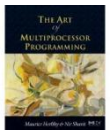
Optimistic: Lock and Load



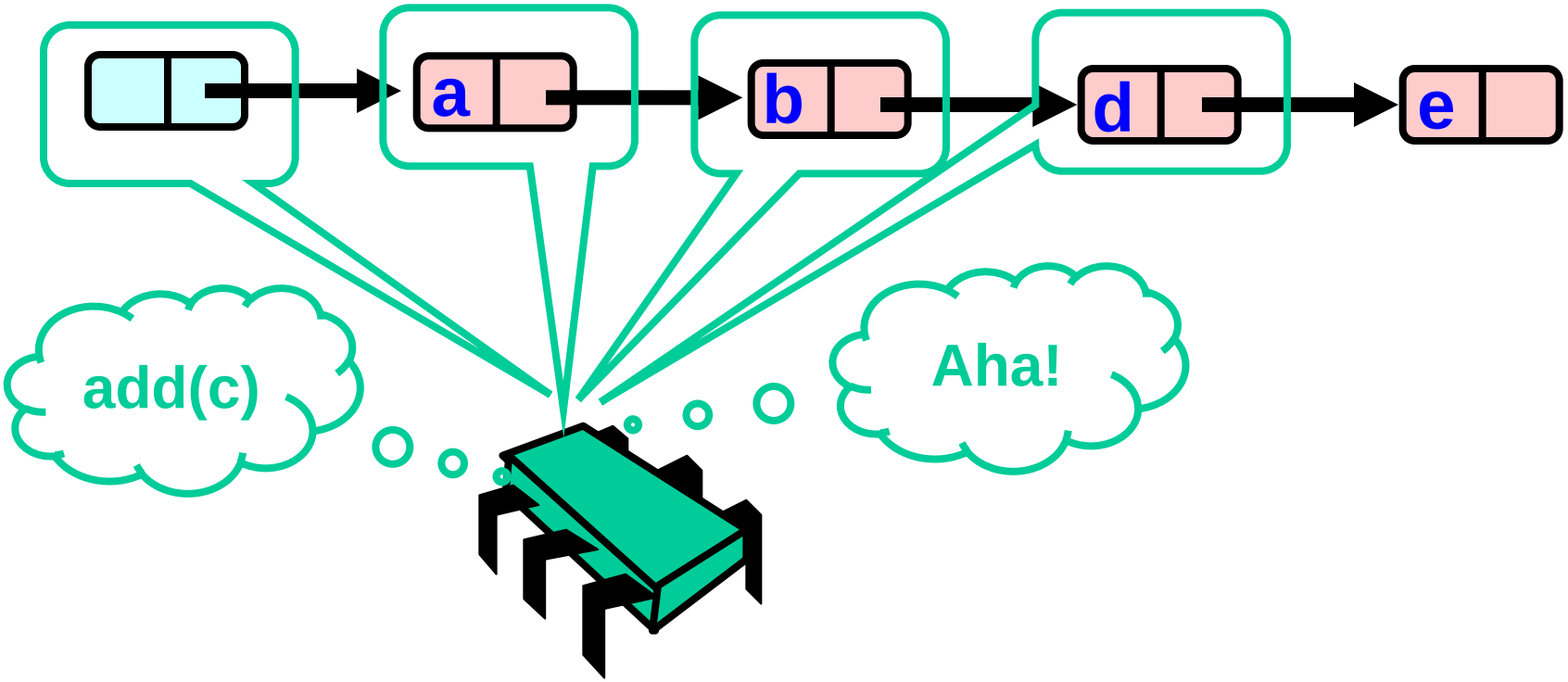


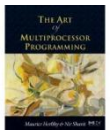
Optimistic: Lock and Load





What could go wrong?





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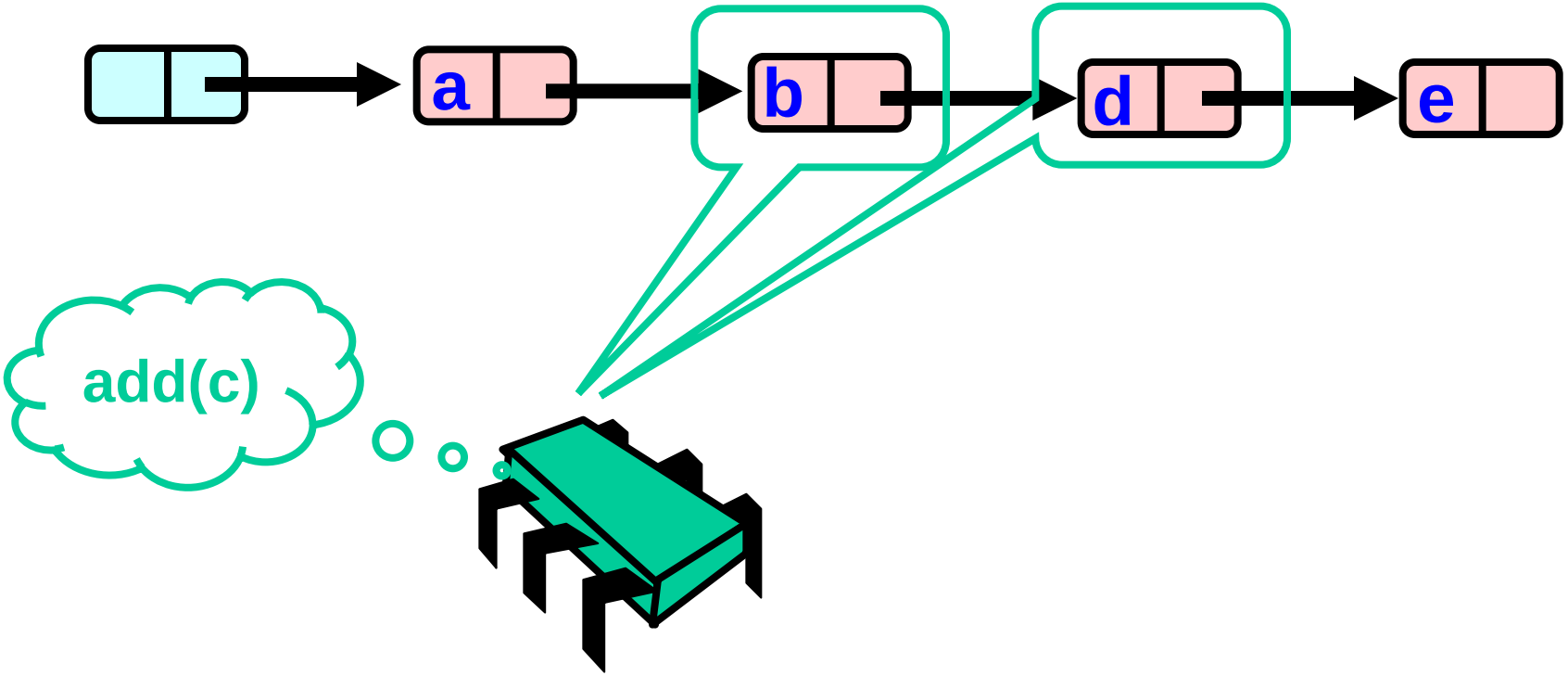

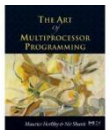

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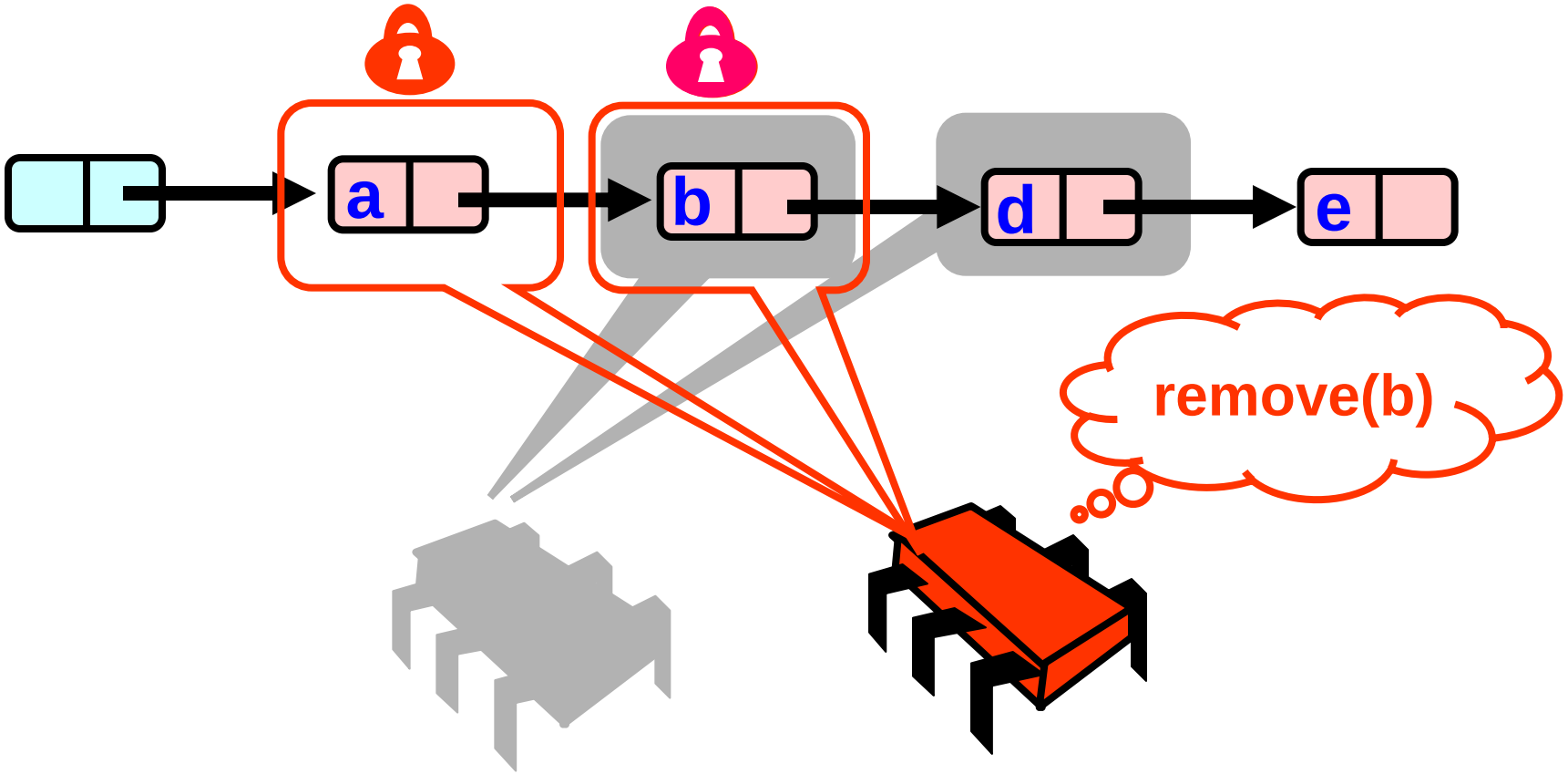

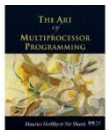

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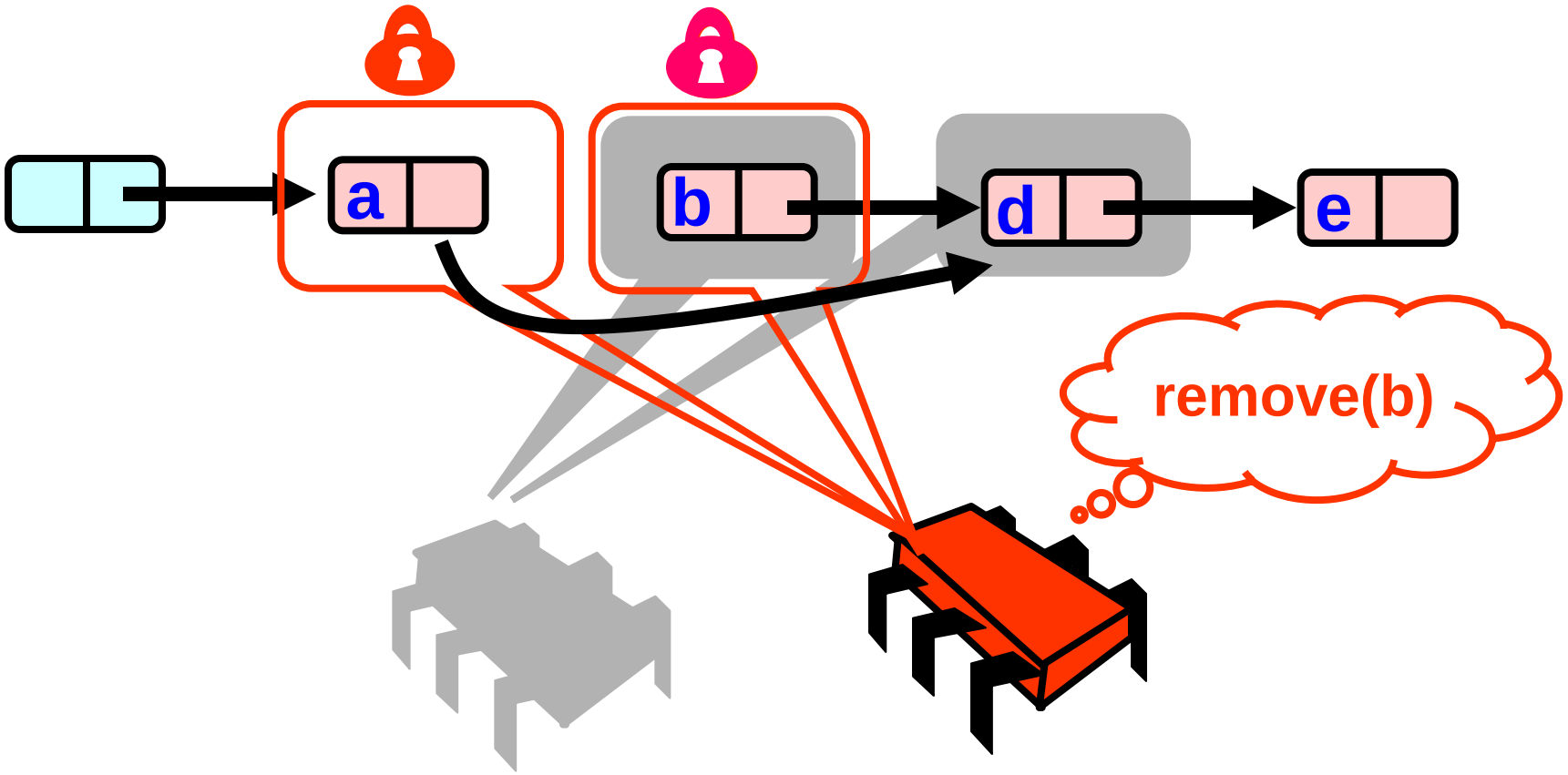

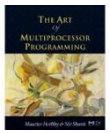

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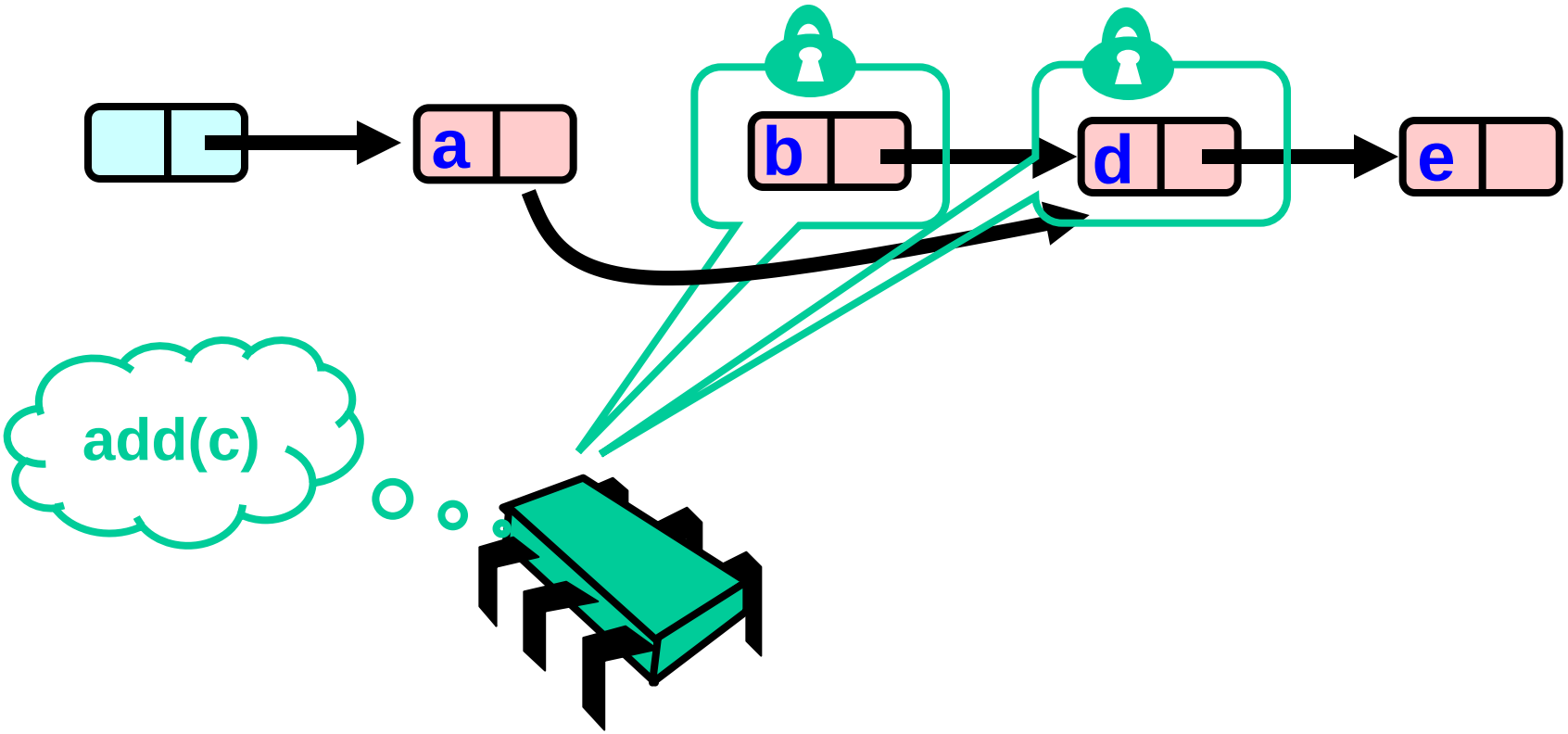

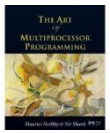

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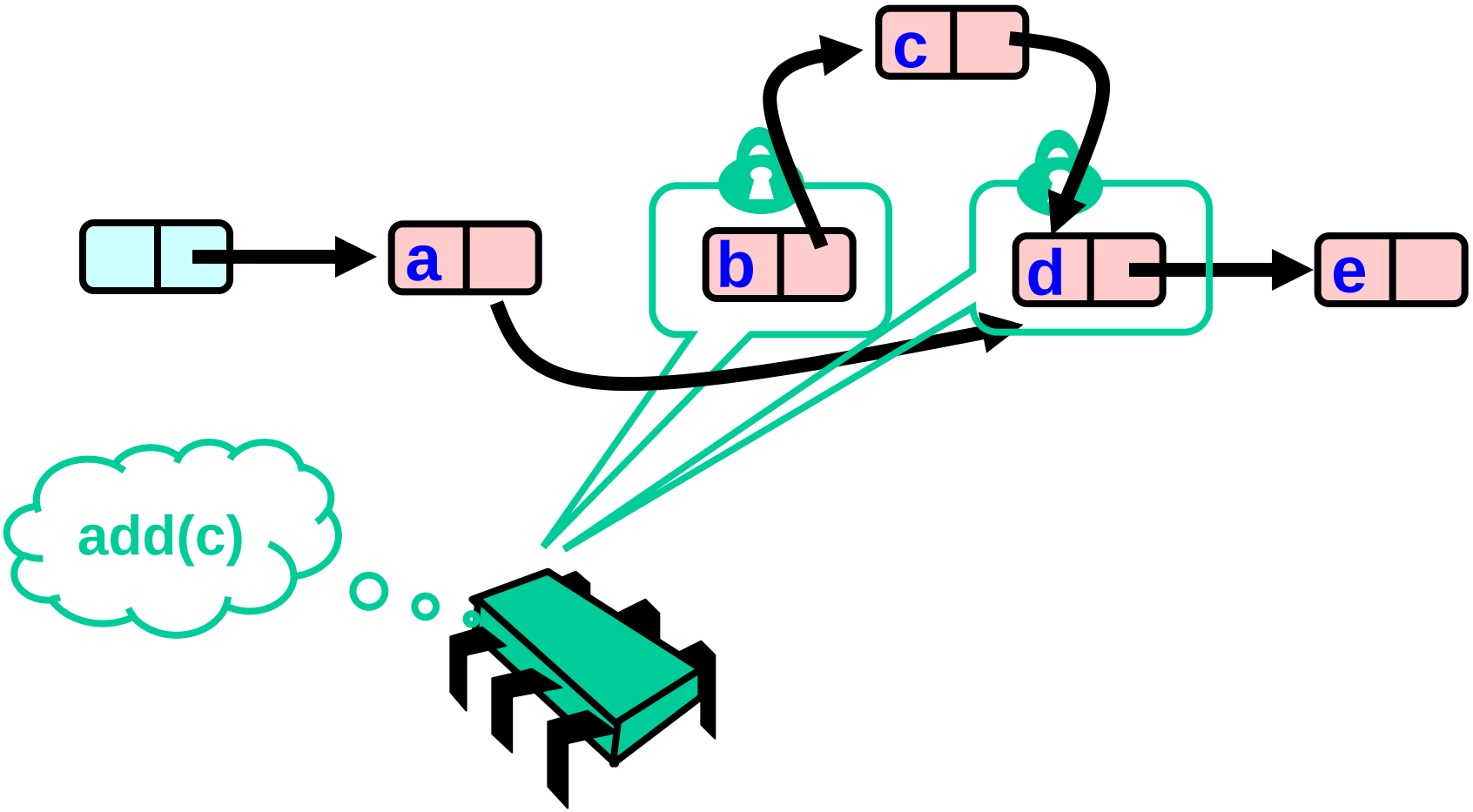

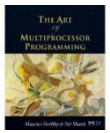

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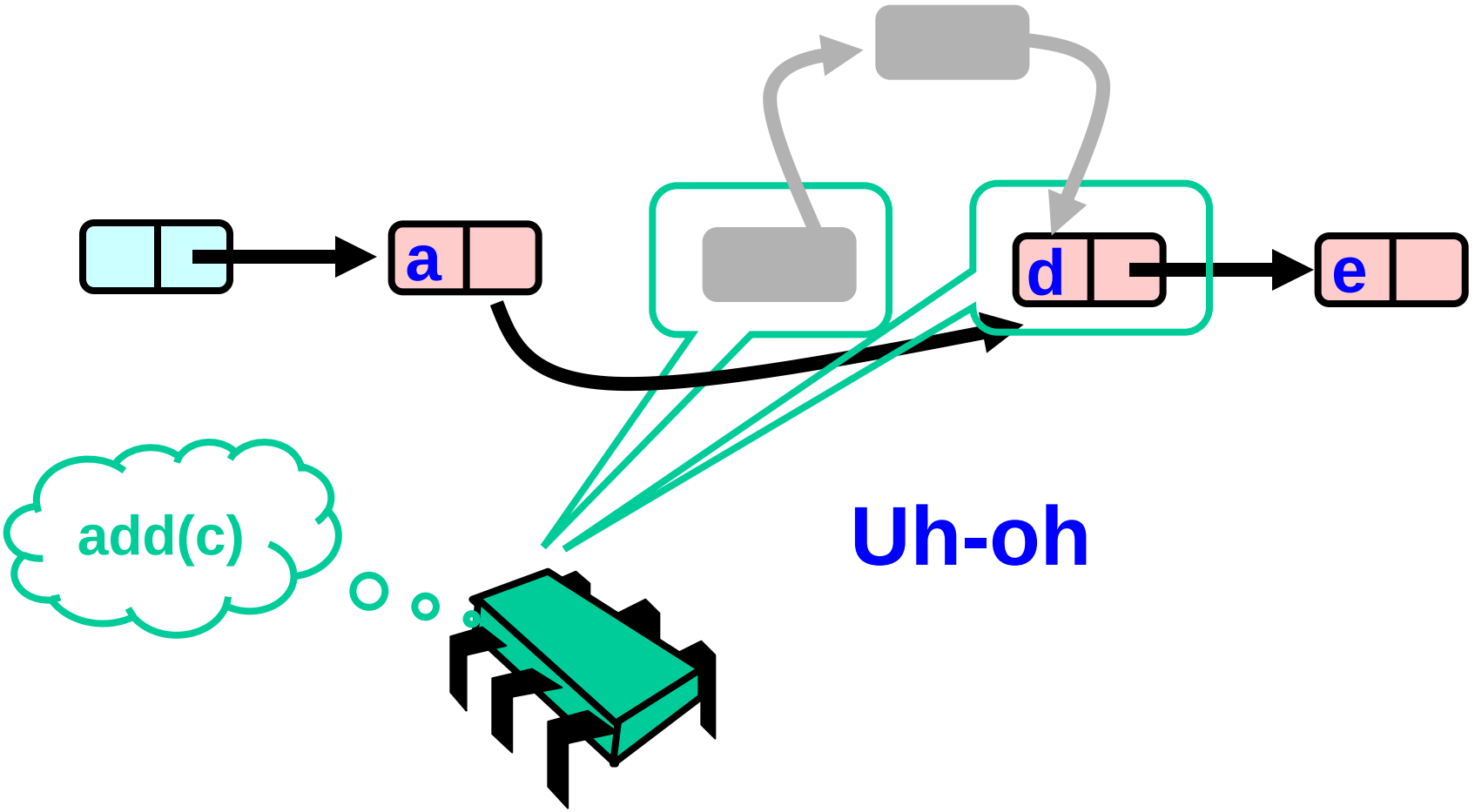
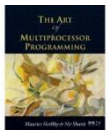
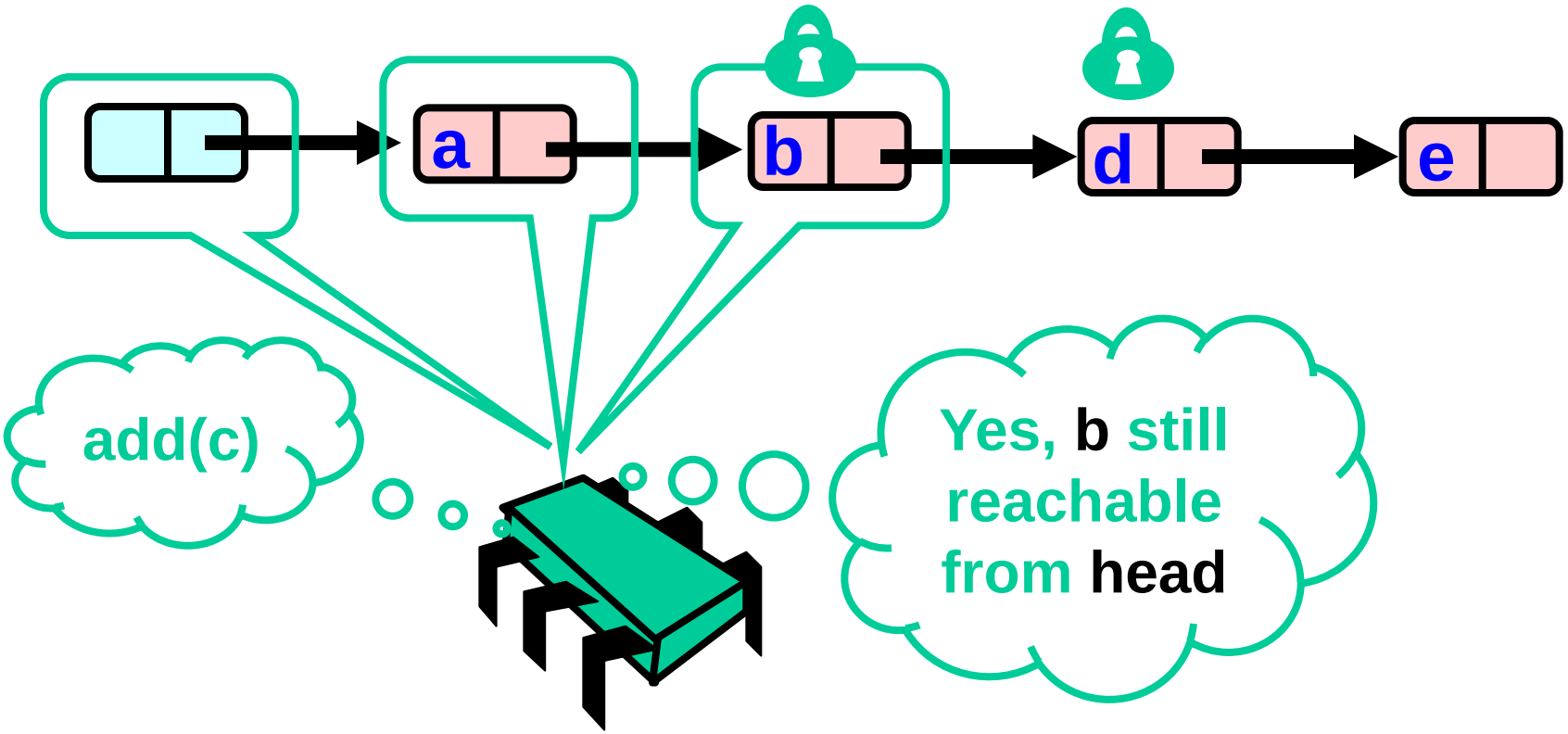
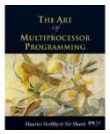


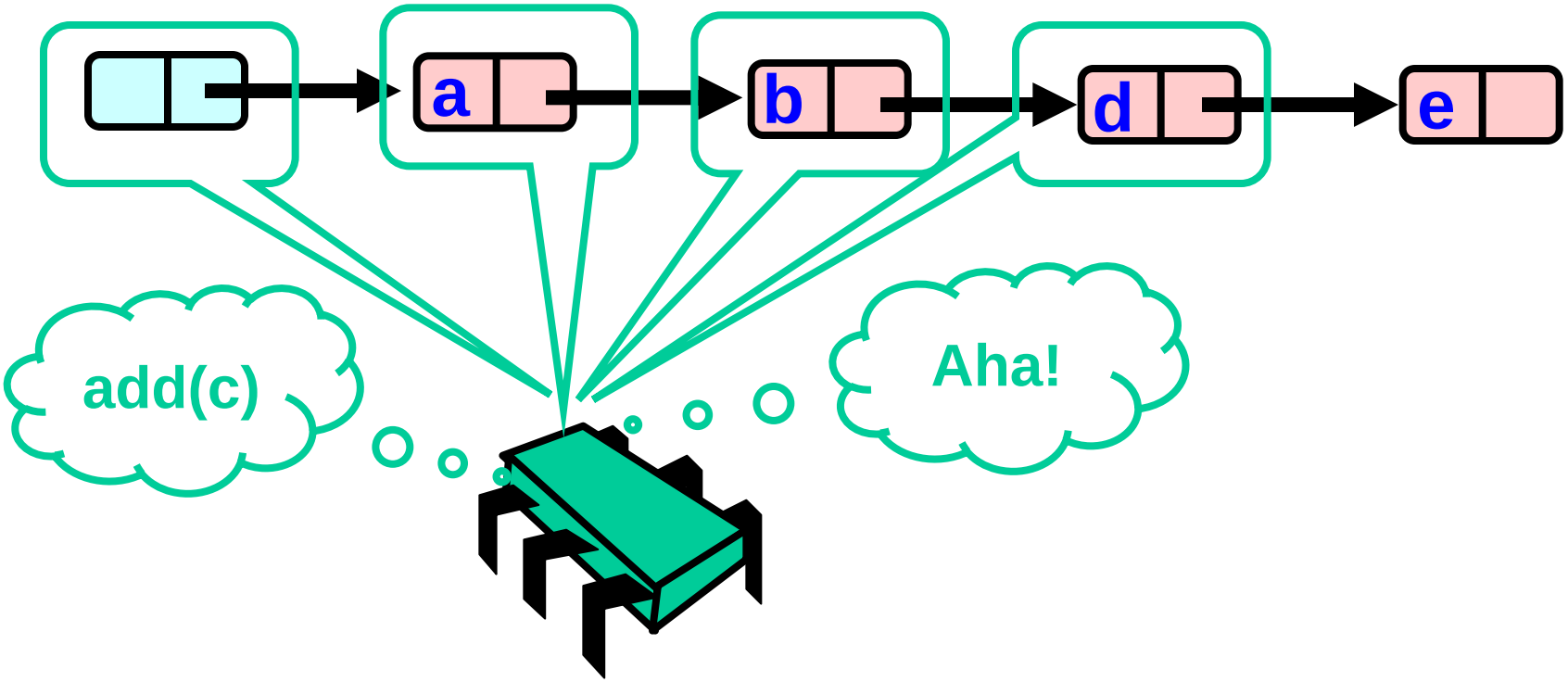


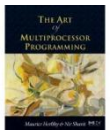
Validate – Part 1





What Else Could Go Wrong?





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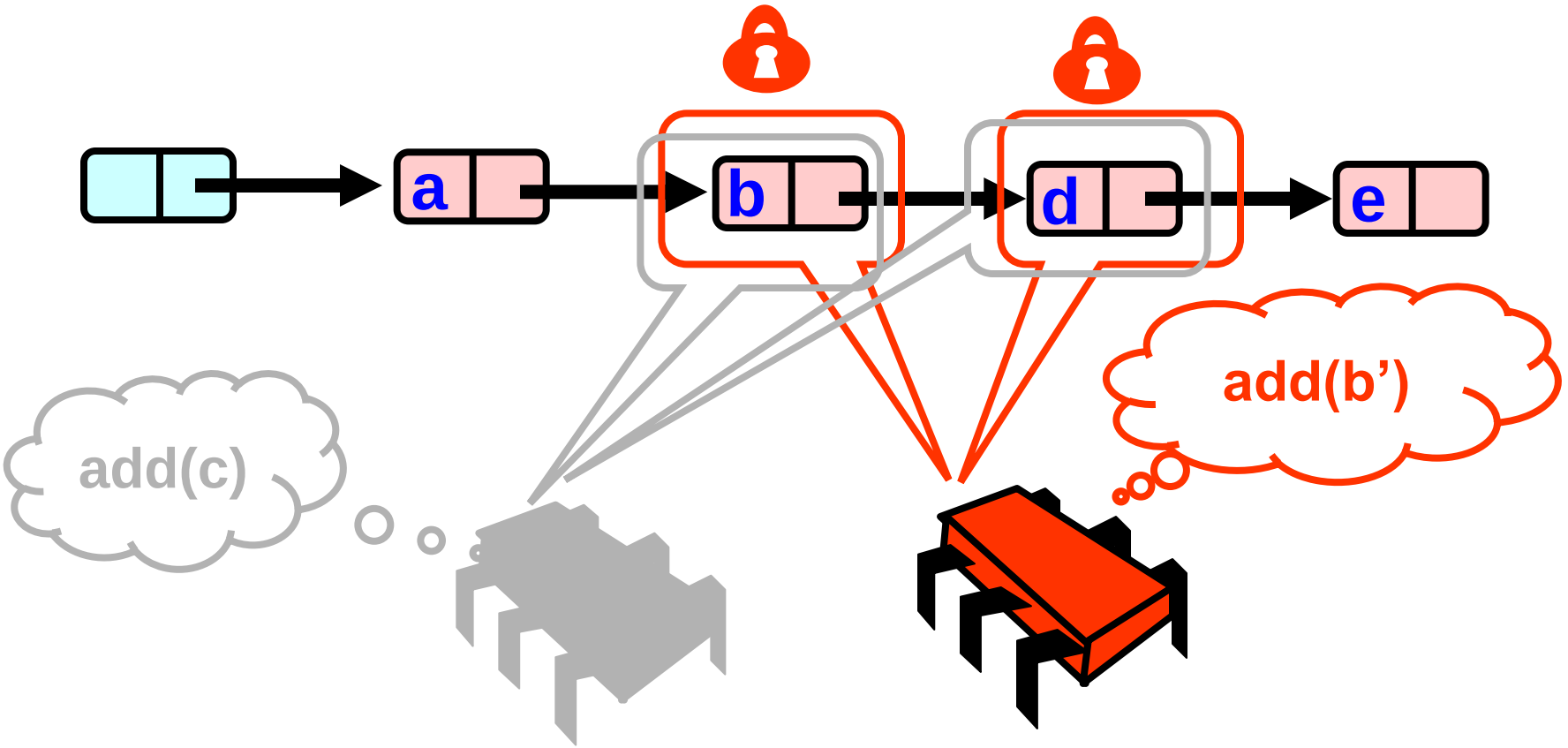

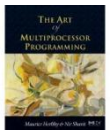

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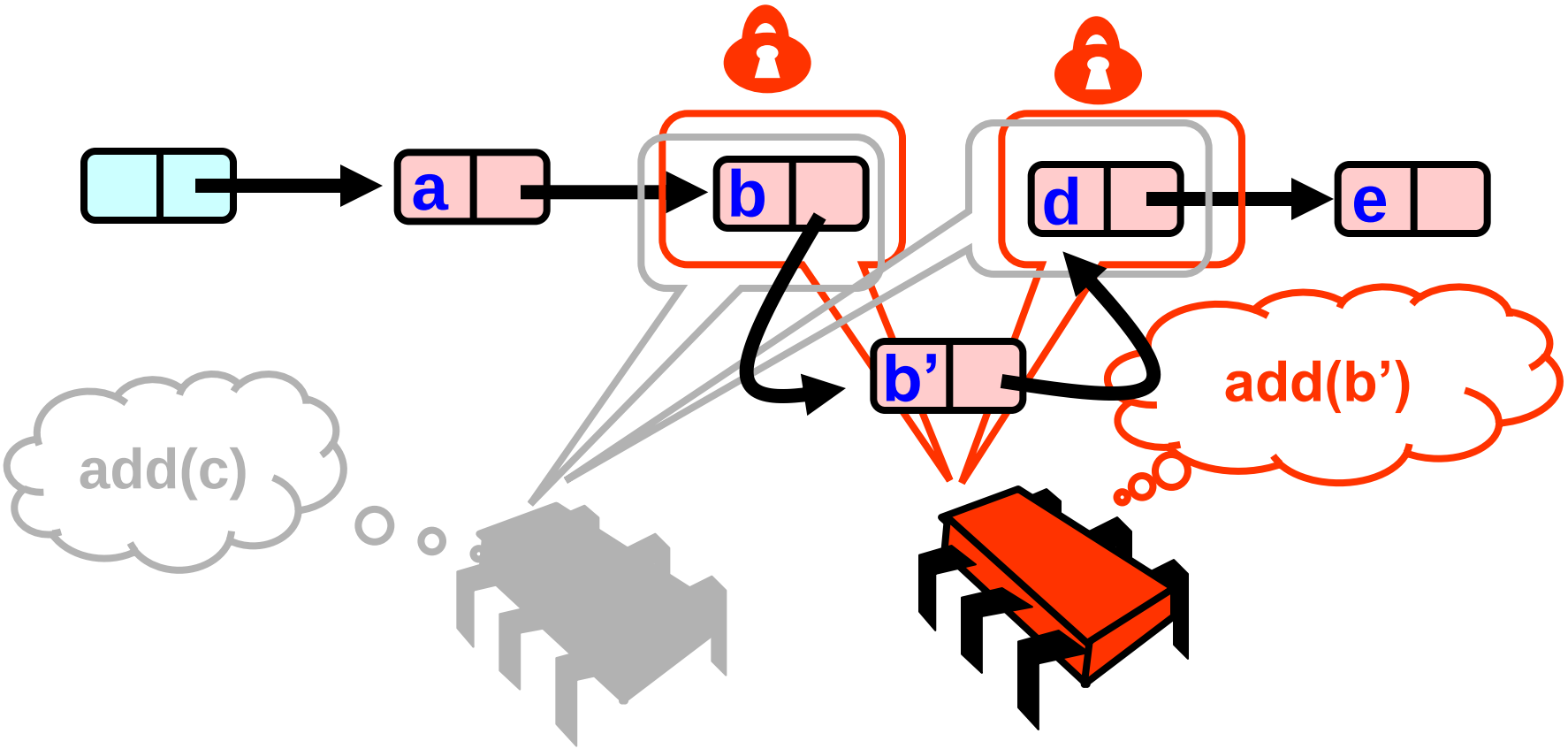

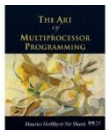

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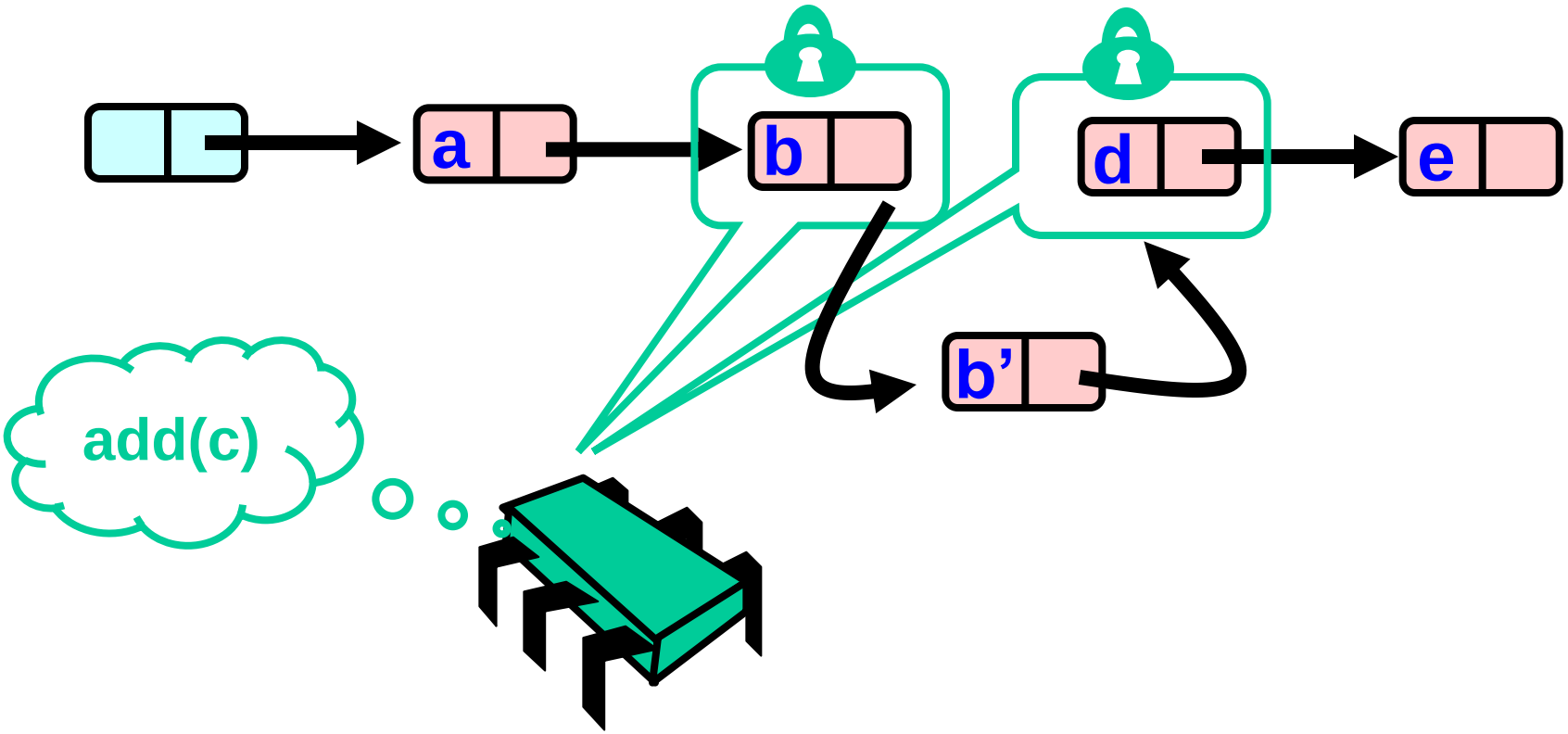

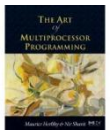

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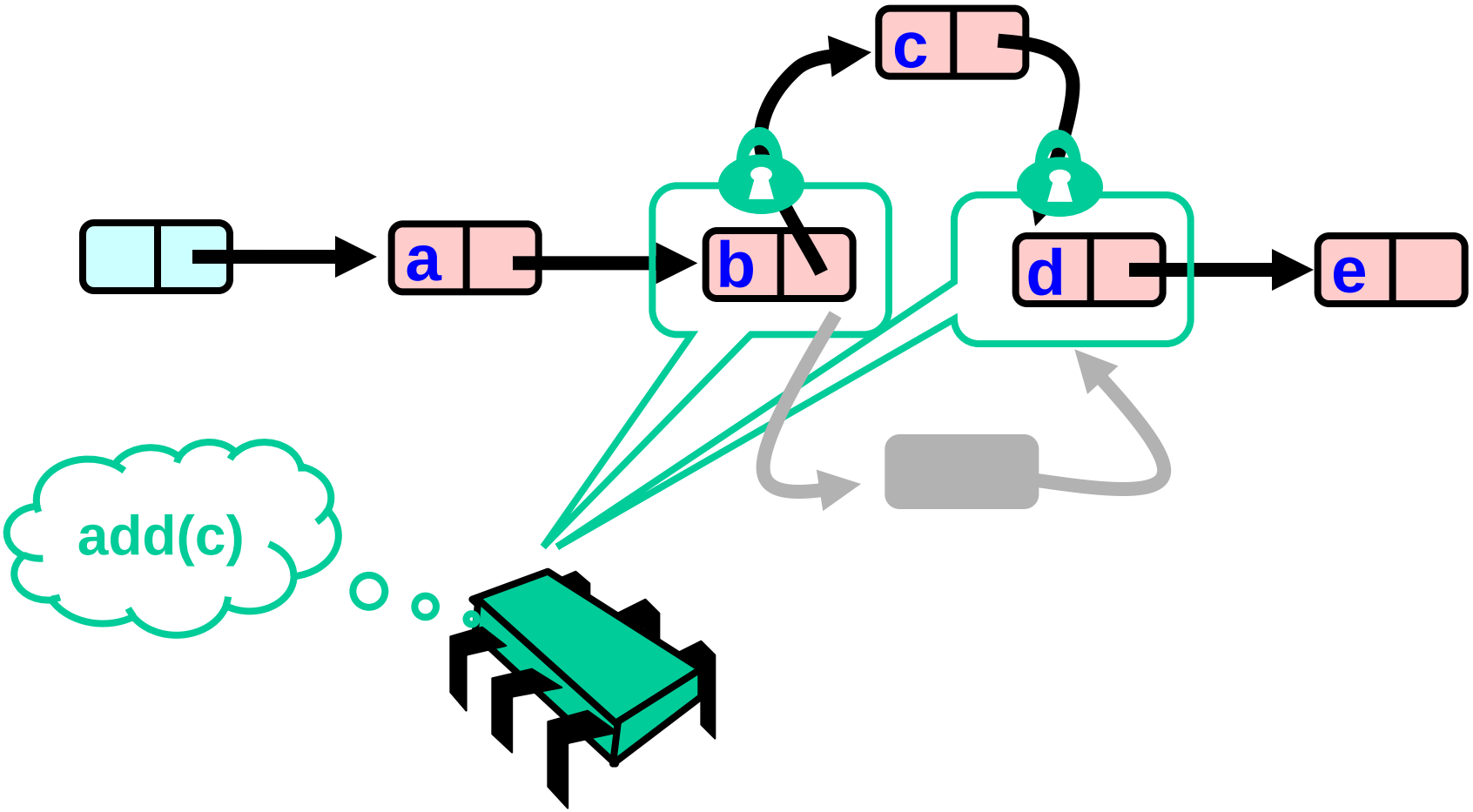
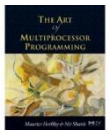
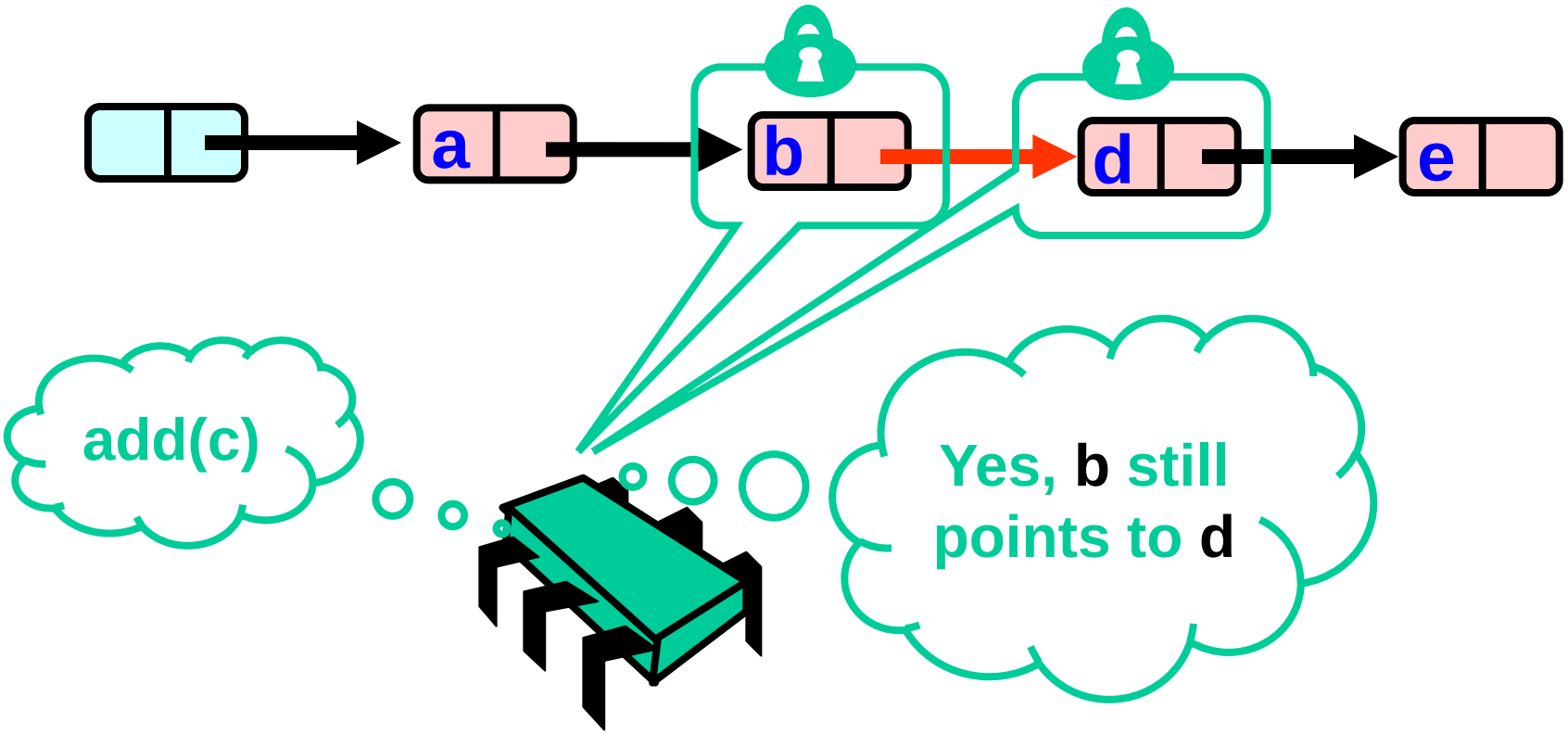
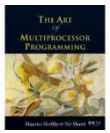




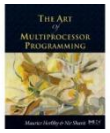
Validate Part 2 (while holding locks)





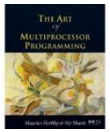
Invariants

- Careful: we may traverse deleted nodes
- But we establish properties by
  - Validation
  - After we lock target nodes

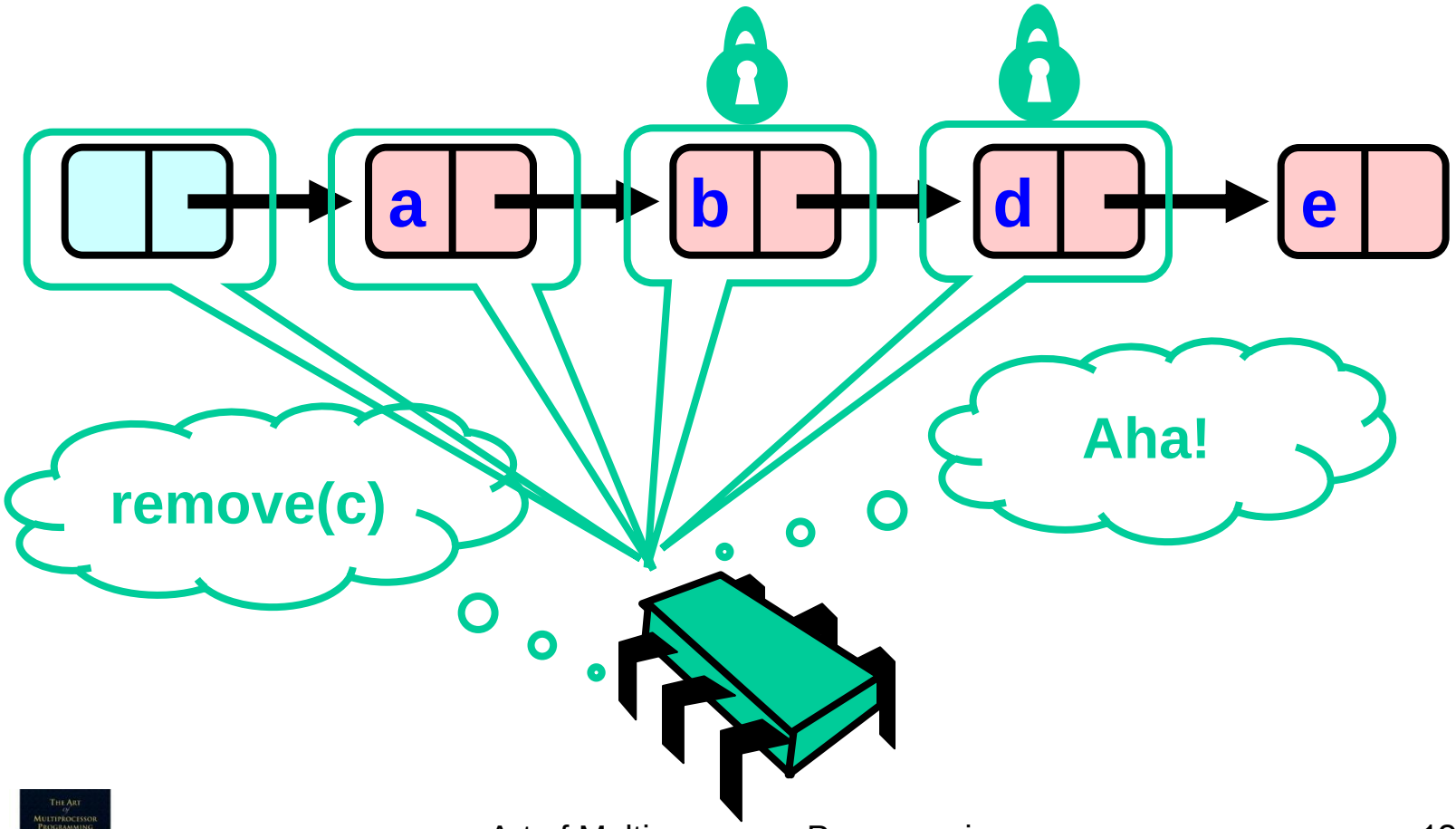


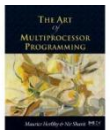
Correctness

- If
  - Nodes b and c both locked
  - Node b still accessible
  - Node c still successor to b
- Then
  - Neither will be deleted
  - OK to delete and return true

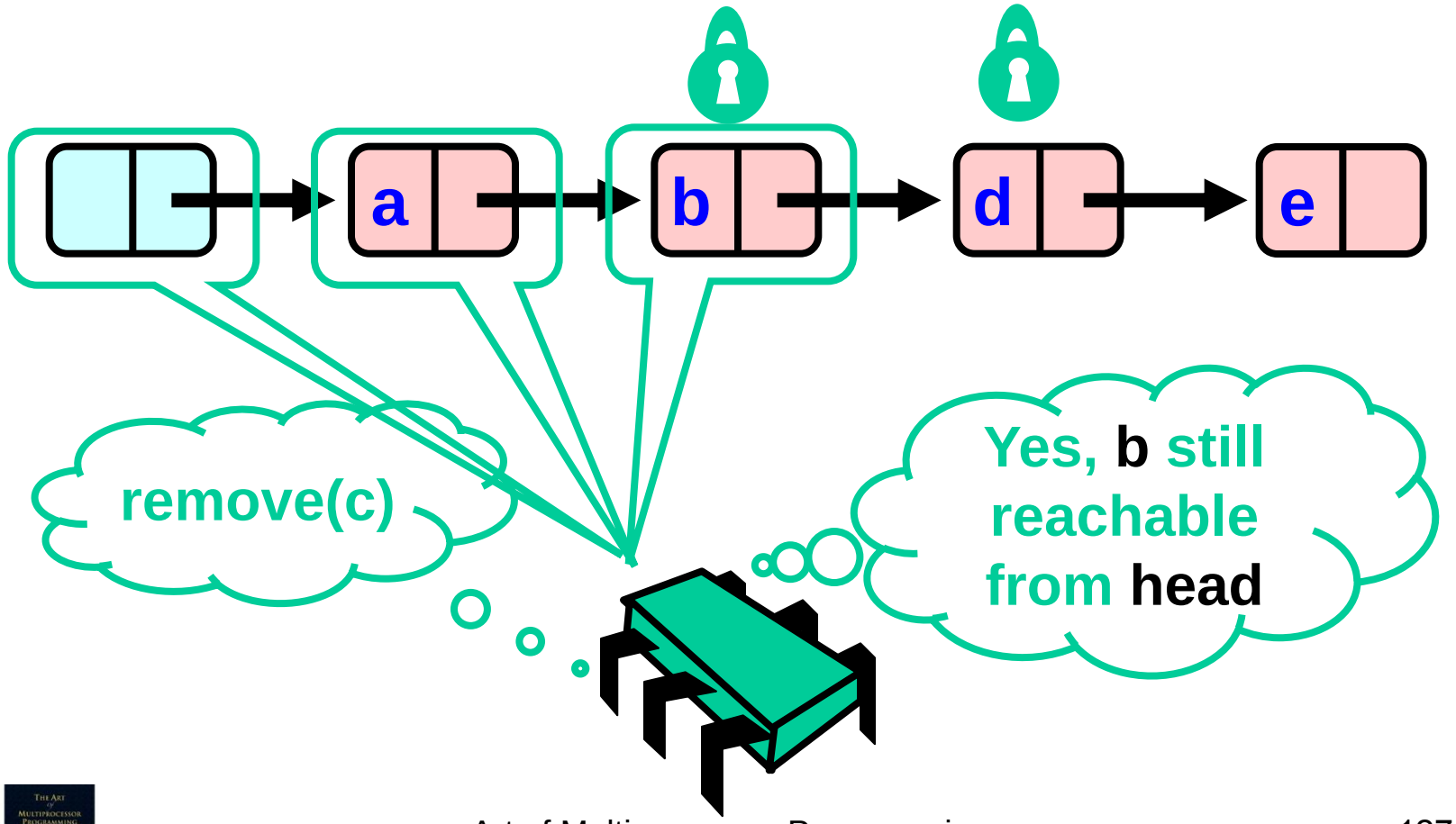


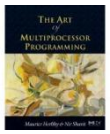
Unsuccessful Remove



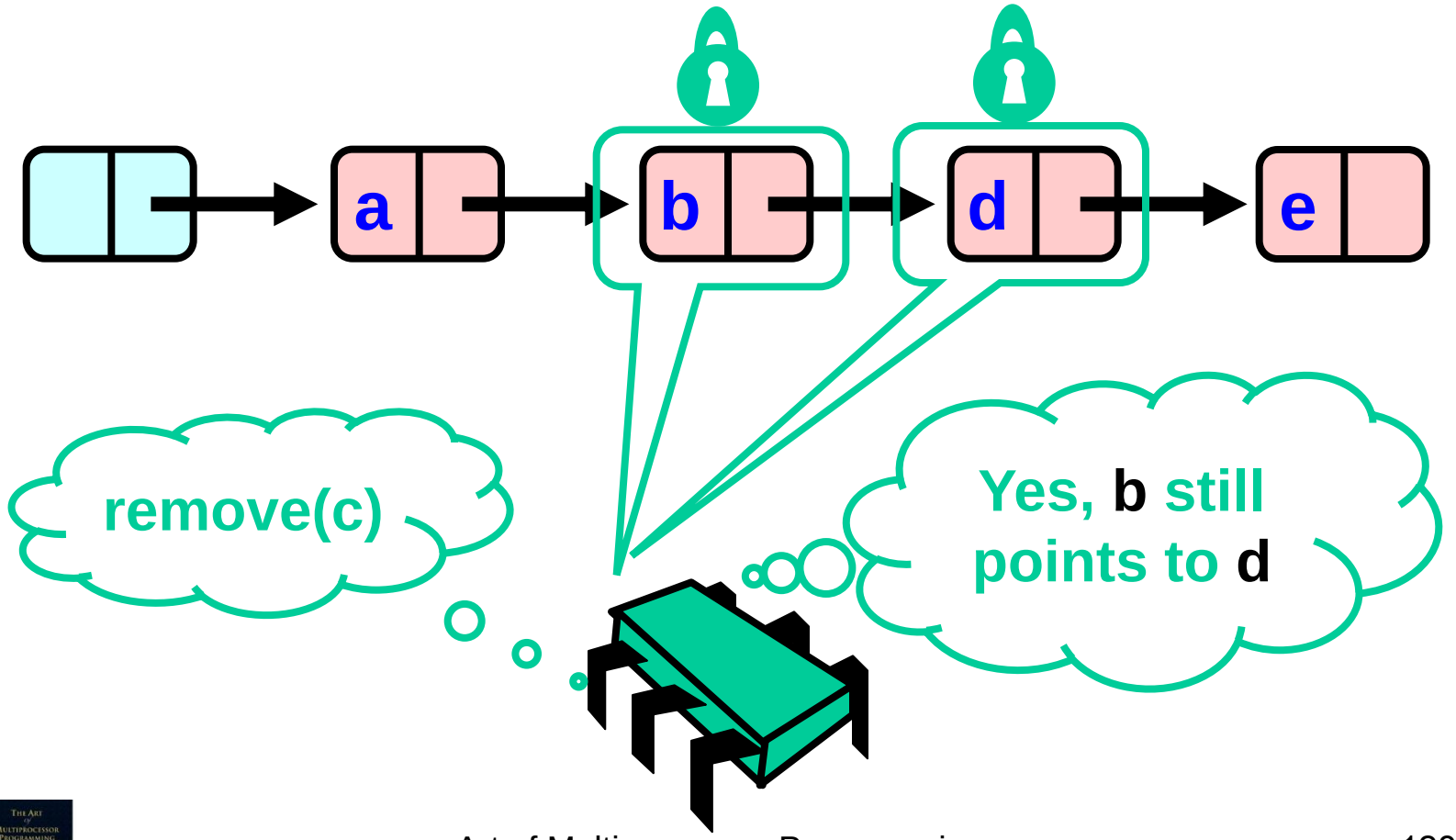


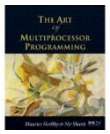
Validate (1)



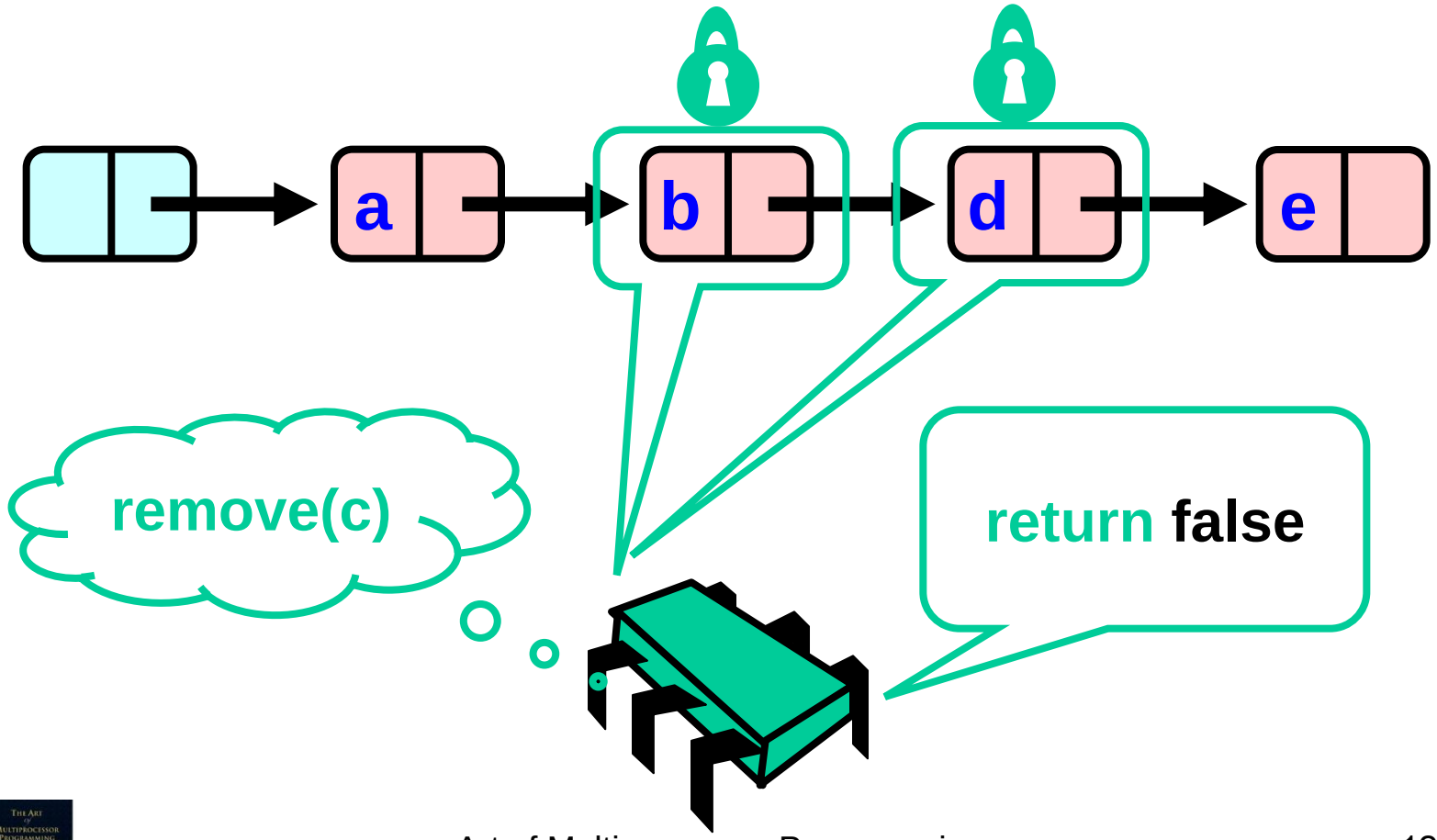


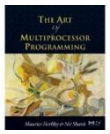
Validate (2)





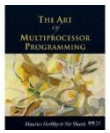
OK Computer





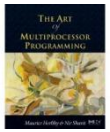
Correctness

- If
  - Nodes b and d both locked
  - Node b still accessible
  - Node d still successor to b
- Then
  - Neither will be deleted
  - No thread can add c after b
  - OK to return false



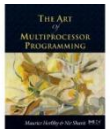
Optimistic List

- Limited hot-spots
  - Targets of add(), remove(), contains()
  - No contention on traversals
- Moreover
  - Traversals are wait-free
  - Food for thought …



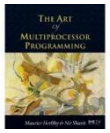
So Far, So Good

- Much less lock acquisition/release
  - Performance
  - Concurrency
- Problems
  - Need to traverse list twice
  - contains() method acquires locks



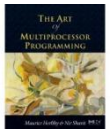
Evaluation

- Optimistic is effective if
  - cost of scanning twice without locks
    is less than
  - cost of scanning once with locks
- Drawback
  - contains() acquires locks
  - 90% of calls in many apps



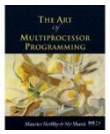
Lazy List

- Like optimistic, except
  - Scan once
  - **`contains(x)`** never locks …
- Key insight
  - Removing nodes causes trouble
  - Do it “lazily”

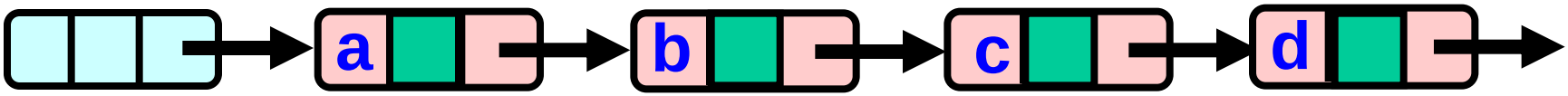


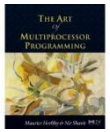
Lazy List

- `remove()`
  - Scans list (as before)
  - Locks predecessor & current (as before)
- Logical delete
  - Marks current node as removed (new!)
- Physical delete
  - Redirects predecessor's next (as before)

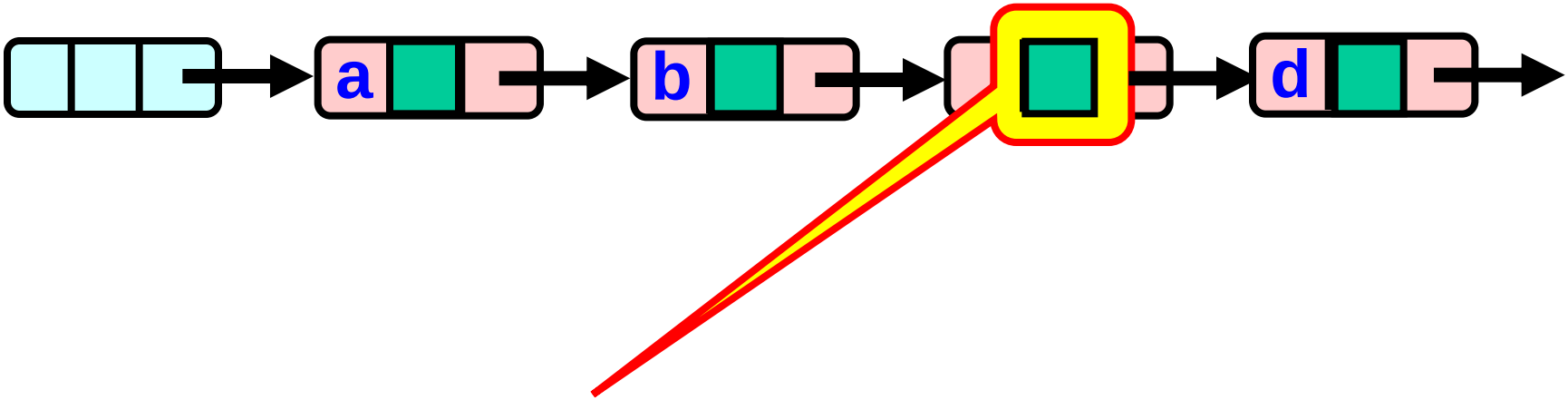


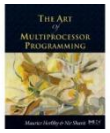
Lazy Removal



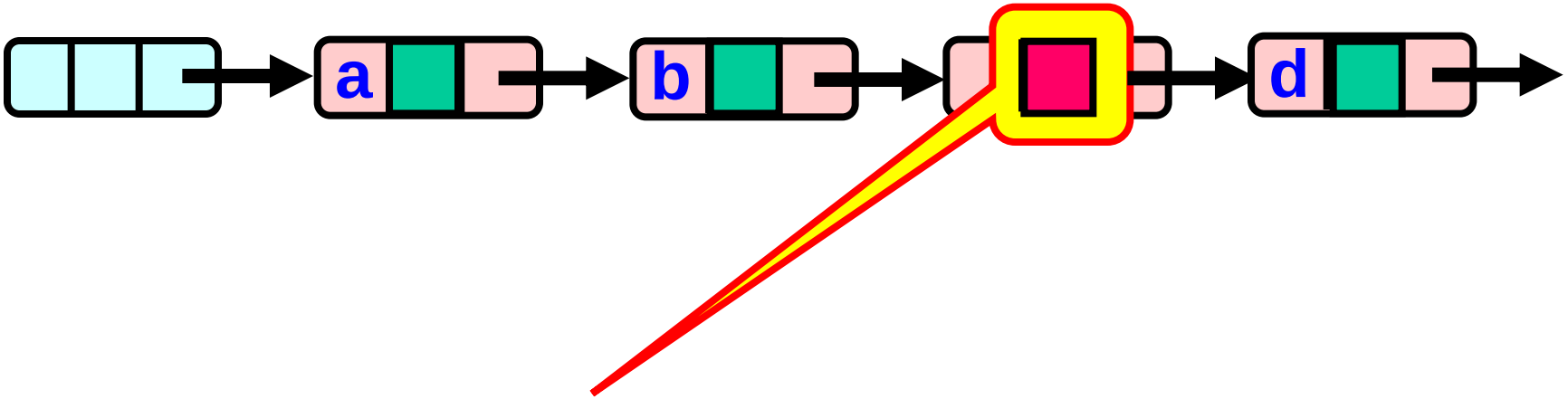


Lazy Removal

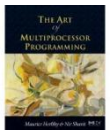




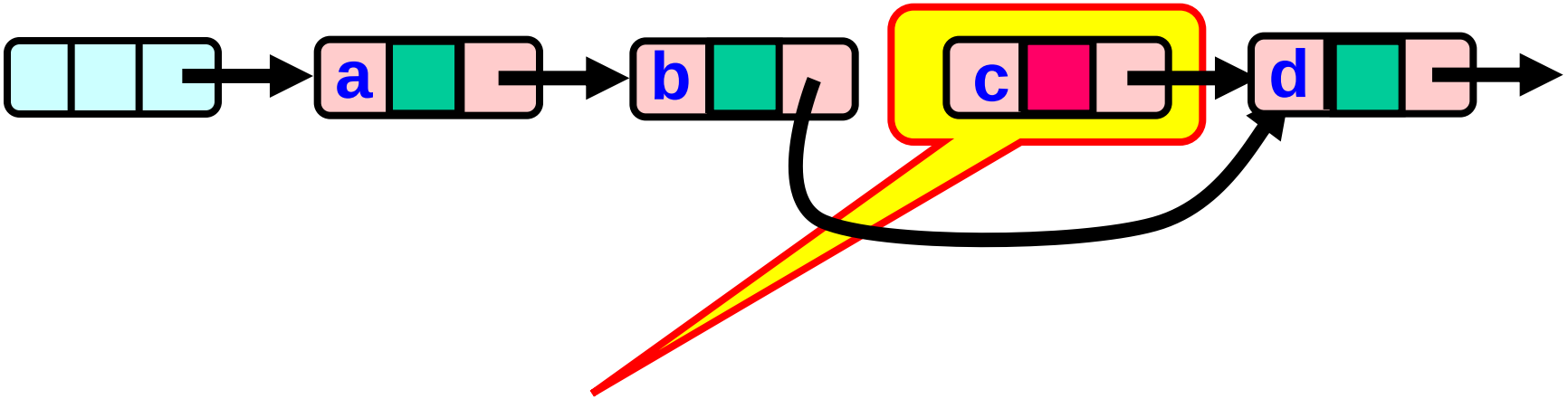
Lazy Removal



Logically deleted

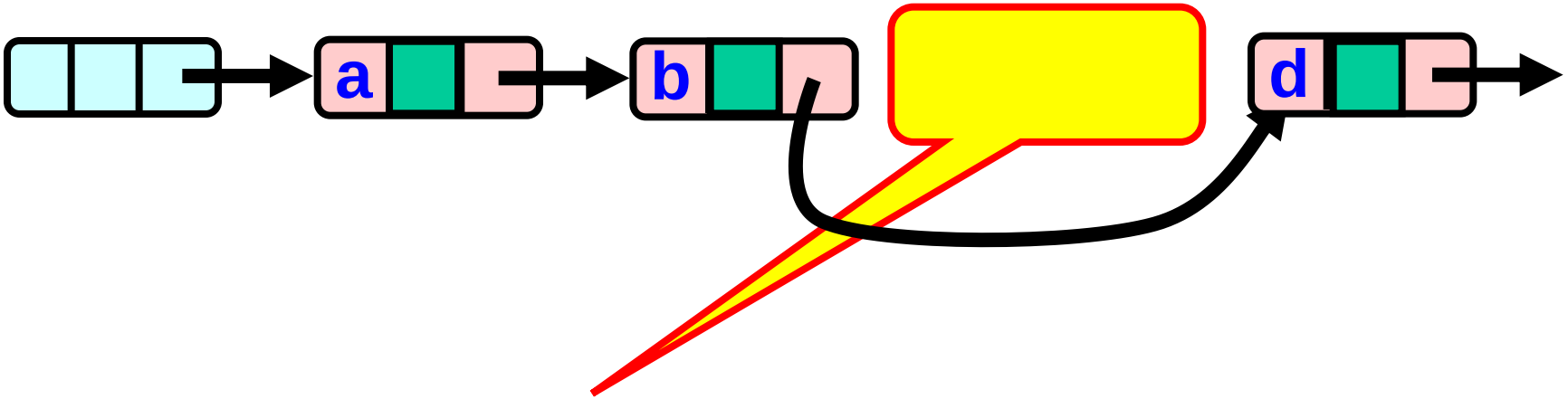


Lazy Removal



Physically deleted

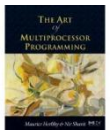
Lazy Removal



Physically deleted

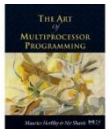
Lazy List

- All Methods
  - Scan through locked and marked nodes
  - Removing a node doesn't slow down other method calls …
- Must still lock pred and curr nodes.

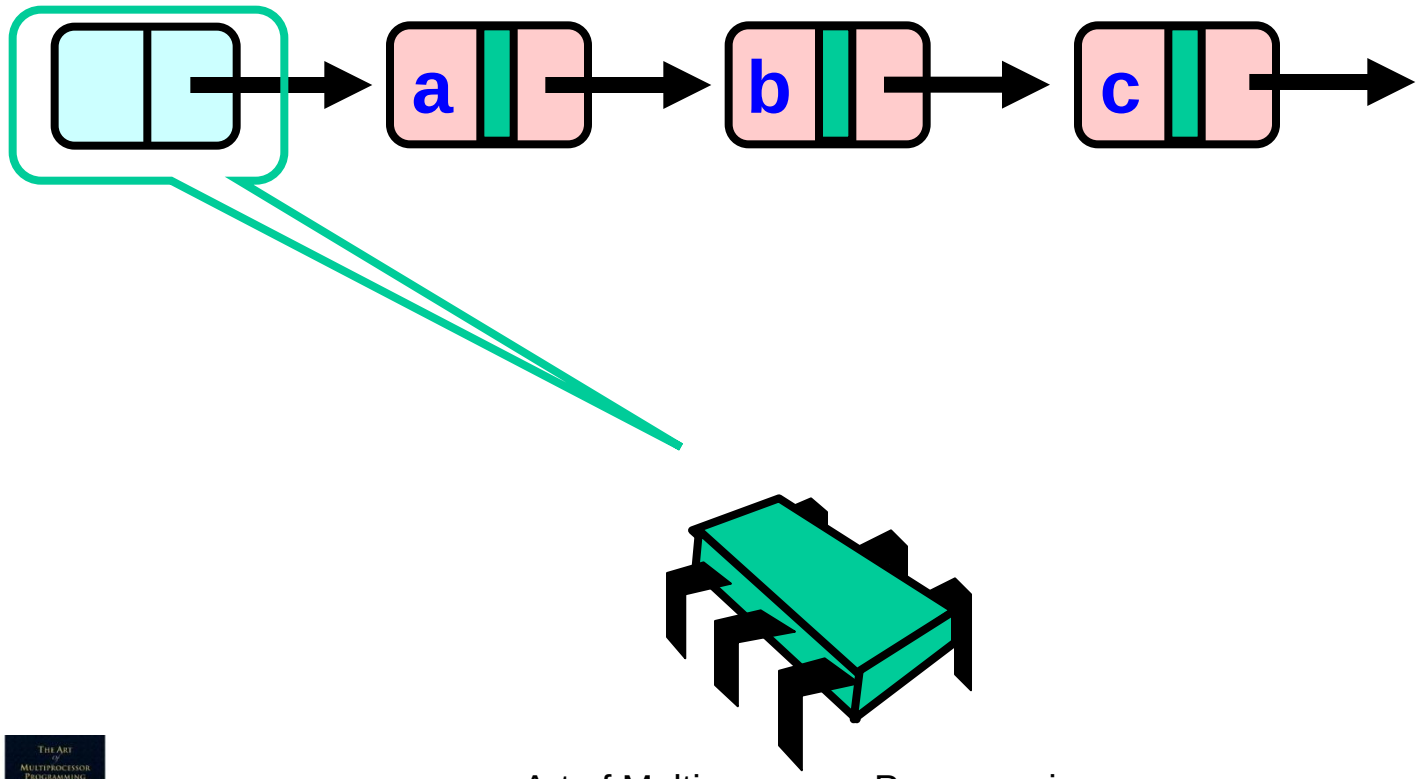


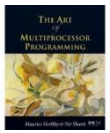
Validation

- No need to rescan list!
- Check that pred is not marked
- Check that curr is not marked
- Check that pred points to curr

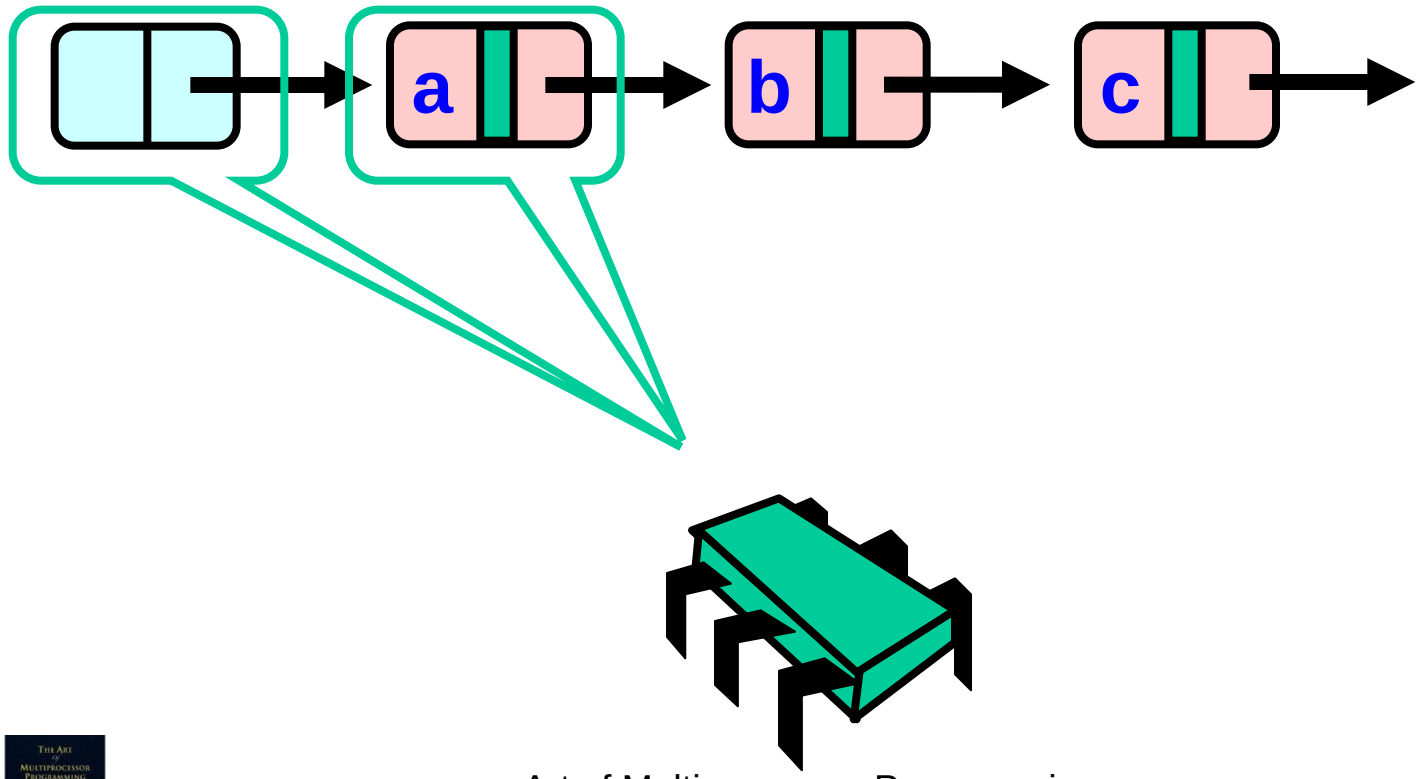


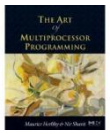
Business as Usual





Business as Usual





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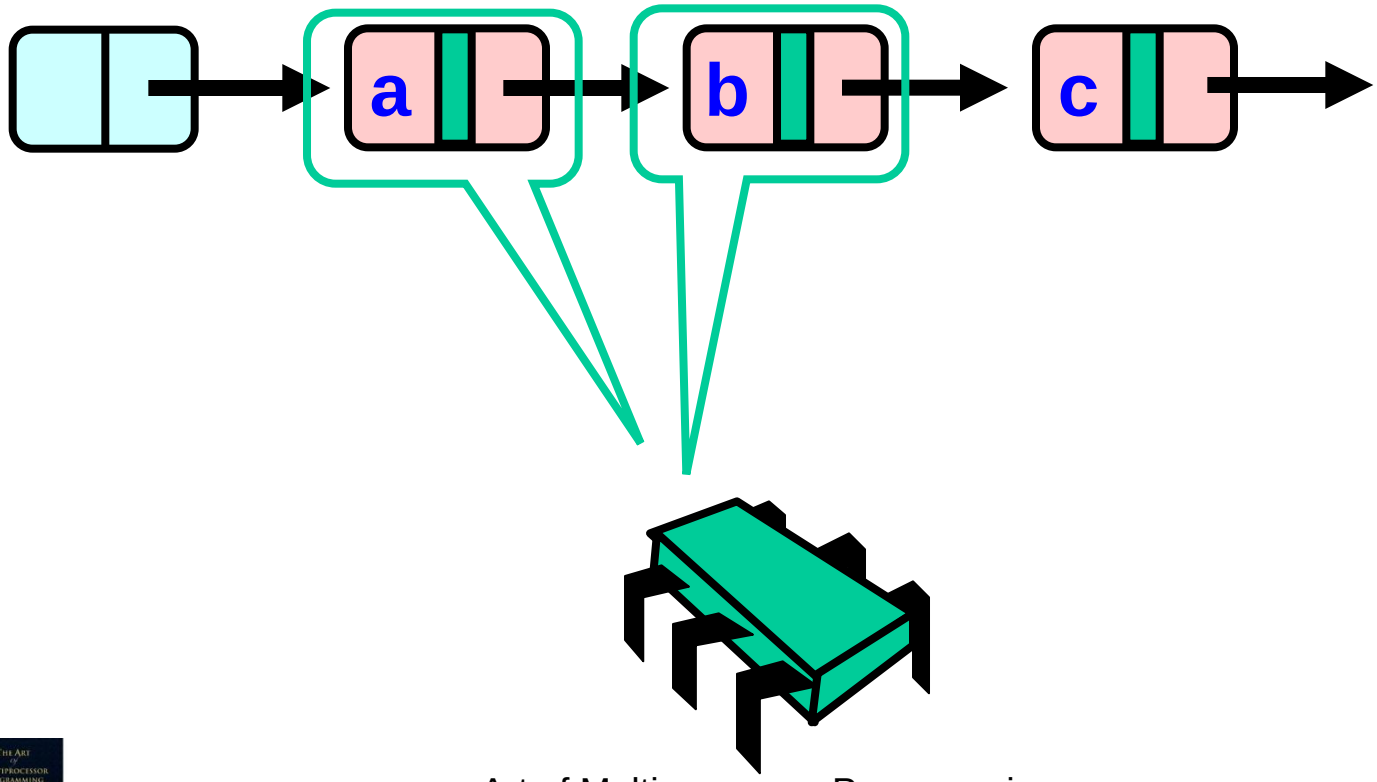

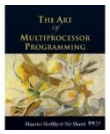

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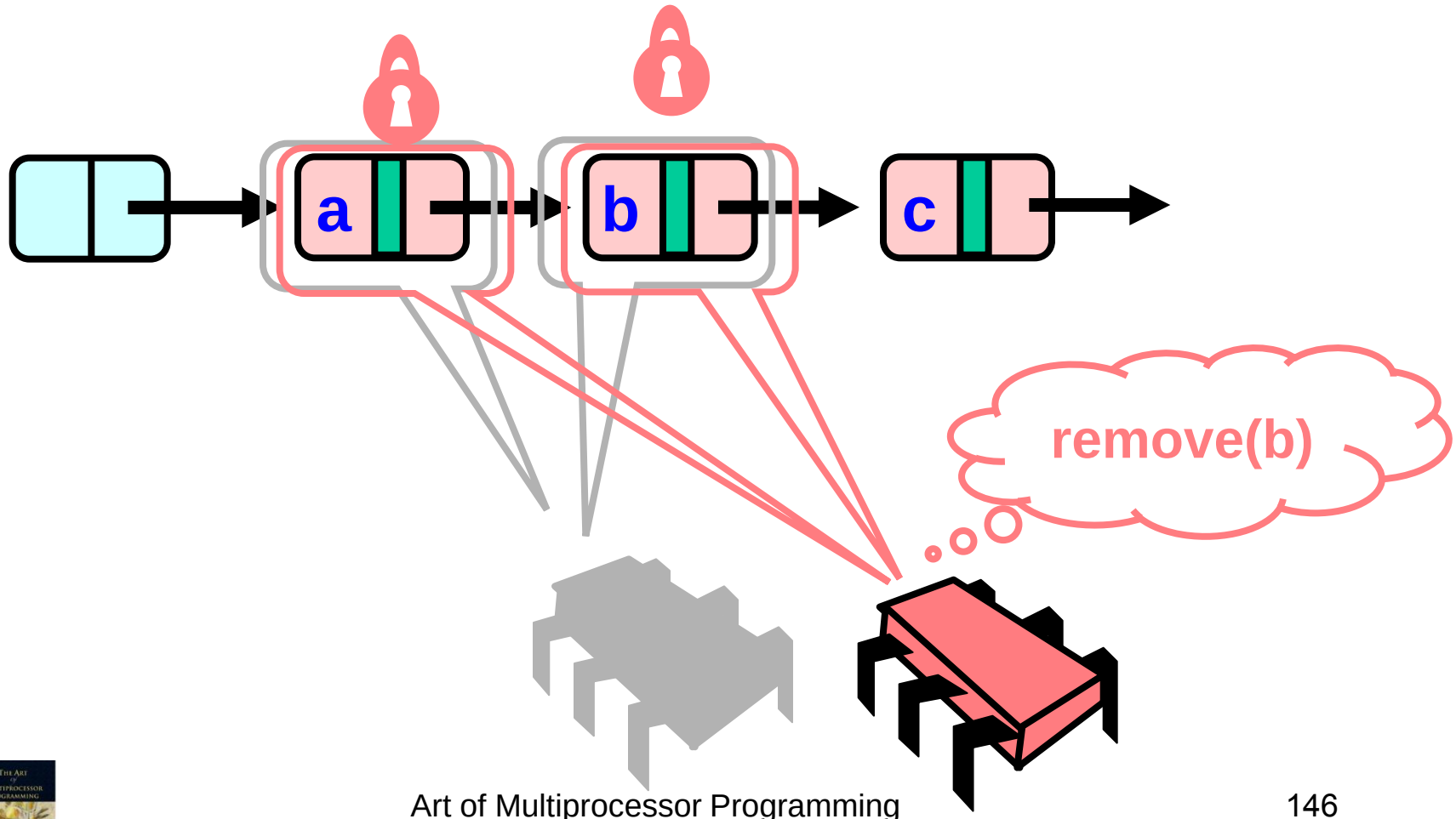
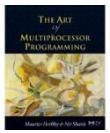
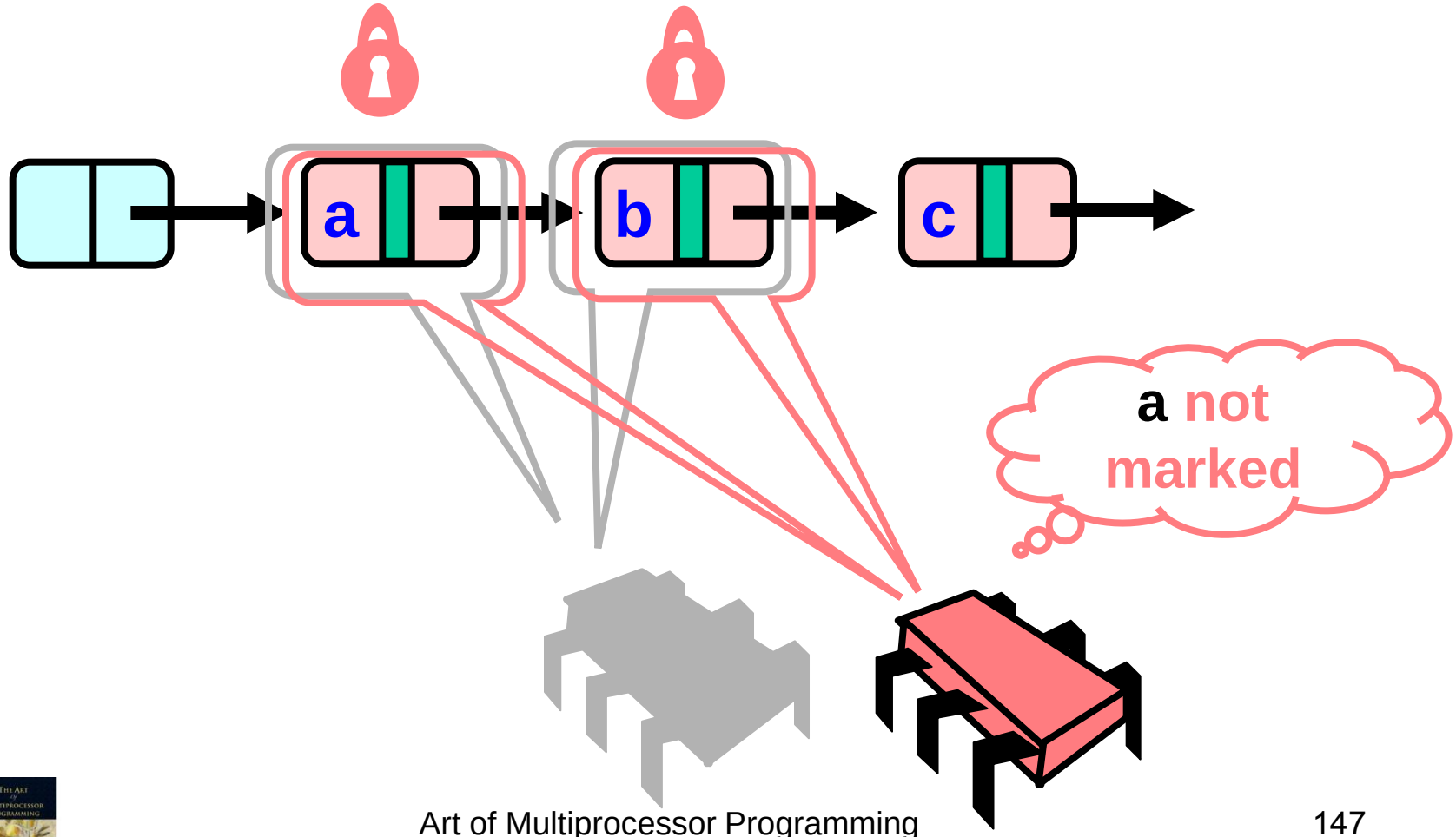
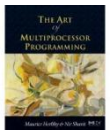




Business as Usual





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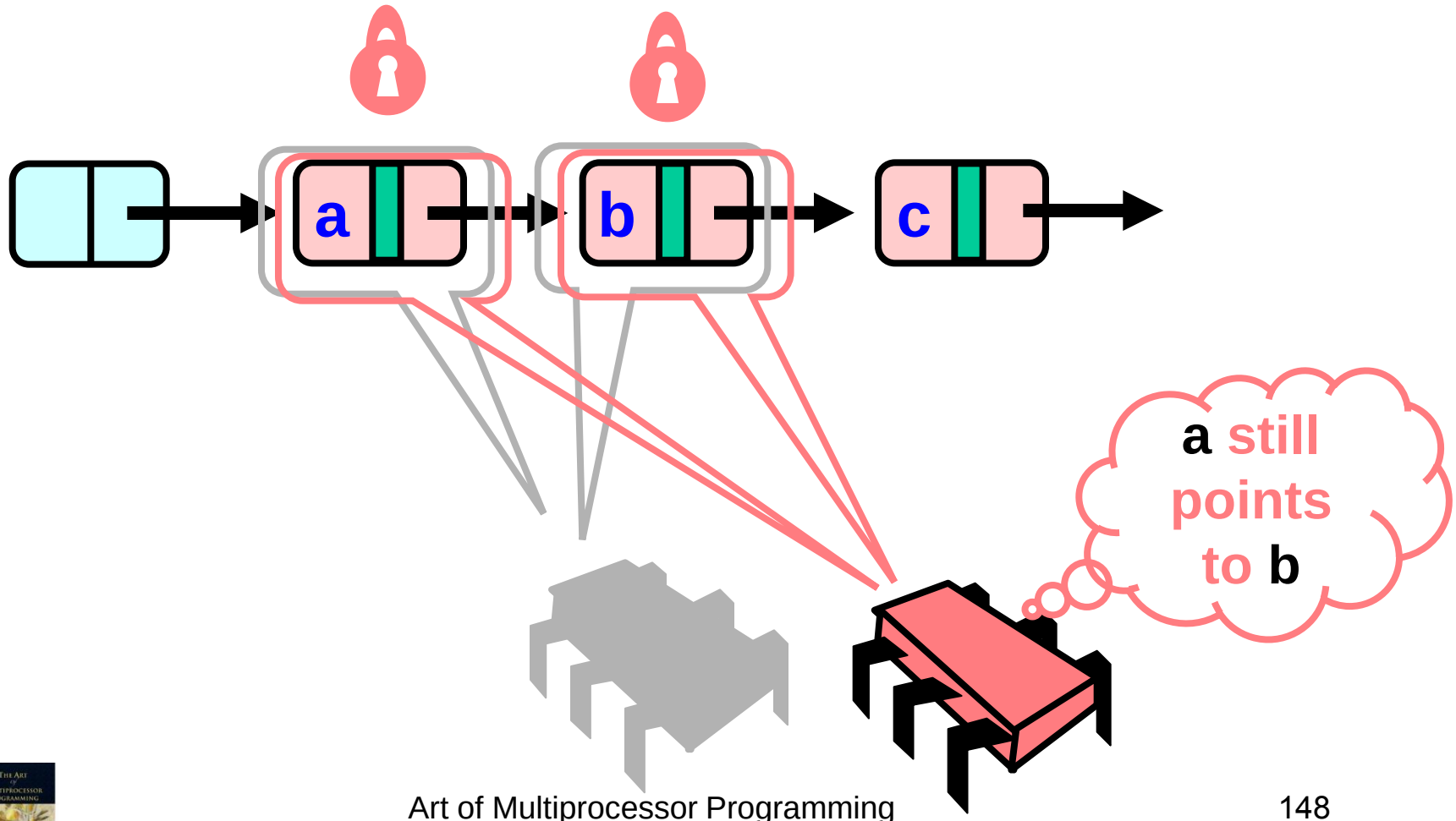

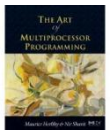

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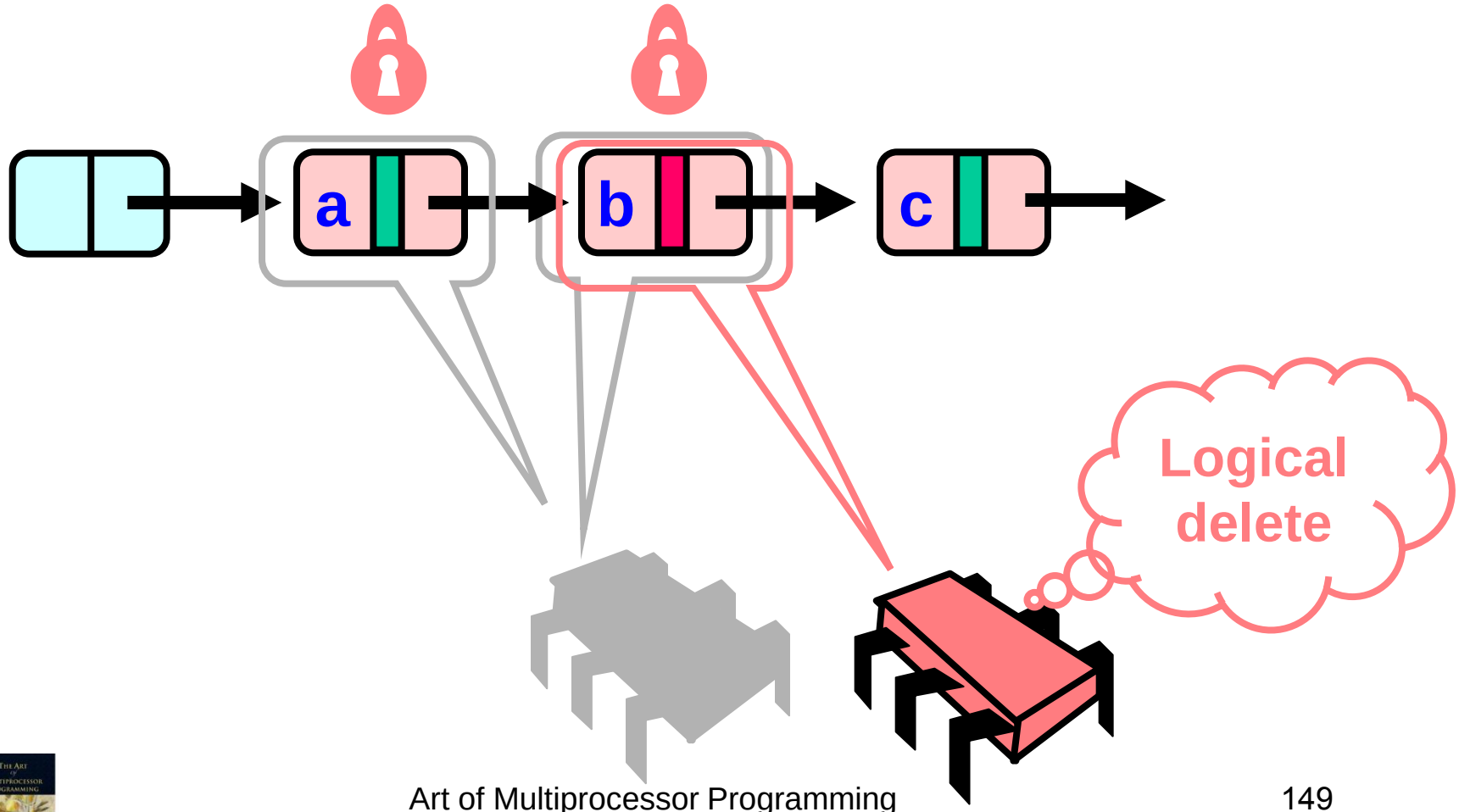

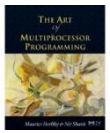

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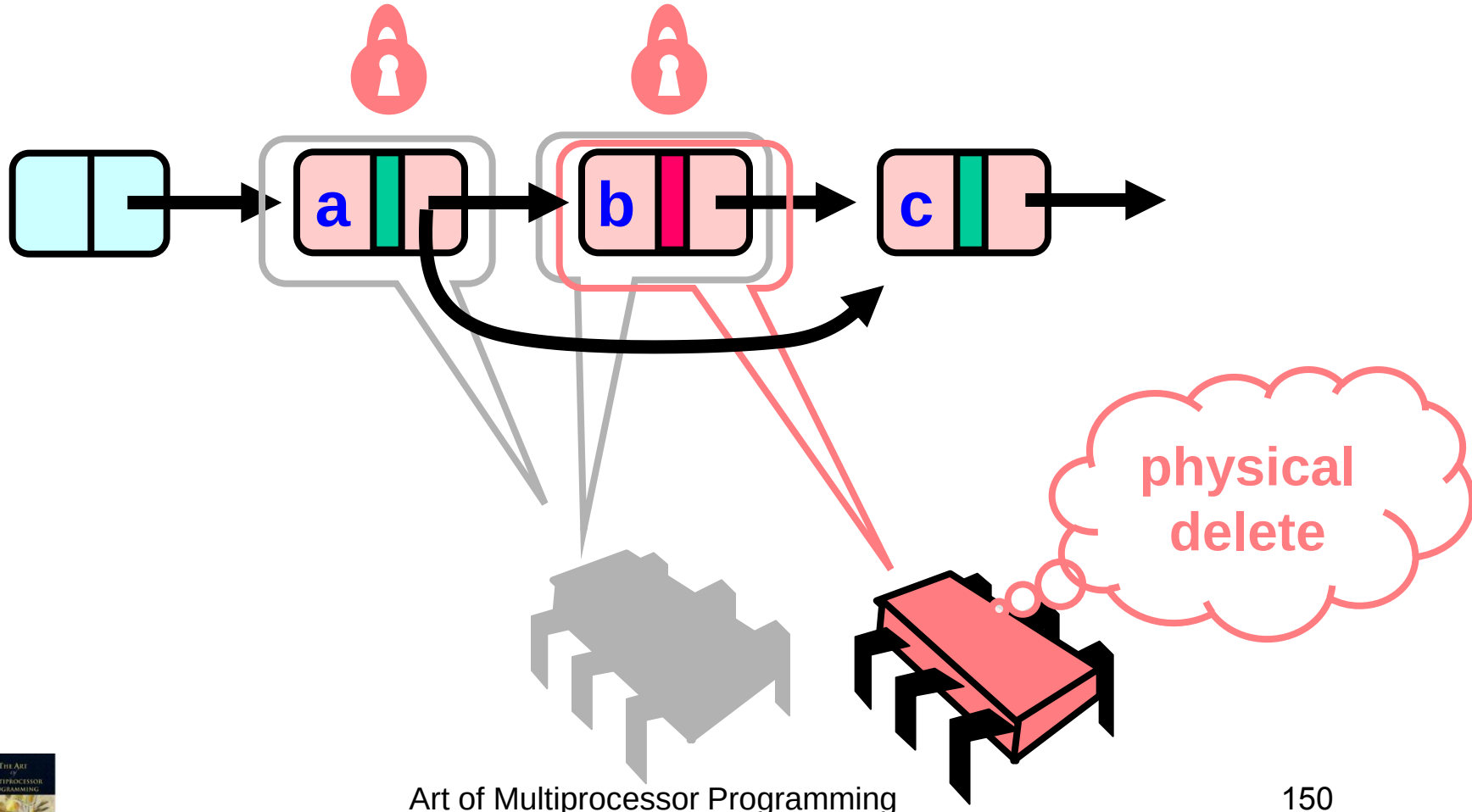
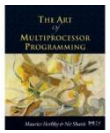
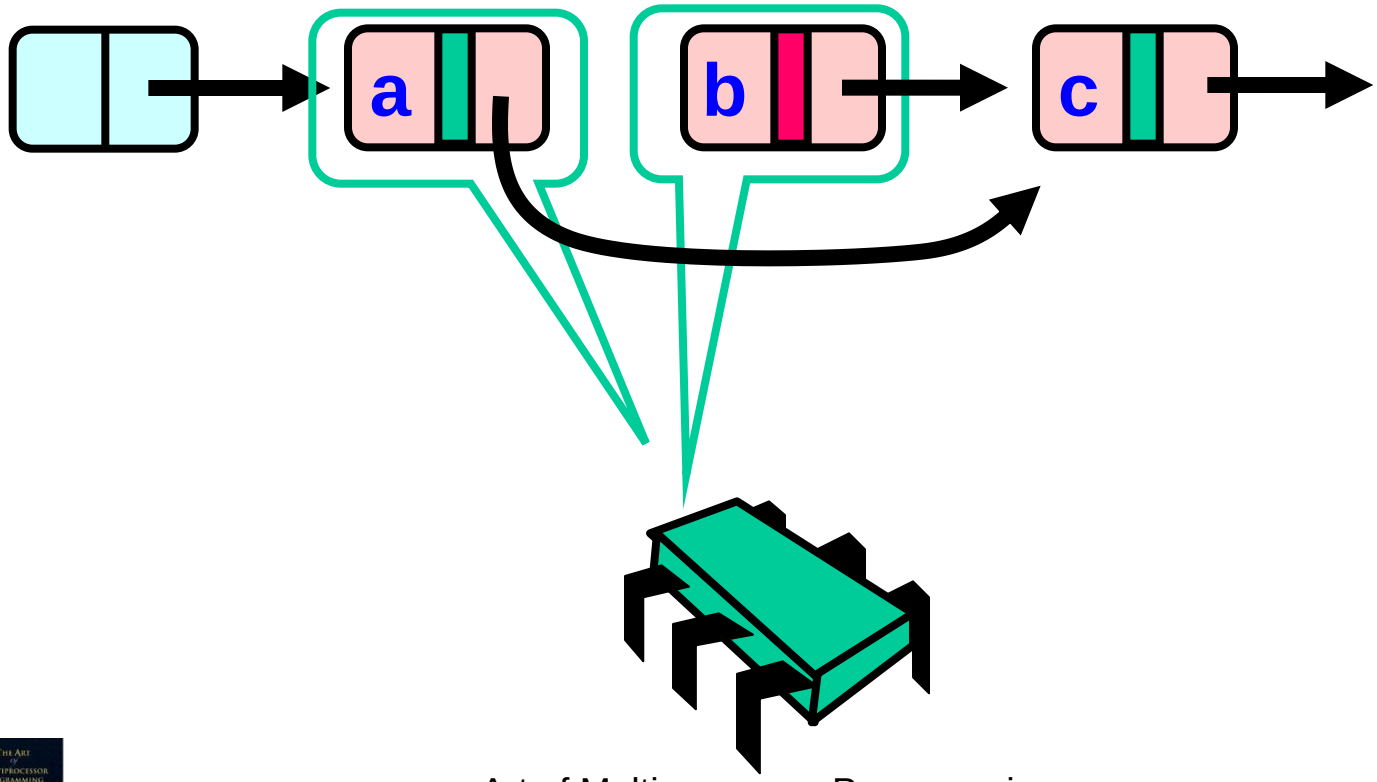
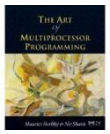




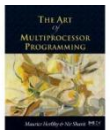
Business as Usual





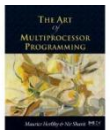
Invariant

- An item is in the set if
  - not marked
  - reachable from head
  - and if not yet traversed it is reachable from pred



Validation

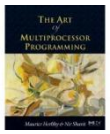
```
private boolean
  validate(Node pred, Node curr) {
 return
  !pred.marked &&
  !curr.marked &&
  pred.next == curr);
  }
```



List Validate Method

```
private boolean
  validate(Node pred, Node curr) {
 return
  !pred.marked &&
  !curr.marked &&
  pred.next == curr);
  }
```

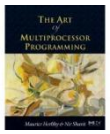
Predecessor not Logically removed



List Validate Method

```
private boolean
  validate(Node pred, Node curr) {
 return
  !pred.marked &&
  !curr.marked &&
  pred.next == curr);
  }
```

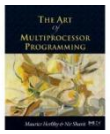
Current not Logically removed



List Validate Method

```
private boolean
  validate(Node pred, Node curr) {
 return
  !pred.marked &&
  !curr.marked &&
  pred.next == curr);
  }
```

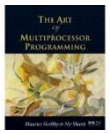
Predecessor still
Points to current



Contains

```
public boolean contains(Item item) {
  int key = item.hashCode();
  Node curr = this.head;
  while (curr.key < key) {
    curr = curr.next;
  }
  return curr.key == key && !curr.marked;
}
```

Start at the head



Contains

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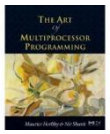
  while (curr.key < key) {
    curr = curr.next;
  }
  return curr.key == key && !curr.marked;
}
```

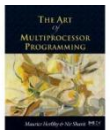
Search key range



Contains

```
public boolean contains(Item item) {
  int key = item.hashCode();
  Node curr = this.head;
  while (curr.key < key) {
    curr = curr.next;
  }
  return curr.key == key && !curr.marked;
}
```

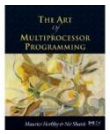
Traverse without locking
(nodes may have been removed)



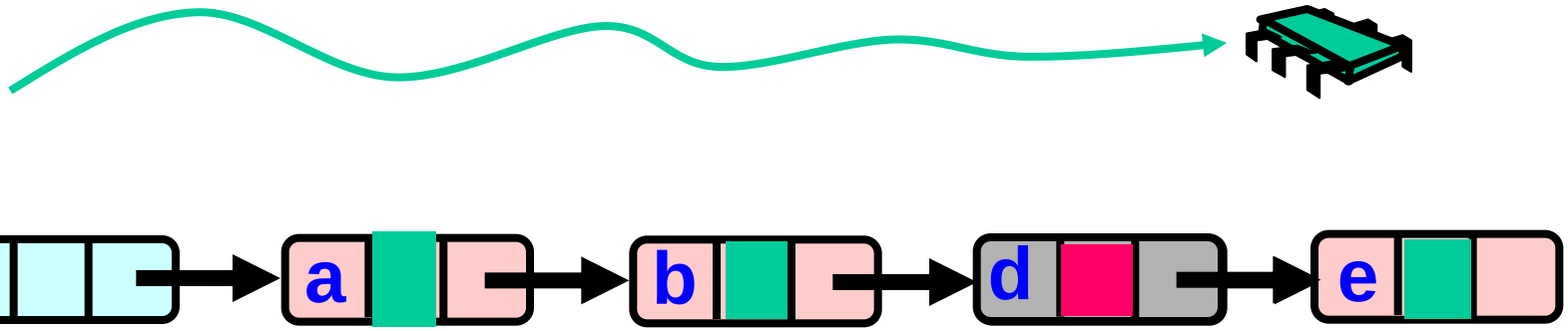
Contains

```
public boolean contains(Item item) {
  int key = item.hashCode();
  Node curr = this.head;
  while (curr.key < key) {
    curr = curr.next;
  }
  return curr.key == key && !curr.marked;
}
```

Present and undeleted?

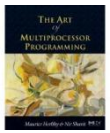


Summary: Wait-free Contains

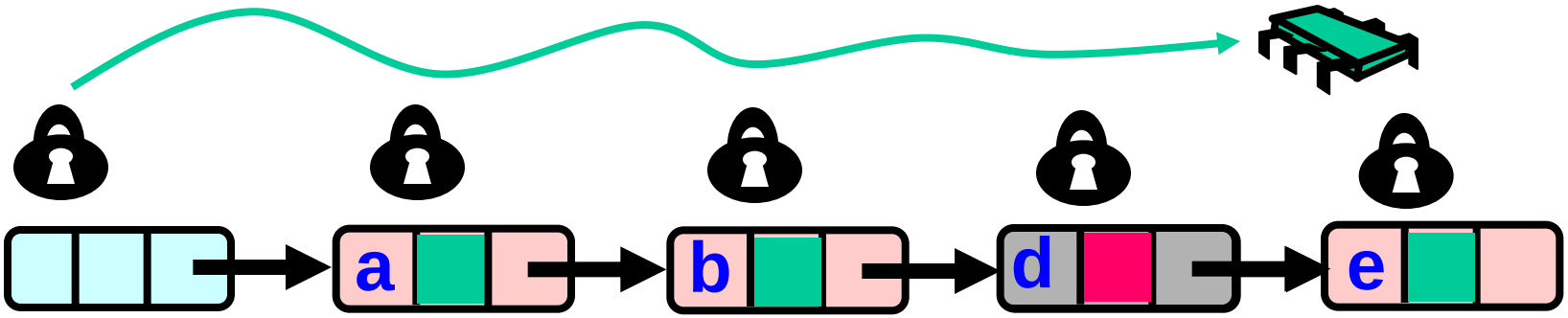


Use Mark bit + list ordering

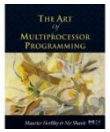
1. Not marked → in the set
2. Marked or missing → not in the set



Lazy List

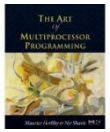


Lazy add() and remove() + Wait-free contains()



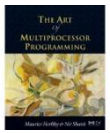
Evaluation

- Good:
  - contains() doesn't lock
  - In fact, its wait-free!
  - Good because typically high % contains()
  - Uncontended calls don't re-traverse
- Bad
  - Contended add() and remove() calls do re-traverse
  - Traffic jam if one thread delays



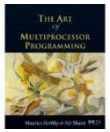
Traffic Jam

- Any concurrent data structure based on mutual exclusion has a weakness
- If one thread
  - Enters critical section
  - And “eats the big muffin”
    - Cache miss, page fault, descheduled …
  - Everyone else using that lock is stuck!
  - Need to trust the scheduler….



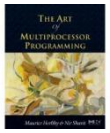
Reminder: Lock-Free Data Structures

- No matter what …
  - Guarantees minimal progress in any execution
  - i.e. Some thread will always complete a method call
  - Even if others halt at malicious times
  - Implies that implementation can't use locks



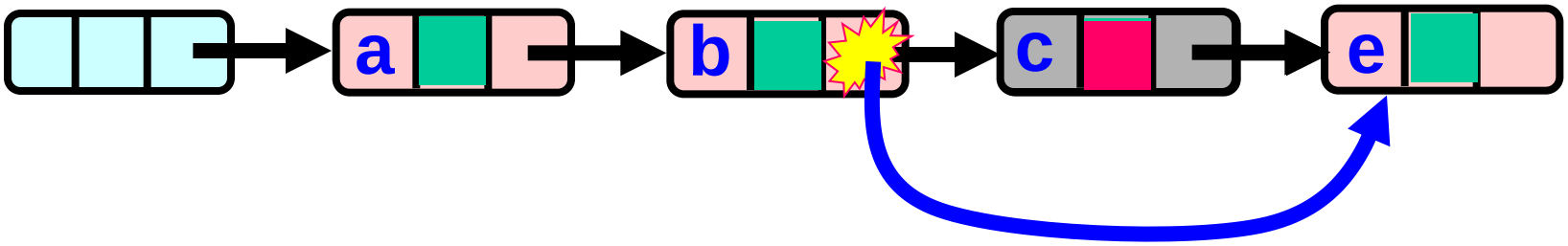
Lock-free Lists

- Next logical step
  - Wait-free contains()
  - lock-free add() and remove()
- Use only compareAndSet()
  - What could go wrong?



Lock-free Lists

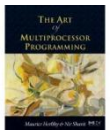
Logical Removal



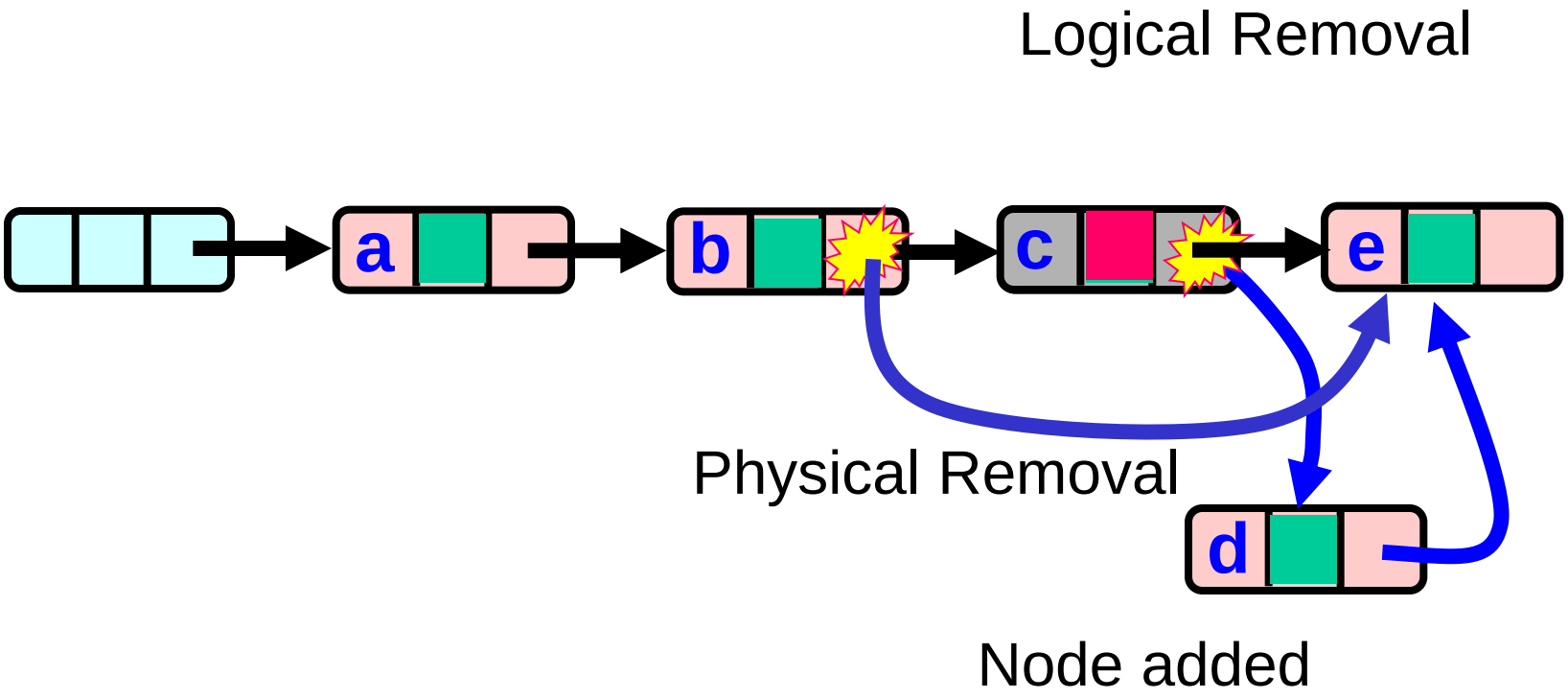
Physical Removal

Use CAS to verify pointer is correct

Not enough!

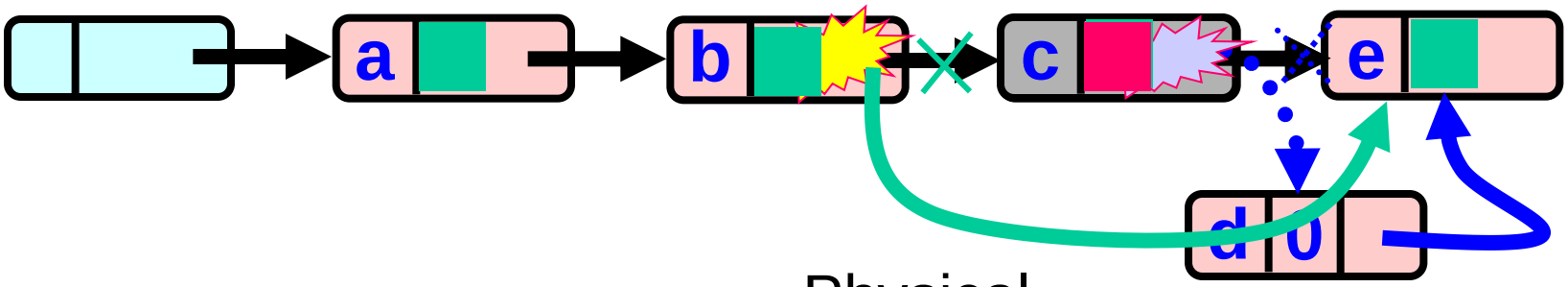


Problem…



The Solution: Combine Bit and Pointer

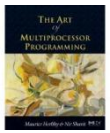
Logical Removal =
Set Mark Bit



Physical Removal CAS

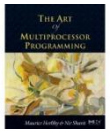
Failed CAS: Node not added after logical Removal

Mark-Bit and Pointer are CASed as one (`AtomicMarkableReference`)

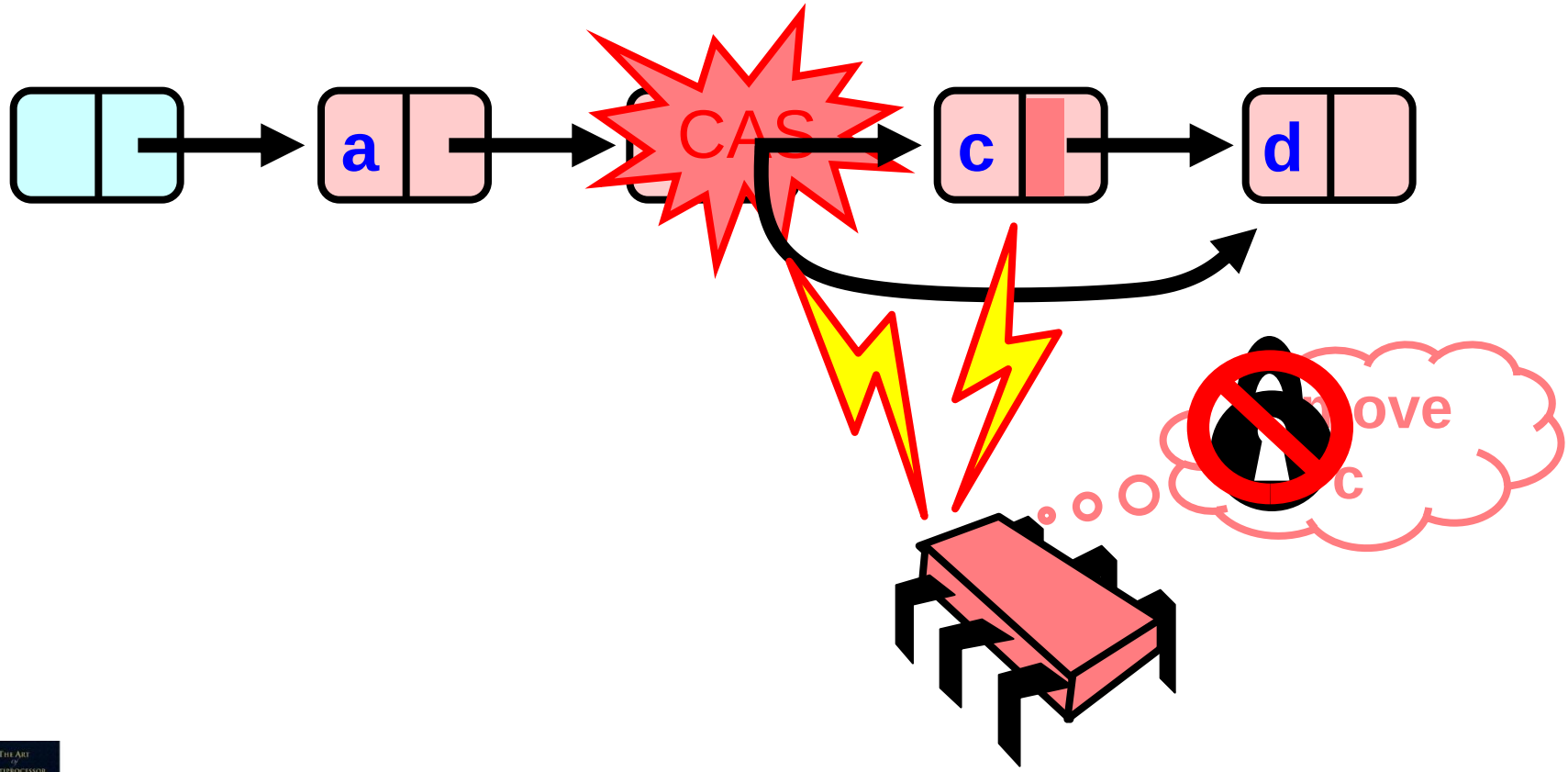


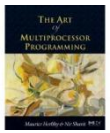
Solution

- Use AtomicMarkableReference
- Atomically
  - Swing reference and
  - Update flag
- Remove in two steps
  - Set mark bit in next field
  - Redirect predecessor's pointer



Removing a Node





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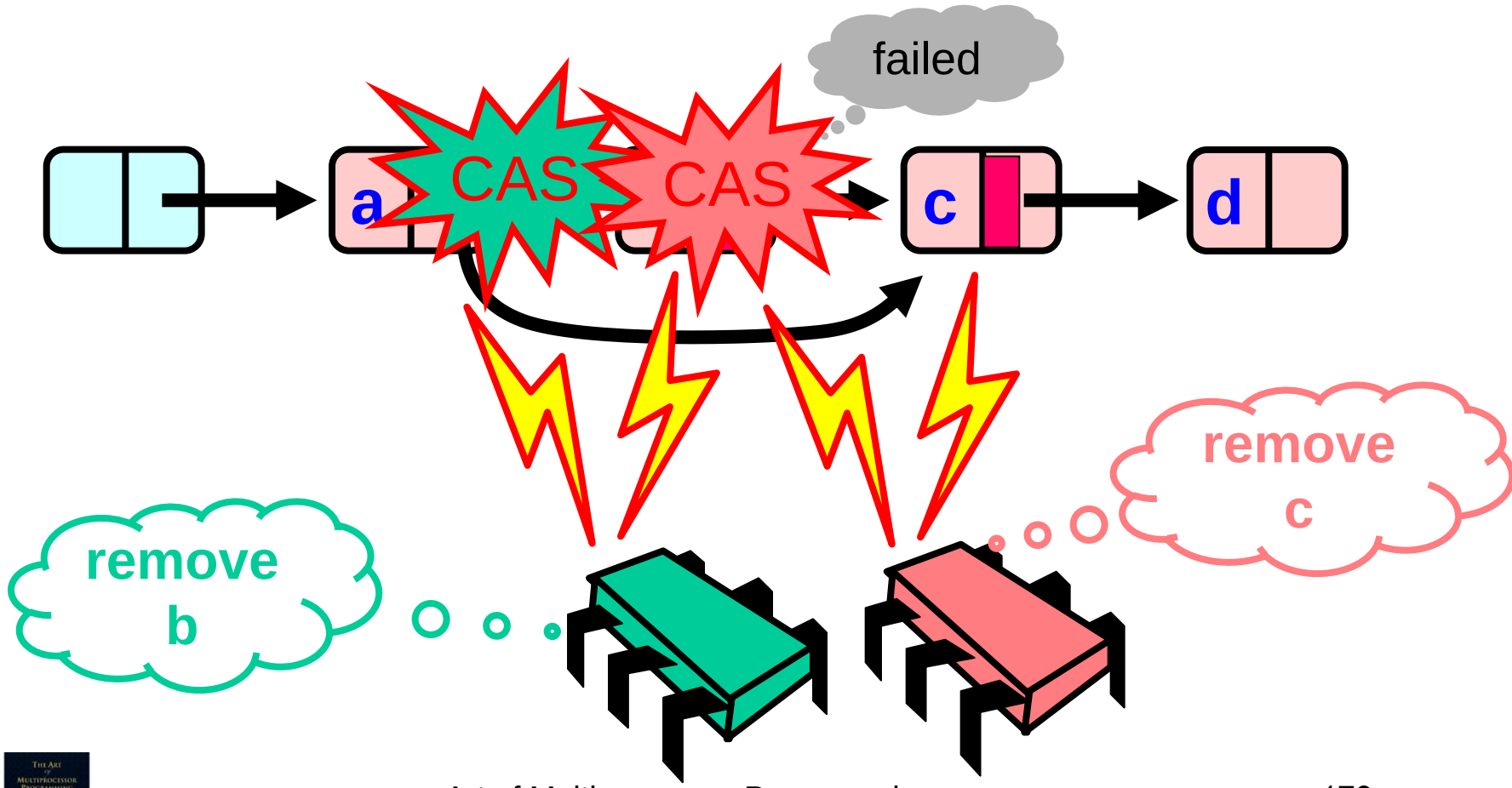

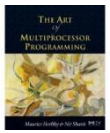

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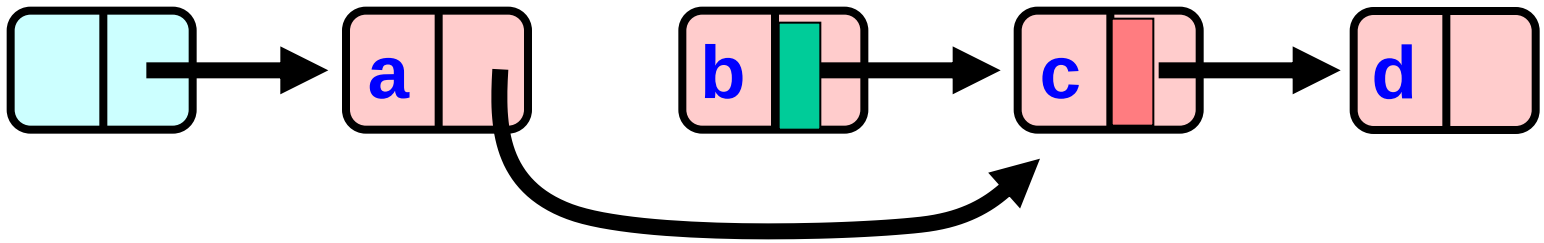
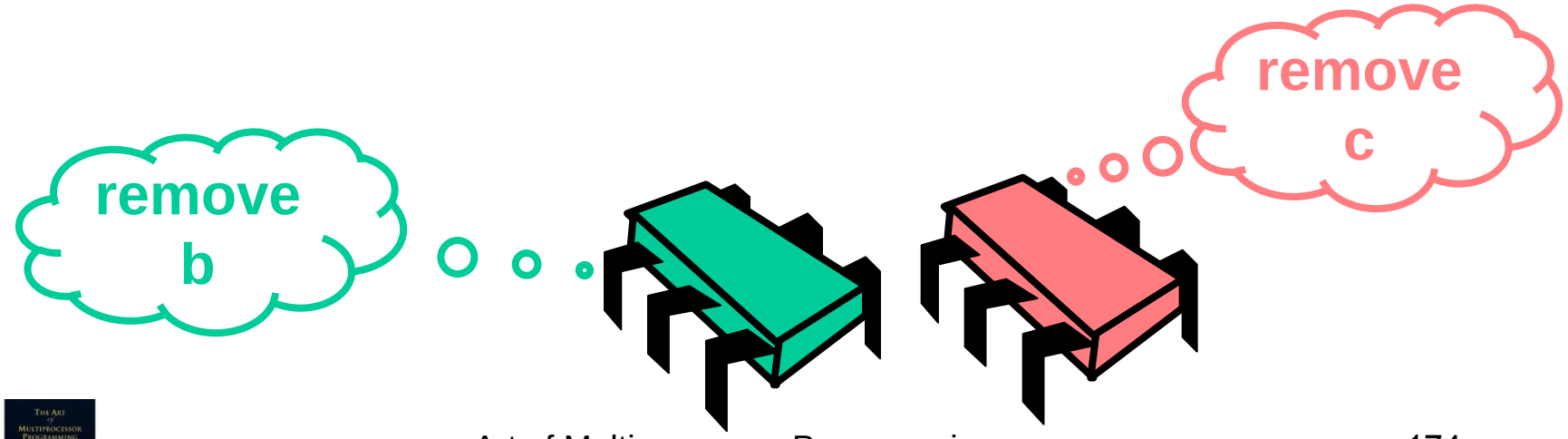
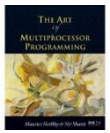
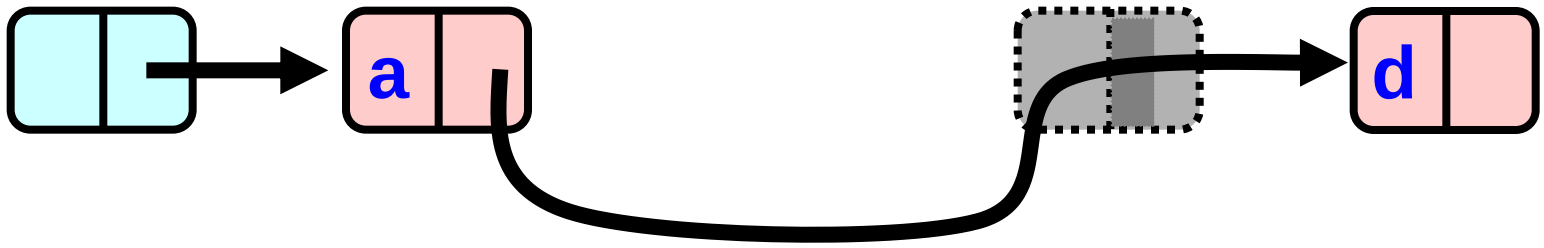
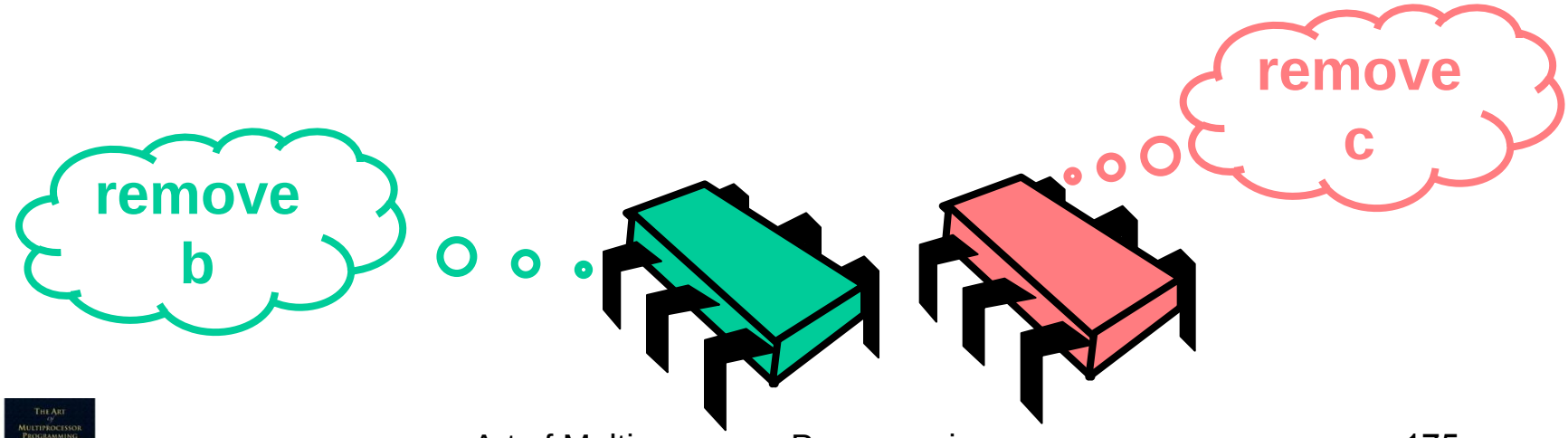


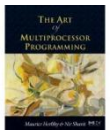




Removing a Node

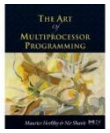




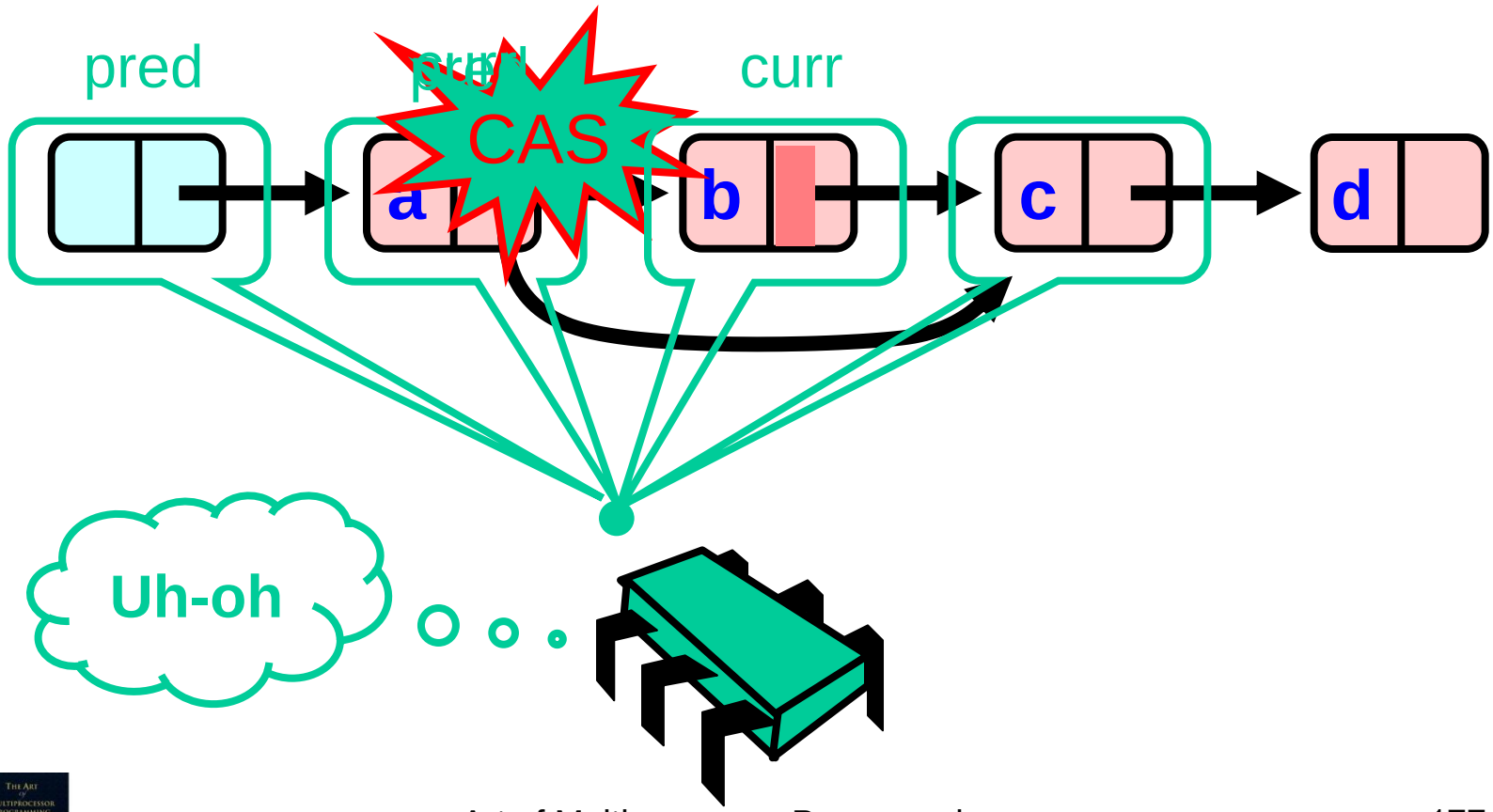


Traversing the List

- Q: what do you do when you find a "logically" deleted node in your path?
- A: finish the job.
  - CAS the predecessor's next field
  - Proceed (repeat as needed)

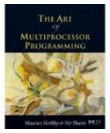


Lock-Free Traversal (only Add and Remove)

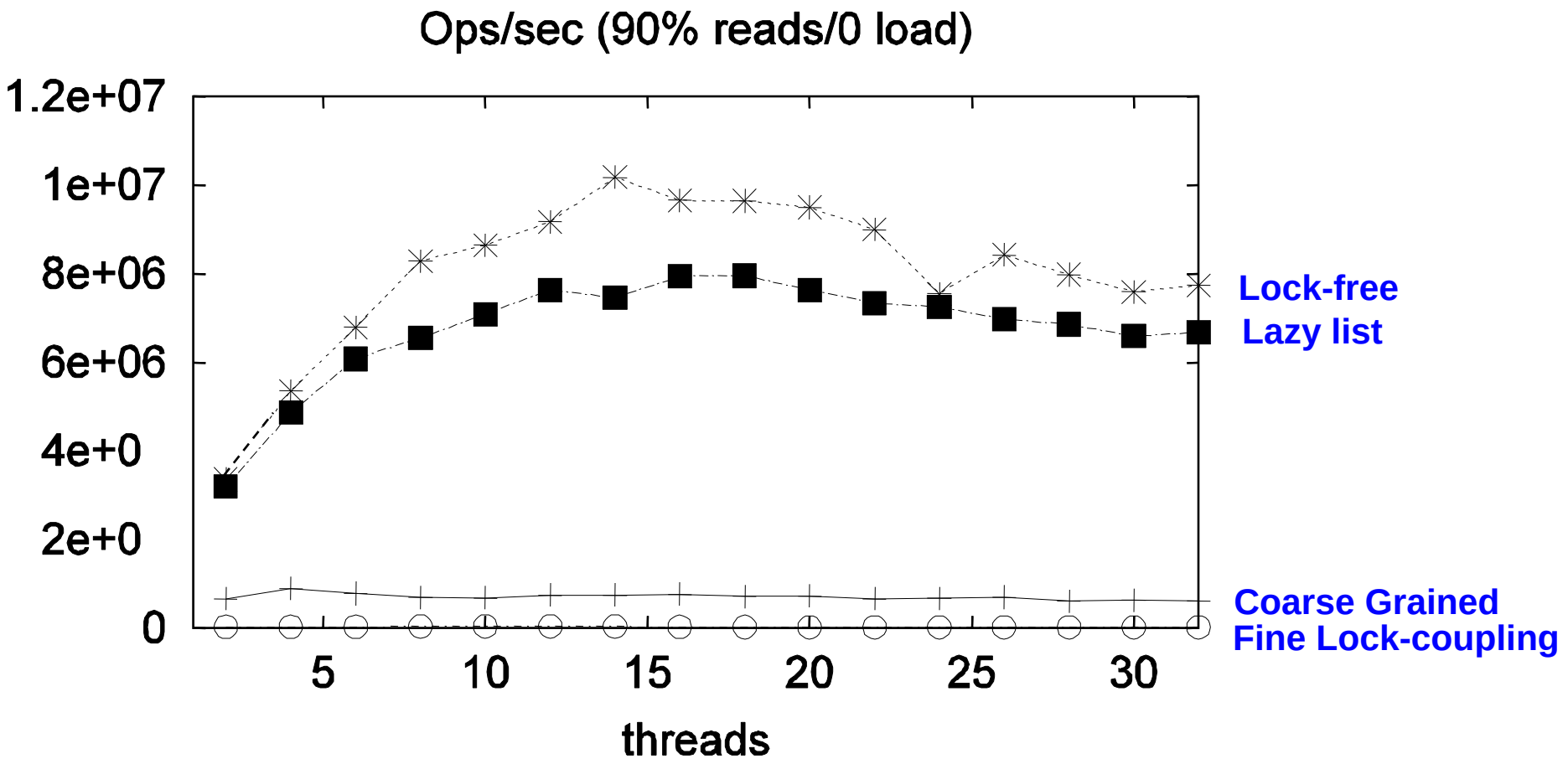


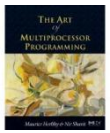
Performance

On 16 node shared memory machine
Benchmark throughput of Java List-based Set algs. Vary % of Contains() method Calls.

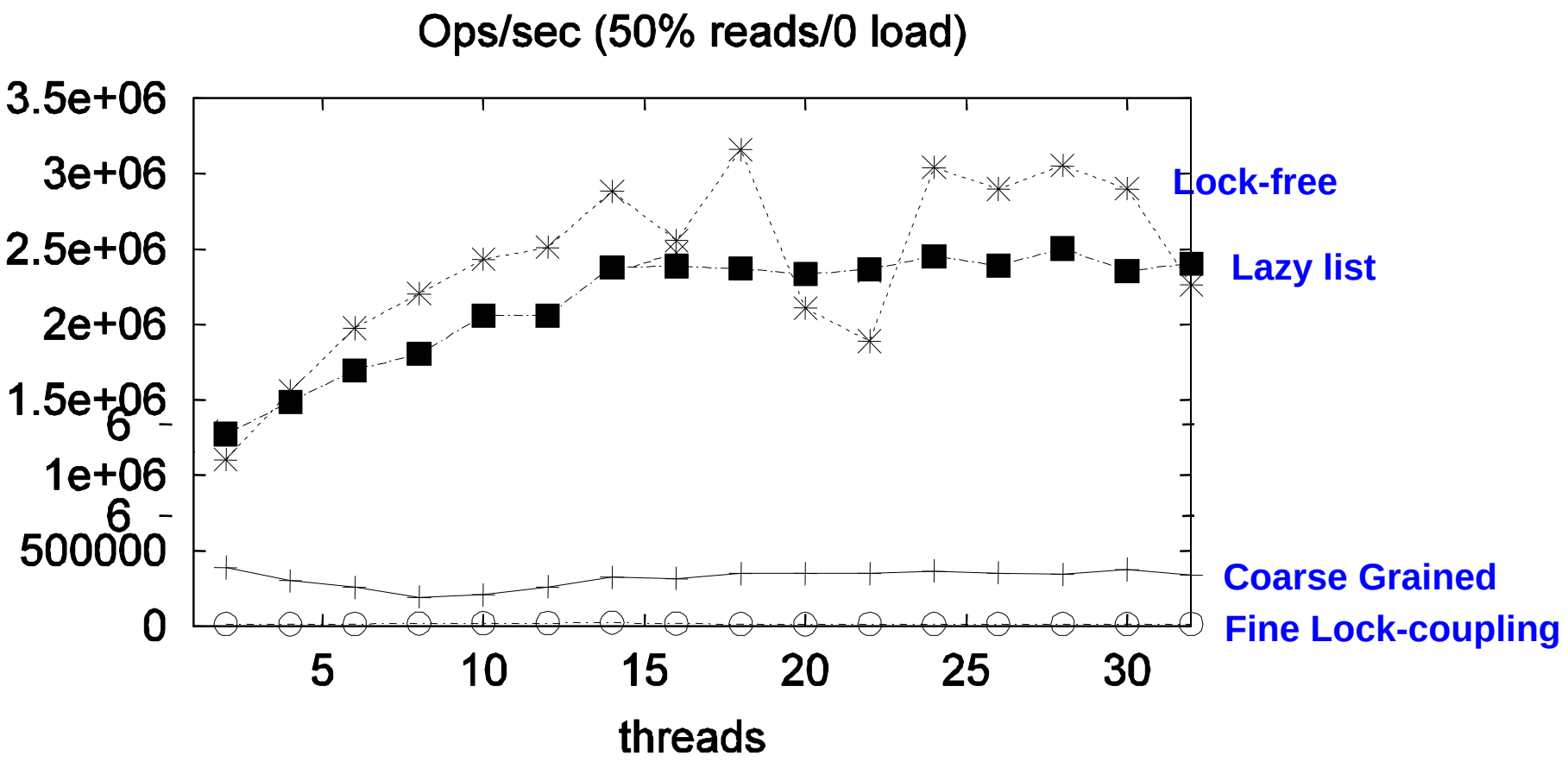


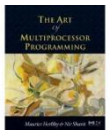
High Contains Ratio



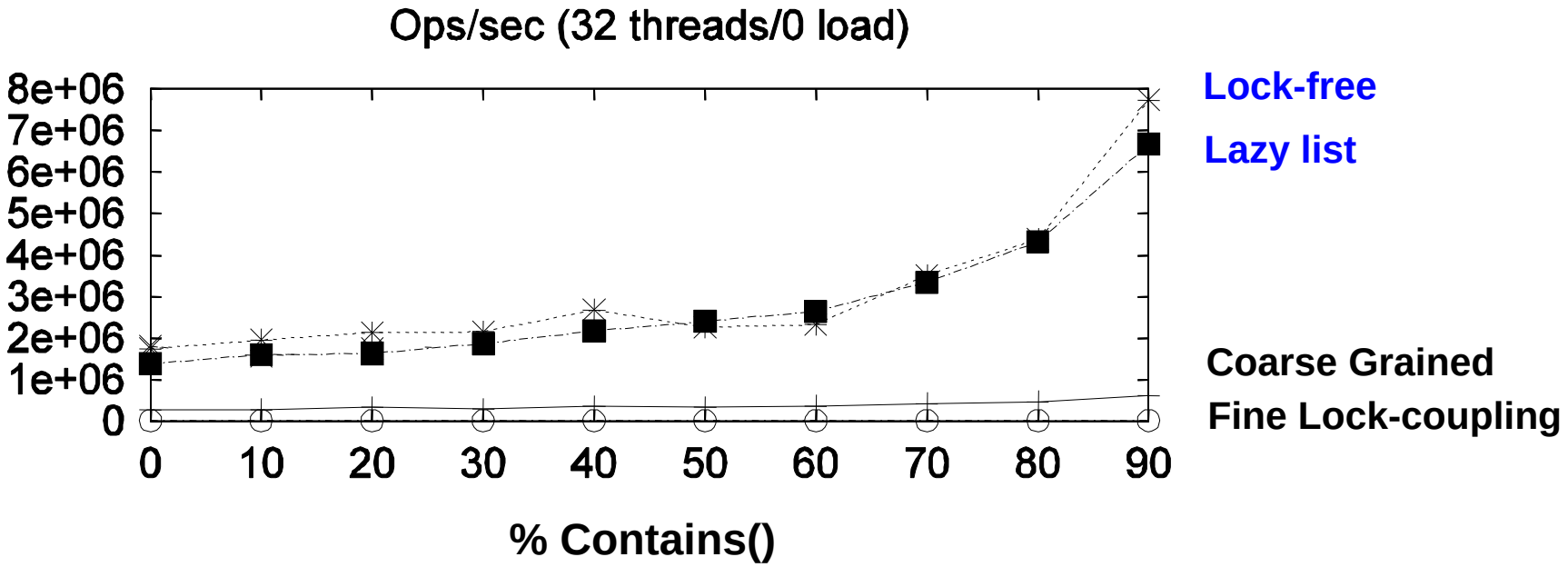


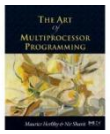
Low Contains Ratio





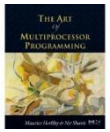
As Contains Ratio Increases





Summary

- Coarse-grained locking
- Fine-grained locking
- Optimistic synchronization
- Lock-free synchronization



“To Lock or Not to Lock”

- Locking vs. Non-blocking: Extremist views on both sides
- The answer: nobler to compromise, combine locking and non-blocking
  - Example: Lazy list combines blocking add() and remove() and a wait-free contains()
  - Remember: Blocking/non-blocking is a property of a method