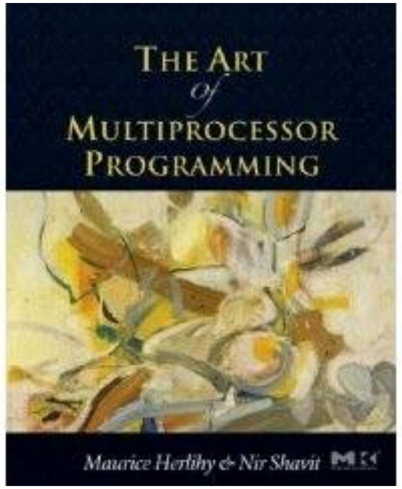
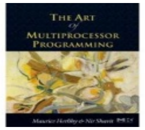
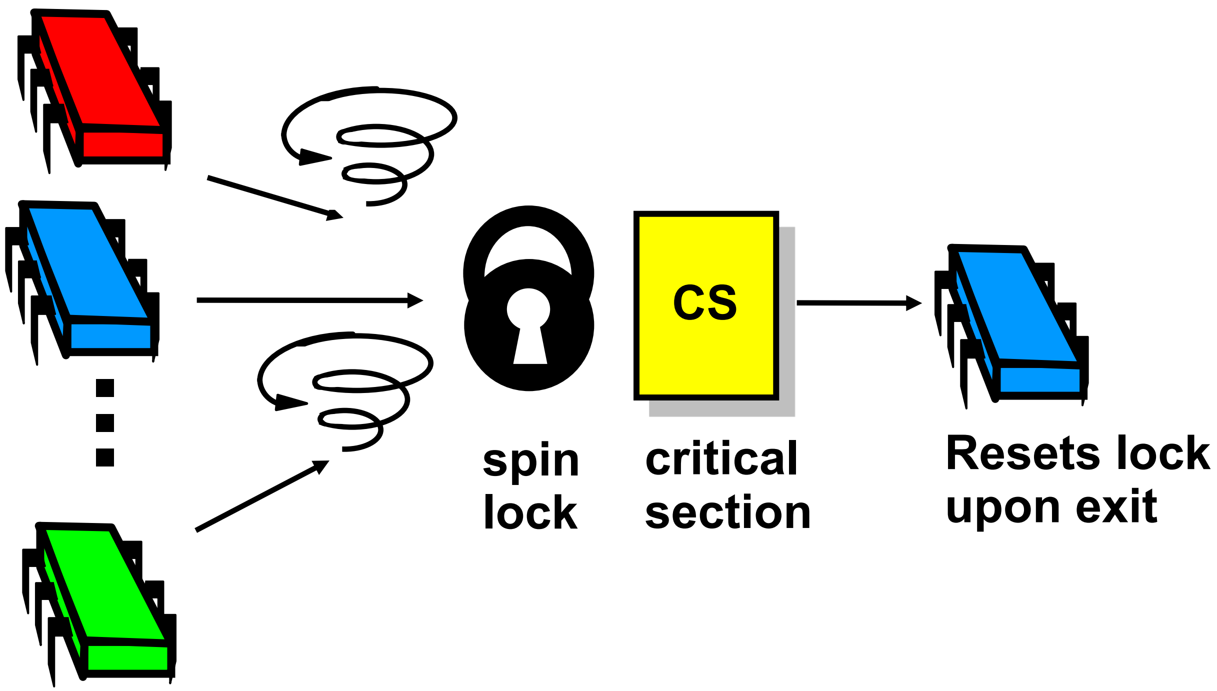
Linked Lists: Locking, Lock-Free, and Beyond …



Hyungsoo Jung



Last Lecture: Spin-Locks



Today: Concurrent Objects

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

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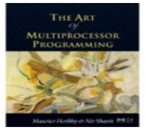
- Adding threads should not lower throughput
  - Contention effects
  - Mostly fixed by Queue locks
- Should increase throughput
  - Not possible if inherently sequential
  - Surprising things are parallelizable



Coarse-Grained Synchronization

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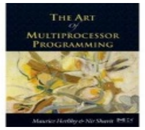
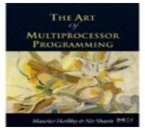
    - In simple cases



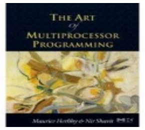
Coarse-Grained Synchronization

- Each method locks the object
  - Avoid contention using queue 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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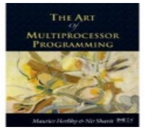
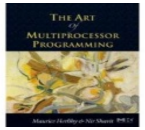


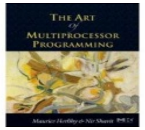
Coarse-Grained Synchronization

- 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 …

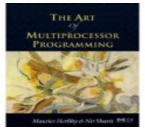


This Lecture

- 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 …
- 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 …
- Advantages
  - No Scheduler Assumptions/Support
- Disadvantages
  - Complex
  - Sometimes high overhead

Linked List

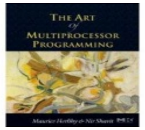
- Illustrate these patterns …
- Using a list-based Set
  - Common application
  - Building block for other apps

Set Interface

- Unordered collection of items
- 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

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



List-Based Sets

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public interface Set<T> {
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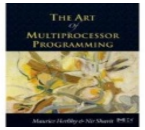
Add item to set



List-Based Sets

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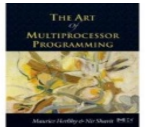
Remove item from set



List-Based Sets

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

Is item in set?

List Node

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

List Node

```
public class Node {
 public T item;
 public int key;
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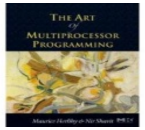
item of interest



List Node

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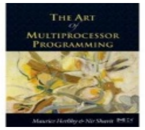
}
```

Usually hash code

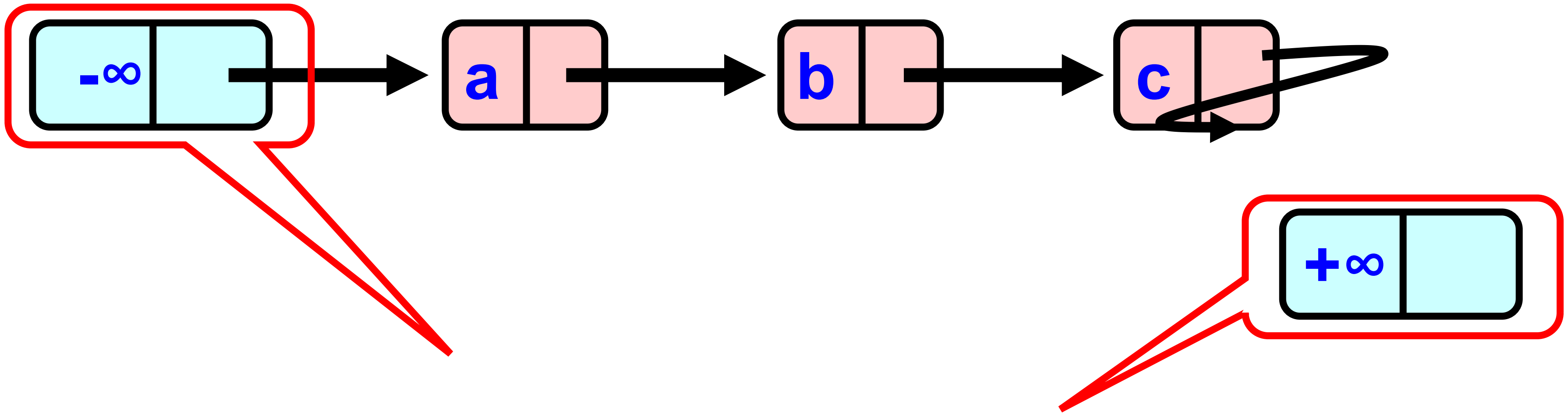
List Node

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

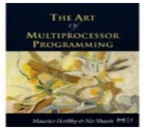
Reference to next node



The List-Based Set



Sorted with Sentinel nodes
(min & max possible keys)

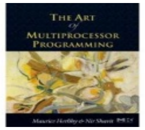


Reasoning about Concurrent Objects

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

Specifically …

- Invariants preserved by
  - `add()`
  - `remove()`
  - `contains()`
- Most steps are trivial
  - Usually one step tricky
  - Often linearization point

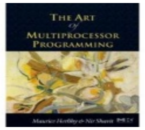


Interference

- Invariants make sense only if
  - methods considered
  - are the only modifiers

Interference

- Invariants make sense only if
  - methods considered
  - are the only modifiers
- Language encapsulation helps
  - List nodes not visible outside class

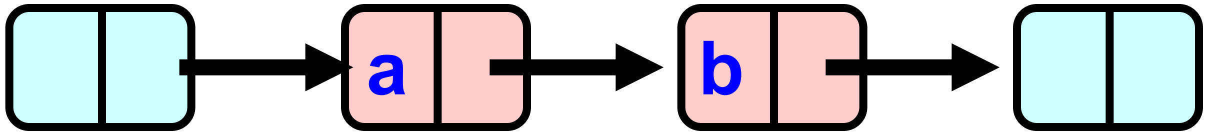


Interference

- Freedom from interference needed even for removed nodes
  - Some algorithms traverse removed nodes
  - Careful with **malloc()** & **free()** !
- Garbage collection helps here

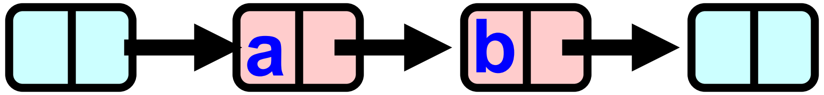
Abstract Data Types

- Concrete representation:



- Abstract Type:
  - {a, b}

Abstract Data Types

- Meaning of rep given by abstraction map
  - S() = {**a**,**b**}

Rep Invariant

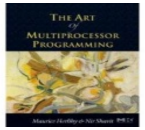
- Which concrete values meaningful?
  - Sorted?
  - Duplicates?
- Rep invariant
  - Characterizes legal concrete reps
  - Preserved by methods
  - Relied on by methods

Blame Game

- Rep invariant is a **contract**
- Suppose
  - **add()** leaves behind 2 copies of x
  - **remove()** removes only 1
- Which is incorrect?

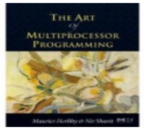
Blame Game

- Suppose
  - **add()** leaves behind 2 copies of x
  - **remove()** removes only 1
- Which is incorrect?
  - If rep invariant says *no duplicates*
    - **add()** is incorrect
  - Otherwise
    - **remove()** is incorrect



Rep Invariant (partly)

- Sentinel nodes
  - tail reachable from head
- Sorted
- No duplicates

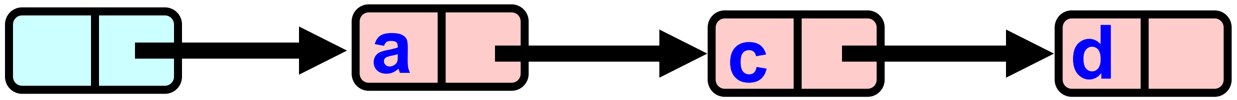


Abstraction Map

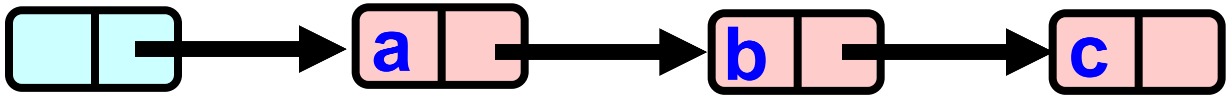
- S(head) =
  - { x | there exists a such that
    - a reachable from head and
    - a.item = x
  - }

Sequential List Based Set

Add()



Remove()



Sequential List Based Set

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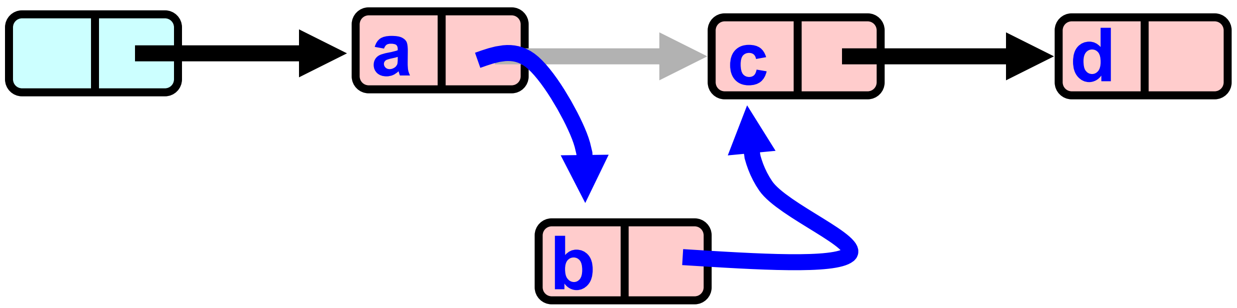
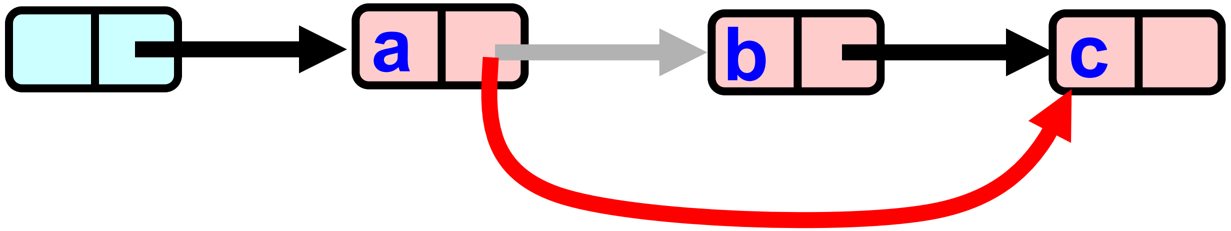
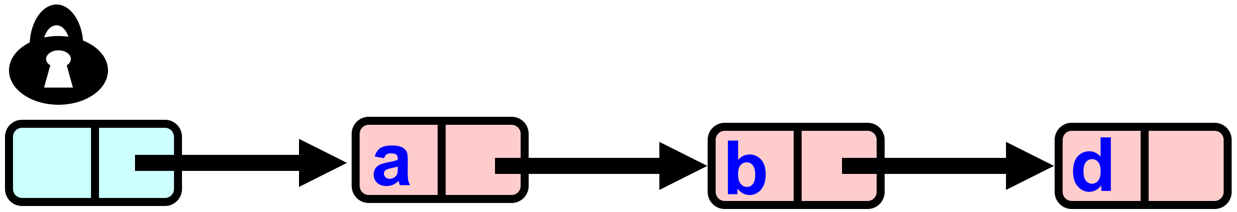


Remove()



Coarse-Grained Locking



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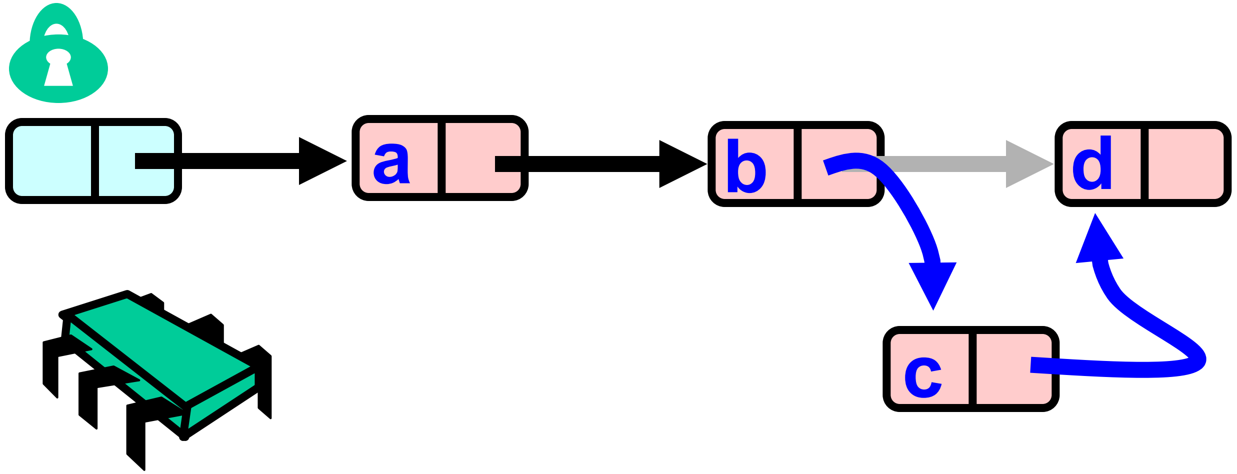

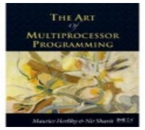

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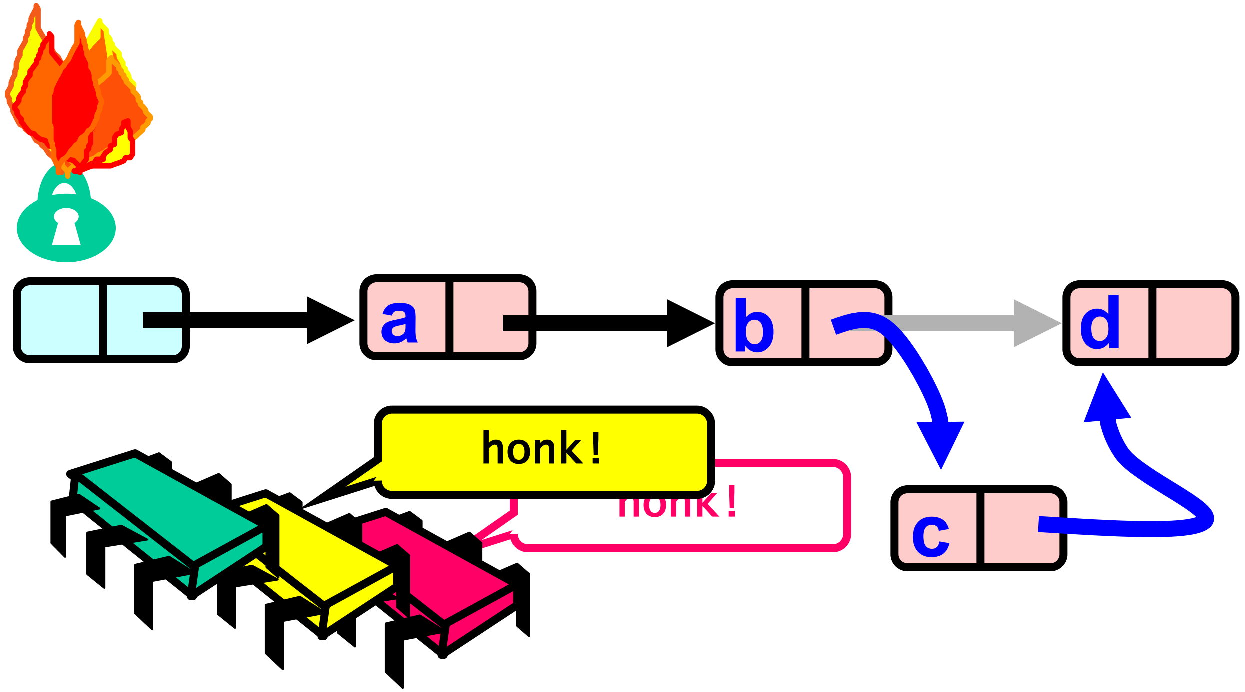
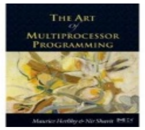


Simple but hotspot + bottleneck

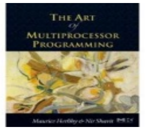


Coarse-Grained Locking

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

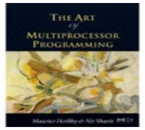
Coarse-Grained Locking

- 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



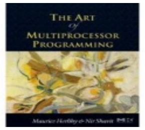
Fine-grained Locking

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

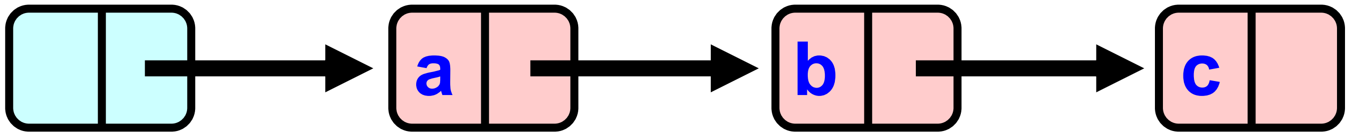


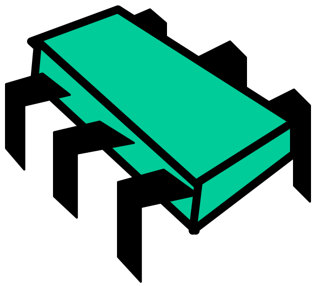
Fine-grained Locking

- 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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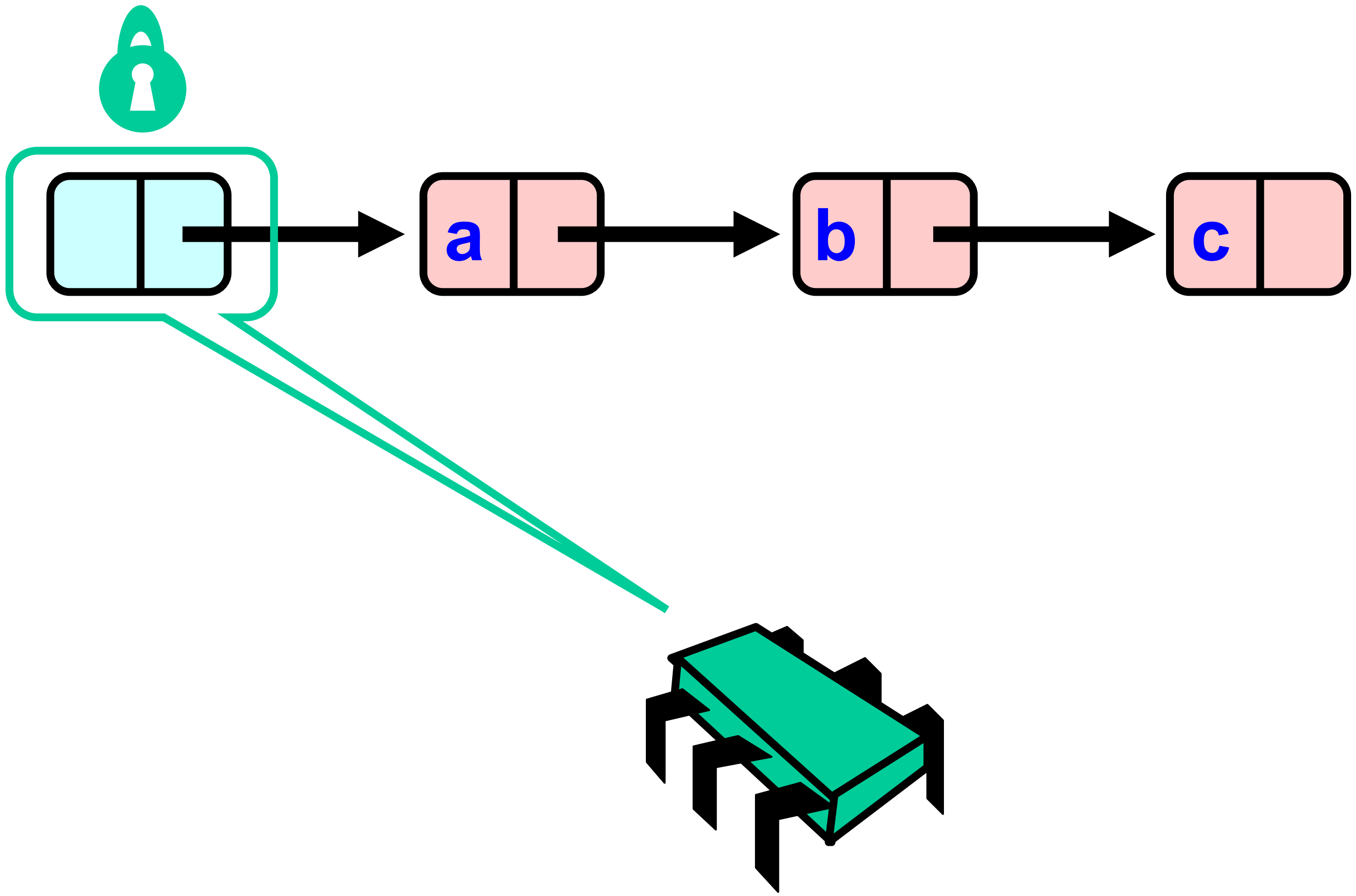

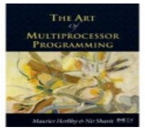

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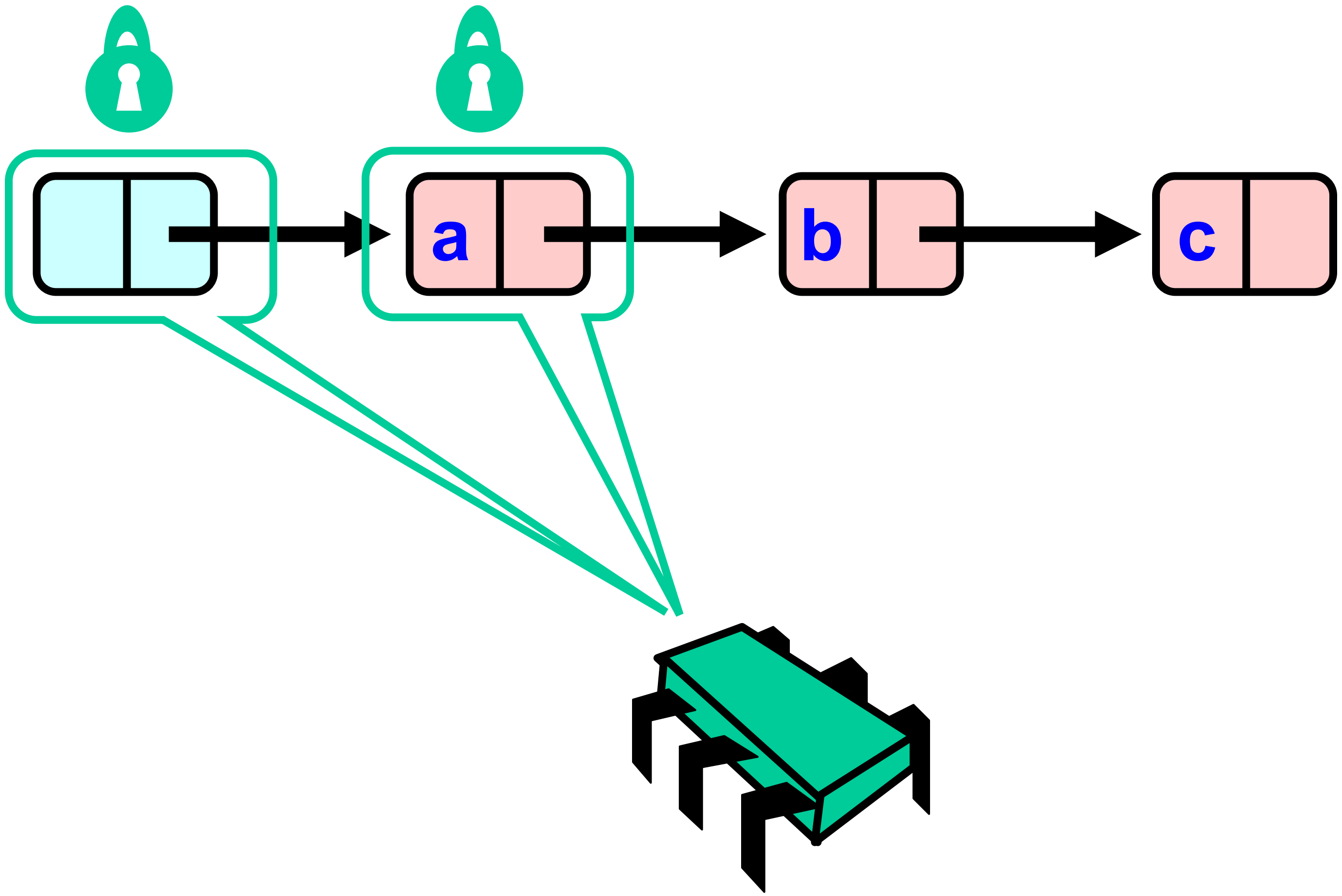

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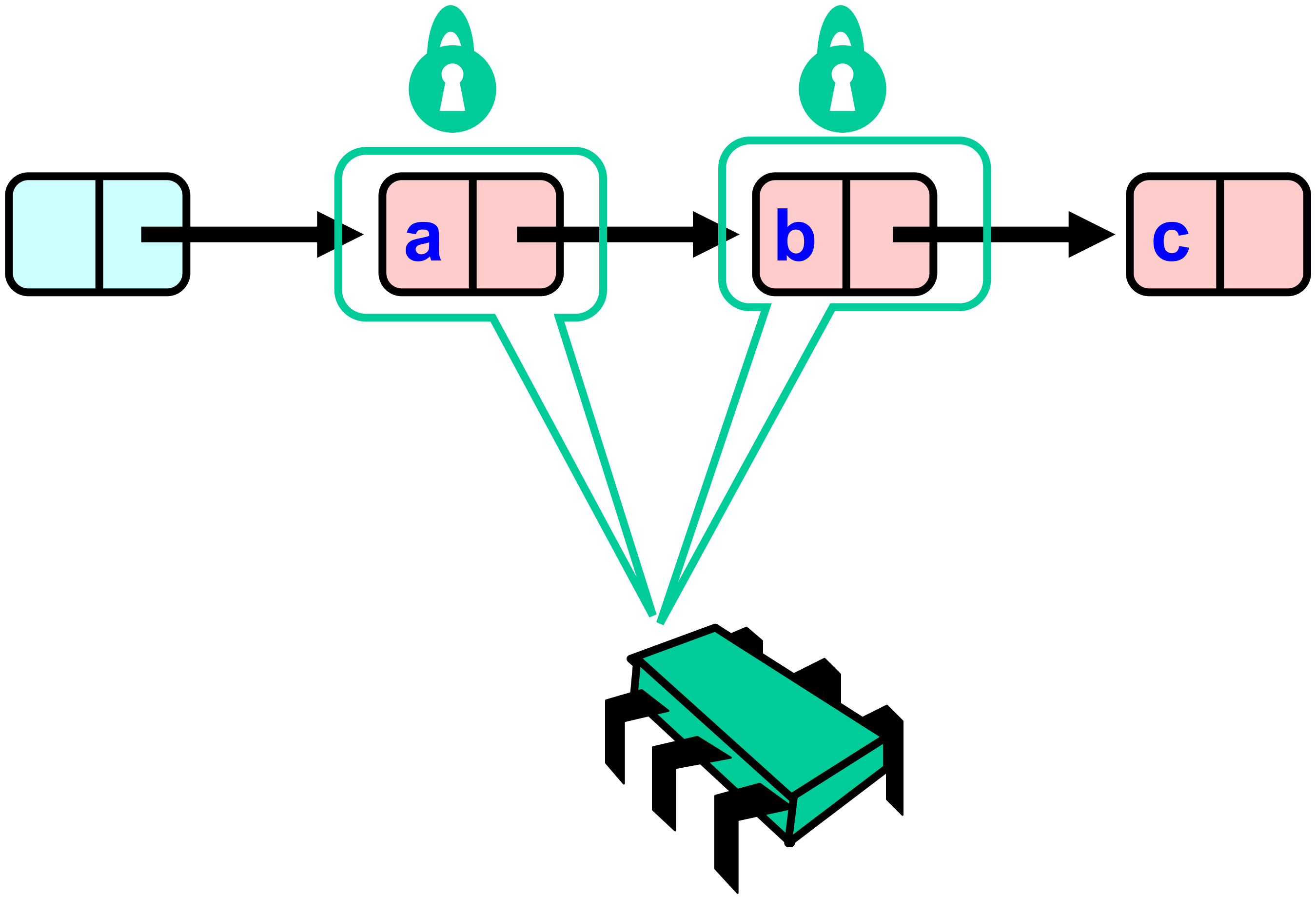

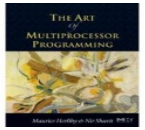

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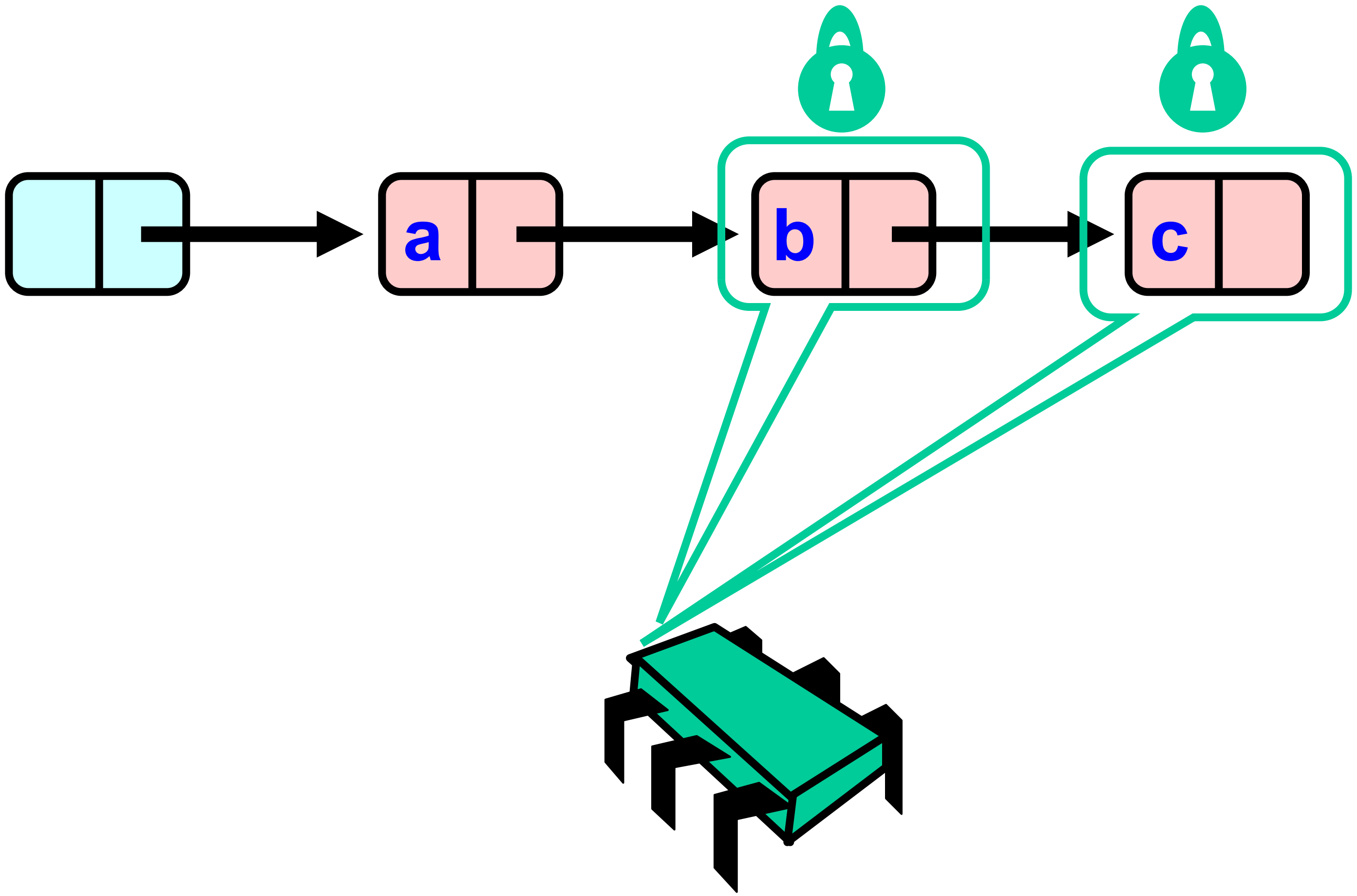
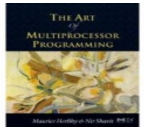
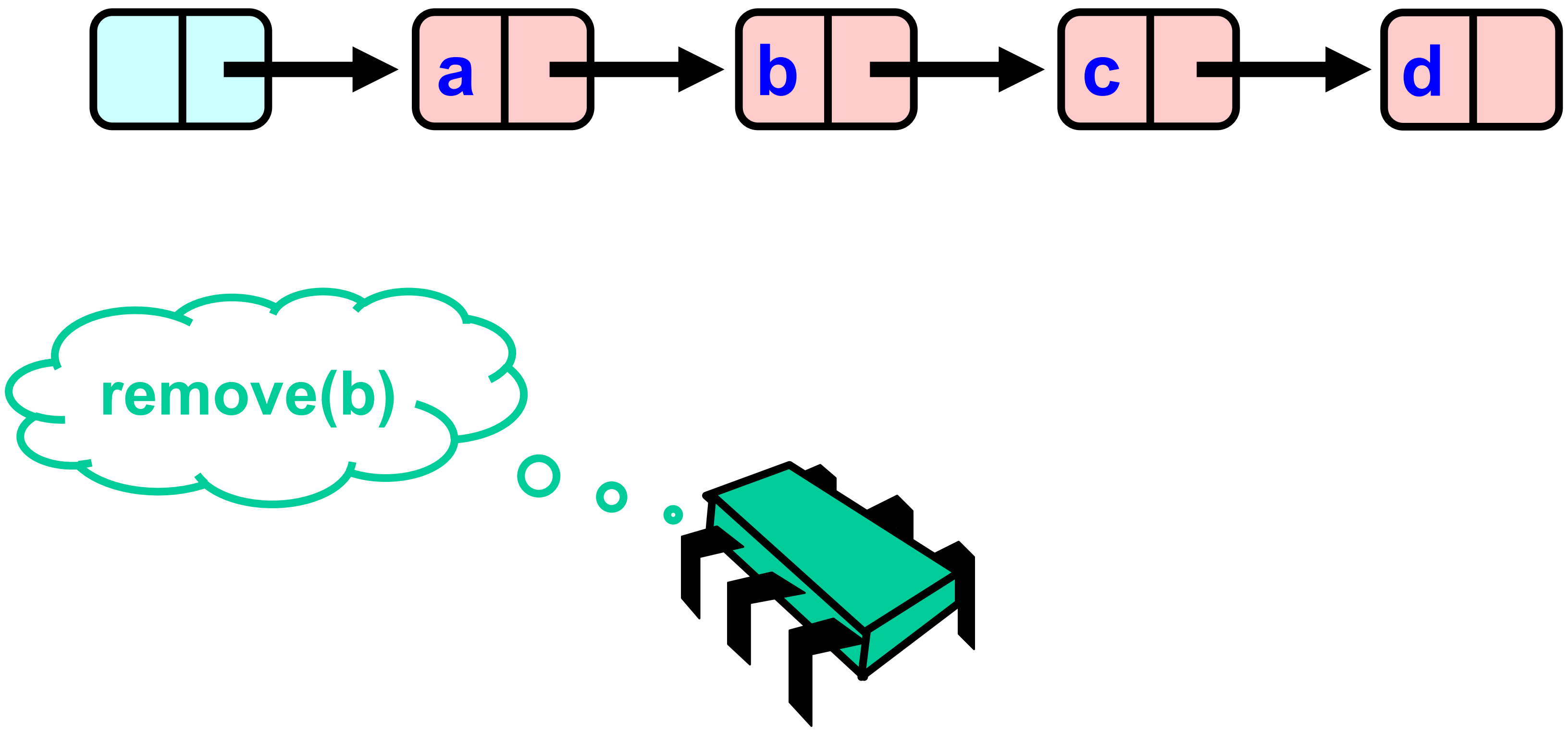




Removing a Node



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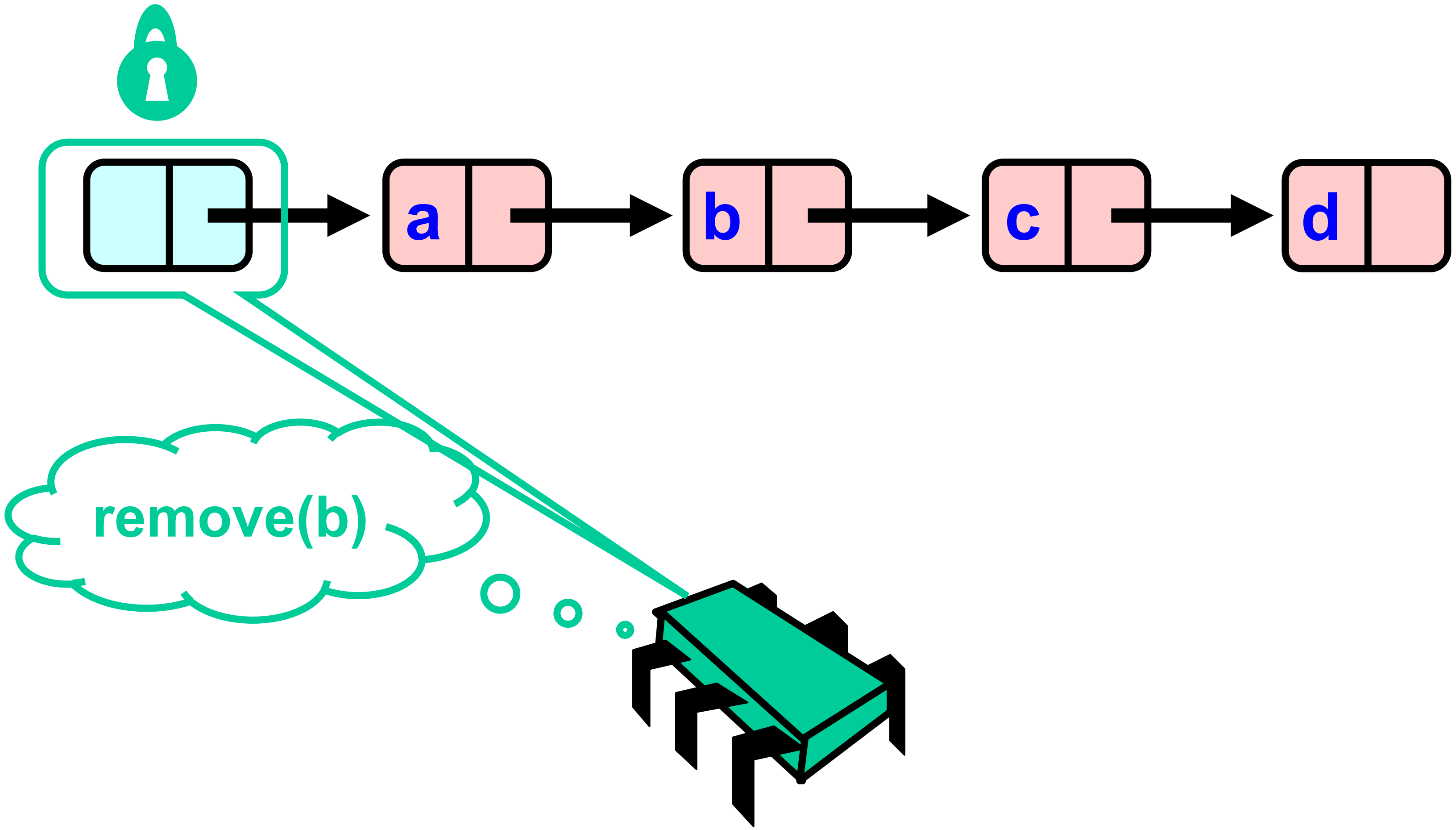

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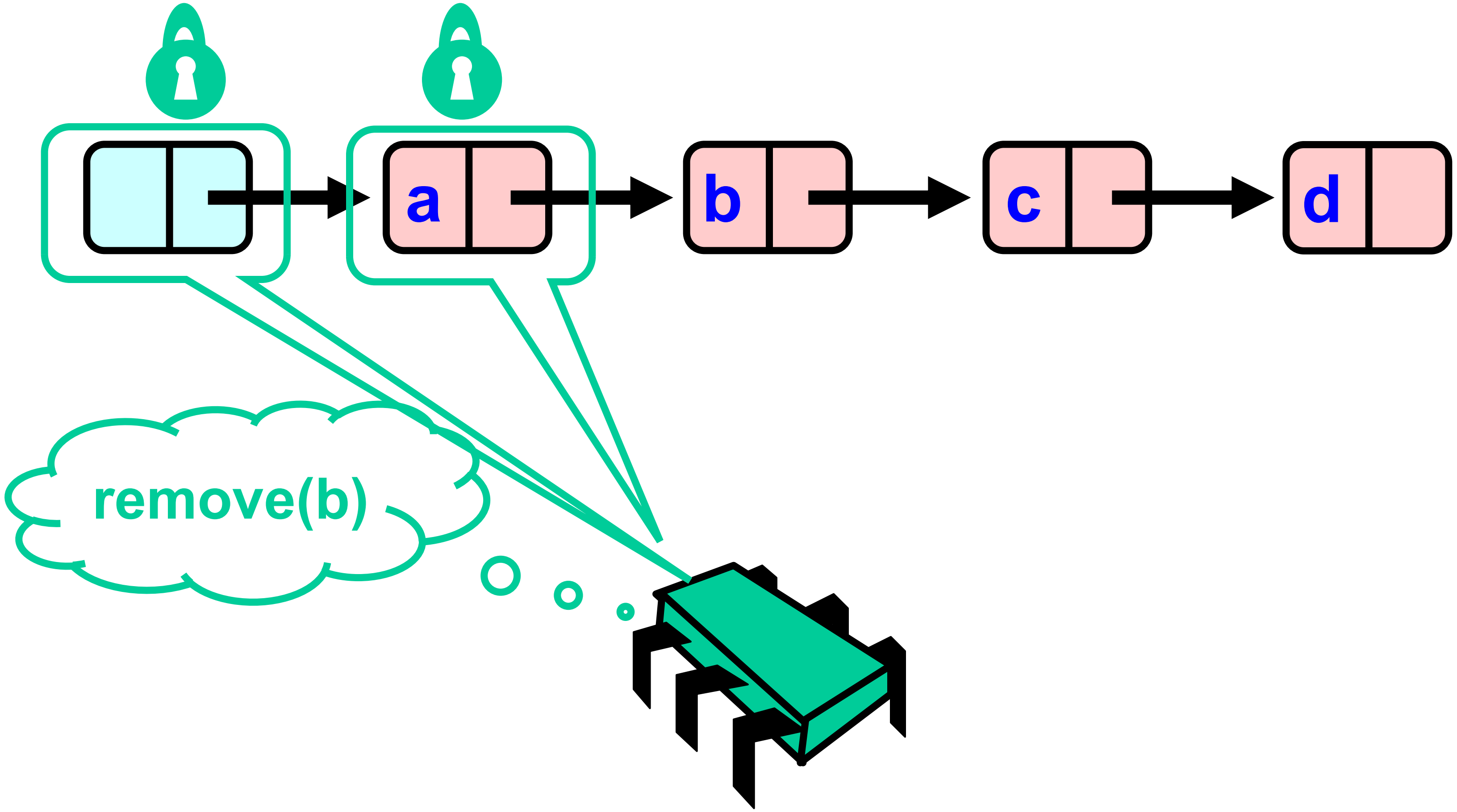

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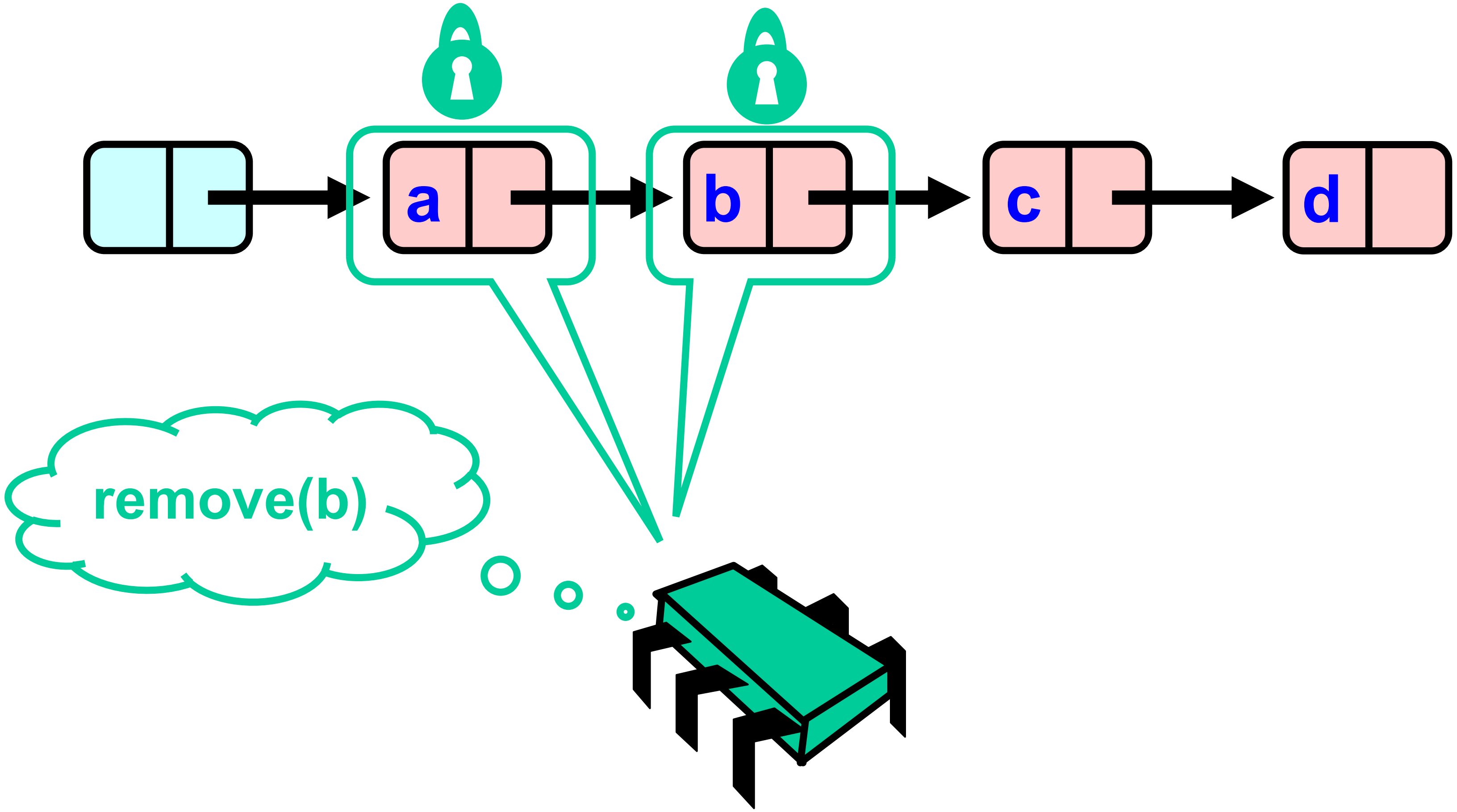

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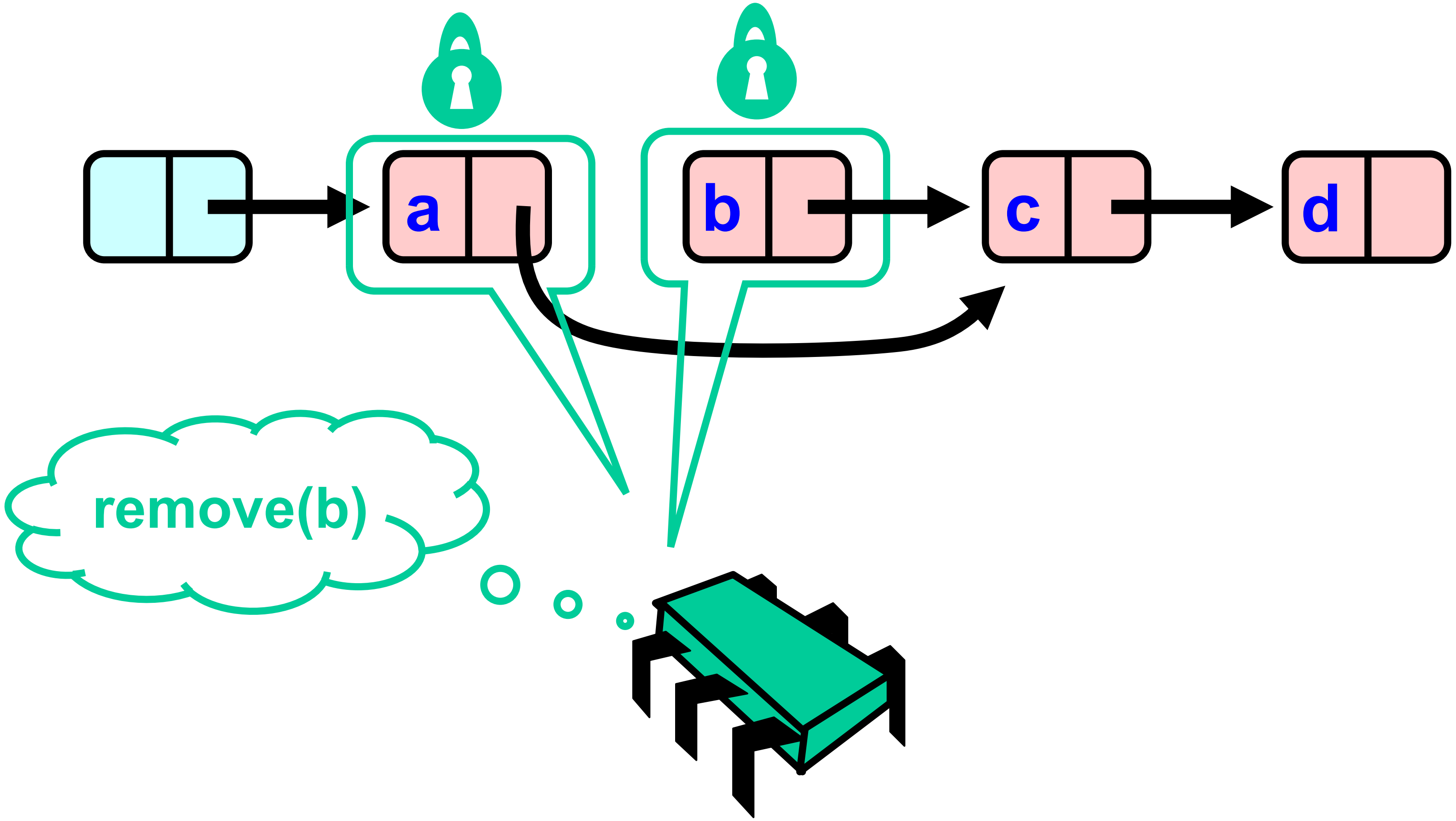

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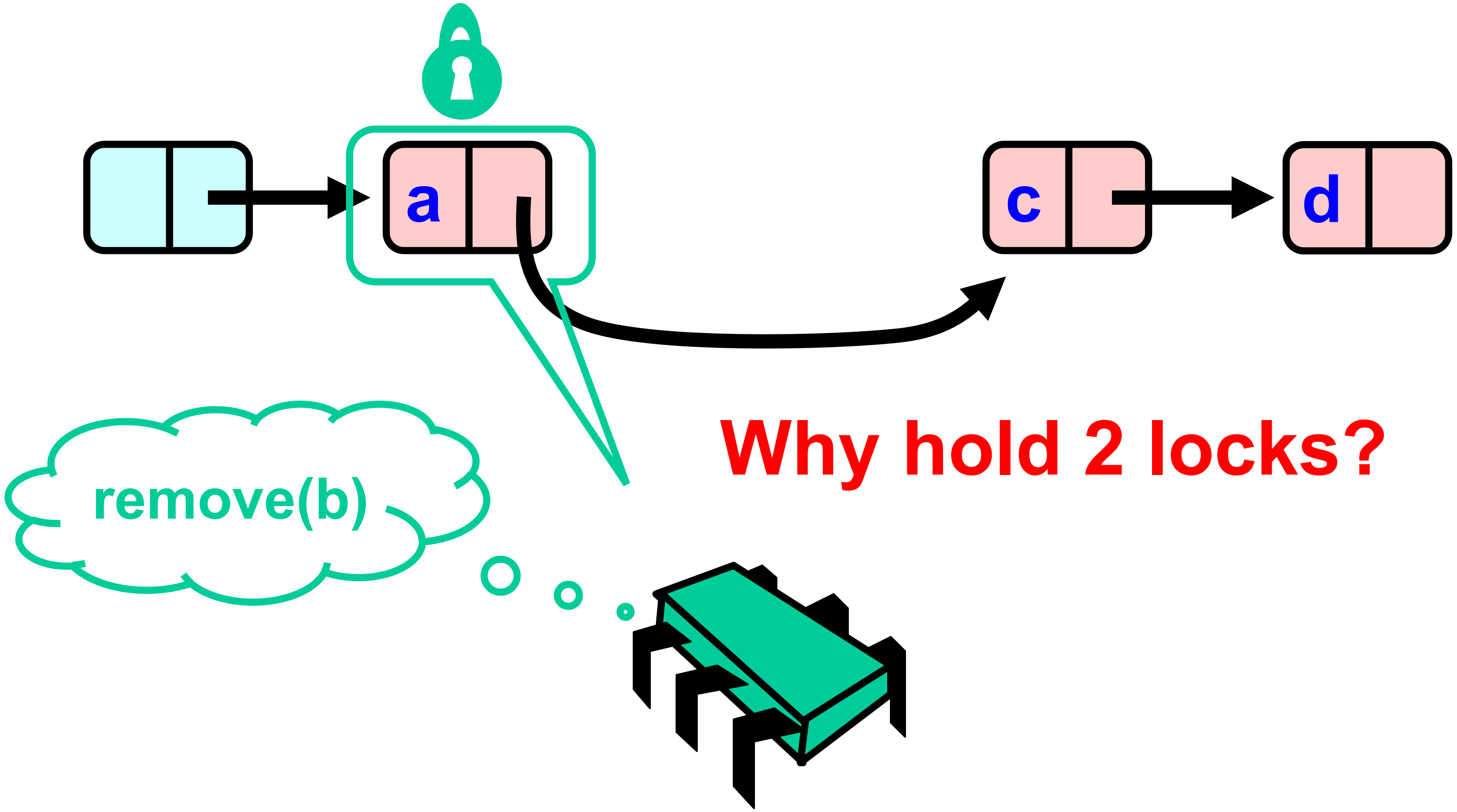
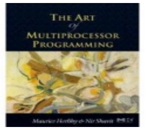
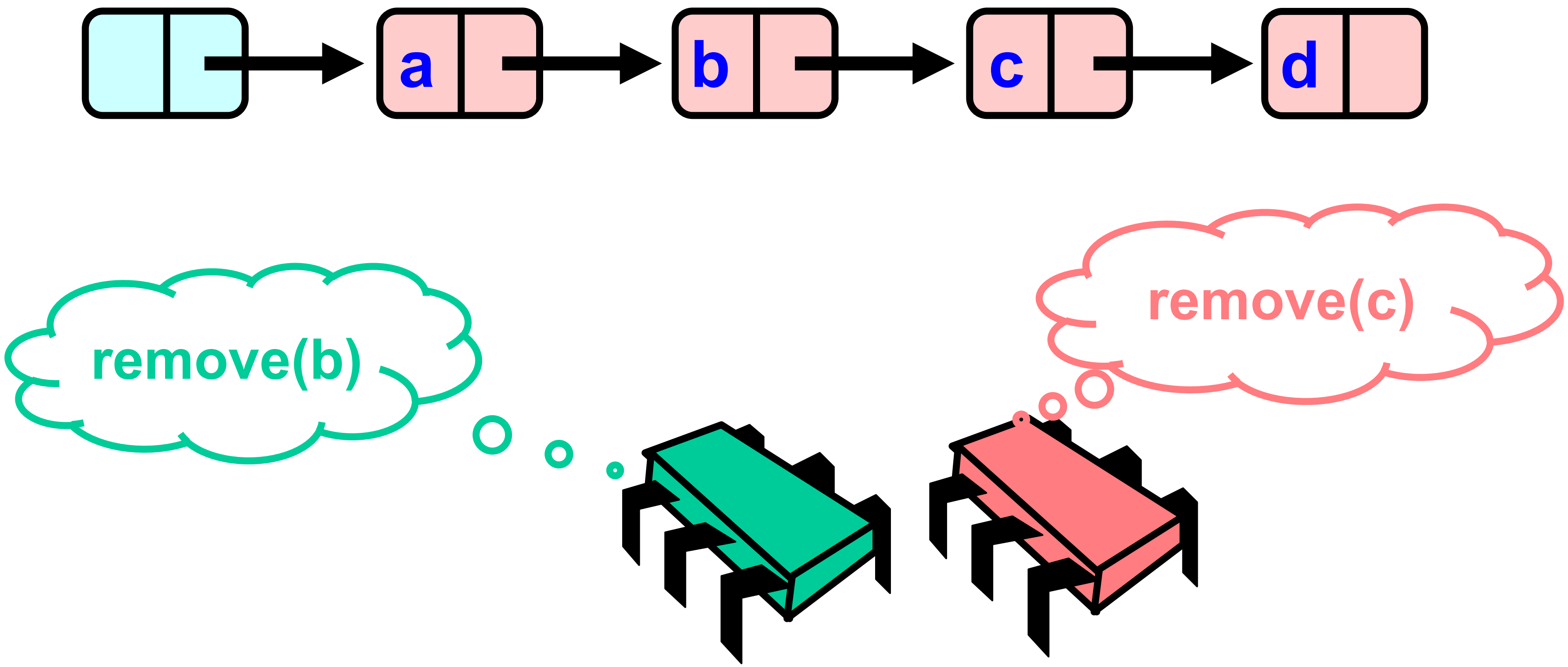


Why hold 2 locks?



Concurrent Removes



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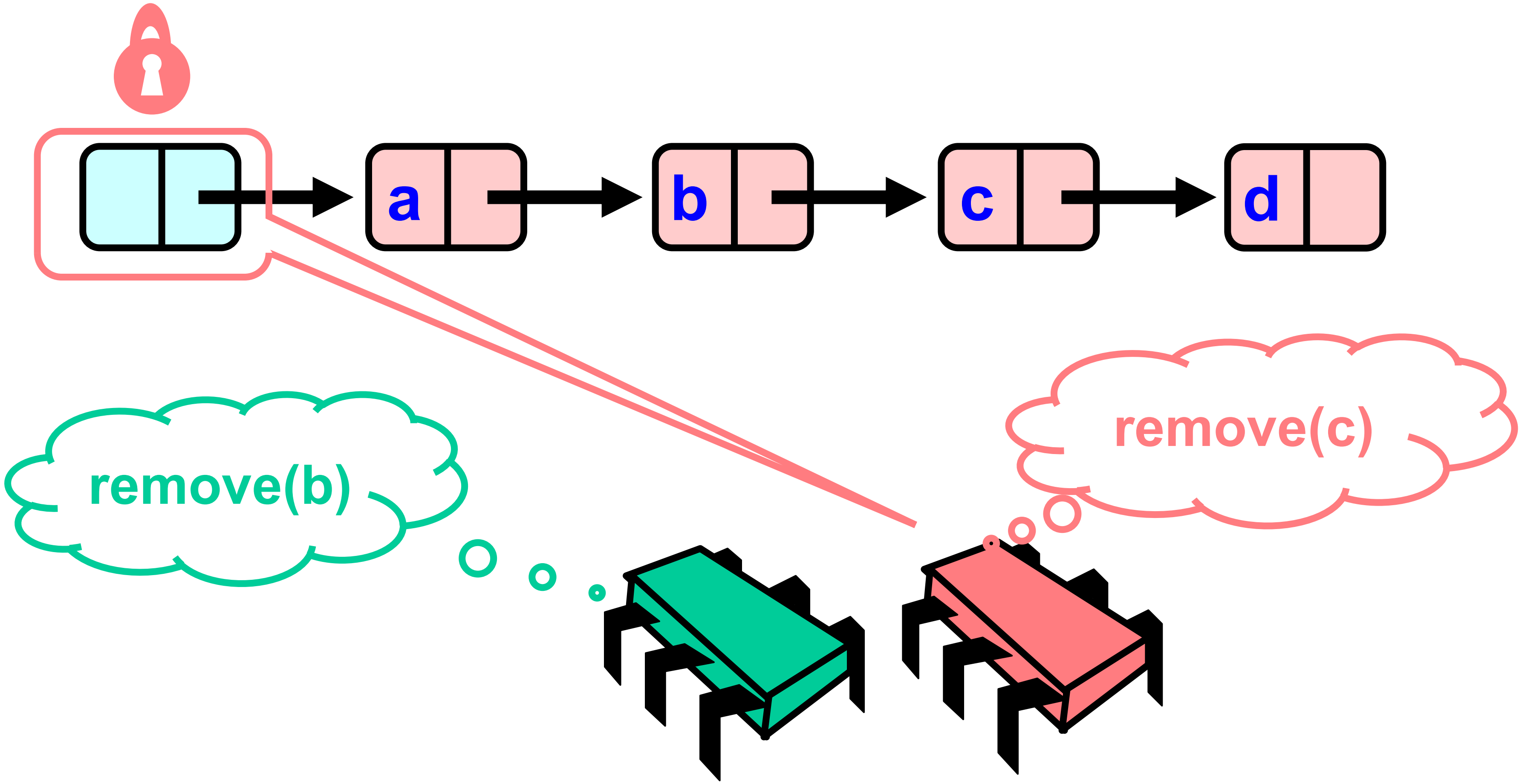

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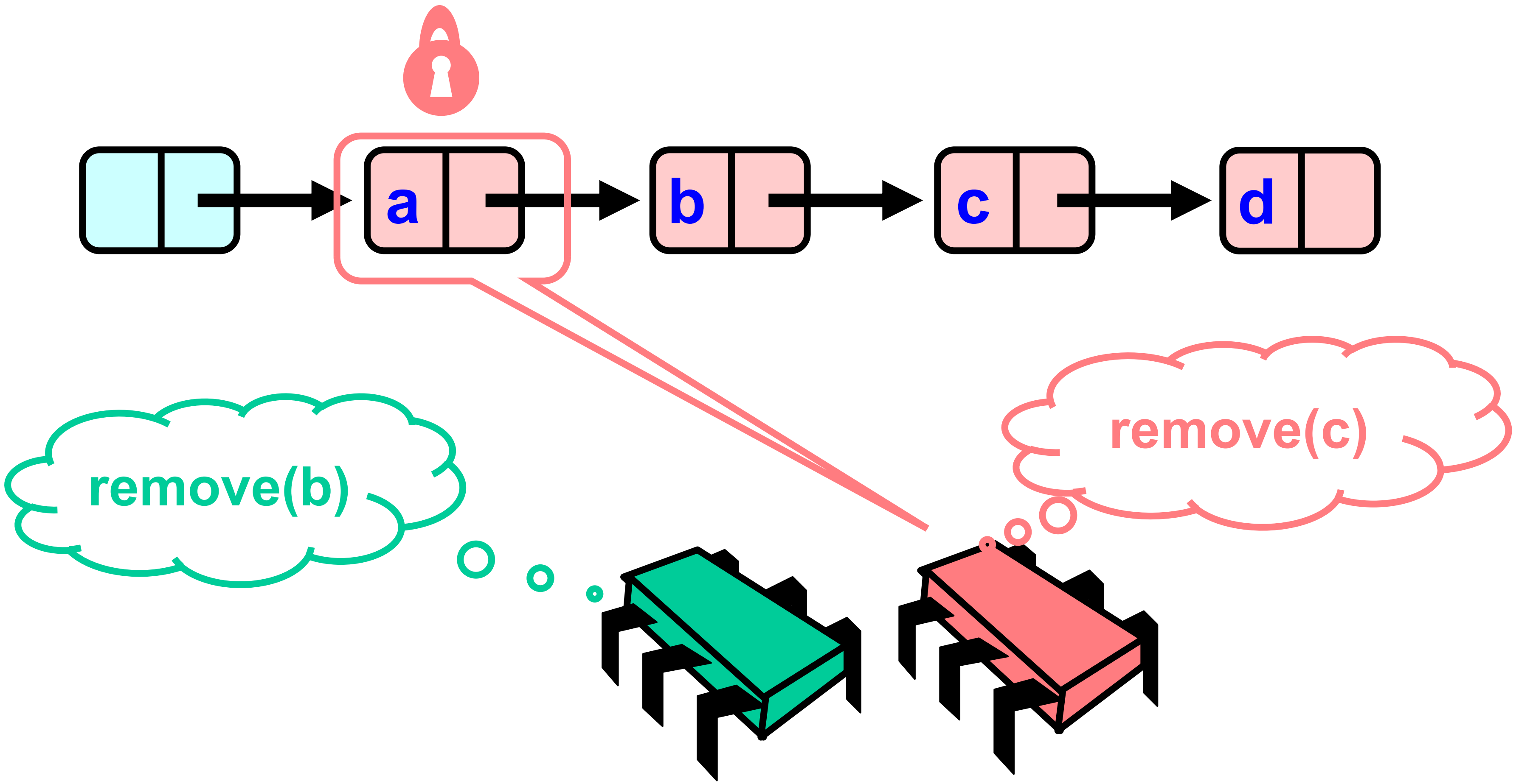

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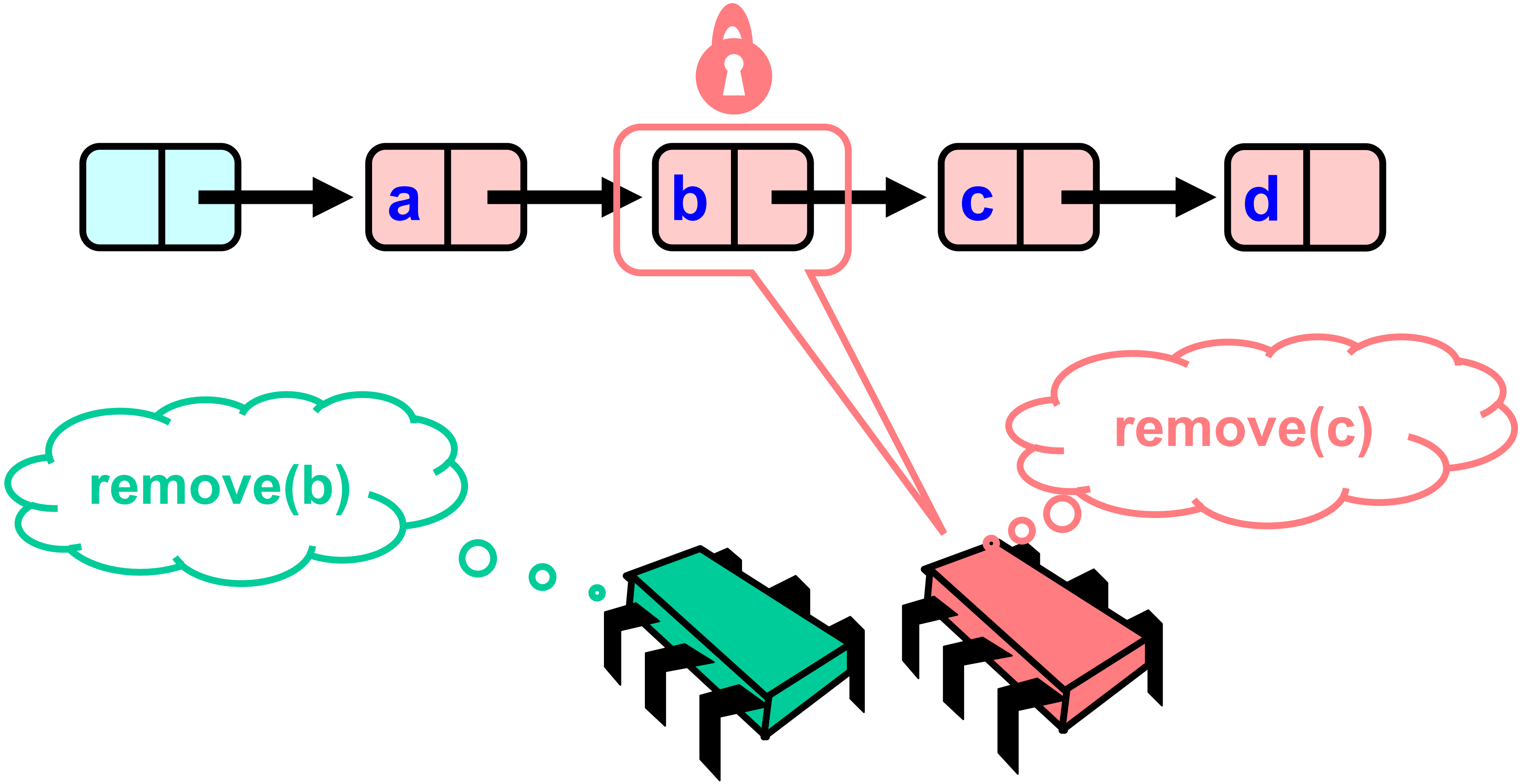
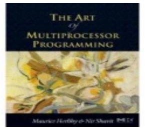
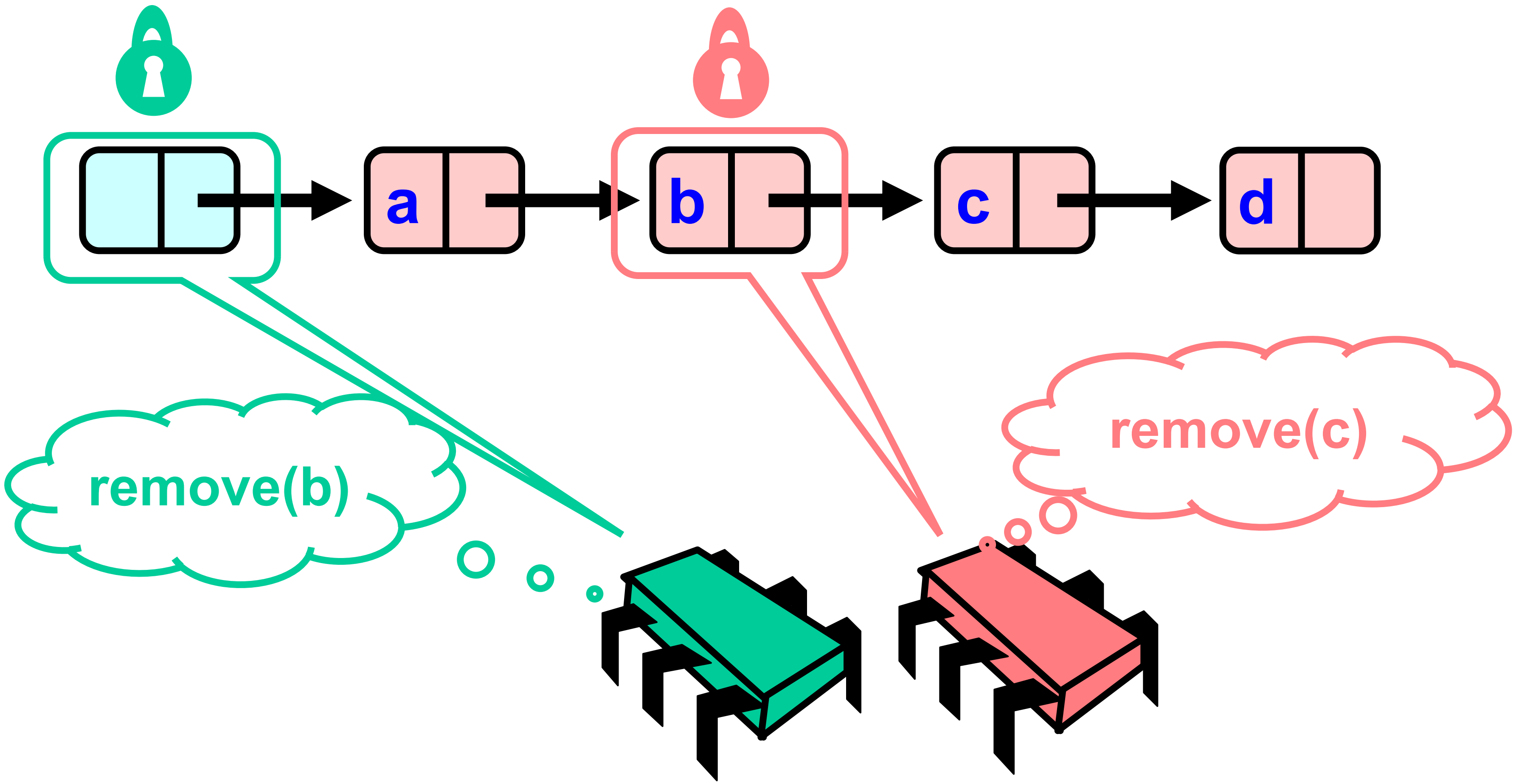
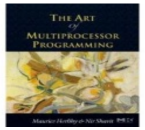


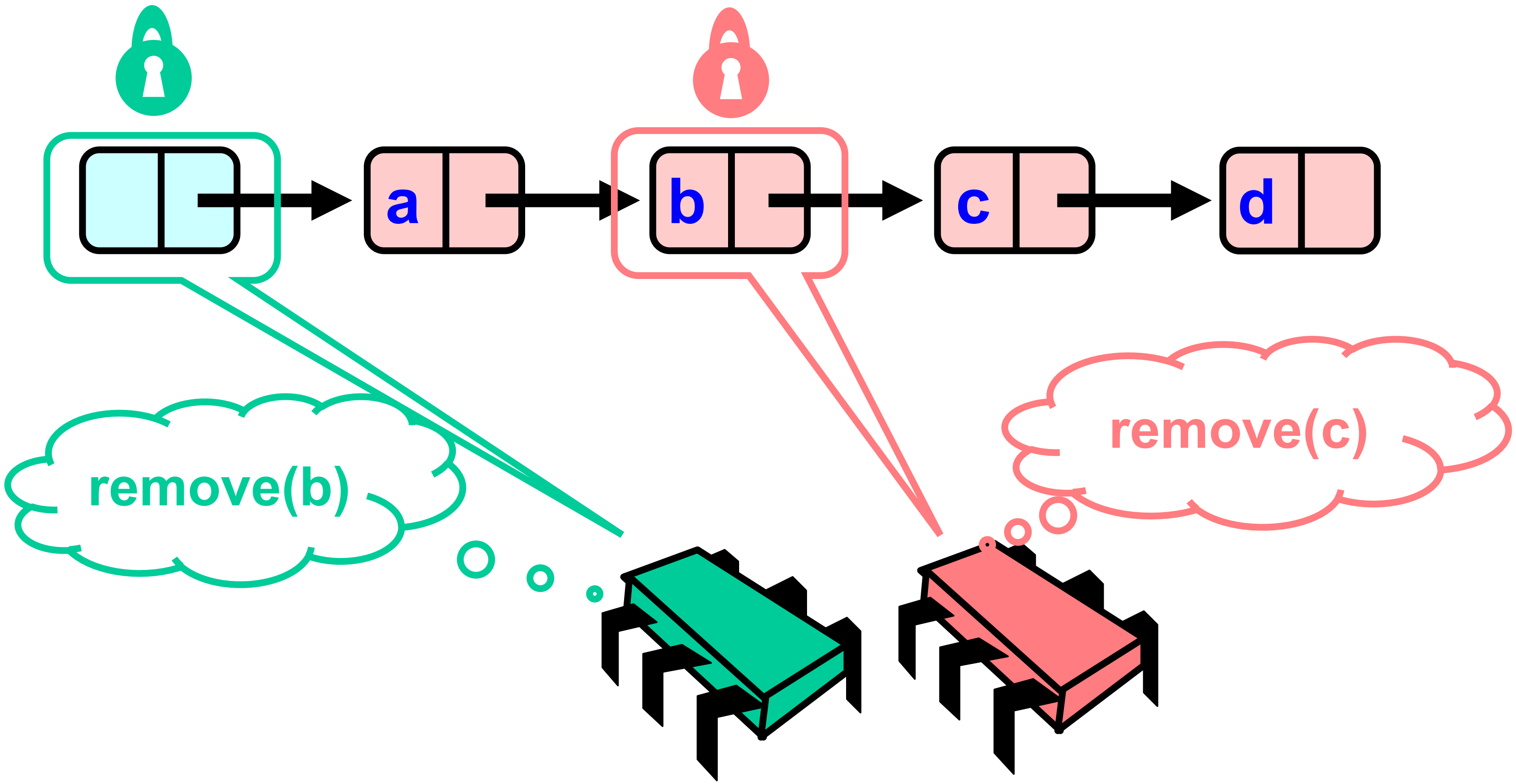


Concurrent Removes

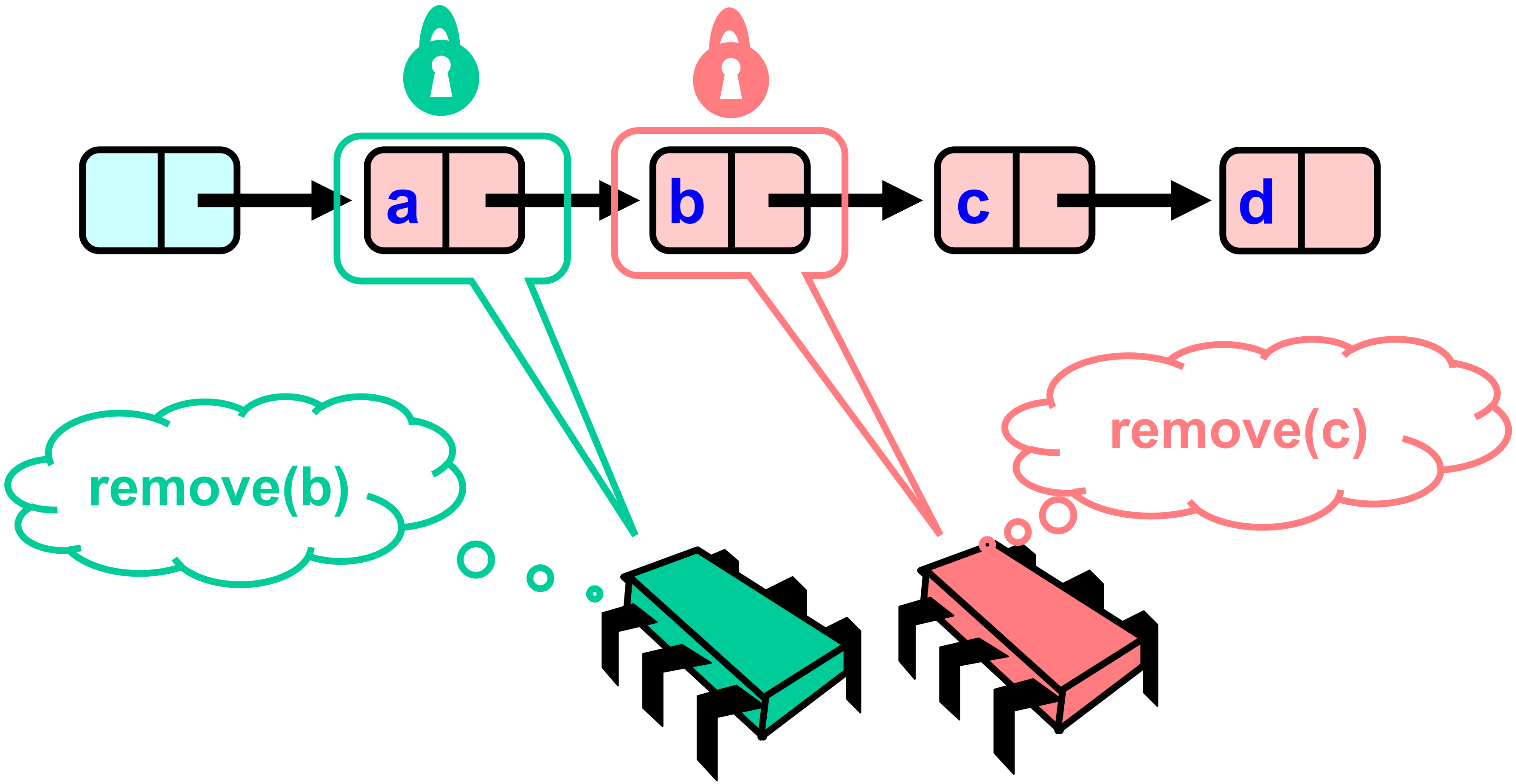




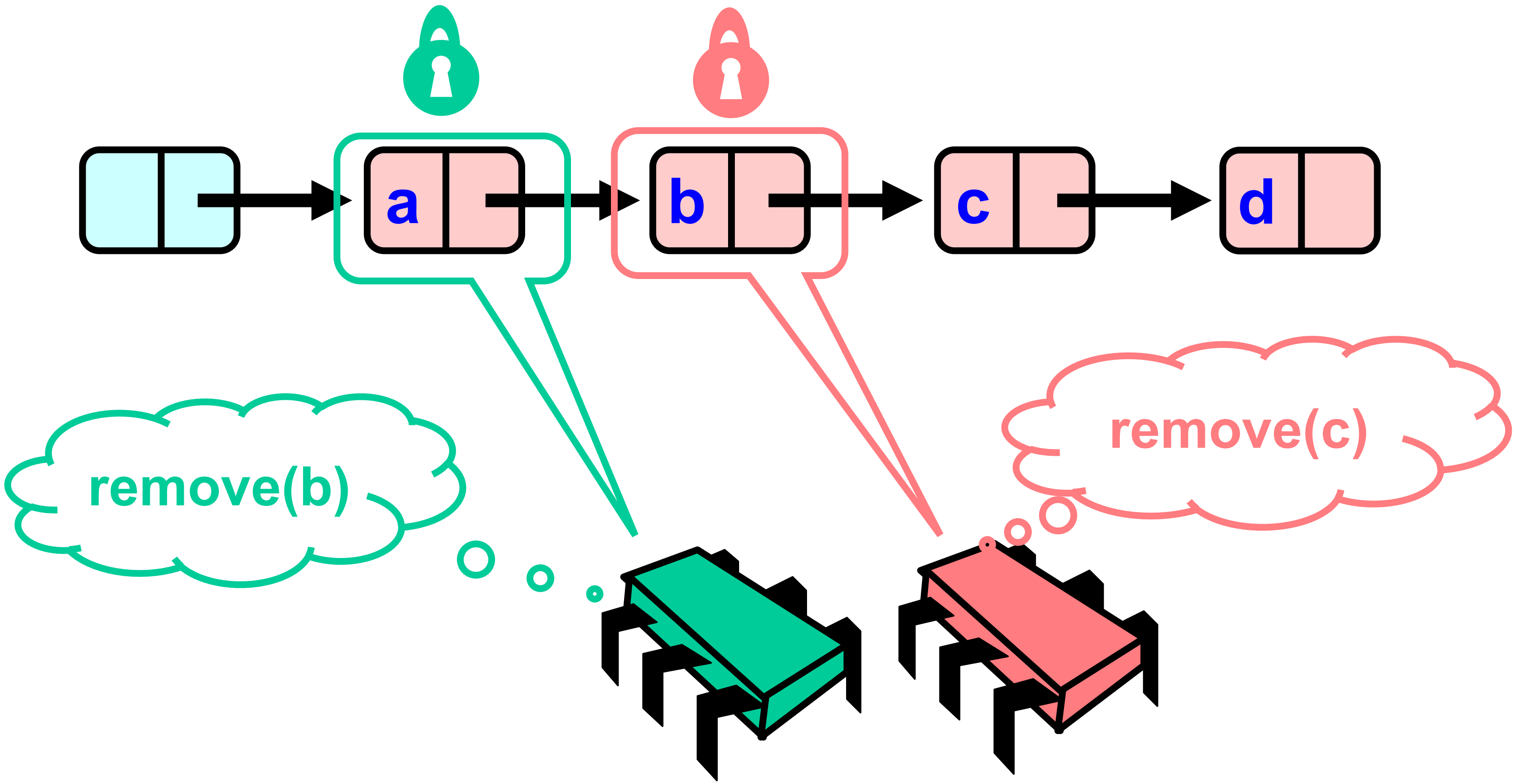
Concurrent Removes



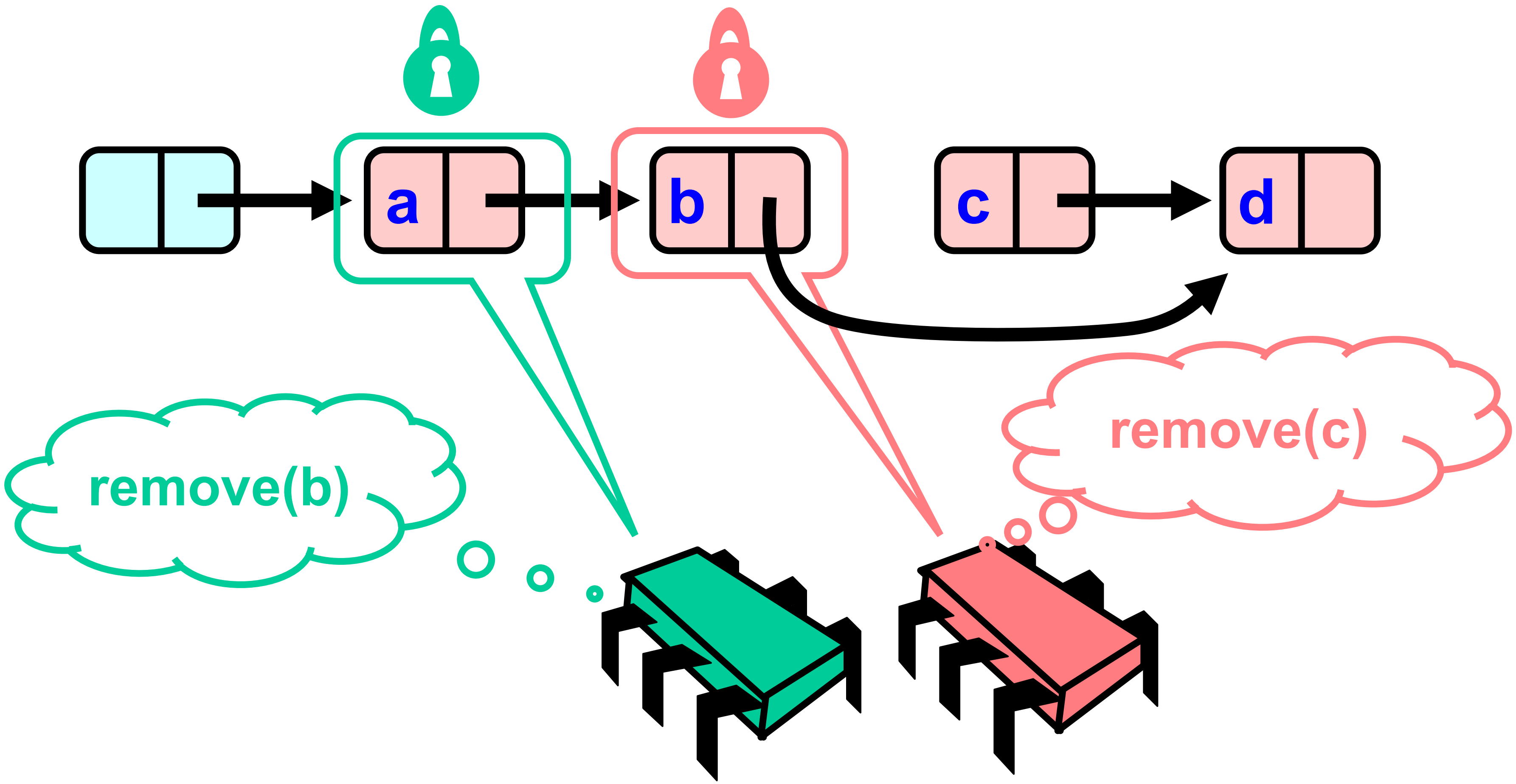
Concurrent Removes

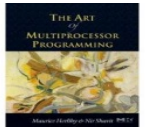


Concurrent Removes

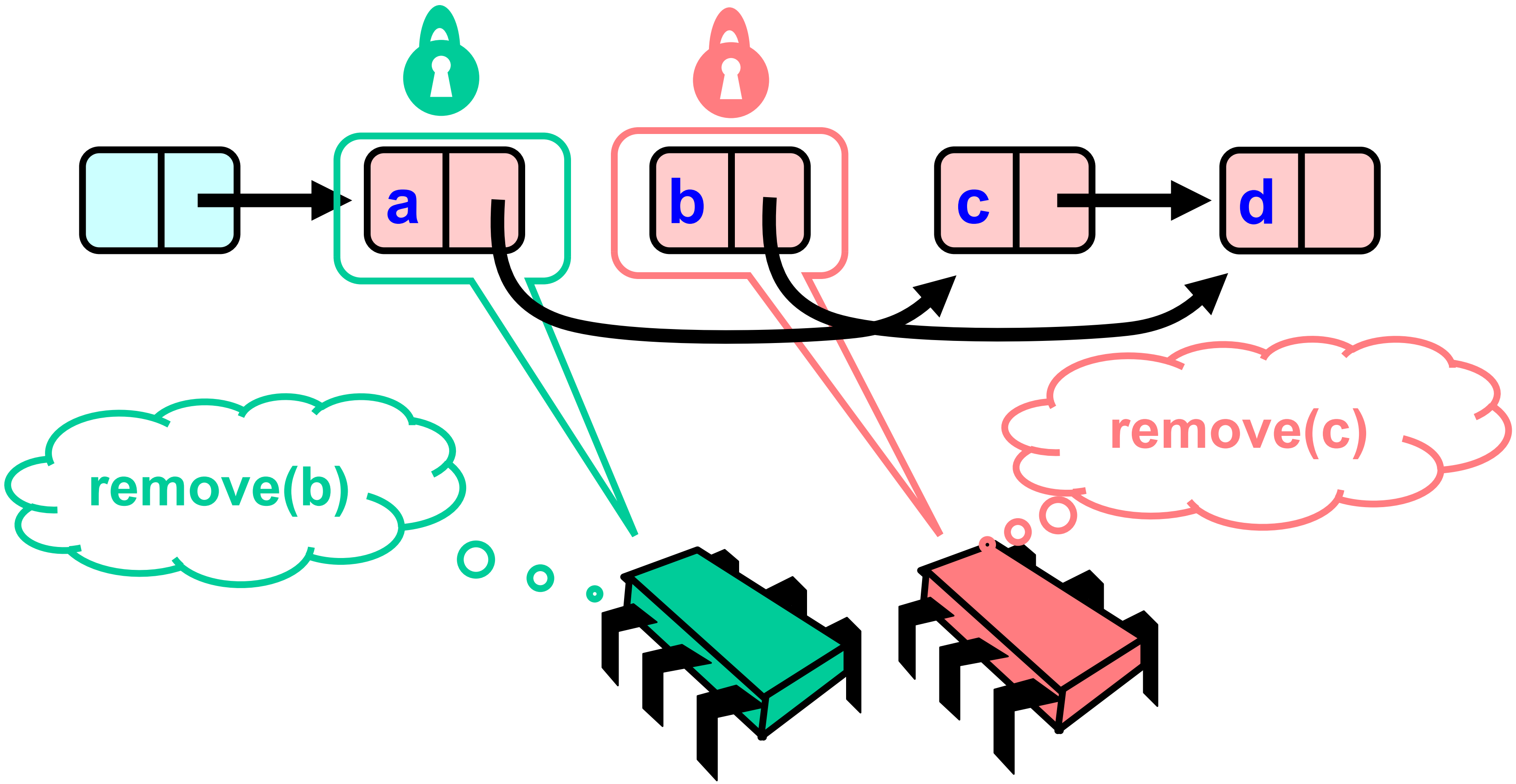


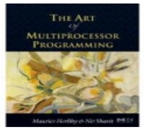
Concurrent Removes



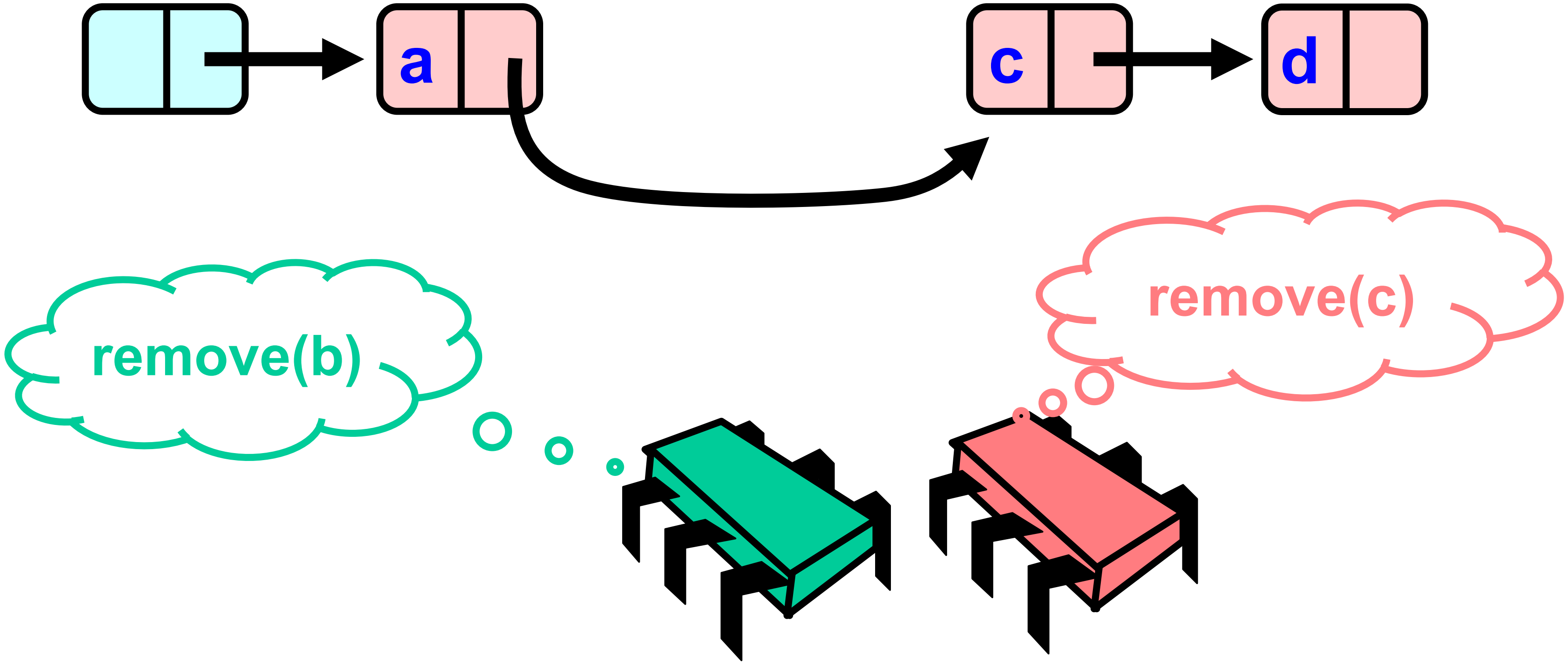


Concurrent Removes

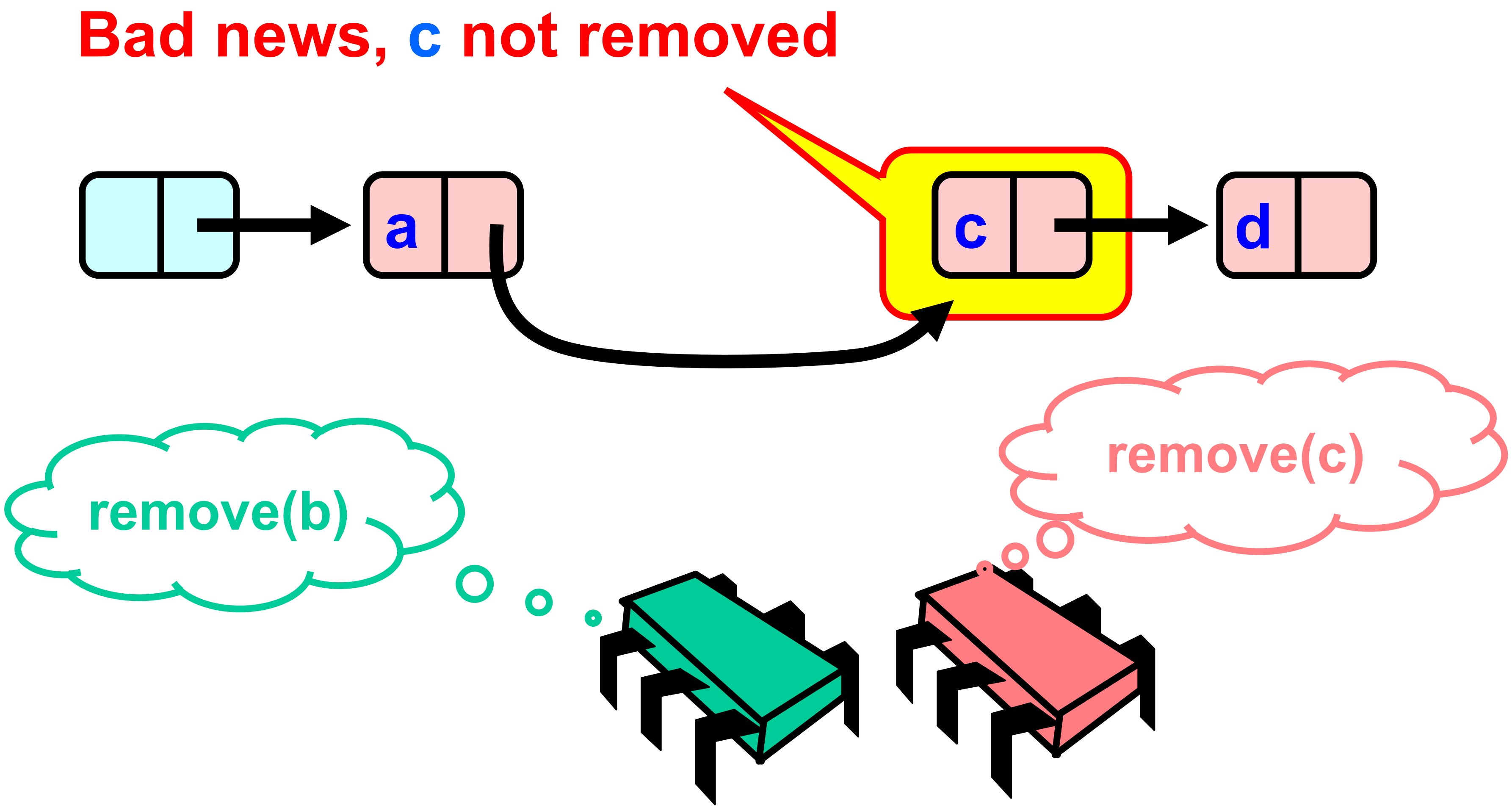


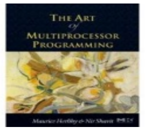


Uh, Oh



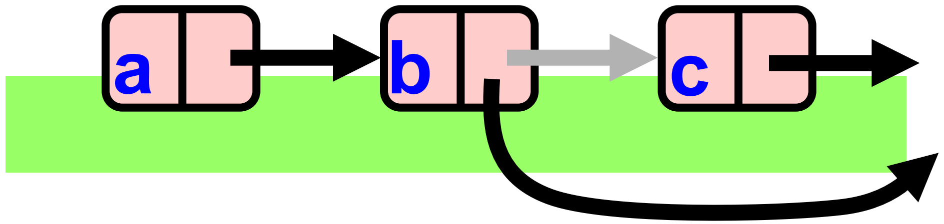
Uh, Oh


Bad news, c not removed
a
c
d
remove(b)
remove(c)

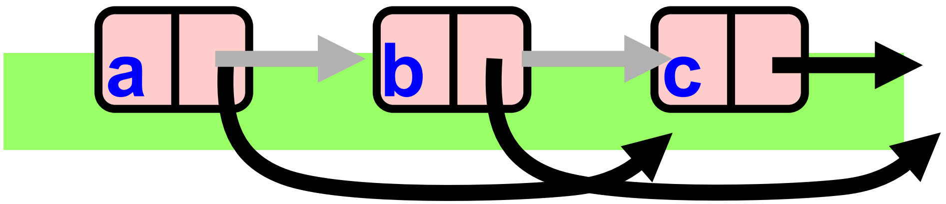

The Art of Multiprocessor Programming

Problem

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



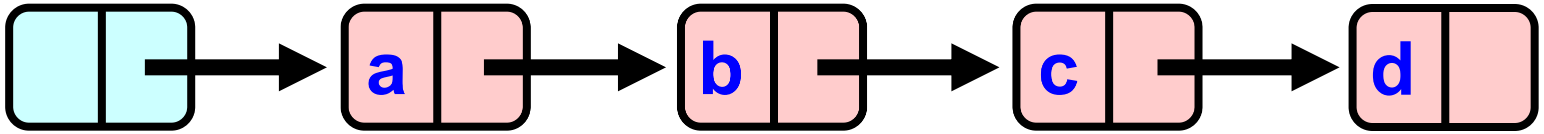
- Problem is,
  - Someone deleting b concurrently could direct a pointer to c

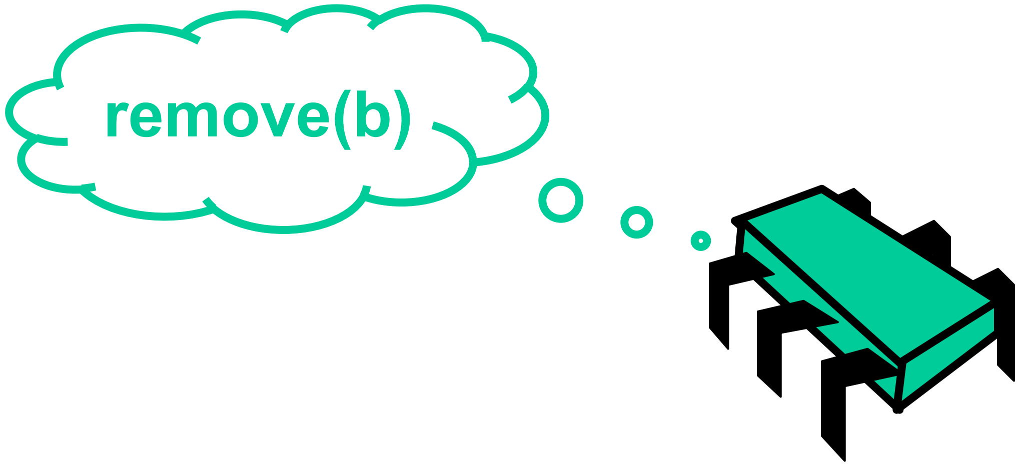


Insight

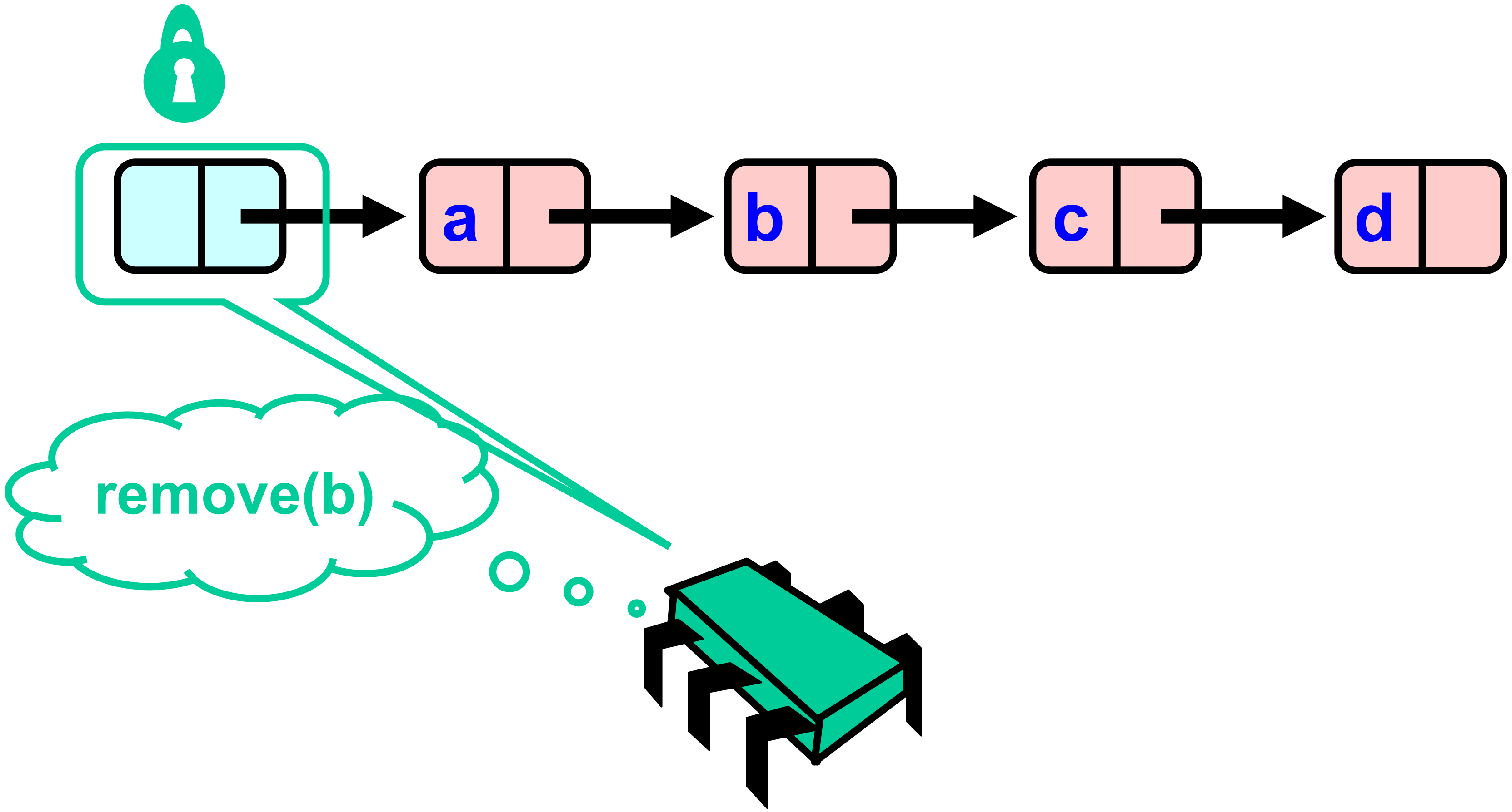
- If a node is locked
  - No one can delete node's *successor*
- If a thread locks
  - Node to be deleted
  - And its predecessor
  - Then it works

Hand-Over-Hand Again

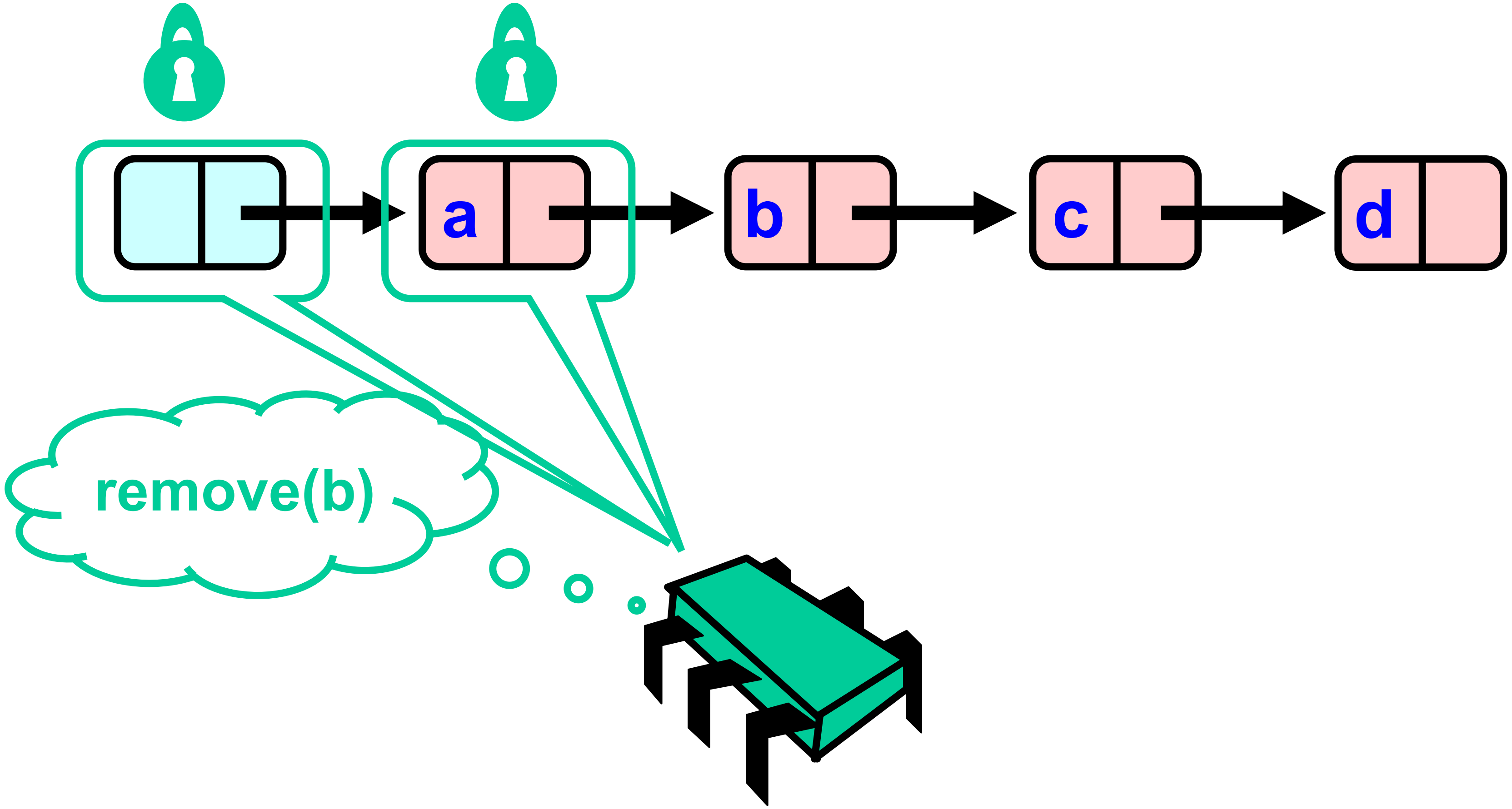




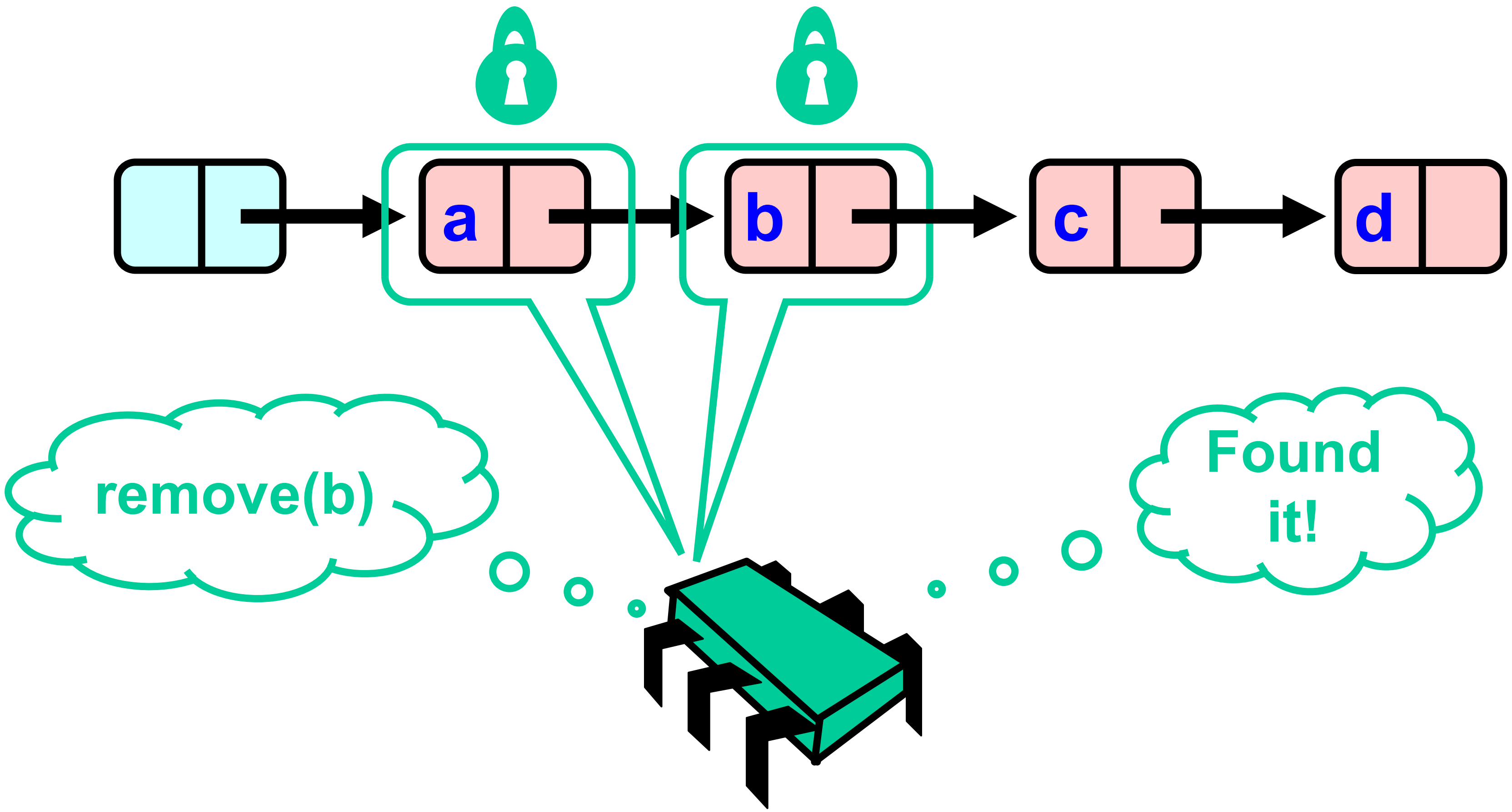
Hand-Over-Hand Again

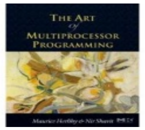


Hand-Over-Hand Again

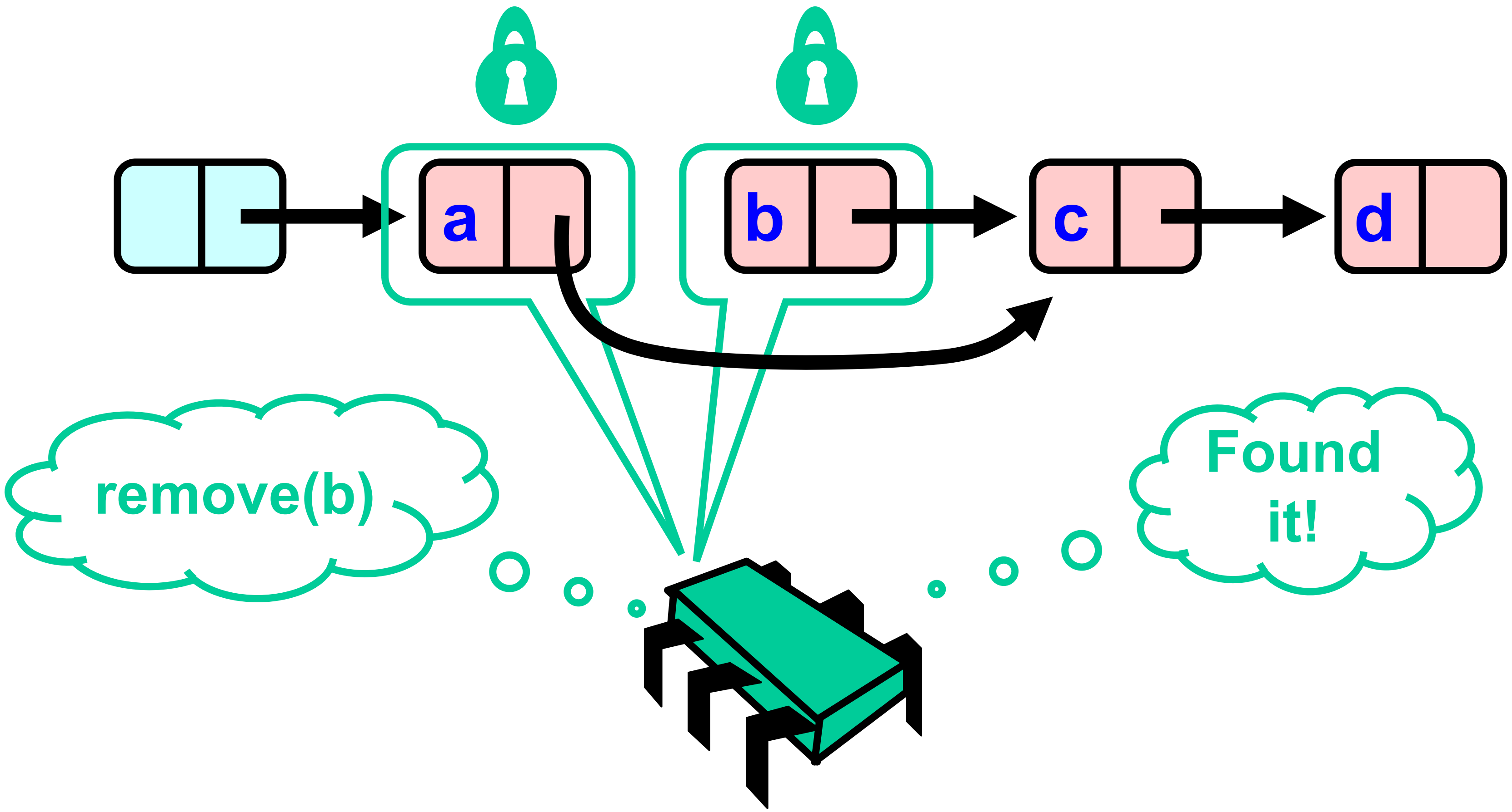


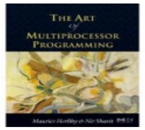
Hand-Over-Hand Again



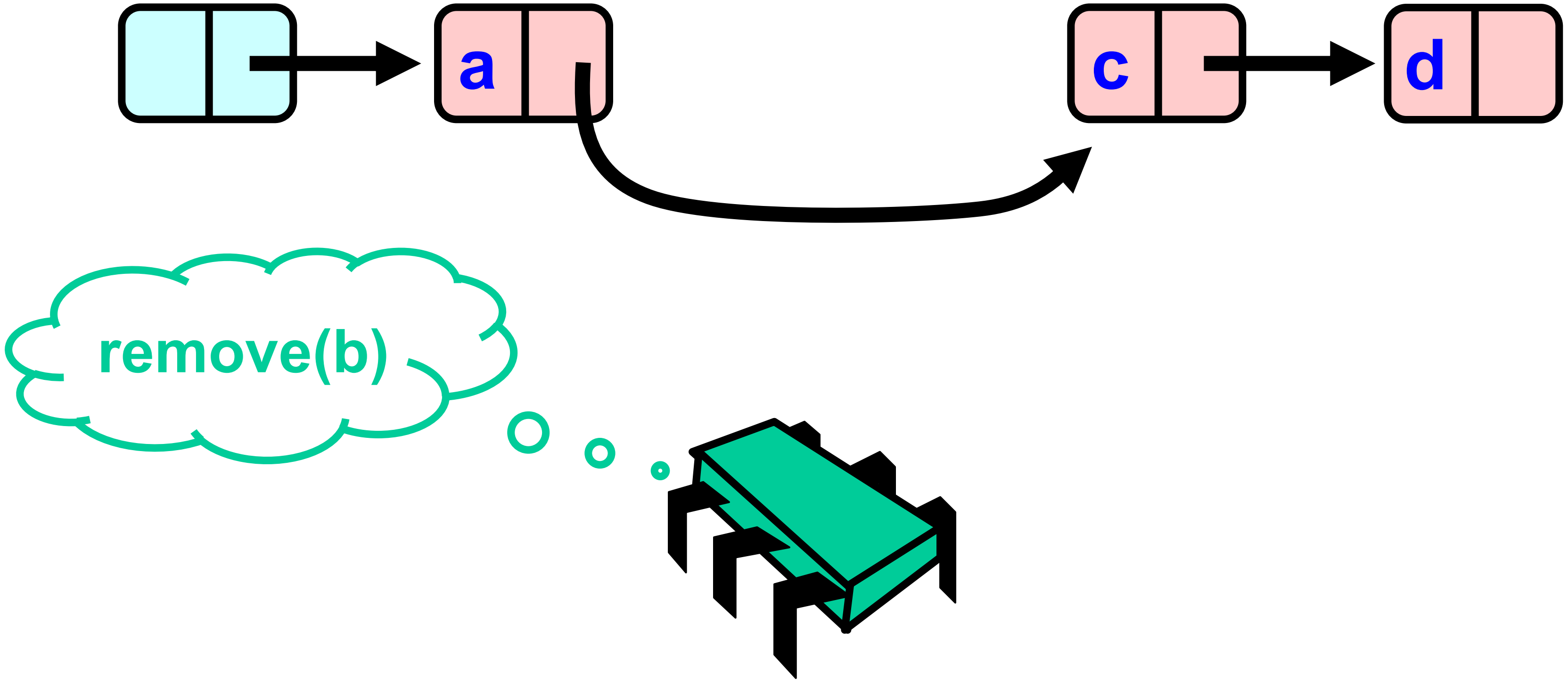


Hand-Over-Hand Again

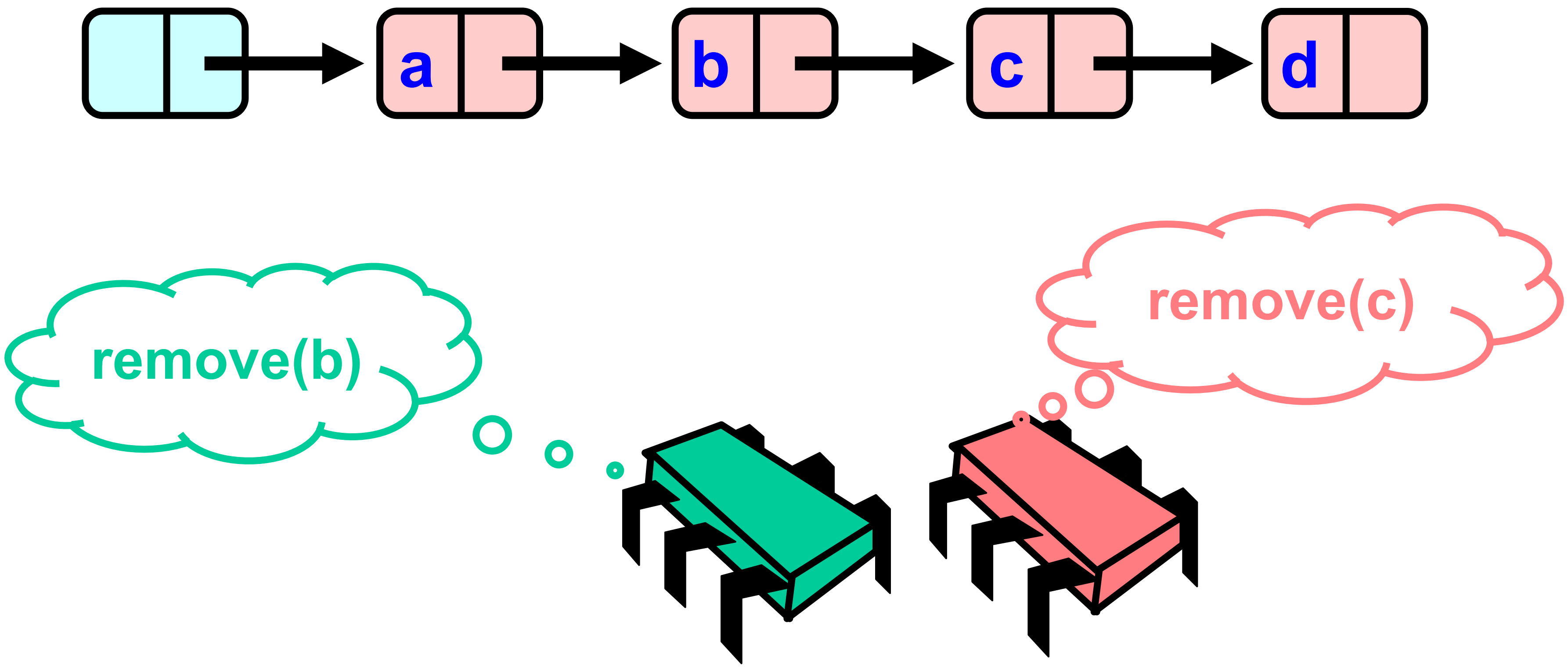




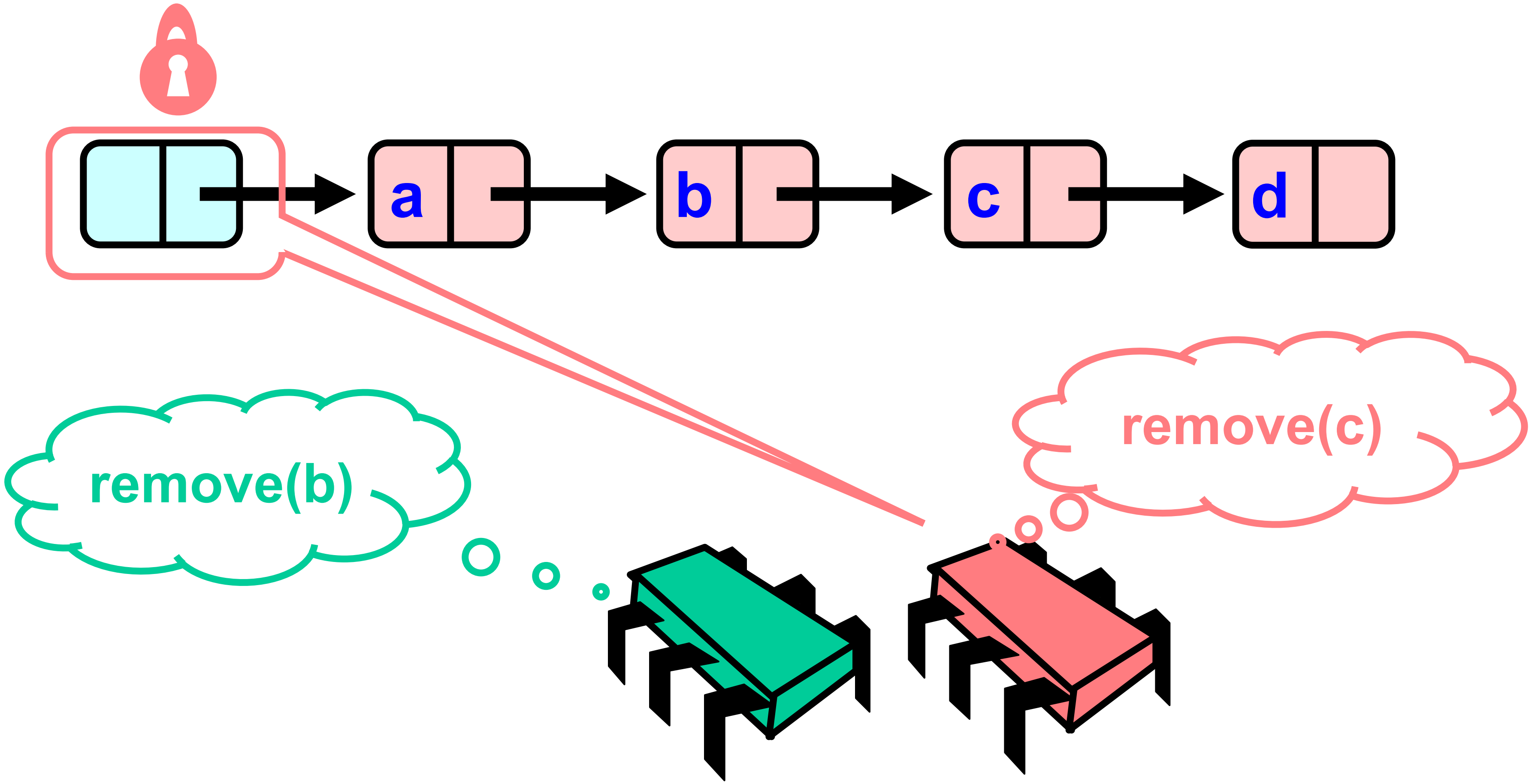
Hand-Over-Hand Again

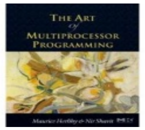


Removing a Node

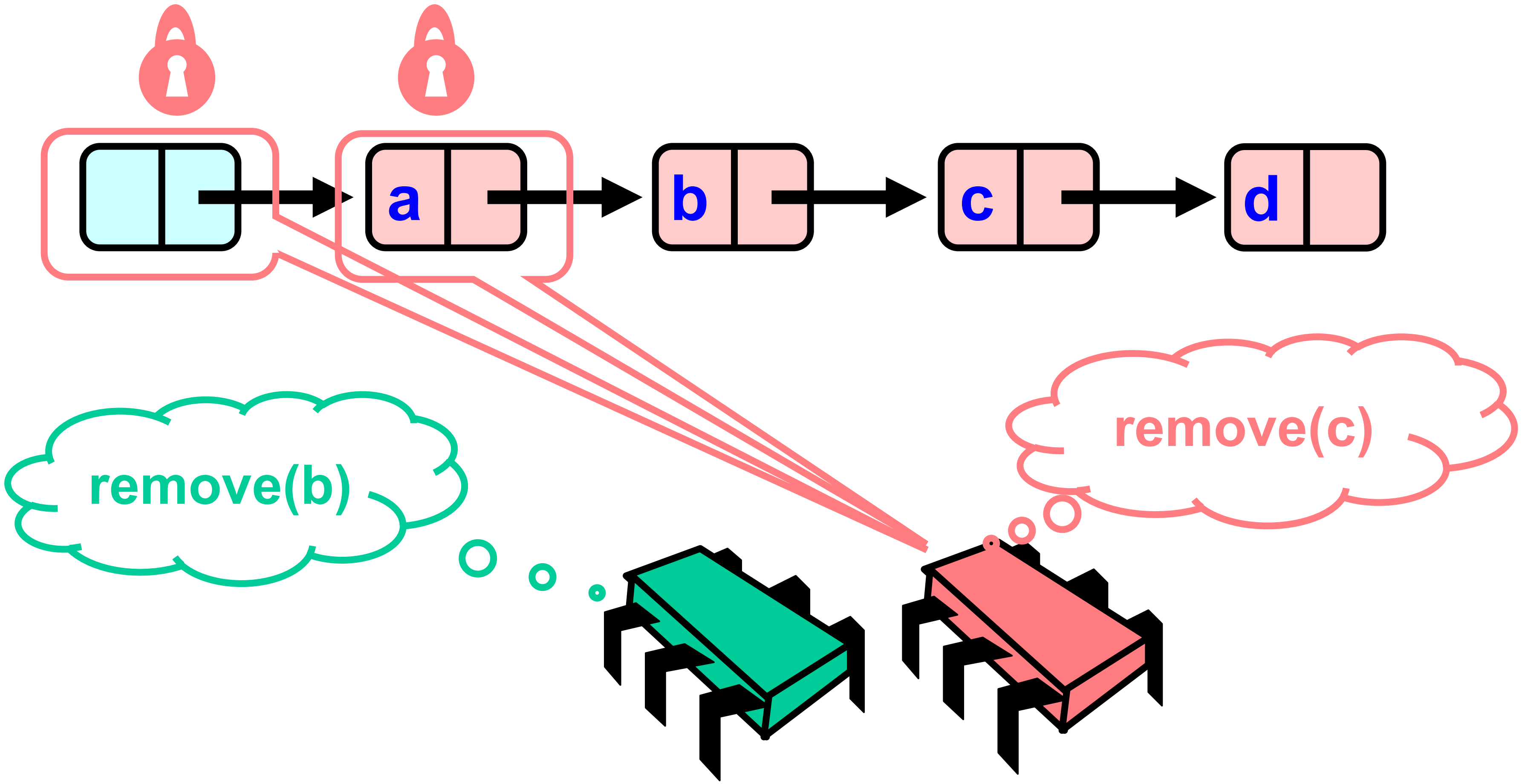


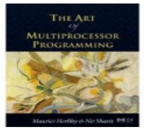
Removing a Node



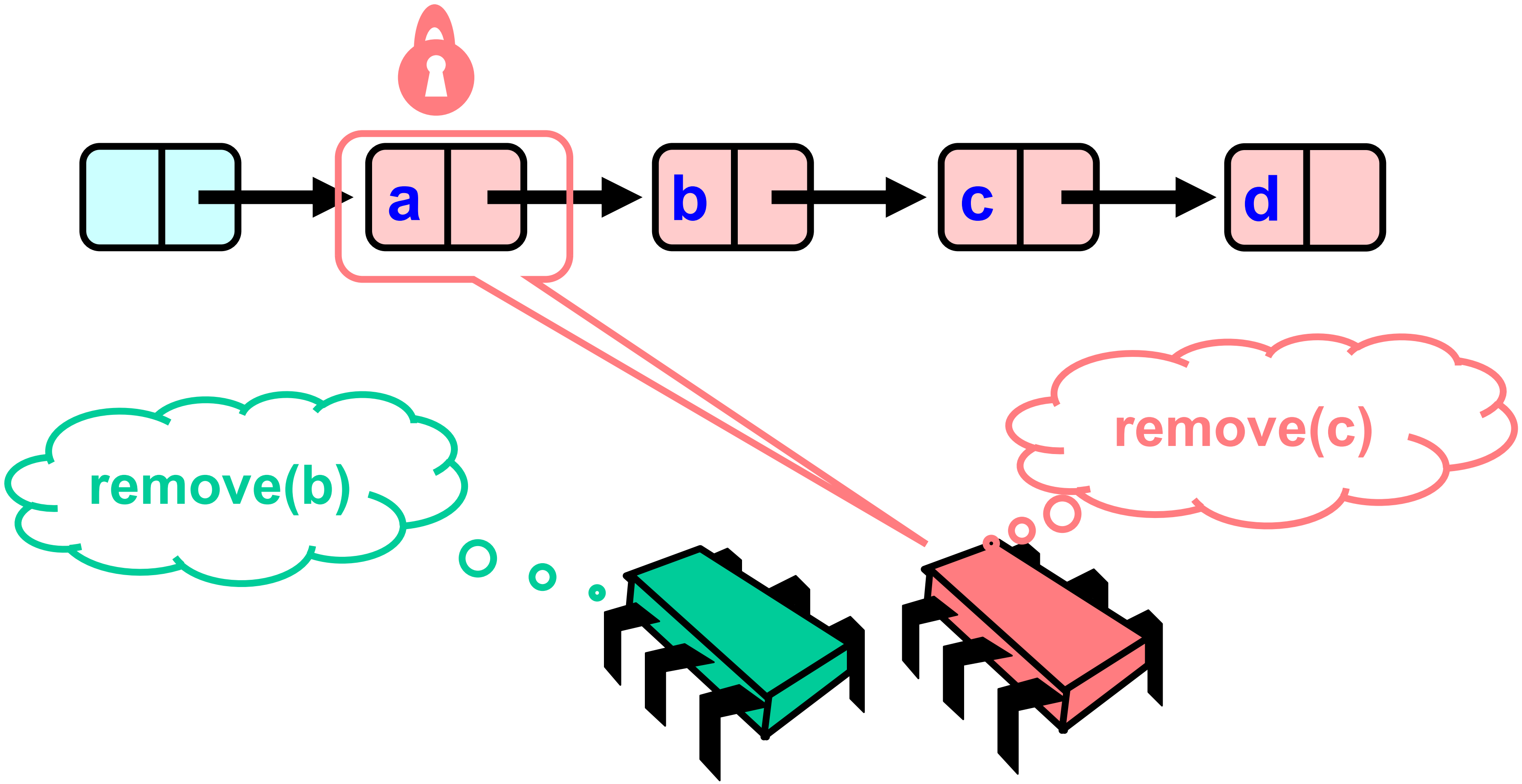


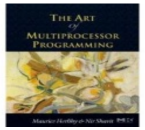
Removing a Node



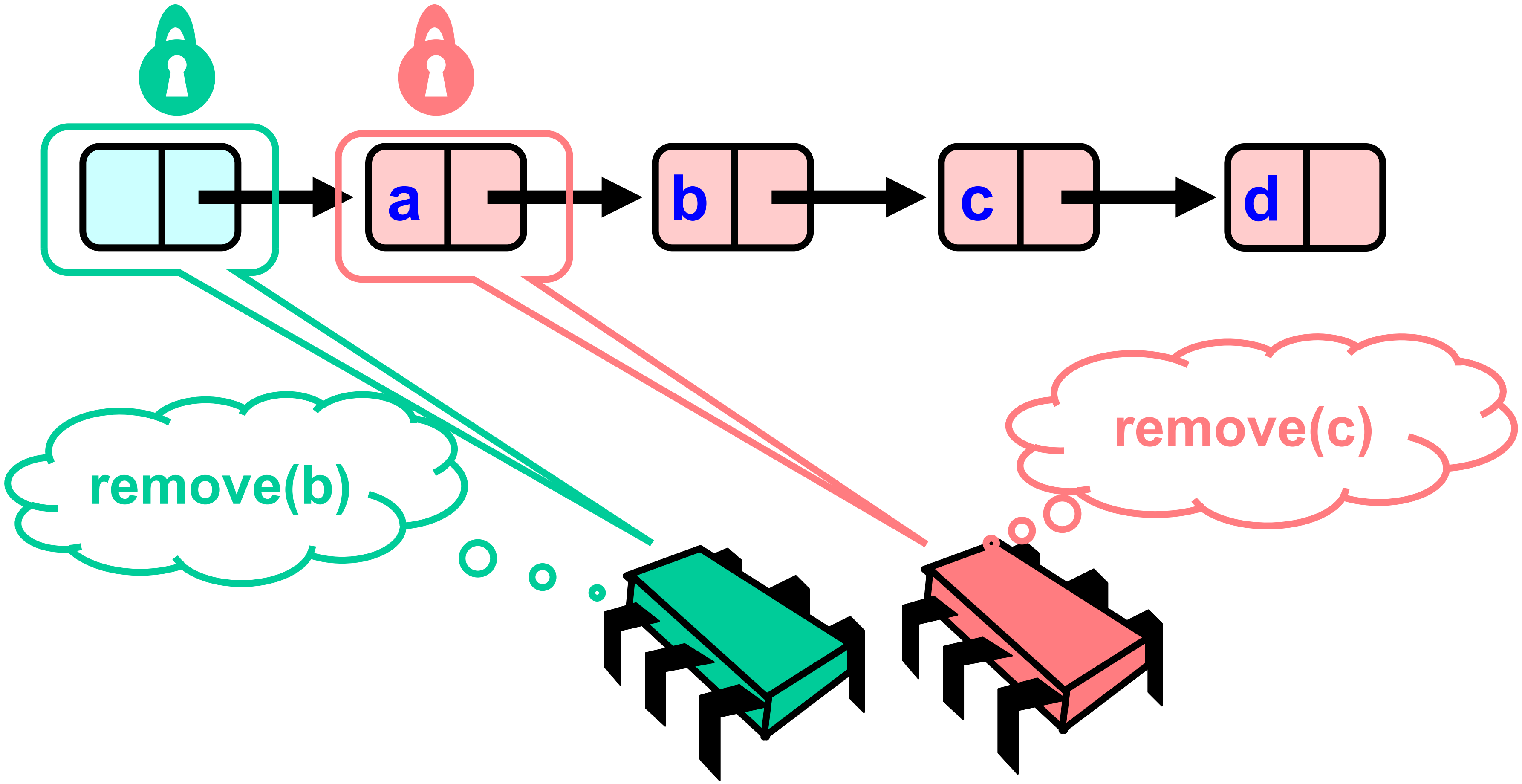


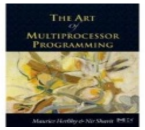
Removing a Node



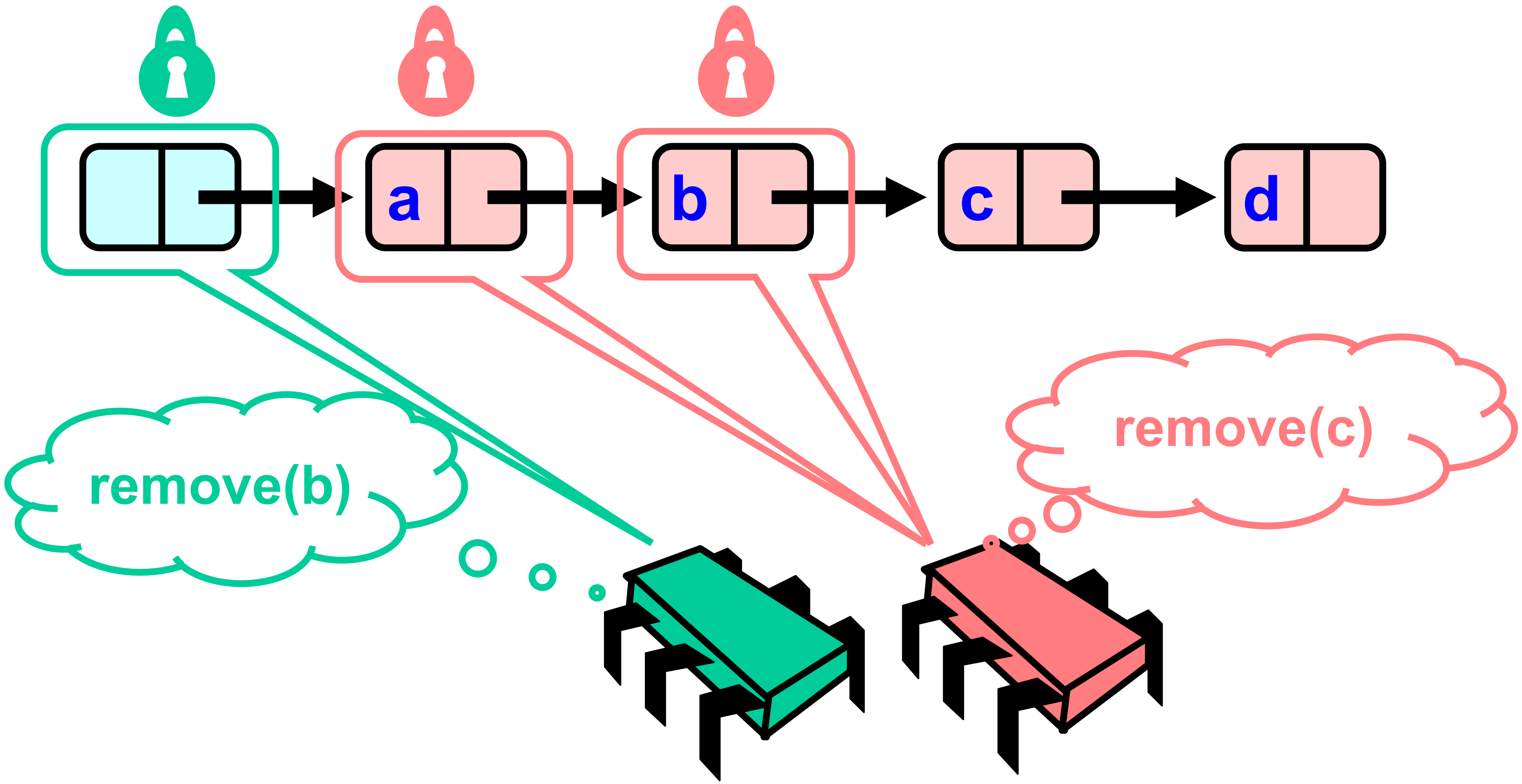


Removing a Node

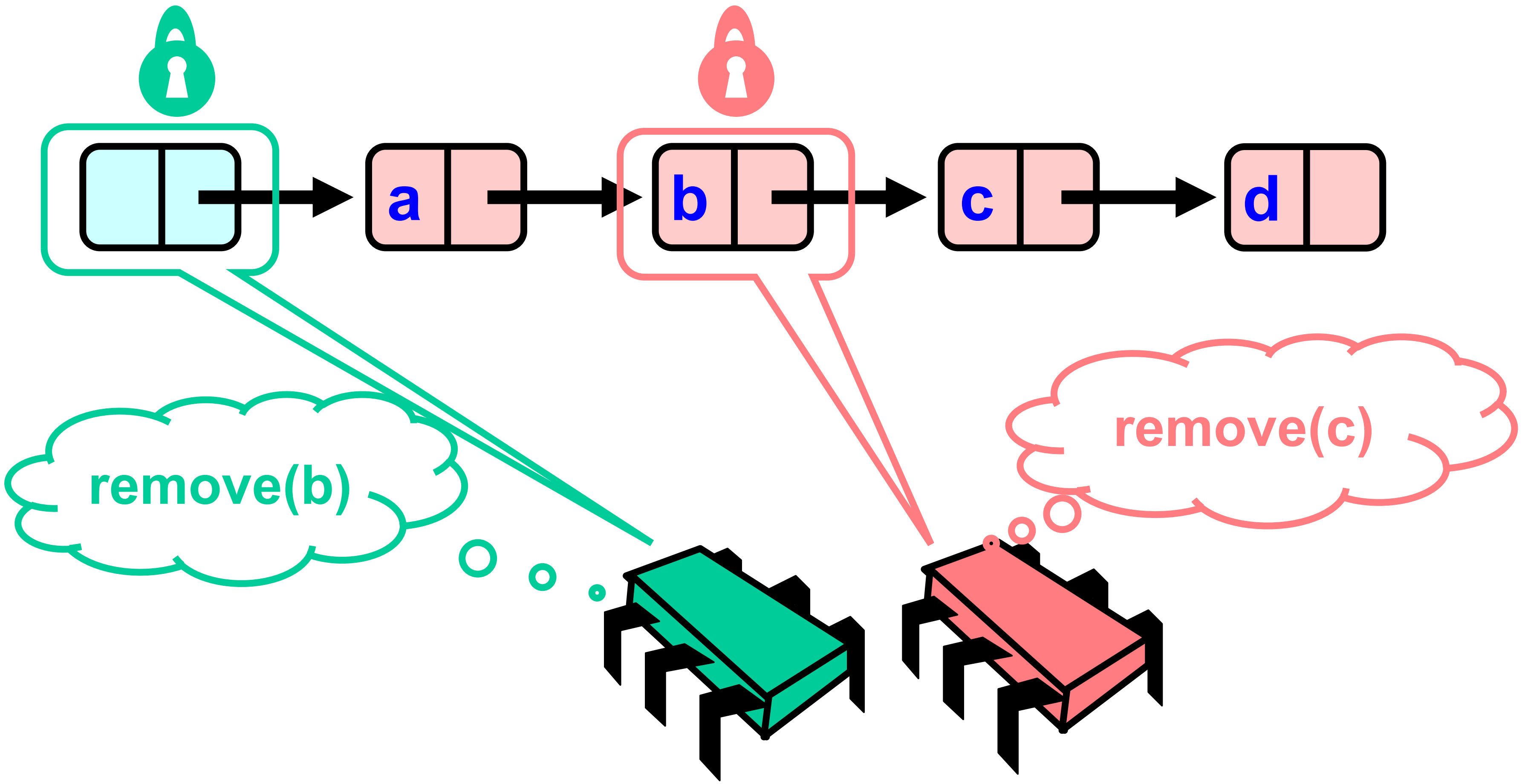




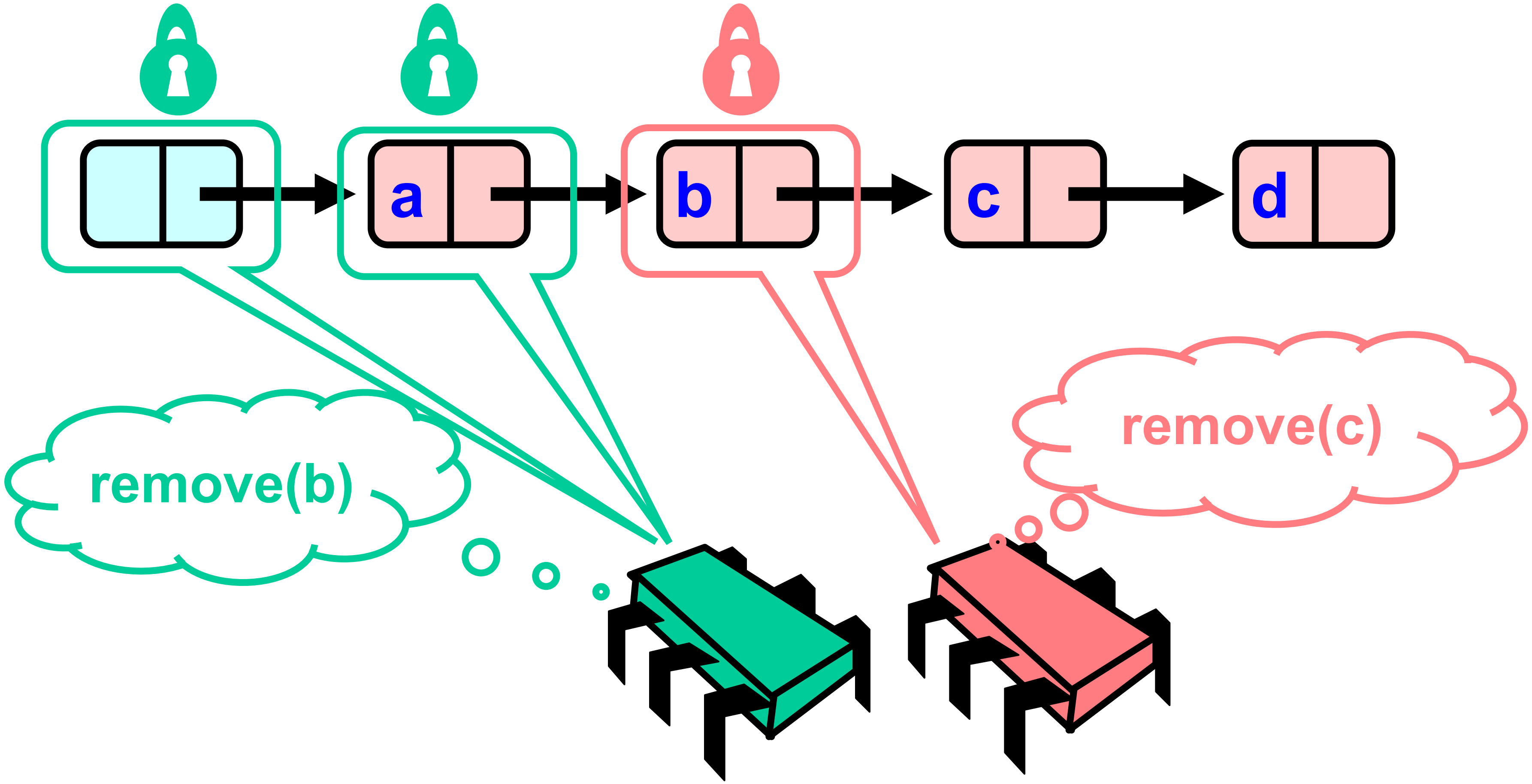
Removing a Node



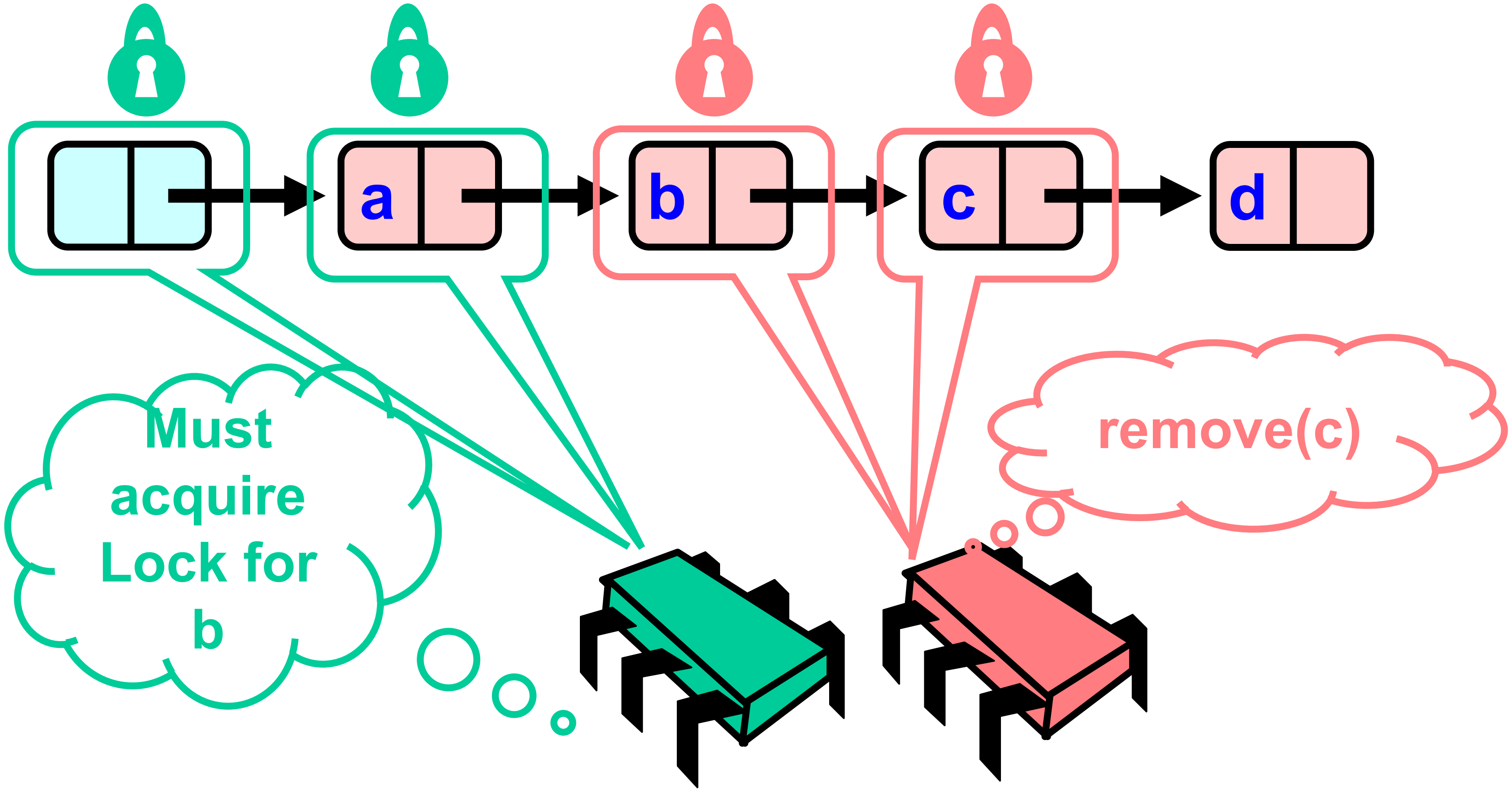
Removing a Node

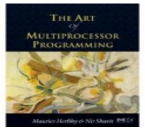


Removing a Node

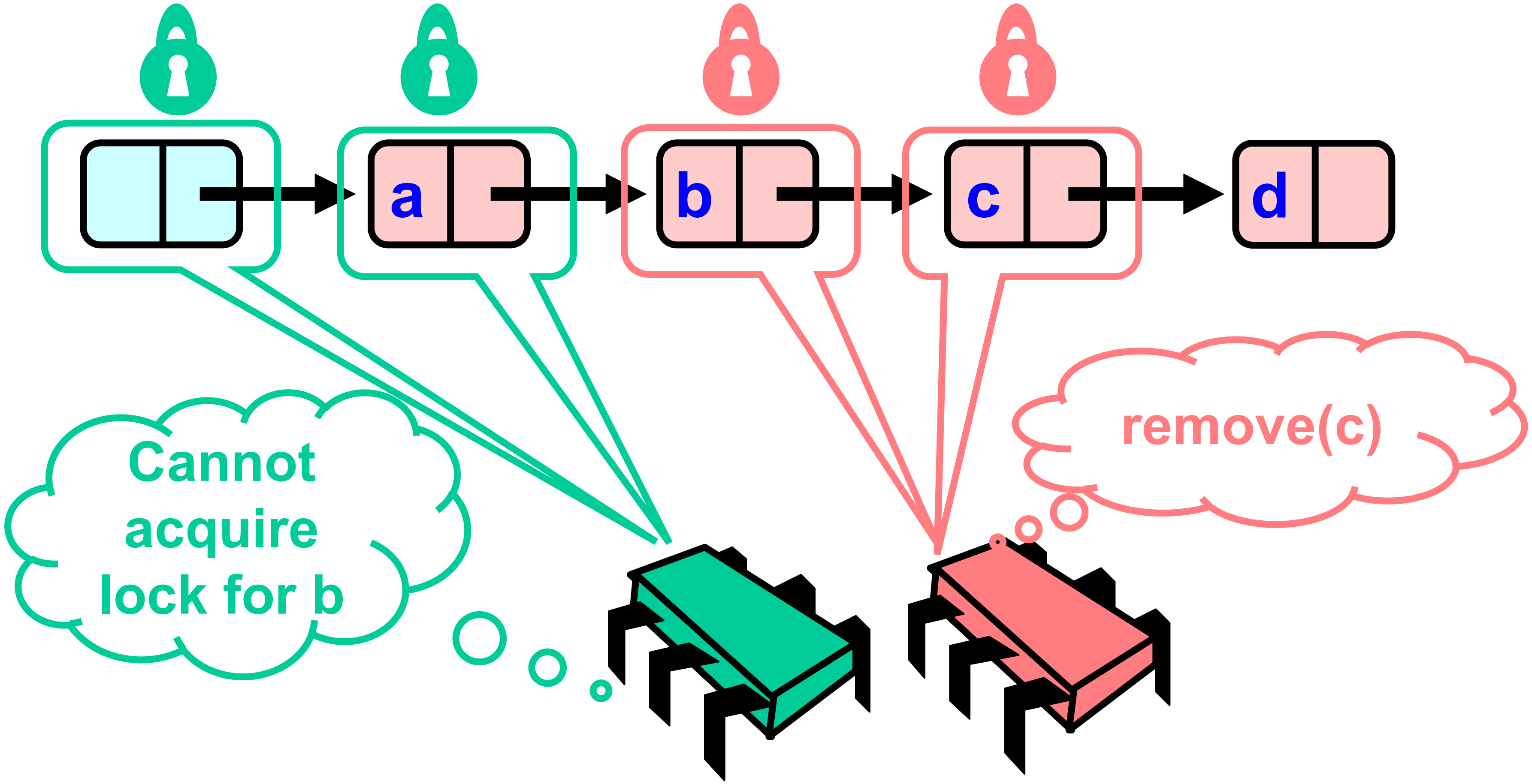


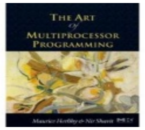
Removing a Node



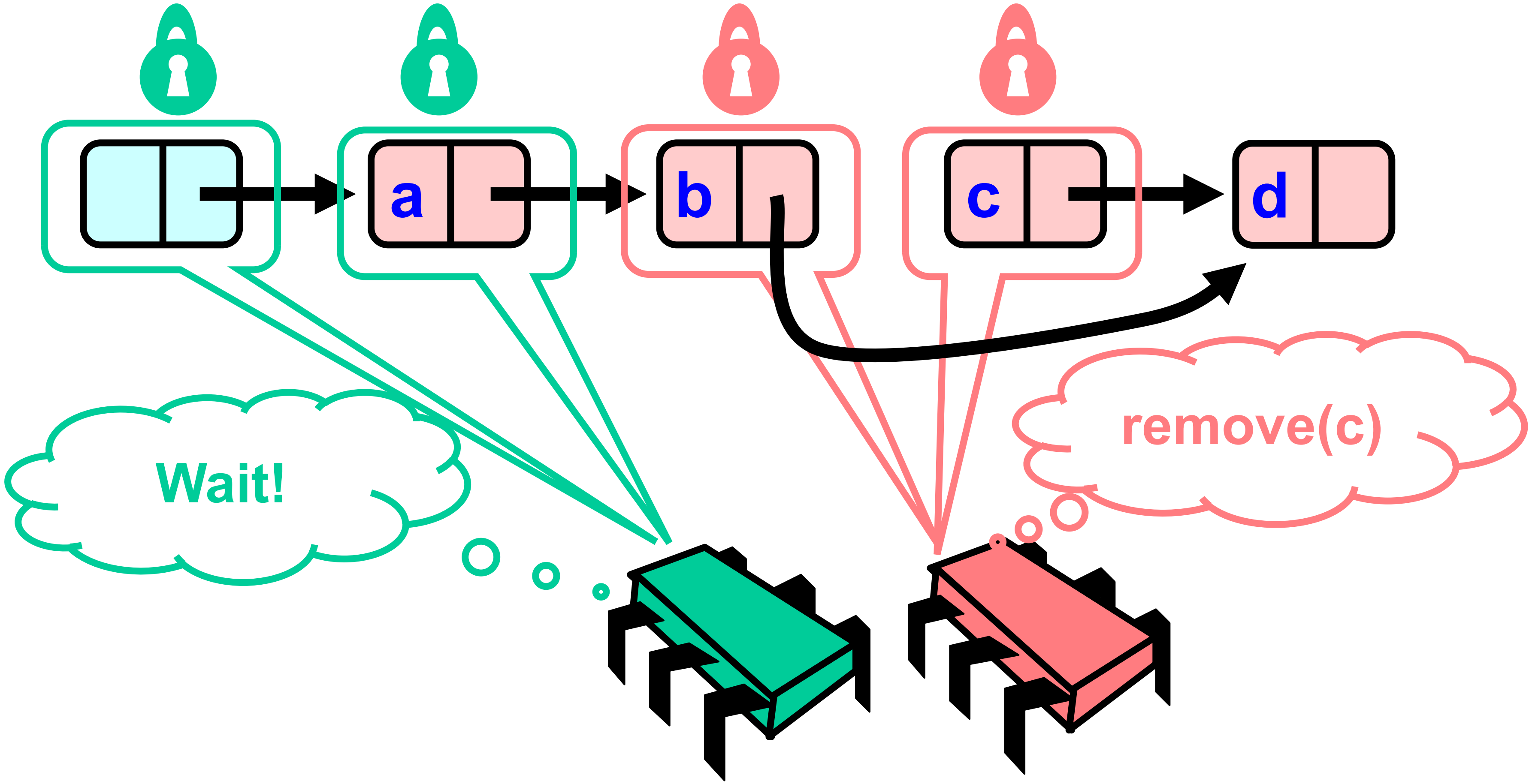


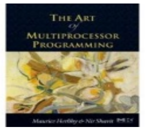
Removing a Node



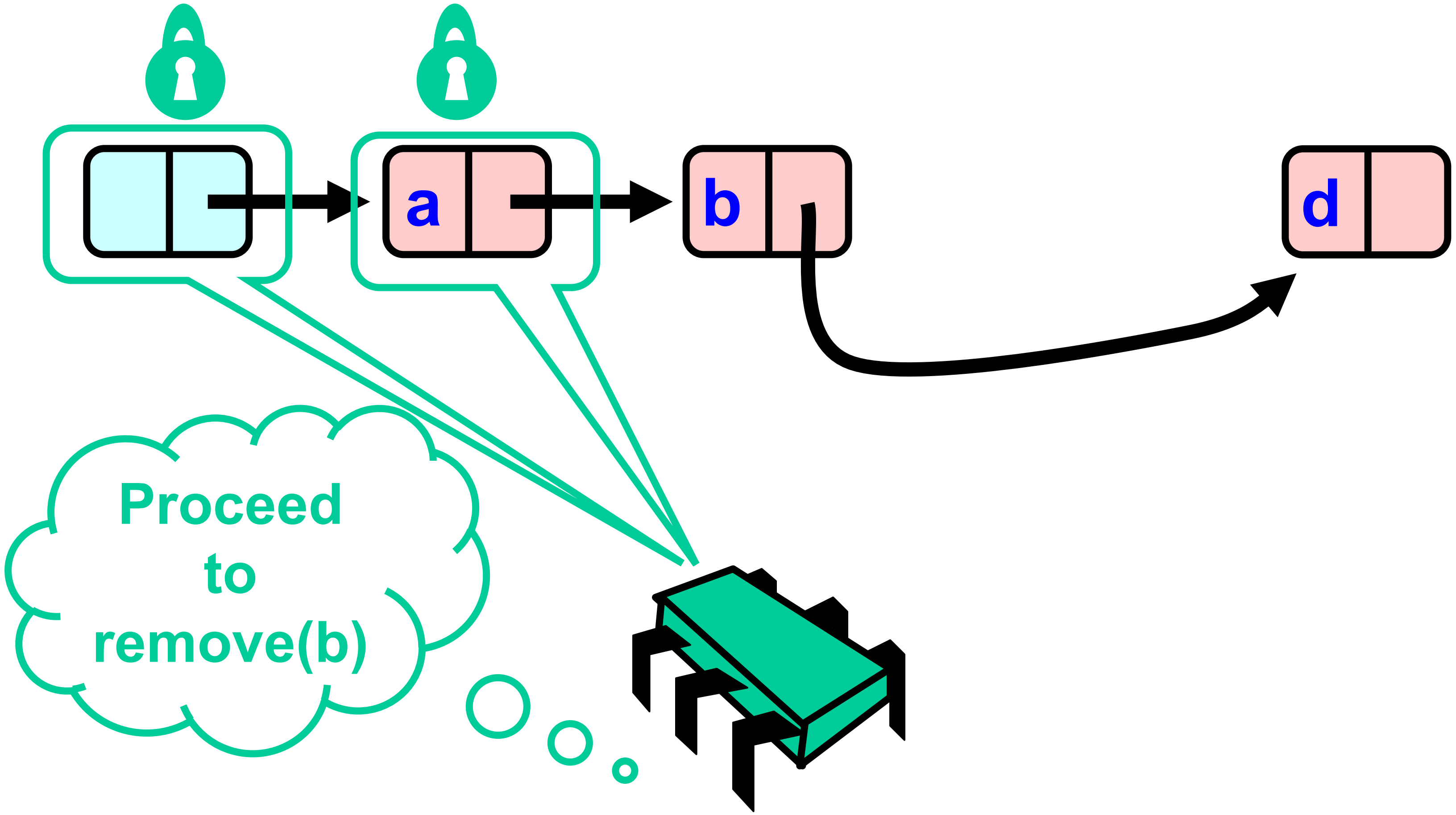


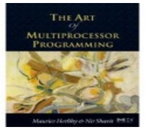
Removing a Node



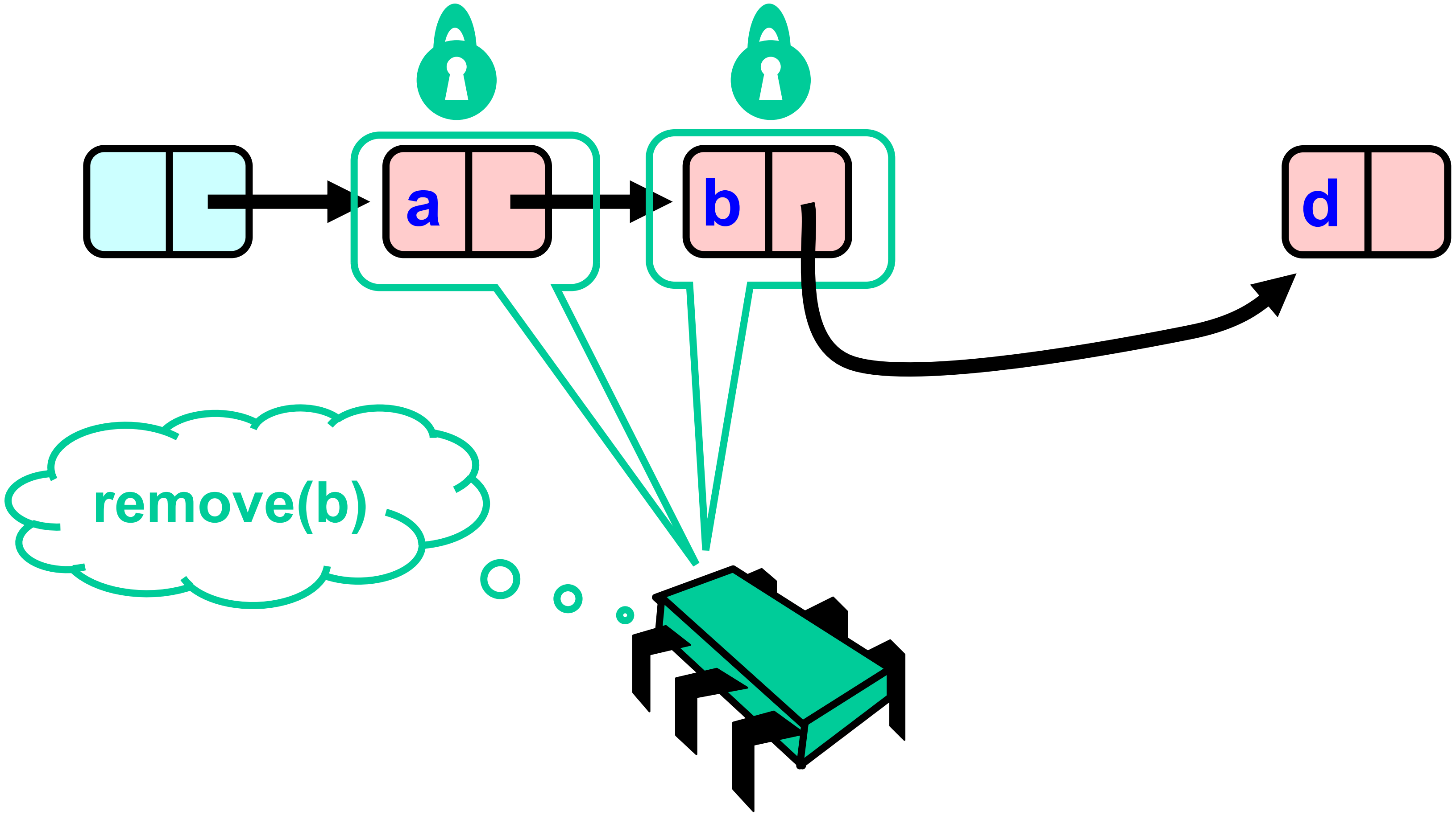


Removing a Node

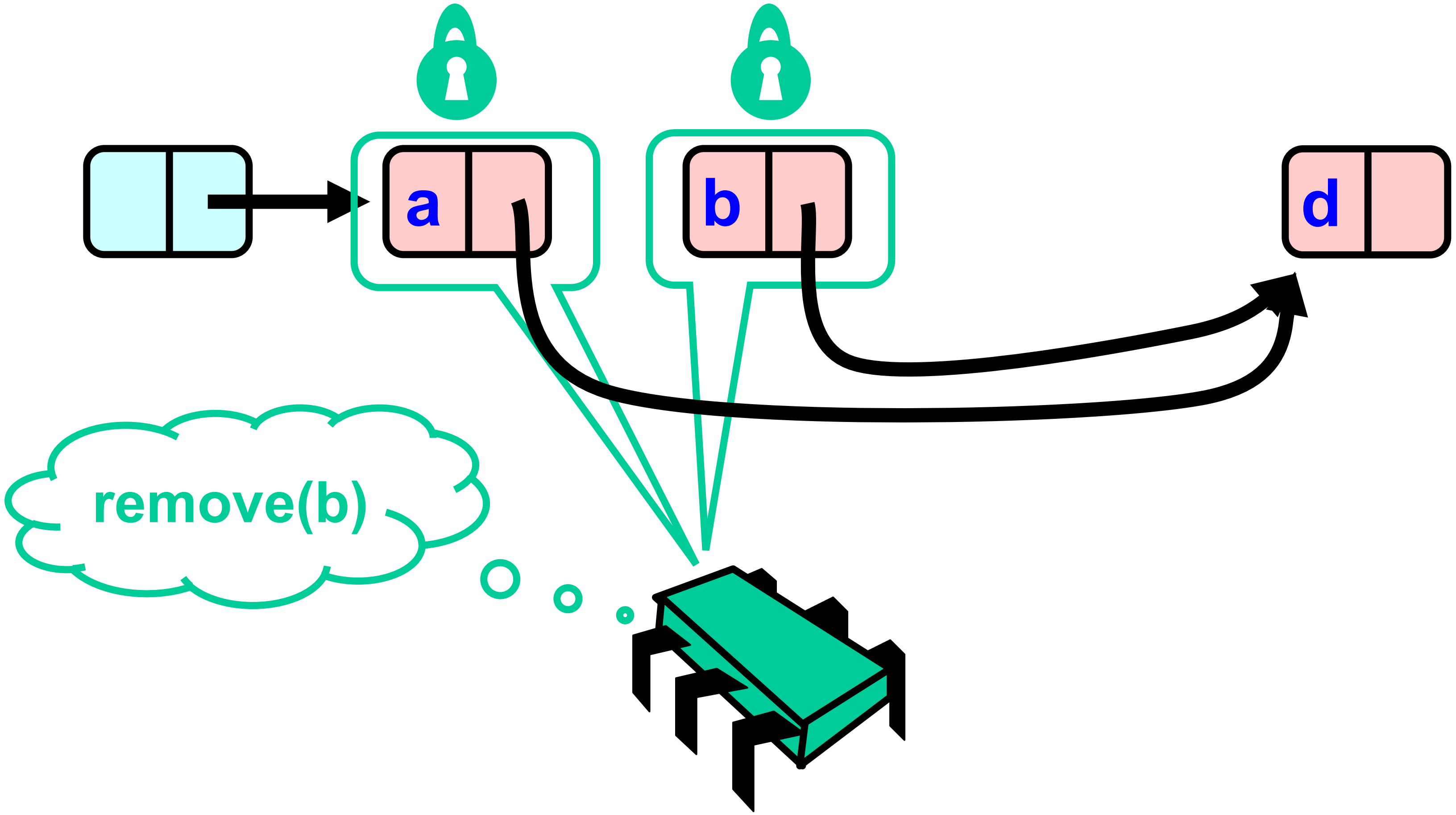




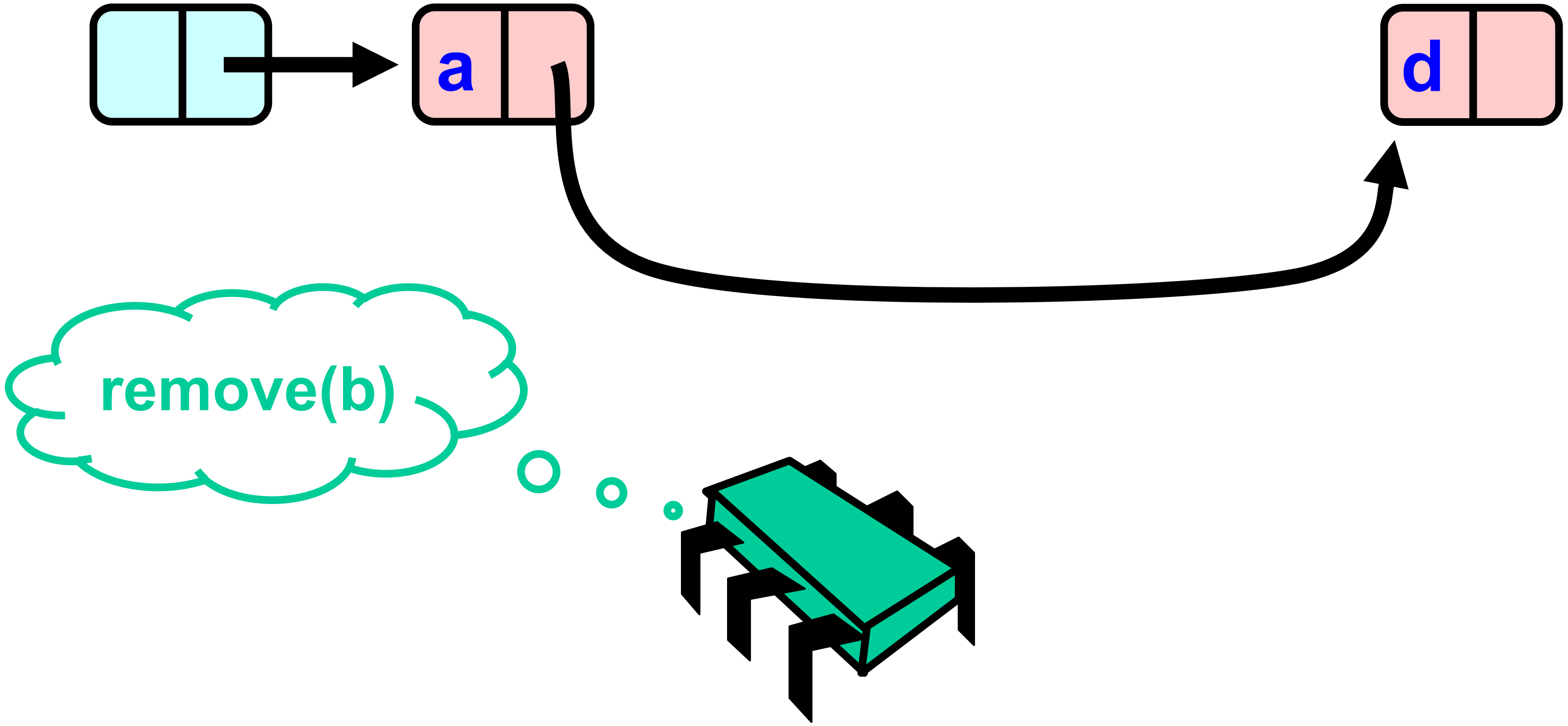
Removing a Node



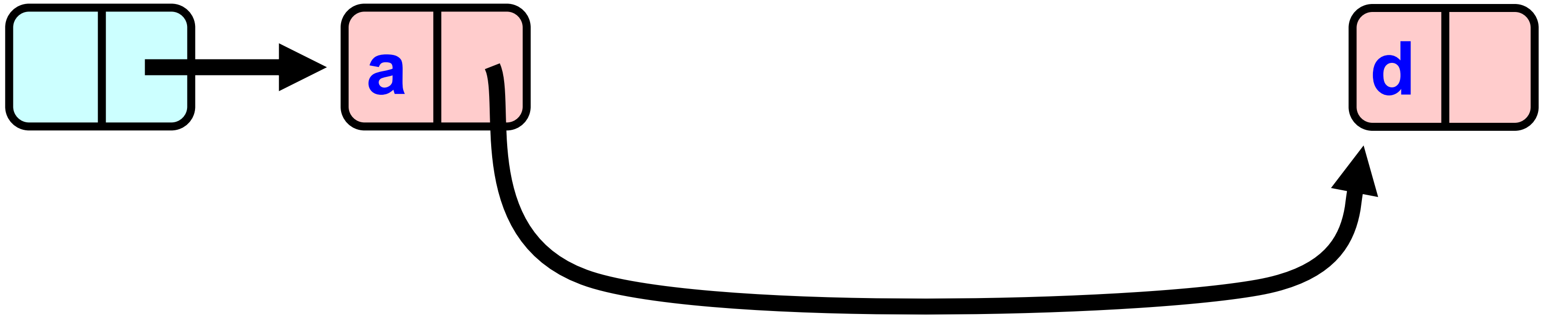
Removing a Node



Removing a Node



Removing a Node



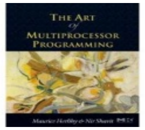
Remove method

```java
public boolean remove(Item item) {
 int key = item.hashCode();
 Node pred, curr;
 try {
   …
 } finally {
  curr.unlock();
  pred.unlock();
 }}
```

Remove method

```
public boolean remove(Item item) {
 int key = item.hashCode();
 Node pred, curr;
 try {
   …
 } finally {
  curr.unlock();
  pred.unlock();
 }}
```

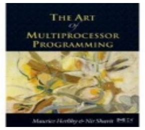
Key used to order node



Remove method

```
public boolean remove(Item item) {
 int key = item.hashCode();
 Node pred, curr;
 try {
   …
 } finally {
  currNode.unlock();
  predNode.unlock();
 }}
```

Predecessor and current nodes



Remove method

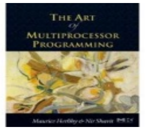
```
public boolean remove(Item item) {
 int key = item.hashCode();
 Node pred, curr;
 try {
  …
 } finally {
  curr.unlock();
  pred.unlock();
 }}
```

Make sure locks released

Remove method

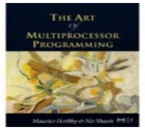
```
public boolean remove(Item item) {
 int key = item.hashCode();
 Node pred, curr;
 try {
   …
 } finally {
  curr.unlock();
  pred.unlock();
 }}
```

Everything else



Remove method

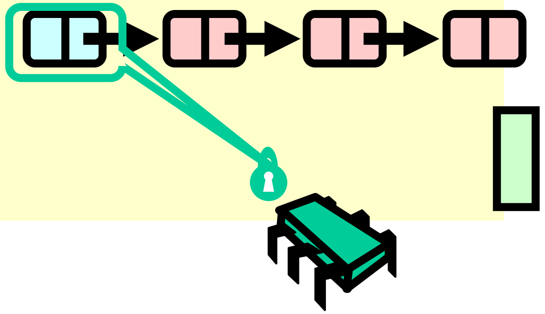
```
try {
 pred = this.head;
 pred.lock();
 curr = pred.next;
 curr.lock();
 …
} finally { … }
```



Remove method

lock pred == head

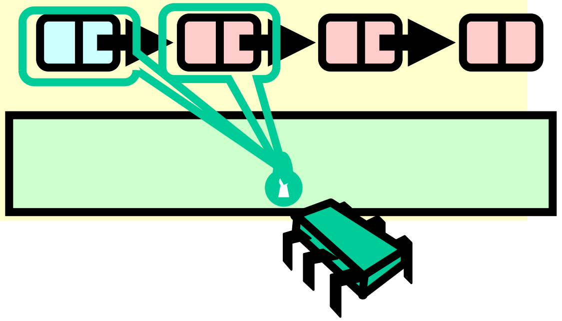
```
try {
 pred = this.head;
 pred.lock();
 curr = pred.next;
 curr.lock();
 …
} finally { … }
```

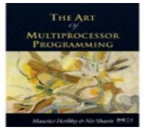


Remove method

```
try {
 pred = this.head;
 pred.lock();
 curr = pred.next;
 curr.lock();
 …
} finally { … }
```

Lock current

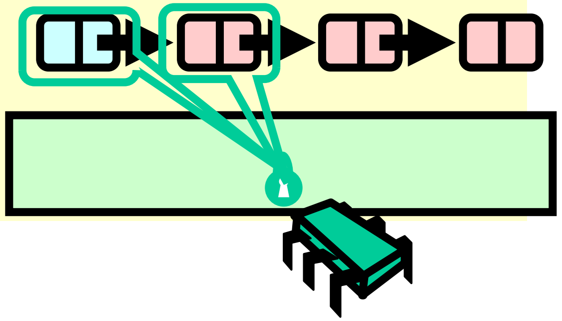




Remove method

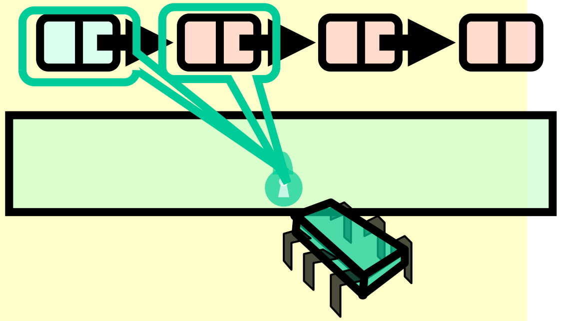
```
try {
 pred = this.head;
 pred.lock();
 curr = pred.next;
 curr.lock();
 ...
} finally { … }
```

Traversing list



Remove: searching

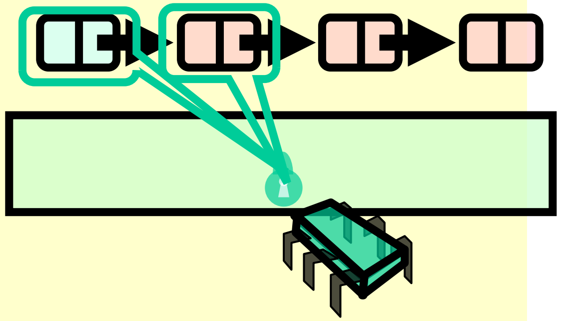
```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```

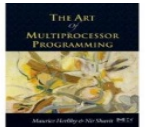


Remove: searching

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
}
return false;
```

Search key range

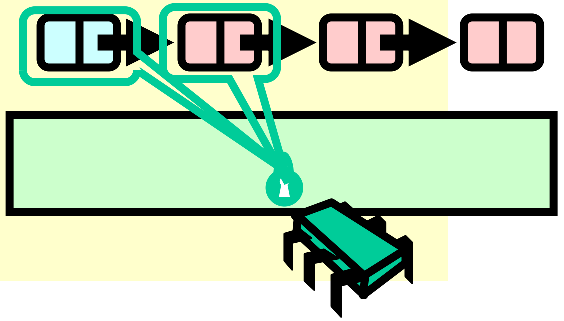




Remove: searching

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```

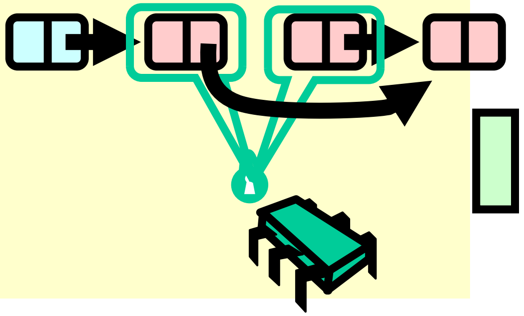
At start of each loop: curr and pred locked

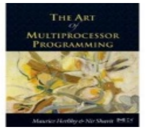


Remove: searching

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
```

If item found, remove node

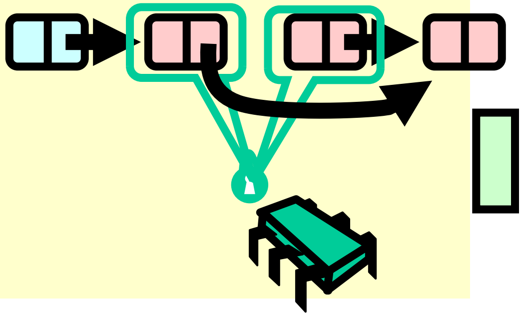


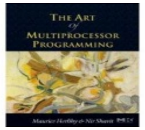


Remove: searching

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
```

If node found, remove it

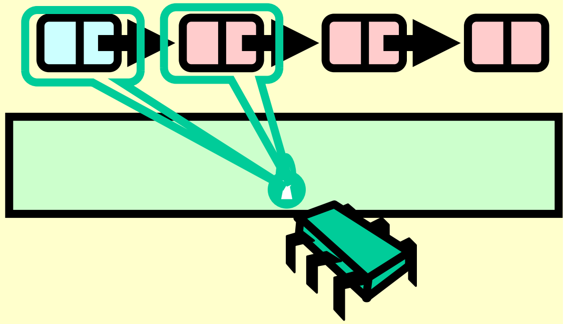




Remove: searching

Unlock predecessor

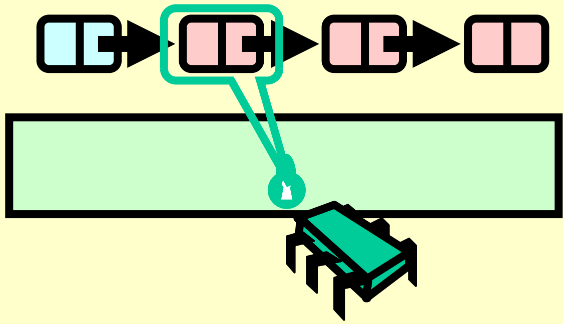
```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```

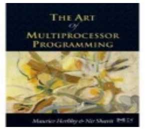


Remove: searching

Only one node locked!

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```

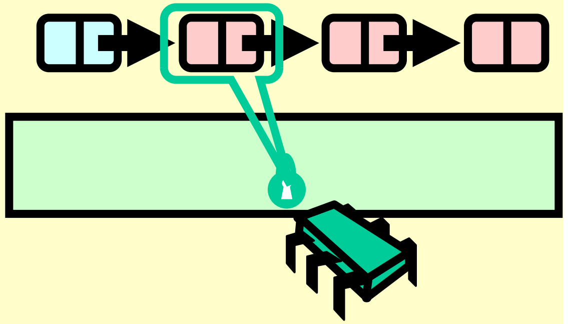


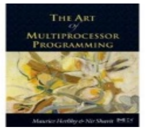


Remove: searching

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```

demote current

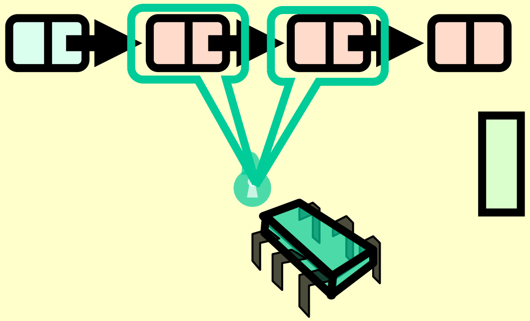




Remove: searching

```
while (curr.key <= key) {
   if (item == curr.item) {
    pred.next = curr.next;
    return true;
   }
   pred.unlock();
   pred = currNode;
   curr = curr.next;
   curr.lock();
  }
  return false;
```

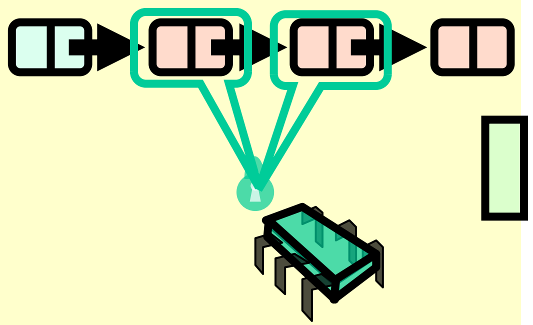
Find and lock new current



Remove: searching

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = currNode;
  curr = curr.next;
  curr.lock();
}
return false;
```

Lock invariant restored



Remove: searching

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```

Otherwise, not present

Why remove() is linearizable

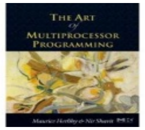
```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```

- **pred** reachable from **head**
- **curr** is **pred.next**
- So **curr.item** is in the set

Why remove() is linearizable

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```

Linearization point if item is present



Why remove() is linearizable

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```

Node locked, so no other thread can remove it ….

Why remove() is linearizable

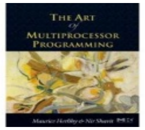
```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```

Item not present

Why remove() is linearizable

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
return false;
```

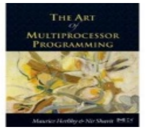
- pred reachable from head
- curr is pred.next
- pred.key < key
- key < curr.key



Why remove() is linearizable

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```

Linearization point



Adding Nodes

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

Same Abstraction Map

- S(head) =
  - { x | there exists a such that
    - a reachable from head and
    - a.item = x
  - }

Rep Invariant

- Easy to check that
  - tail always reachable from head
  - Nodes sorted, no duplicates

Drawbacks

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