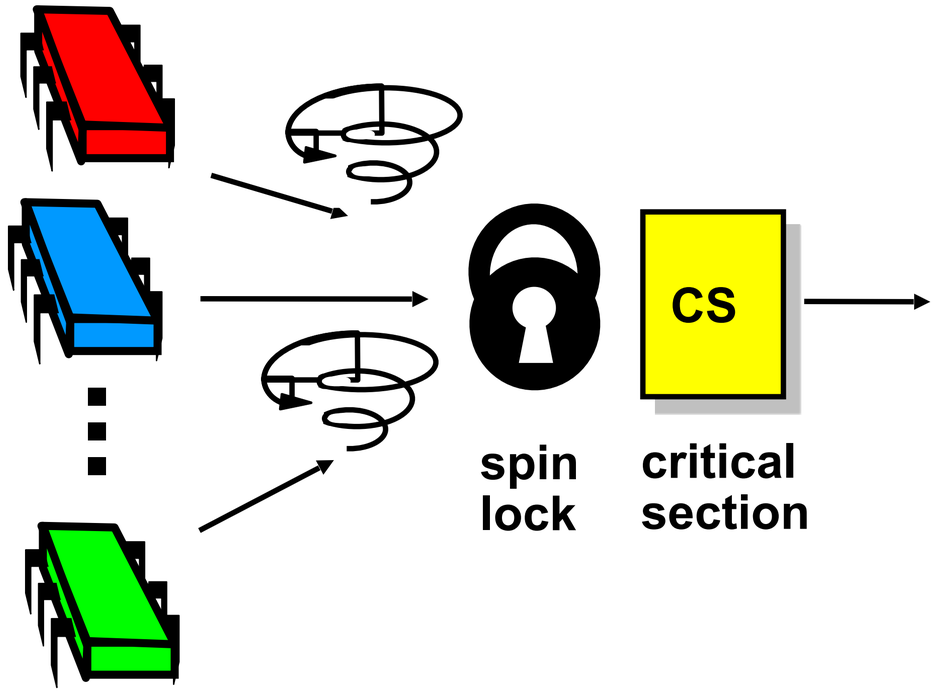
YSC3248: Parallel, Concurrent and Distributed Programming

Concurrent Linked Lists
Part I

Previous Lectures: Spin-Locks



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- Adding threads should not lower throughput
  - Contention effects
  - Can be mitigated by back-offs, arrays, etc.

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- Adding threads should not lower throughput
  - Contention effects
  - Can be mitigated by back-offs, arrays, etc.
- Should increase throughput
  - Not possible if inherently sequential
  - Surprising things are parallelizable

Coarse-Grained Synchronization

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

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    - In simple cases

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  - Avoid contention using queue locks
  - Easy to reason about
    - In simple cases
- So, are we done?

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- Sequential bottleneck
  - Threads “stand in line”

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  - Does not improve throughput
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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 several “patterns”
  - Bag of tricks …
  - Methods that work more than once …

This Lecture

- Introduce several “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 …

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- Split object into
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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 …

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- 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

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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

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  - Use compareAndSet() & relatives …

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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

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- 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

Warm-up:
Testing Concurrent Sets

List-Based Sets

```
trait ConcurrentSet[T] {
  def add(item: T): Boolean
  def remove(item: T): Boolean
  def contains(item: T): Boolean
}
```

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Remove item from set

List-Based Sets

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trait ConcurrentSet[T] {
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Is item in set?

List Node

```
class Node (val item: T) {
  def key : Int
  @volatile var next: Node = _
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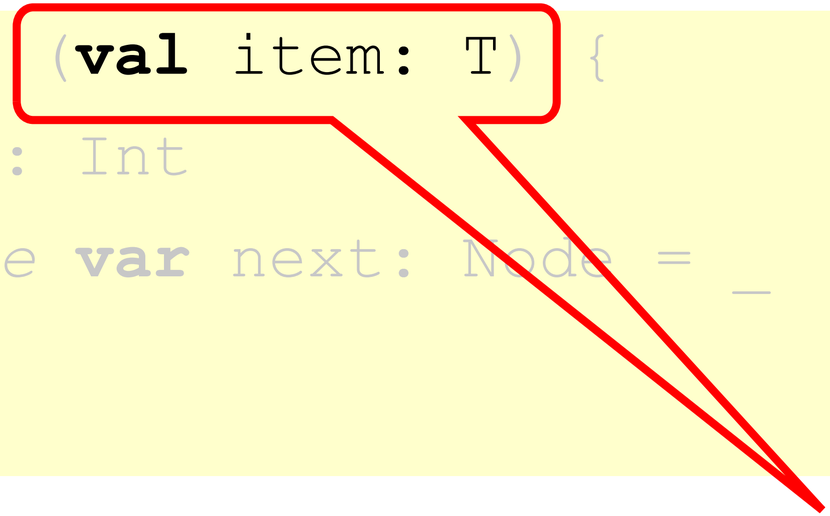


item of interest

List Node

```
class Node (val item: T) {
  def key : Int
  @volatile var next: Node = _
}
```

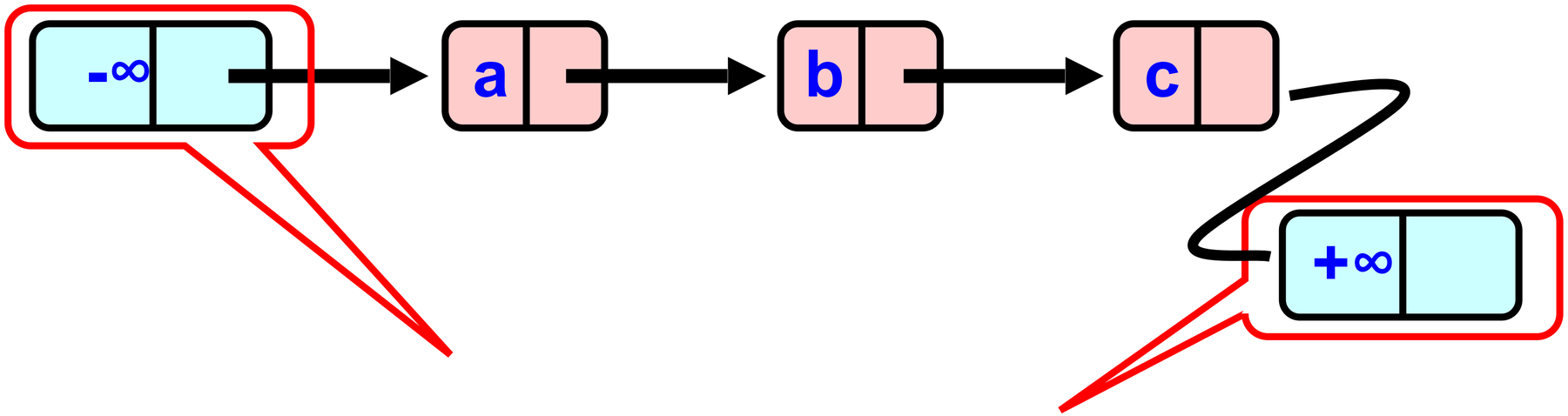
Usually hash code

List Node

```
class Node (val item: T) {
  def key : Int
  @volatile var next: Node = _
}
```

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

Specifically …

- Invariants preserved by
  - **`add()`**
  - **`remove()`**
  - **`contains()`**

Specifically …

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

Interference

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

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  - List nodes *not visible* outside class

Interference

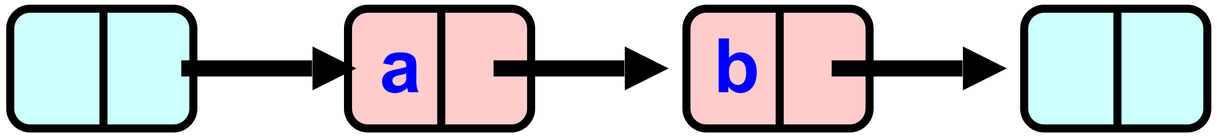
- Invariants make sense only if
  - methods considered
  - are the only modifiers
- Language encapsulation helps
  - List nodes *not visible* outside class
- Similar to *loop invariants*
  - Each method must preserve the invariant (same as each loop iteration)

Interference

- Freedom from interference needed even for removed nodes
  - Some algorithms traverse removed nodes
  - Careful with **`malloc()`** & **`free()`**!
- We rely on garbage collection

Recap: Abstract Data Types

- Concrete representation:

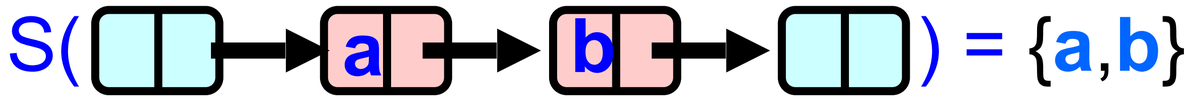


- Abstract Type:

  {**a**, **b**}

Abstract Data Types

- Meaning of rep given by abstraction map



Representation Invariant

- Which concrete values meaningful?
  - Sorted?
  - Duplicates?
- Representation invariant
  - Characterises legal *concrete representations*
  - 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

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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

Lists' Rep Invariant (partly)

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

Abstraction Map

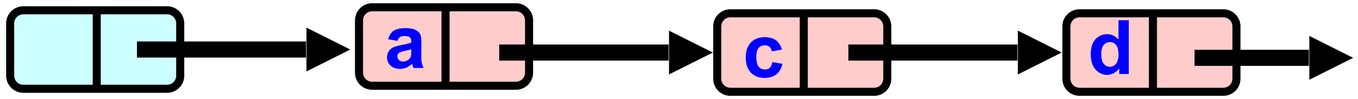
- S(head) =

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

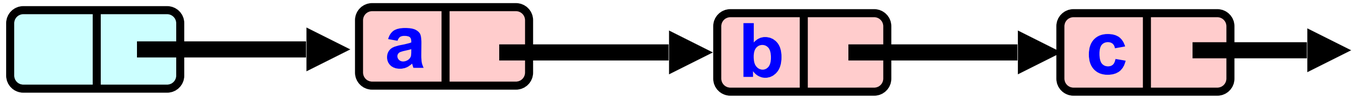
  }

Sequential List Based Set

`add()`



`remove()`



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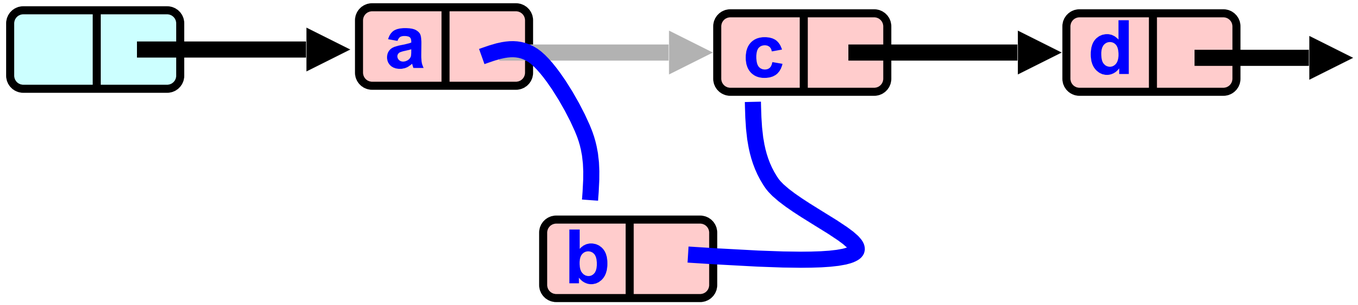

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Sequential List Based Set

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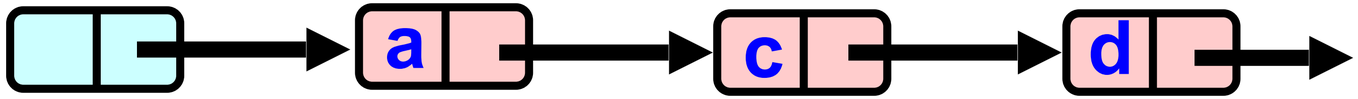

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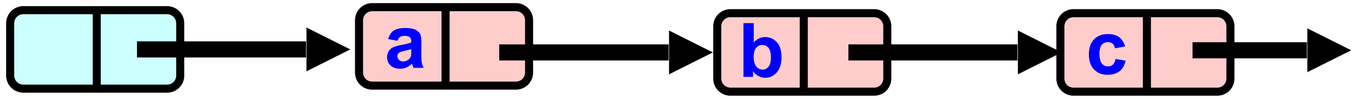

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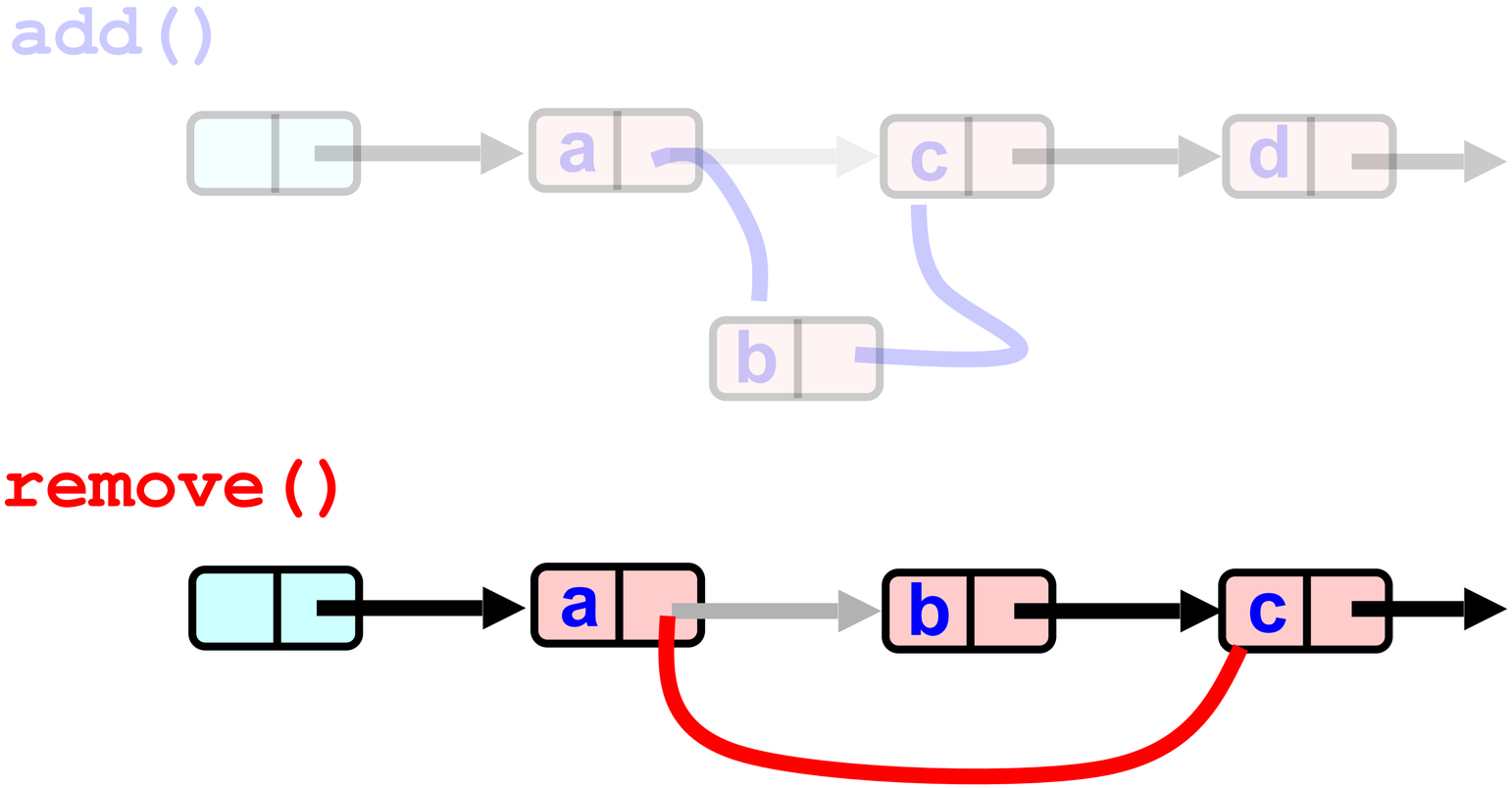
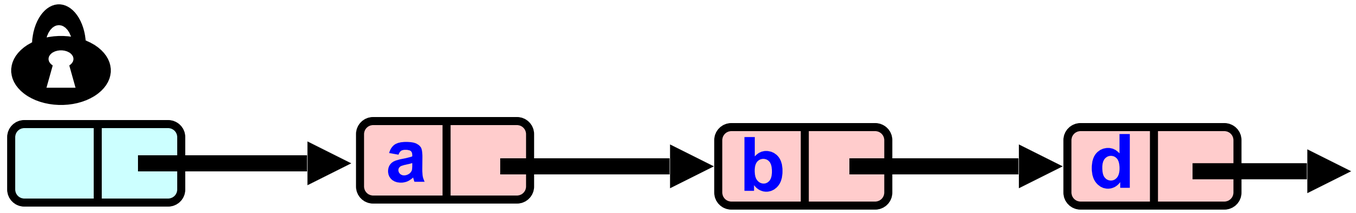


Coarse-Grained Locking



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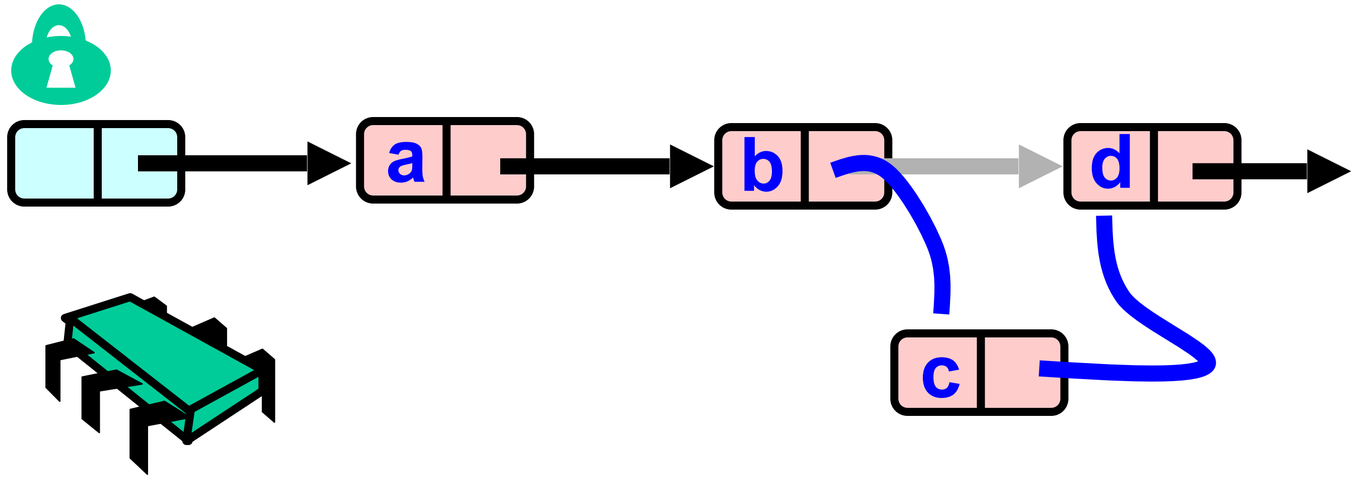

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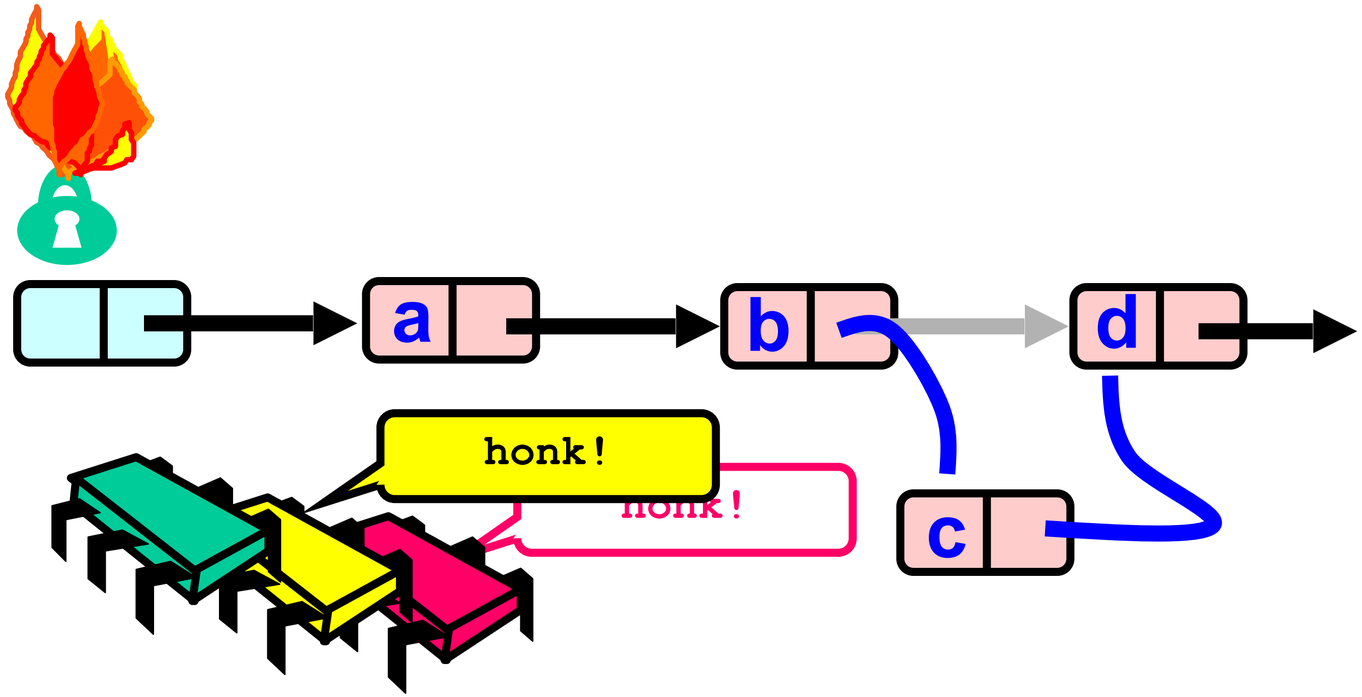


Simple but hotspot + bottleneck

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

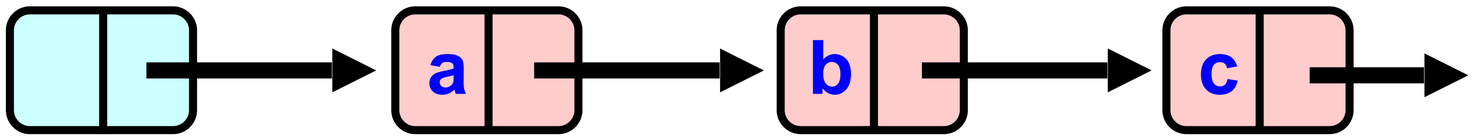
Fine-grained Locking

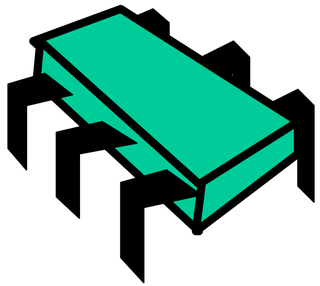
- Requires **careful** thought
  - "Do not meddle in the affairs of wizards, for they are subtle and quick to anger"

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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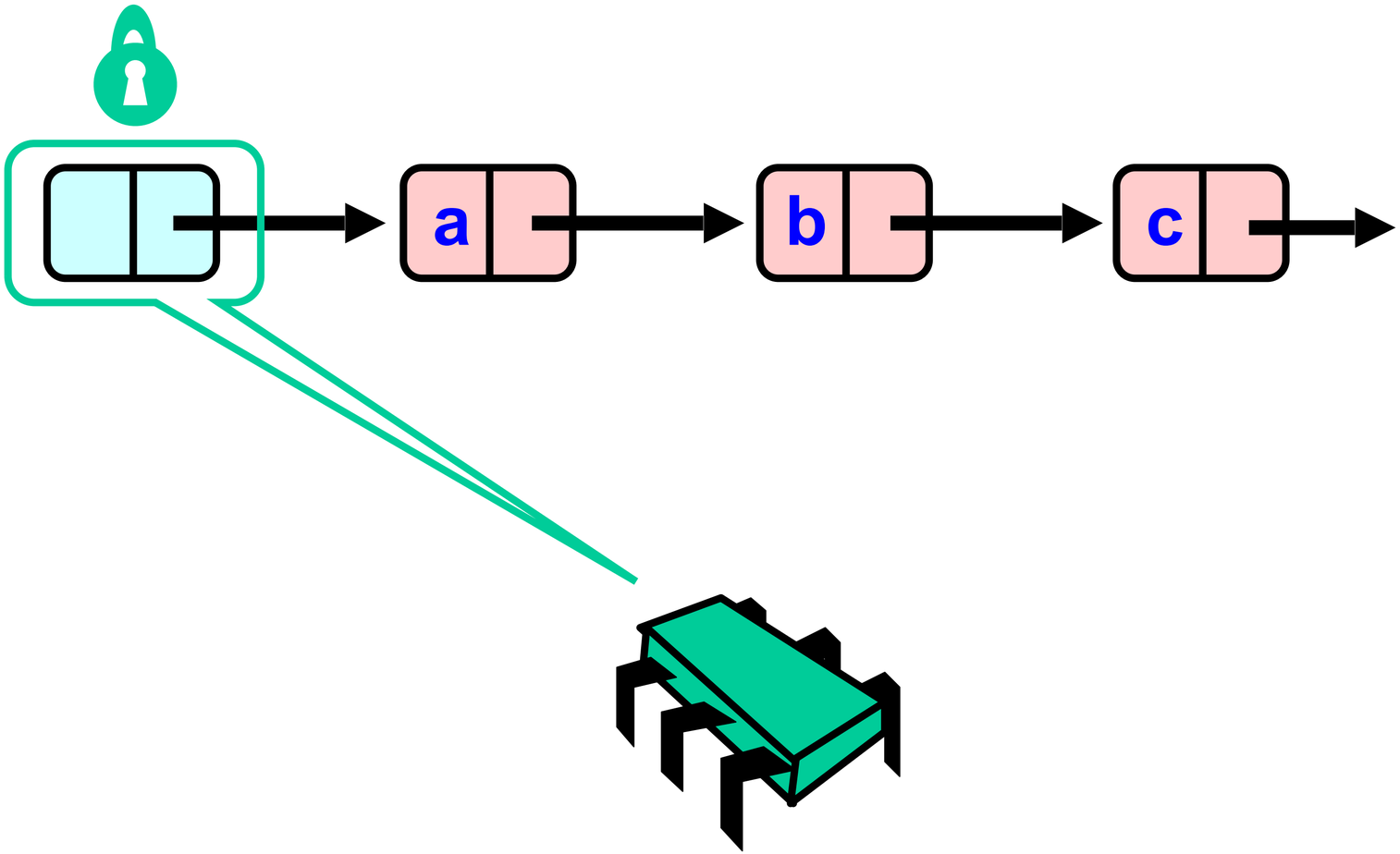

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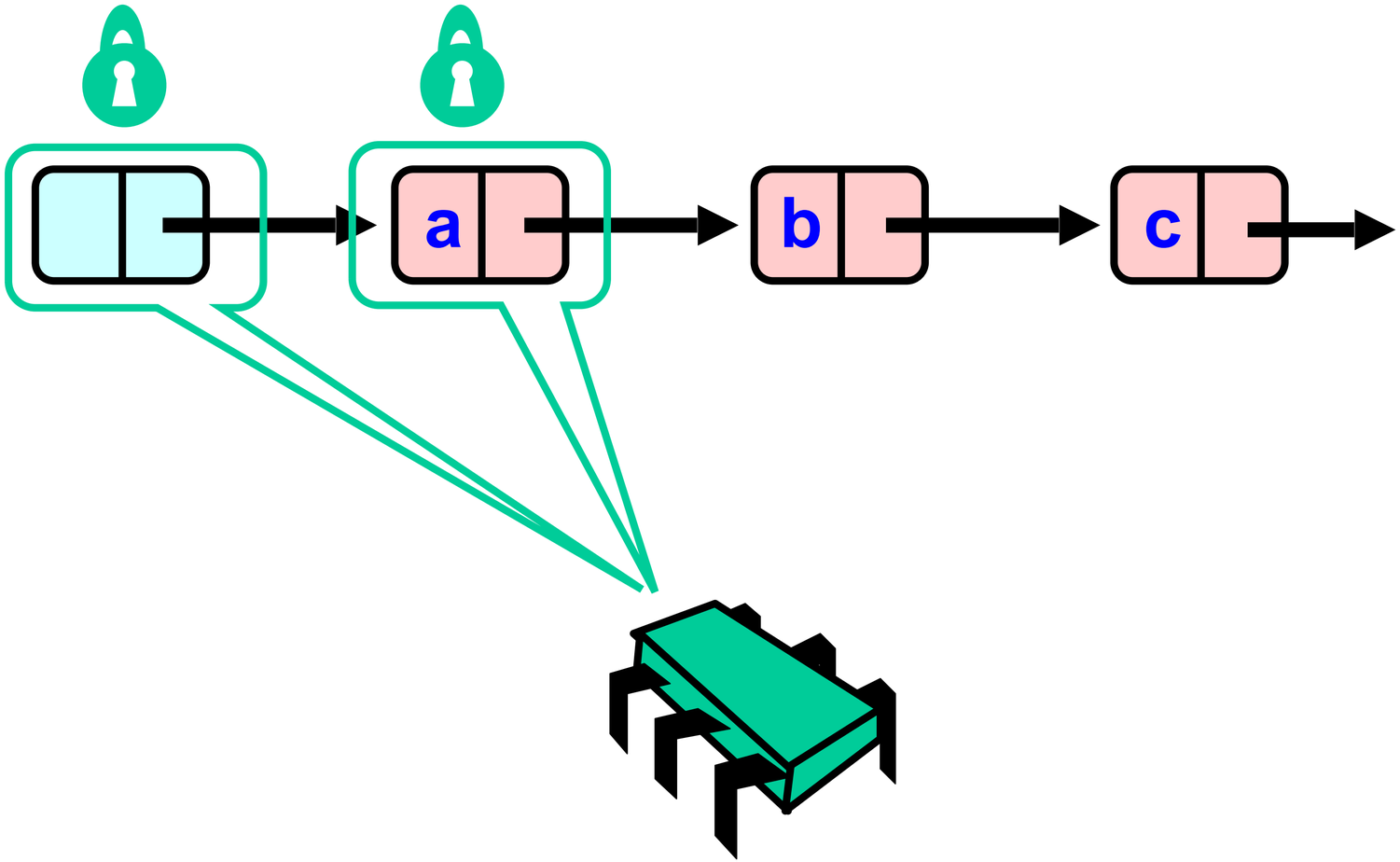

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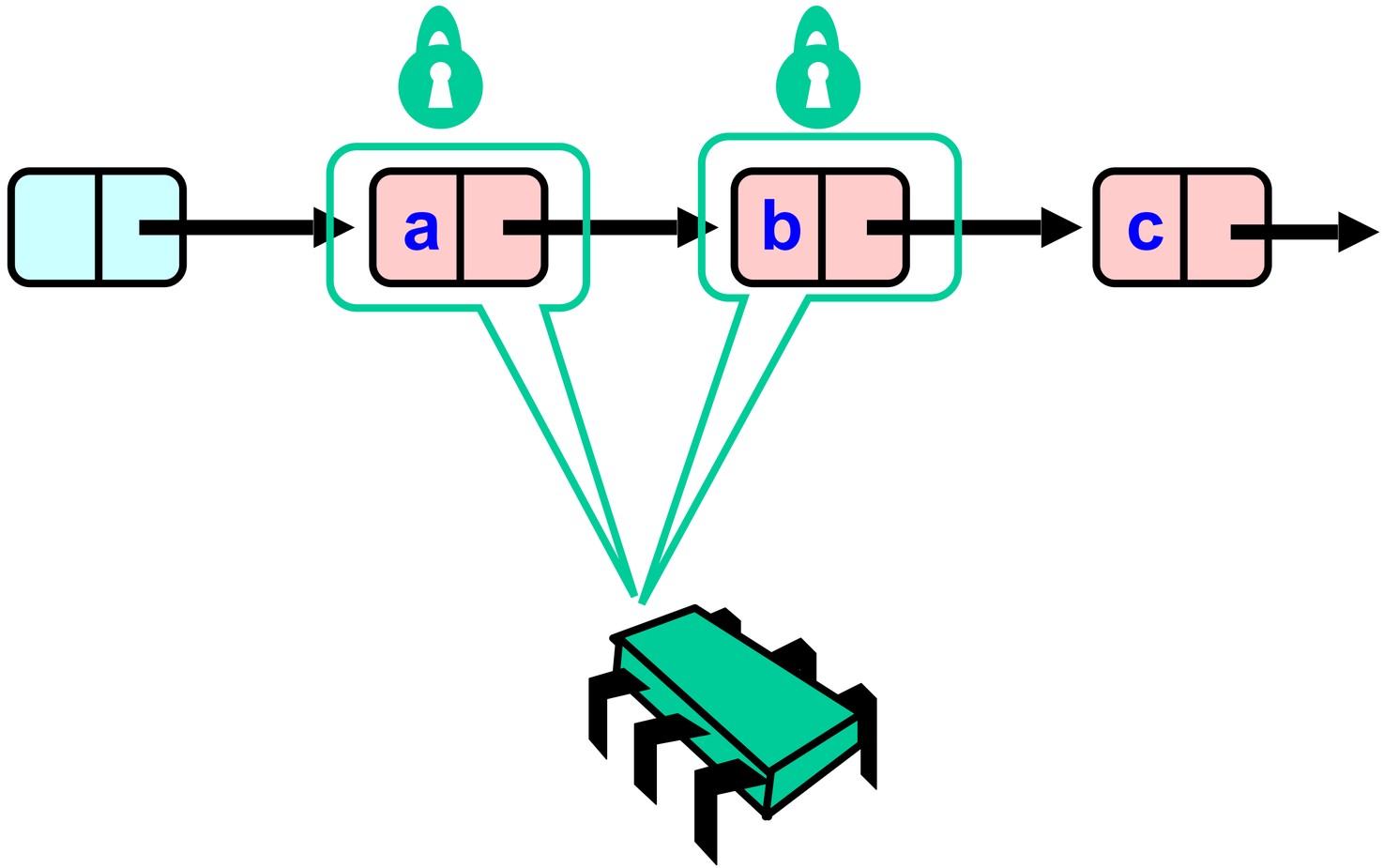

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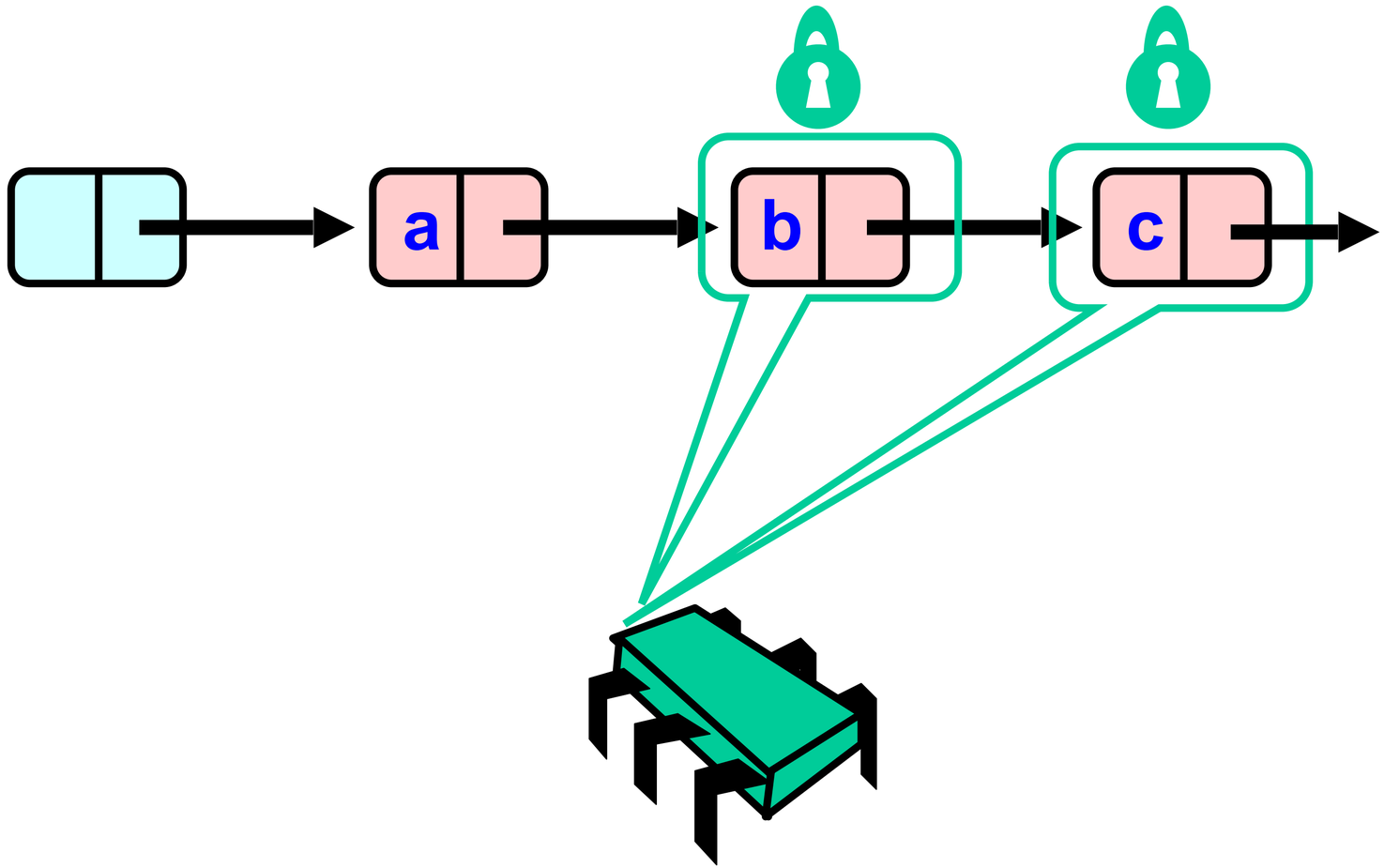
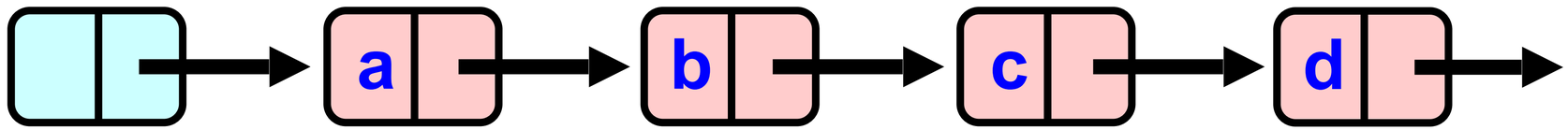
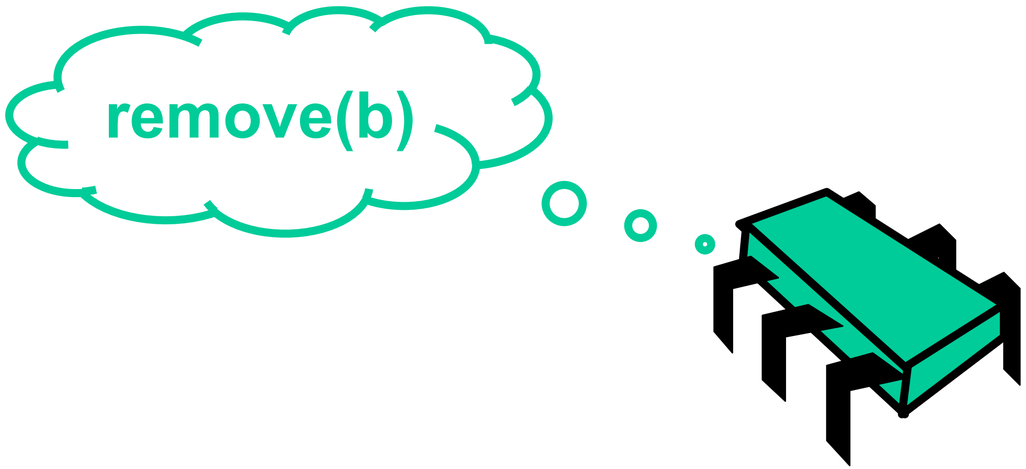


Removing a Node





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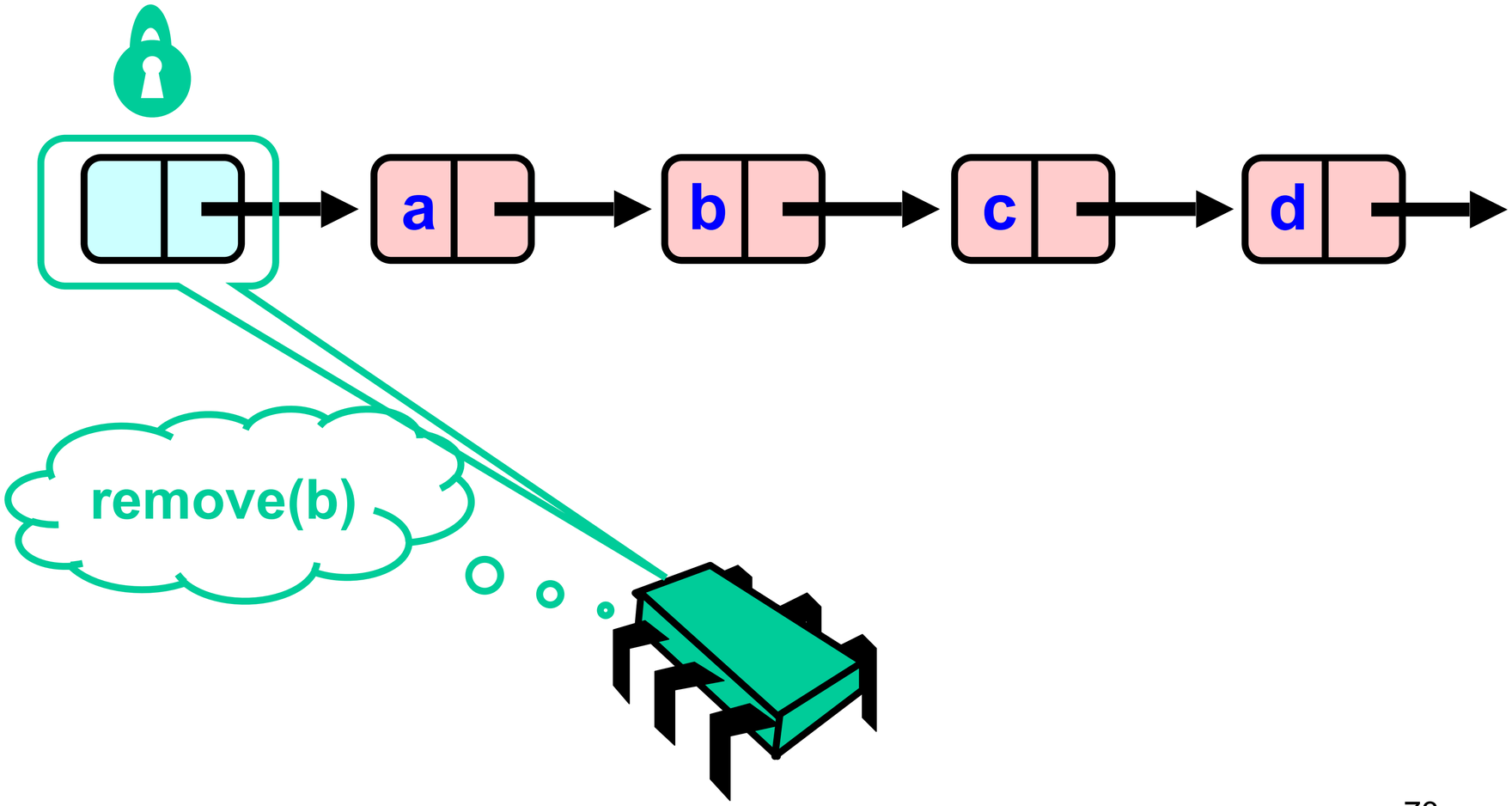

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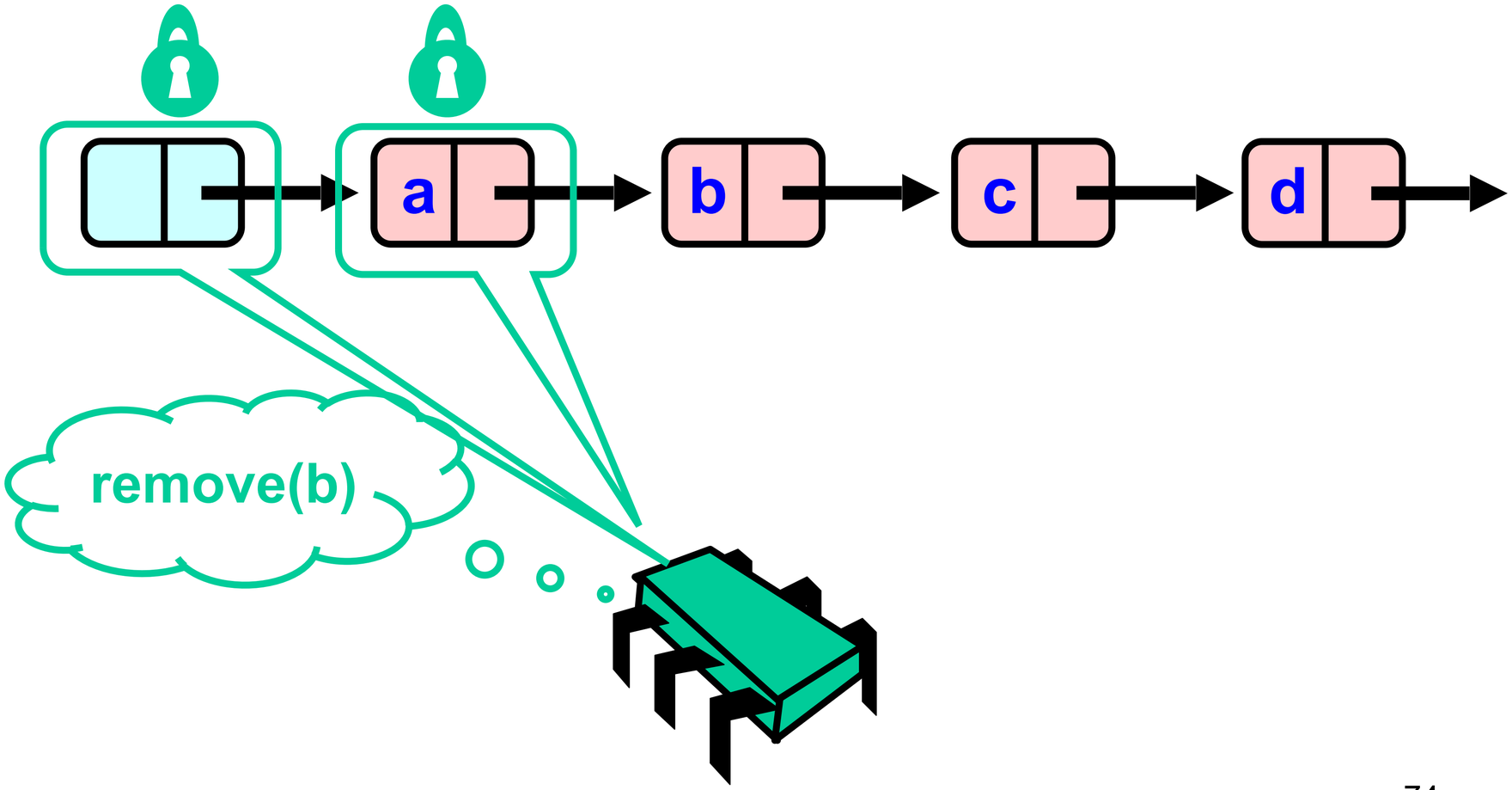

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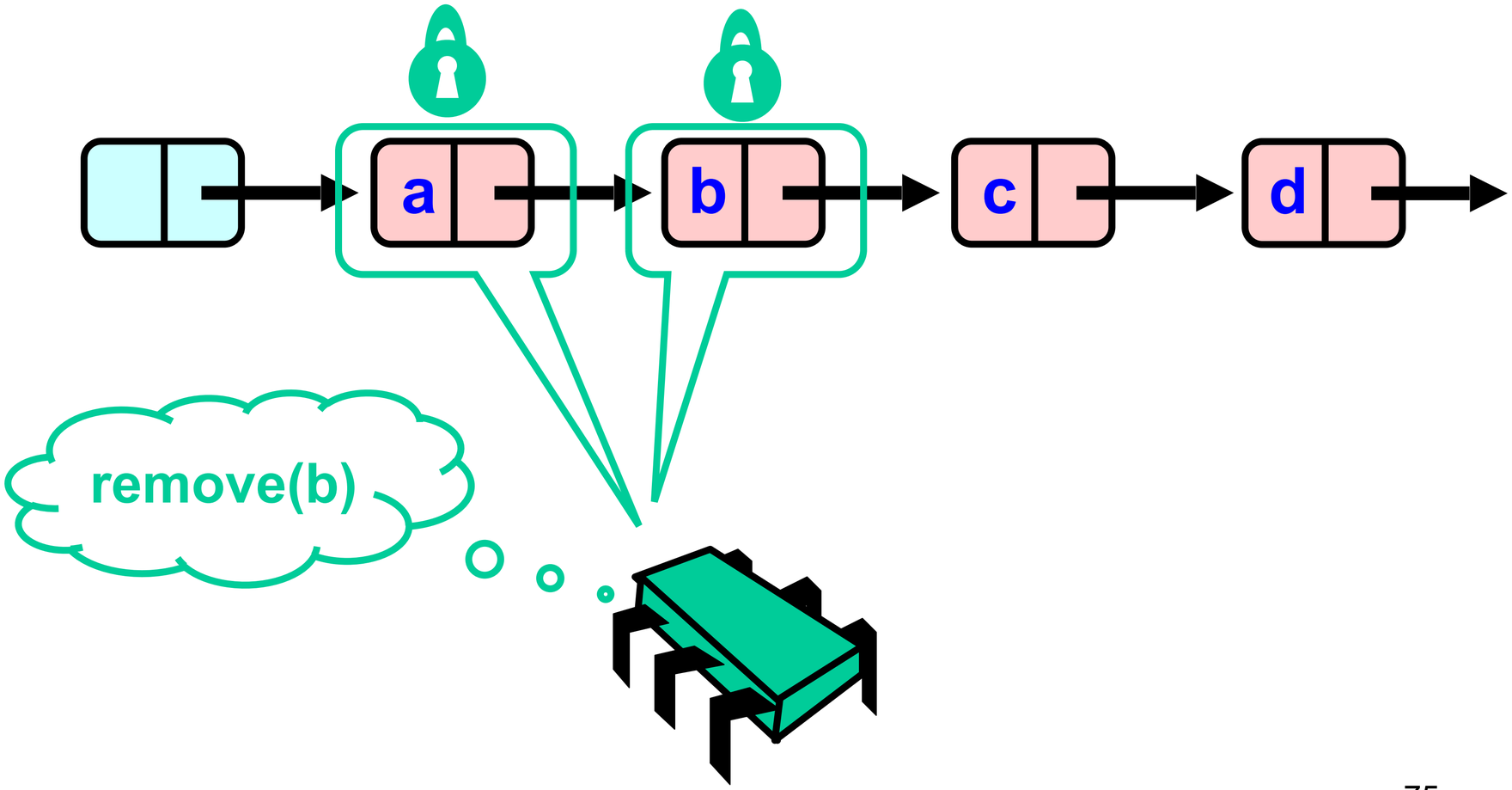

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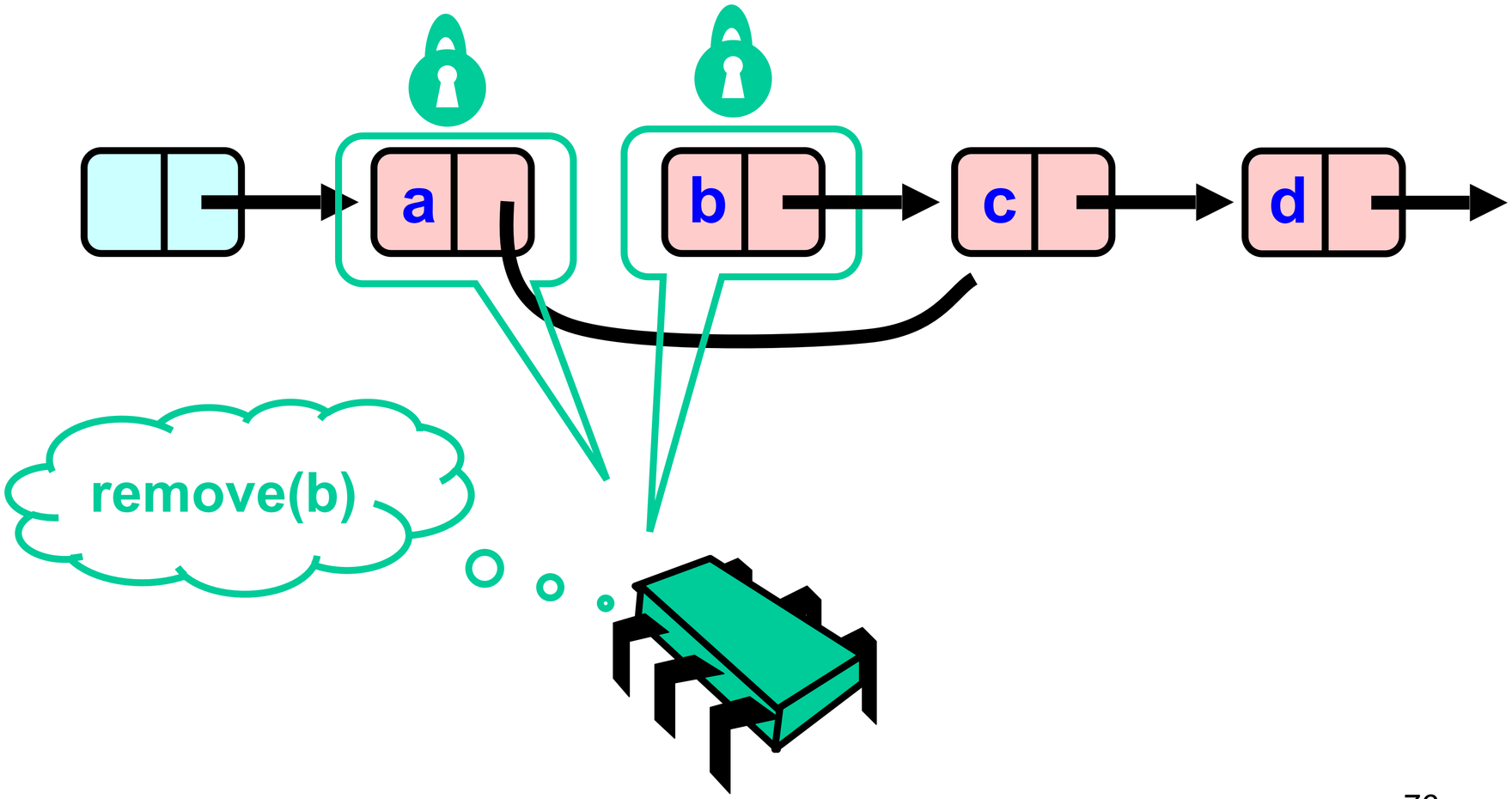

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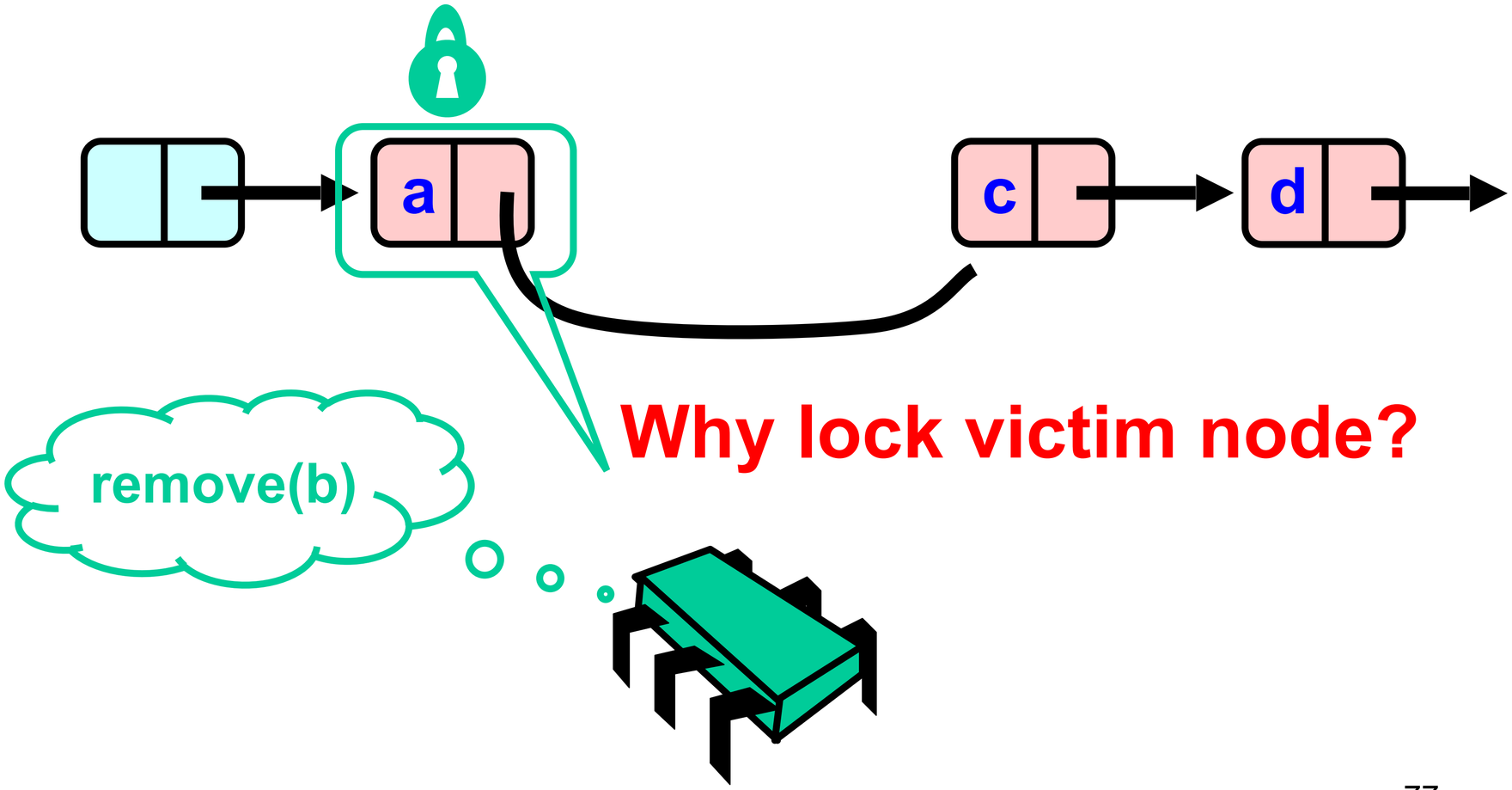
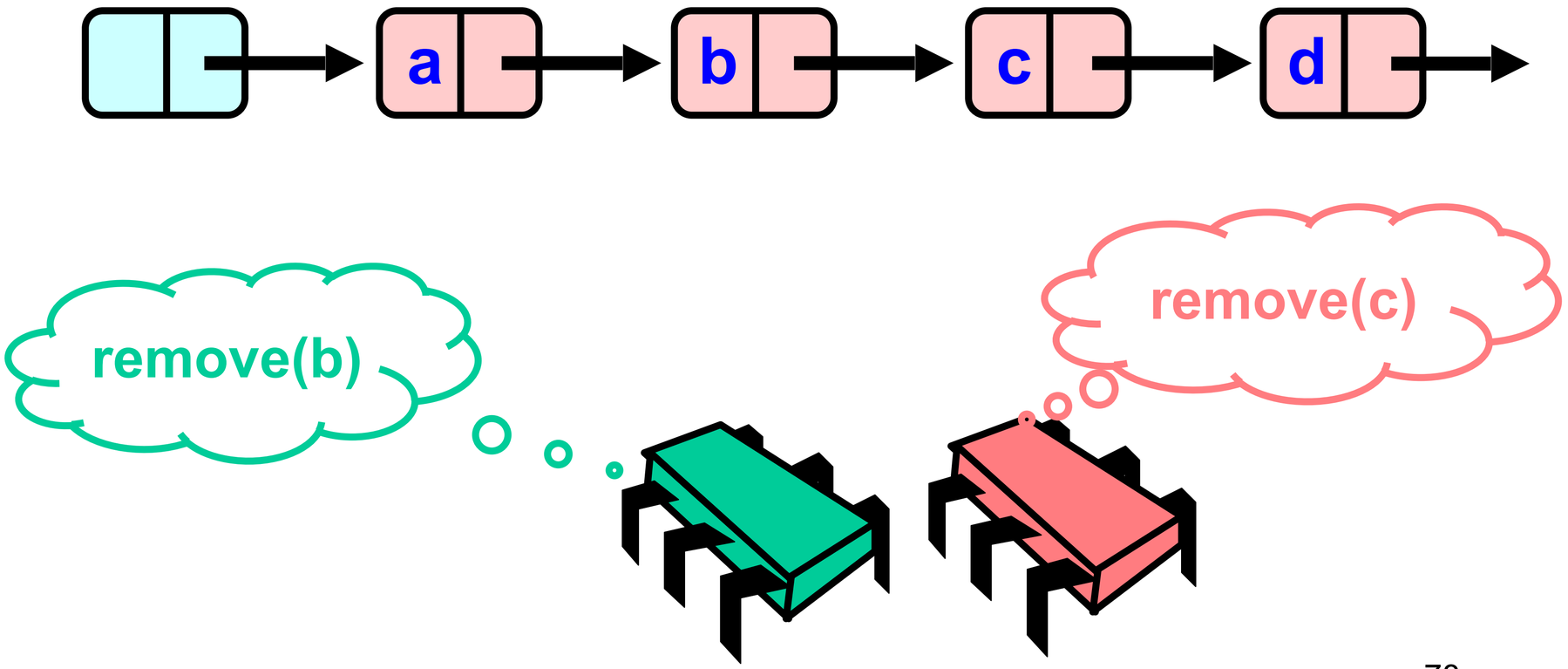


Concurrent Removes



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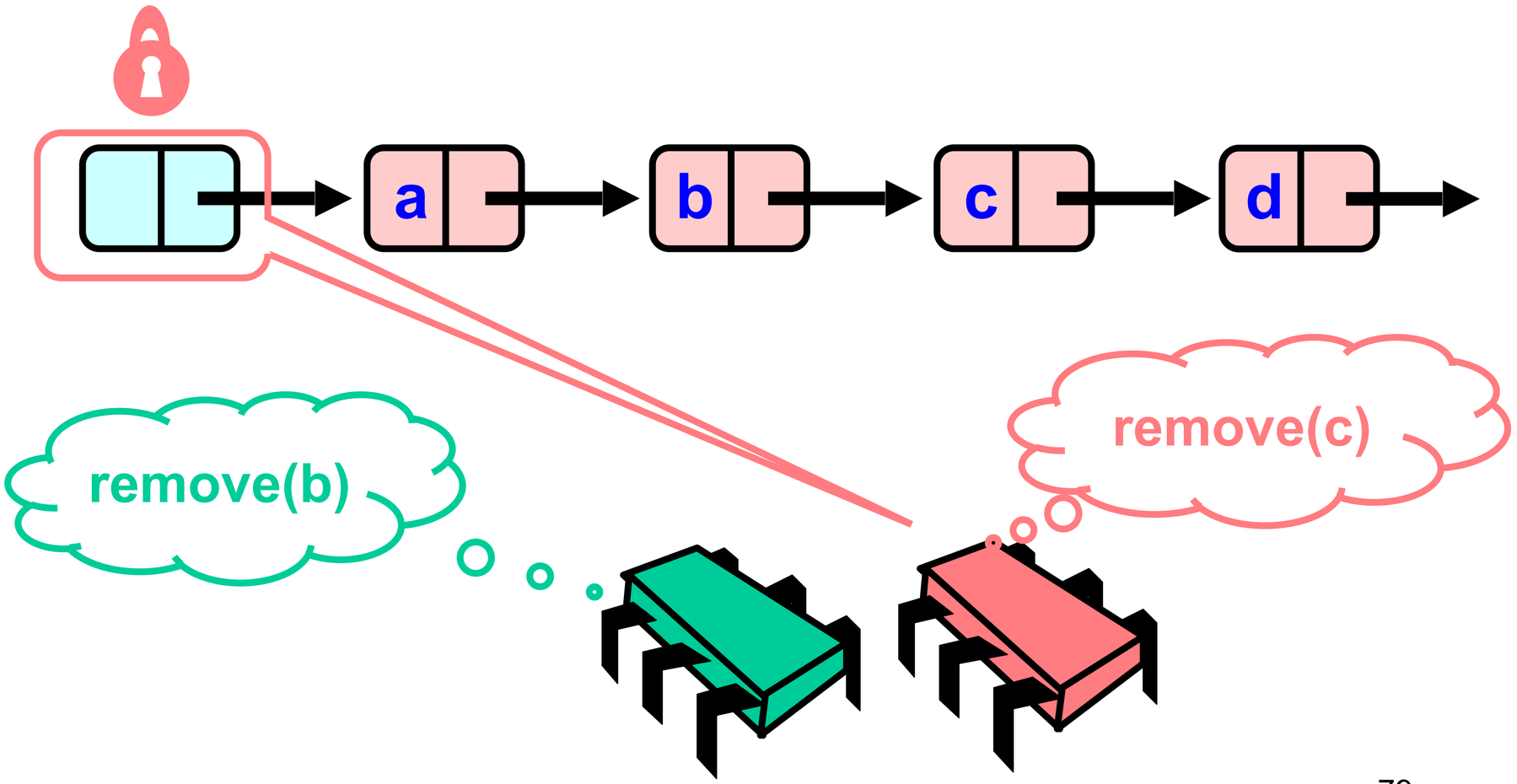

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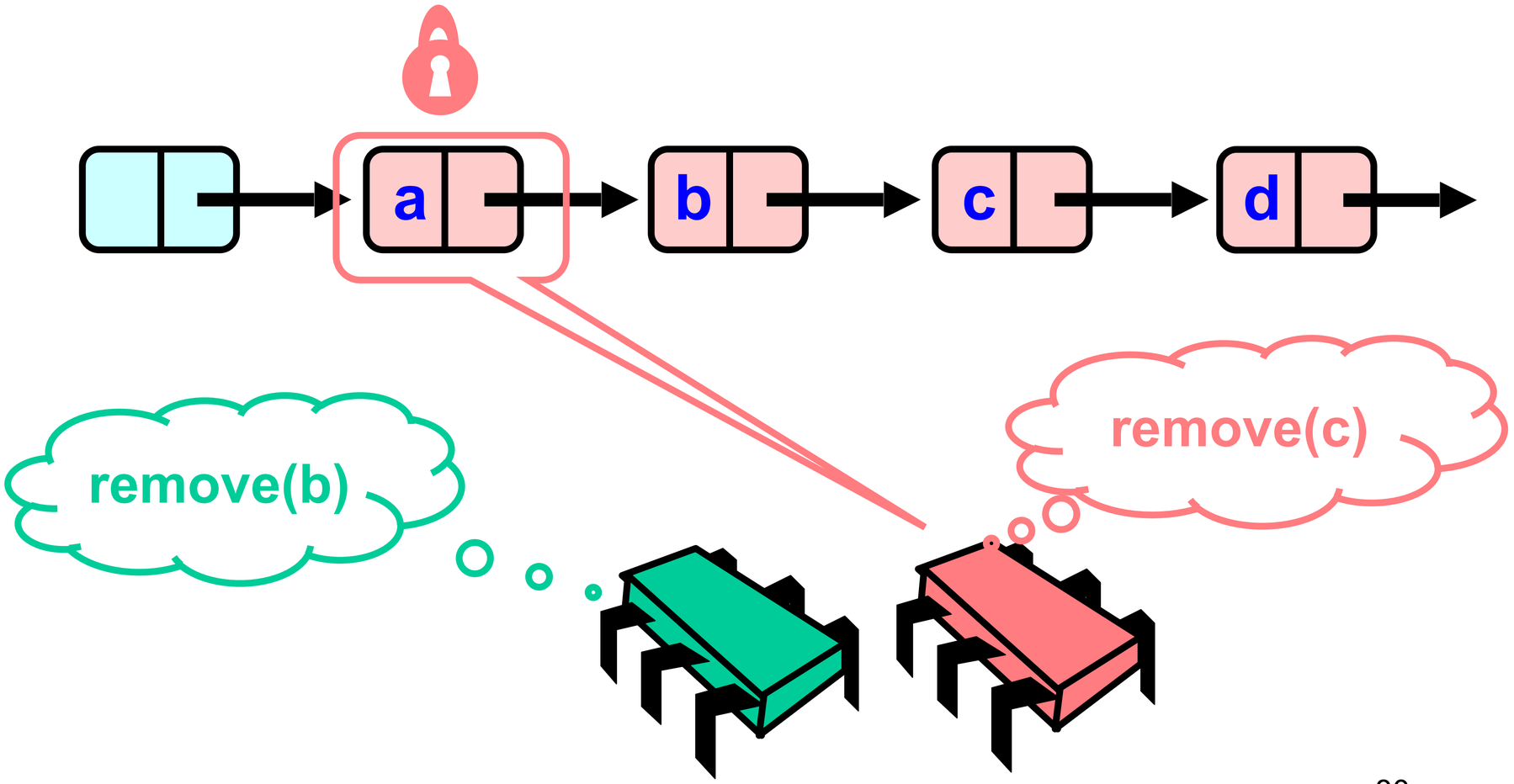

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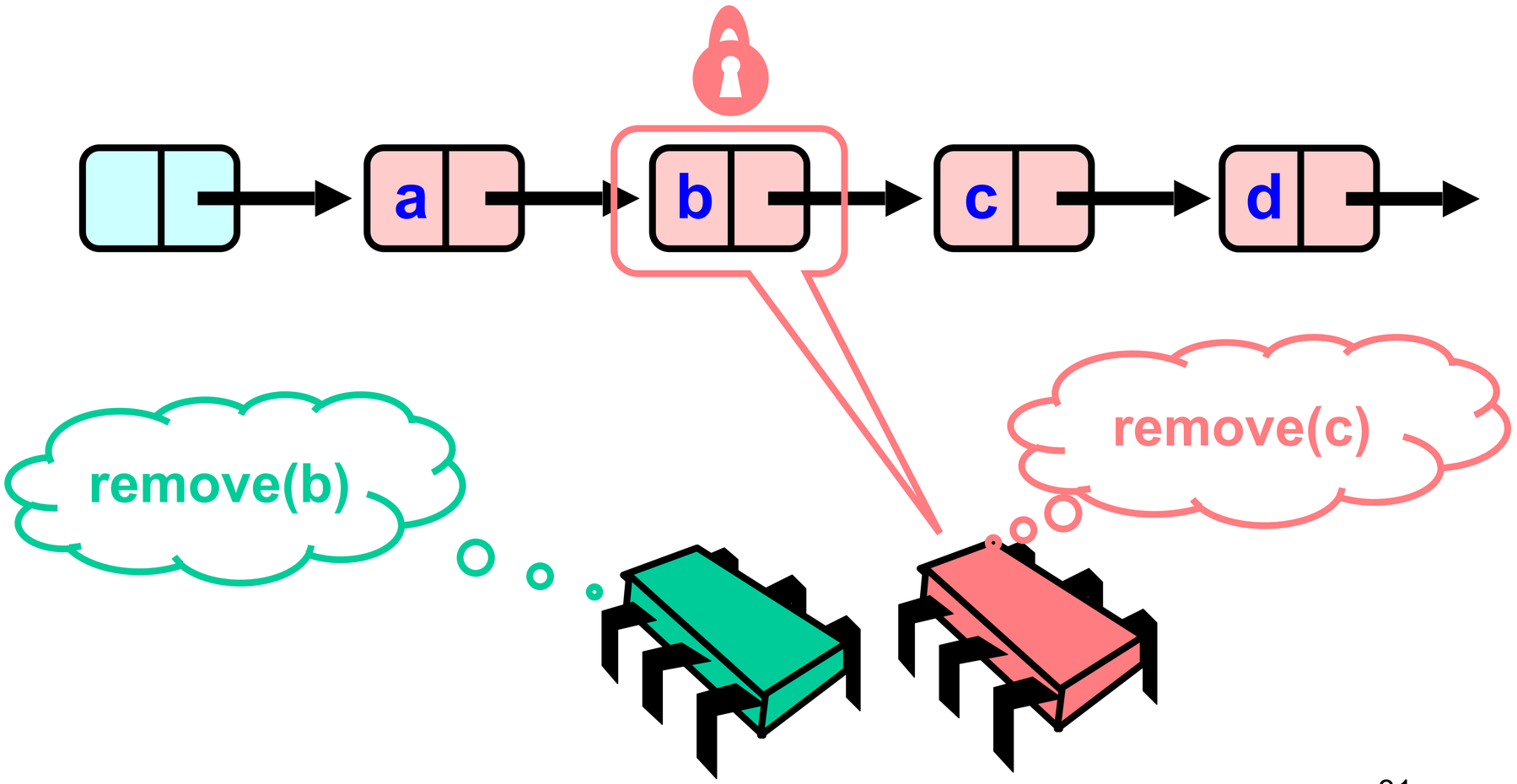

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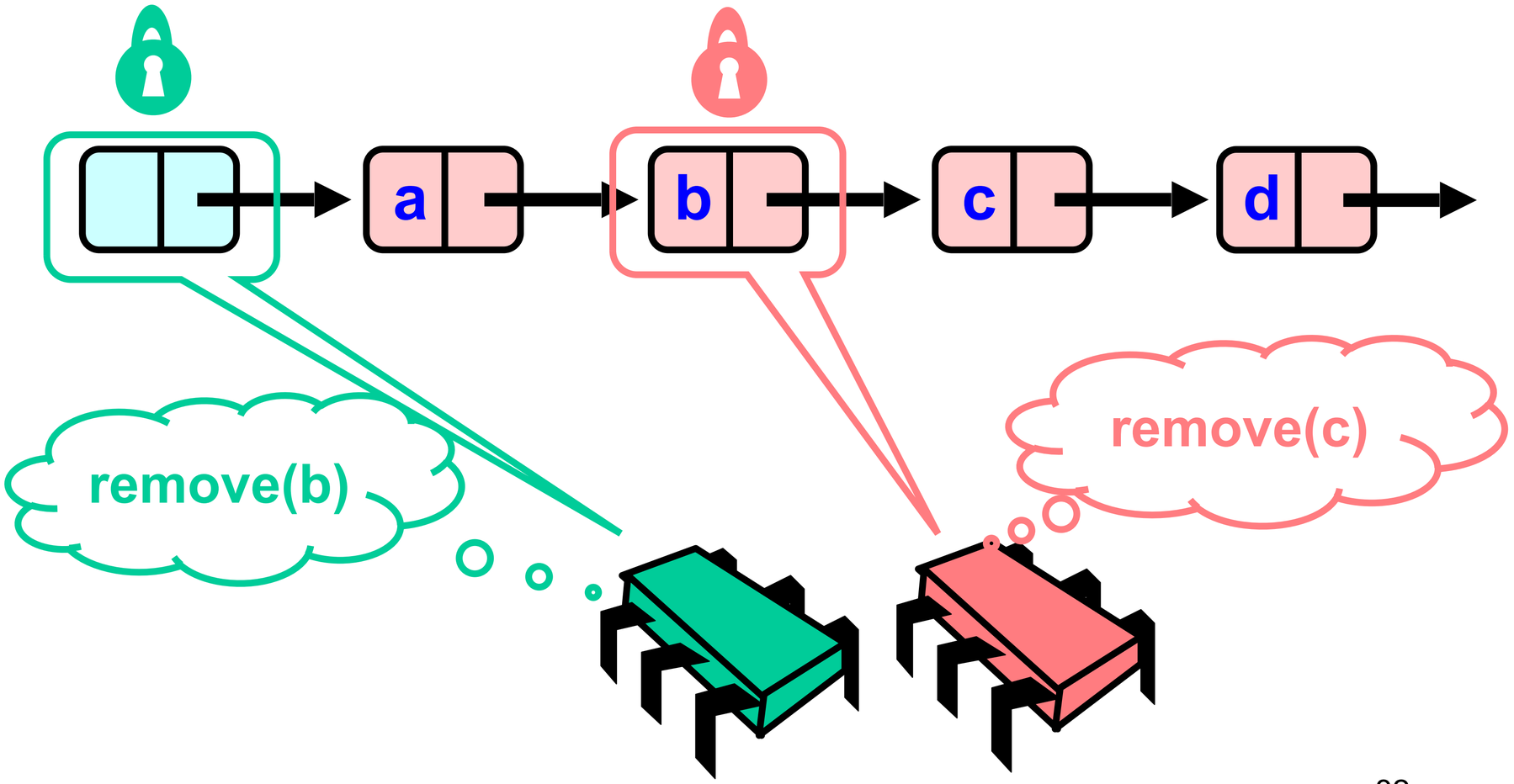

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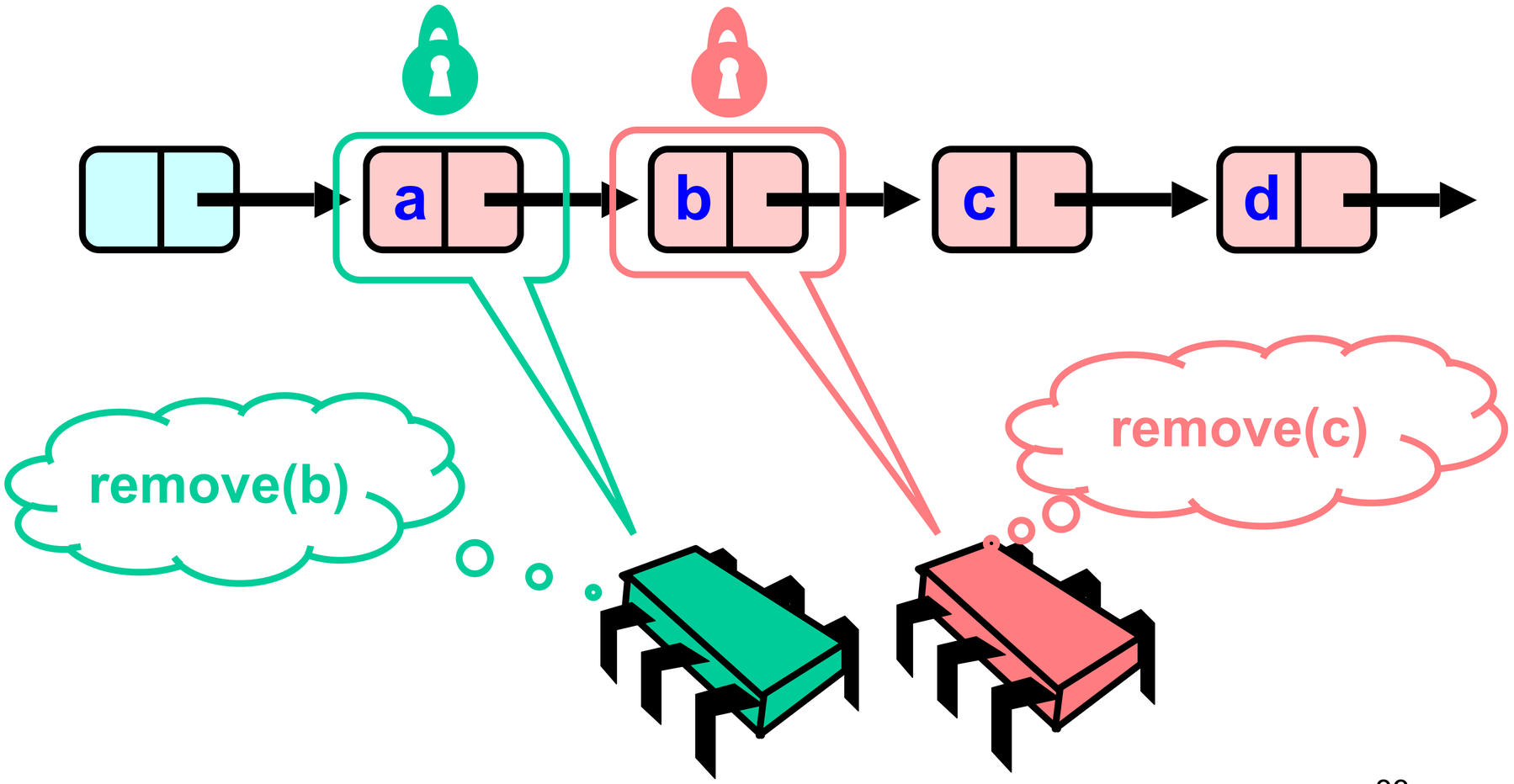

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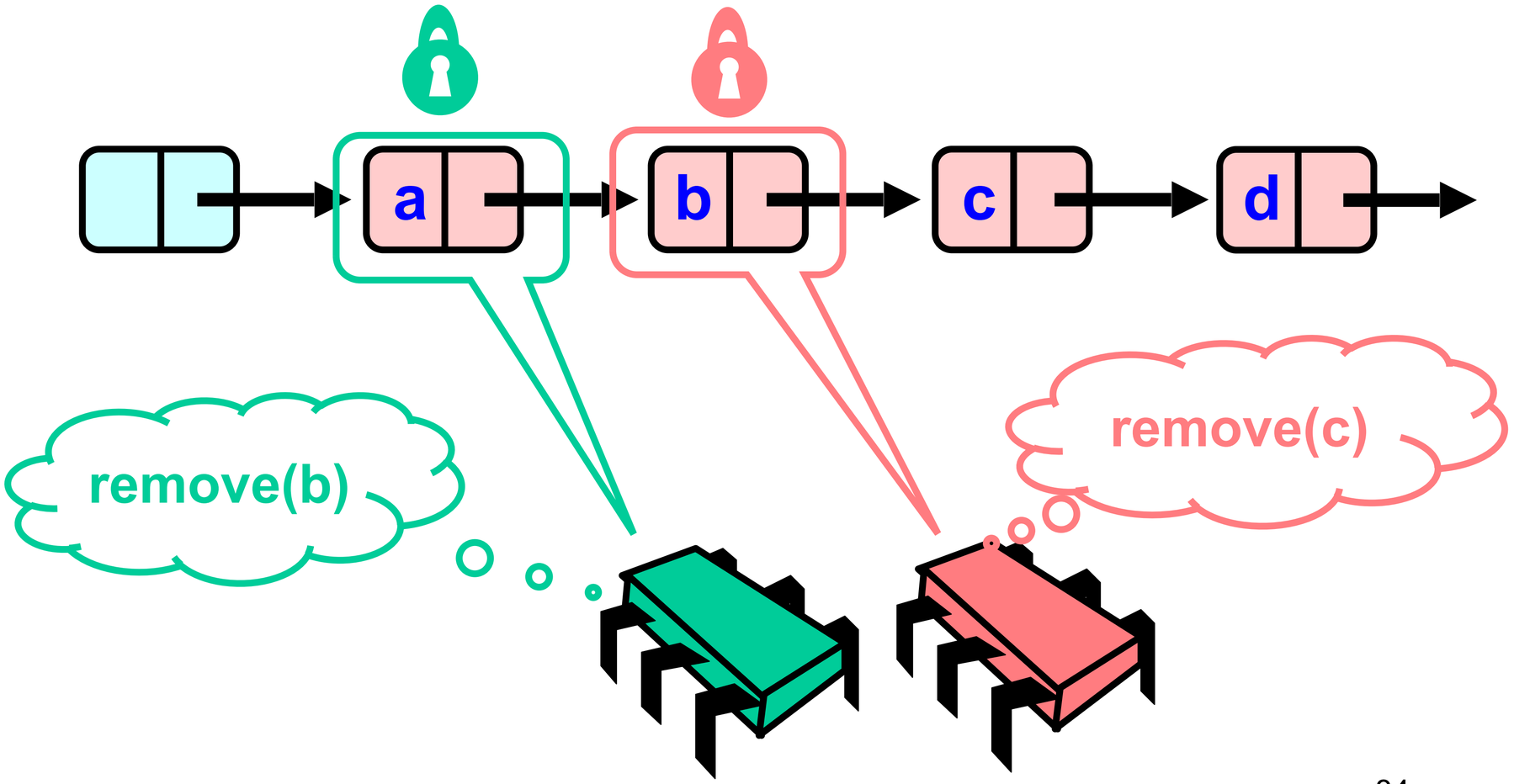

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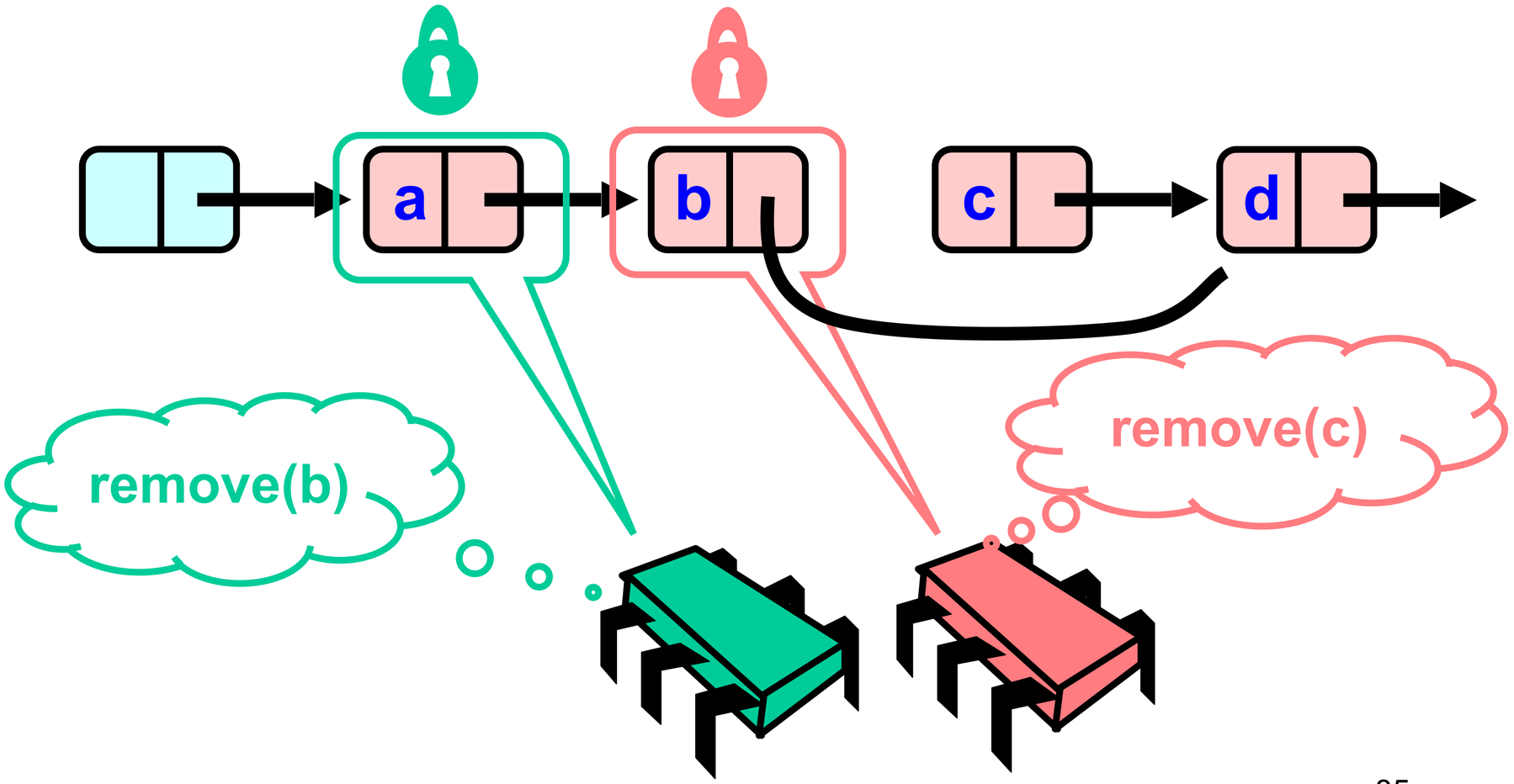

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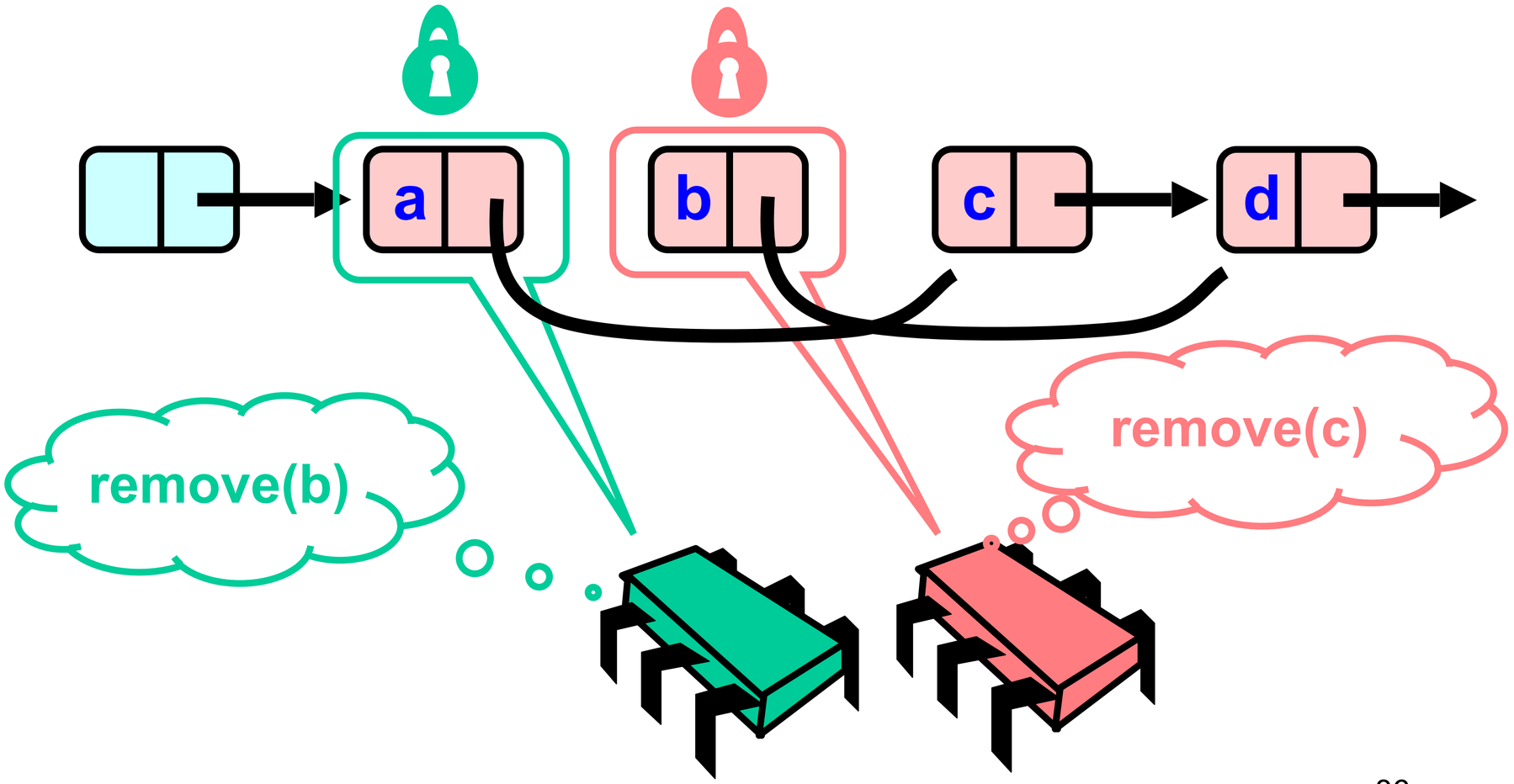
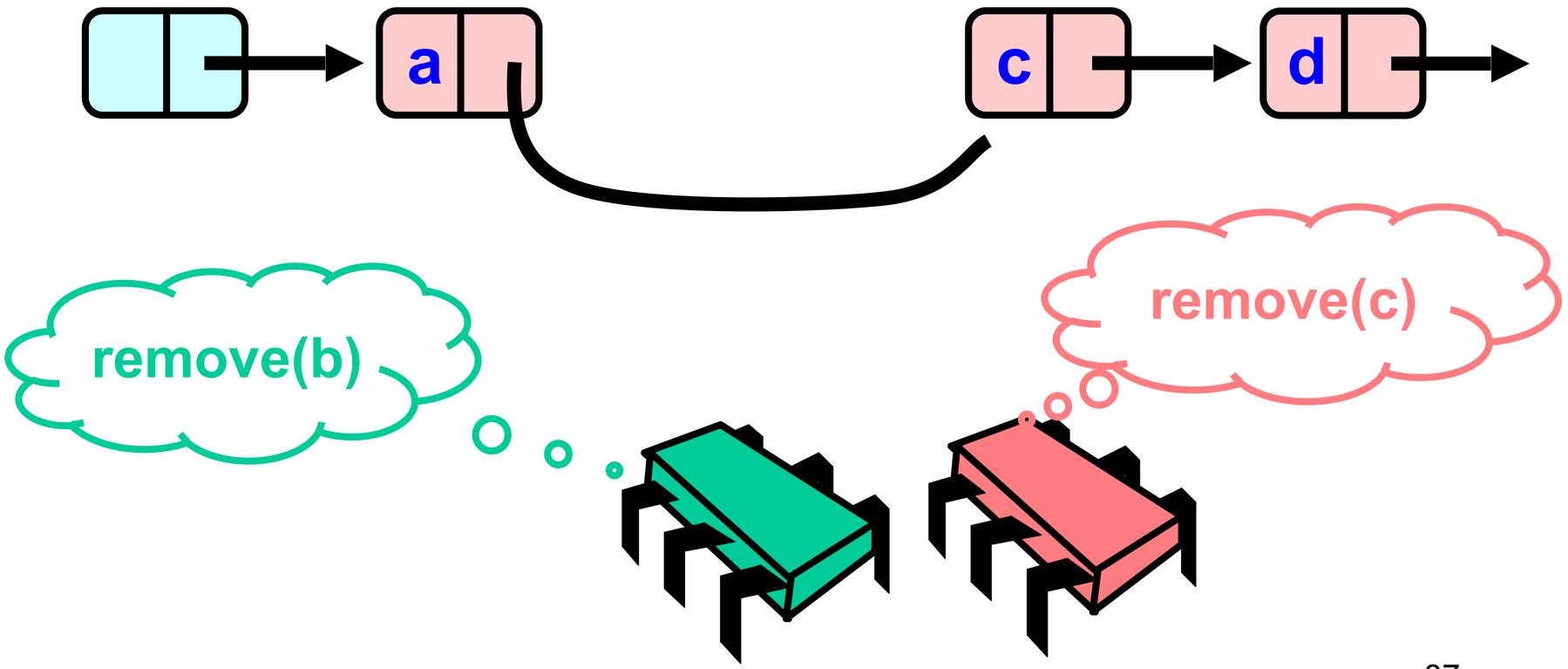


Uh, Oh



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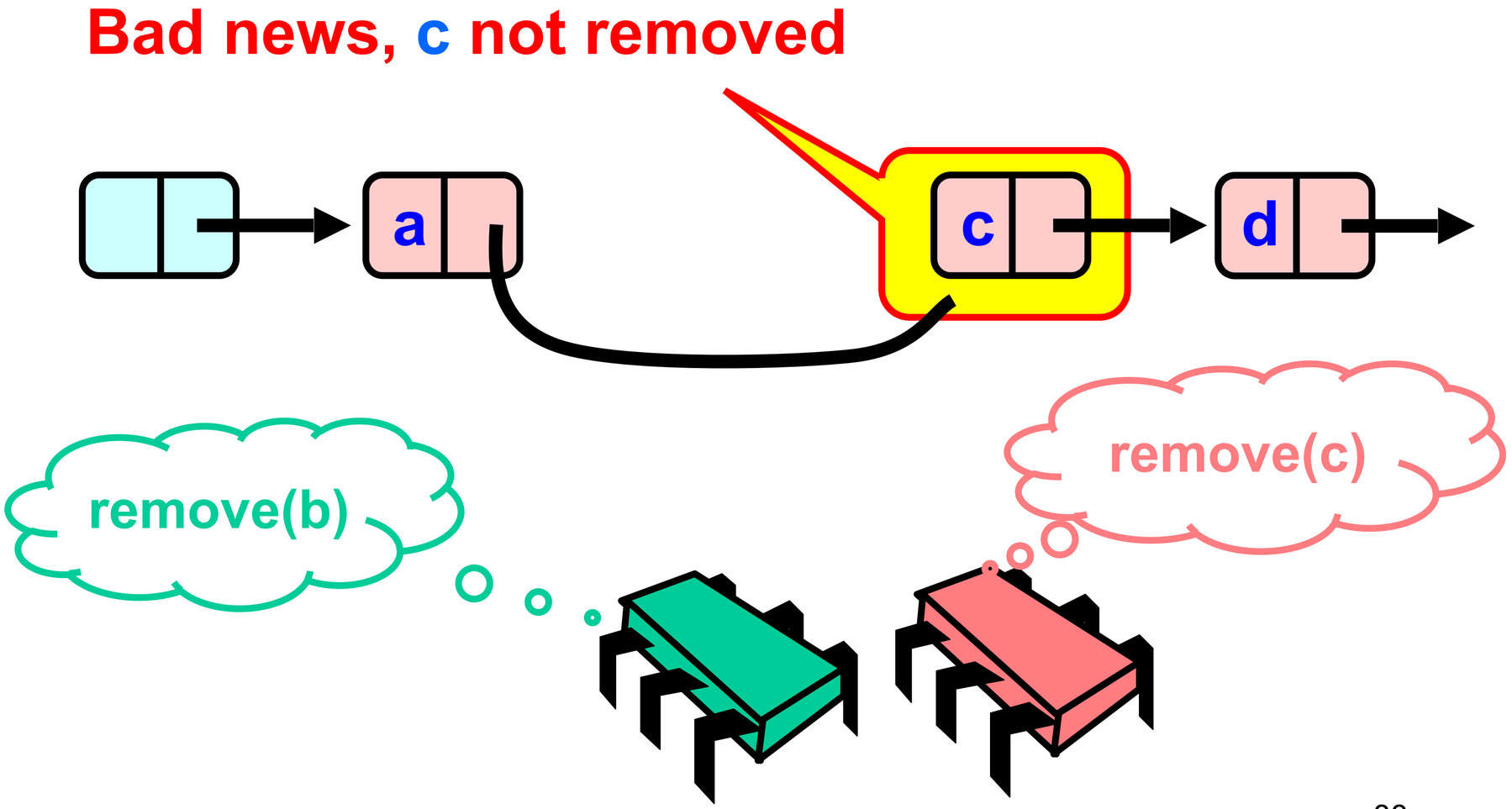
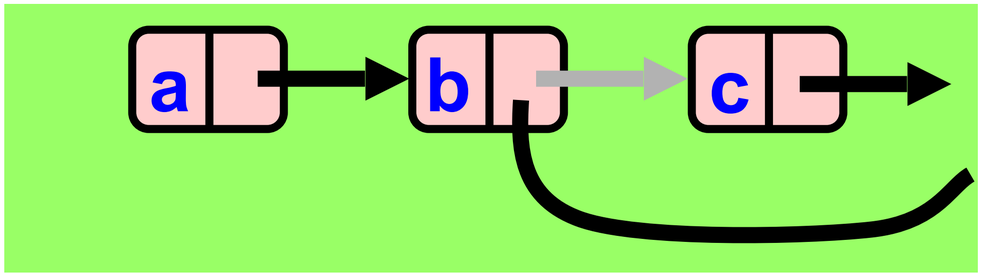
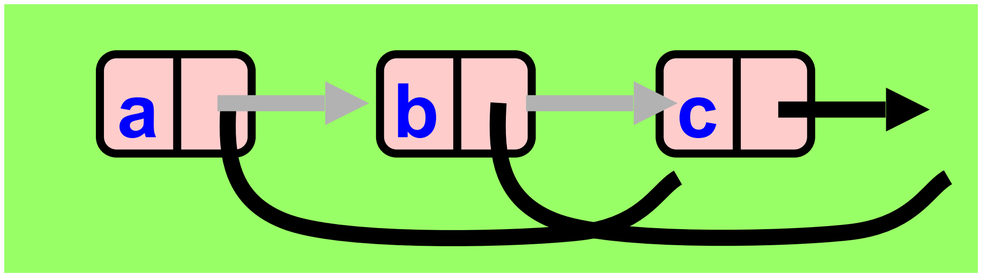


Problem

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



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



Hand-over-Hand Locking: 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

Next Lecture:

Even less locking