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

Companion slides for

The Art of Multiprocessor Programming

by Maurice Herlihy & Nir Shavit

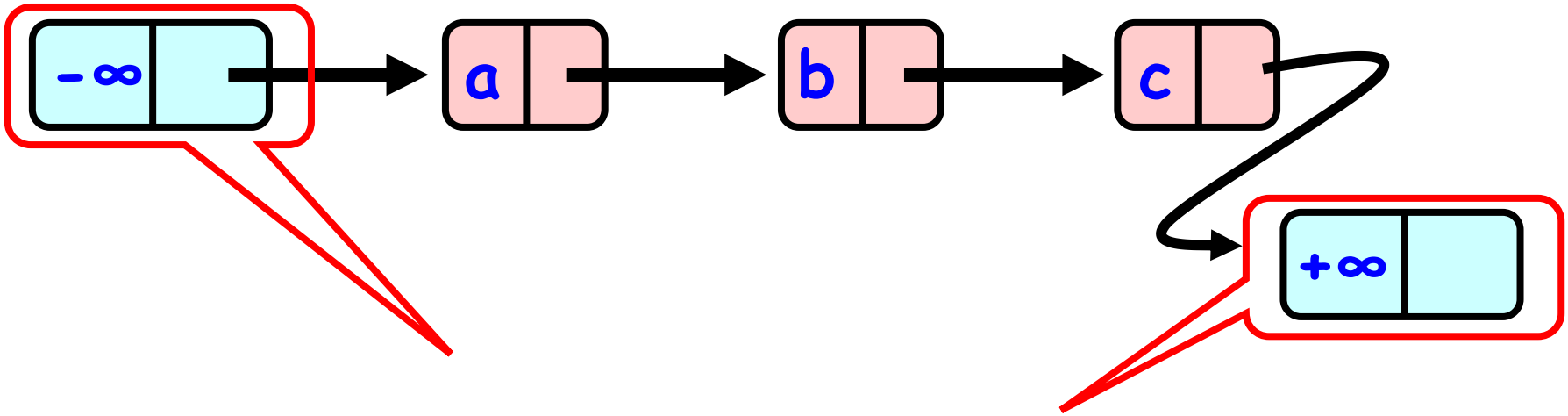
Set Interface

- 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 Node

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

The List-Based Set



Sorted with Sentinel nodes
(min & max possible keys)

Reasoning about Concurrent Objects

- Invariant
  - Property that always holds
- Established by
  - 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
- 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

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 one is incorrect?

Blame Game

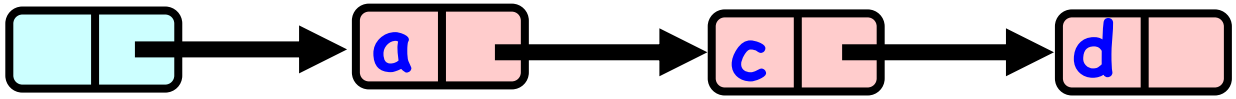
- Suppose
  - **add()** leaves behind 2 copies of x
  - **remove()** removes only 1
- Which one is incorrect?
  - If rep invariant says *no duplicates*
    - **add()** is incorrect
  - Otherwise
    - **remove()** is incorrect

Rep Invariant (partly)

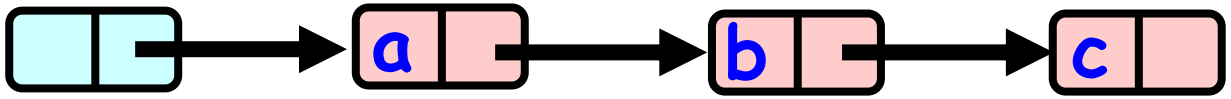
- Sentinel nodes
  - tail reachable from head
- Sorted
- No duplicates

Sequential List Based Set

Add()



Remove()



Sequential List Based Set

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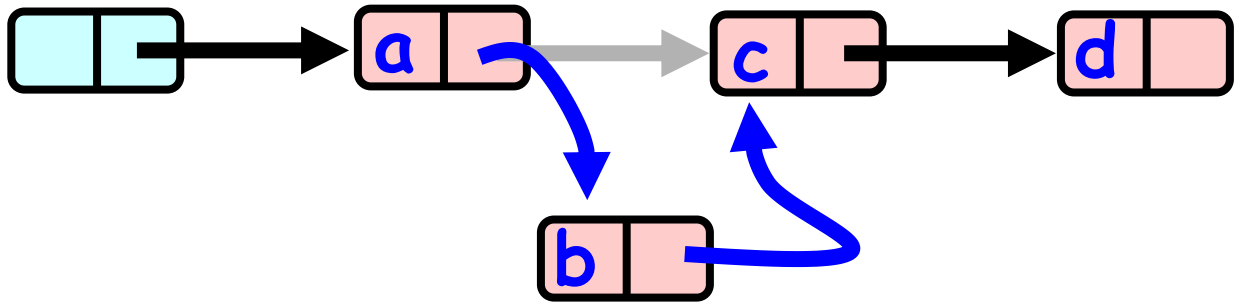
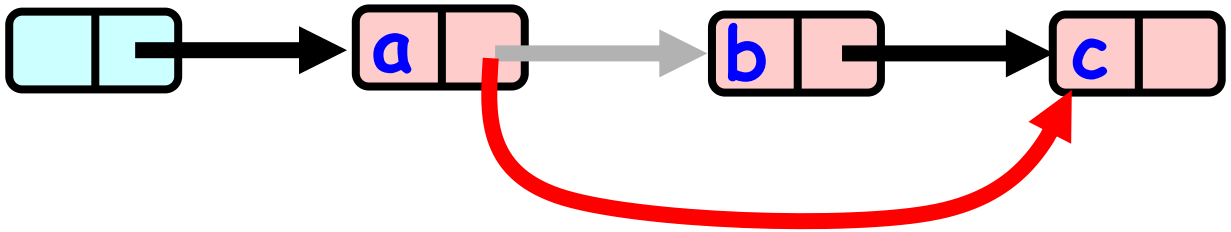
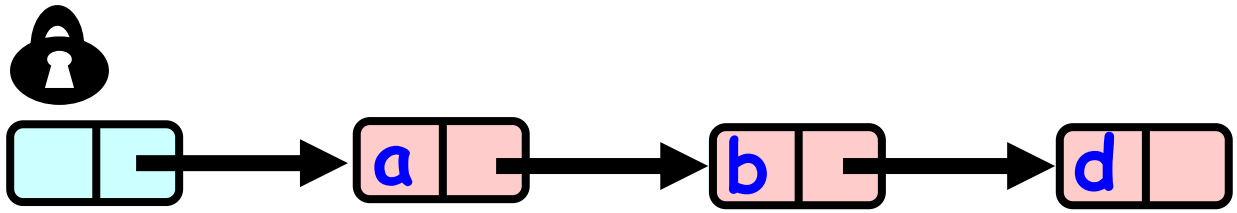


Remove()



Coarse Grained Locking



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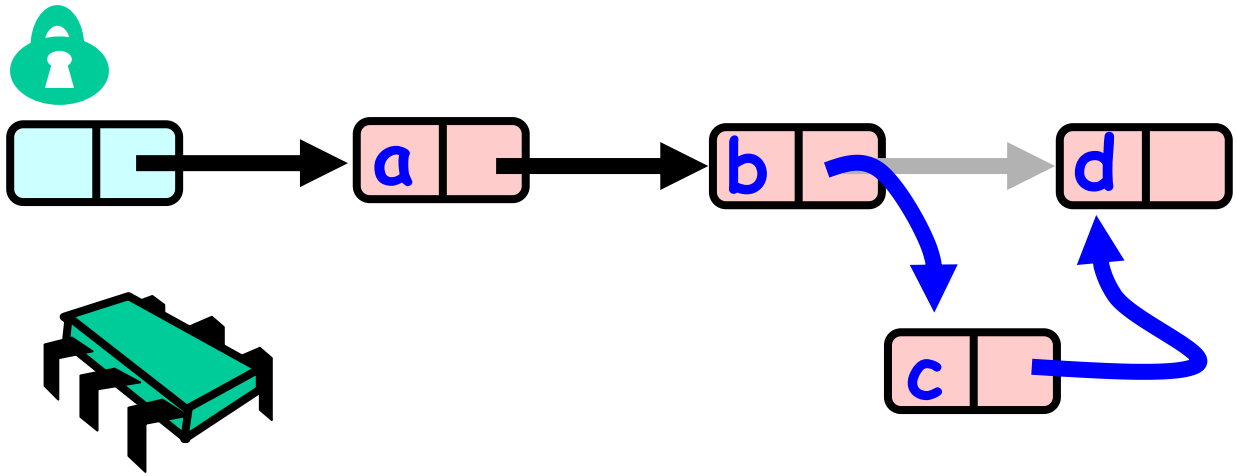

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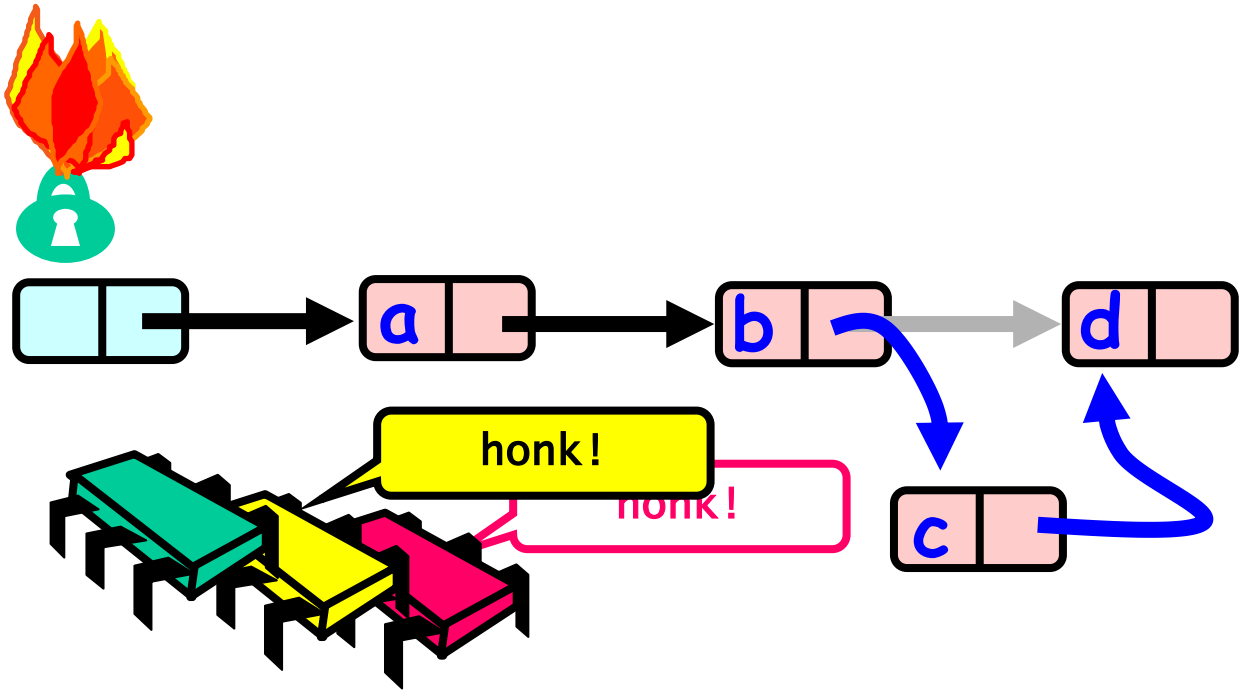


Simple but hotspot + bottleneck

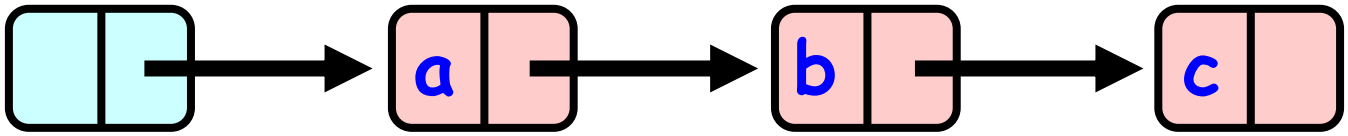
Coarse-Grained Locking

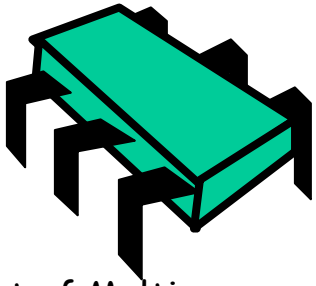
- Easy, same as synchronized methods
  - "One lock to rule them all …"
- Simple, clearly correct
  - Deserves respect!
- Works poorly with contention
  - Queue locks help
  - But bottleneck still an issue

Fine-grained Locking

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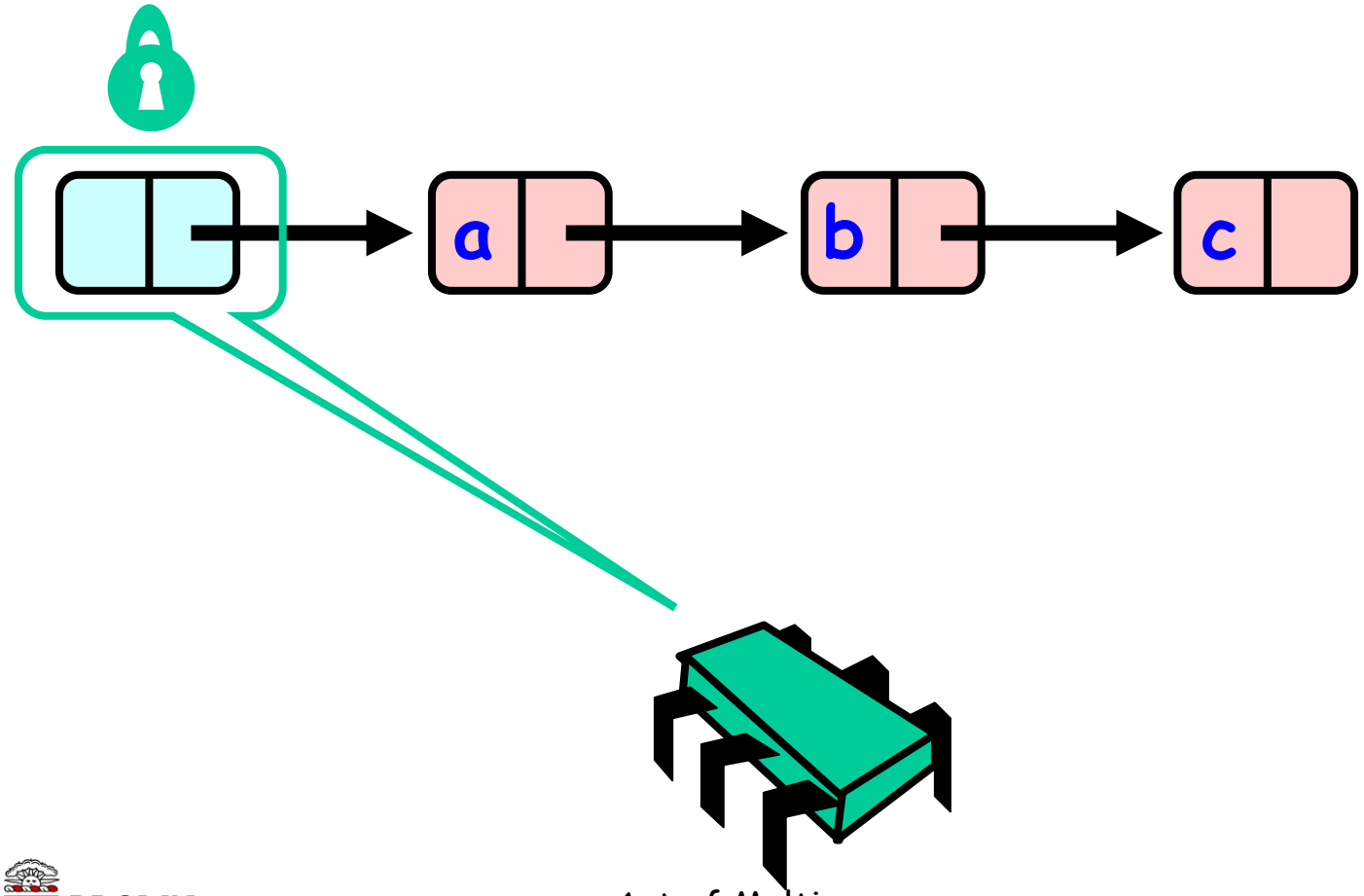

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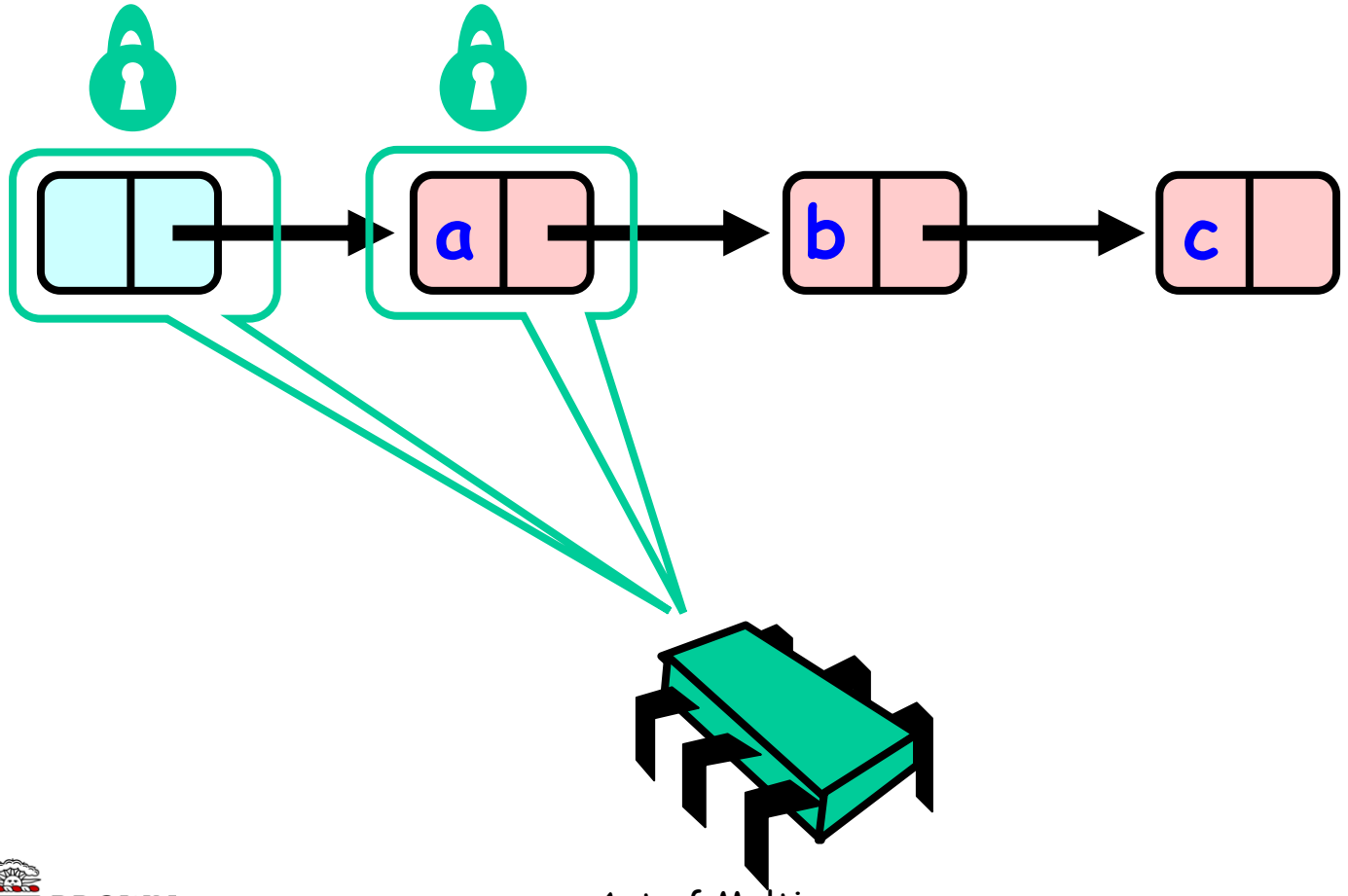

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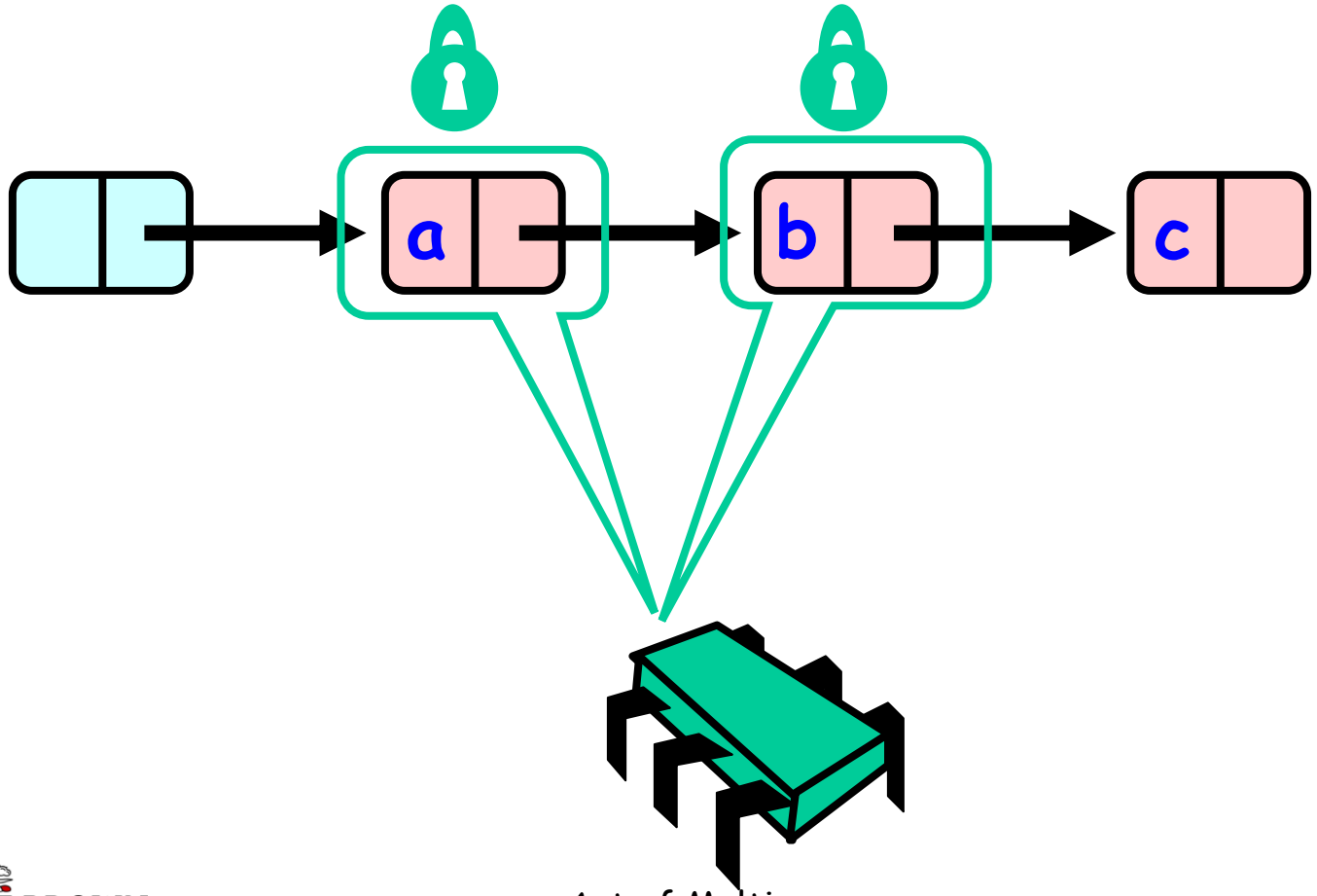

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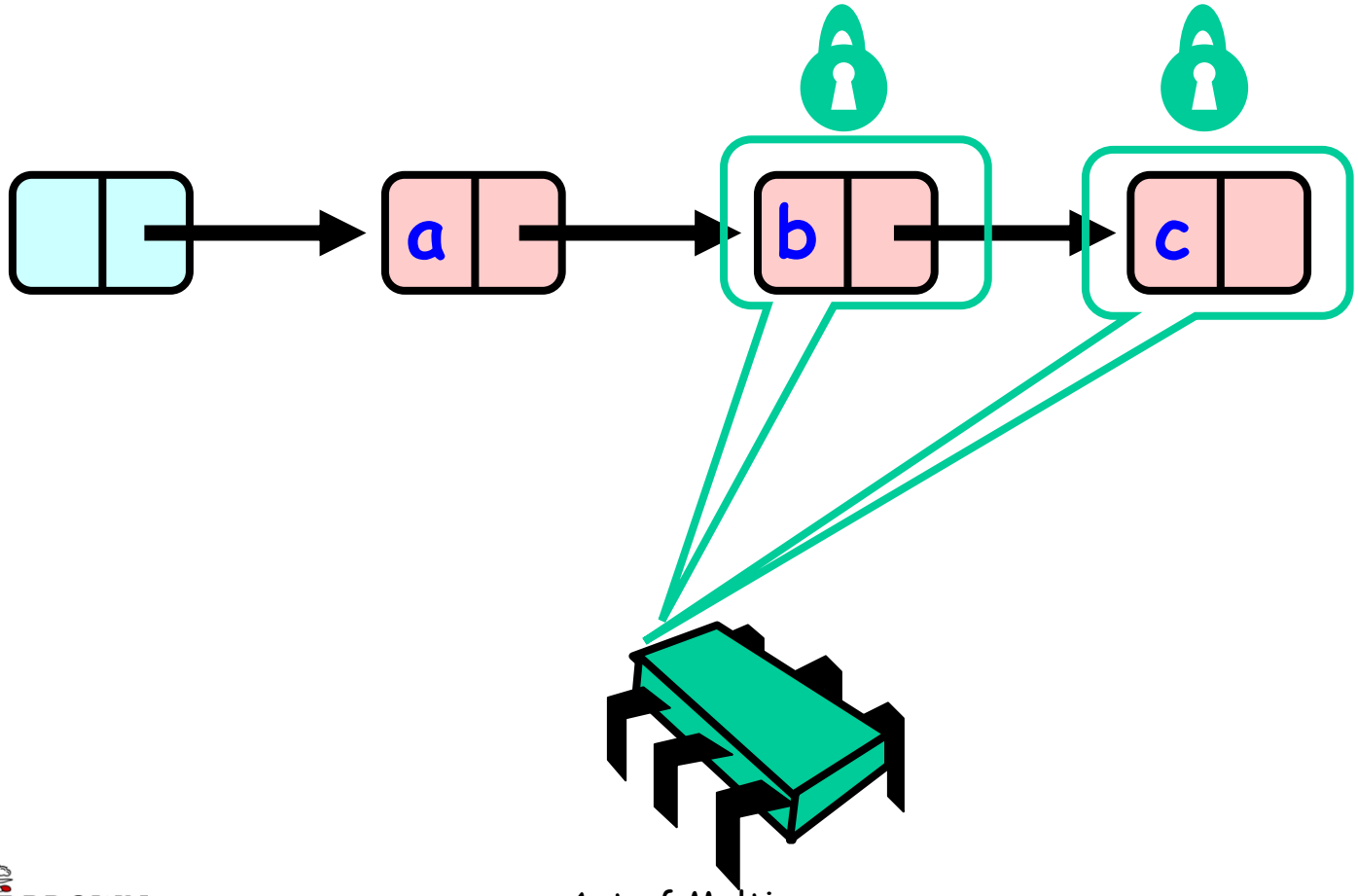
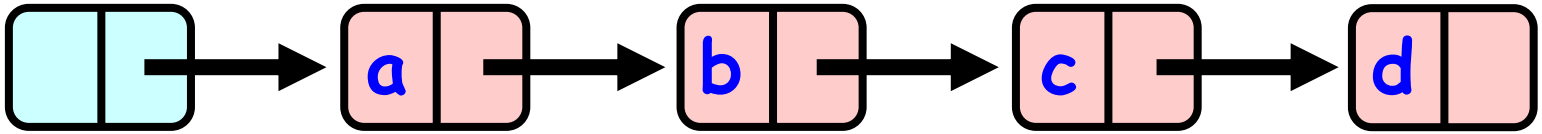
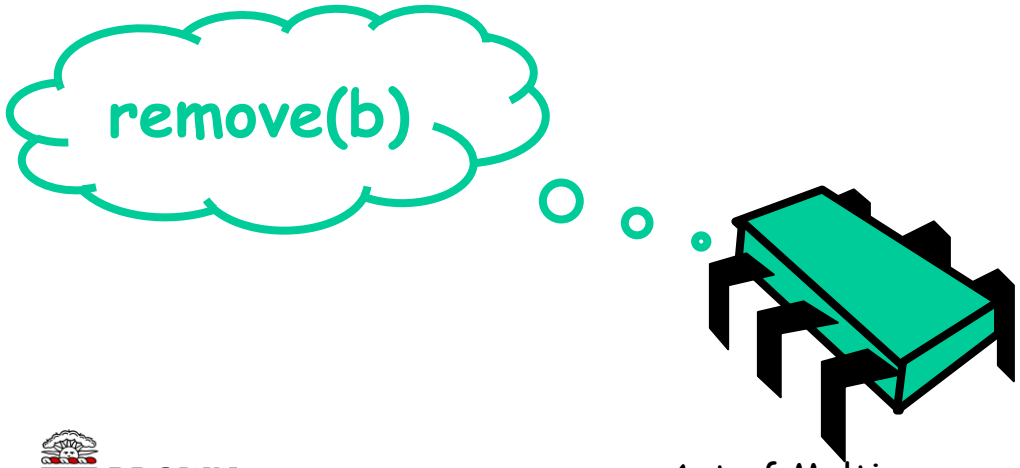


Removing a Node





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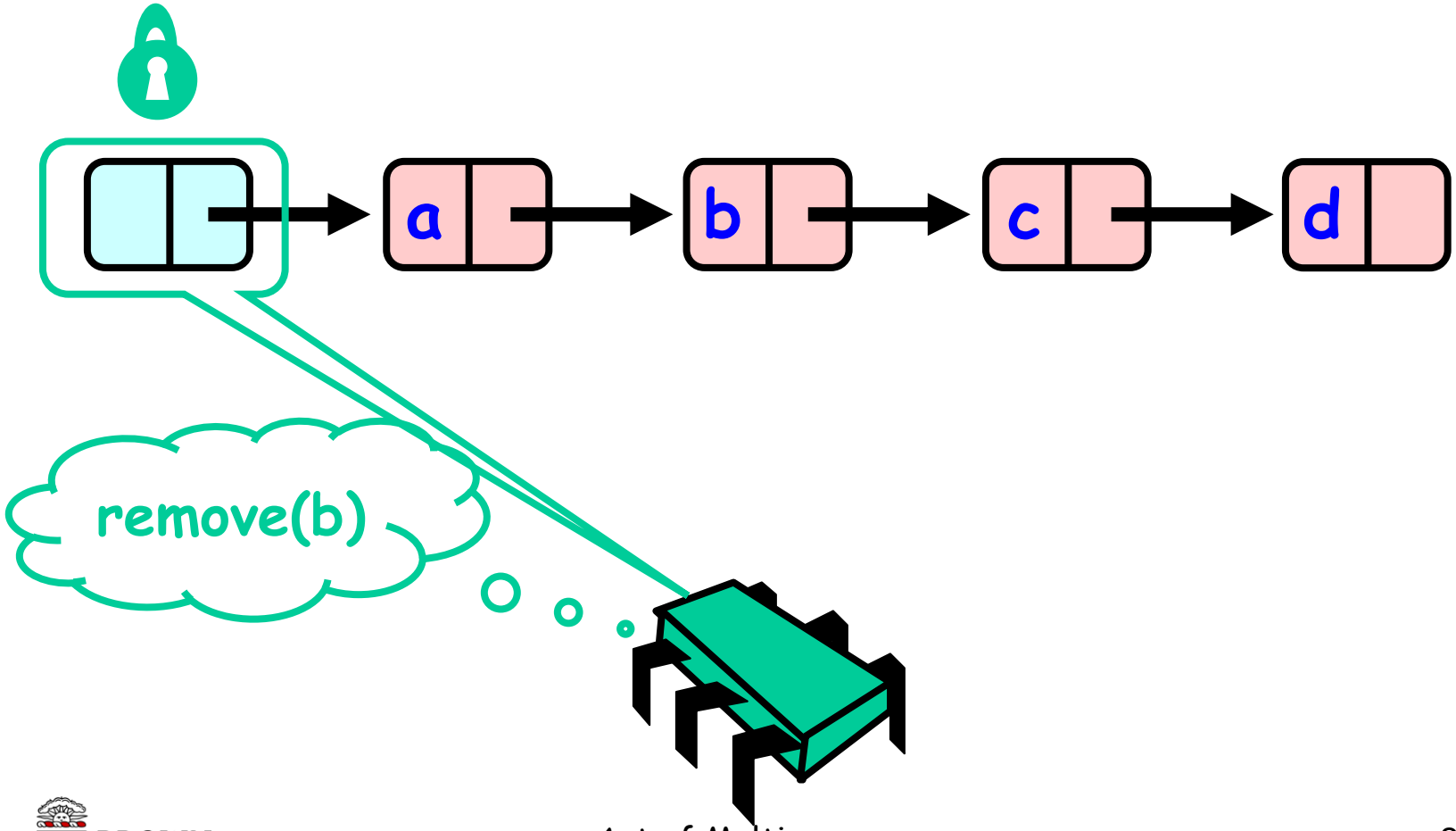

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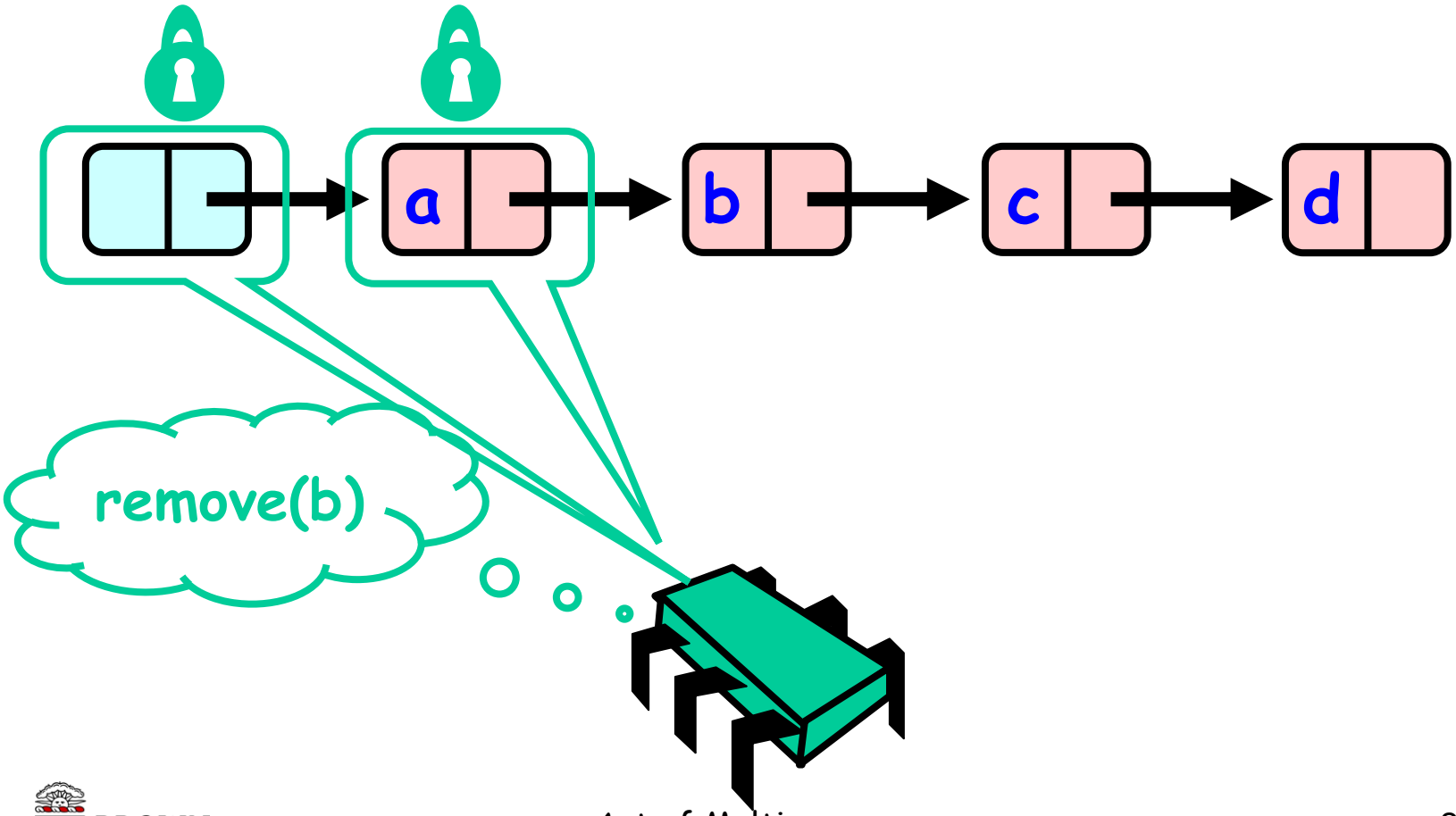

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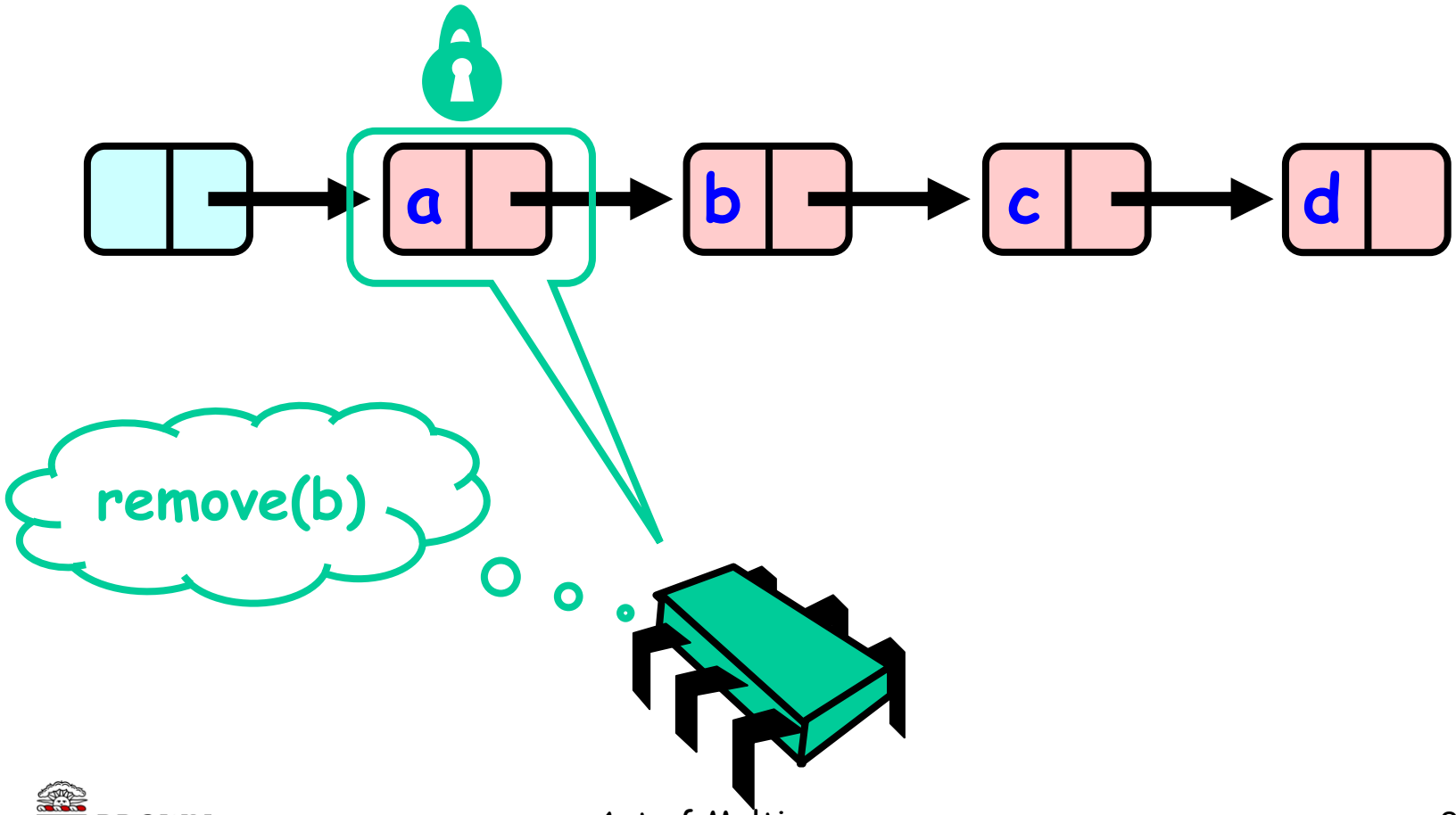

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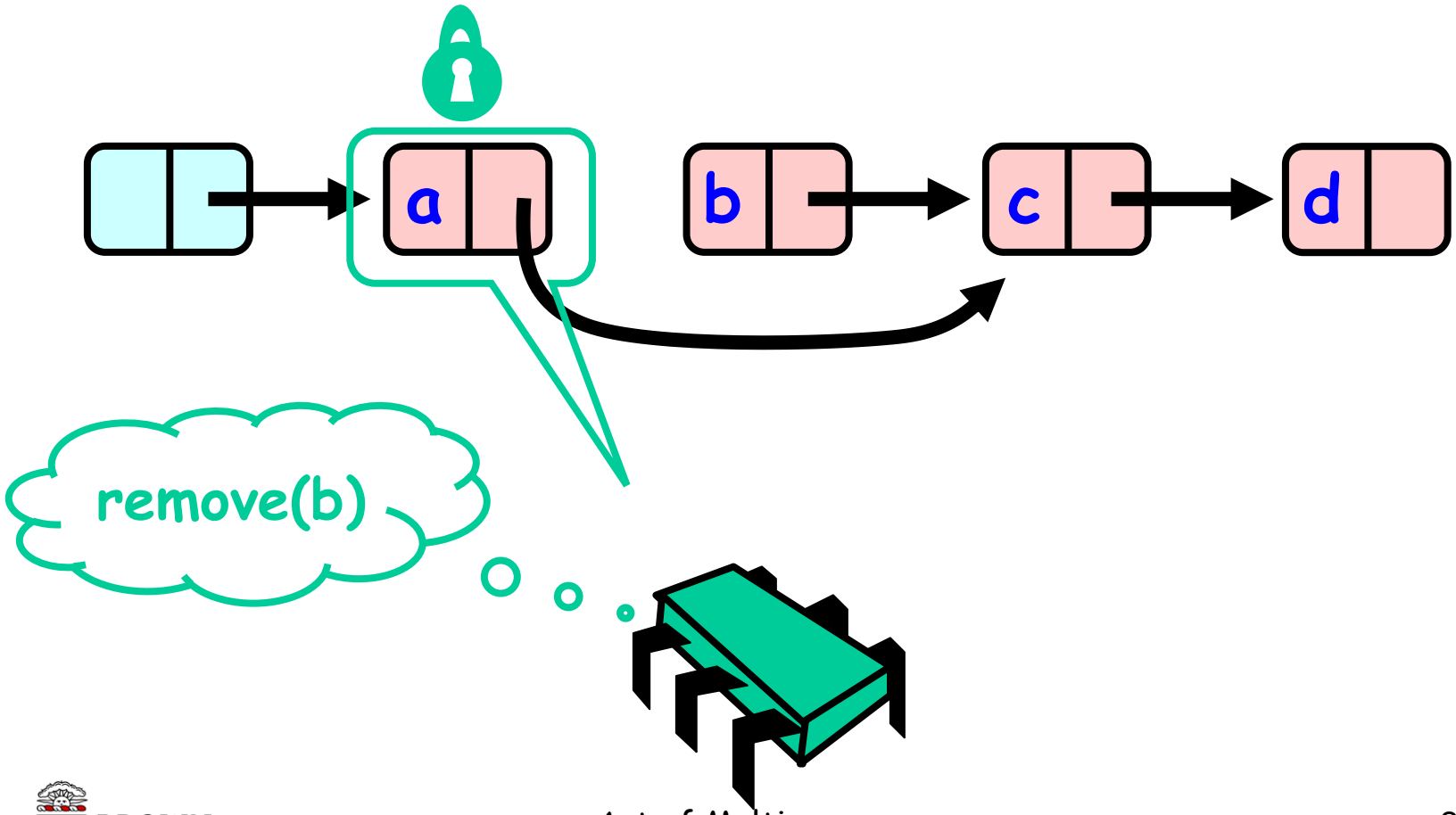

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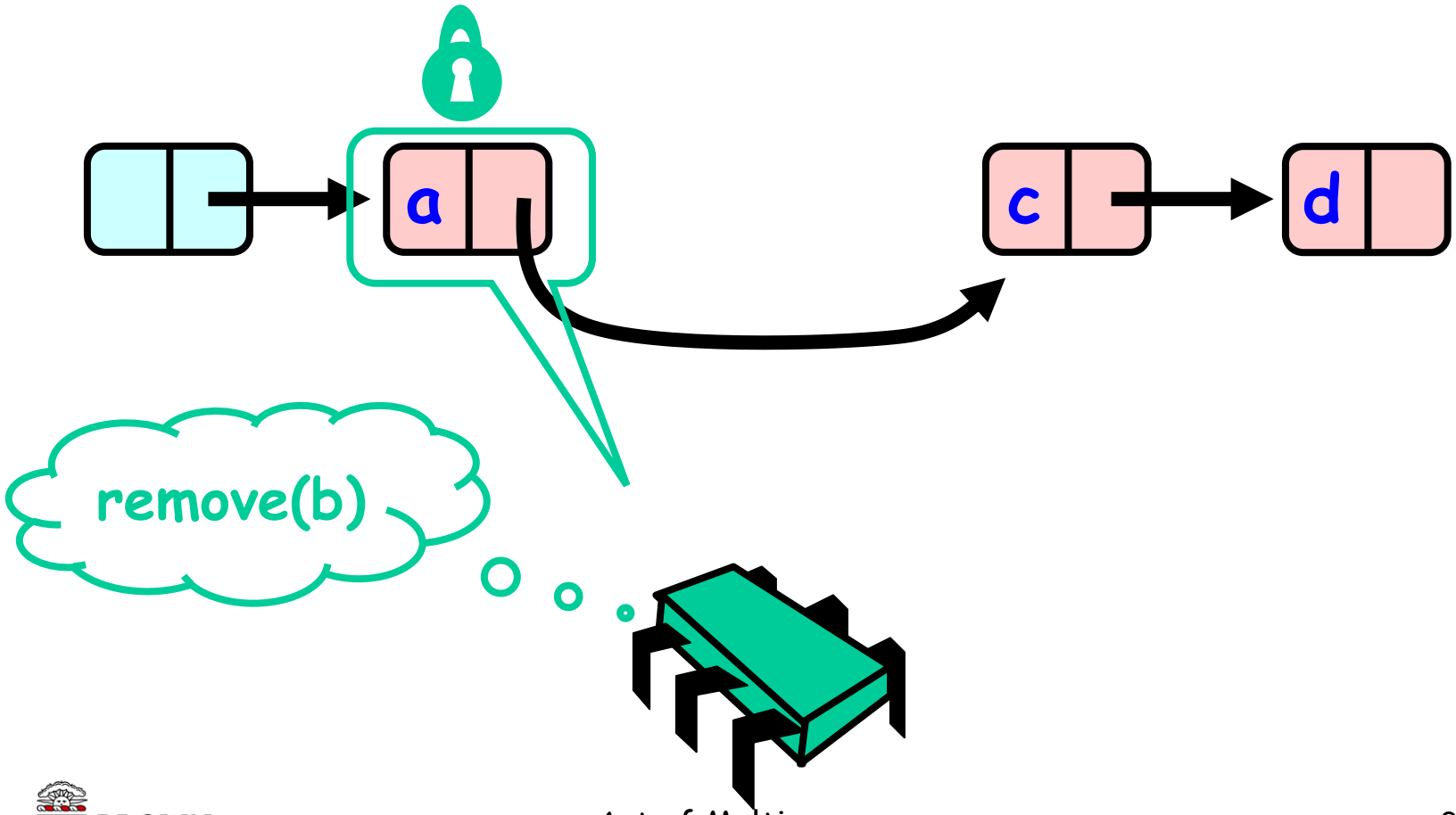

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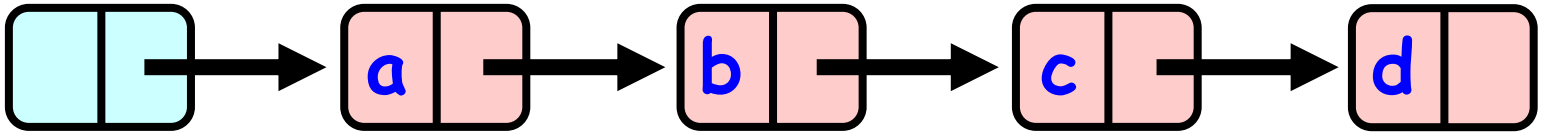

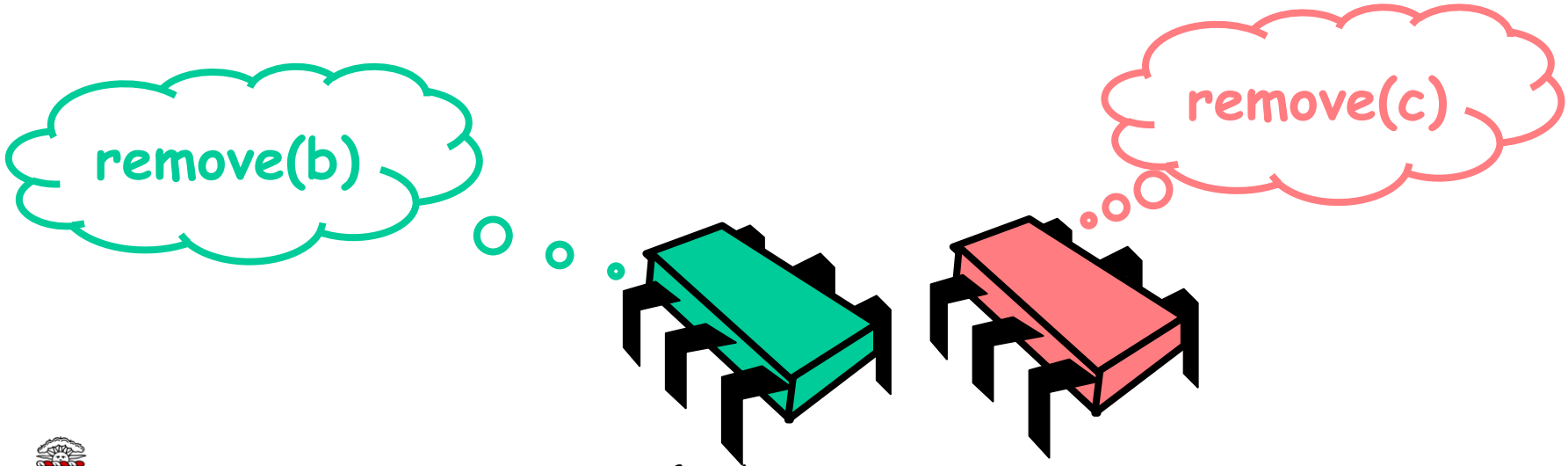

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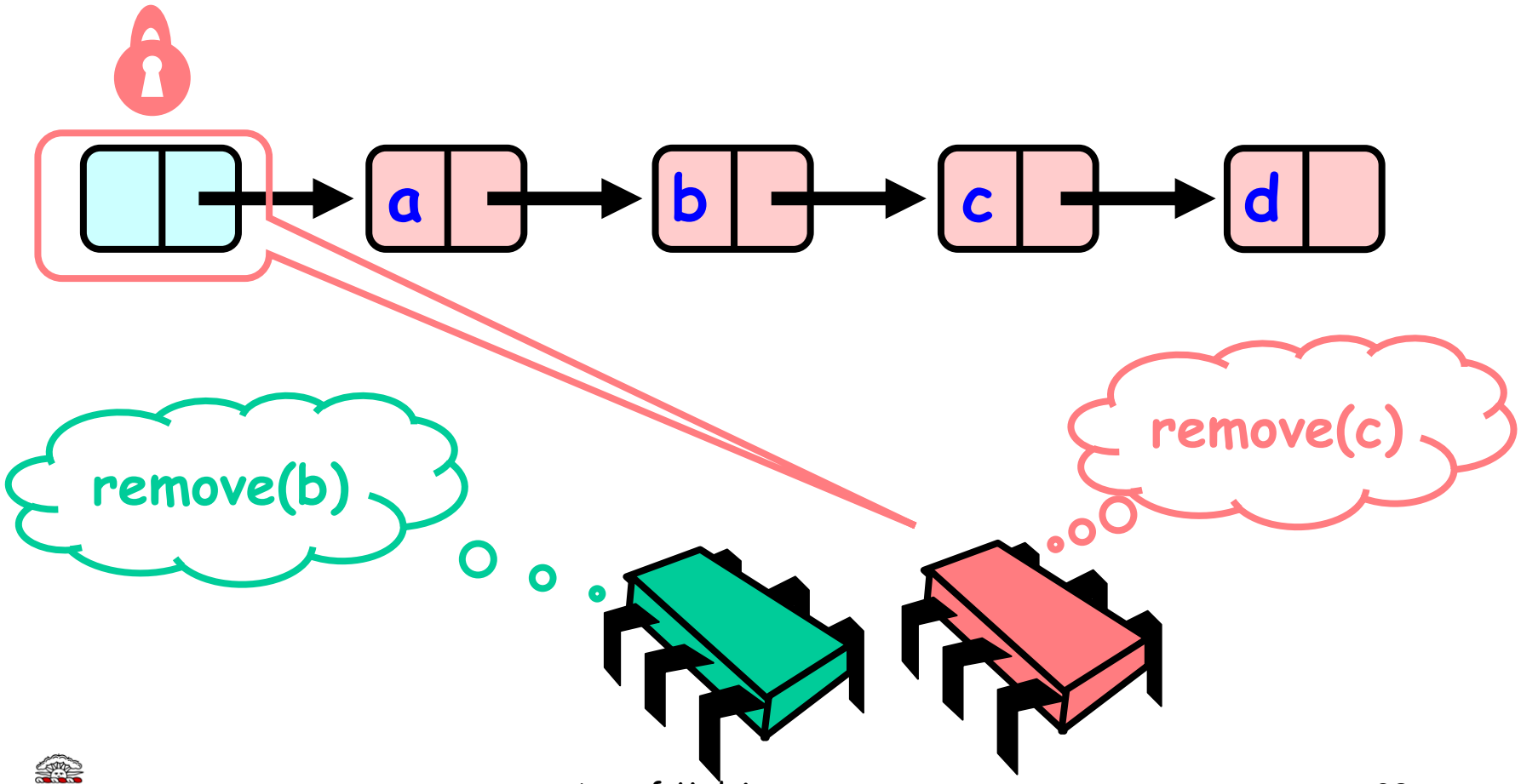

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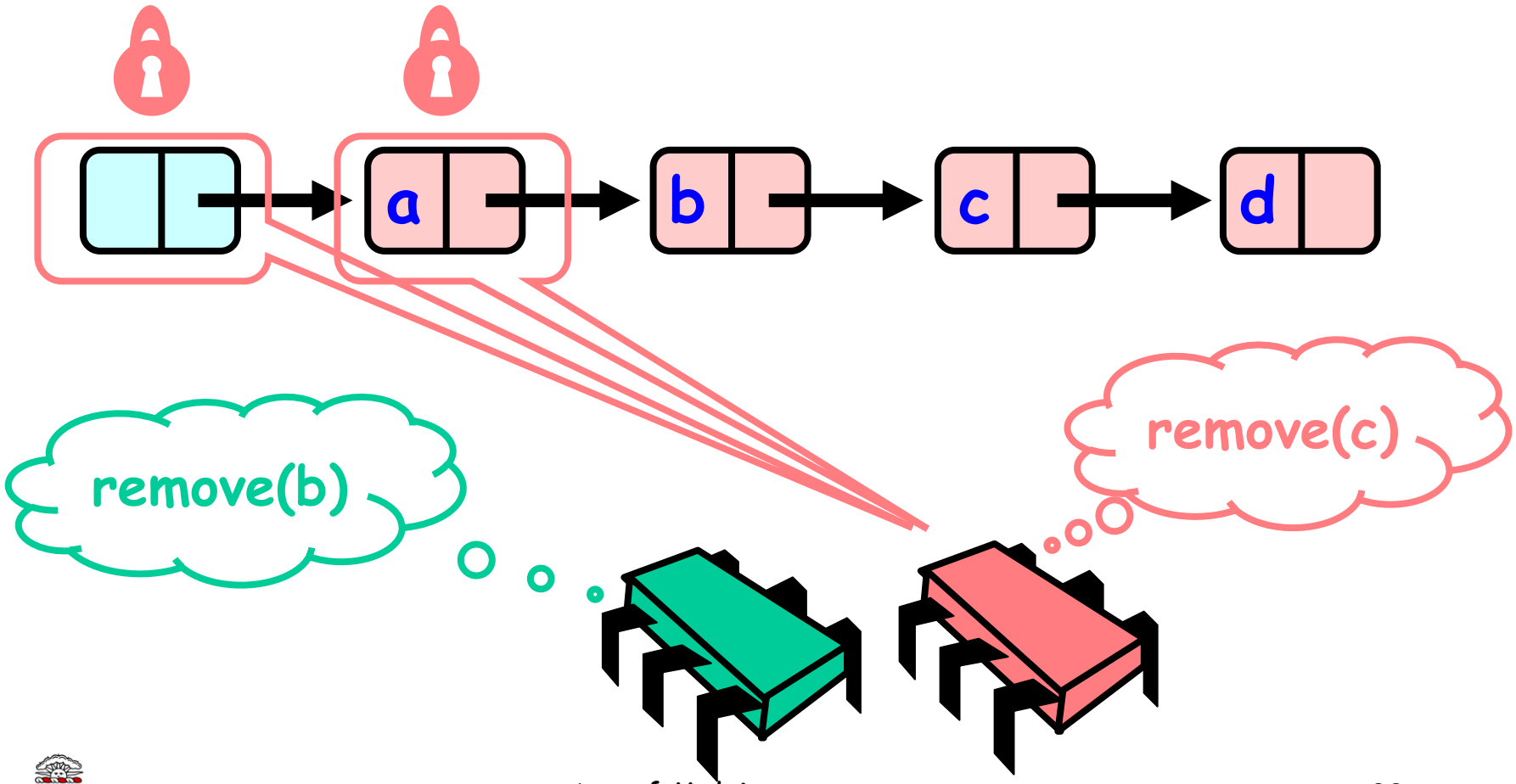

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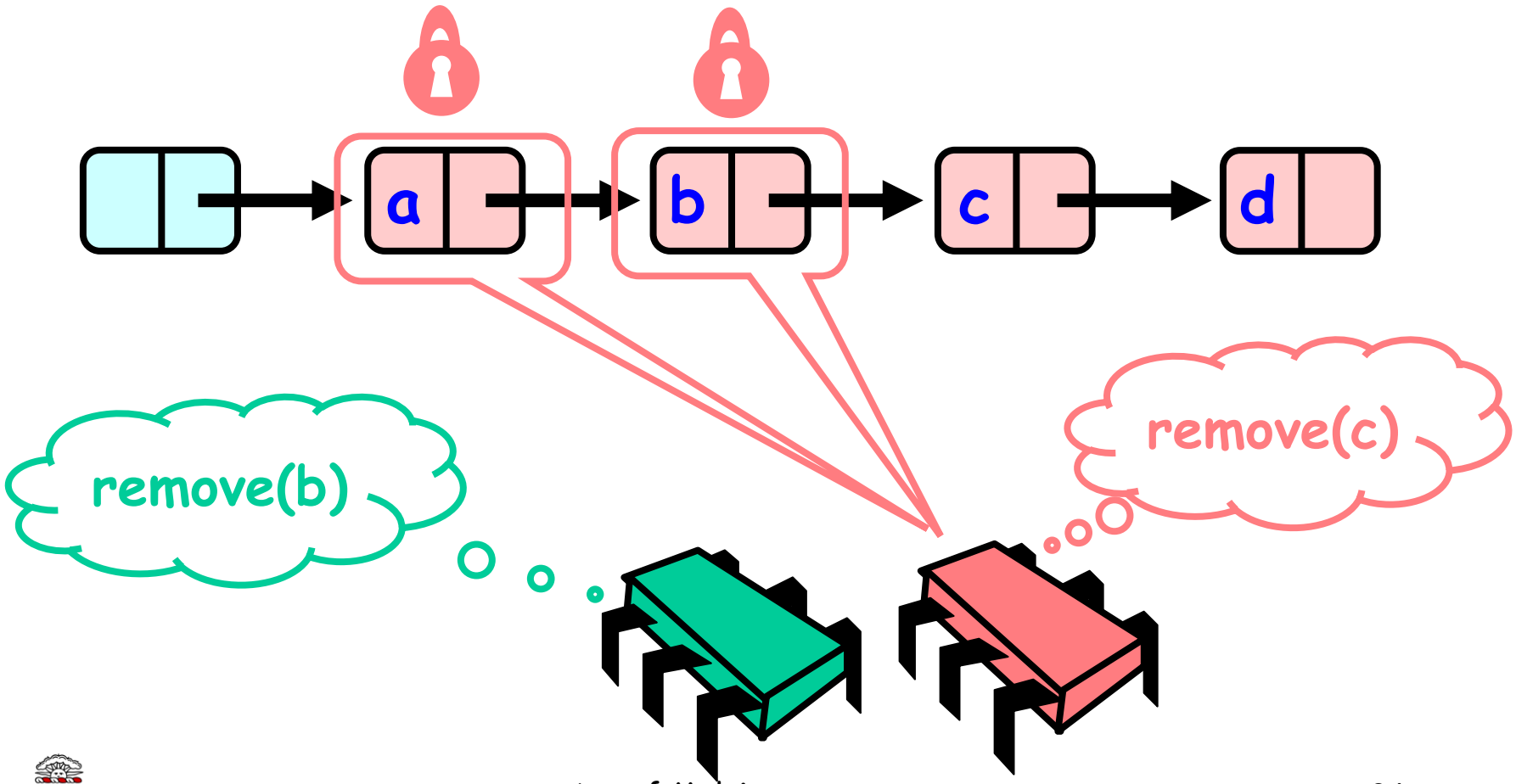

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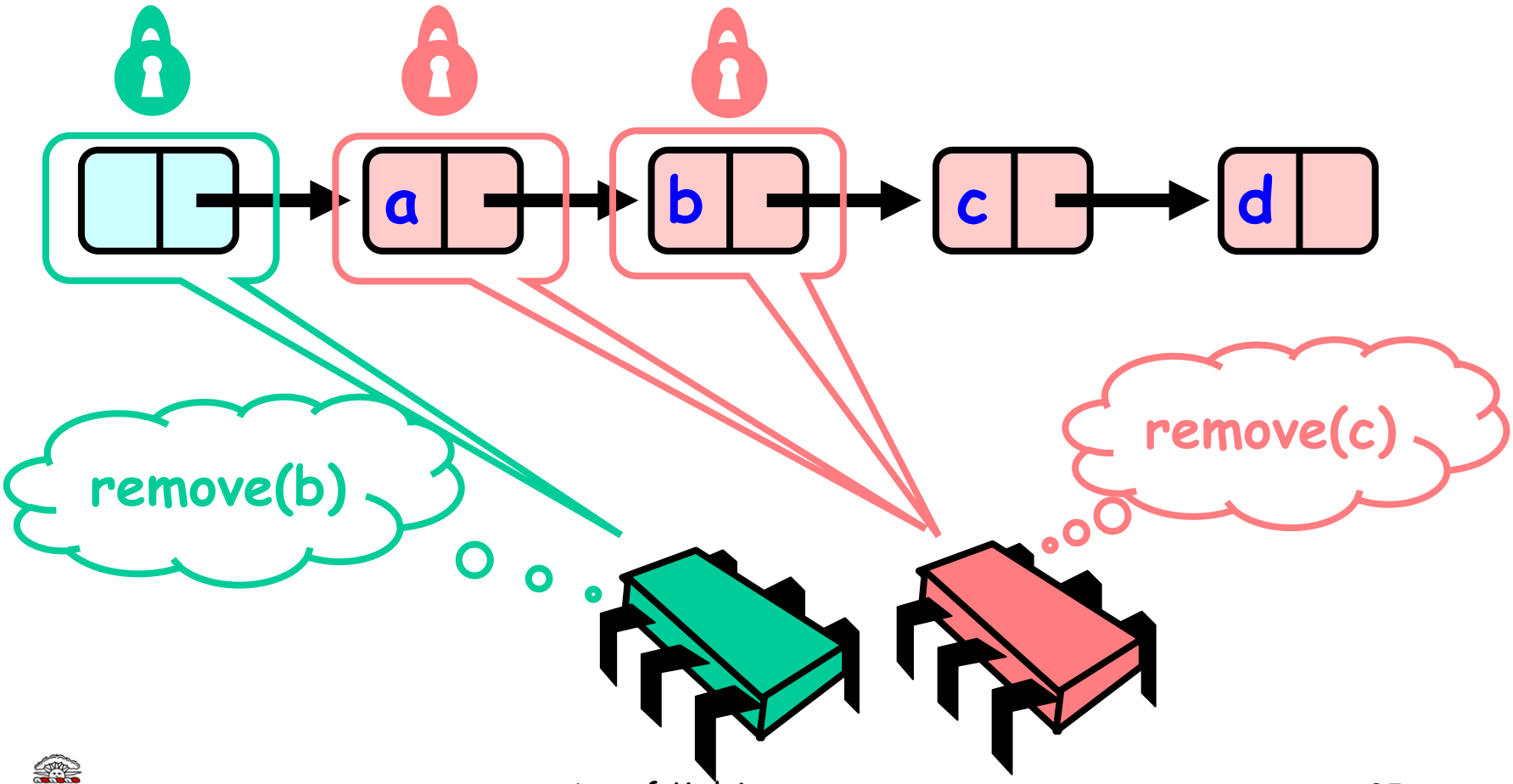

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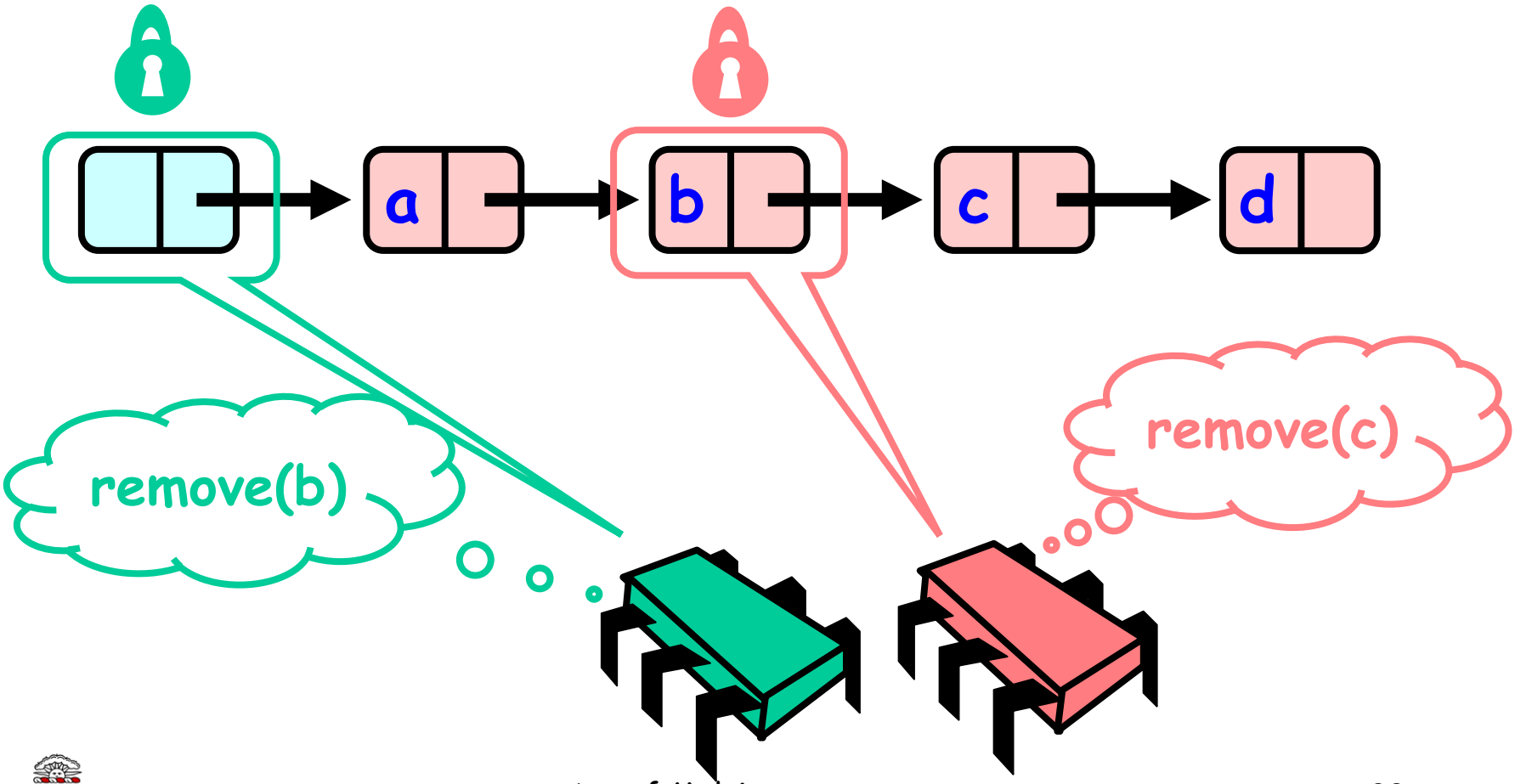

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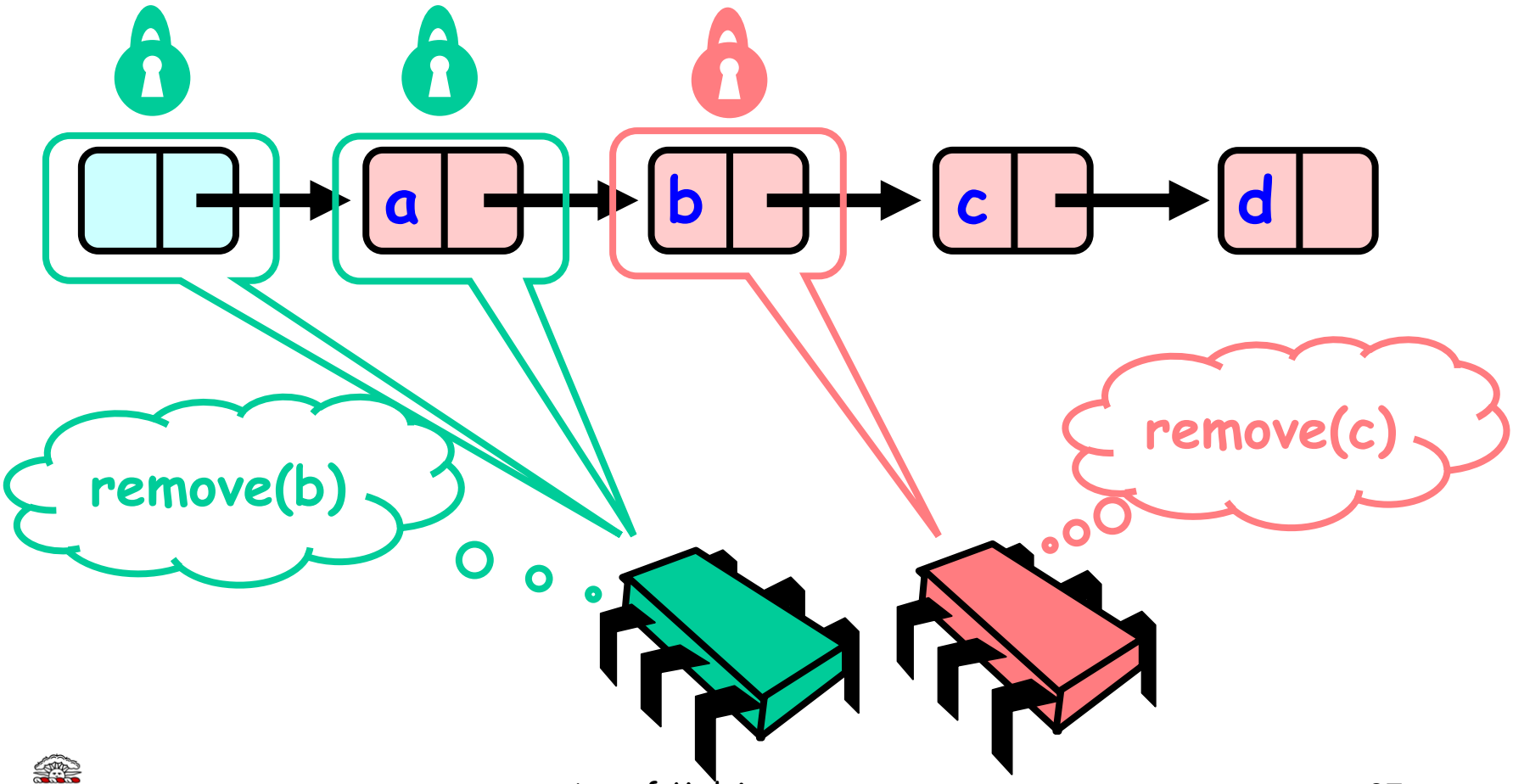

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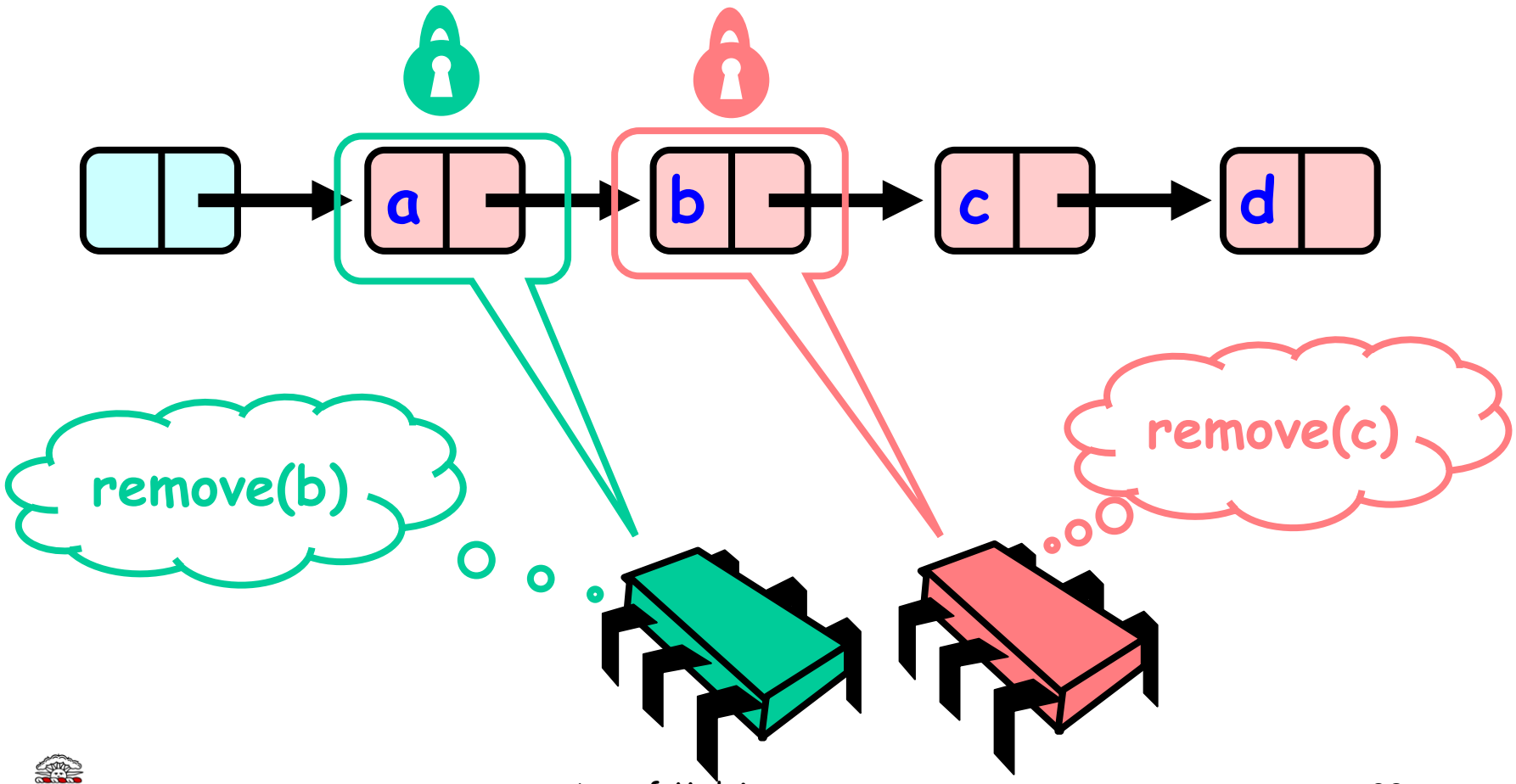
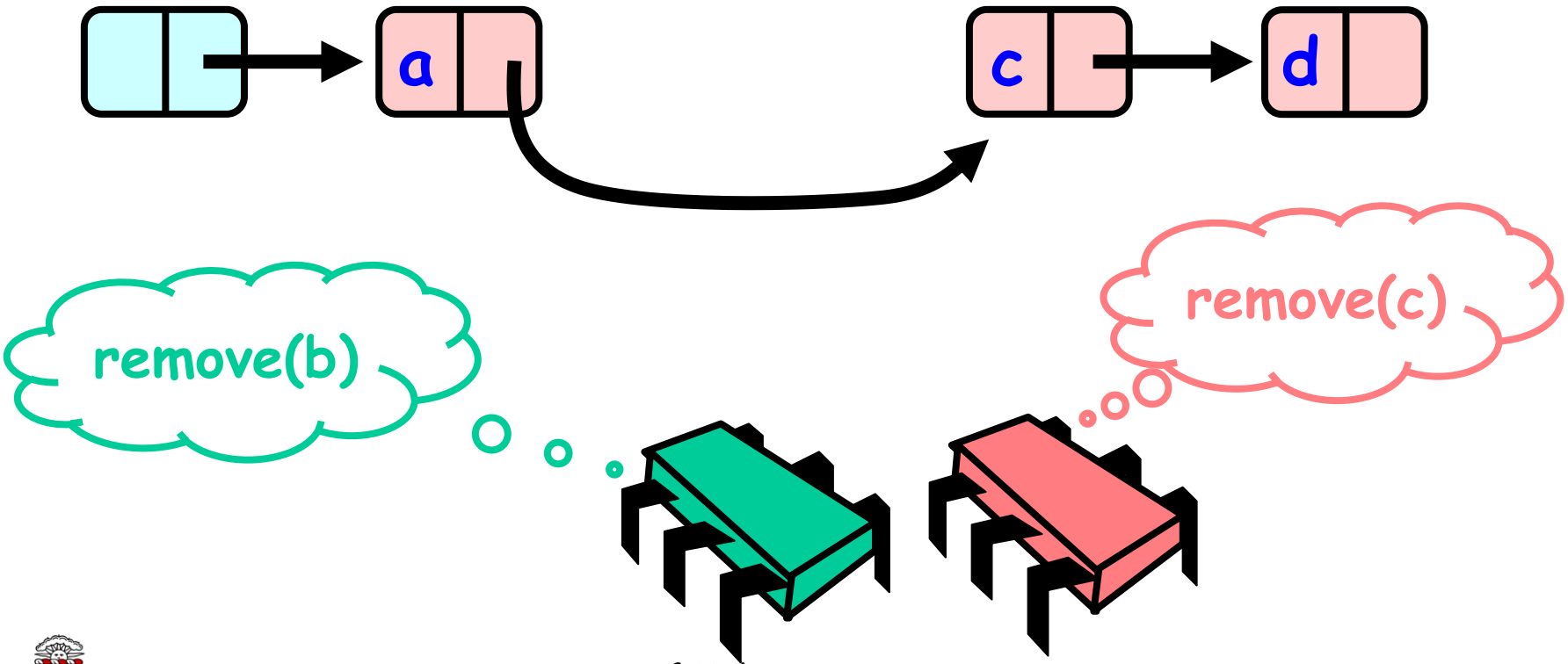


Uh, Oh



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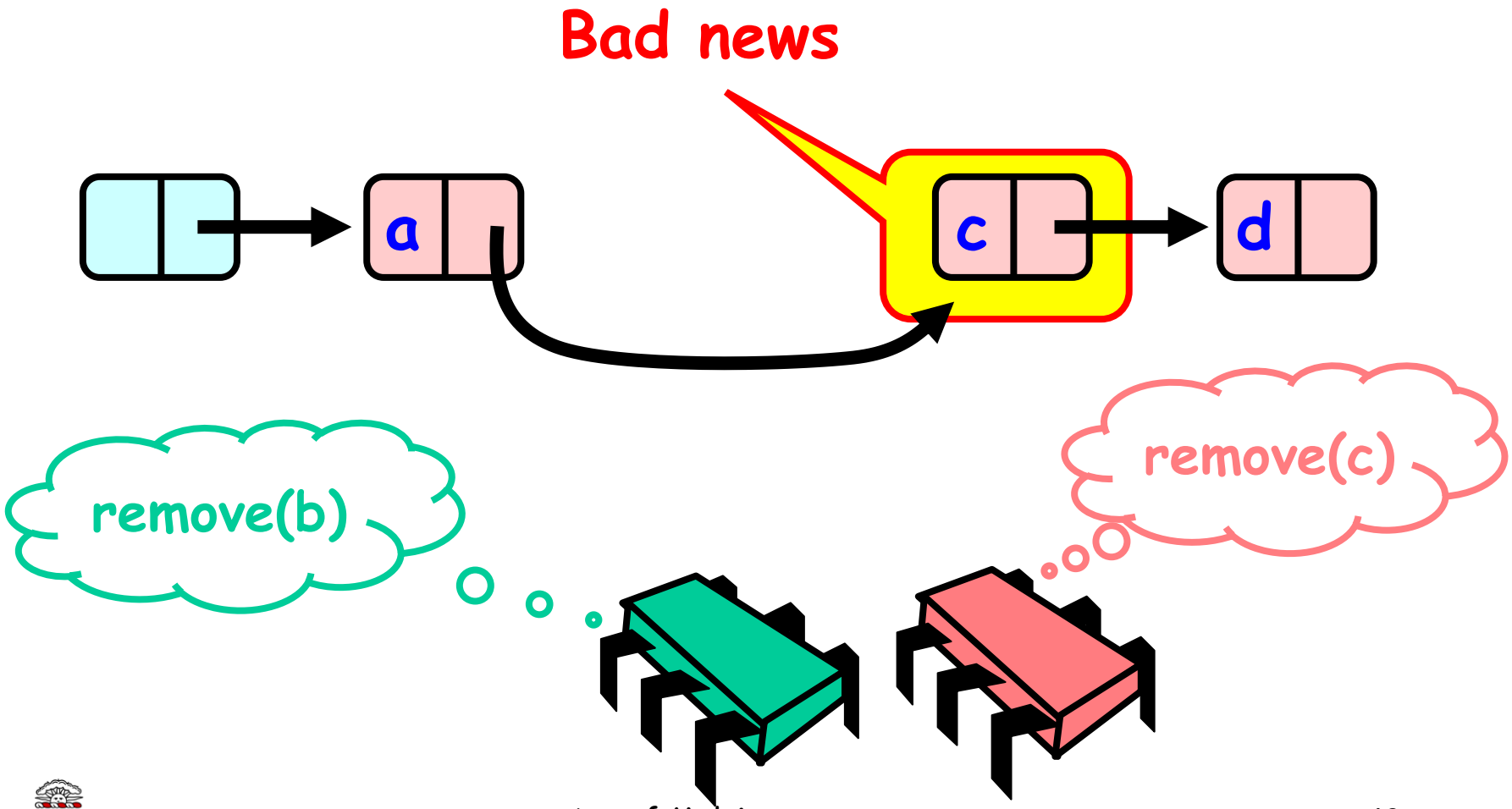
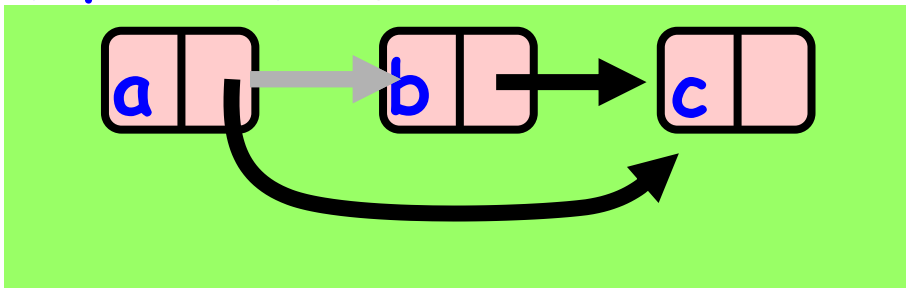
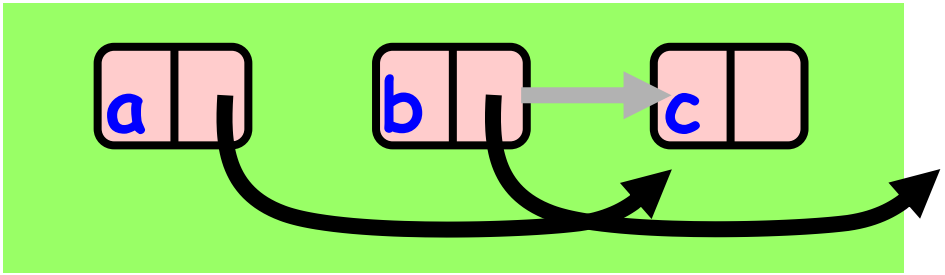


Problem

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



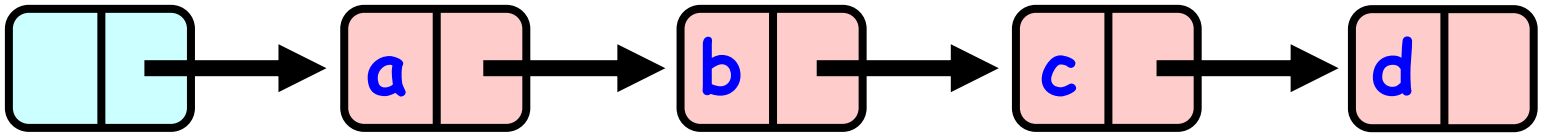
- Problem is,
  - Someone could delete c concurrently

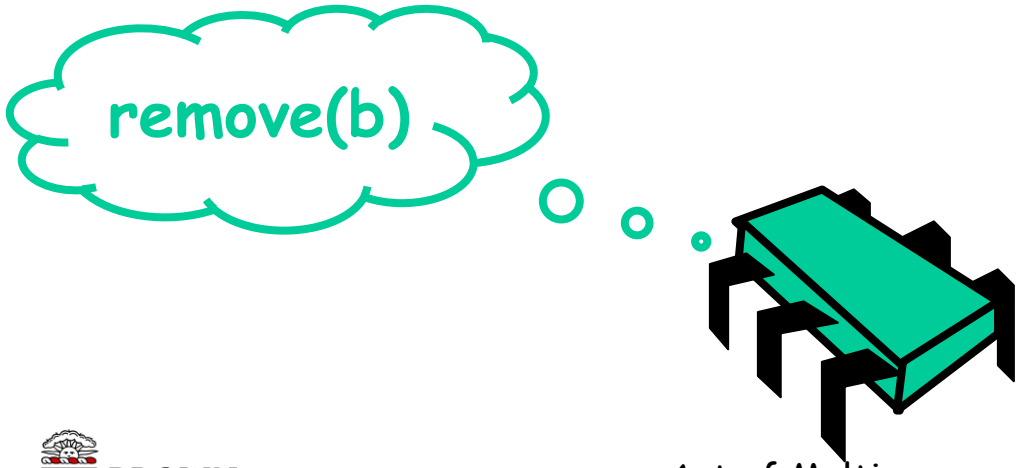


Insight

- 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





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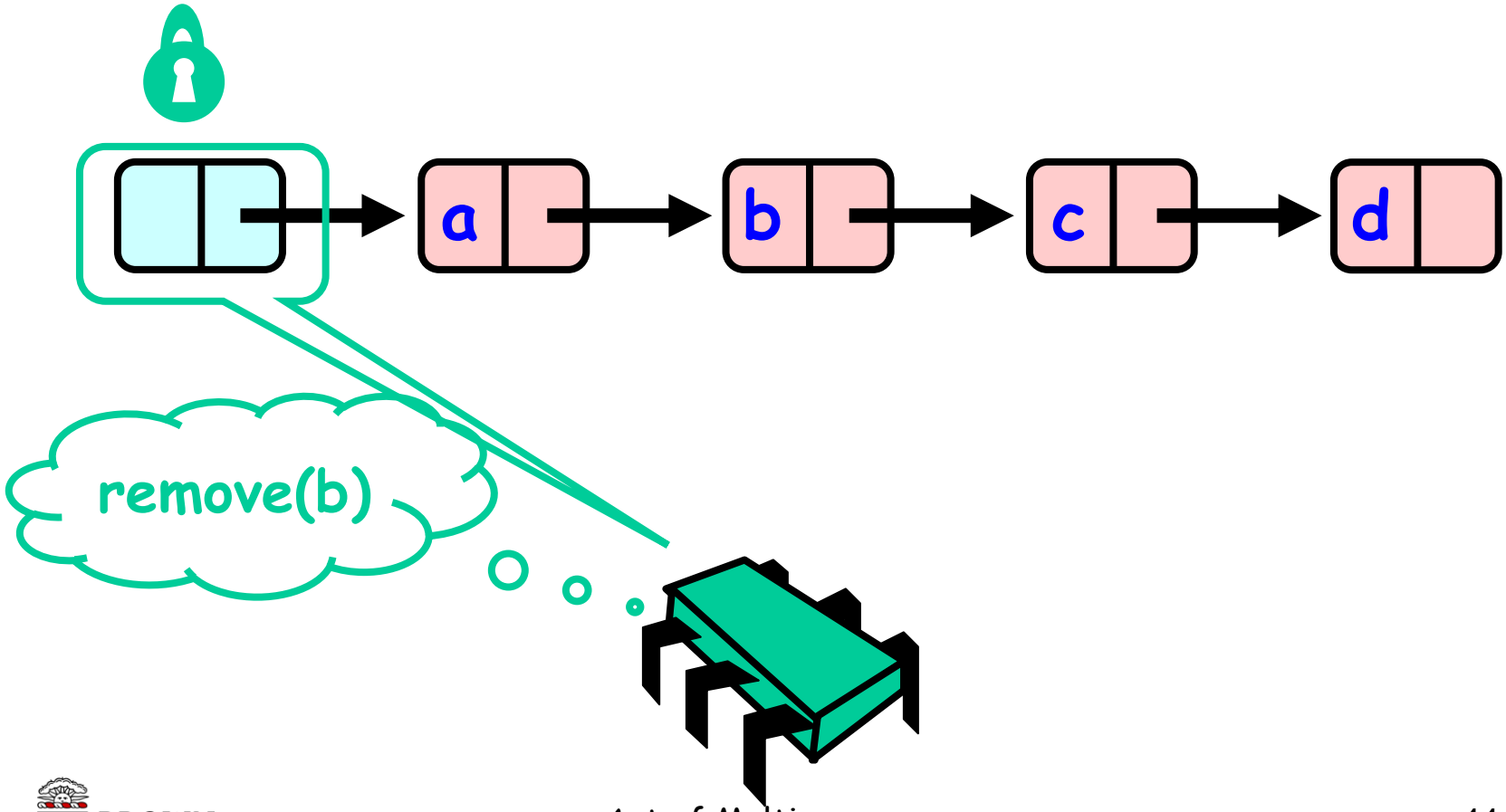

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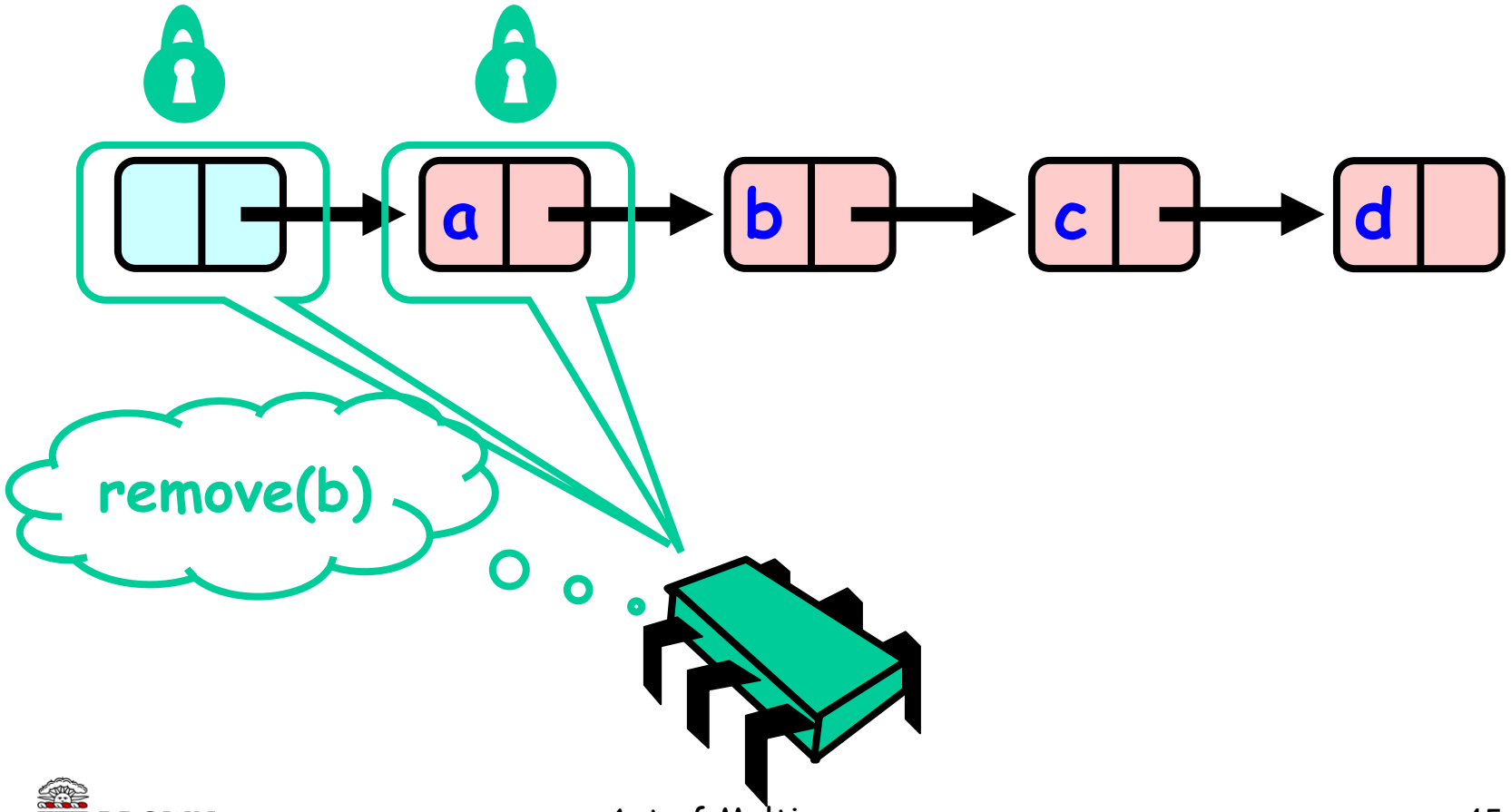

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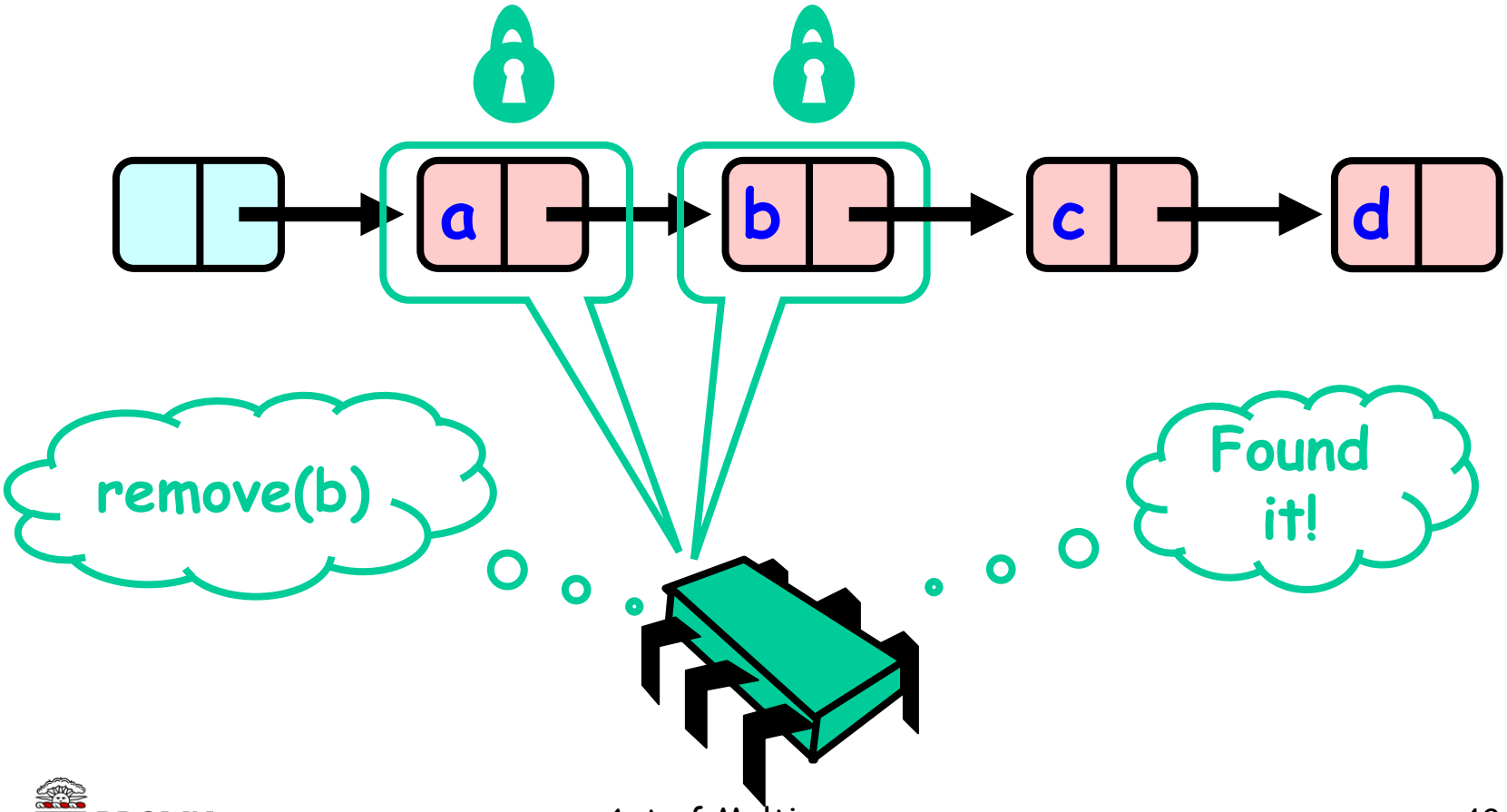

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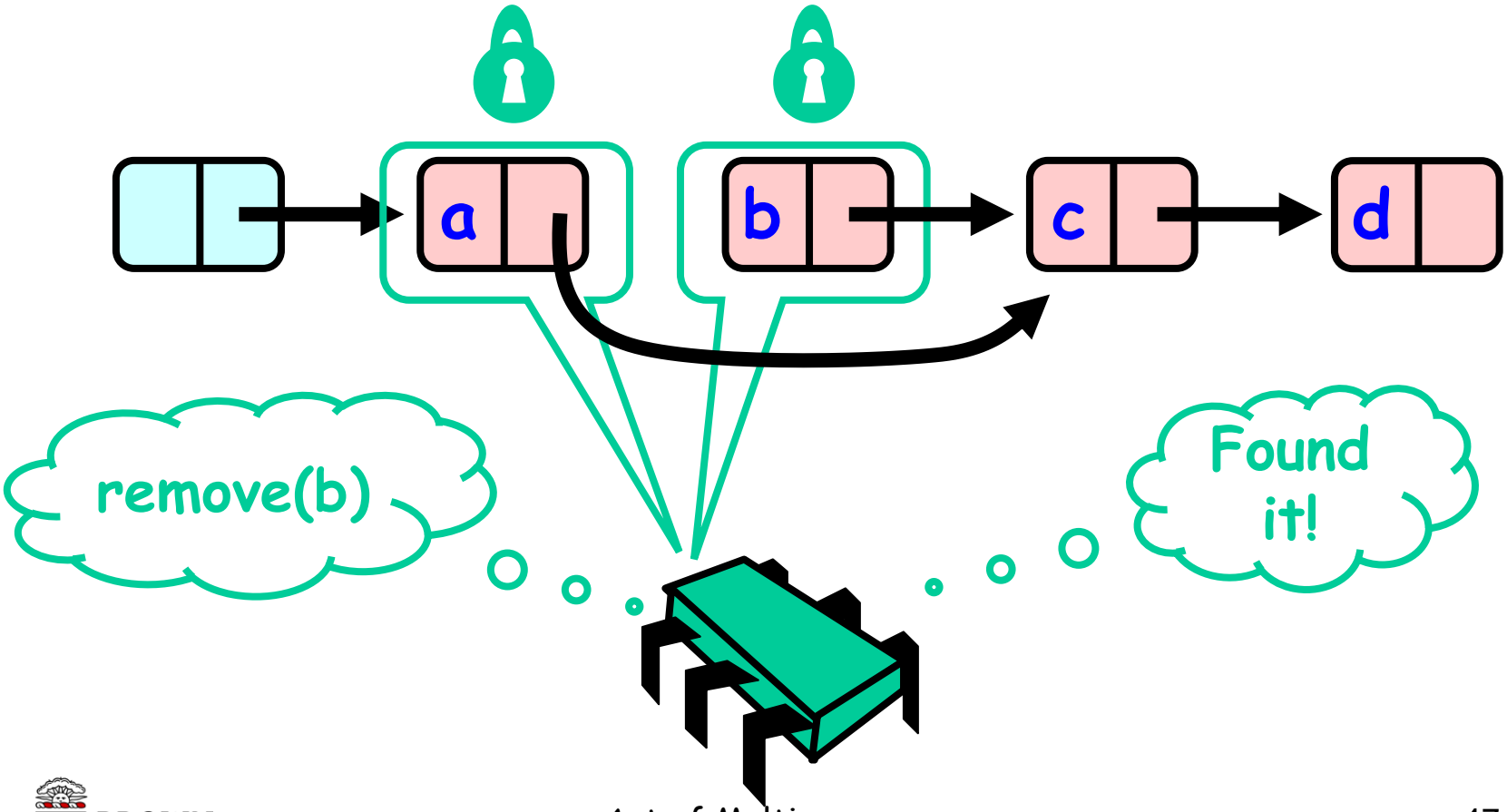

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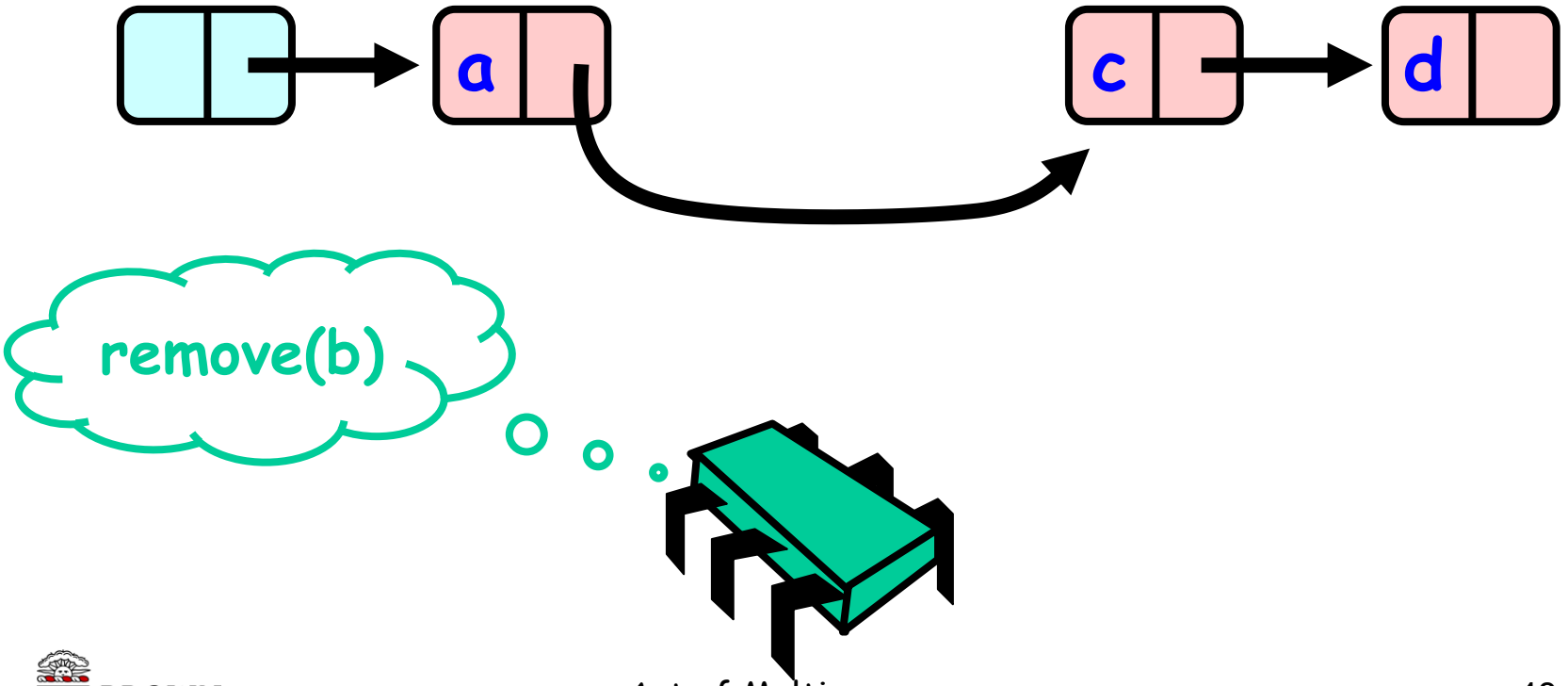
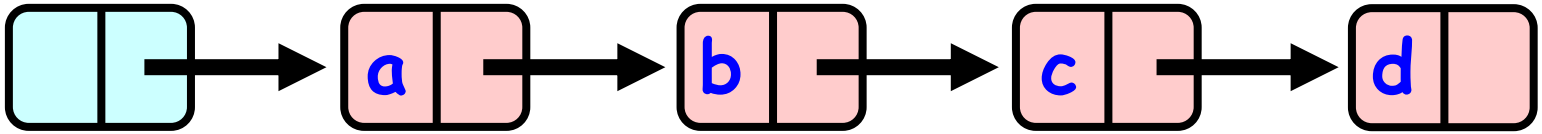
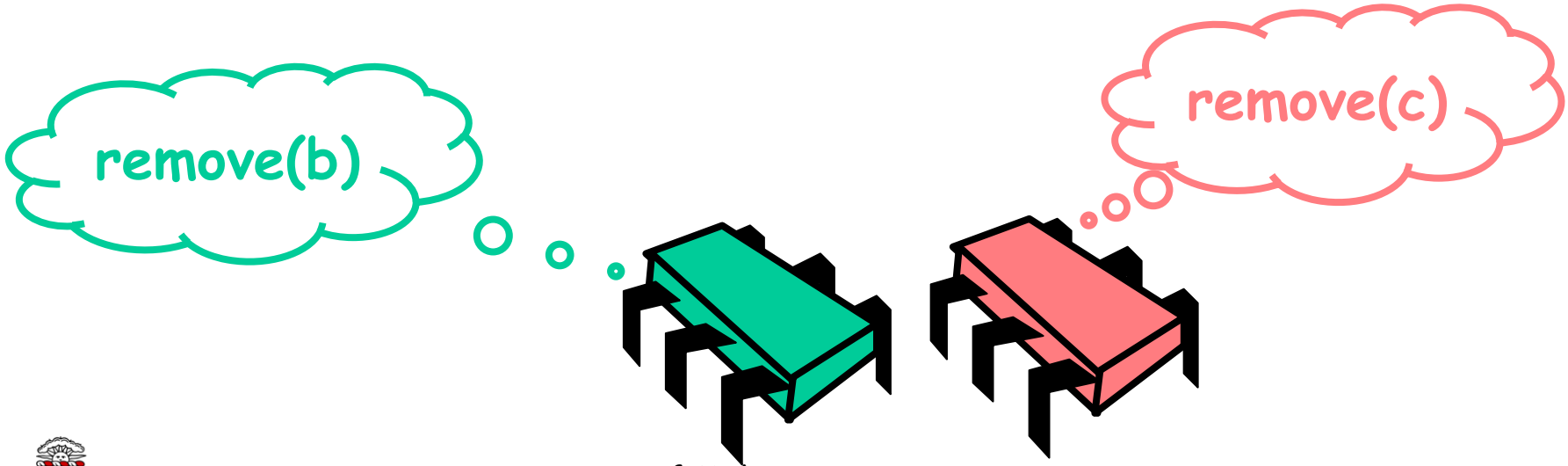
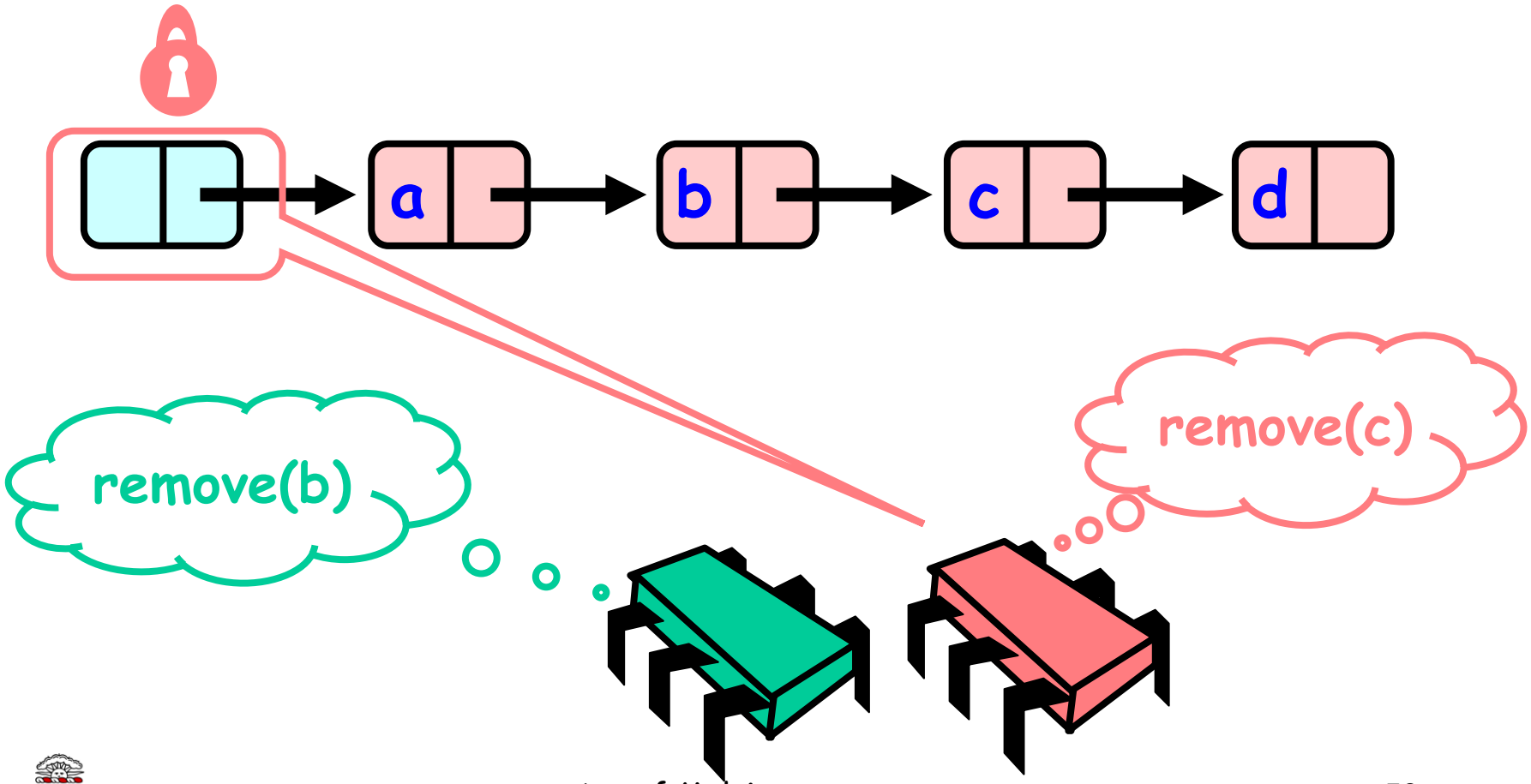


Removing a Node

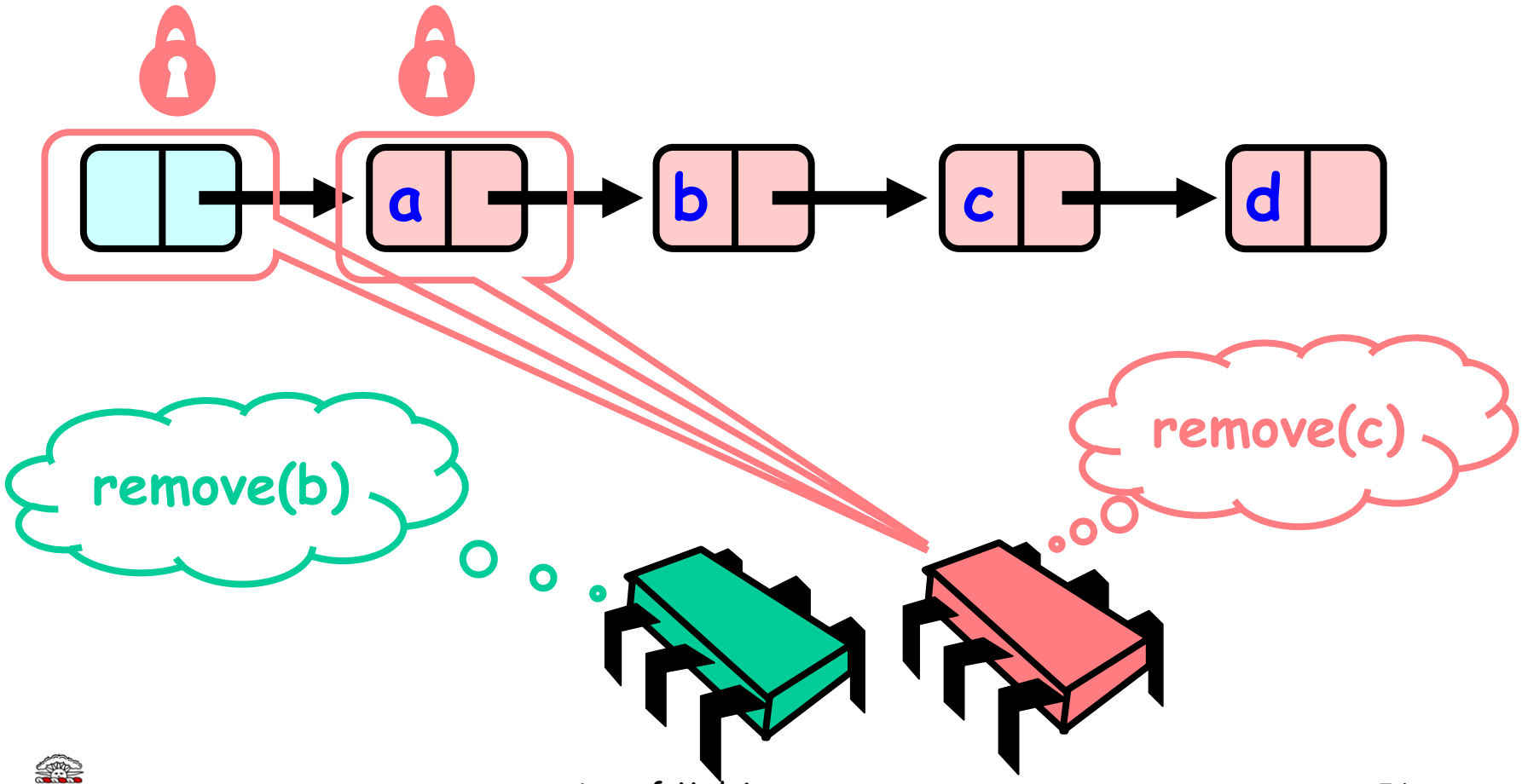




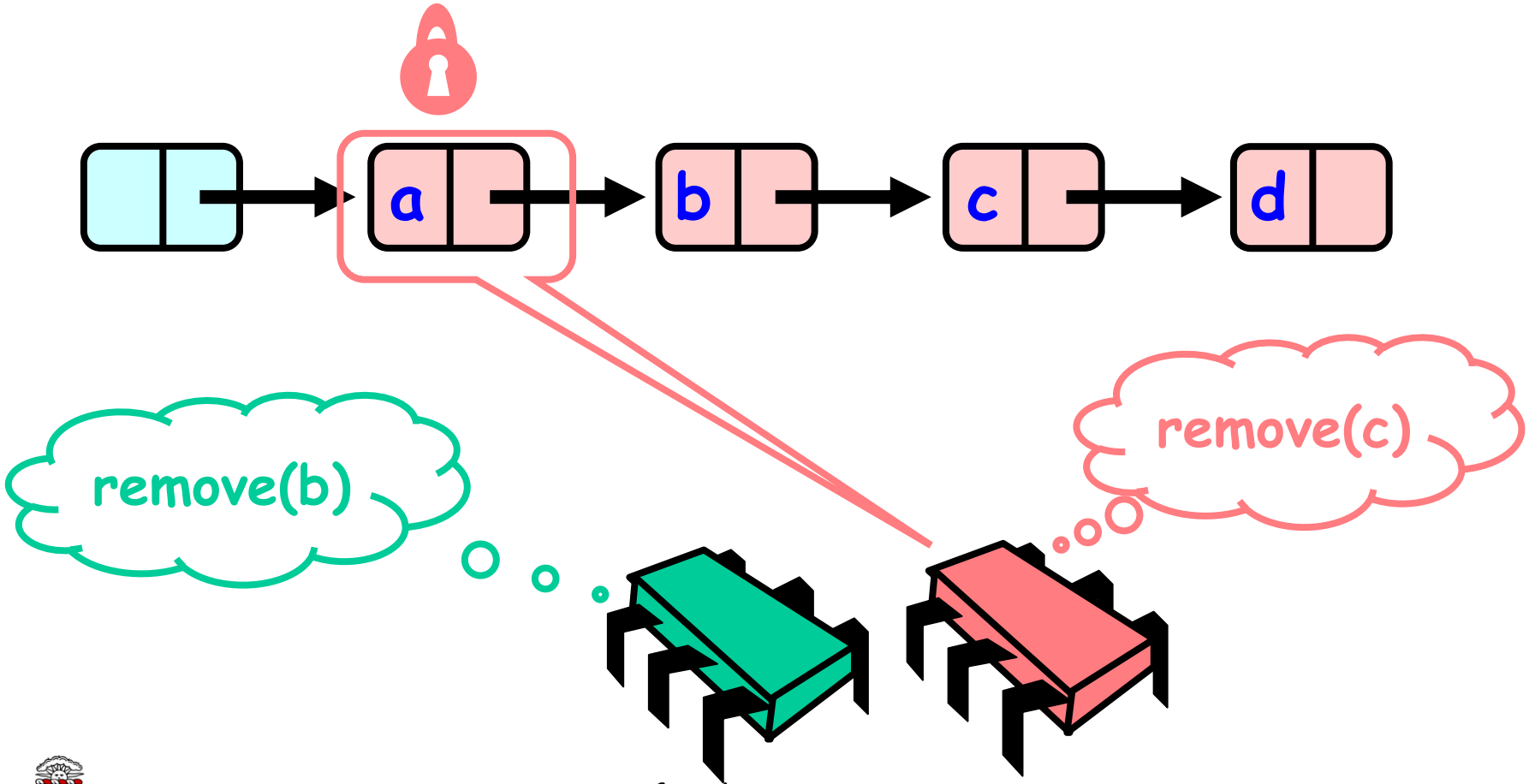
Removing a Node



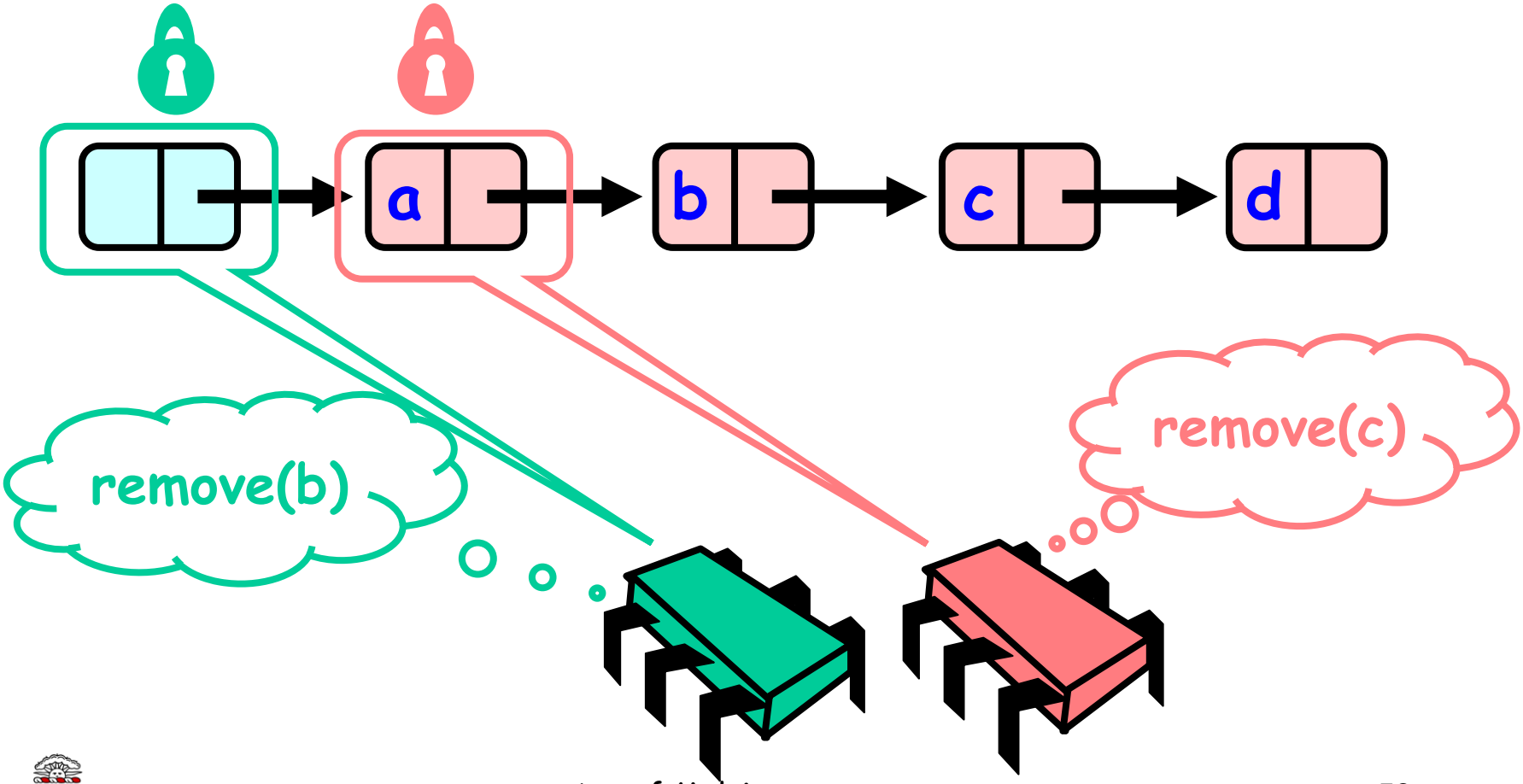
Removing a Node



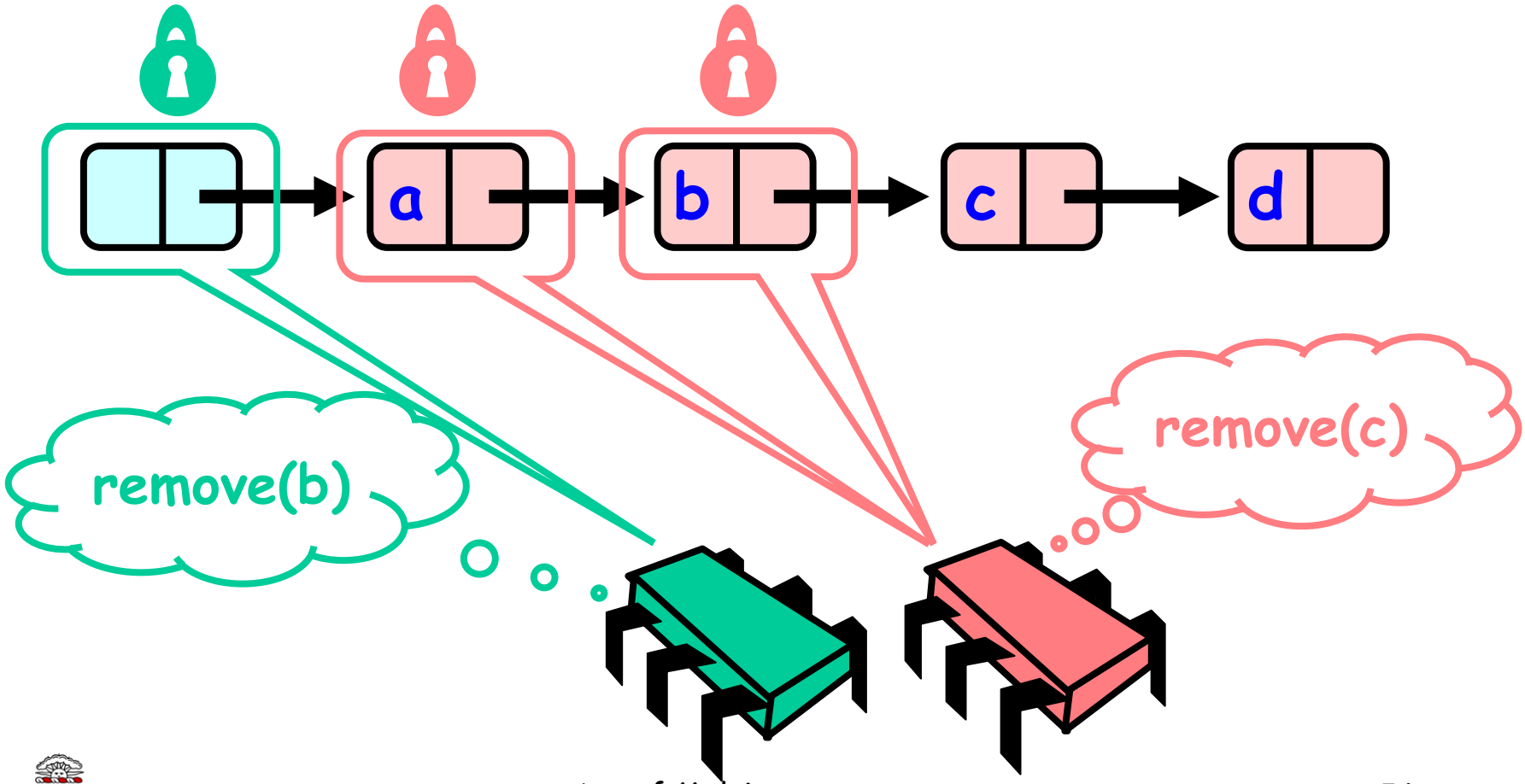
Removing a Node



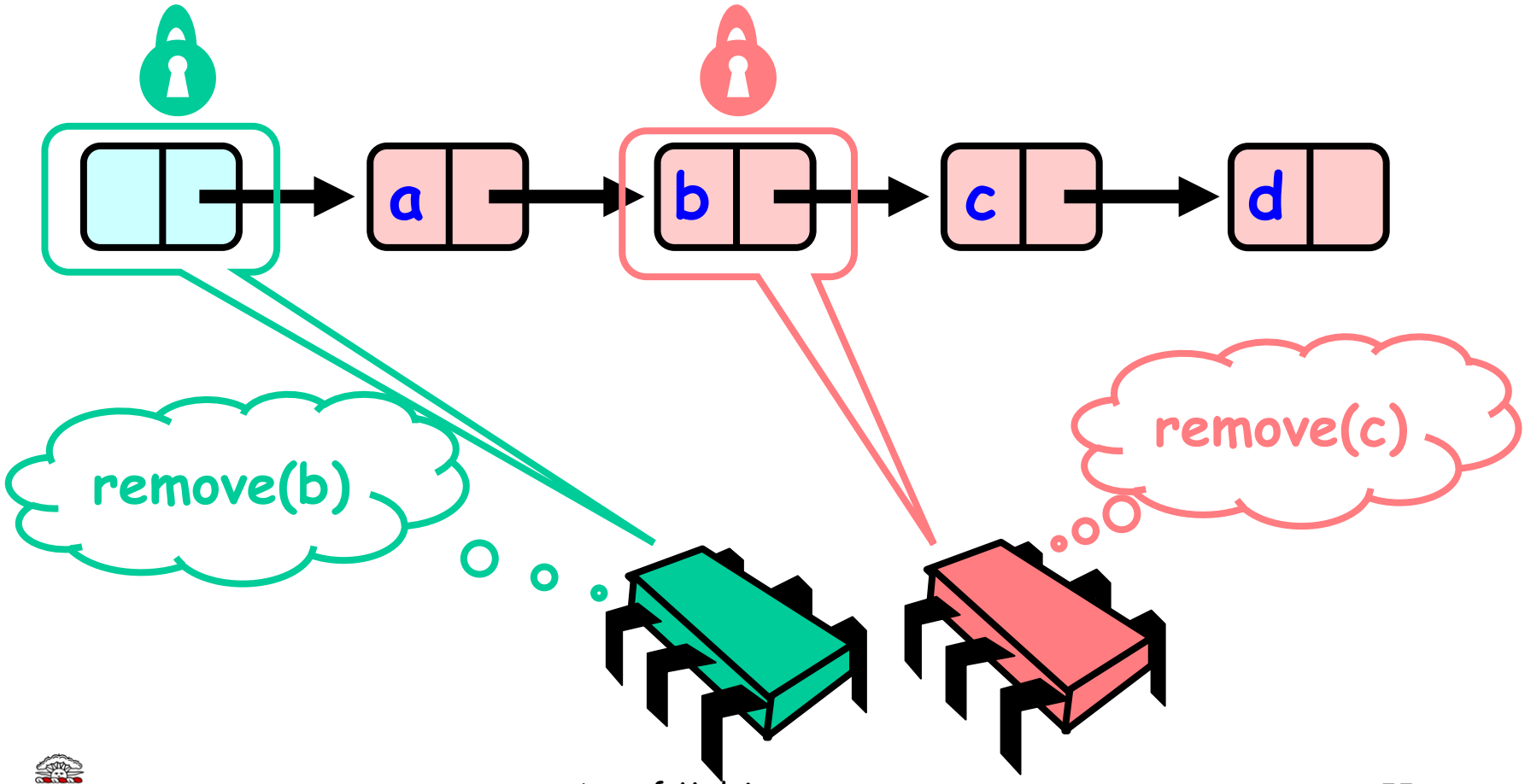
Removing a Node



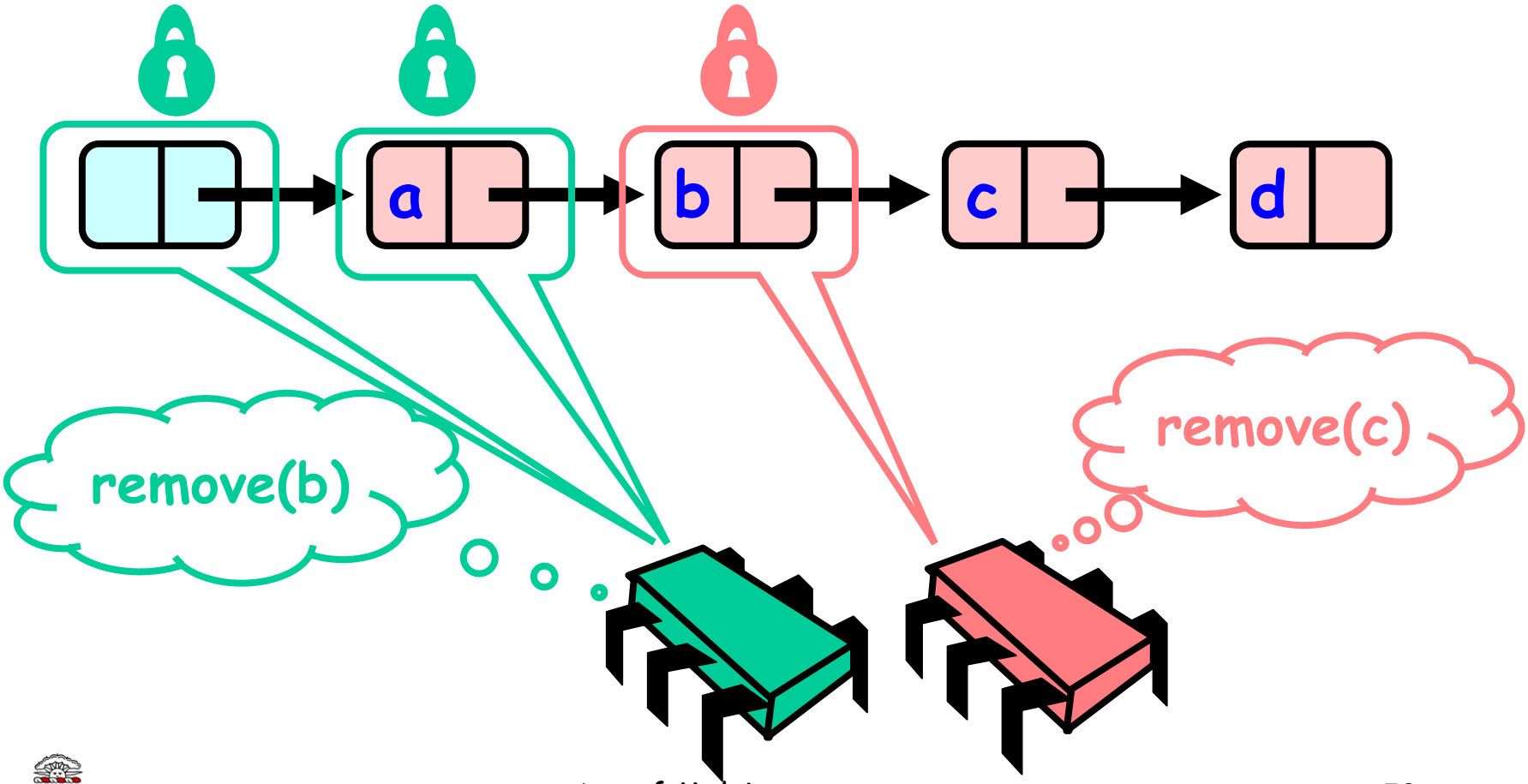
Removing a Node



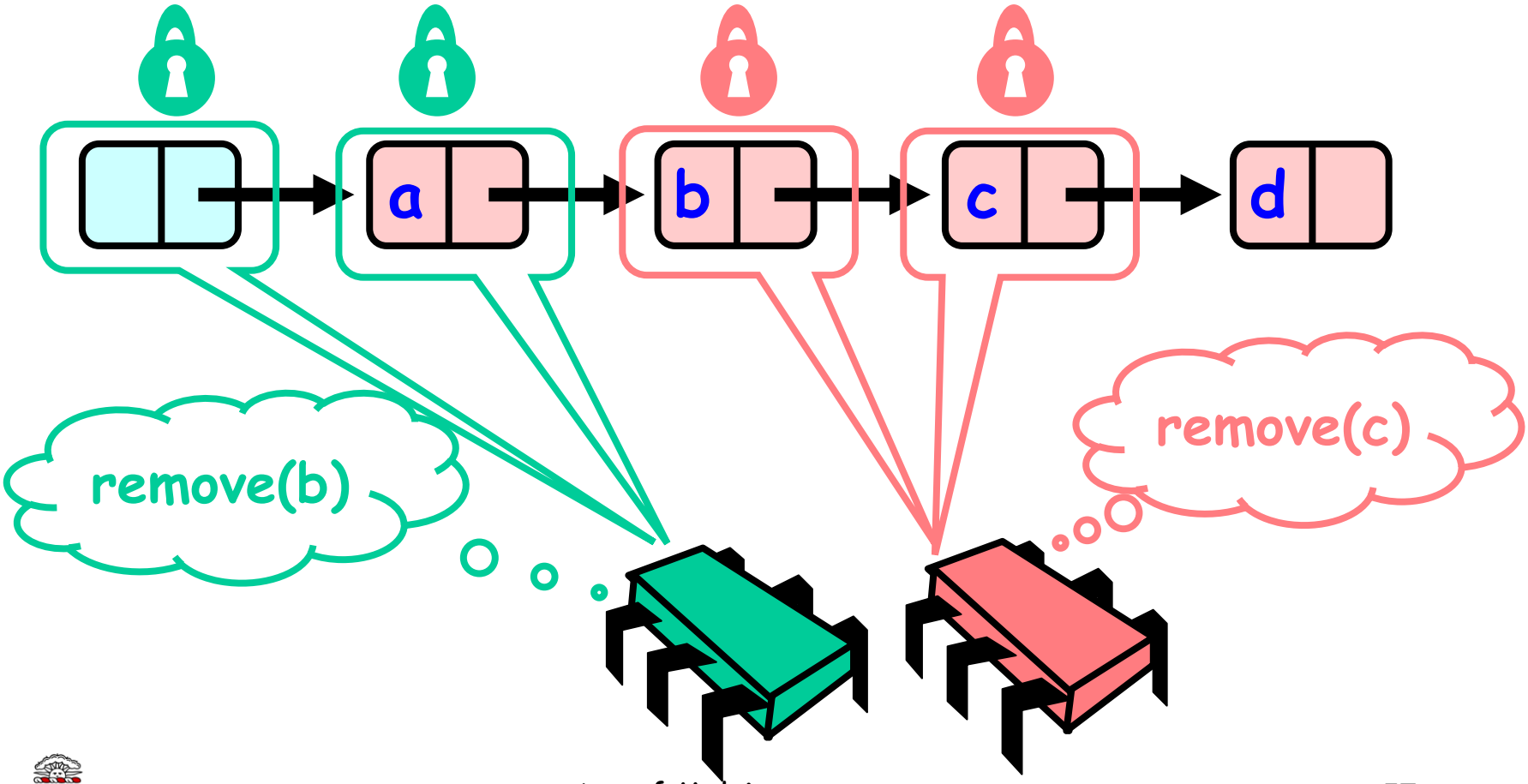
Removing a Node



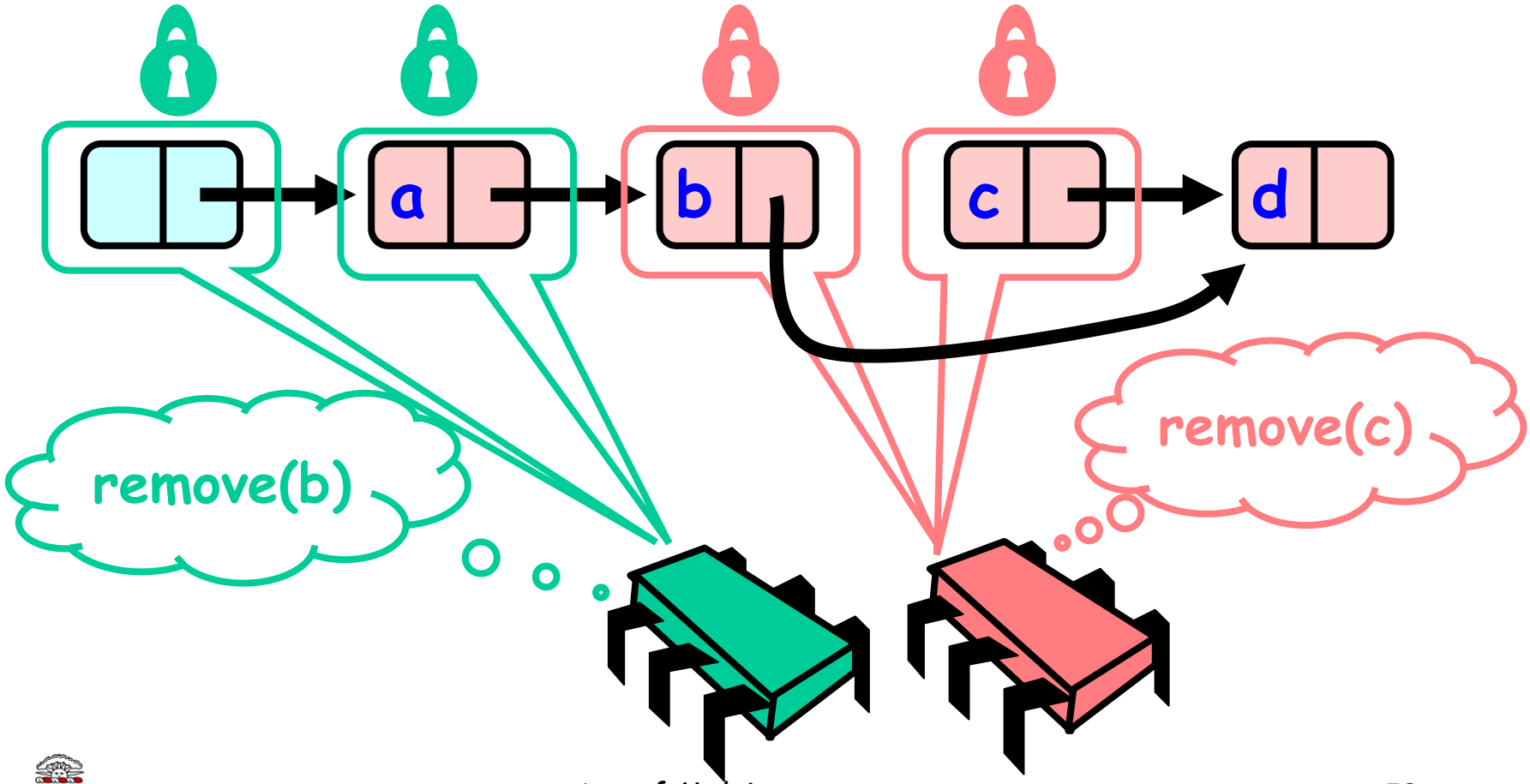
Removing a Node



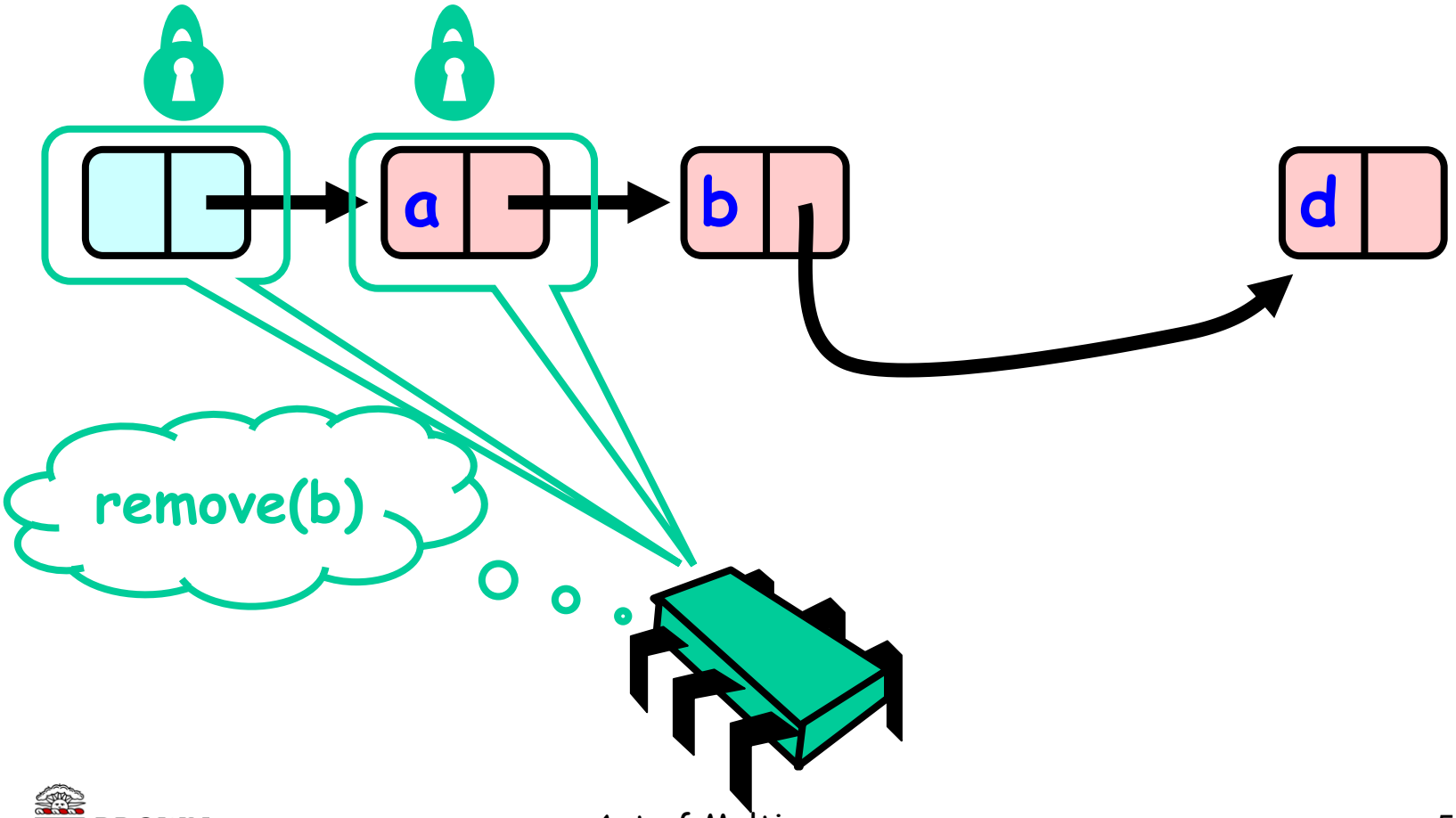
Removing a Node



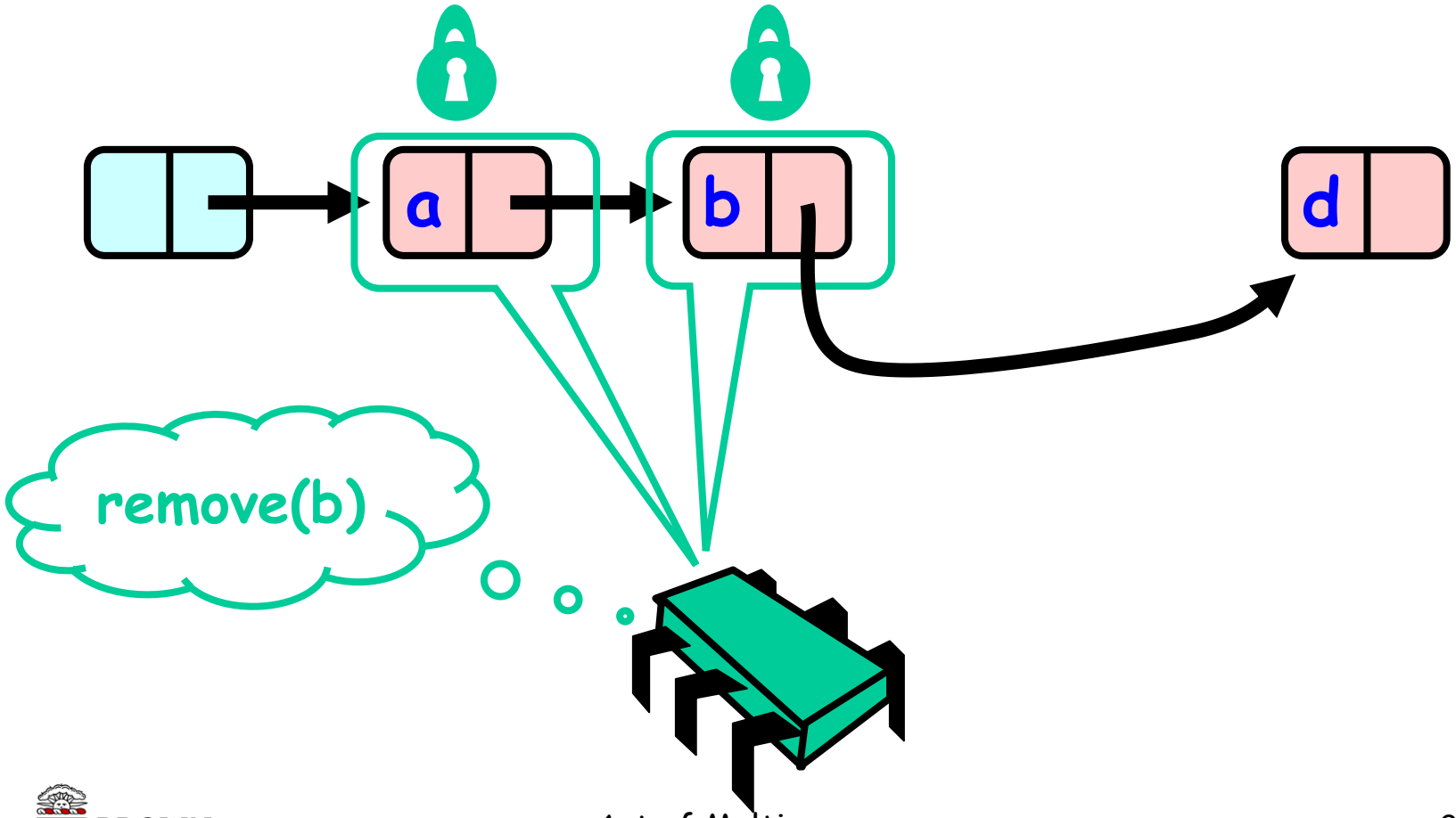
Removing a Node



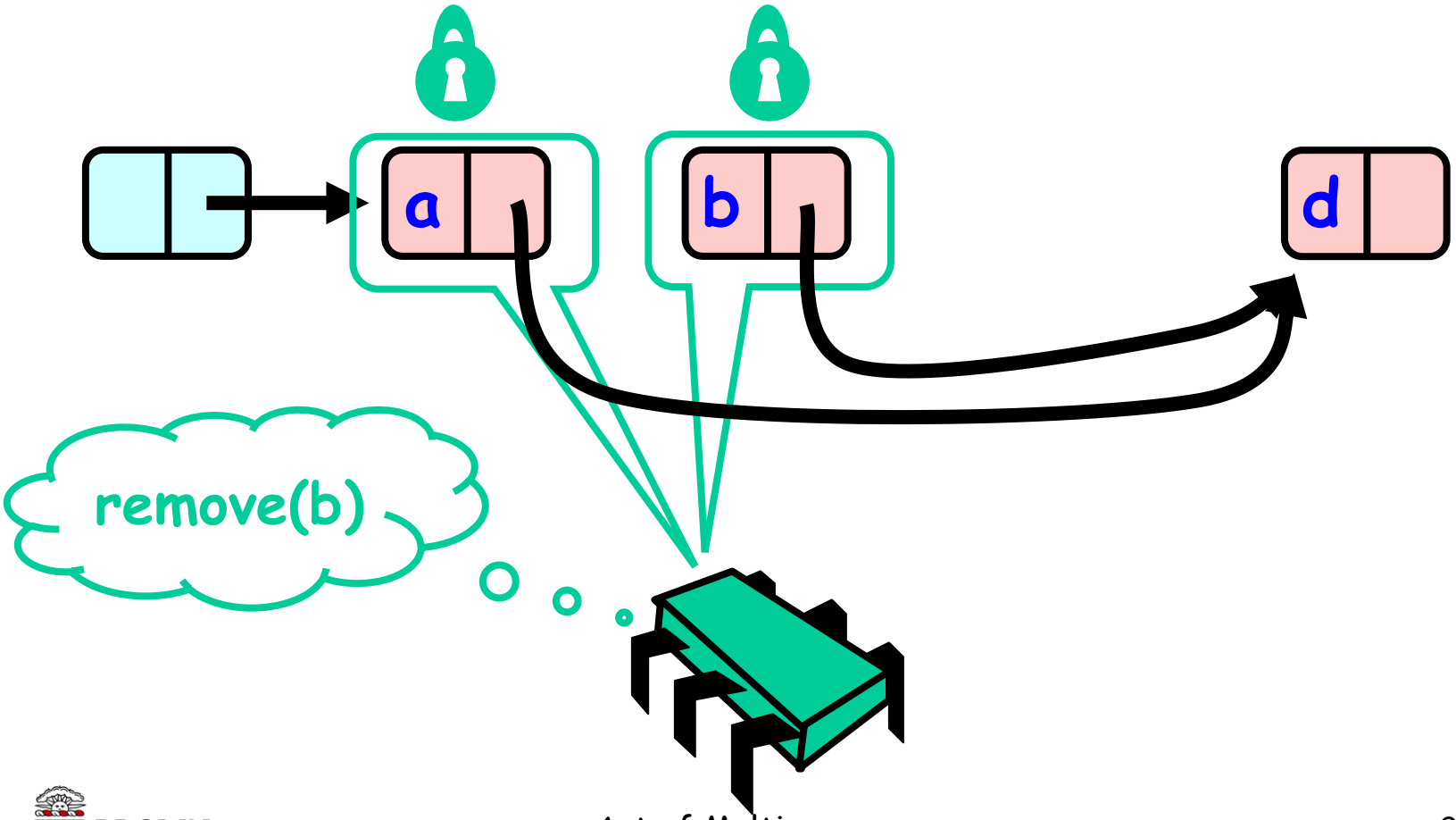
Removing a Node



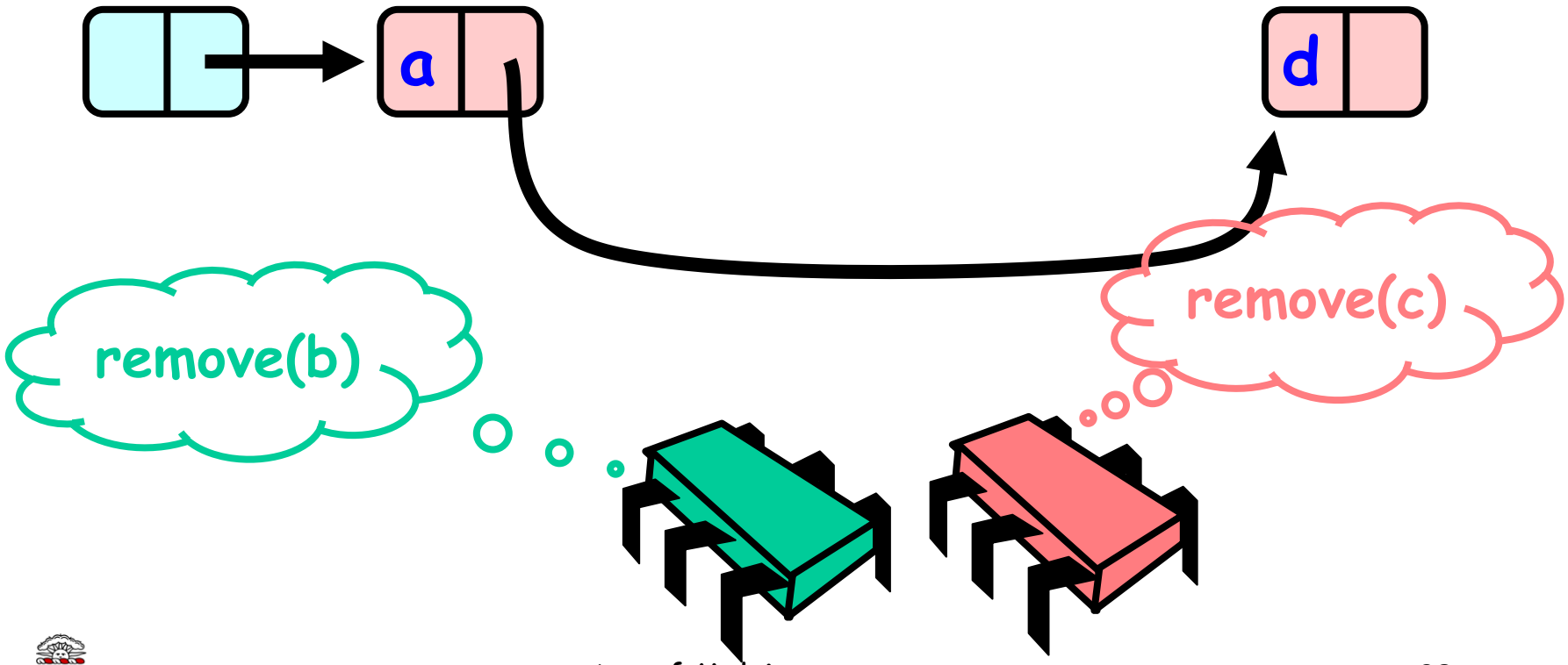
Removing a Node



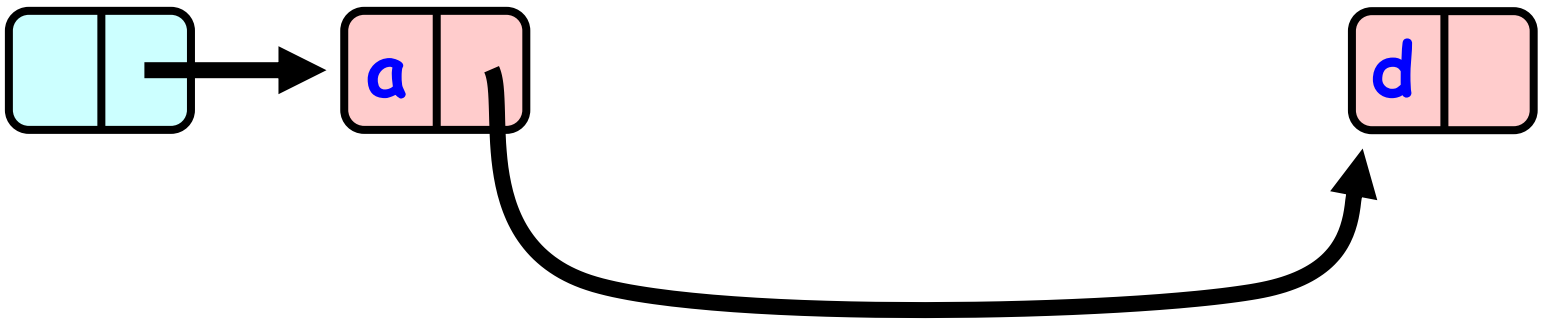
Removing a Node



Removing a Node



Removing a Node



Adding Nodes

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

Rep Invariant

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

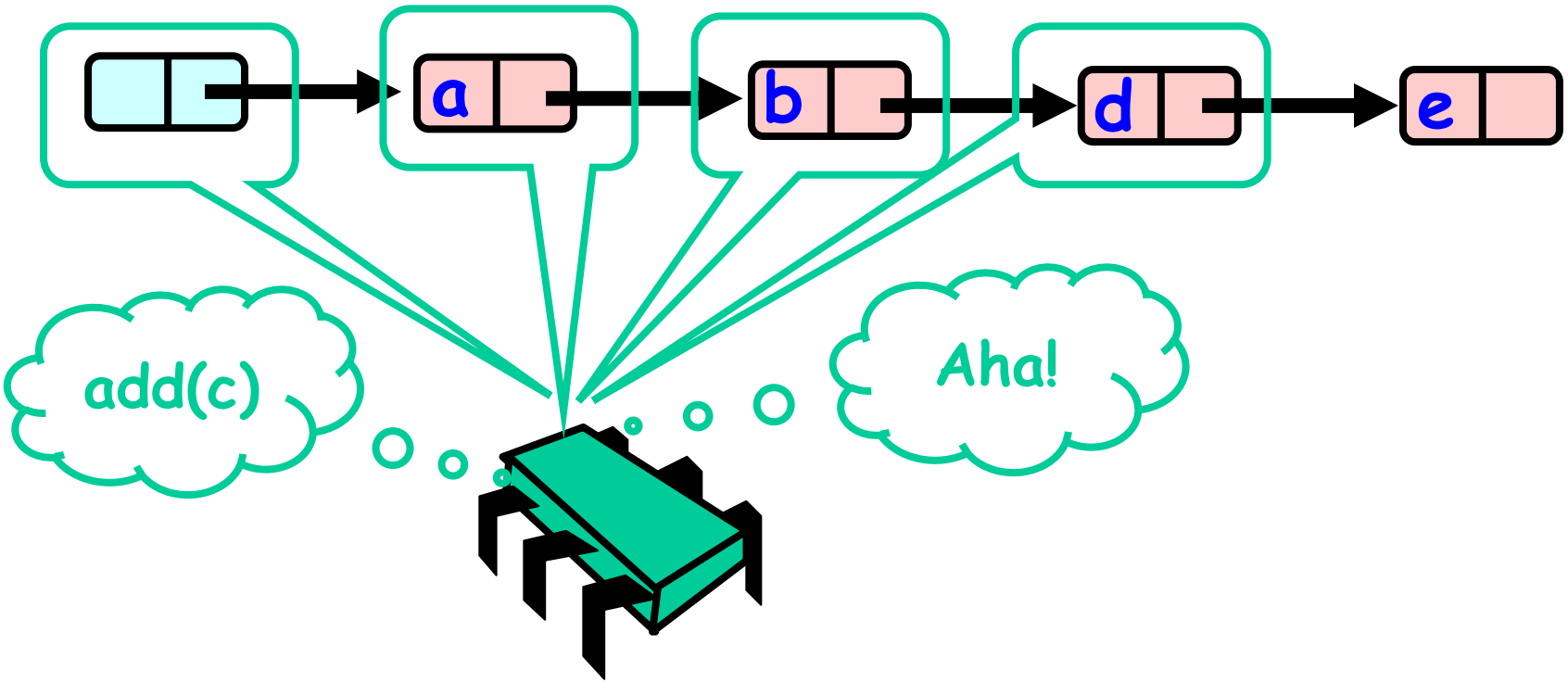
Drawbacks

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

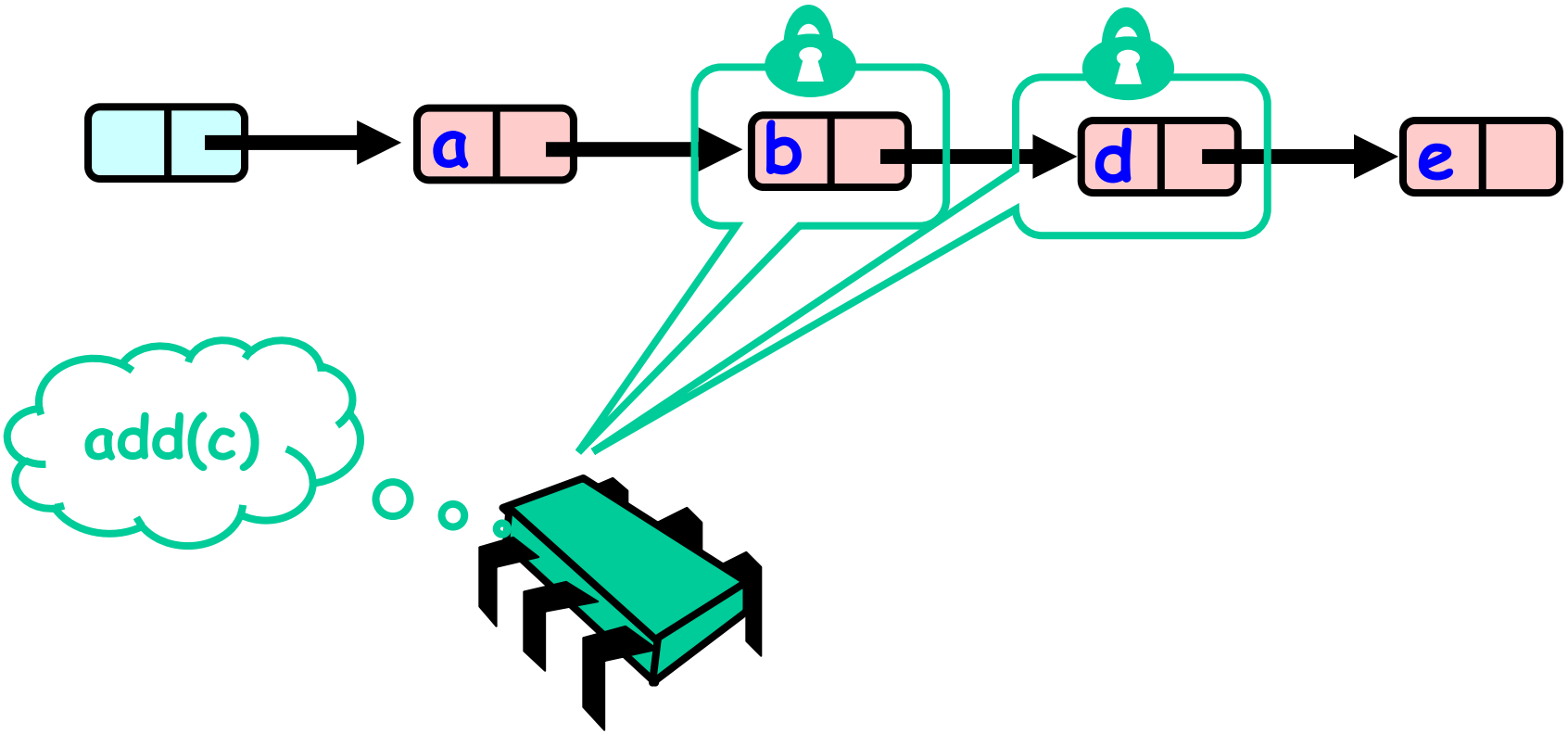
Optimistic Synchronization

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

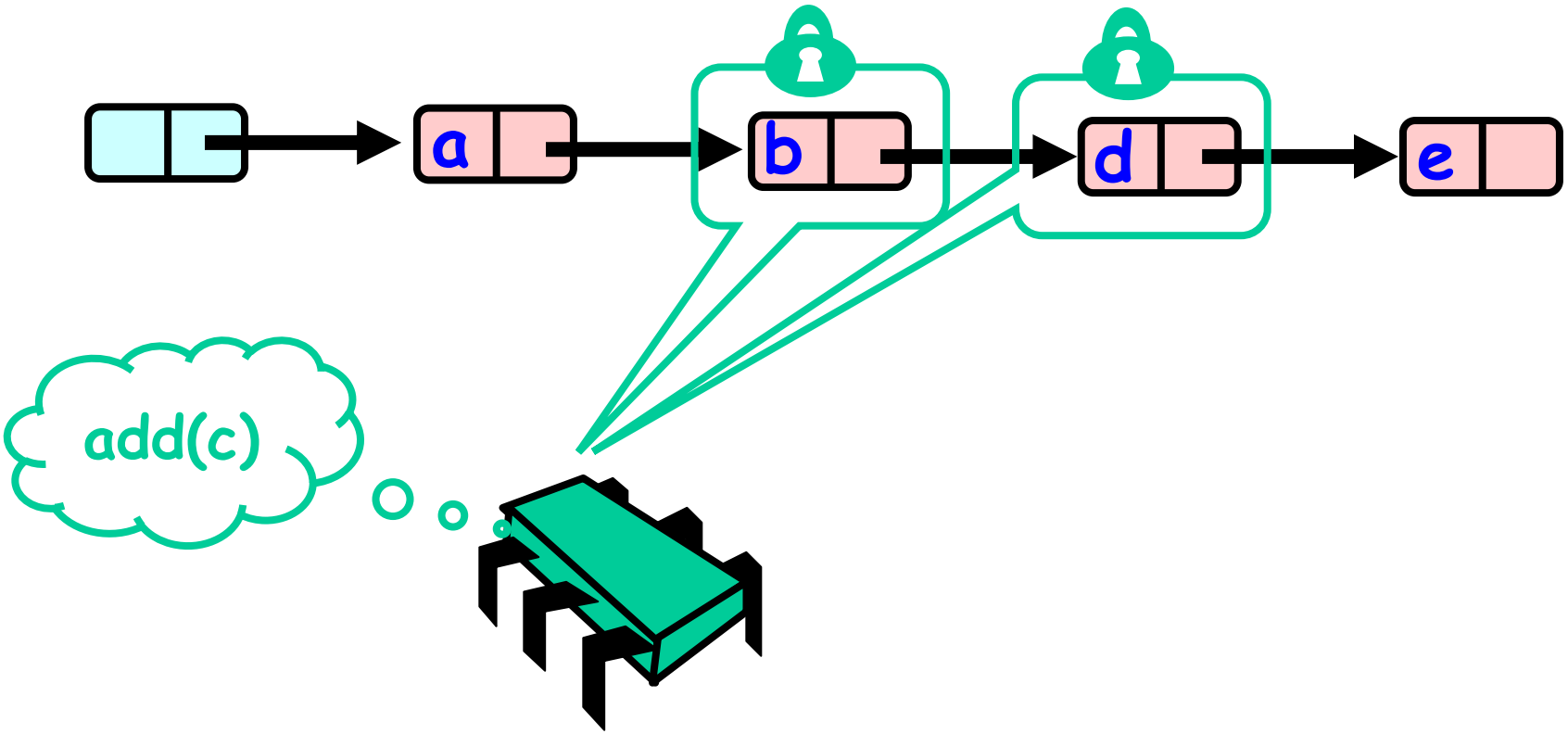
Optimistic: Traverse without Locking



Optimistic: Lock and Load



What Can Possibly Go Wrong?



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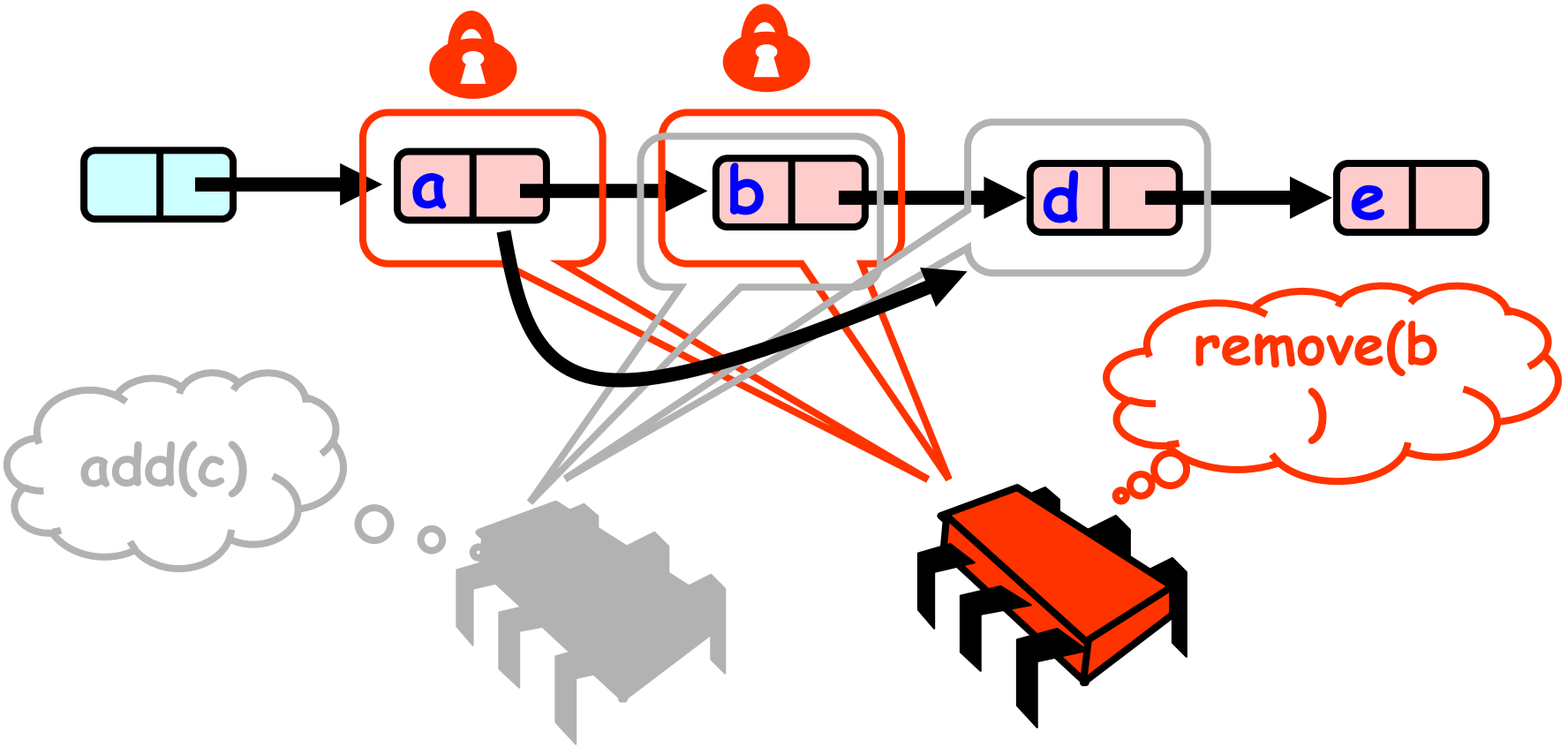
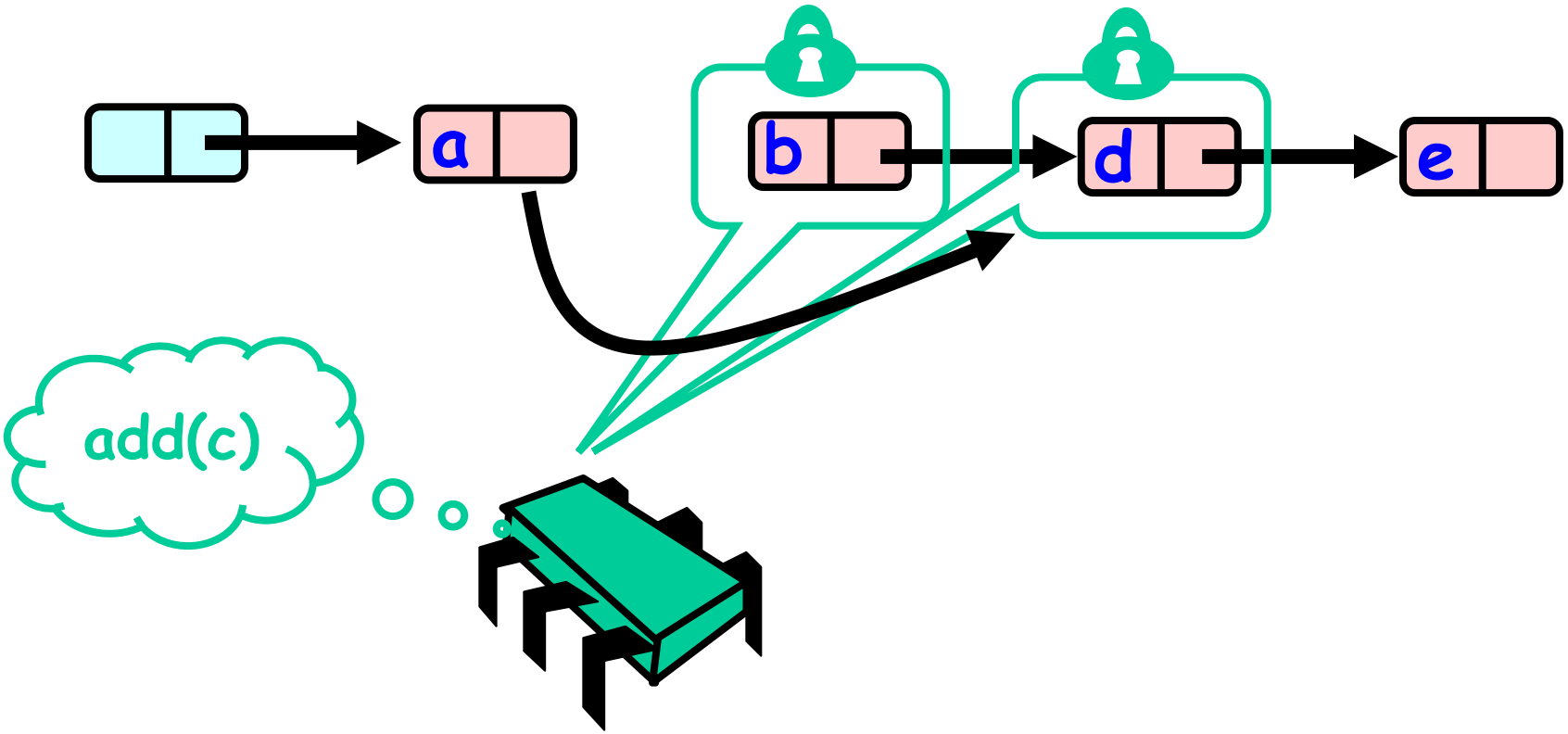
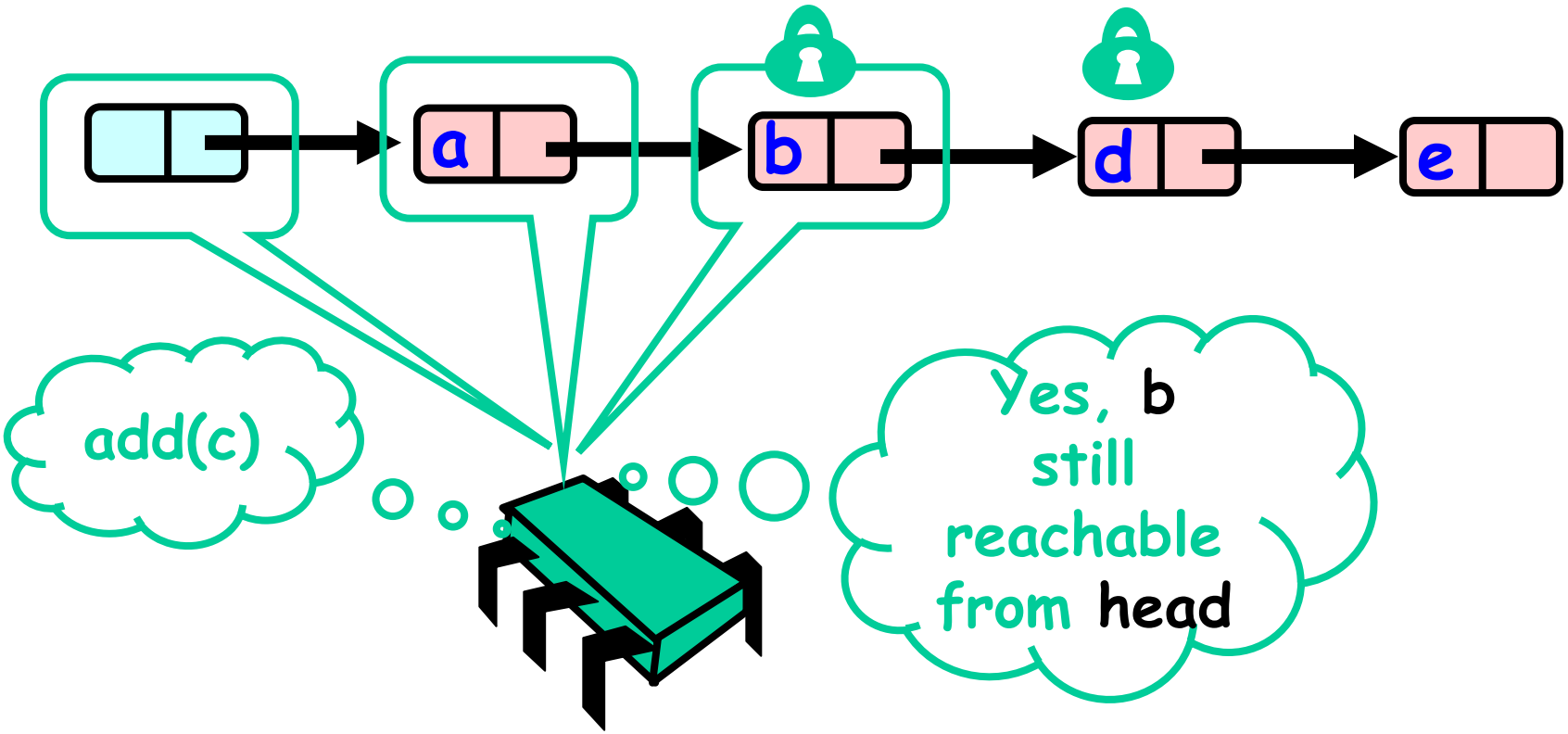


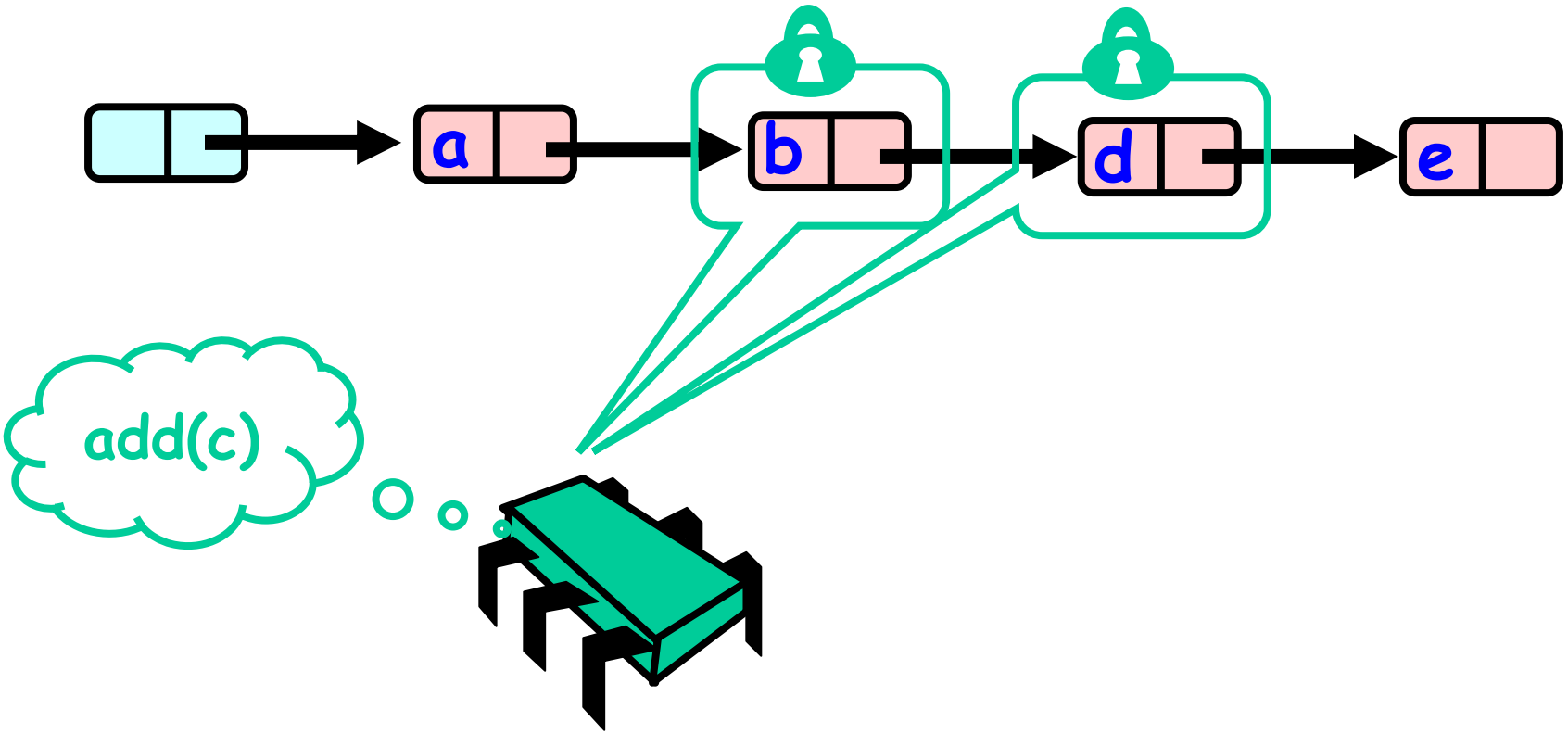
What Can Possibly Go Wrong?



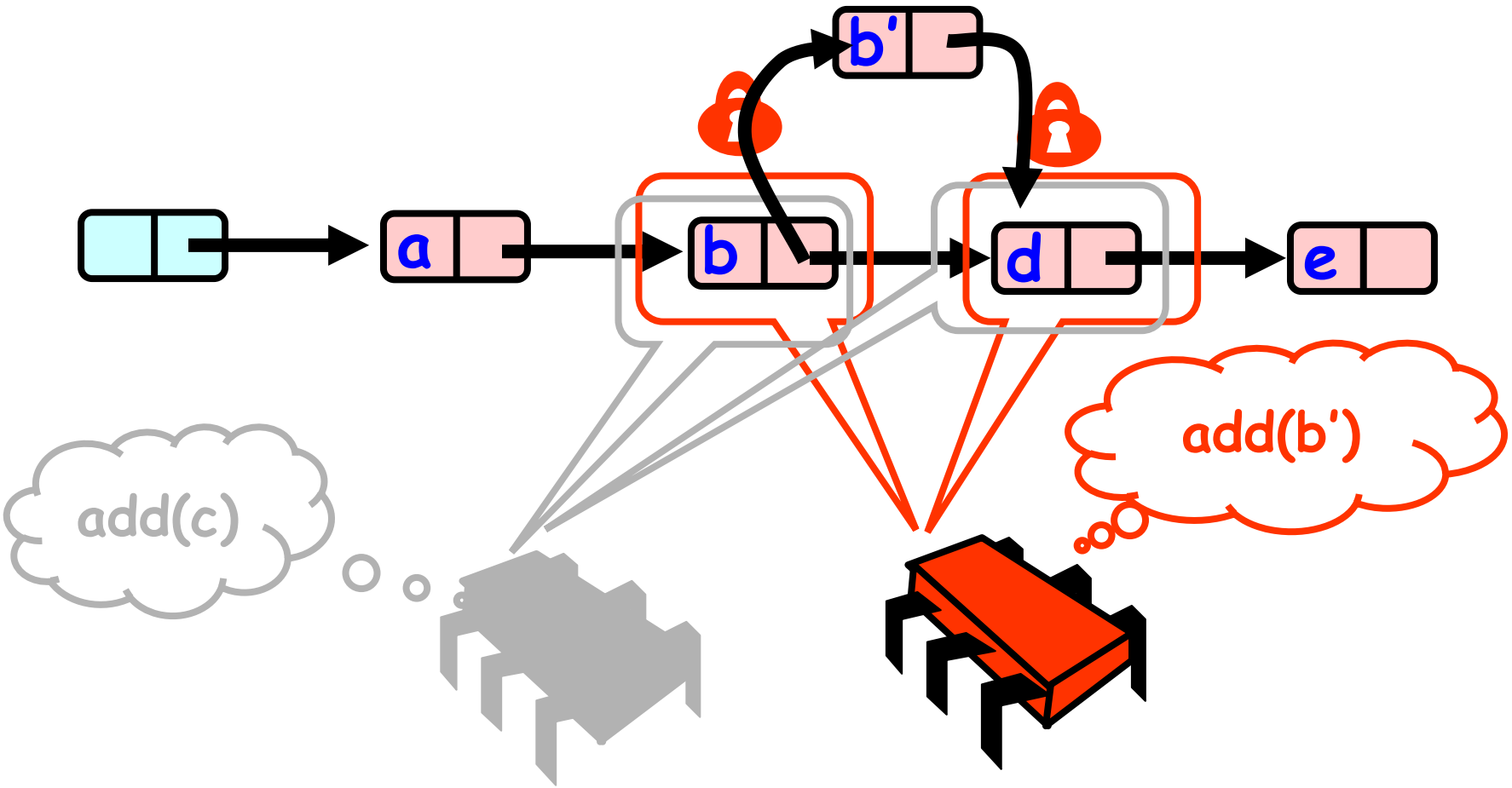
Validate (1)



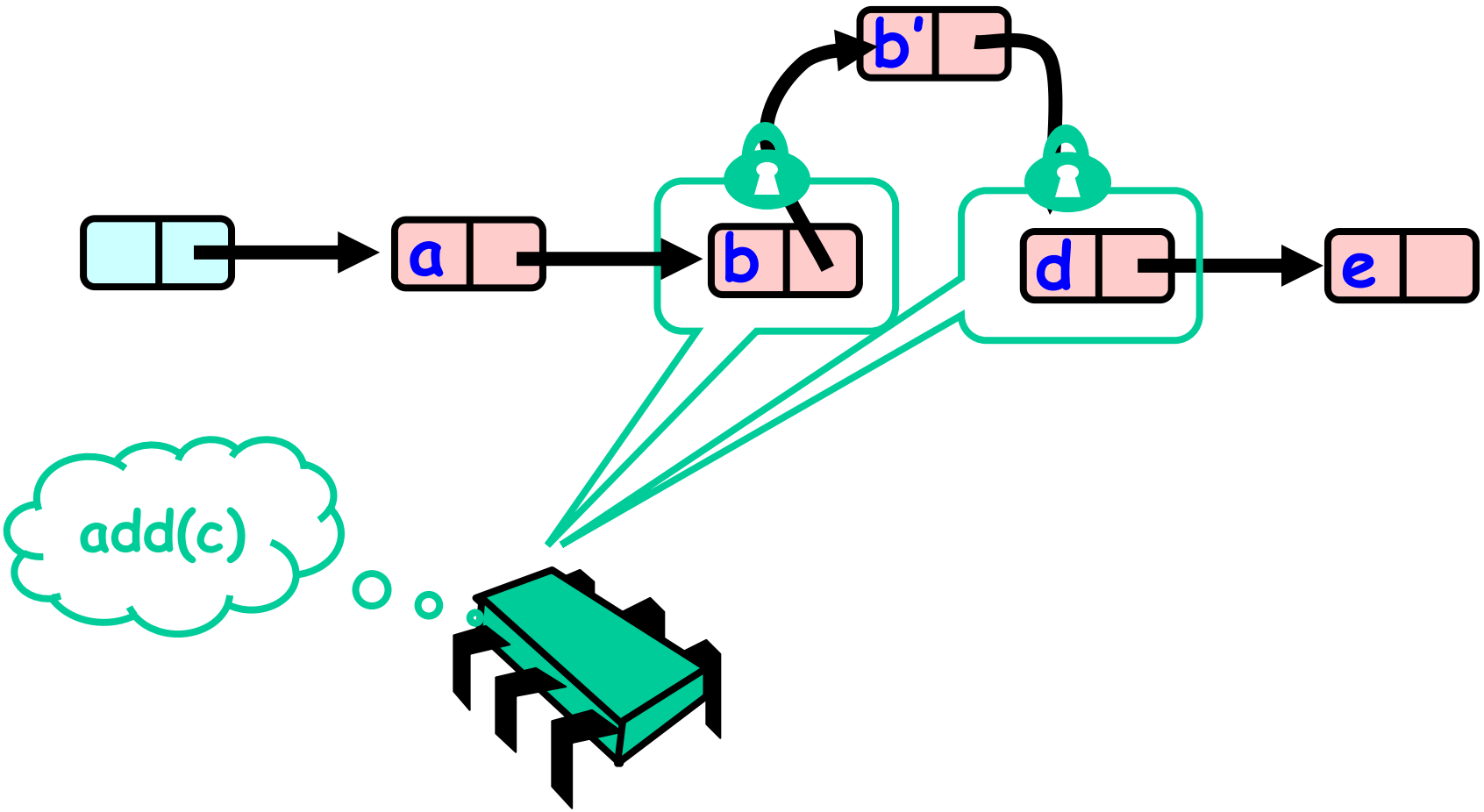
What Else Can Go Wrong?



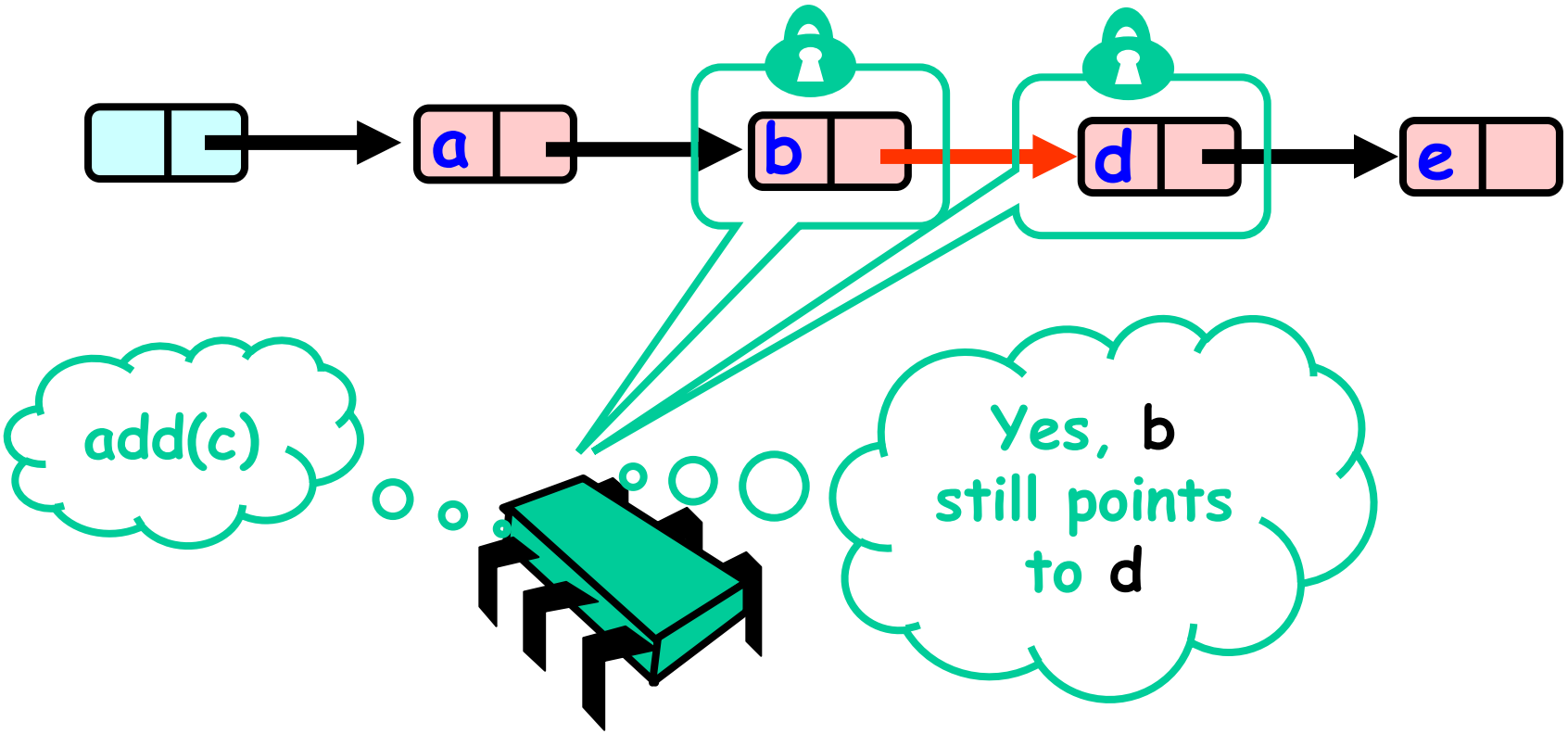
What Else Can Go Wrong?



What Else Can Go Wrong?



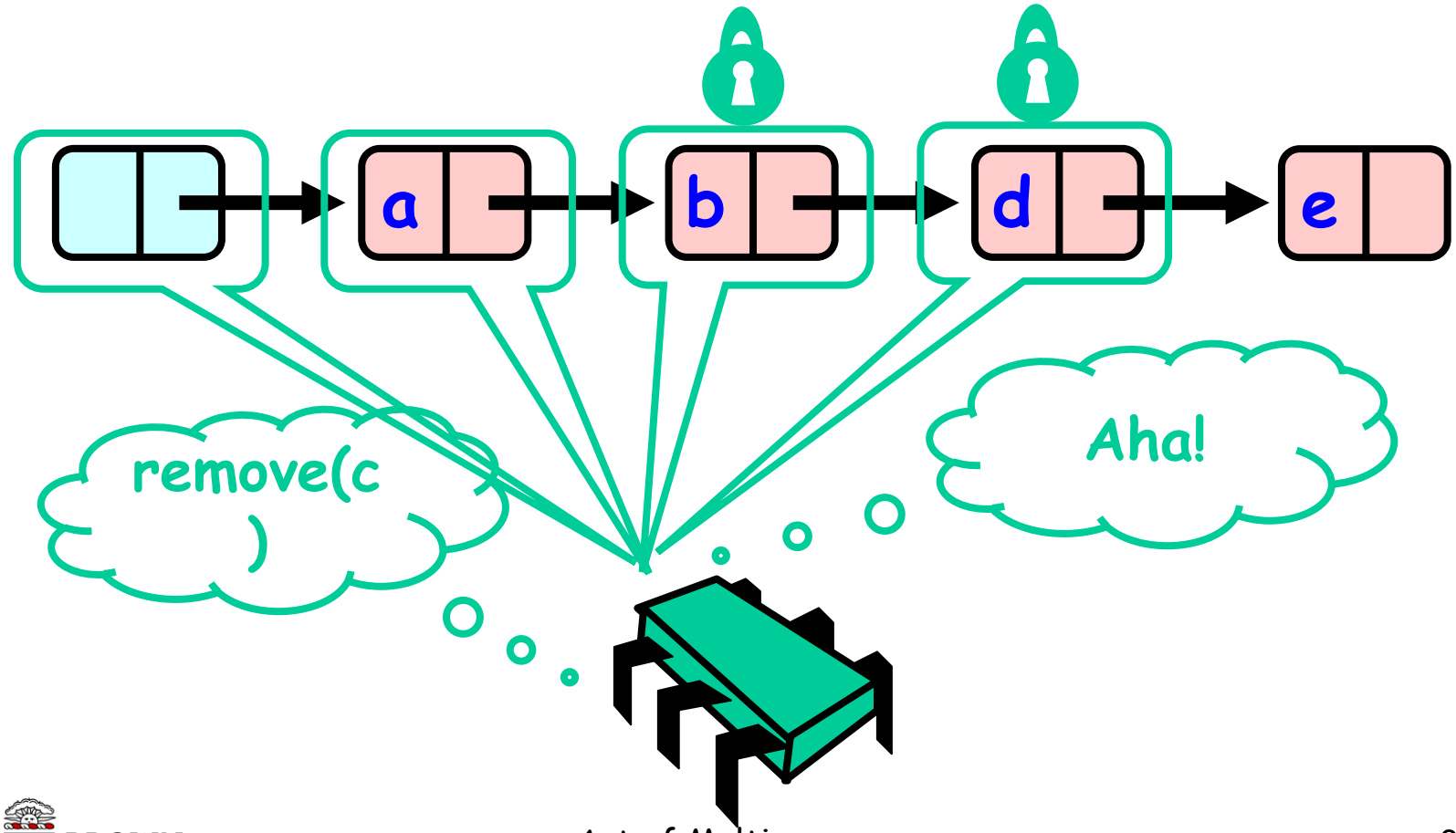
Optimistic: Validate(2)



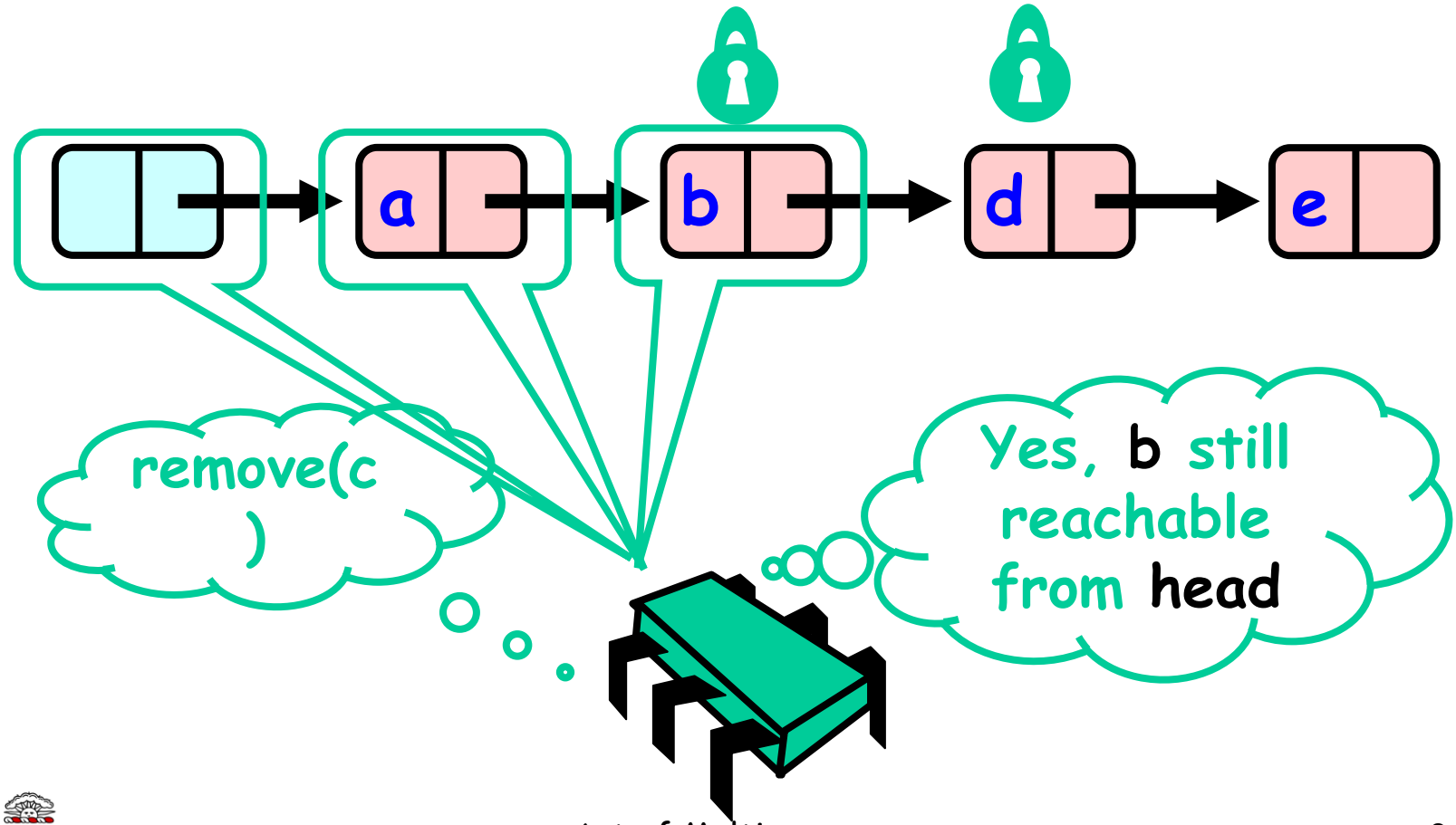
Invariants

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

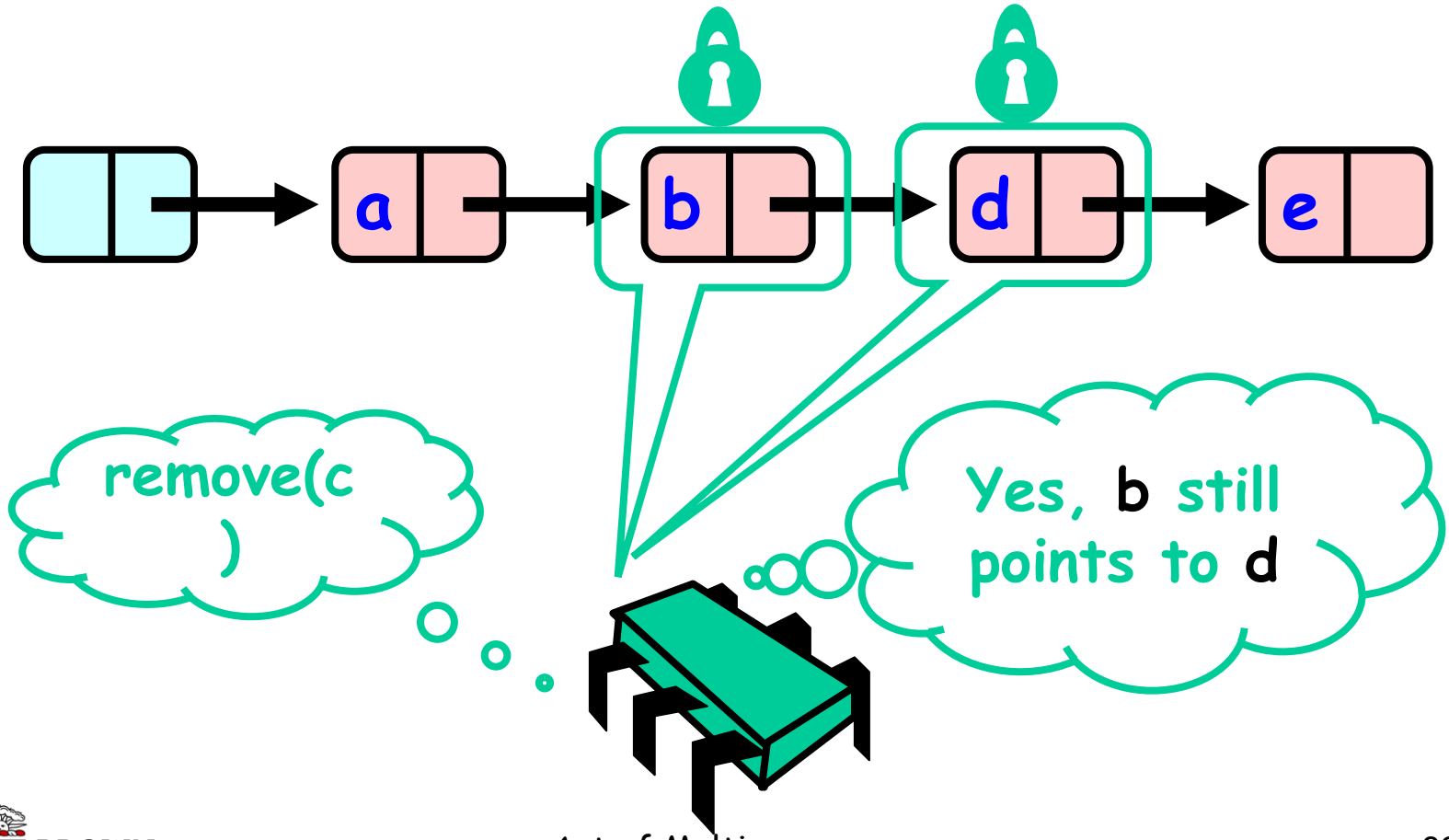
Removing an Absent Node



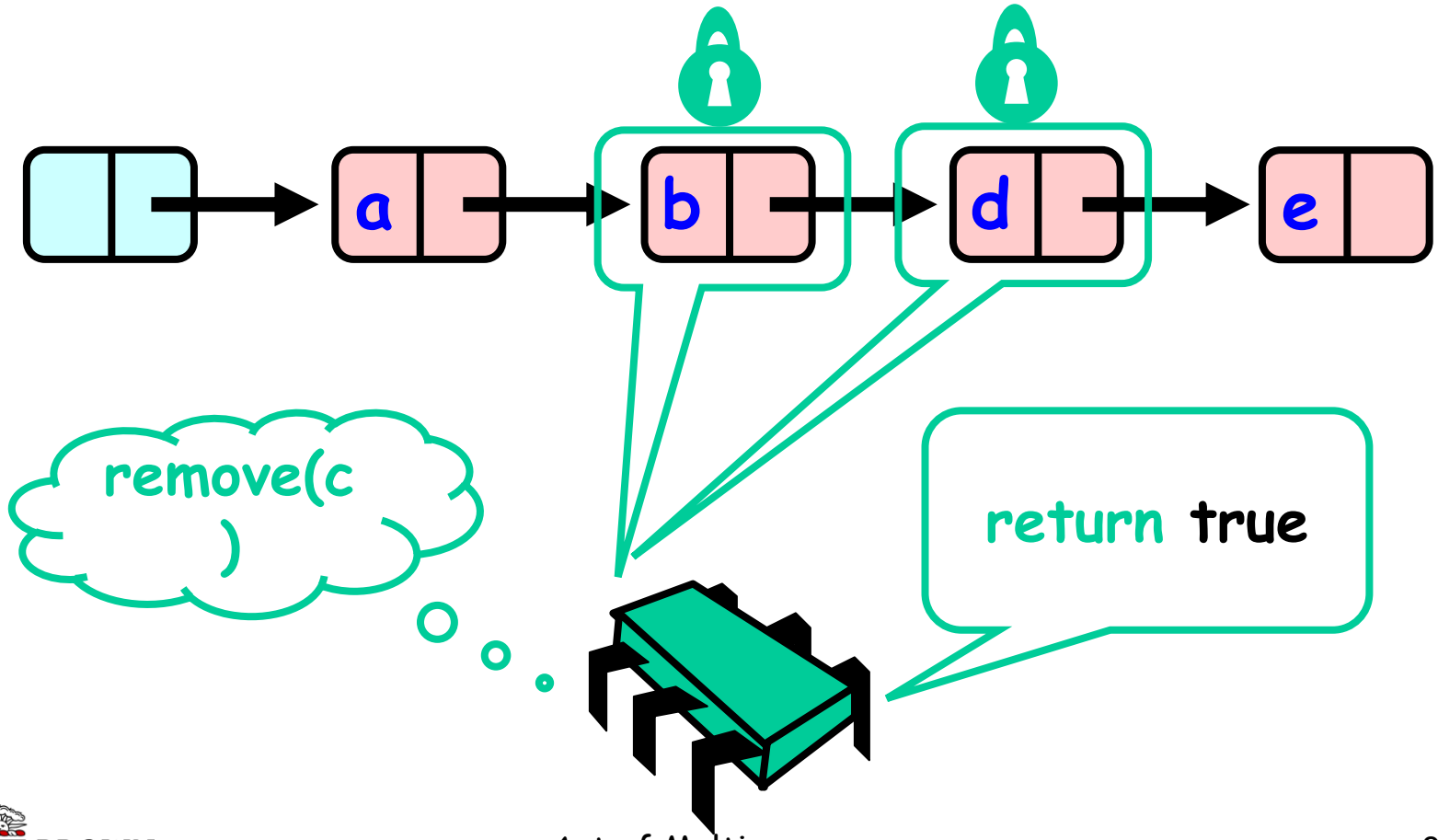
Validate (1)



Validate (2)



OK Computer



Optimistic List

- Limited hot-spots
  - Targets of add(), remove(), contains()
  - No contention on traversals
    - Traversals are **wait-free**

So Far, So Good

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

Evaluation

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

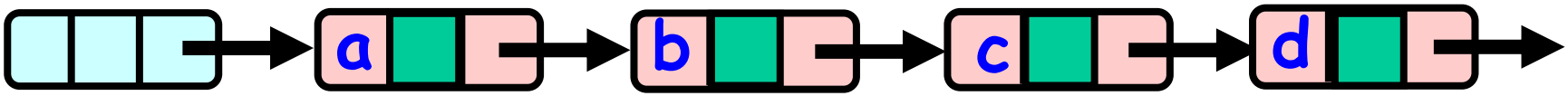
Lazy List

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

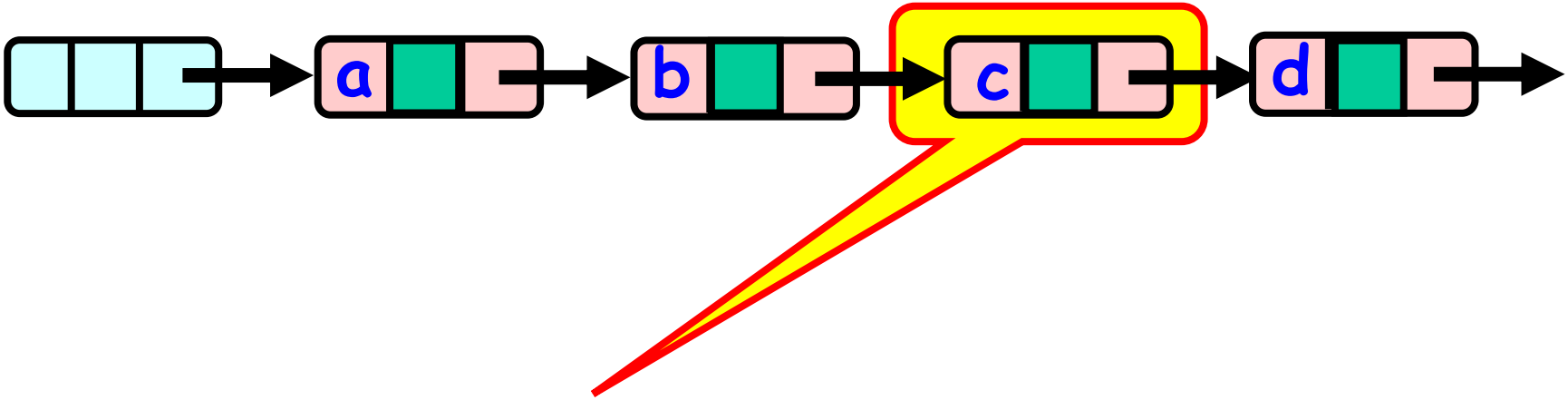
Lazy List

- **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)

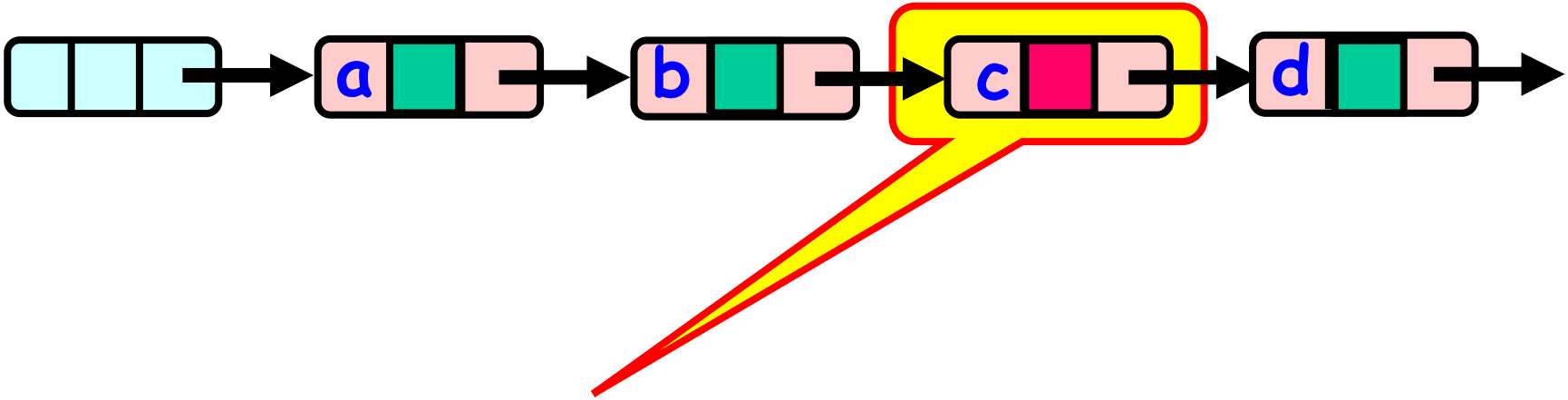
Lazy Removal



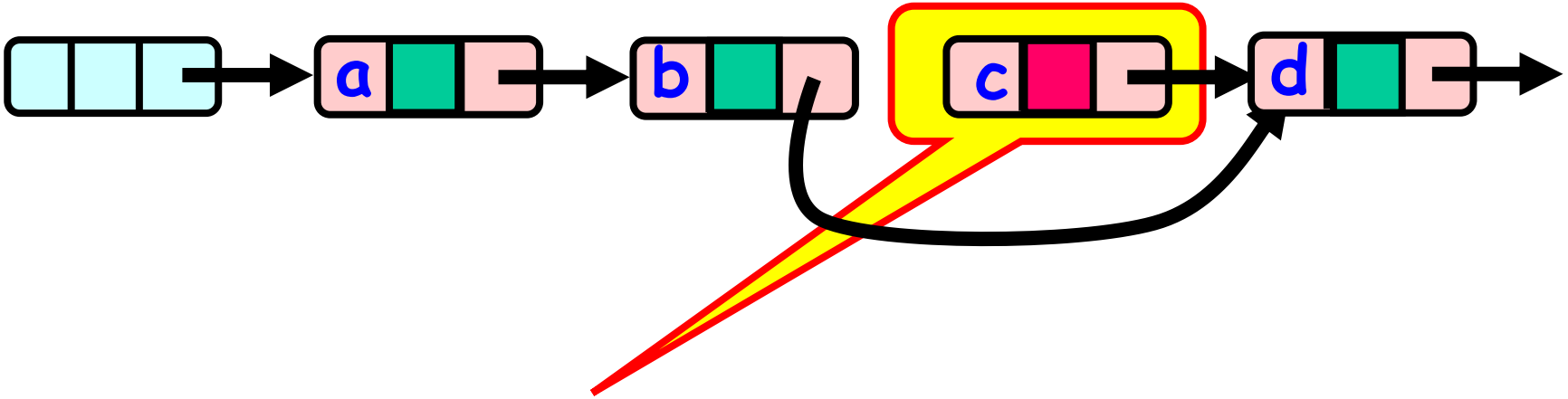
Lazy Removal



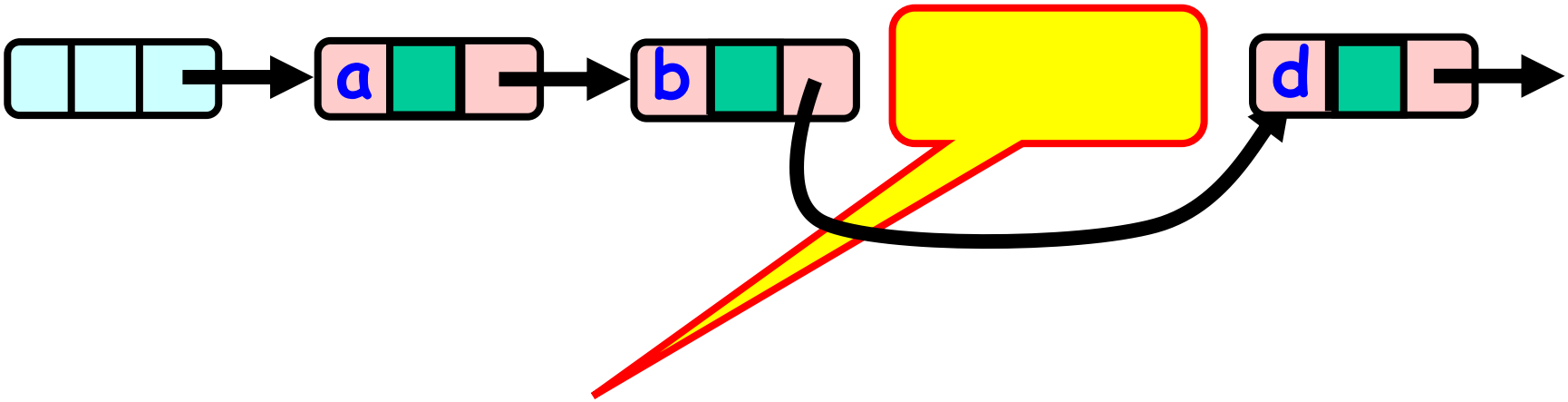
Lazy Removal



Lazy Removal



Lazy Removal



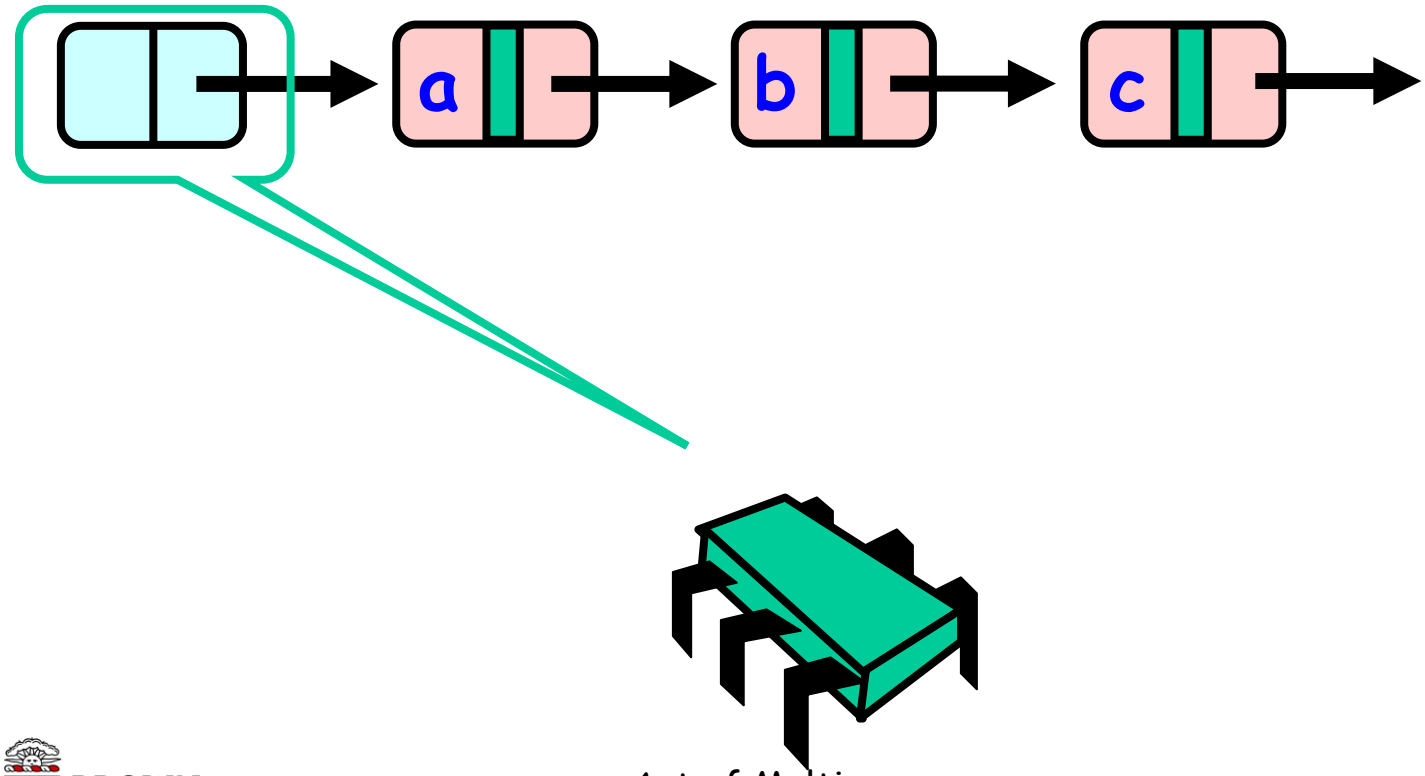
Lazy List

- 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.

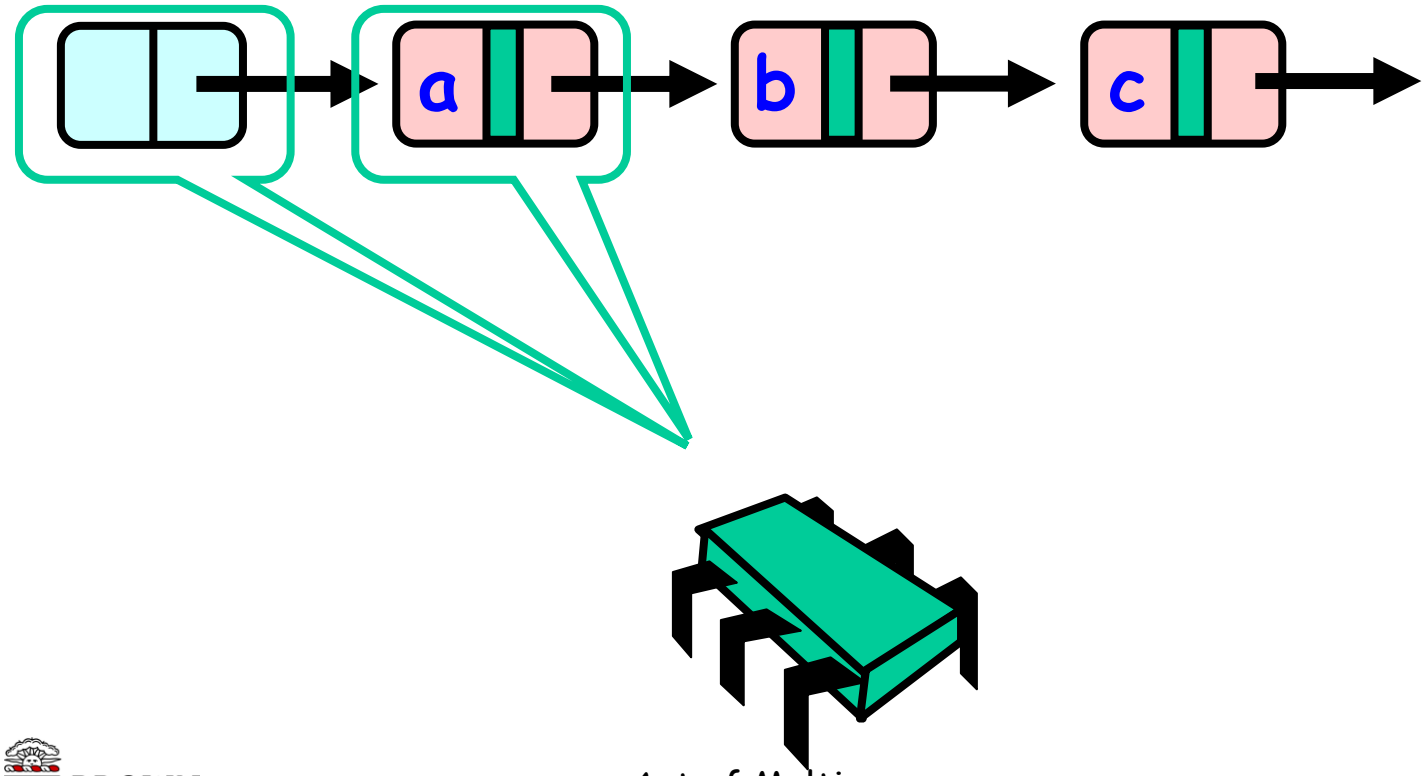
Validation

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

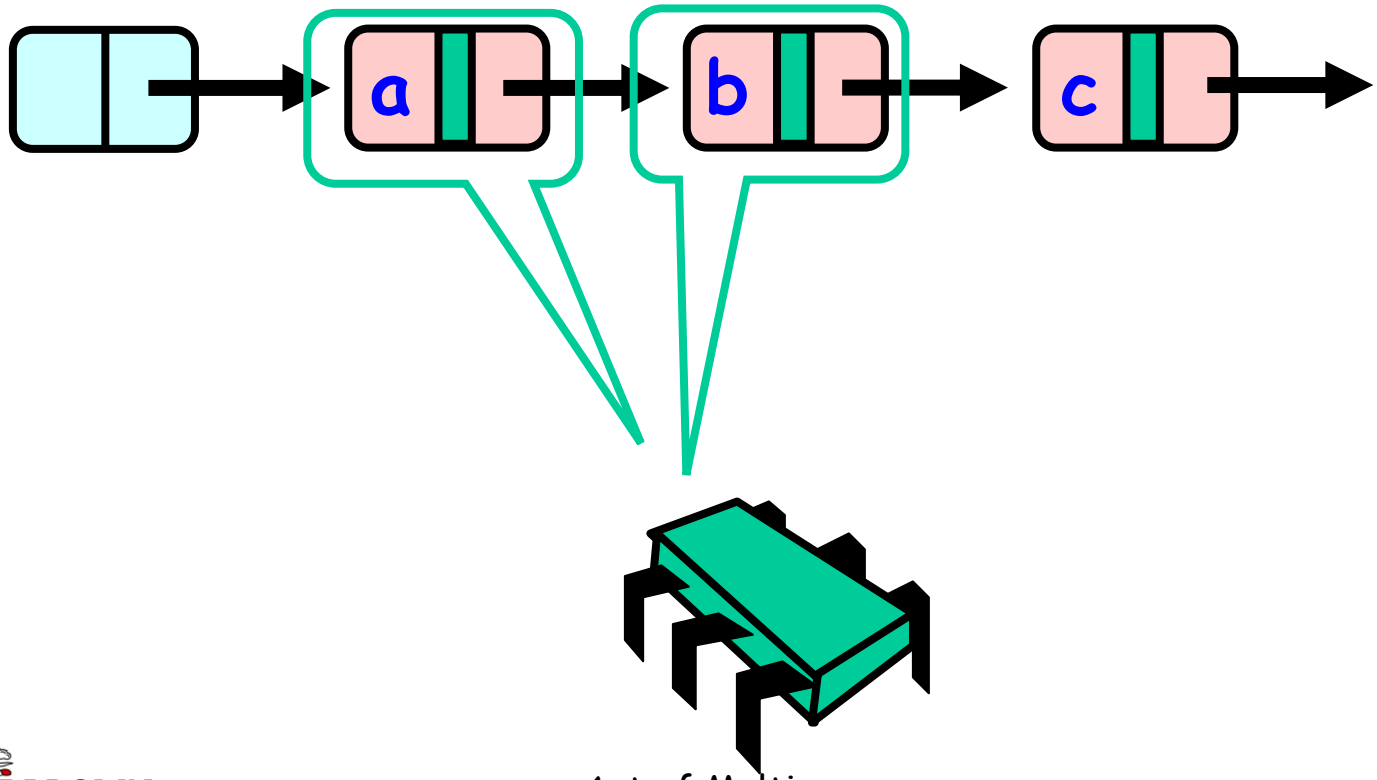
Business as Usual



Business as Usual



Business as Usual



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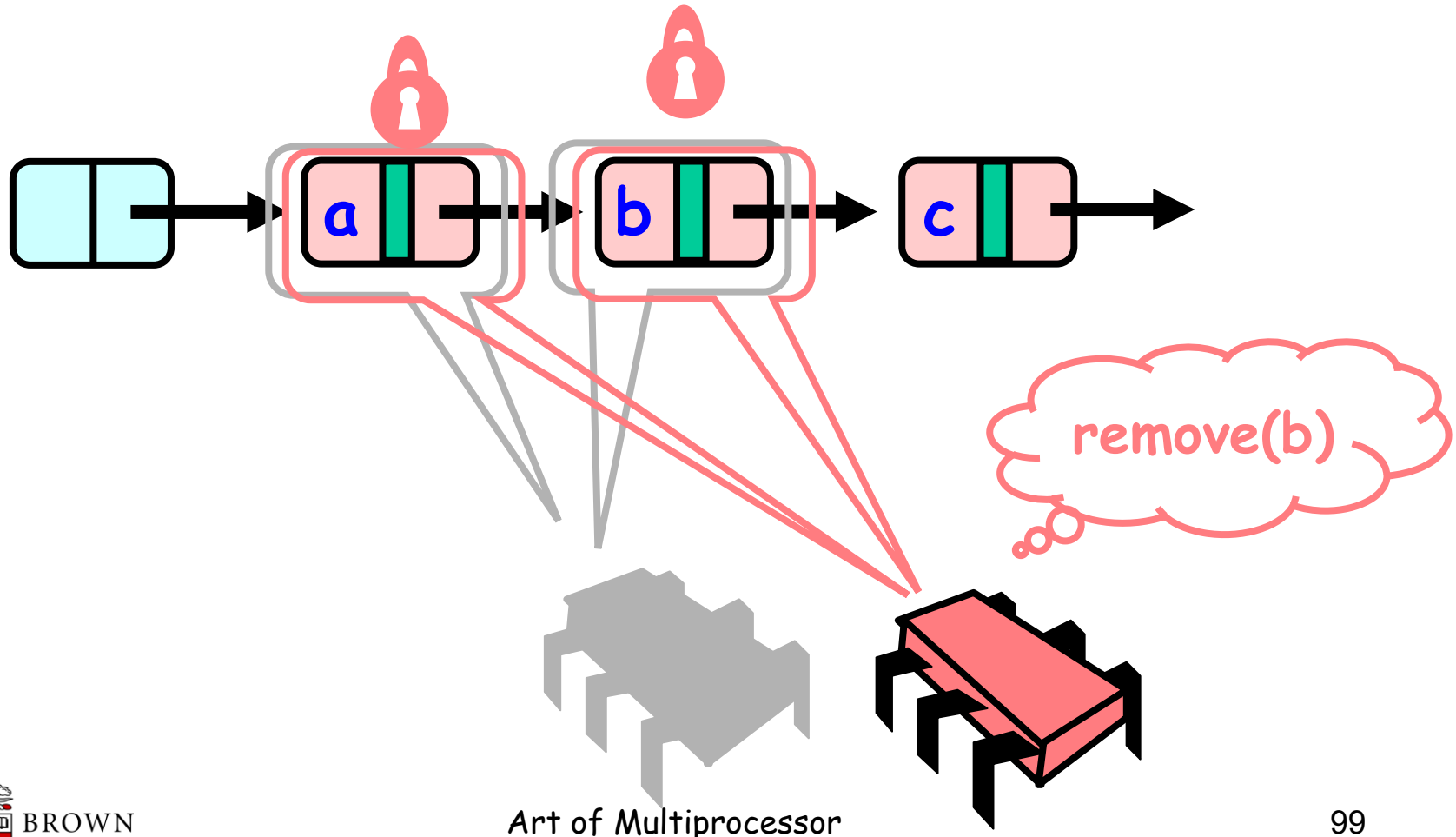
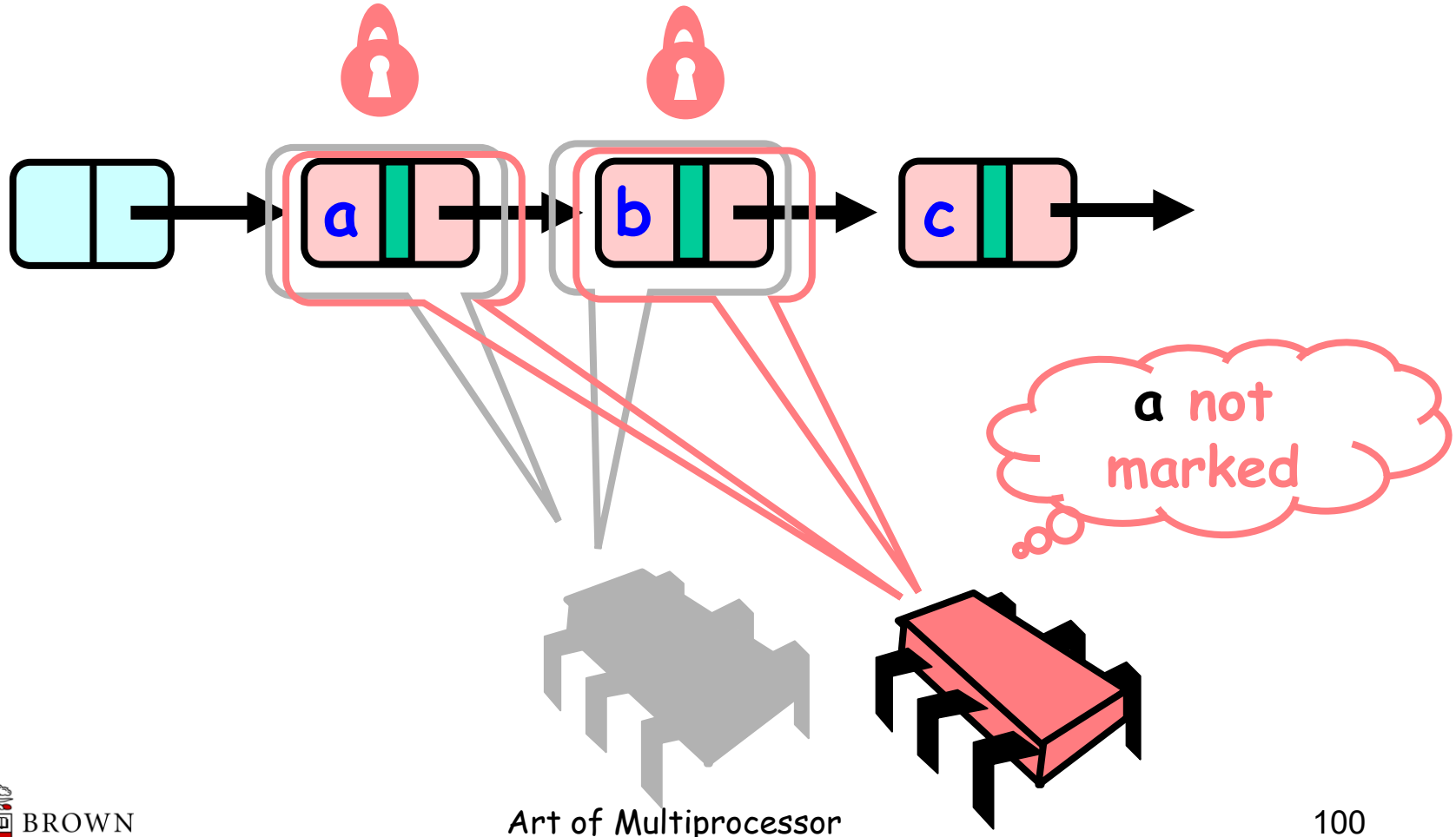
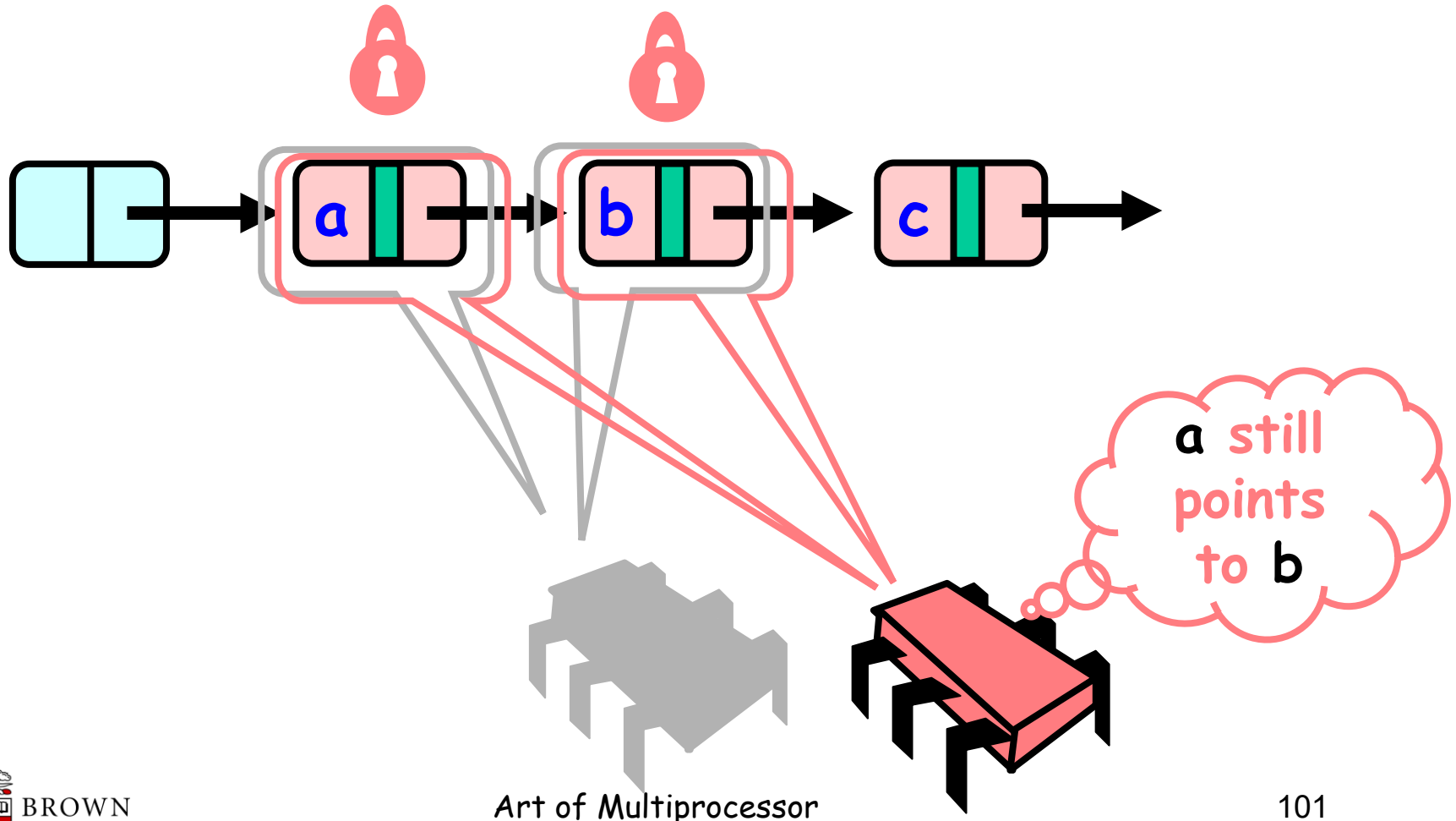


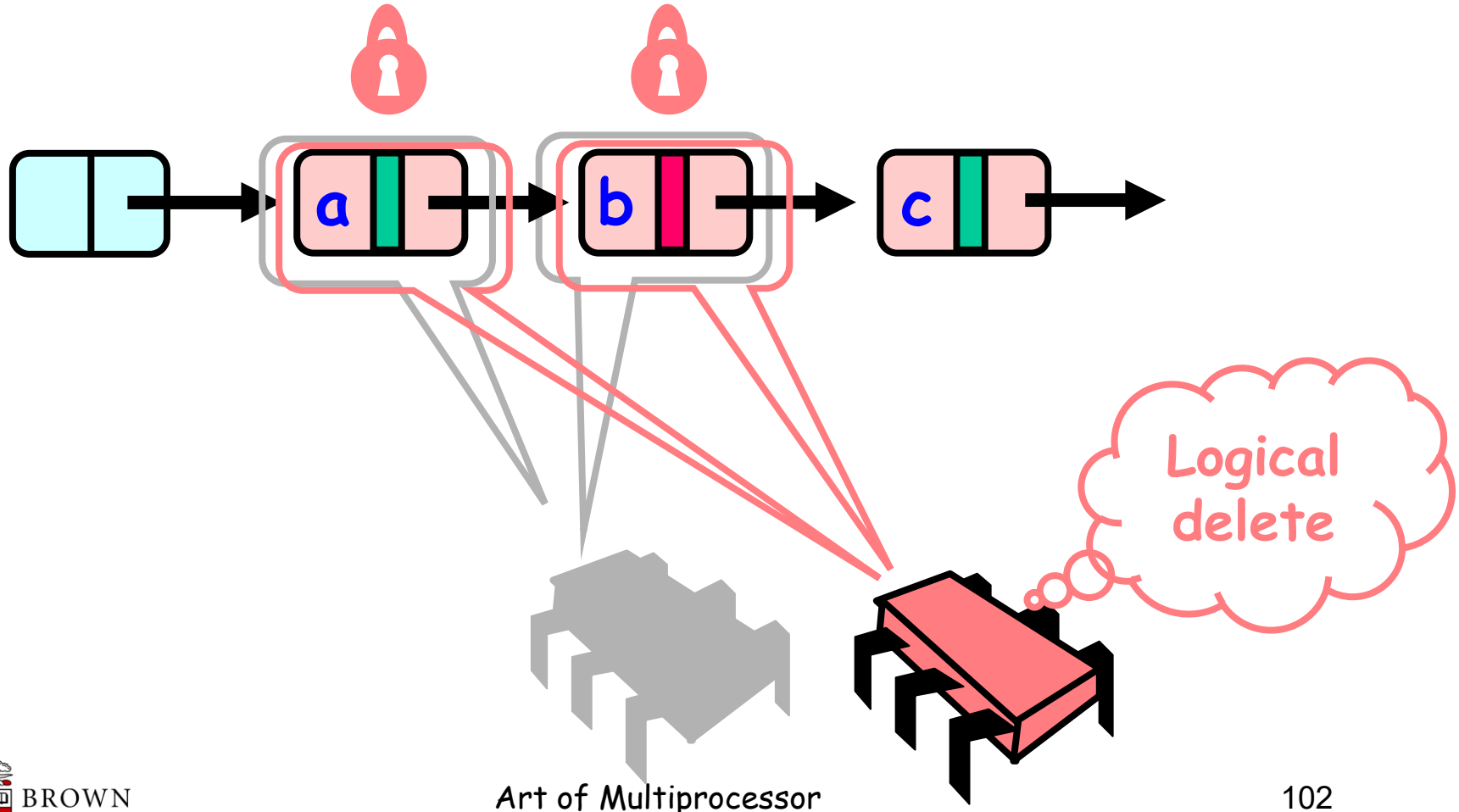
Business as Usual



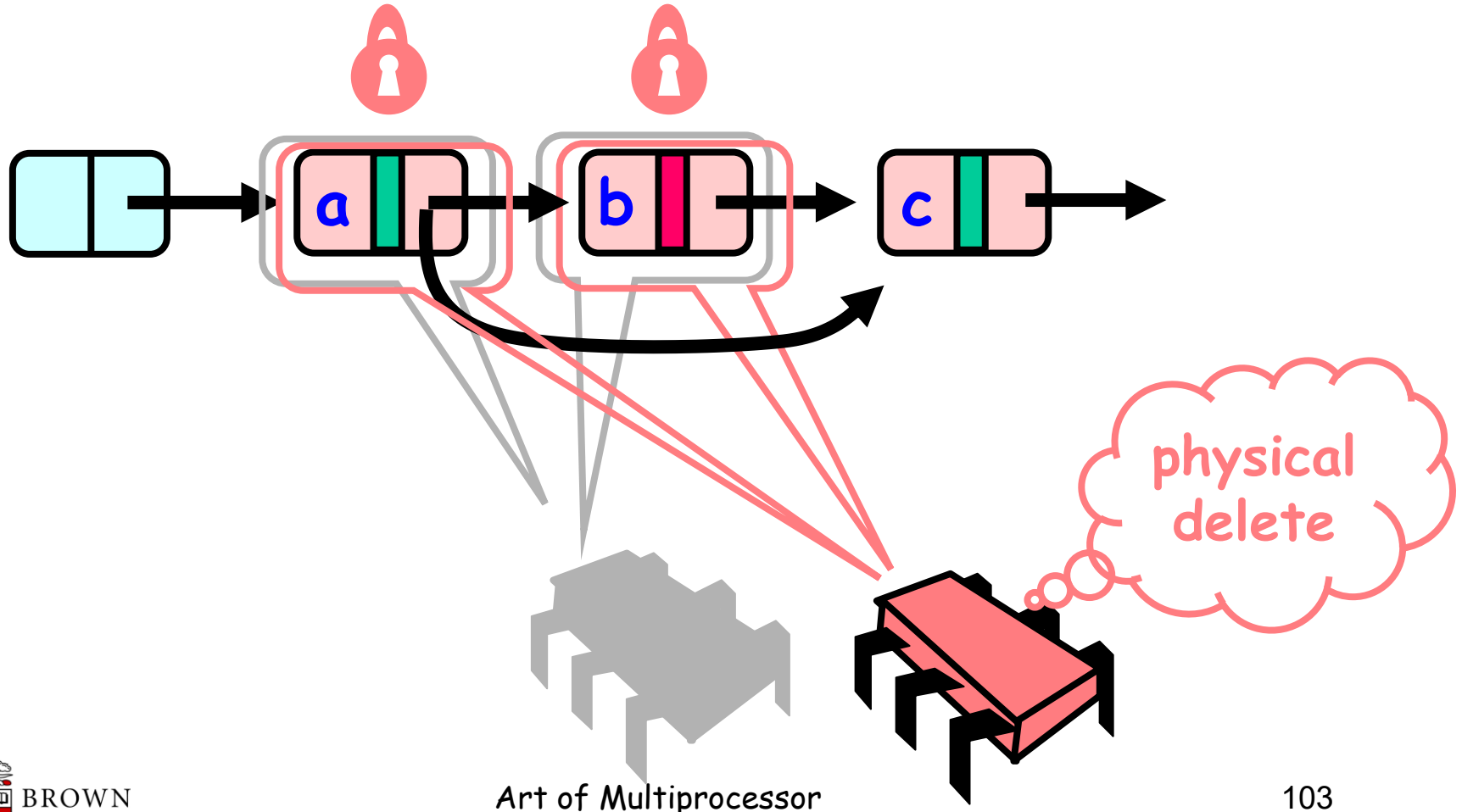
Business as Usual



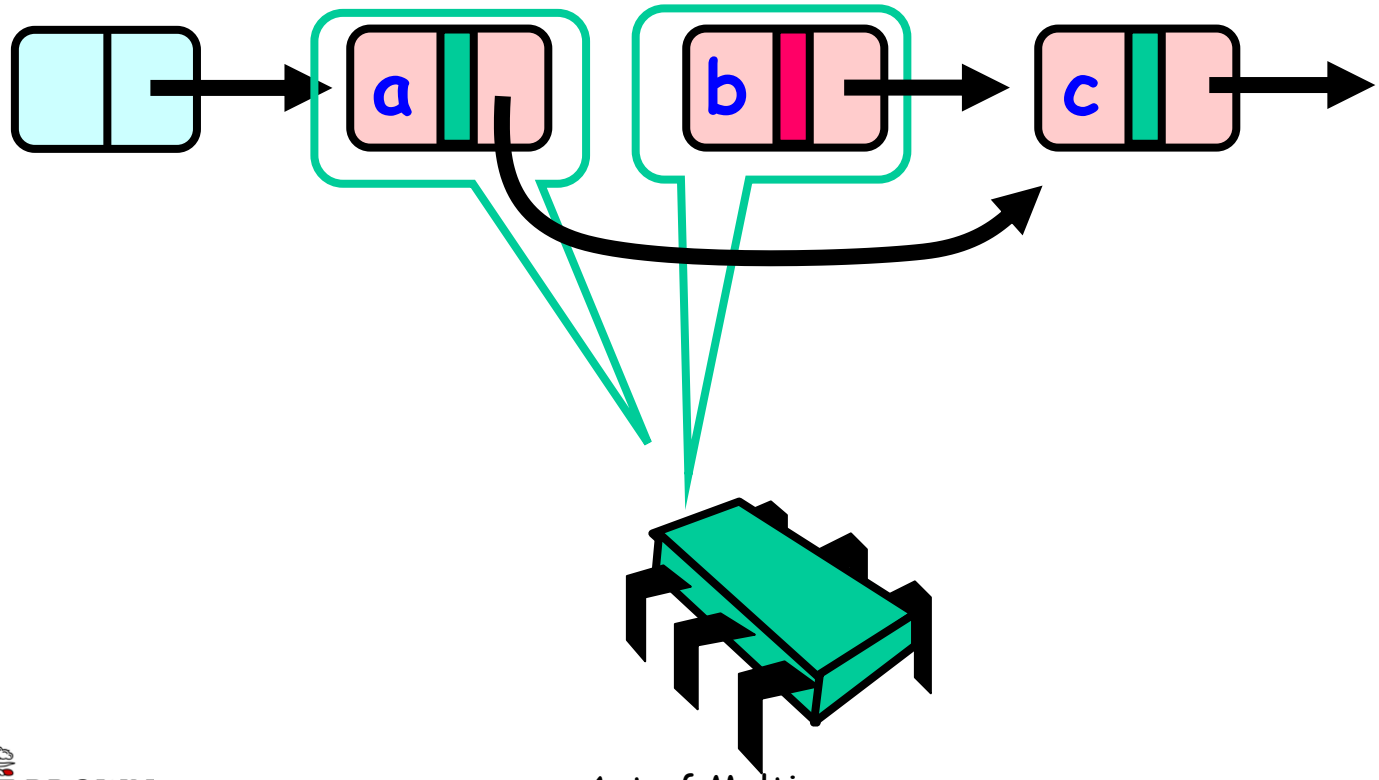
Business as Usual



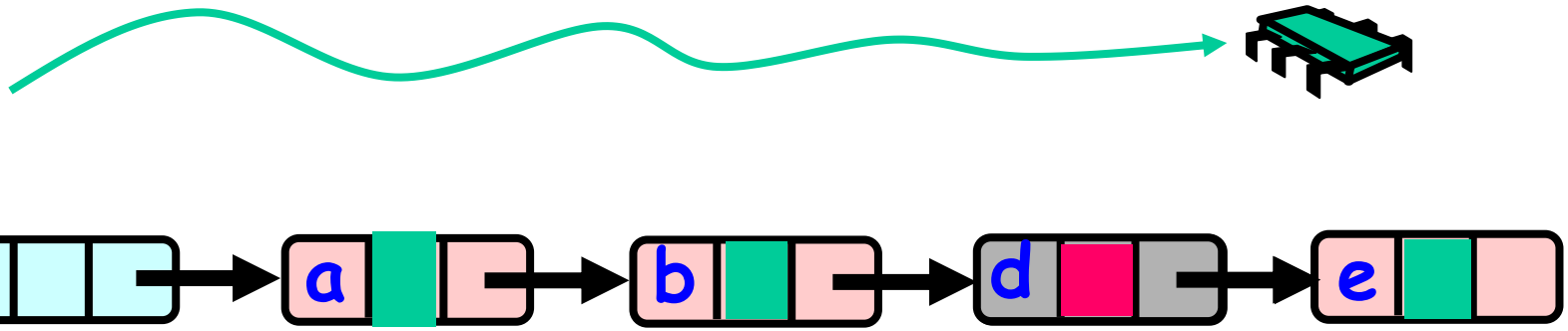
Business as Usual



Business as Usual



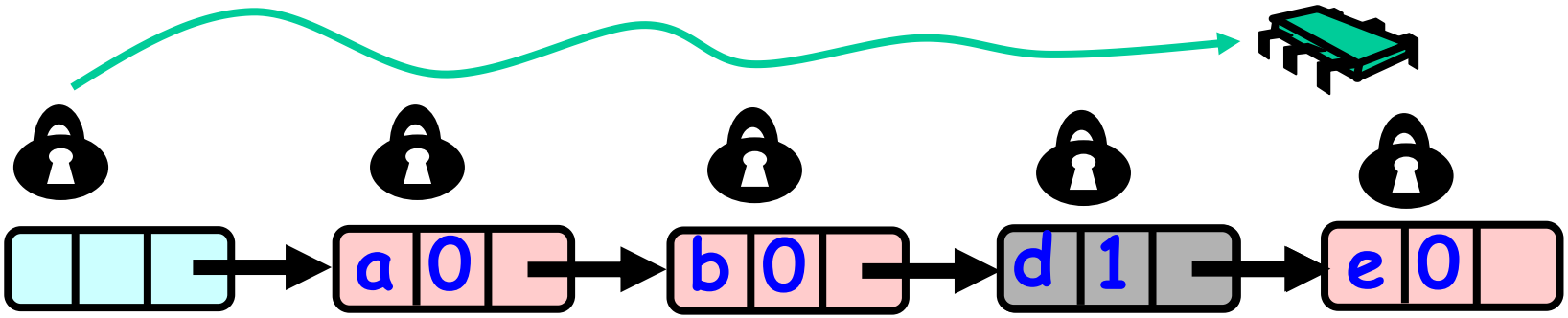
Wait-free Contains – No need to lock in Contains



Use Mark bit + Fact that List is ordered

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 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 …
    - Software error, …
  - Everyone else using that lock is stuck!

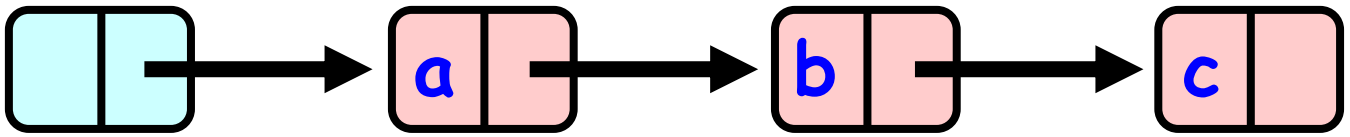
Lock-Free Data Structures

- No matter what …
  - Some thread will complete method call
  - Even if others halt at malicious times
  - Weaker than wait-free, yet
- Implies that
  - You can't use locks (why?)
  - Um, that's why they call it lock-free

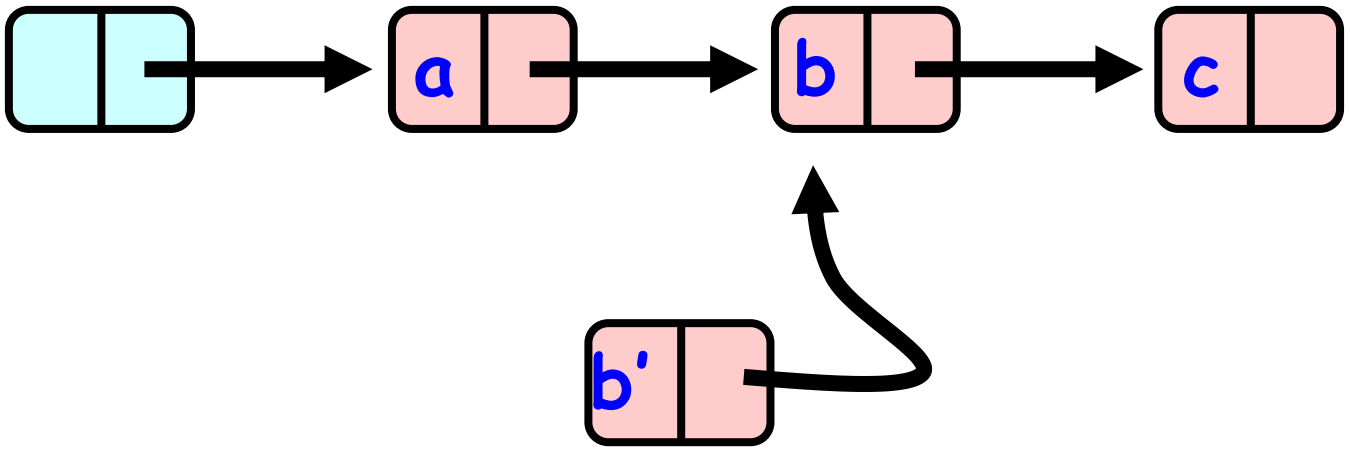
Lock-free Lists

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

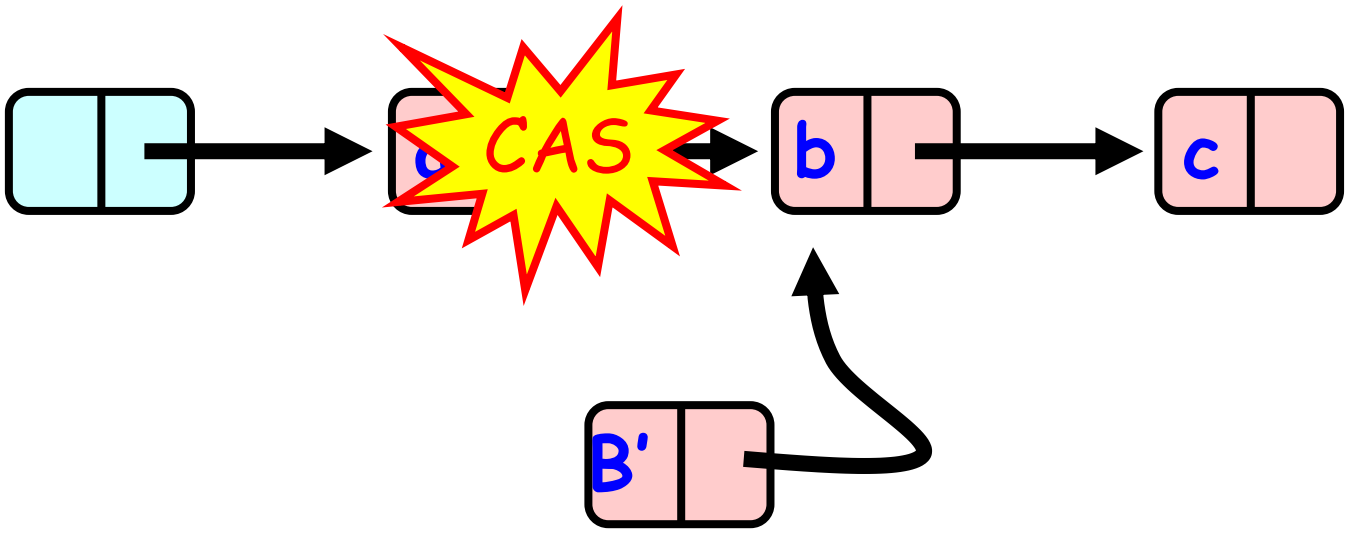
Adding a Node



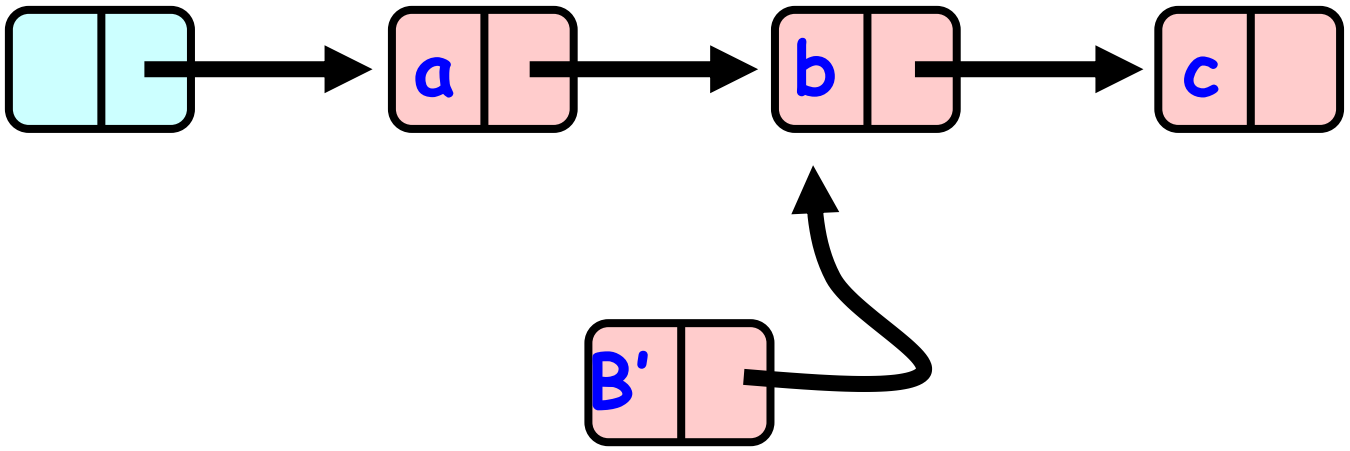
Adding a Node



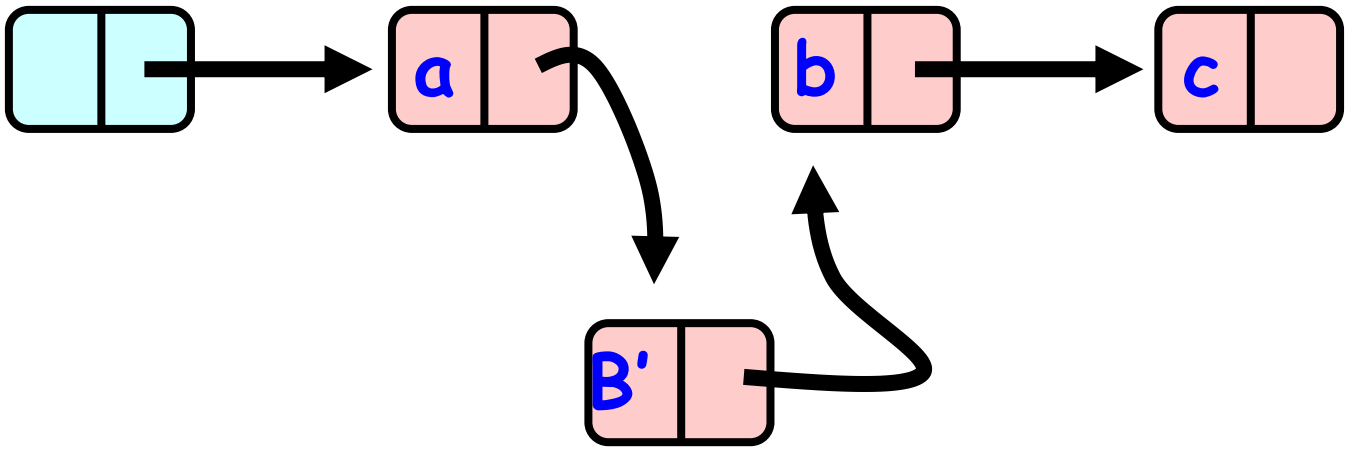
Adding a Node



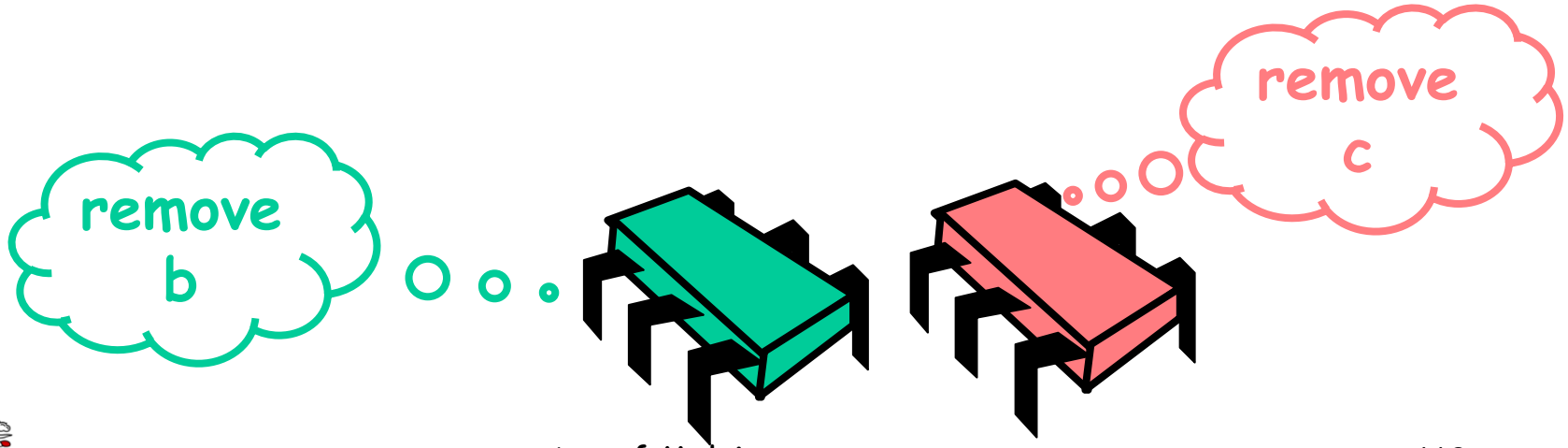
Adding a Node



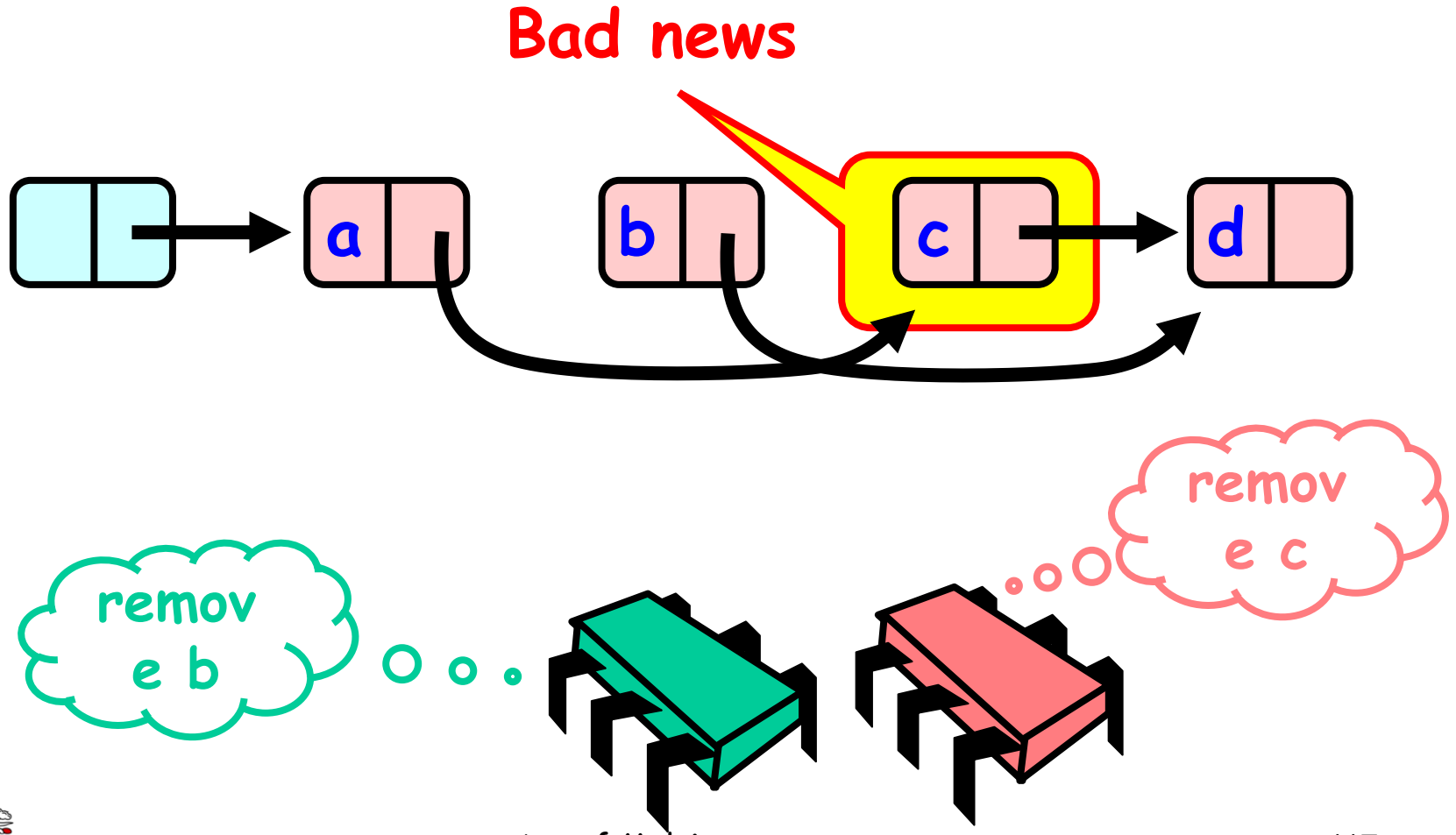
Adding a Node



Removing a Node



Look Familiar?



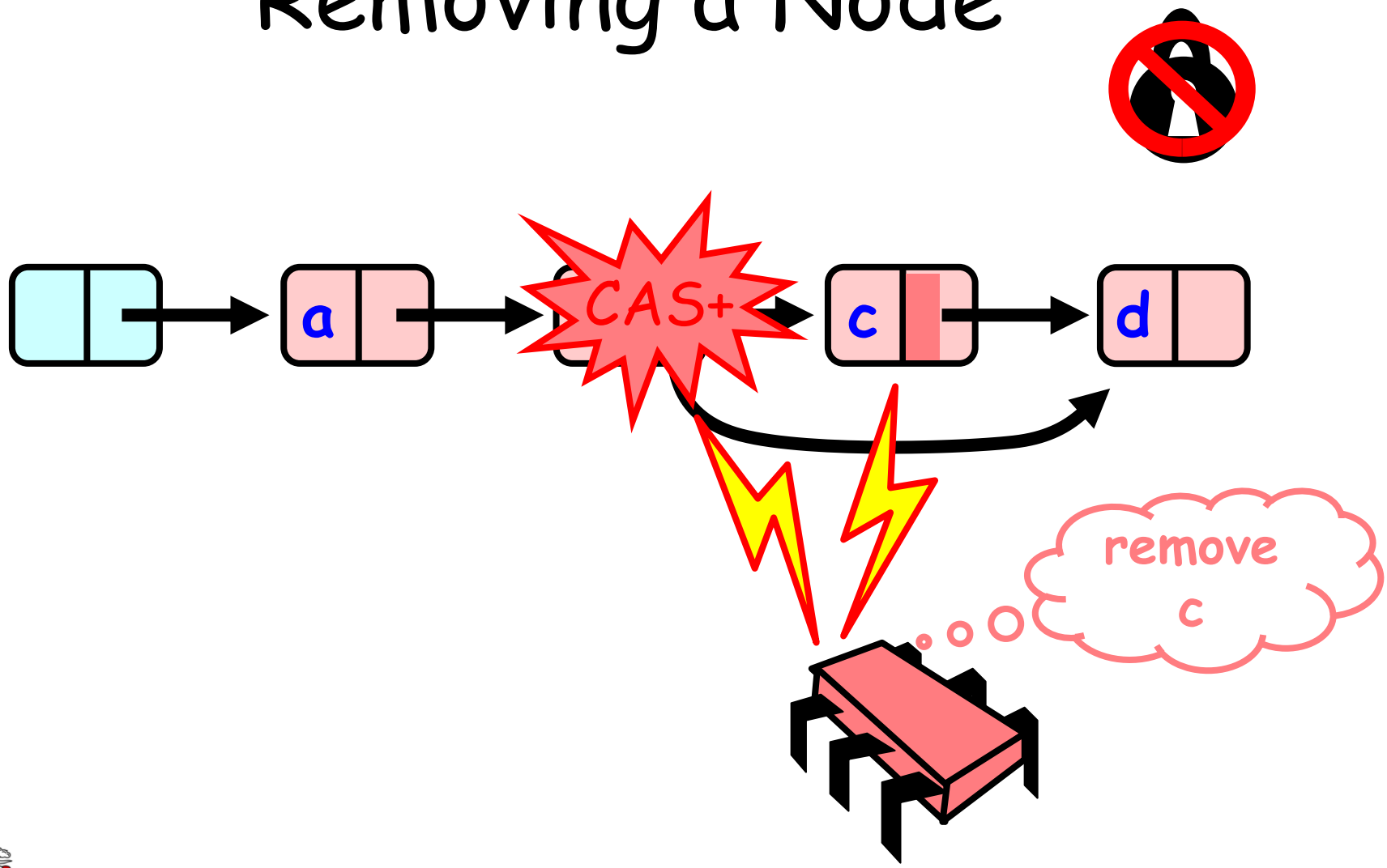
Problem

- Method updates node's next field
- After node has been removed

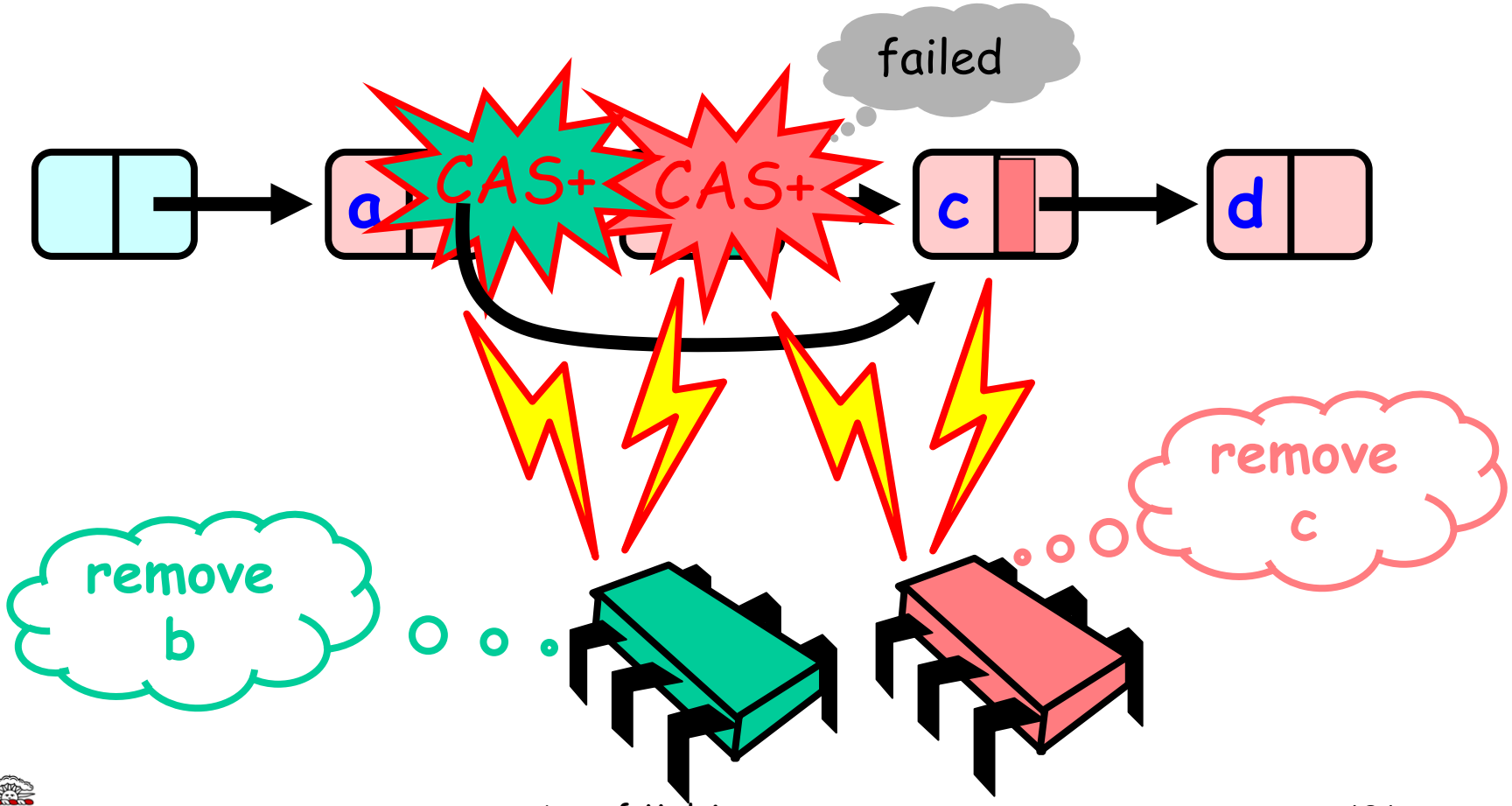
Solution

- Use AtomicMarkableReference (CAS+)
- CAS+: Atomically
  - Check mark bit in next field is unset
  - Check reference unchanged
  - If both true: Swing reference
- Remove in two steps
  - Set mark bit in next field
  - Redirect predecessor's pointer using CAS+

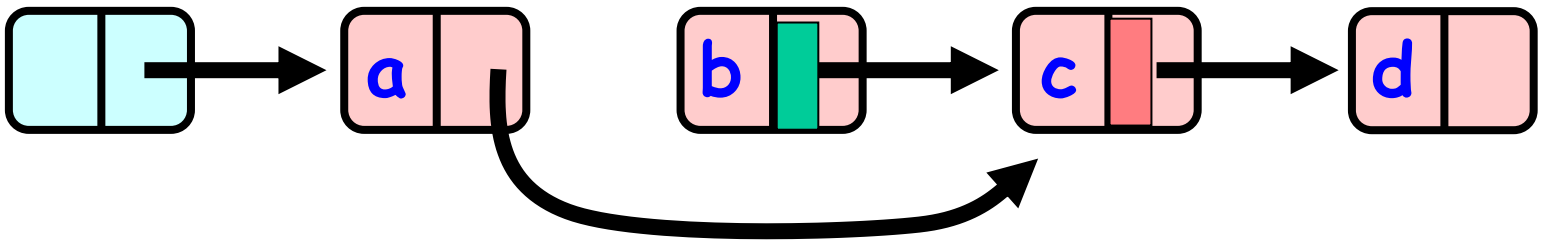
Removing a Node

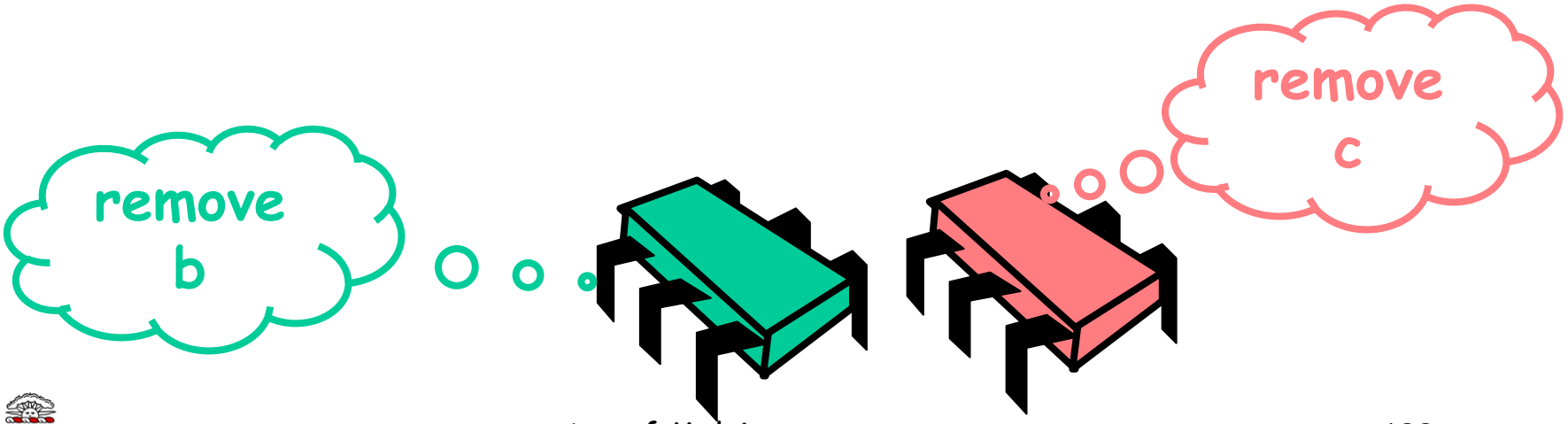


Removing a Node

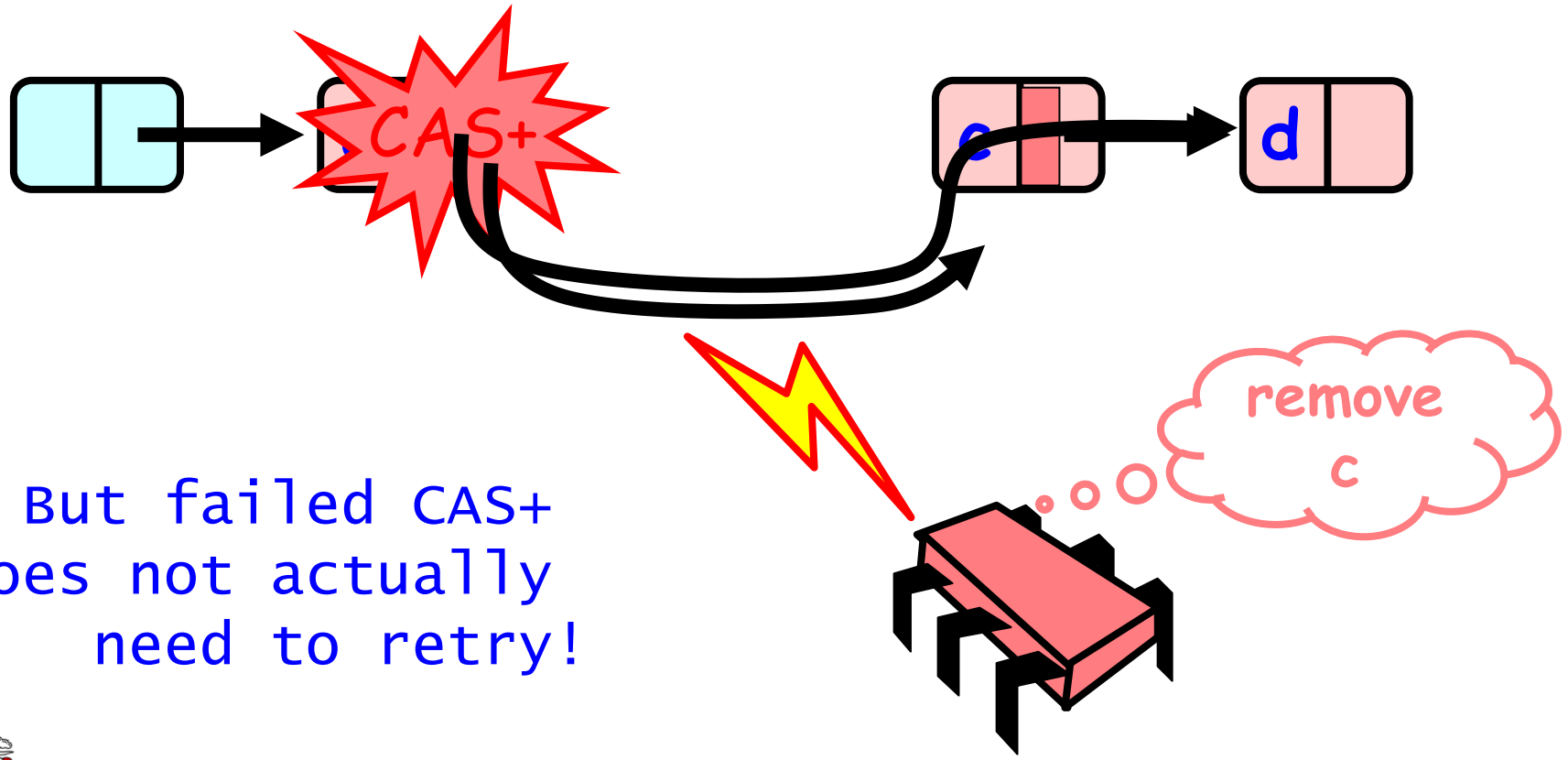


Removing a Node





Removing a Node

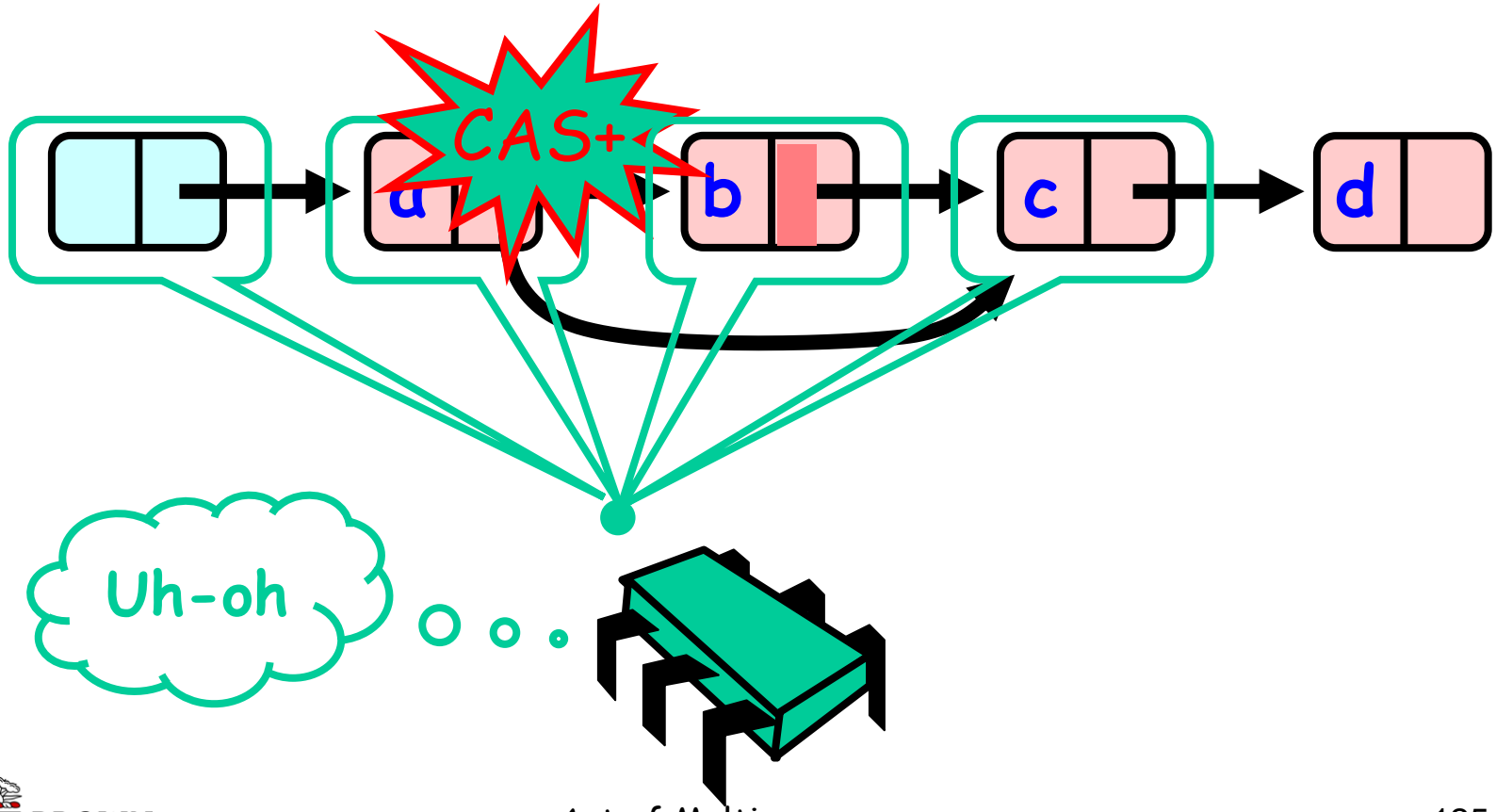


But failed CAS+ does not actually need to retry!

Traversing the List

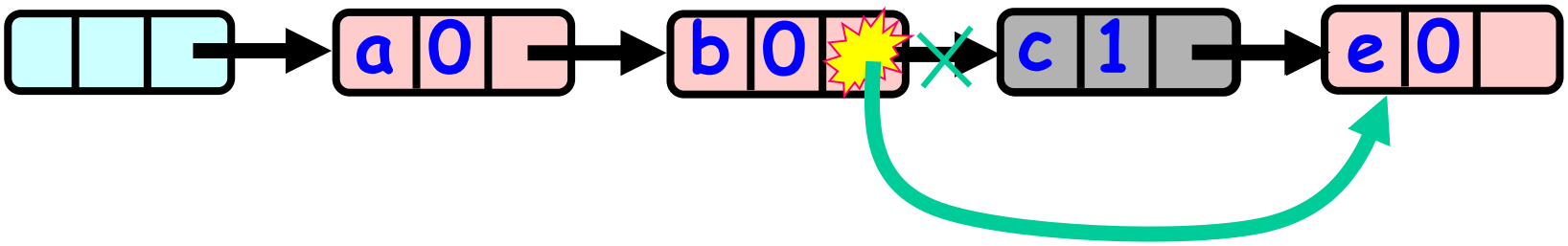
- Q: what do you do when you find a "logically" deleted node in your path?
- A: finish the job.
  - CAS+ the predecessor's next field
  - Proceed (repeat as needed)

Lock-Free Traversal



Lock-free Removal

Logical Removal =
Set Mark Bit

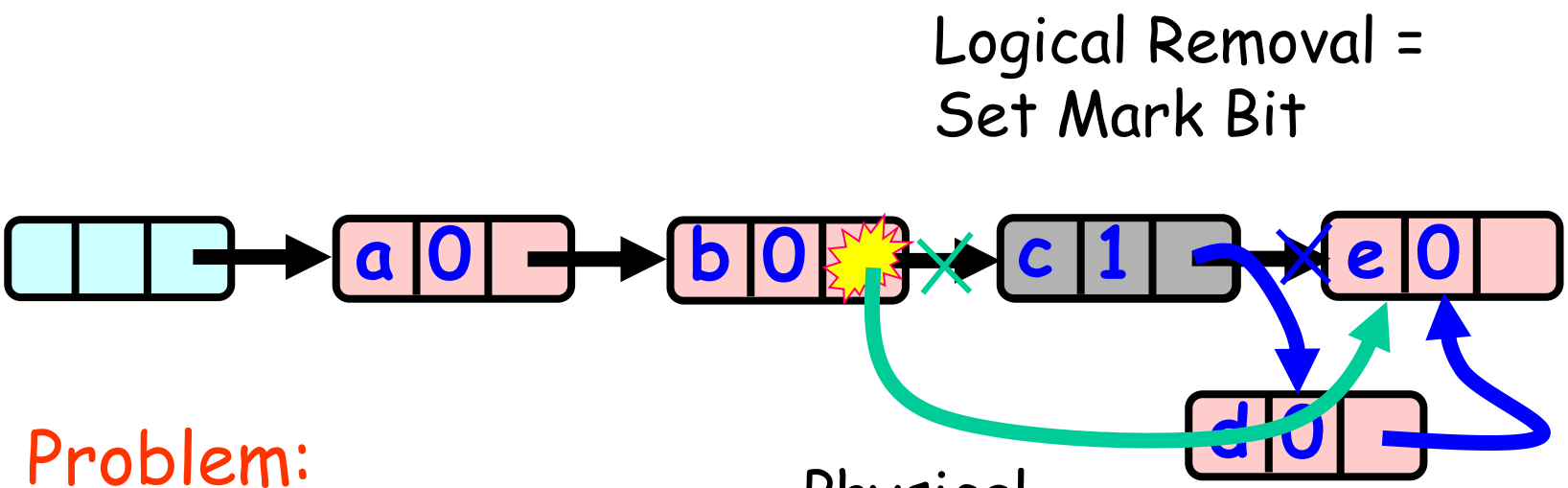


Use CAS+ to verify pointer is correct

Is it enough?

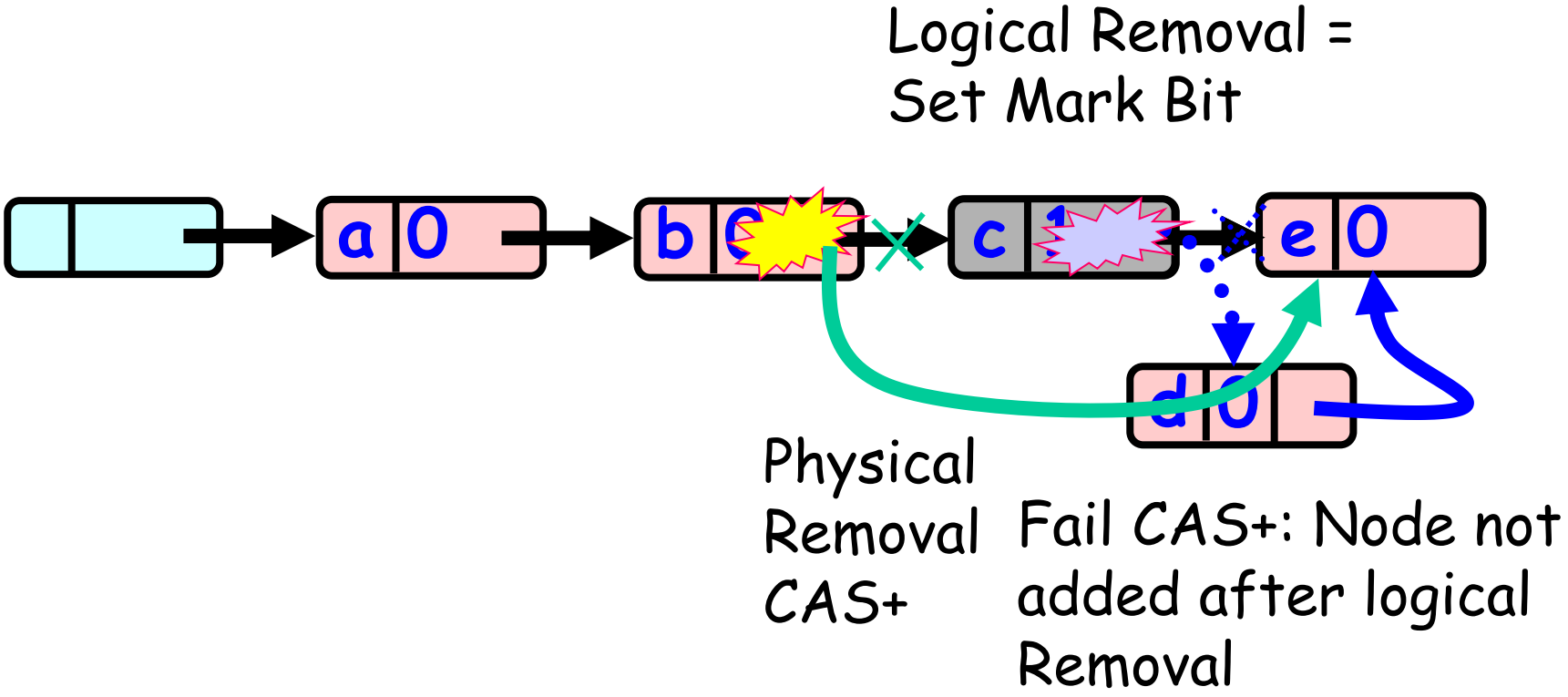
Physical Removal
CAS+ pointer

Lock-free Removal with add

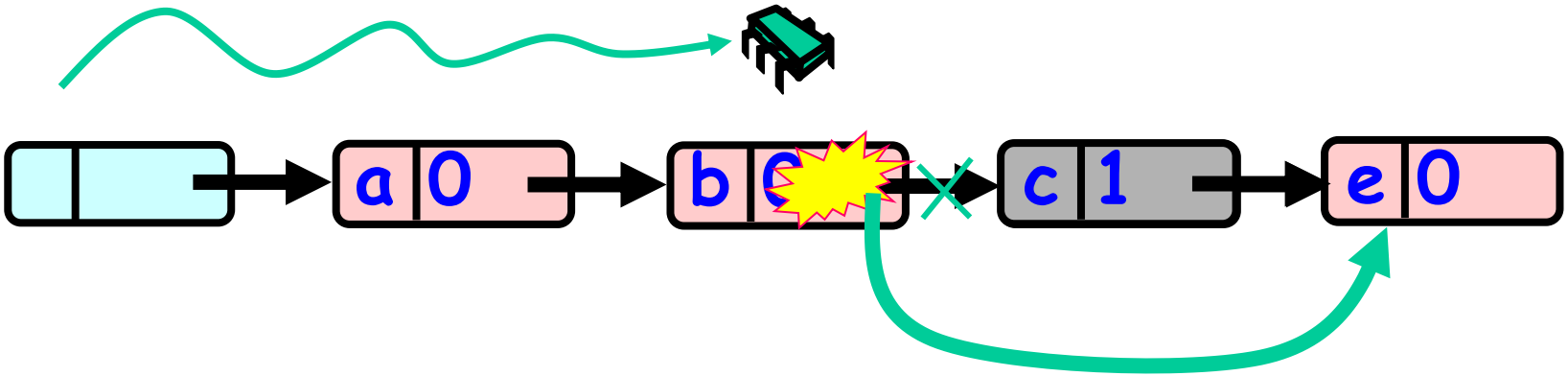


Problem:
d not added to list…
Must Prevent
manipulation of
removed node's pointer

Solution: use CAS+ in ADD()



Summary: A Lock-free Algorithm



1. add() and remove() physically remove marked nodes
2. Wait-free contains() traverses both marked and removed nodes