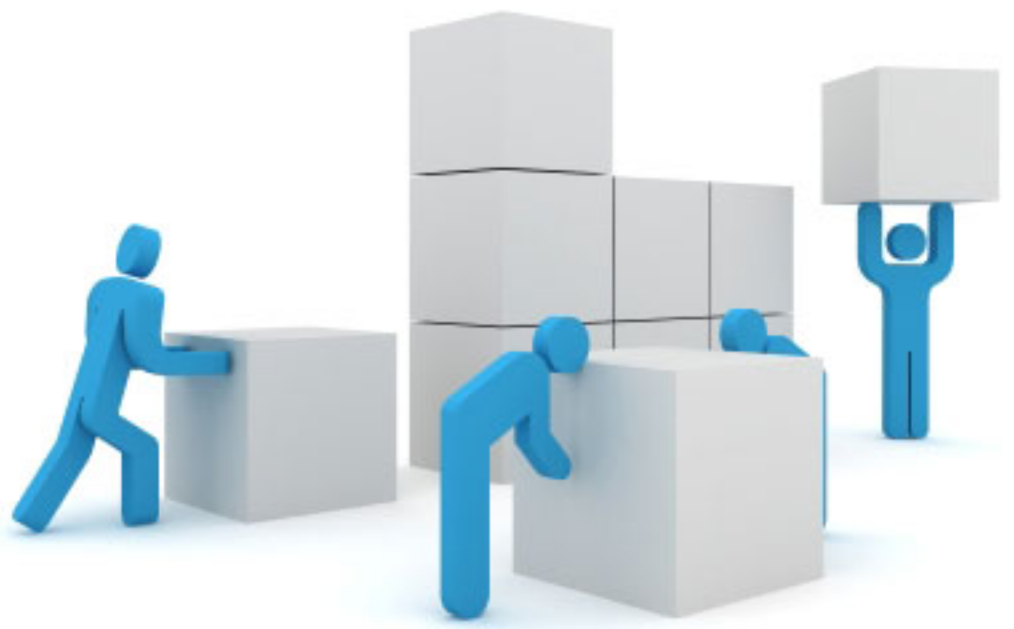
Linked Lists: The Role of Locking

Erez Petrank

Technion

Why Data Structures?

- Concurrent Data Structures are building blocks
  - Used as libraries
  - Construction principles apply broadly

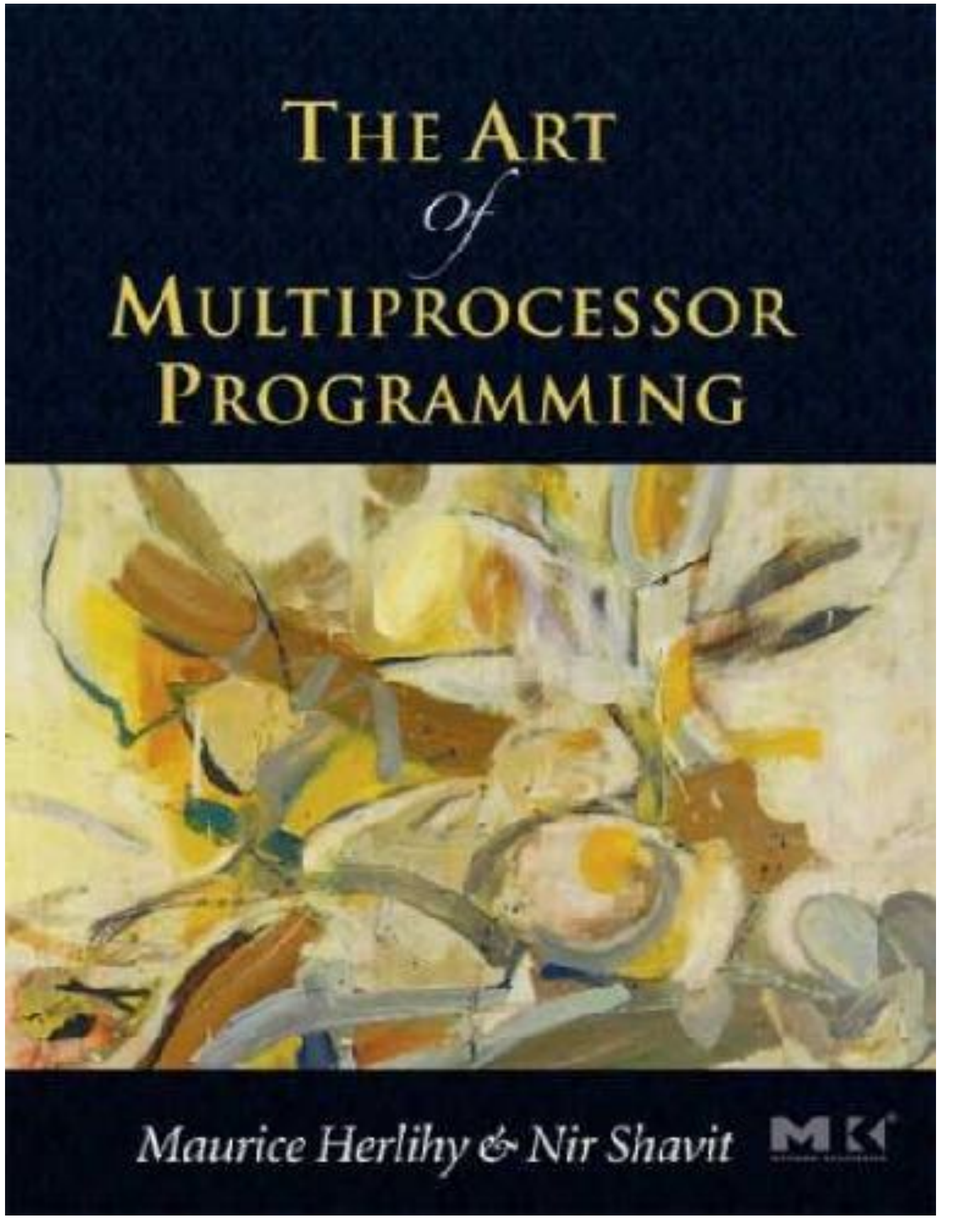


This Lecture

- Designing the first concurrent data structure: the linked-list
  - How do we use locks?
  - How do we achieve progress guarantees

Proper Credit

Several drawings are taken from the book, or from its accompanying slides.



Locking vs. Progress Guarantees

Counter Example

T1	T2
local := counter	local := counter
local++	local++
counter := local	counter := local

concurrent execution is not safe !

Use a Lock

```
Lock (L)
local := counter
local++
counter := local
Unlock(L)
```

Synchronization:
Only one thread can
acquire a lock L

Compare and Swap (CAS)

- CAS (addr, expected, new)

Atomically:

```
If ( MEM[addr] == expected ) {
        MEM[addr] = new
        return (TRUE)
        }
else return (FALSE)
```

Use a Lock or a CAS

```
Lock (L)
local := counter
local++
counter := local
Unlock(L)
```

Synchronization:
Only one thread can acquire a lock L

```
START:
old := counter
new := old ++
if ( ! CAS(&counter,old,new) )
        goto START
```

Synchronization:
Only one thread changes from old in a concurrent CAS.

Use a Lock or a CAS

```
Lock (L)
local := counter
local++
counter := local
Unlock(L)
```

```
START:
old := counter
new := old ++
if ( ! CAS(&counter,old,new) )
        goto START
```

Issues:
Efficiency, scalability, Fairness, progress guarantee, design complexity.

What Does "Lock-Free" Mean?

- First try: "never using a lock".
- Well, is this using a lock? (word is initially zero.)

```
while (!CAS(&word,0,1)) {}
local := counter
local++
counter := local
word := 0
```

- It is not easy to say if something is a "lock".

What Does "Lock-Free" Mean?

- Better: "No matter which interleaving is scheduled, my program will make progress.".
- A.k.a. non-blocking.
- Our second example is lock-free.

```
START:
old := counter
new := old ++
if ( ! CAS(&counter,old,new) )
        goto START
```

Lock-Freedom

Lock-Freedom

If you schedule enough steps across all threads, one of them will make progress.

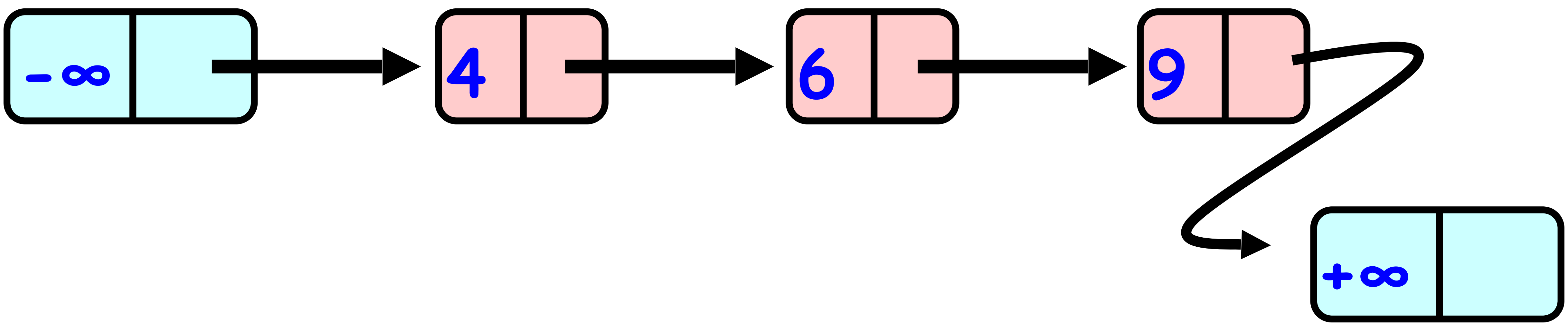
- Realistic (though difficult):
  Various lock-free data structures exist in the literature (stack, queue, hashing, skiplist, trees, etc.).

- Advantages:
  Worst-case responsiveness, scalability, no deadlocks, no livelocks, added robustness to threads fail-stop.

Linked List: Our First Example

Fine-grained locking and lock-freedom

The Linked List

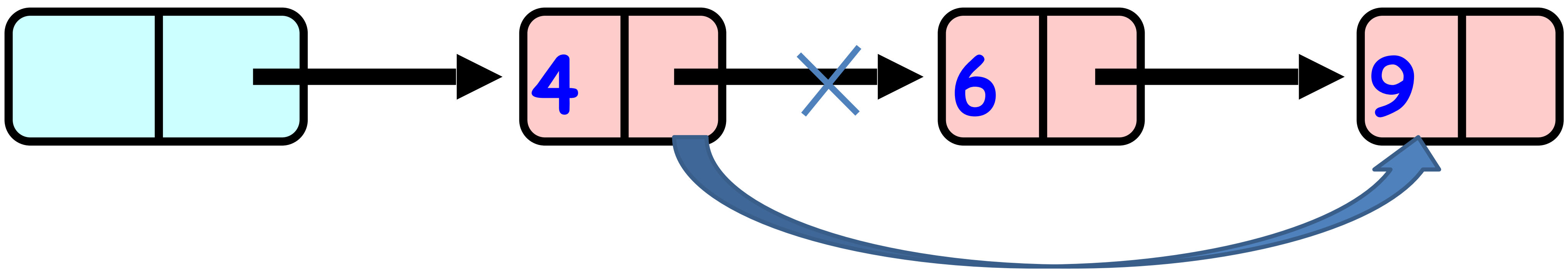


Support: insert, delete, contains.

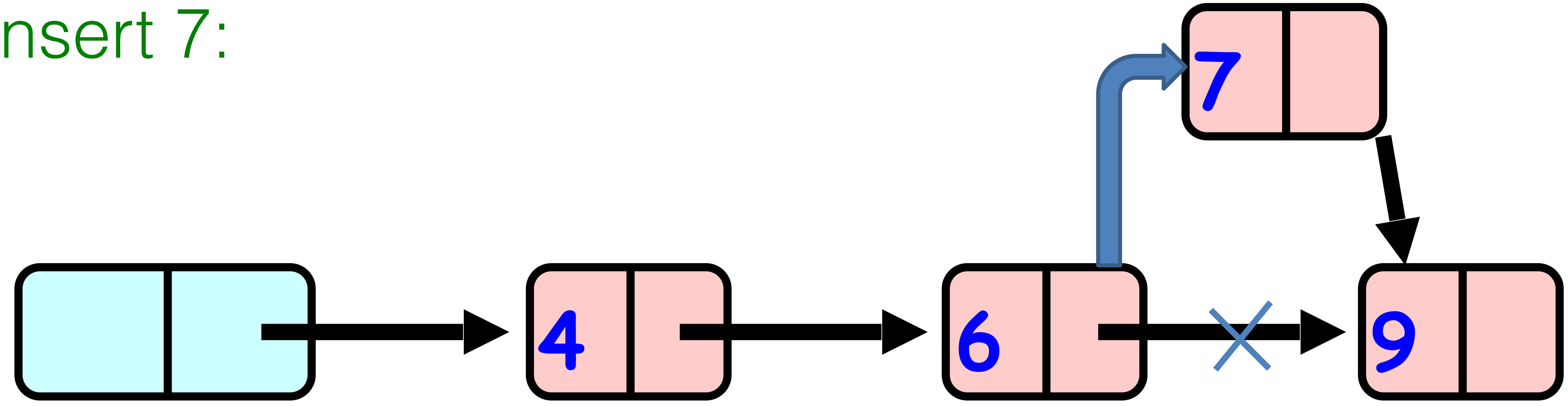
Implements a set: no duplicates, order maintained.

Sequential Implementation

- Delete 6:

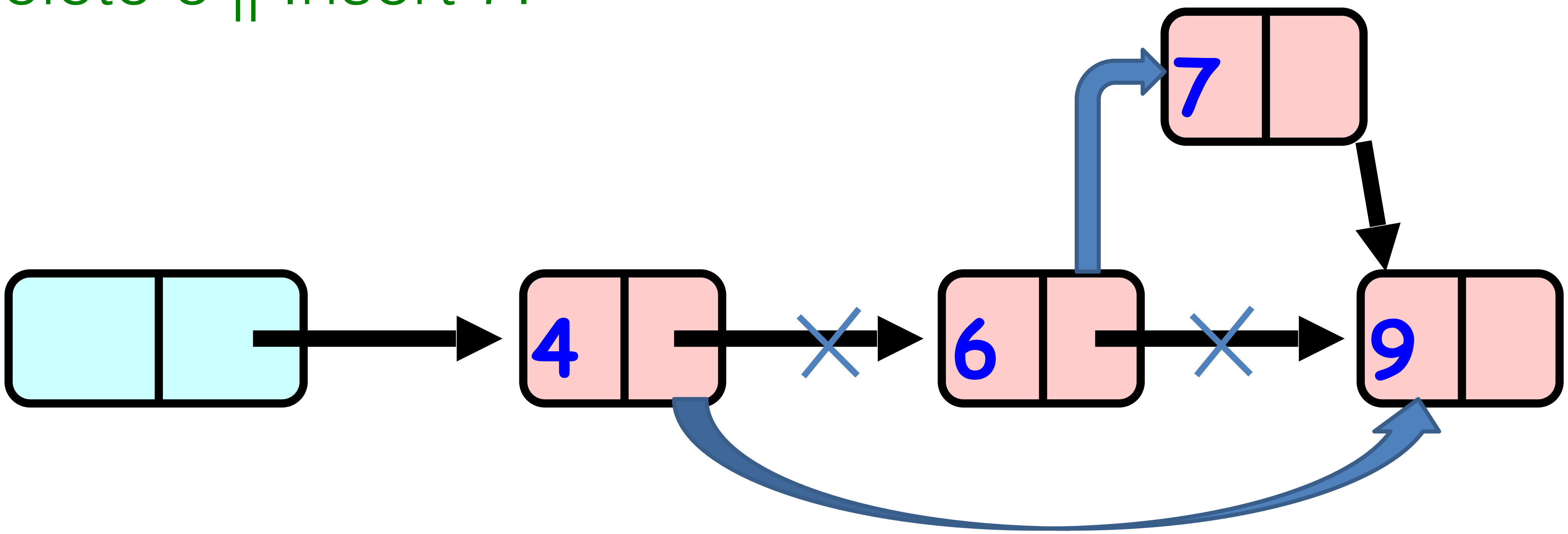


- Insert 7:



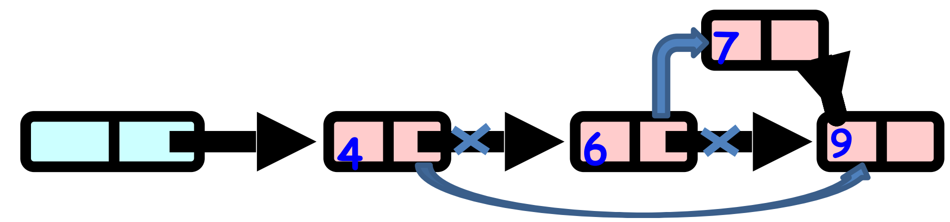
But don’t try this concurrently!

- Delete 6 || Insert 7:

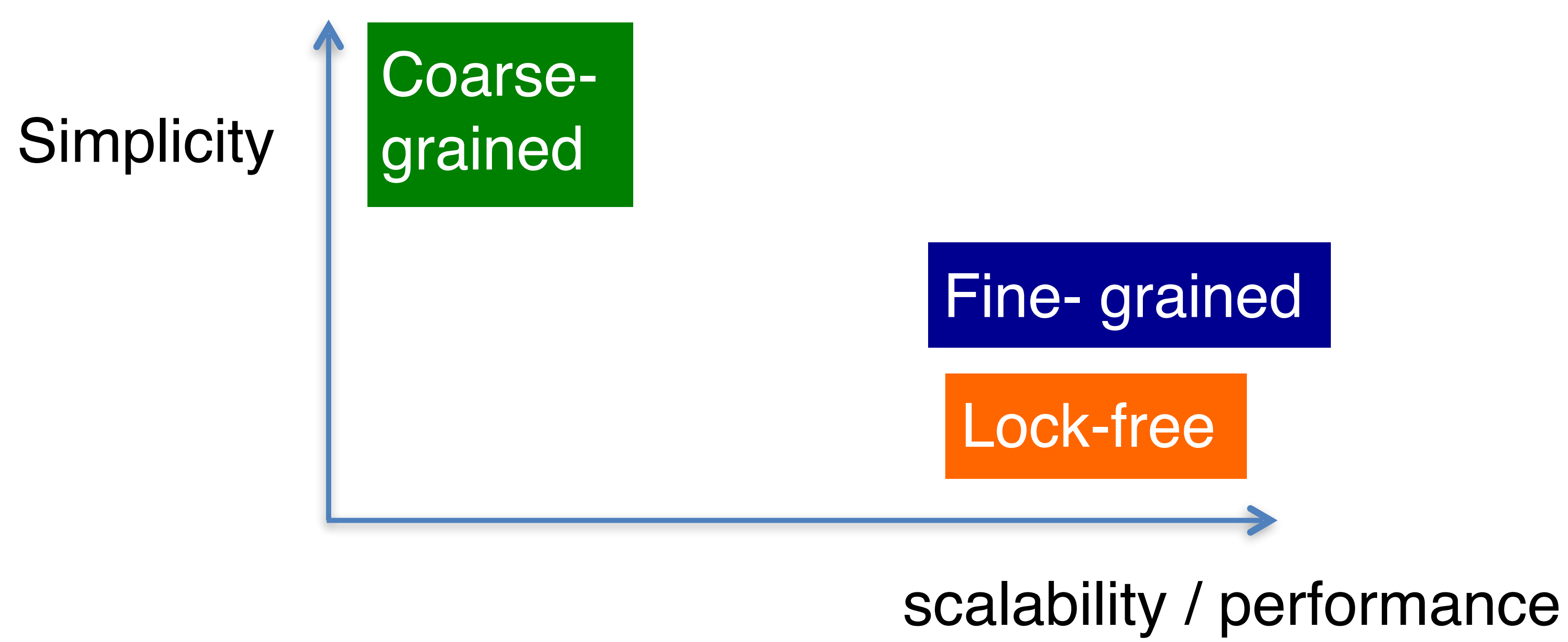


- A similar problem with concurrent deletes.

Solutions



- Coarse-grained locking.
  - Sequential with overhead…
- Fine-grained locking
  - hand-over-hand, optimistic, lazy synchronization.
- Lock-free (or wait-free) implementation.



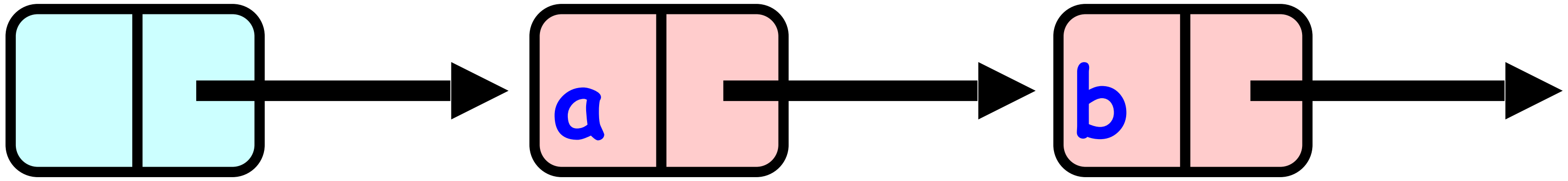
scalability / performance

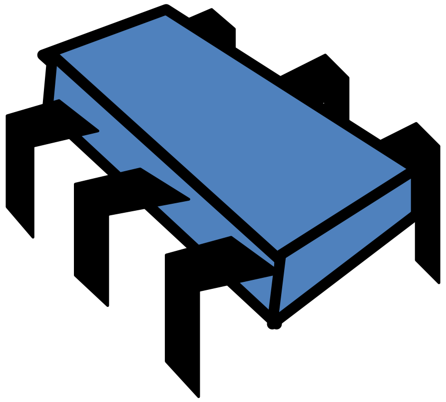
Fine-Grained Locking #1:

Hand-Over-Hand

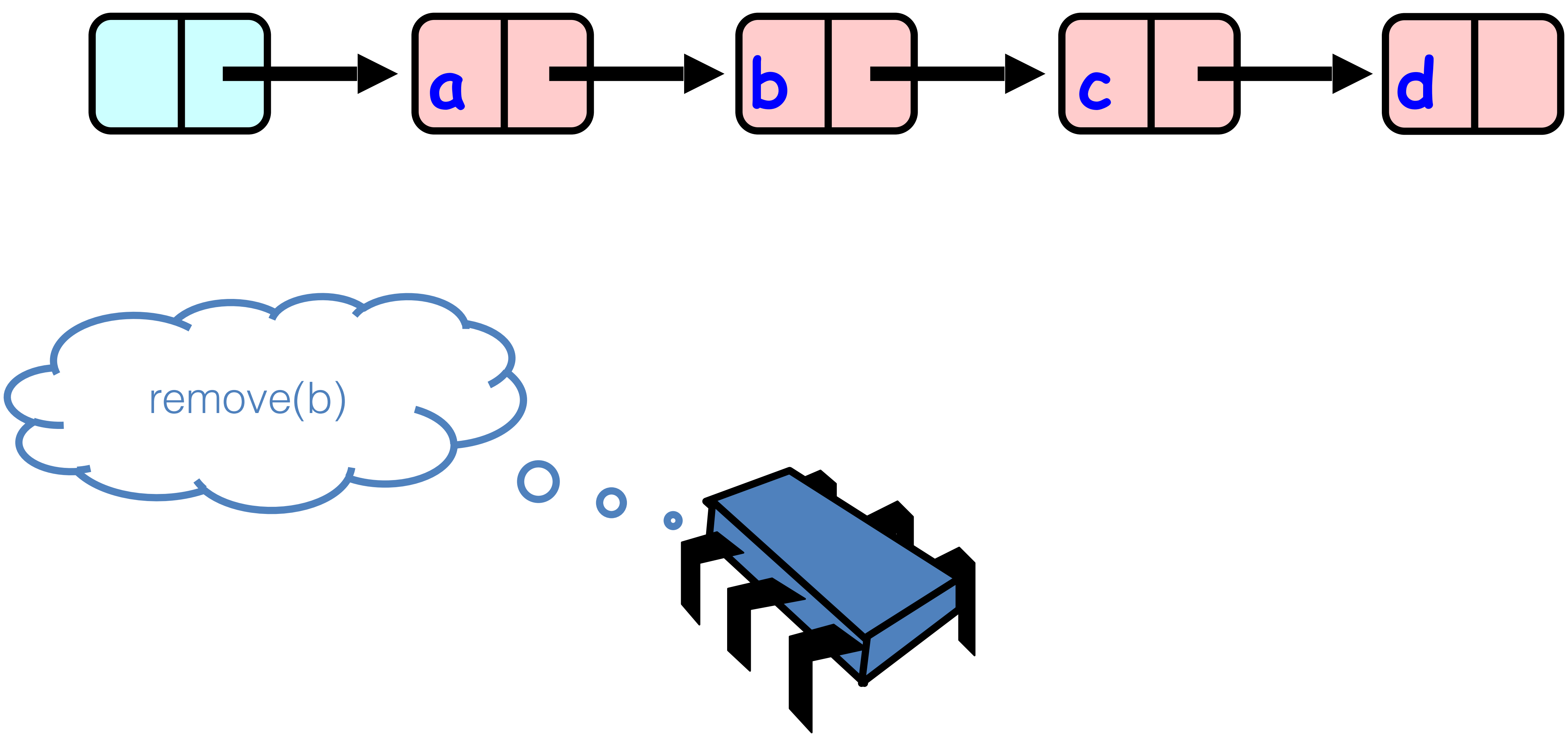
Hand-over-Hand locking

[Bayer-Schkolnik 1977]

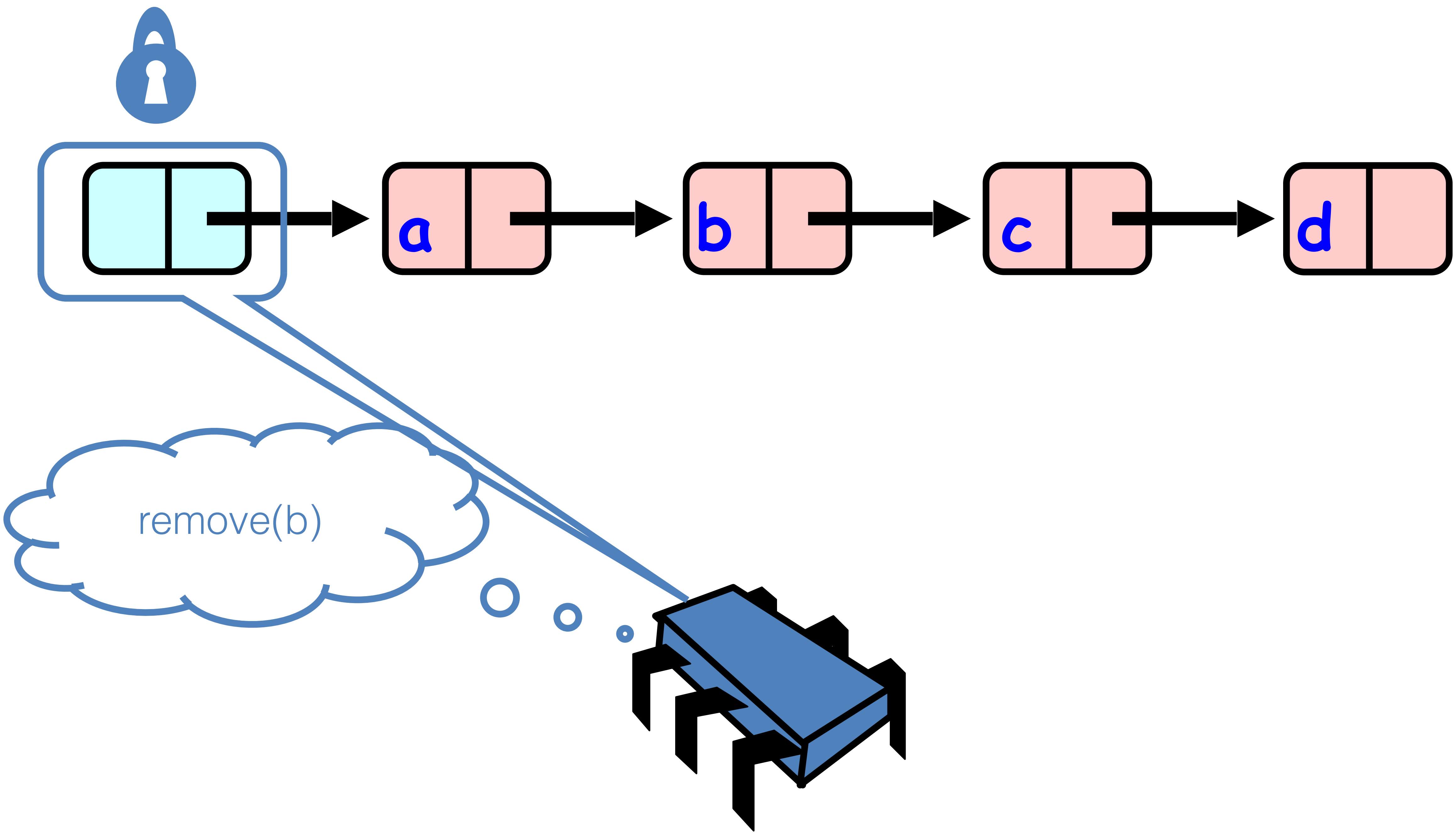




Operation 1: Remove a Node



Removing a Node



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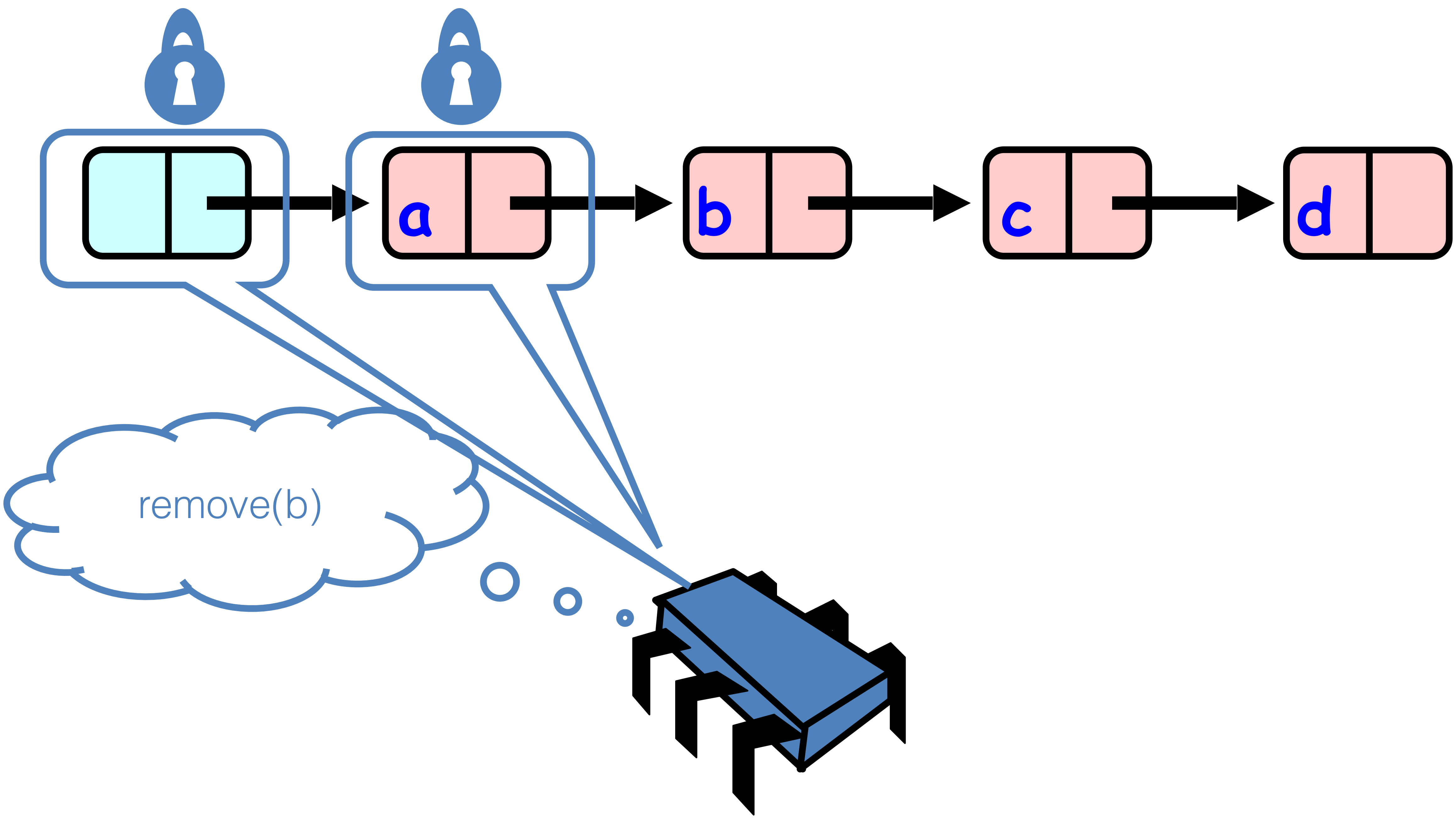
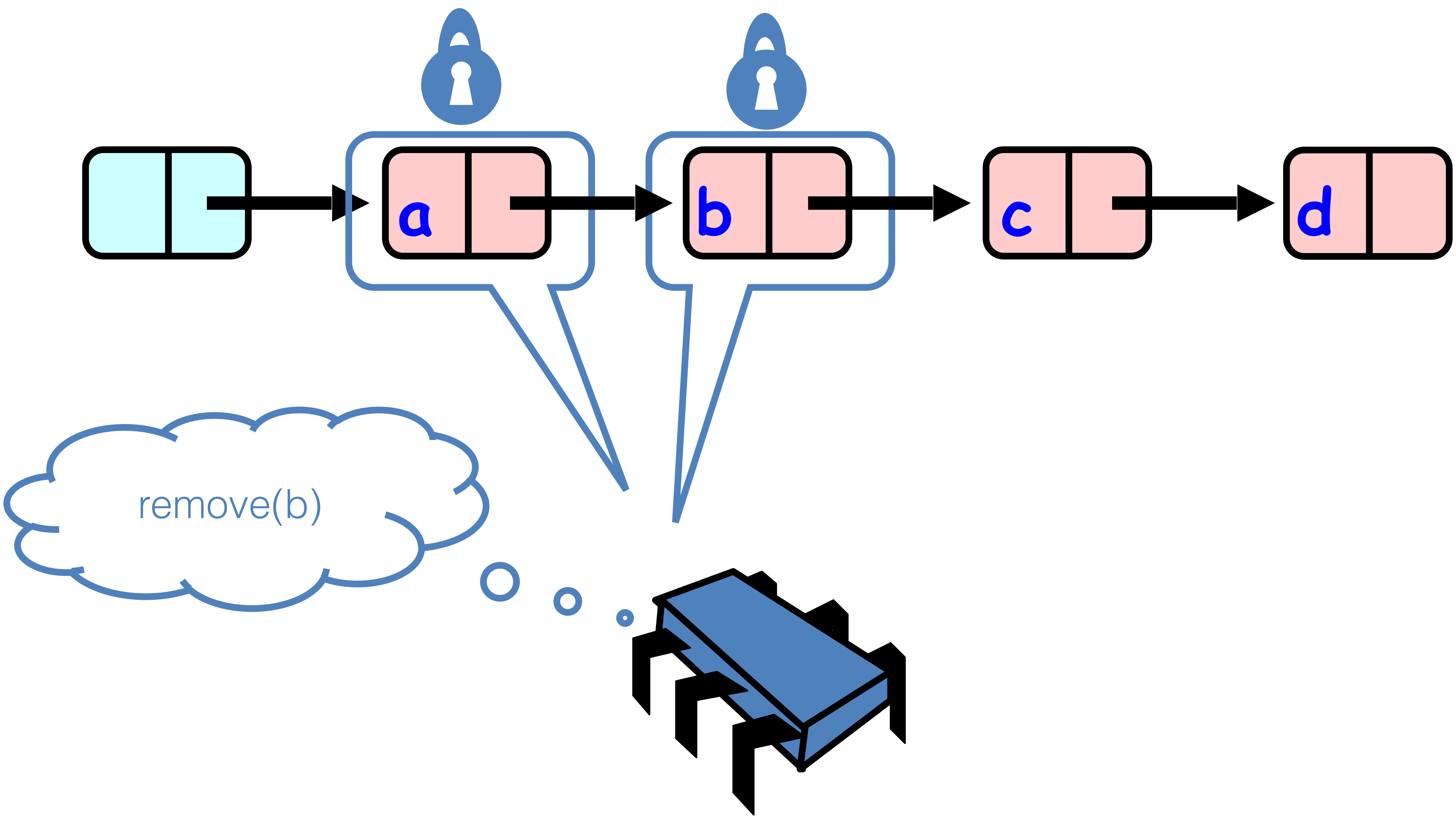


Removing a Node



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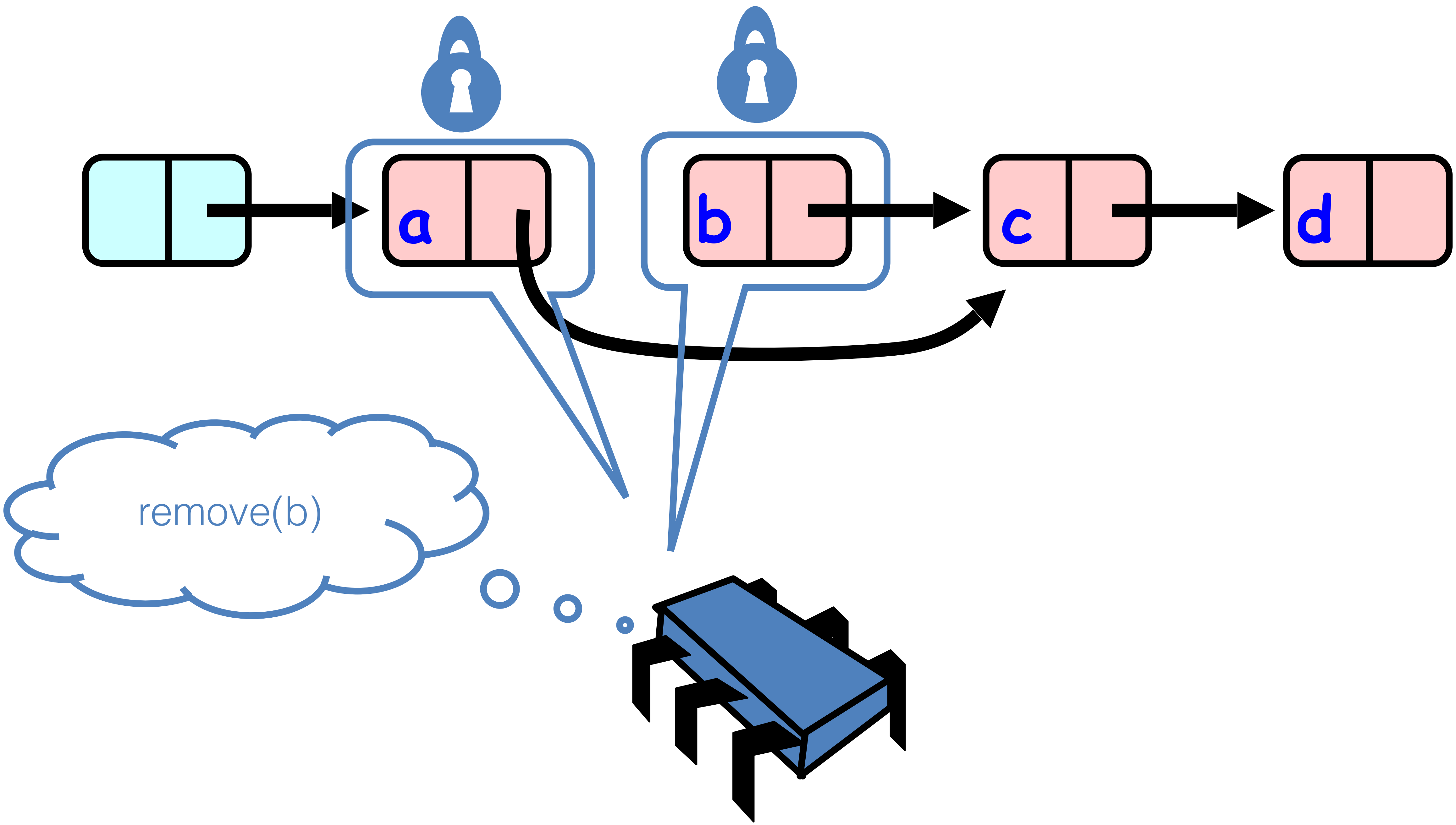

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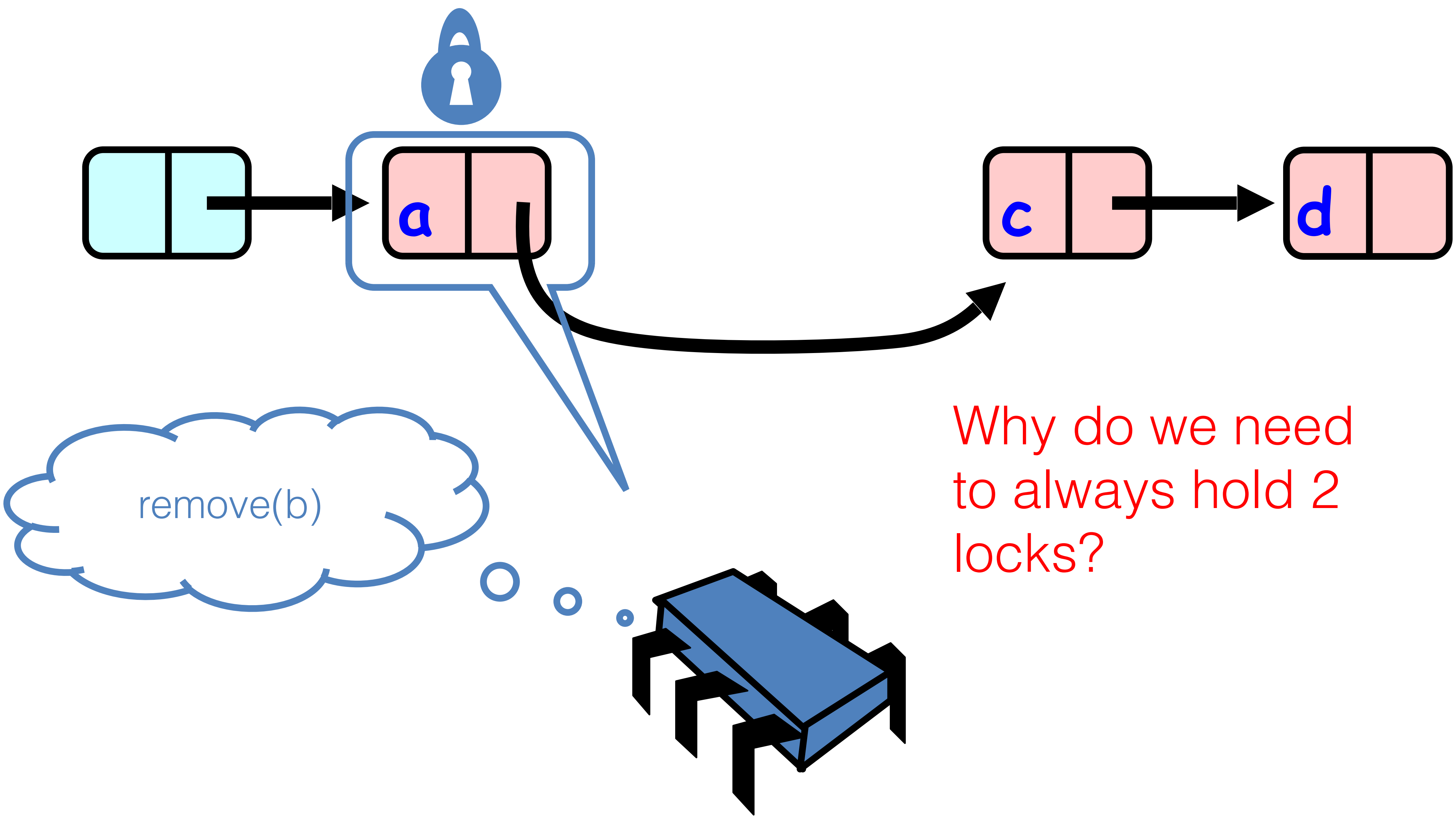
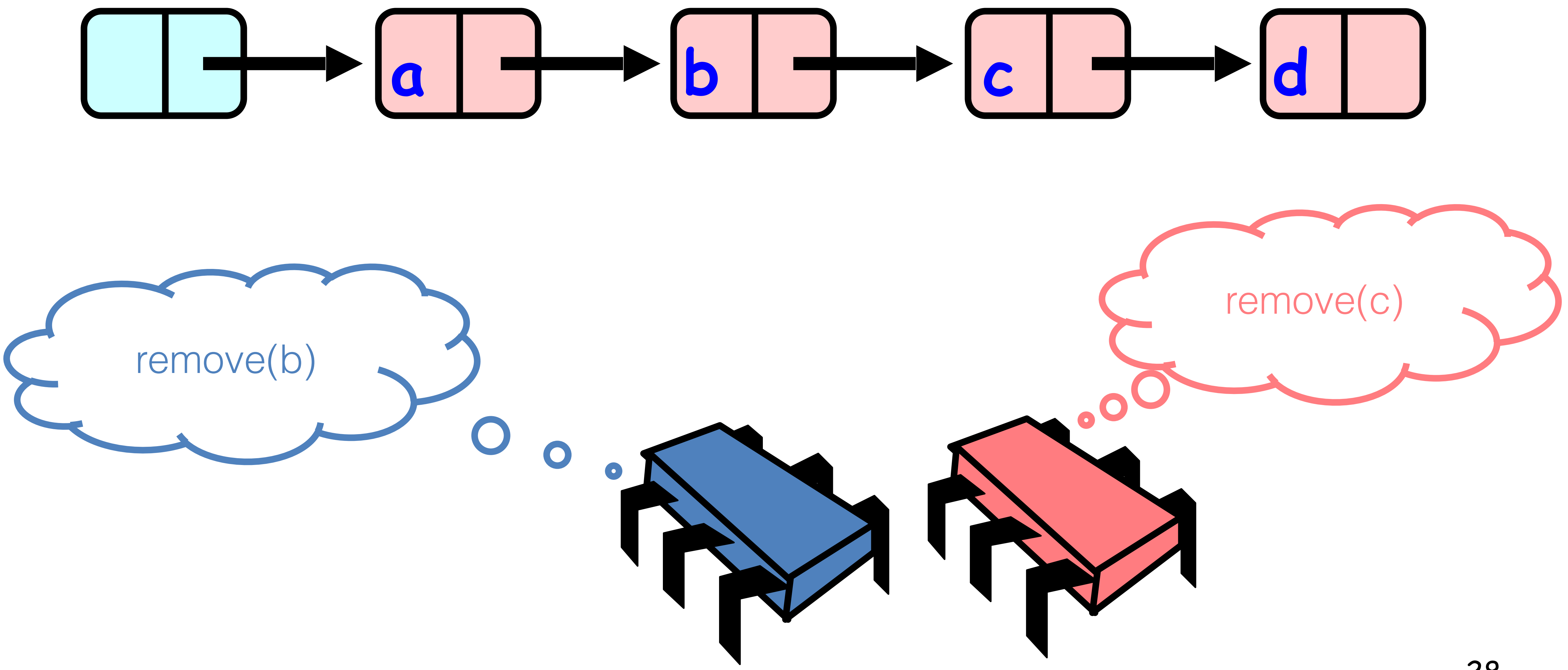
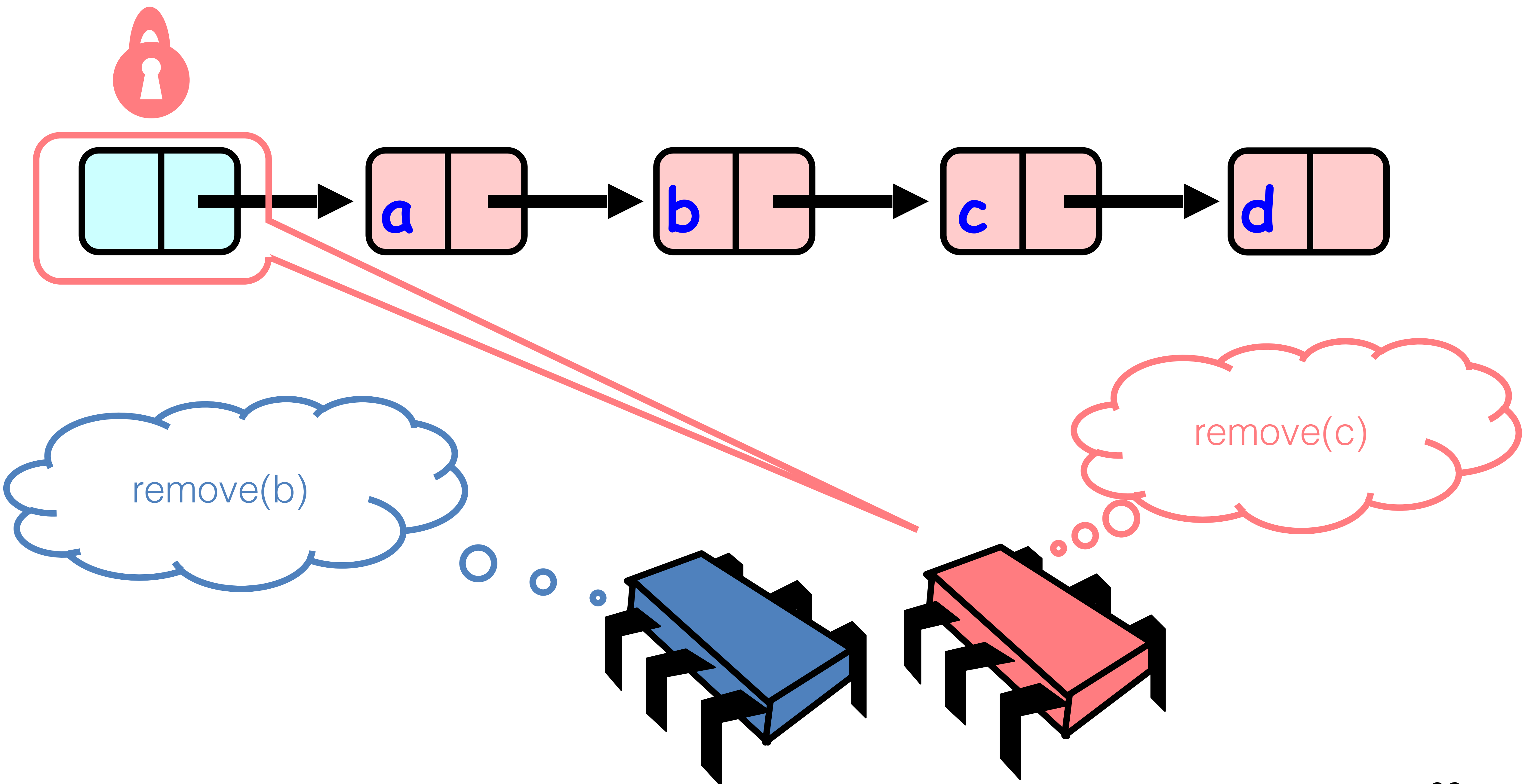


Why do we need to always hold 2 locks?

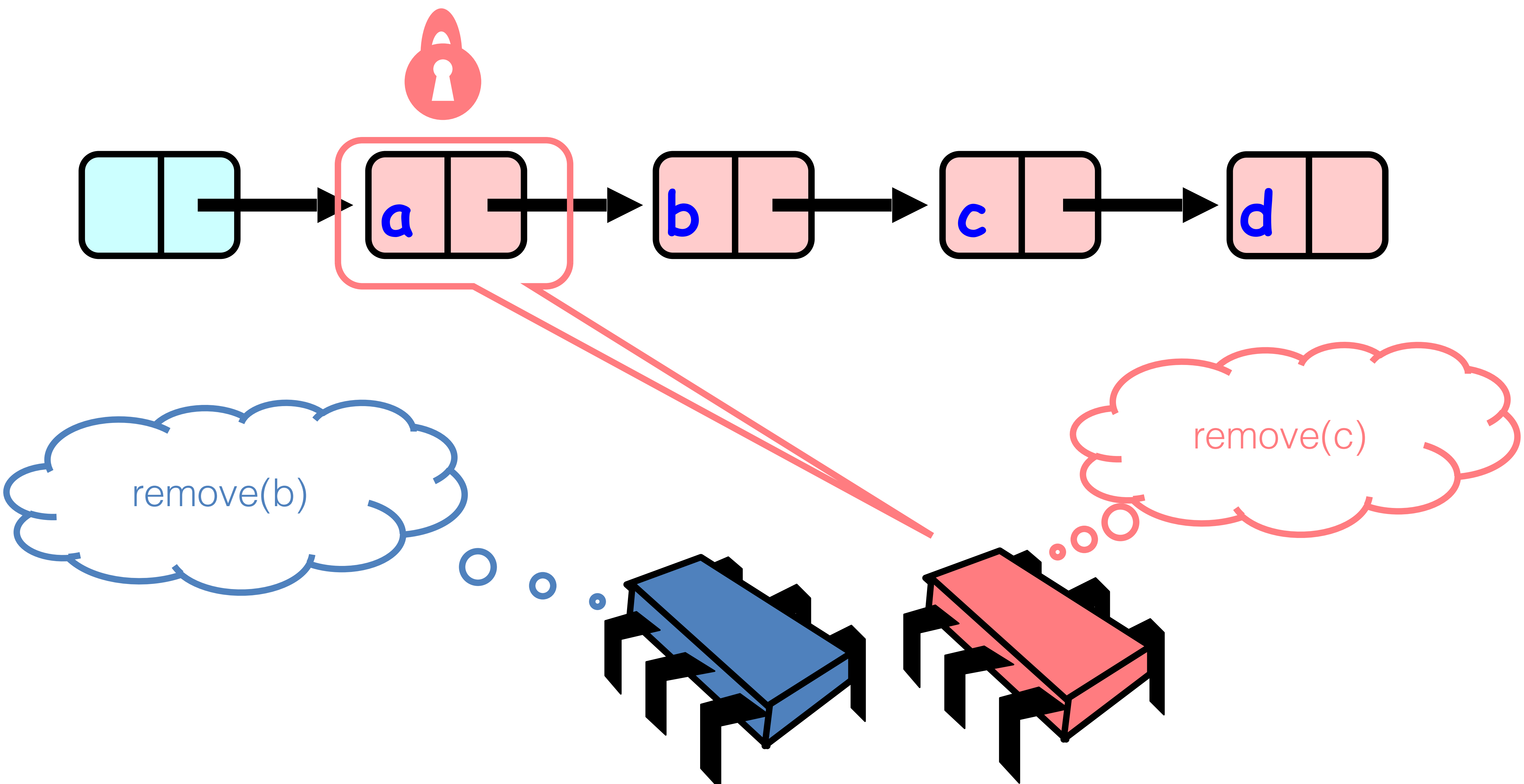
Concurrent Removes



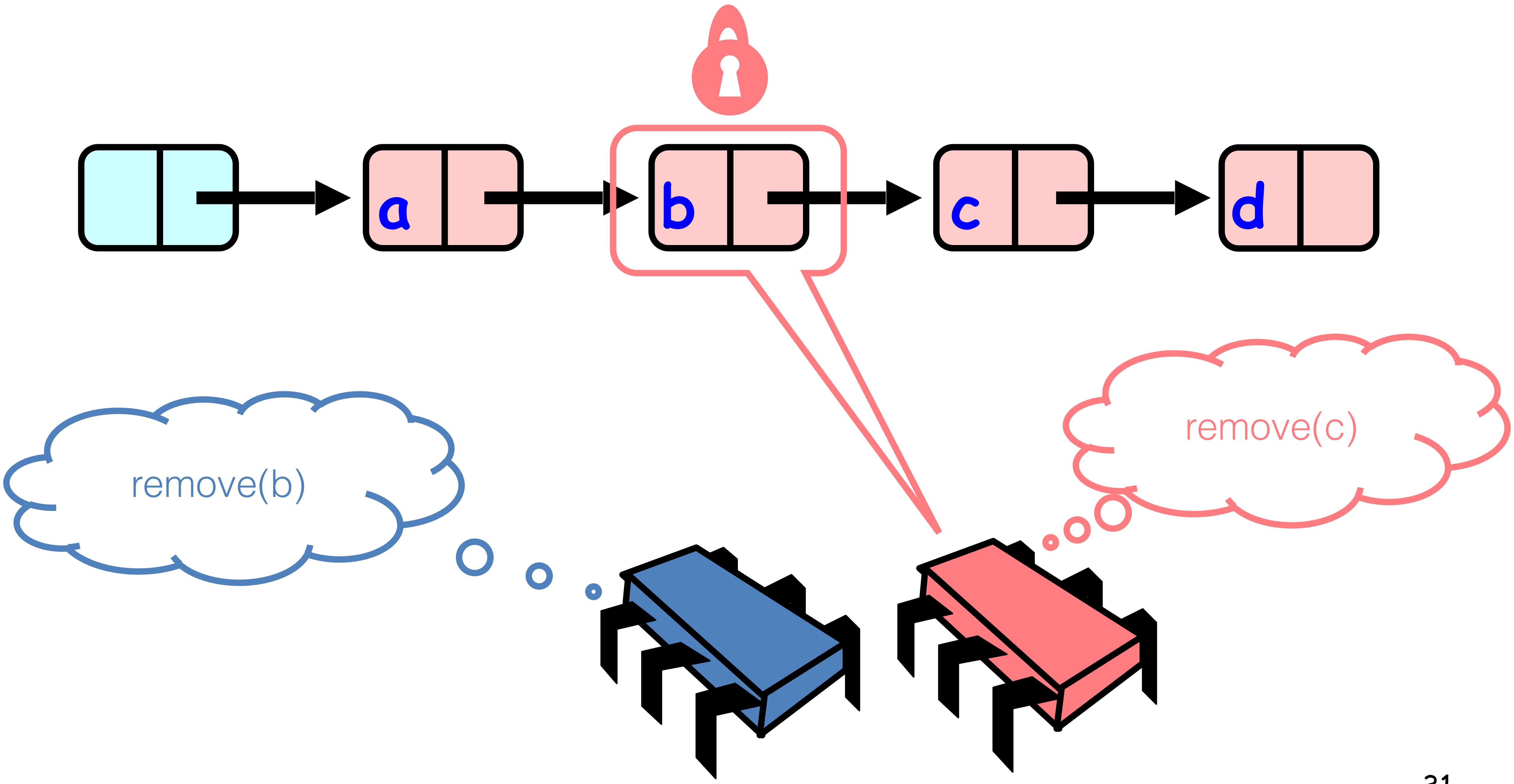
Concurrent Removes



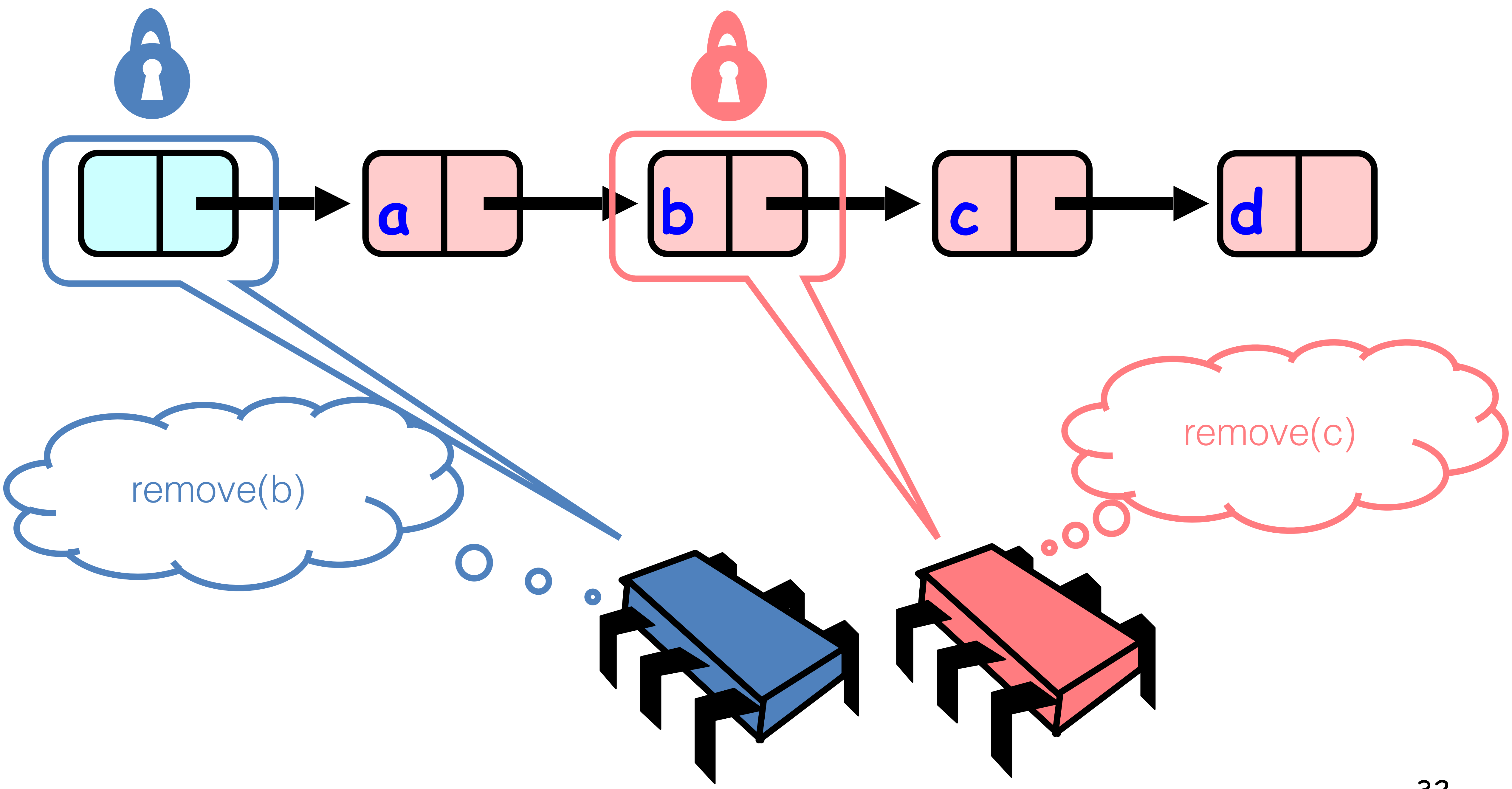
Concurrent Removes



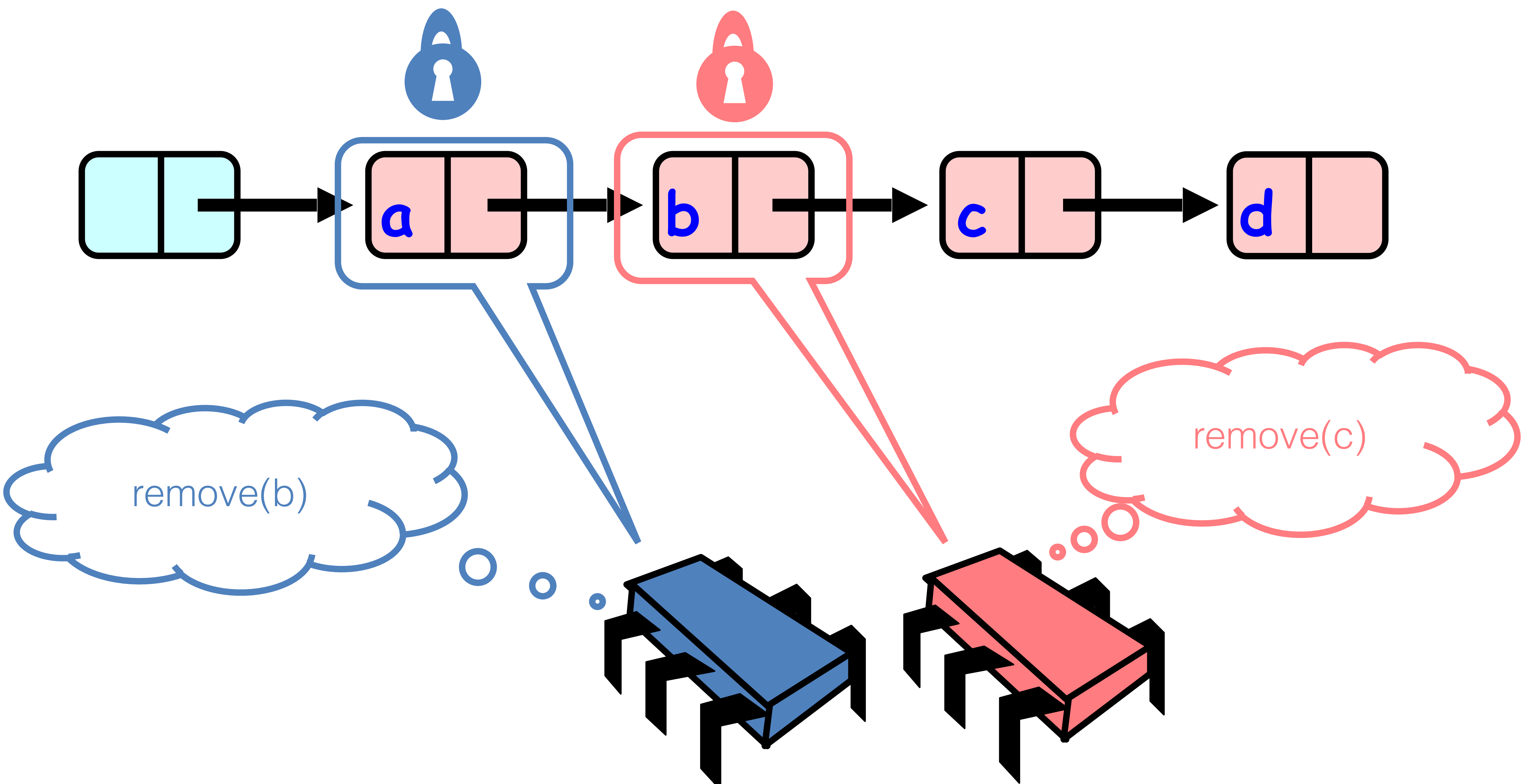
Concurrent Removes



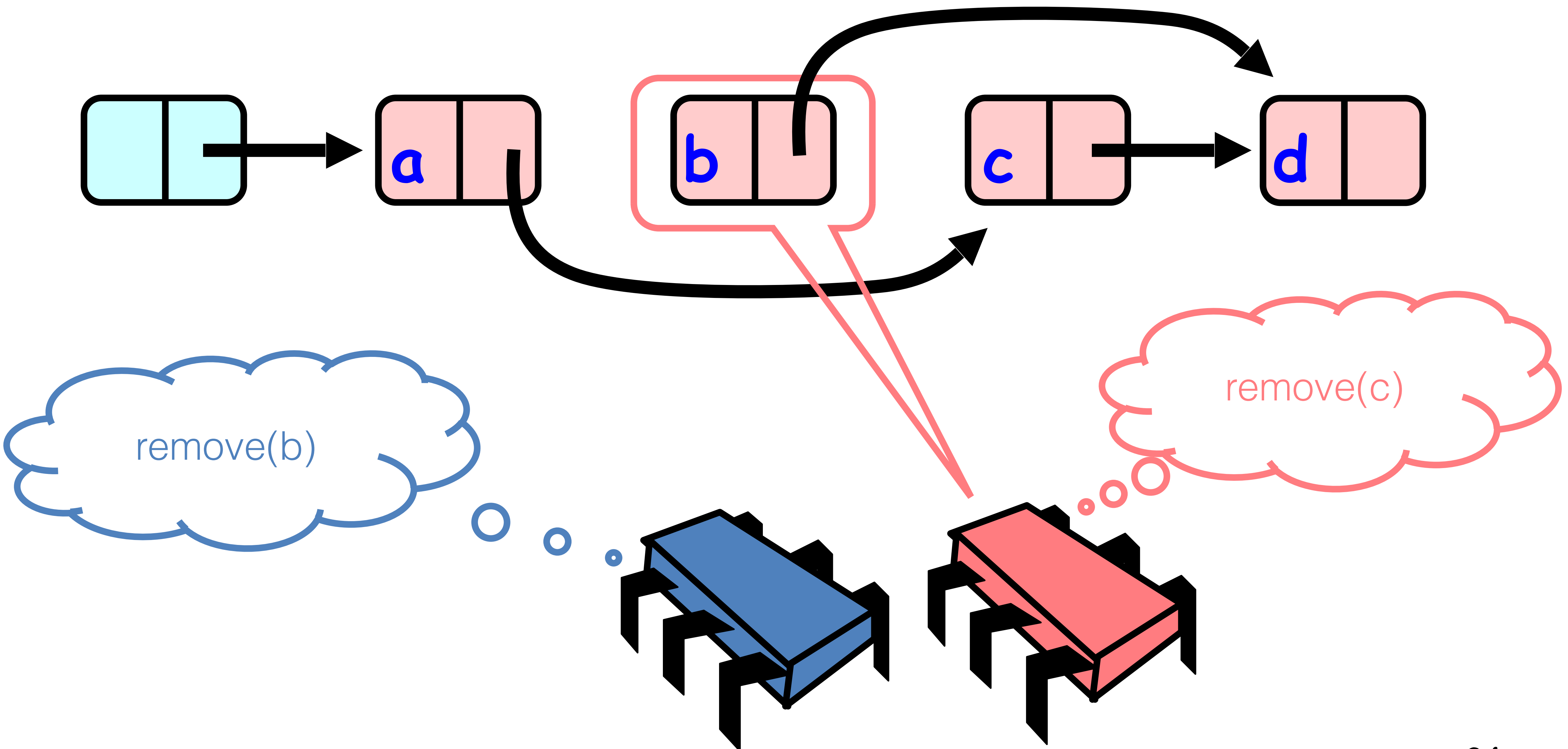
Concurrent Removes



Concurrent Removes



Uh, Oh



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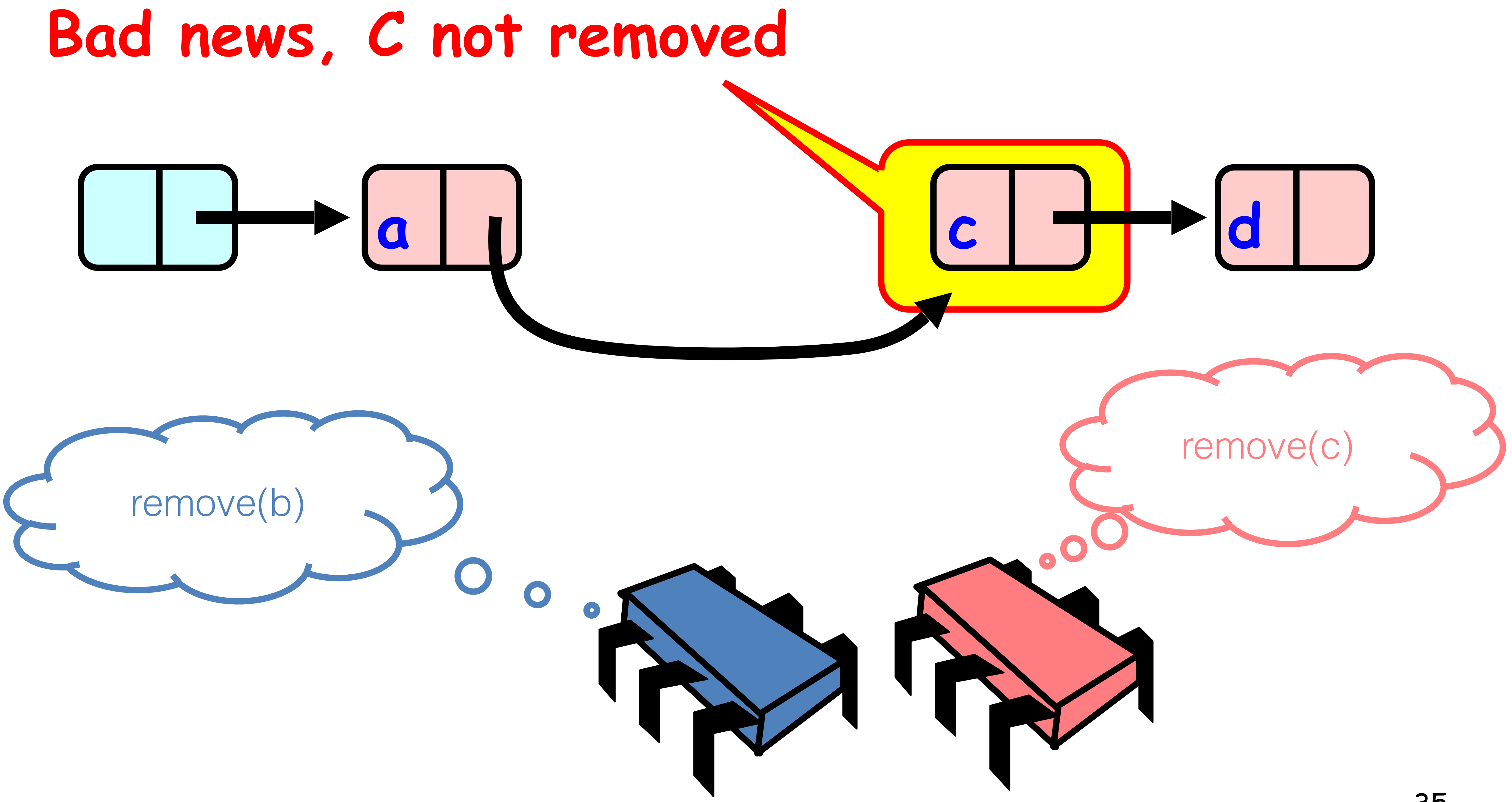
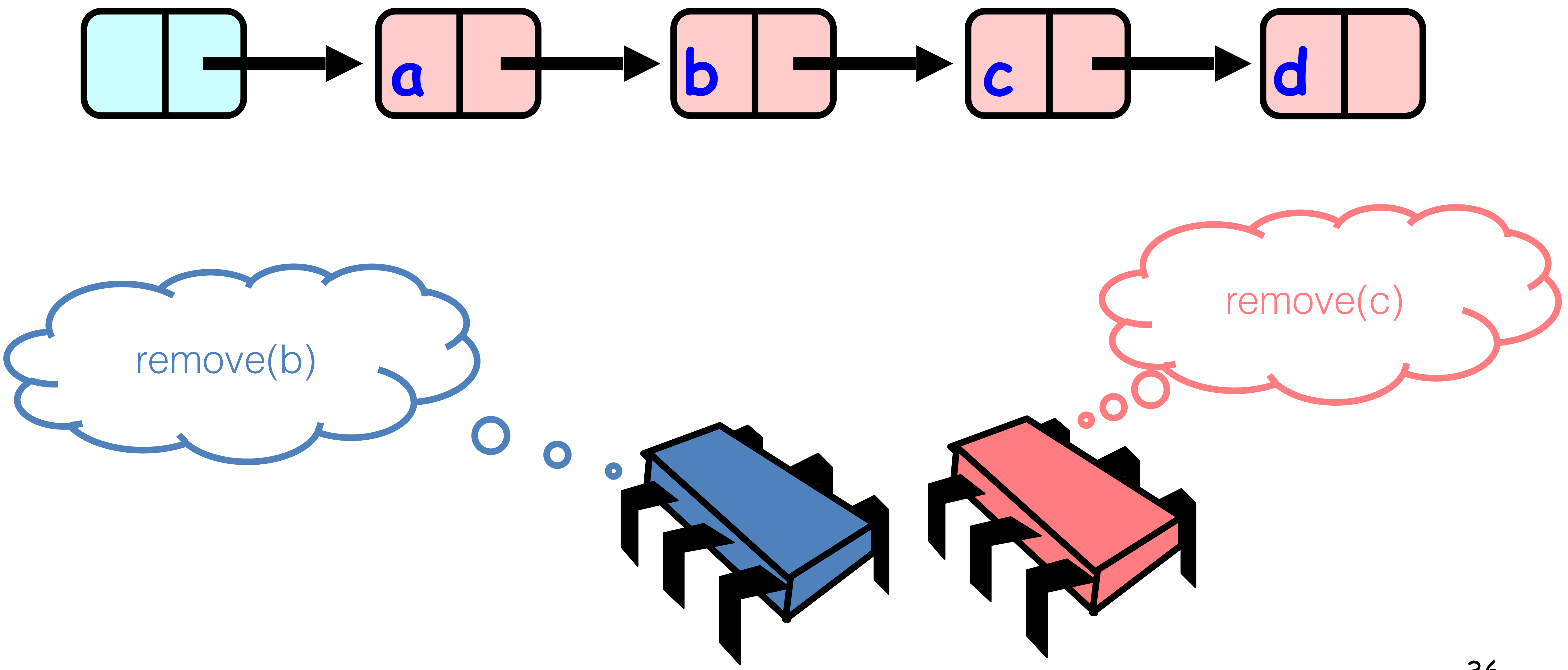
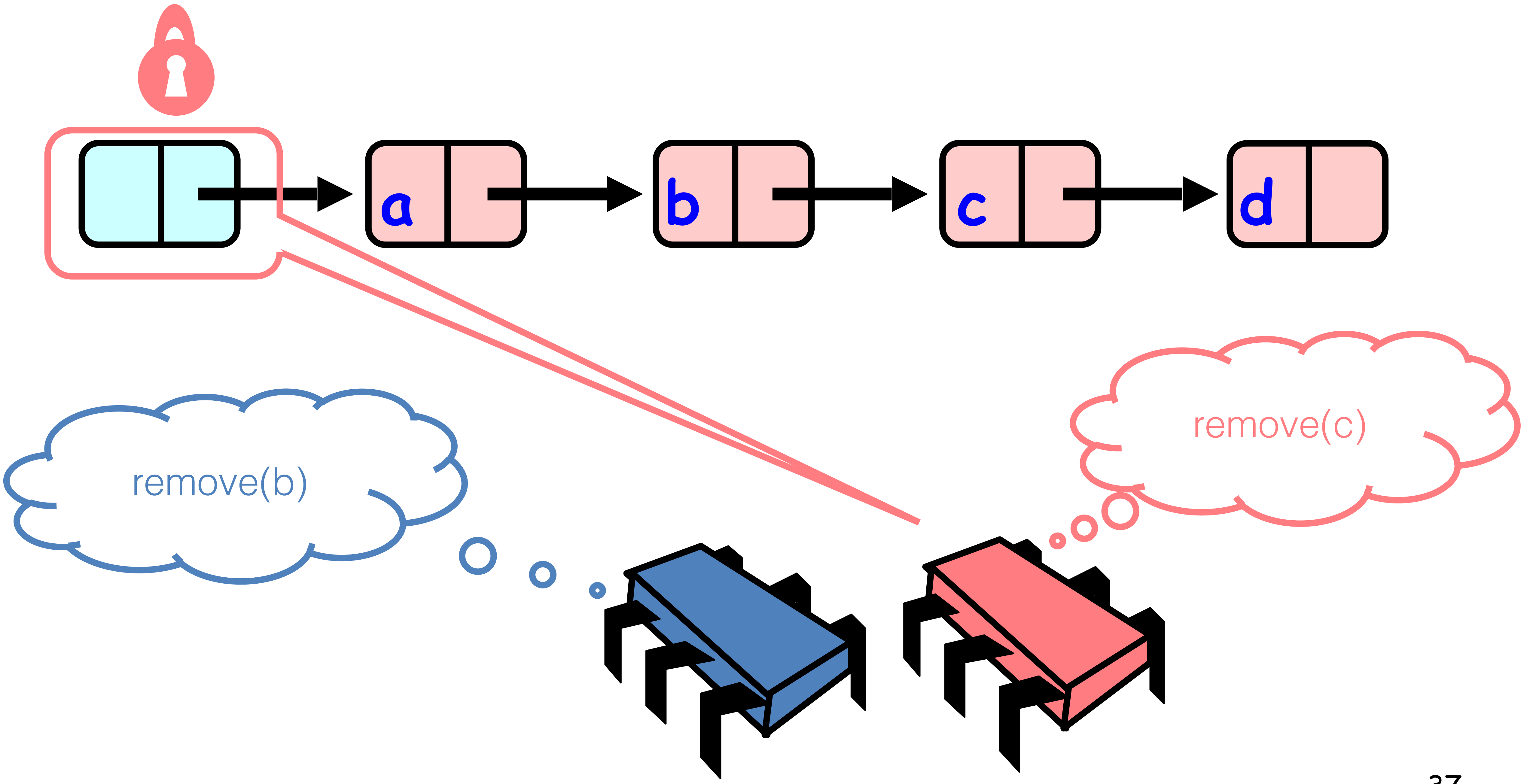


With Two Locks



Removing a Node



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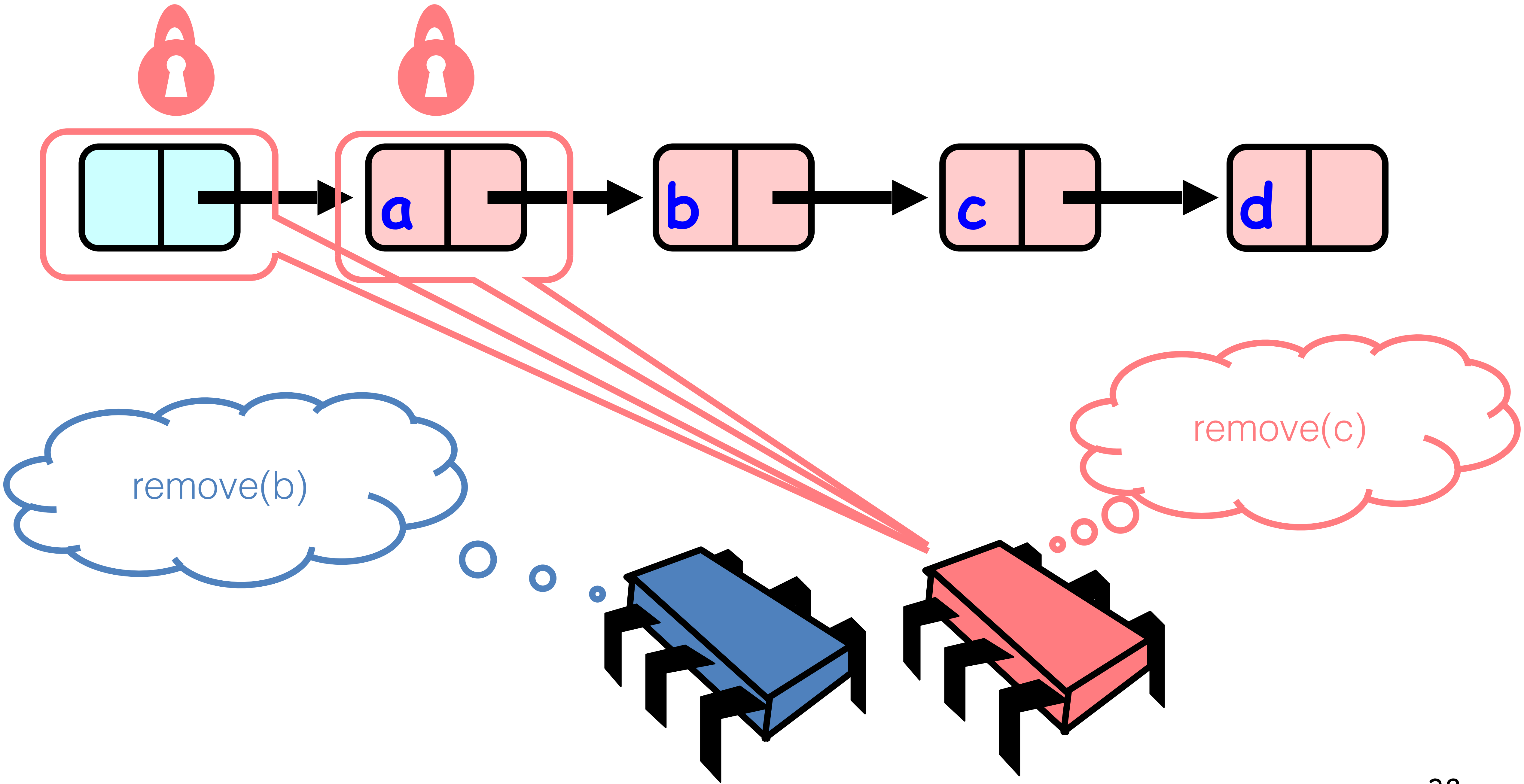

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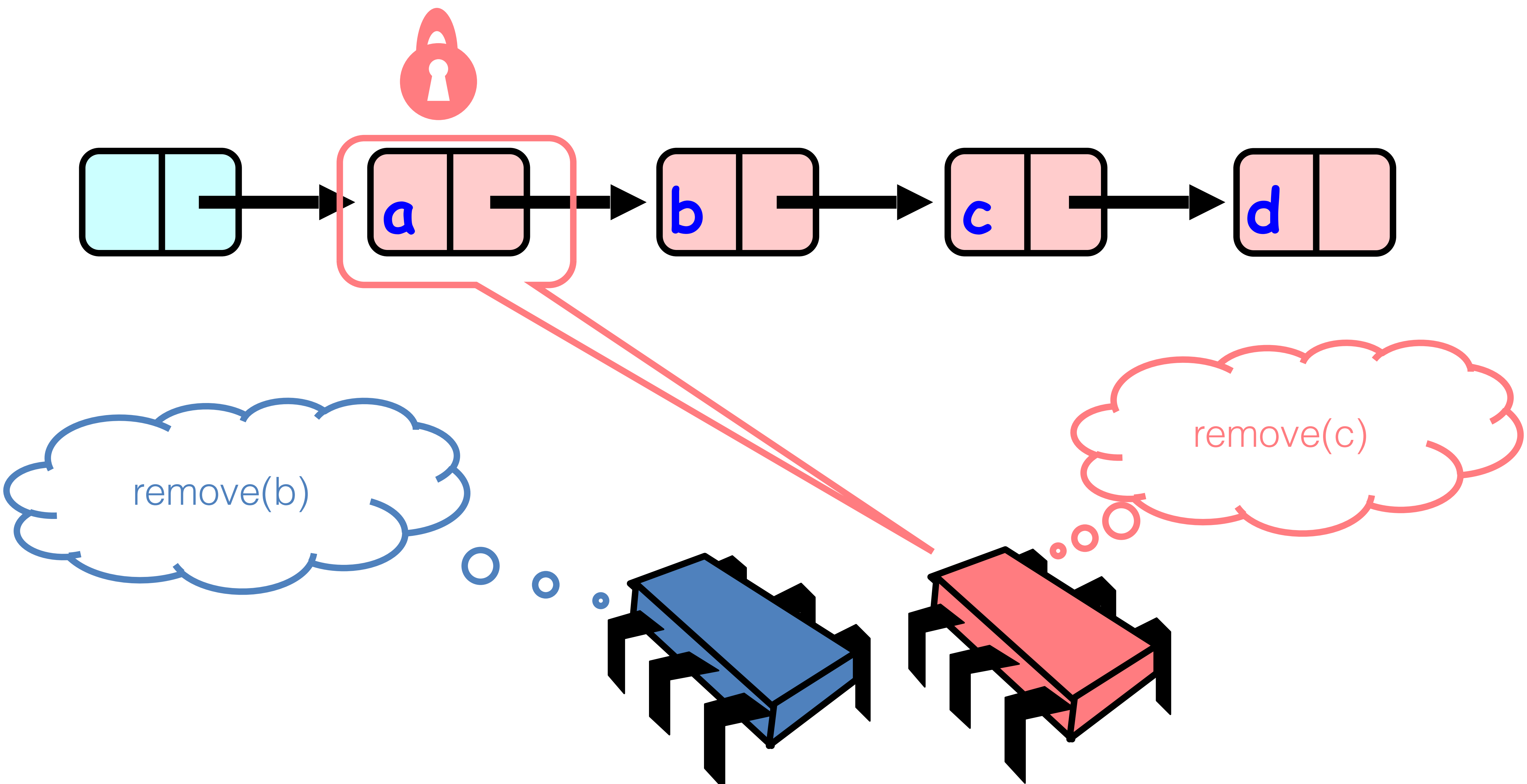

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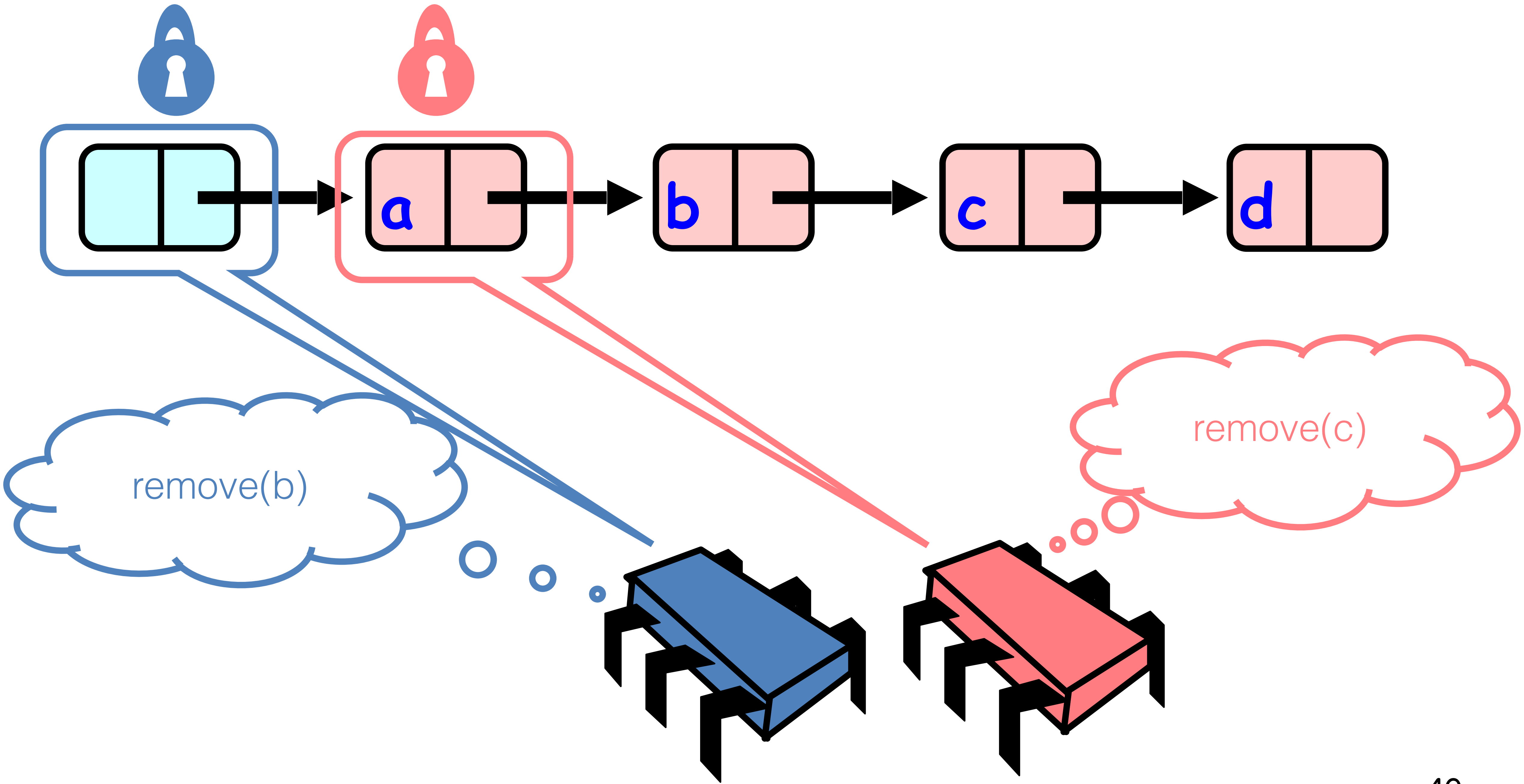

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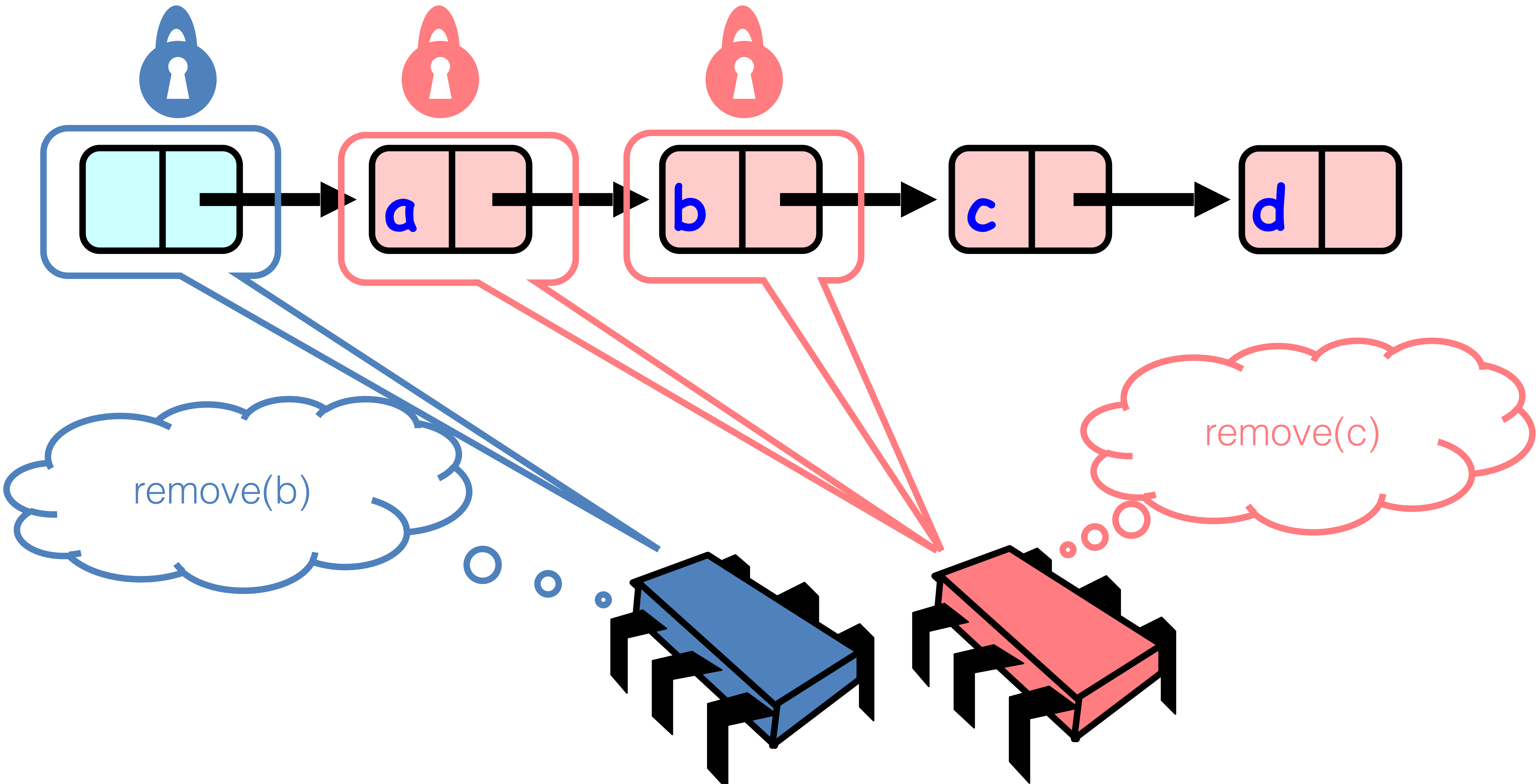

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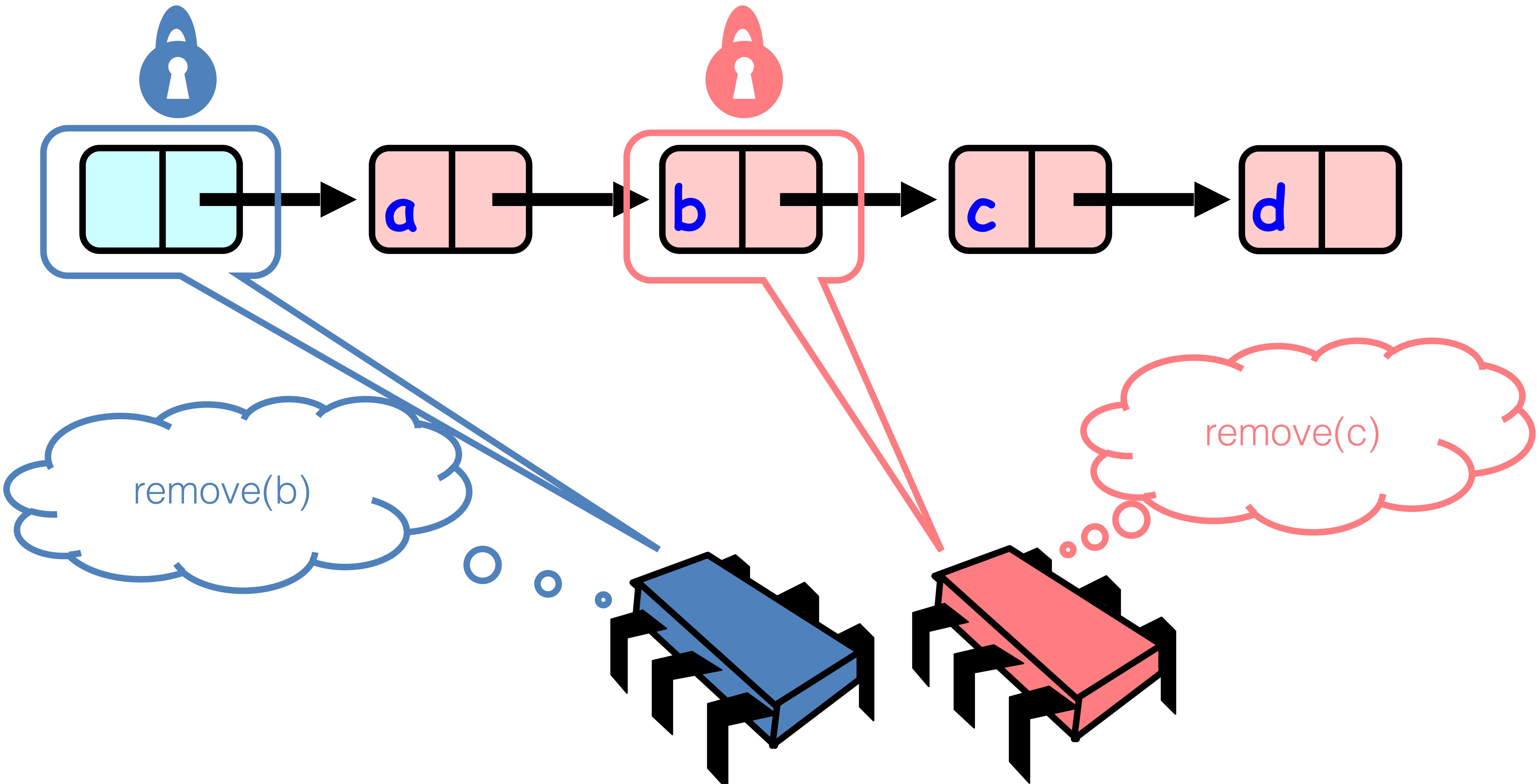

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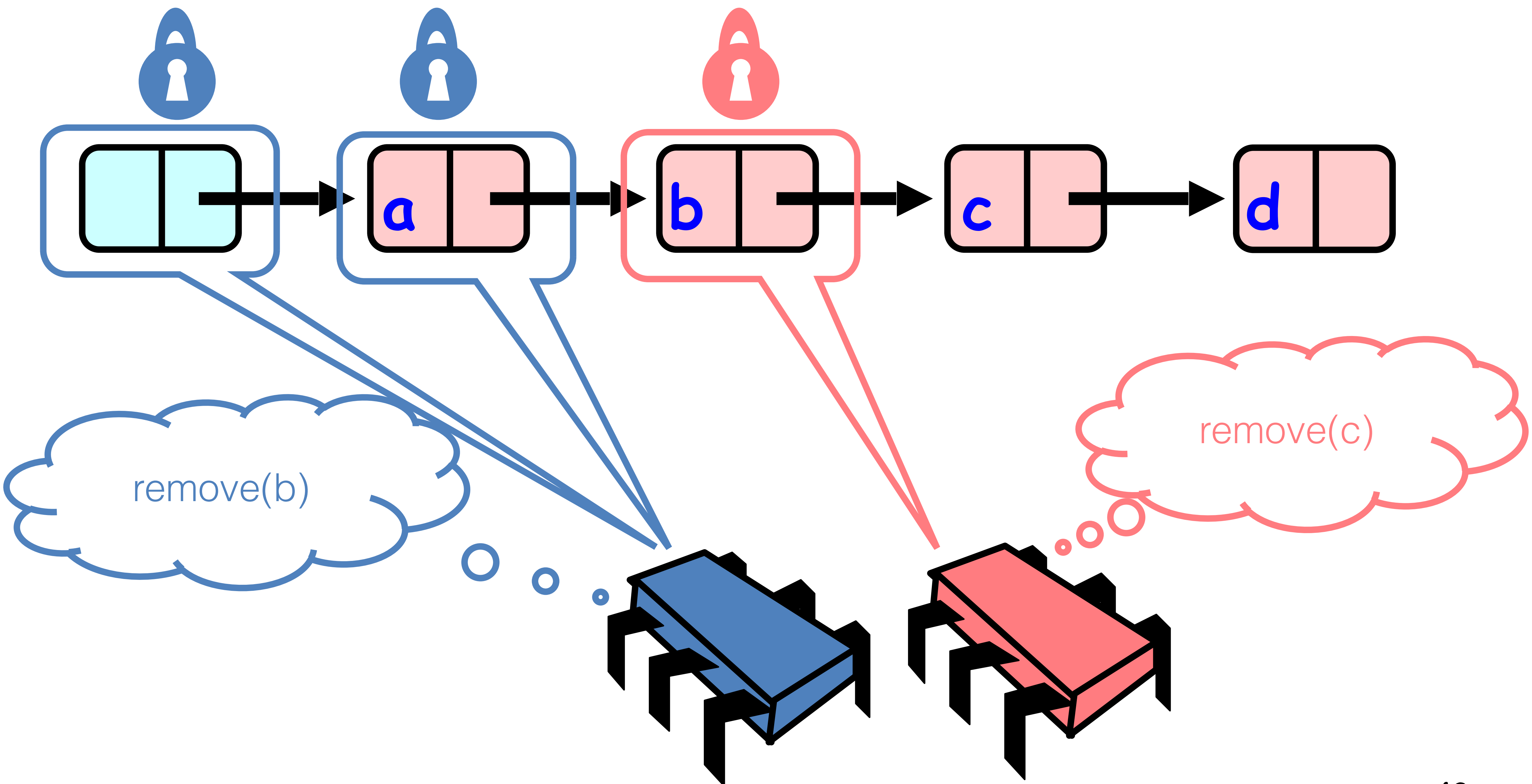
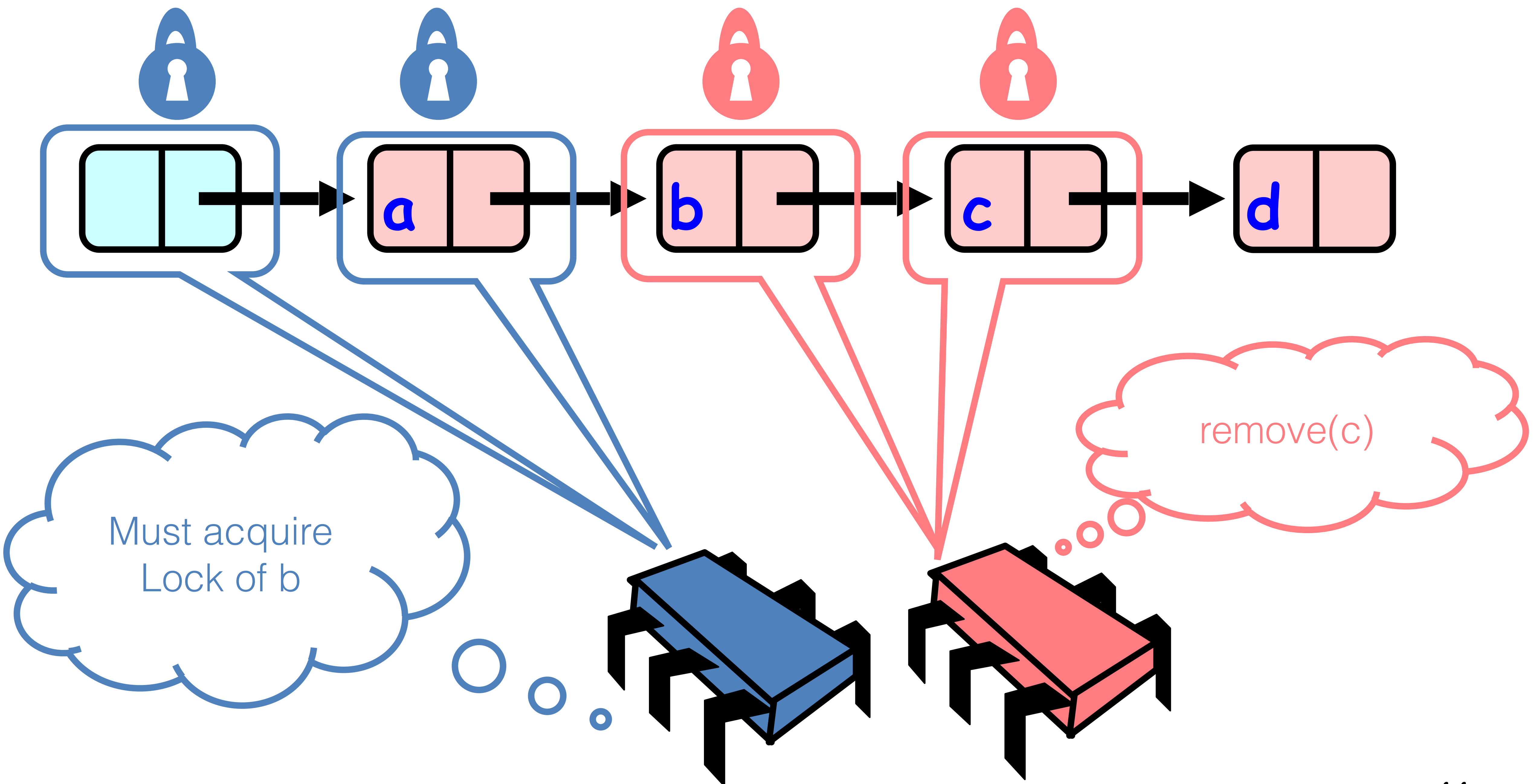


Removing a Node



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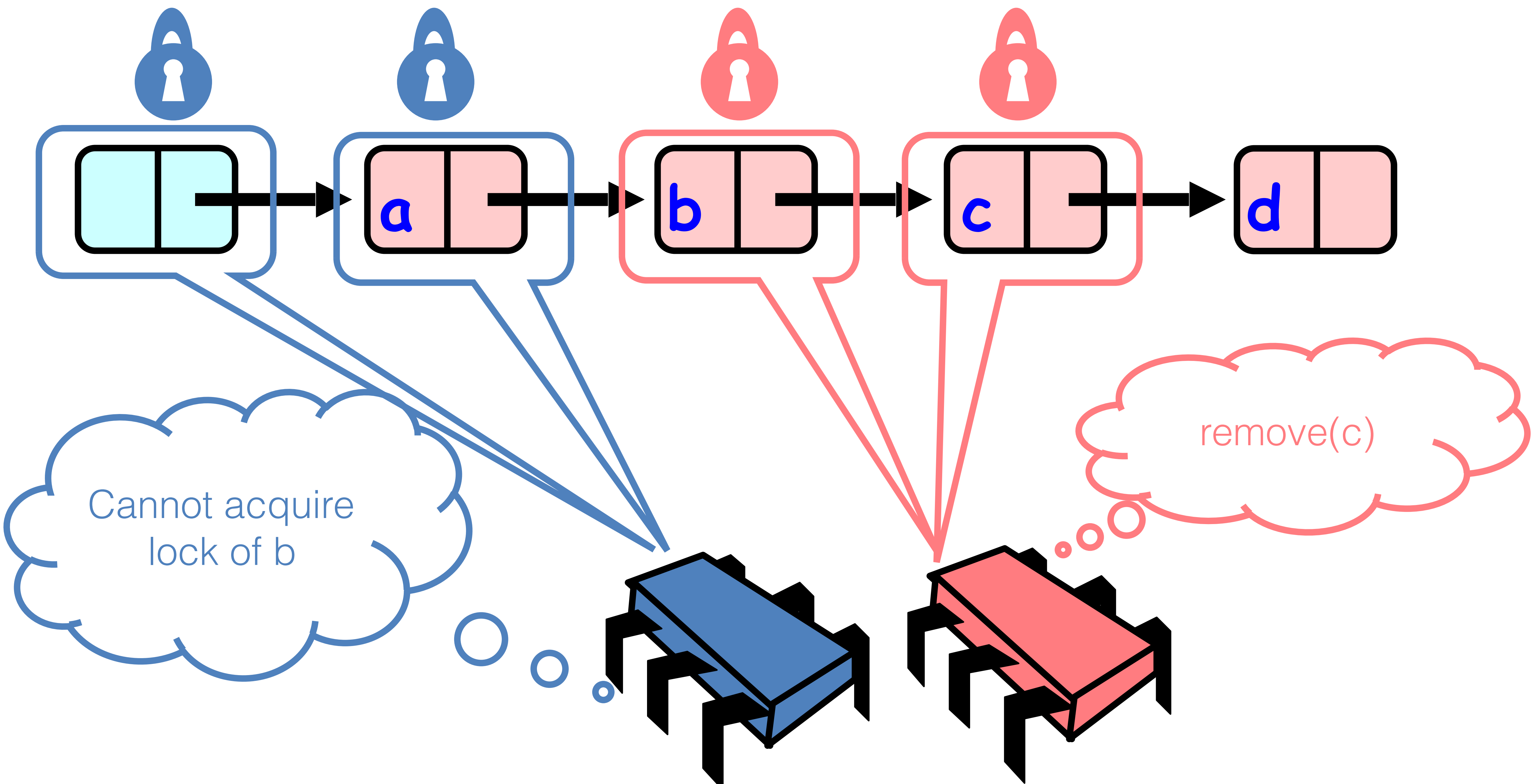

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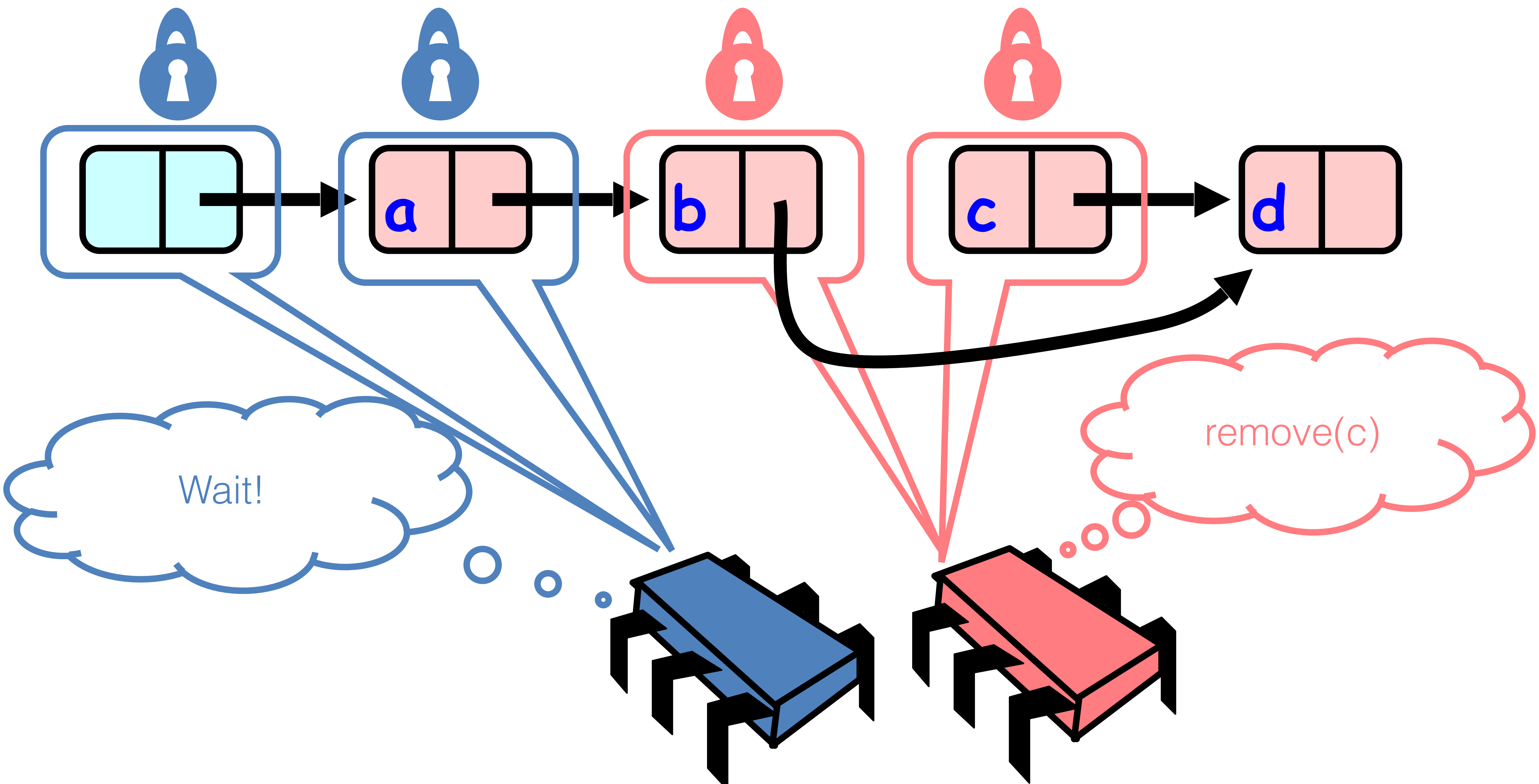

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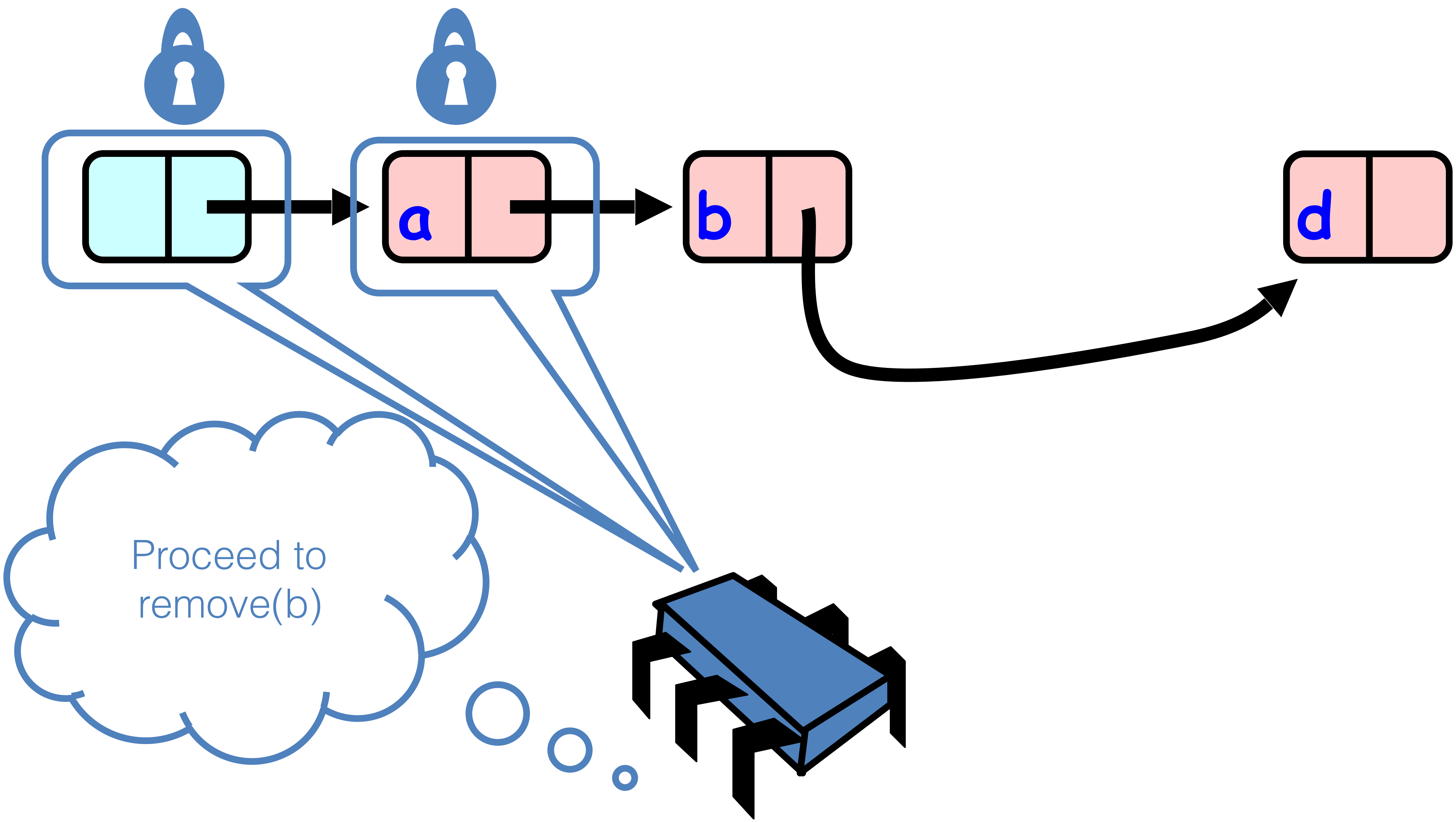

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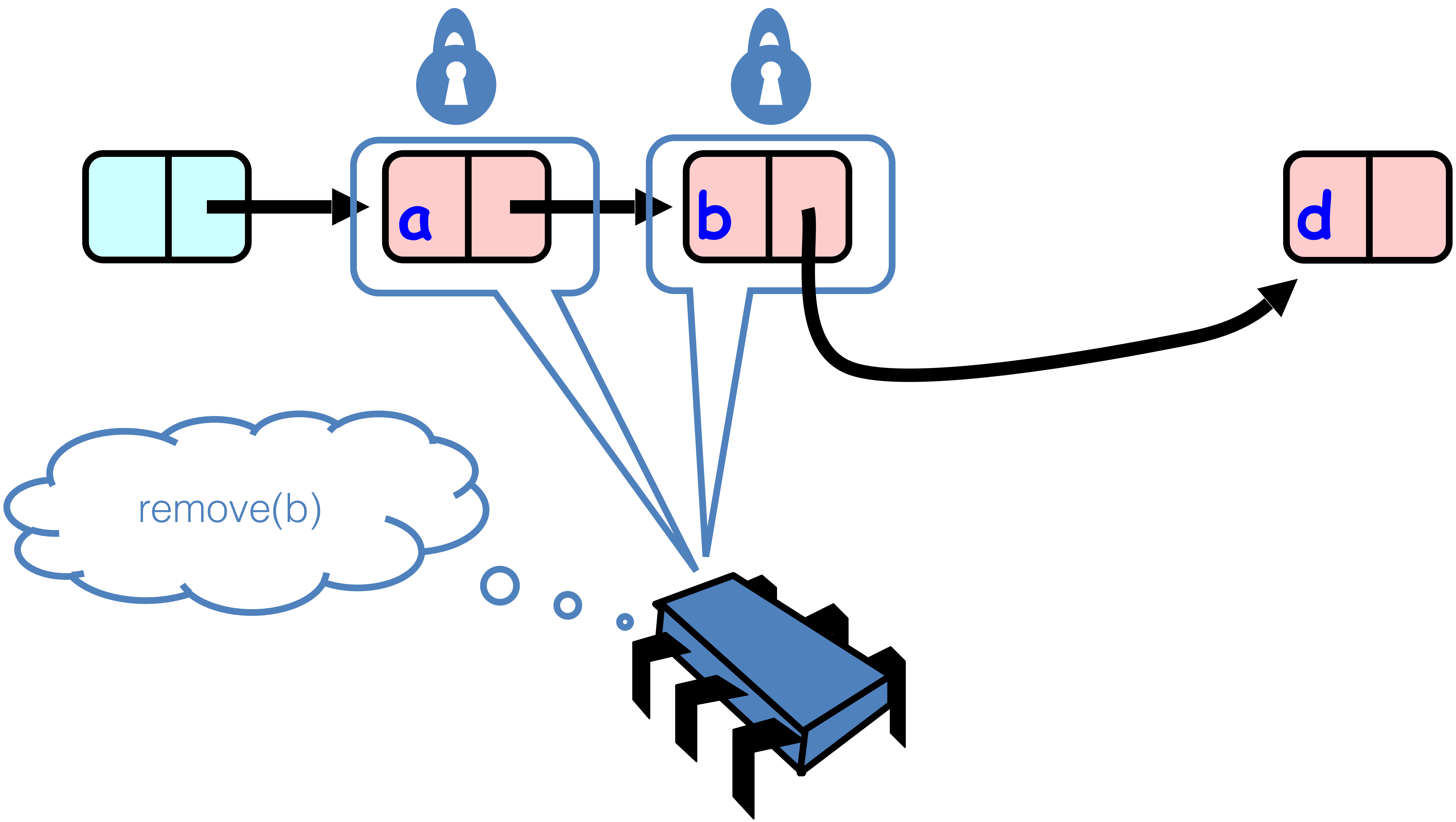

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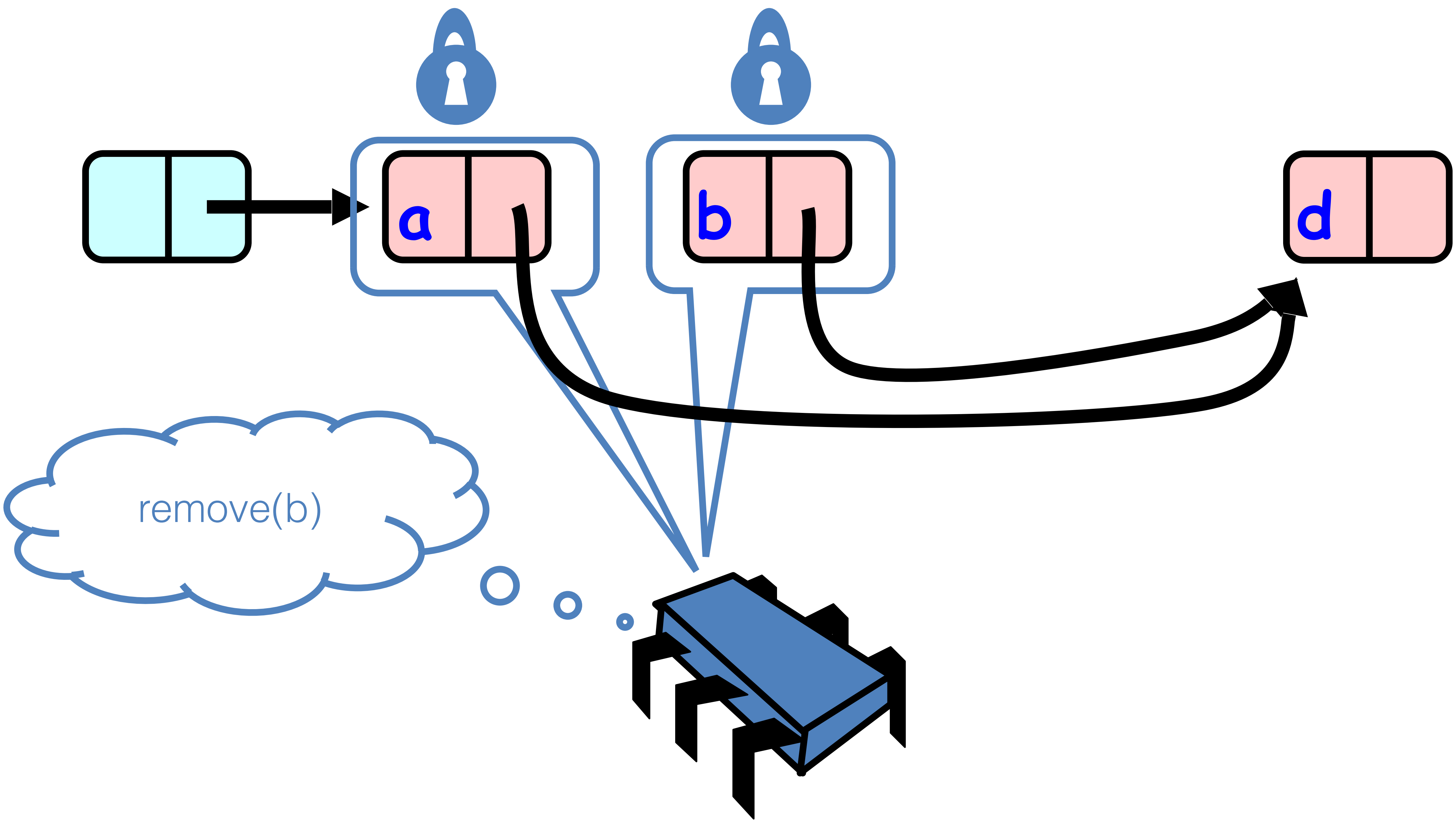
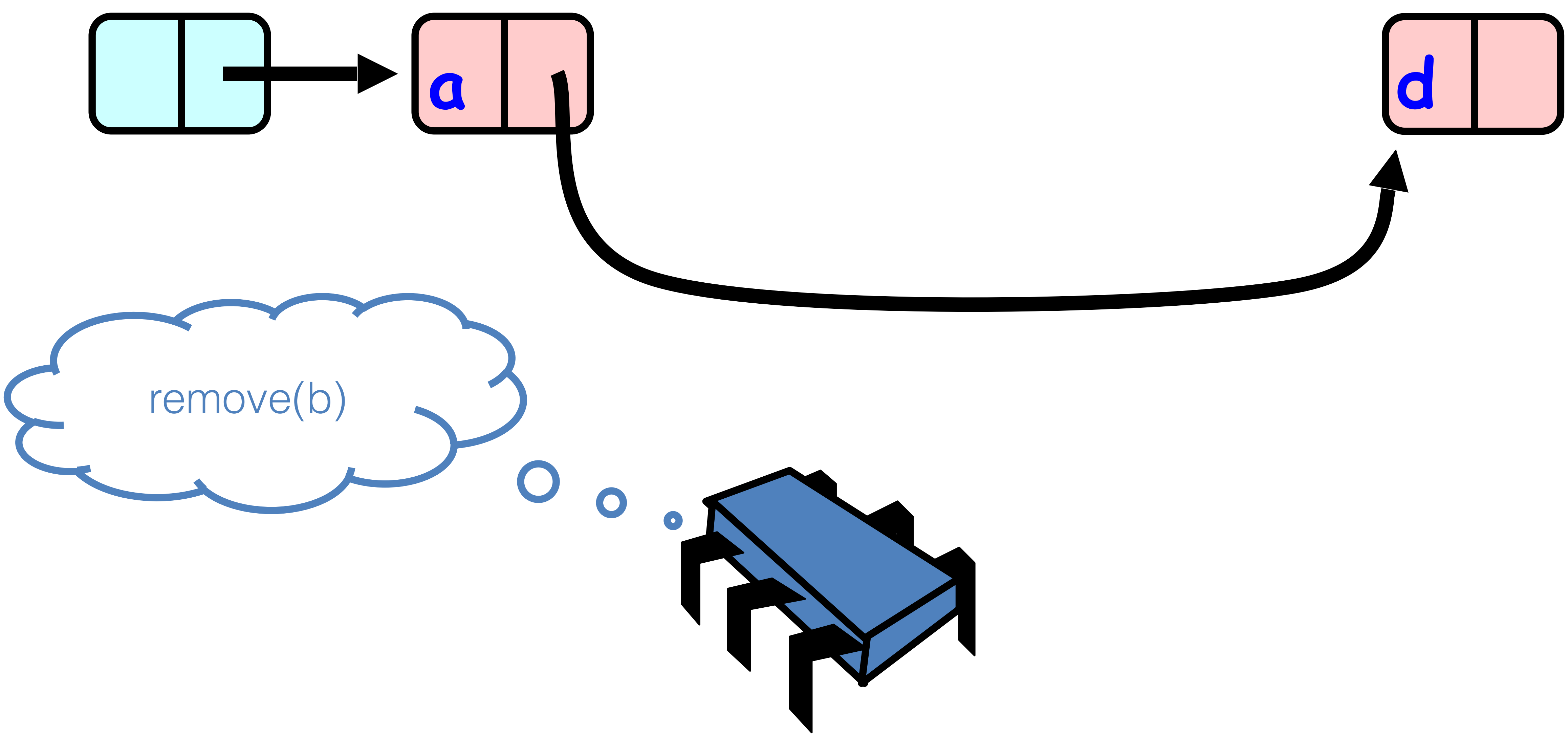
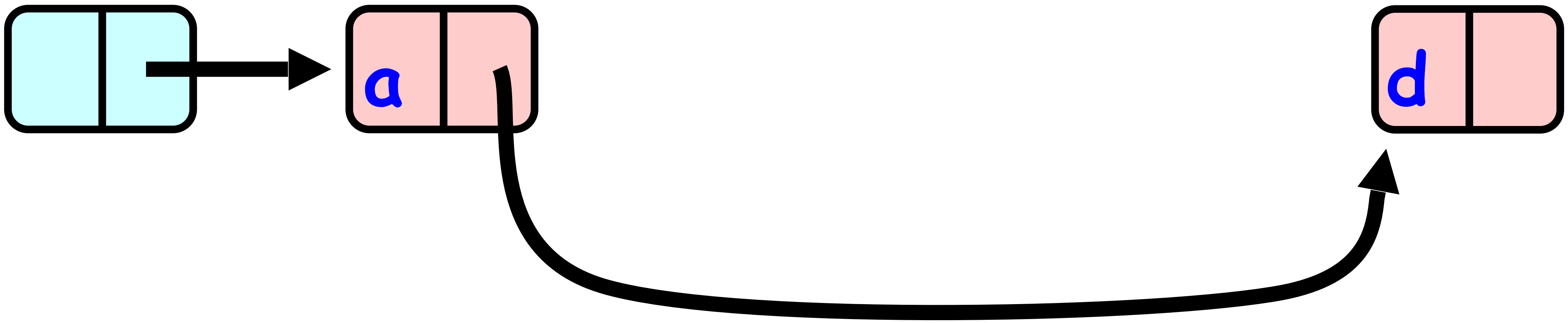


Removing a Node



Removing a Node



Adding Nodes

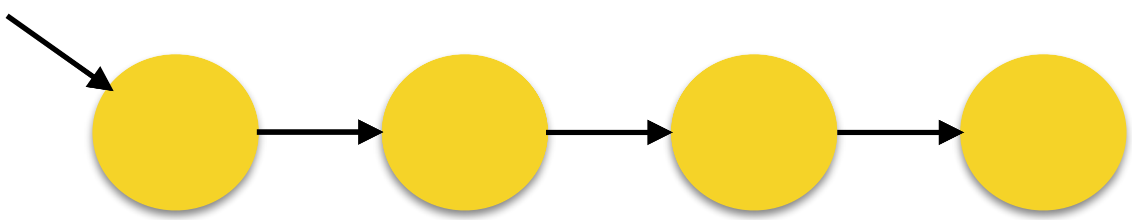
- To add node e
  - Go hand-over-hand
  - Lock predecessor
  - Lock successor
- Neither can be deleted
- Actually it is enough to lock predecessor (for an insert).
  - But must go hand-over-hand.

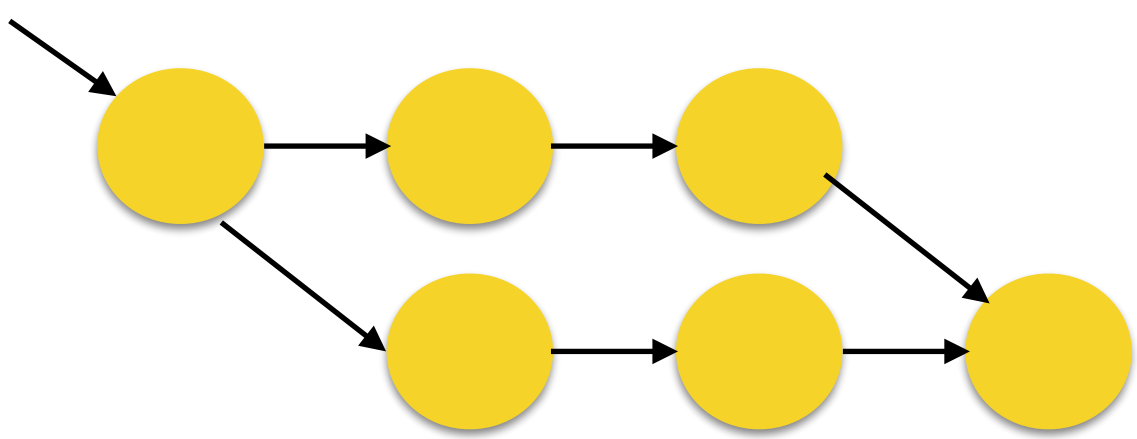
No Deadlock

- In general, no deadlock if locks are always acquired in the same order.

Why Is It Correct

- The idea: snapshot.
- Each thread sees all operations executed “earlier”, and no operation that started “afterwards”.
- Start time: take head’s lock.
- Implications:
  - sequentialization of operations
  - Good only for “hierarchical” data structures.





Properties

- Scalability better than coarse-grained locking.
- But long chains of threads waiting for the first thread to advance.
  - Limited parallelism.
- Excessive locking harms performance.

- Can we obtain more parallelism and better performance?

Second List: Optimistic

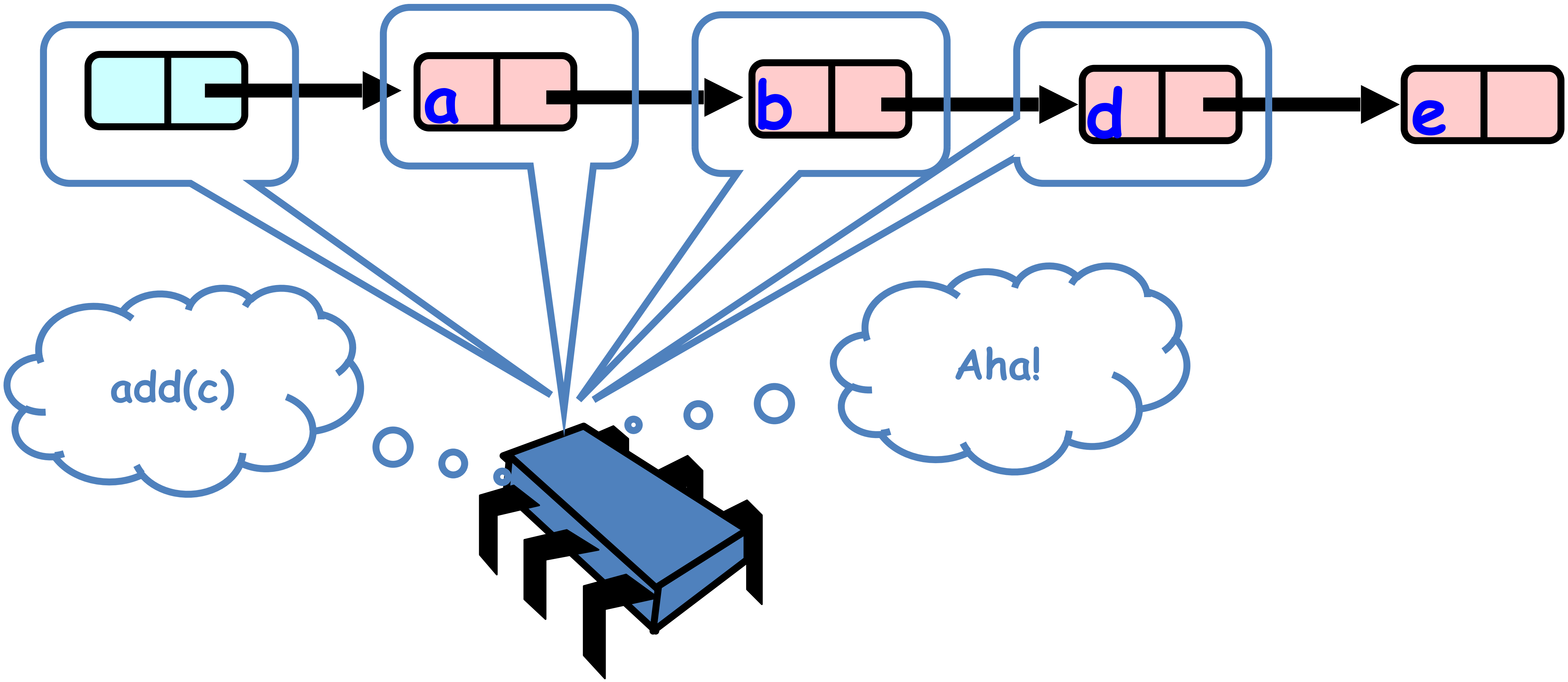
(First was hand-over-hand.)

Optimistic Synchronization

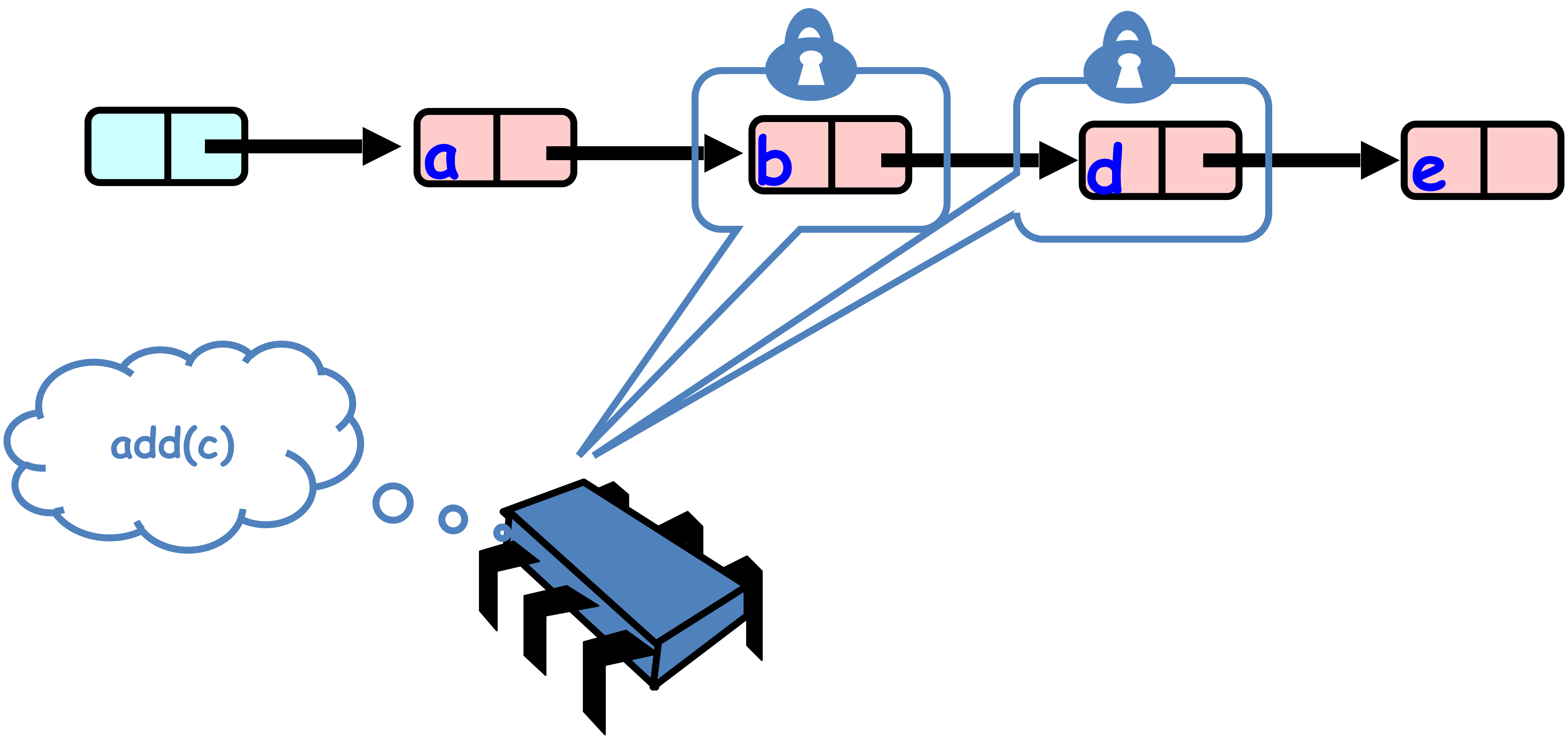
[Herlihy-Shavit 2008]

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

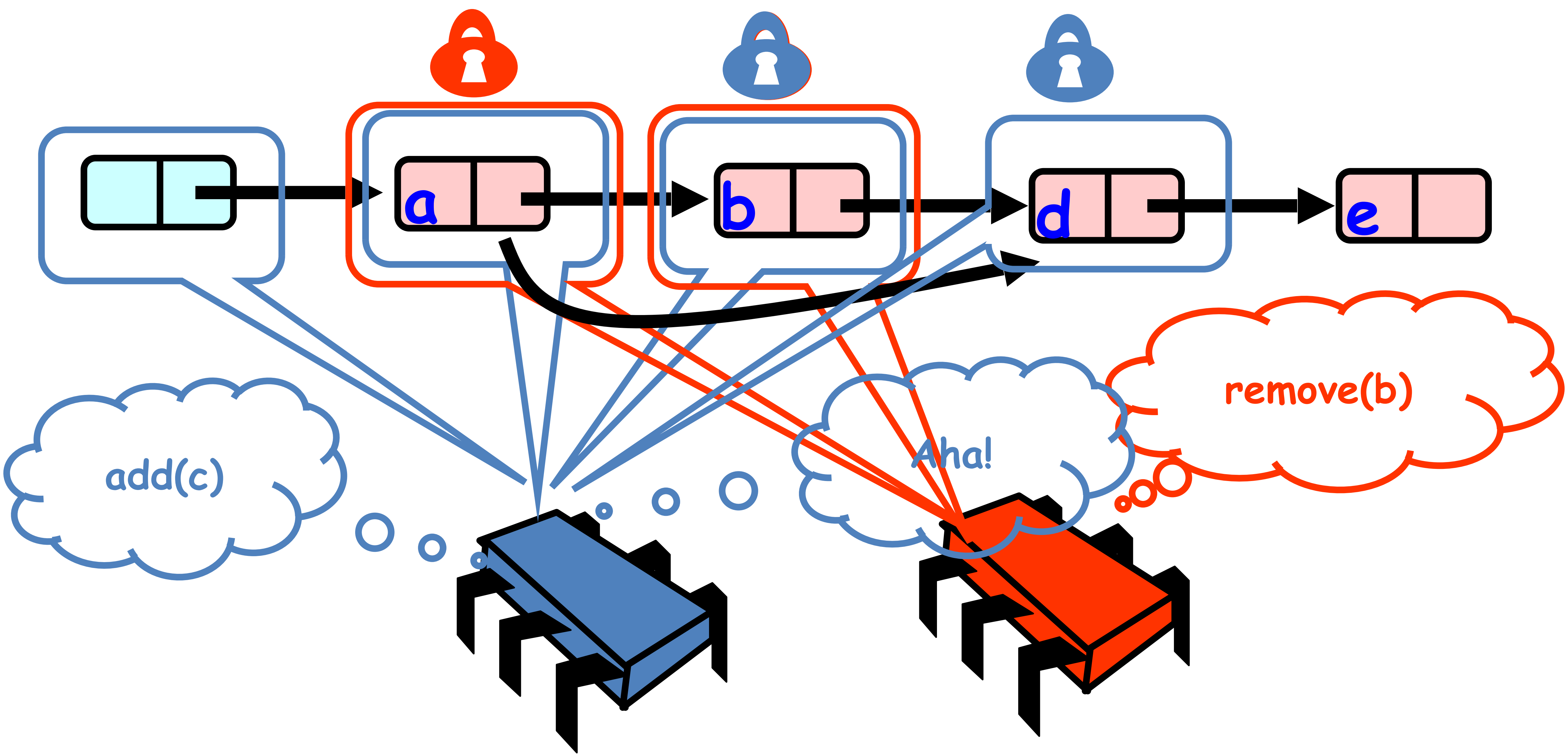
Optimistic: Traverse without Locking



Optimistic: Lock and Load



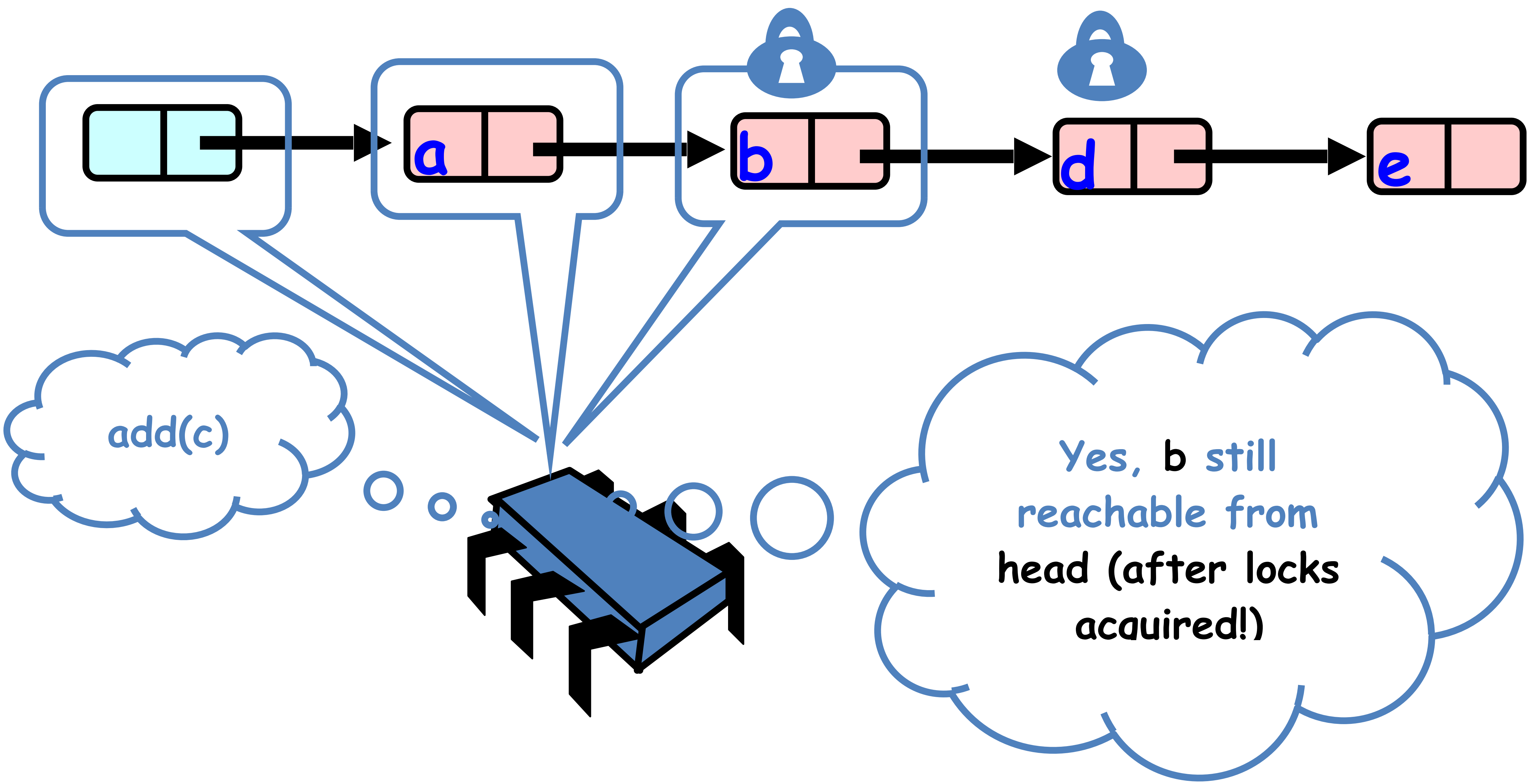
What could go wrong?



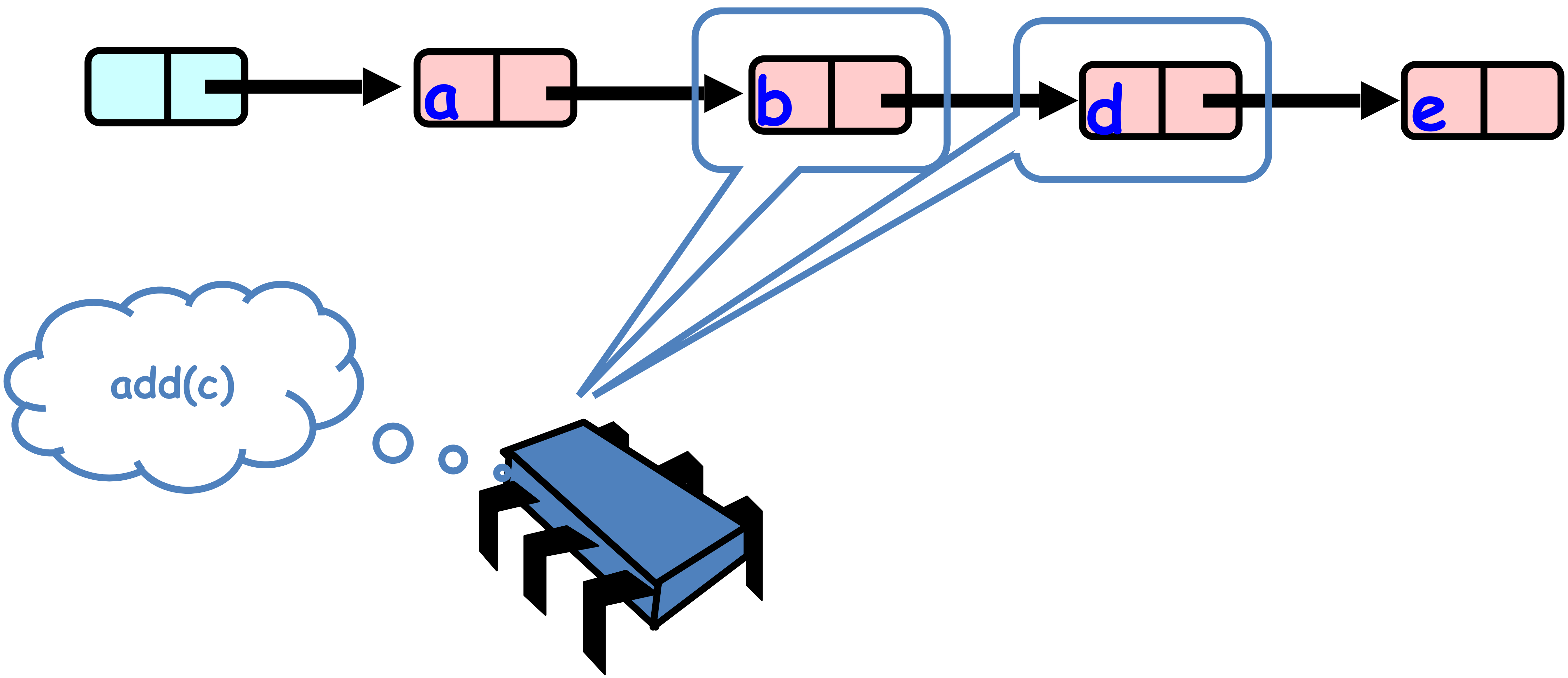
First node must be in the list!

- While holding the lock, check that first node is reachable from the head
- While we hold the lock this node cannot be removed.

Validate – Part 1 (while holding locks)



What Else Can Go Wrong?



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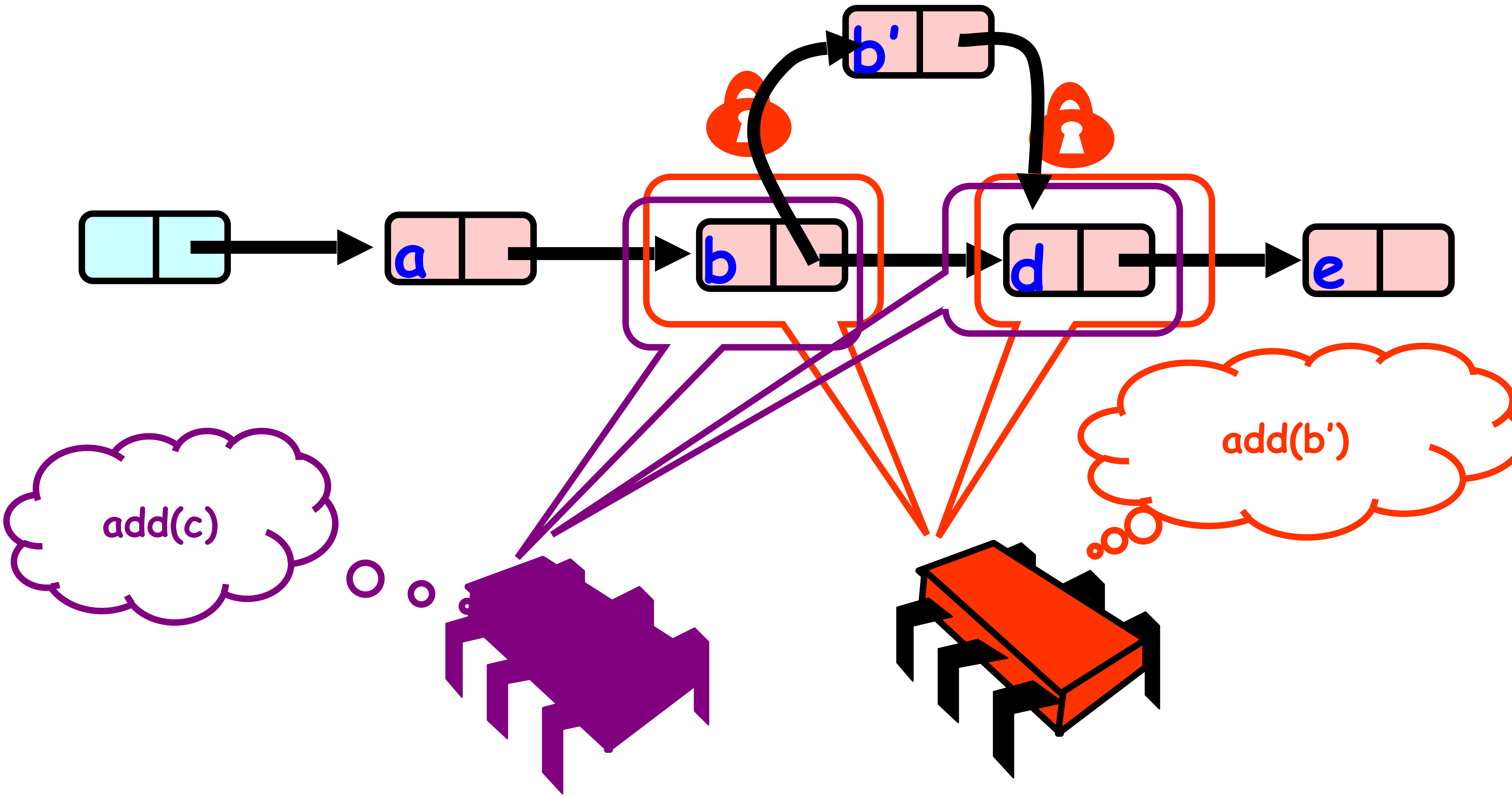
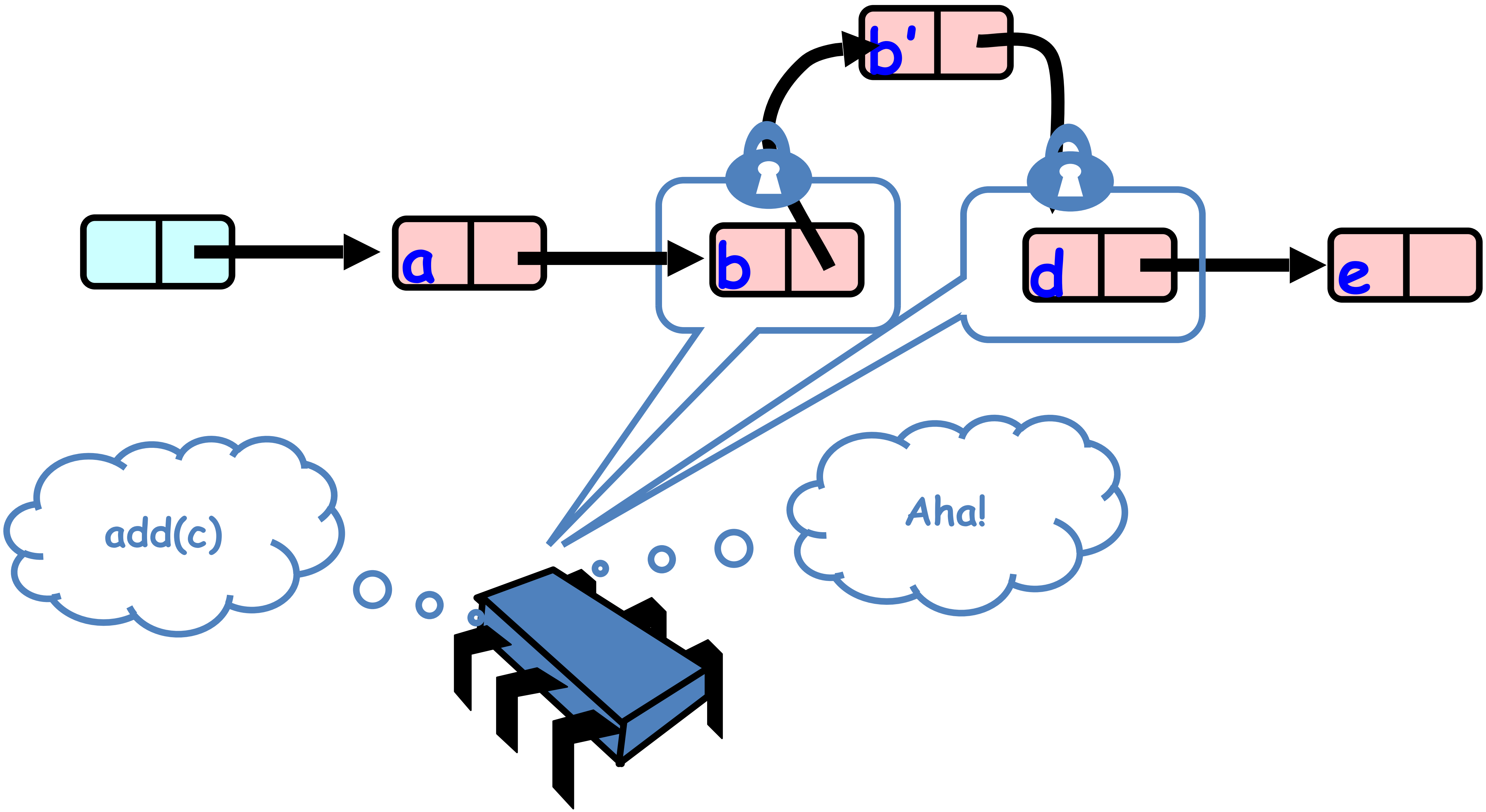


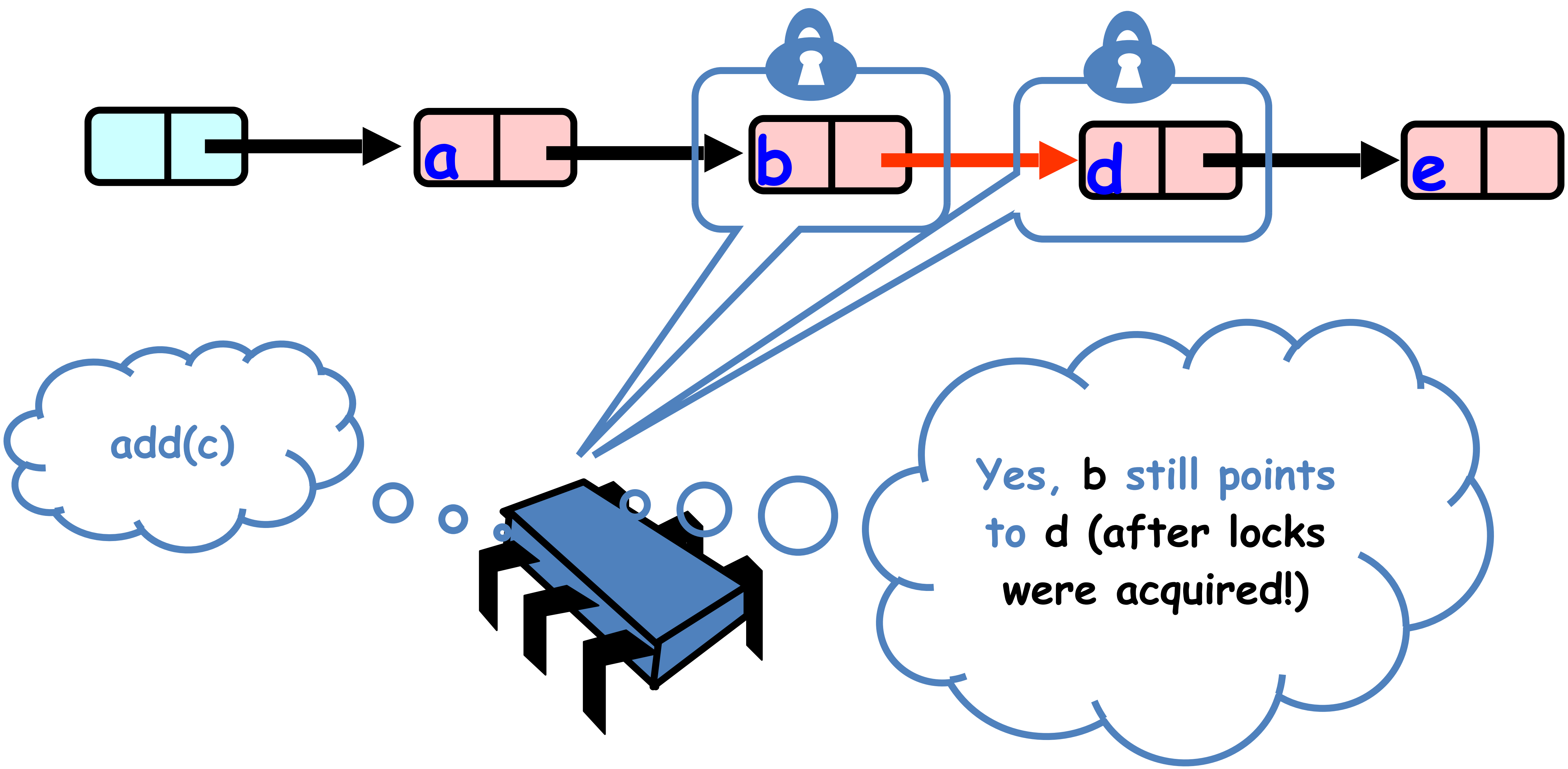
What Else Can Go Wrong?



First node must still point to second!

- Validation 1: first node still reachable.
  - While we hold the lock the node cannot be removed.
- Validation 2: first node pointing to second.
  - While we hold the lock the pointer from the first node cannot be modified (no adding and no removing).

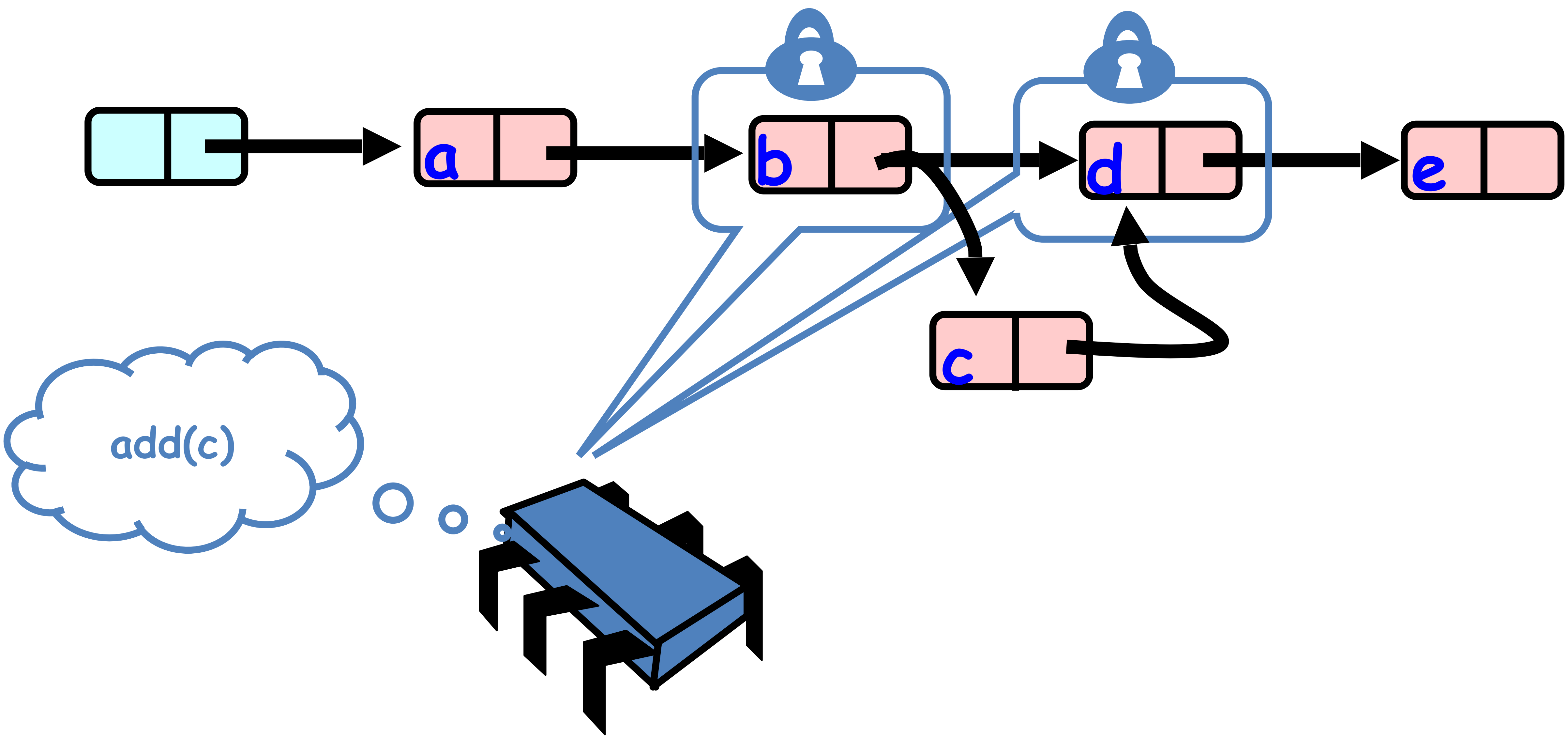
Validate Part 2
(while holding locks)



Validation Failure?

- Upon failure to validate start from scratch.
- Assumed to happen infrequently.

Insert (After Validation)



Optimistic Synchronization

- More parallelism, better scalability.
  - Only lock nodes where actually modifying.
  - Scalability depends on the actual workload.

- Excessive work on validation (double traversal).
  - Less efficient.

- There is another fine-grained locking methodology.
  - But let’s jump to lock-freedom

Third List: Lock-Free

We did hand-over-hand and optimistic

Lock-Freedom

- Don’t use locks.
- And more important: guarantee progress!
  - Complete robustness against worst-case scheduling
  - No swapping problems
  - Even when a thread dies, the other threads will continue to make progress.

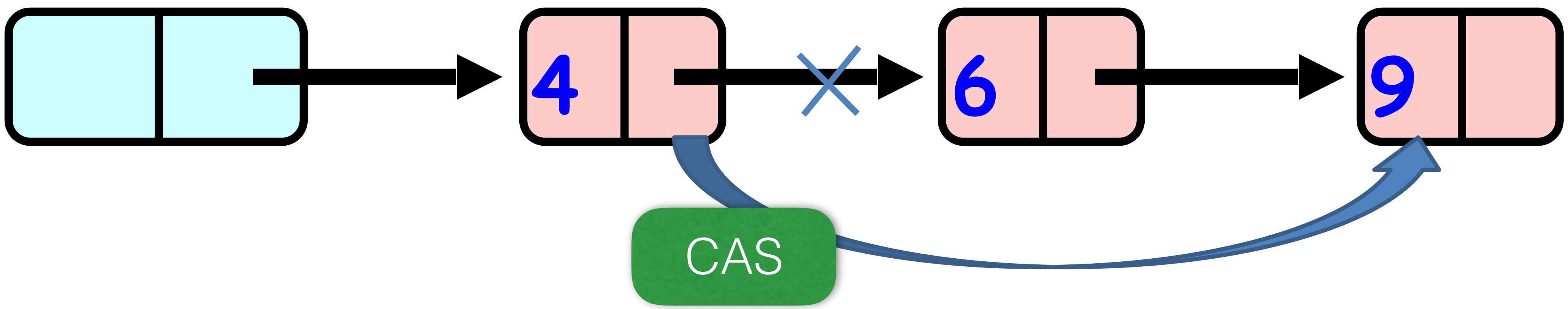
- Design by [Harris 2001], improvement by [Michael 2002].

Lock-Free Linked Lists
[Harris-Michael 2001-2]

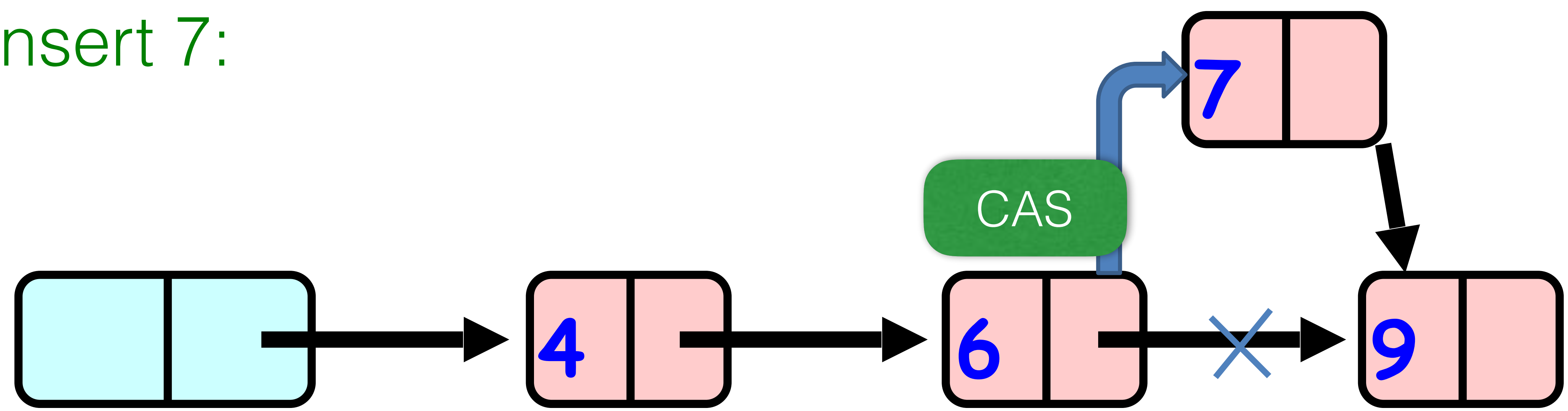
- First attempt: insert/delete using CAS instead of a regular read/write operation.

First Attempt: Use CASes Instead of Locks

- Delete 6:

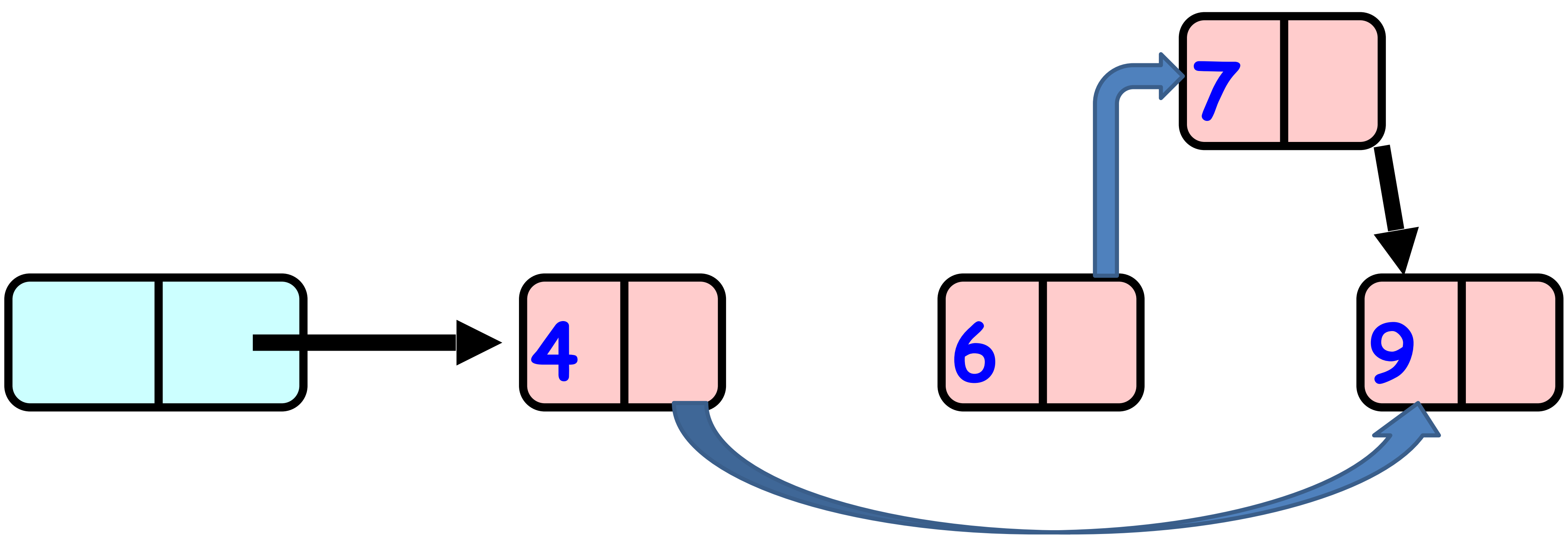


- Insert 7:



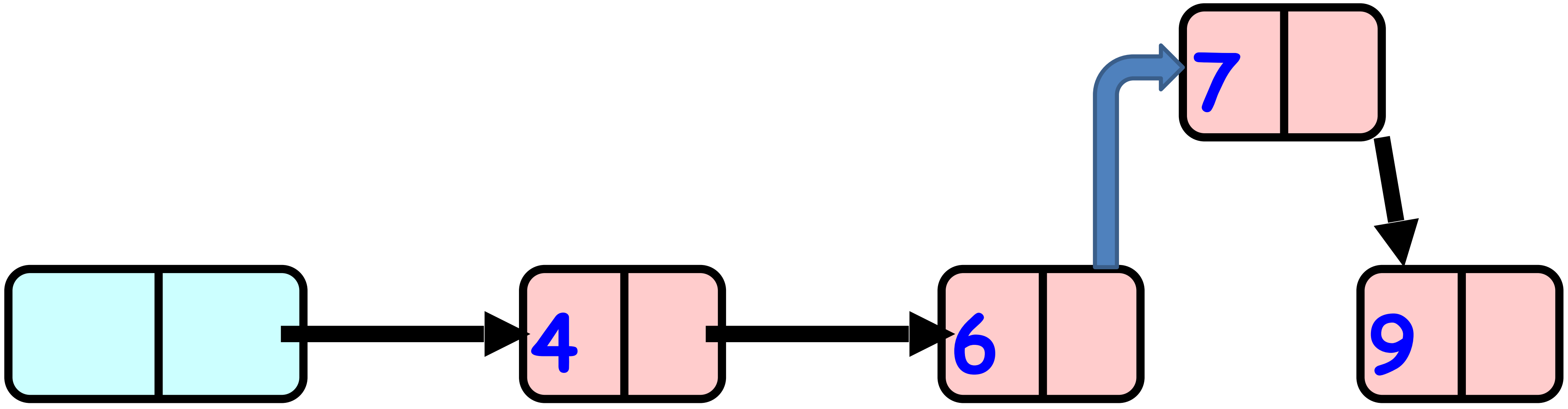
The original problem still exists

- Outcome for deleting 6 and inserting 7 in parallel:



We Keep the Simple Insert

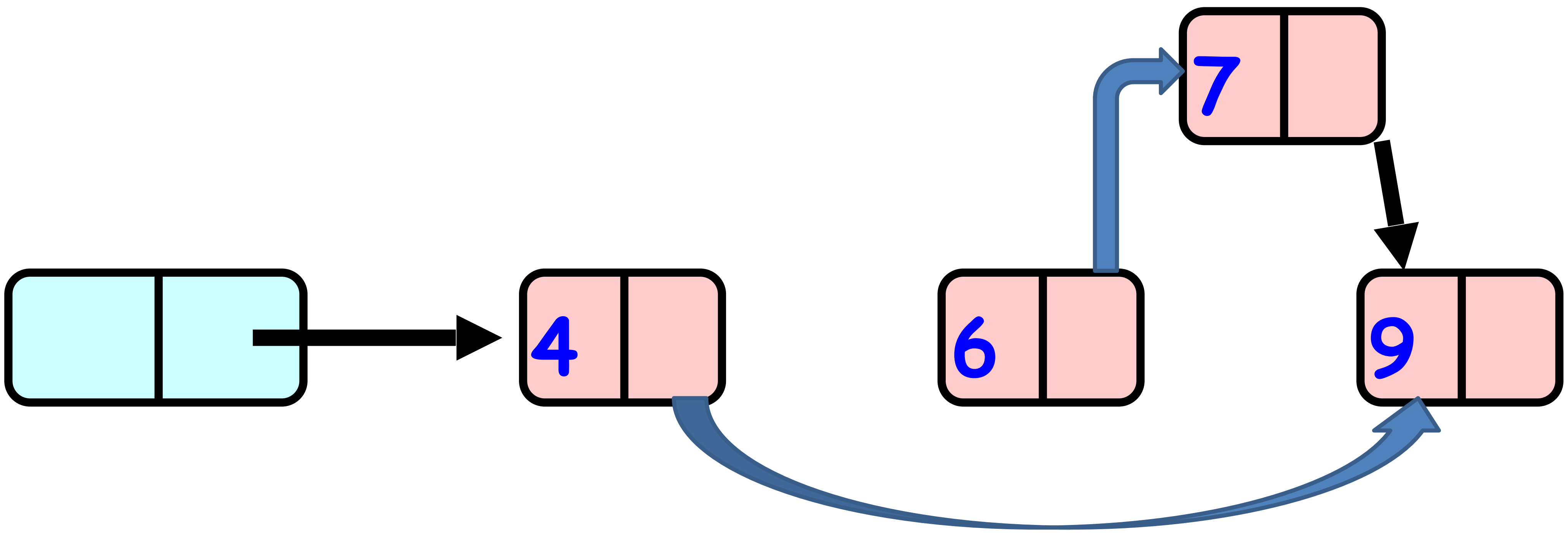
- A single CAS to insert 7, after locally allocating and initializing it.



- But *delete* will be more complicated.

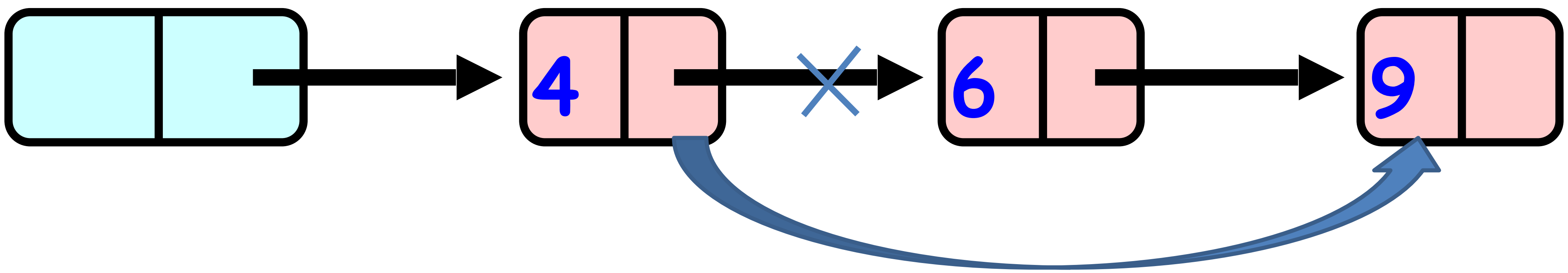
Recall the Problem

- Outcome for deleting 6 and inserting 7 in parallel:



The Crux of the Problem

- When deleting 6, we want to block changes both on the pointer that points at 6, as well as the pointer that points out of 6.



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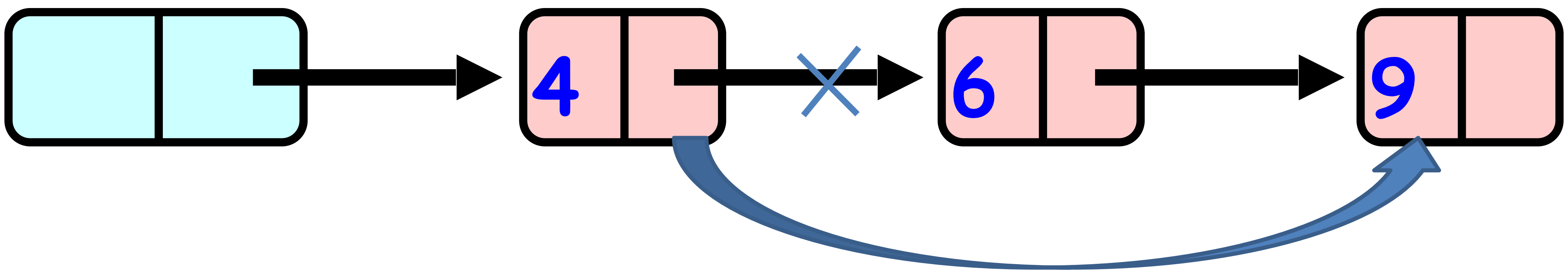
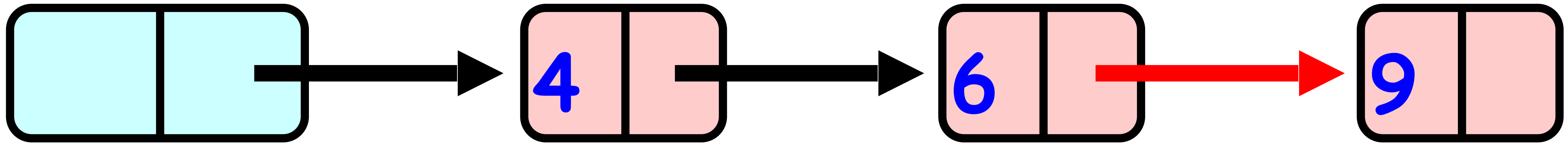


- Harris's idea:

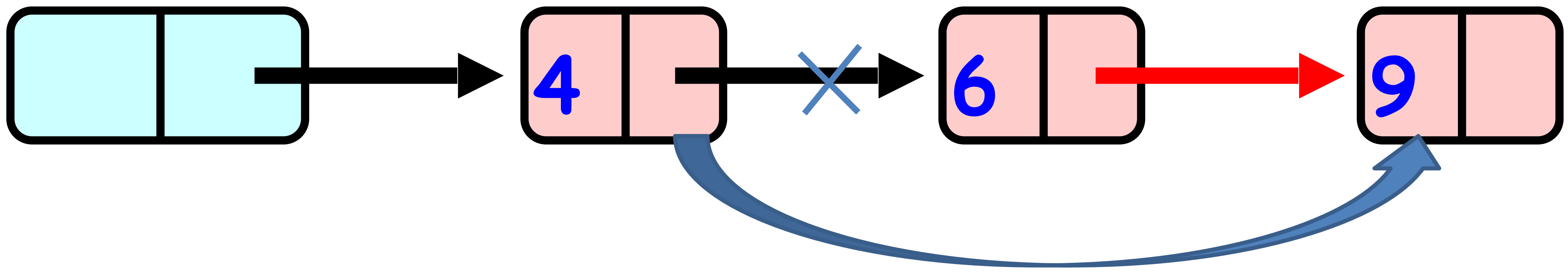
1. "mark" the pointer out of 6, and then
2. "modify" the pointer out of 4.

Solution: Mark & Delete

- Logically delete 6 by marking the outgoing pointer of 6.



- Physically delete 6 by unlinking it from the list.



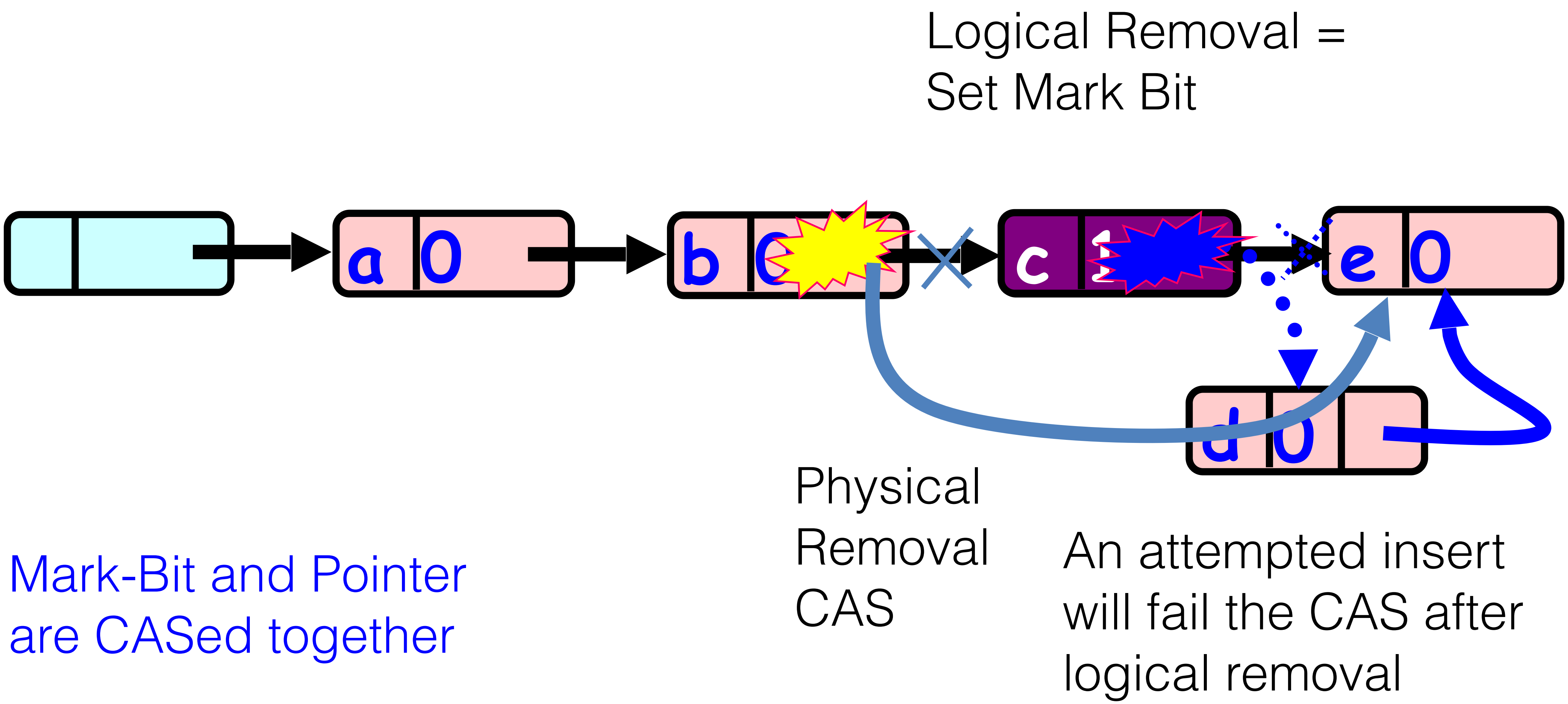
Implementing a “Red Pointer”

- Use least bit.
- Essentially unused with pointers as words are composed of 4 or 8 bytes.

Unmarked: 00010…10100101011100000100

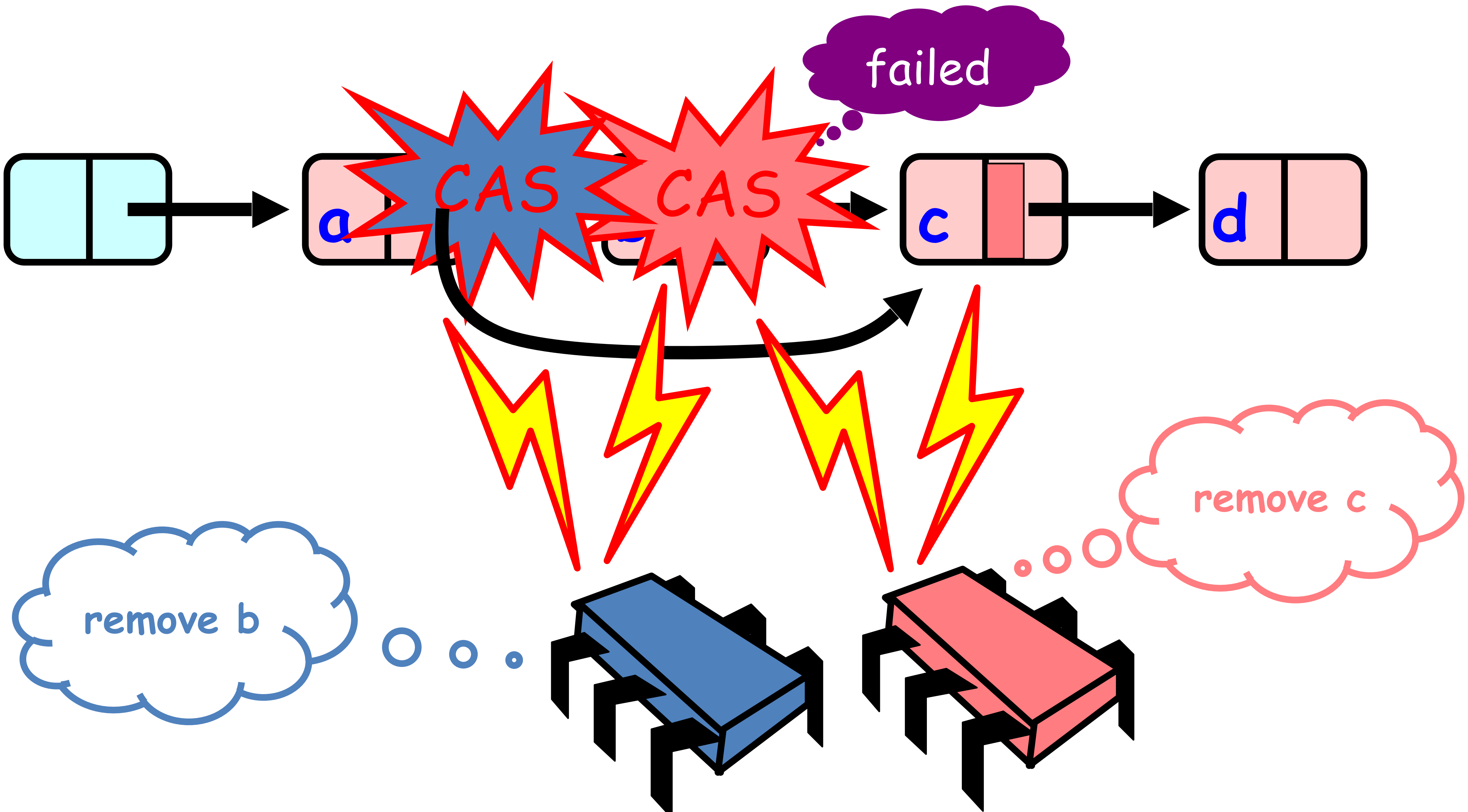
Marked: 00010…10100101011100000101

Logical Deletion

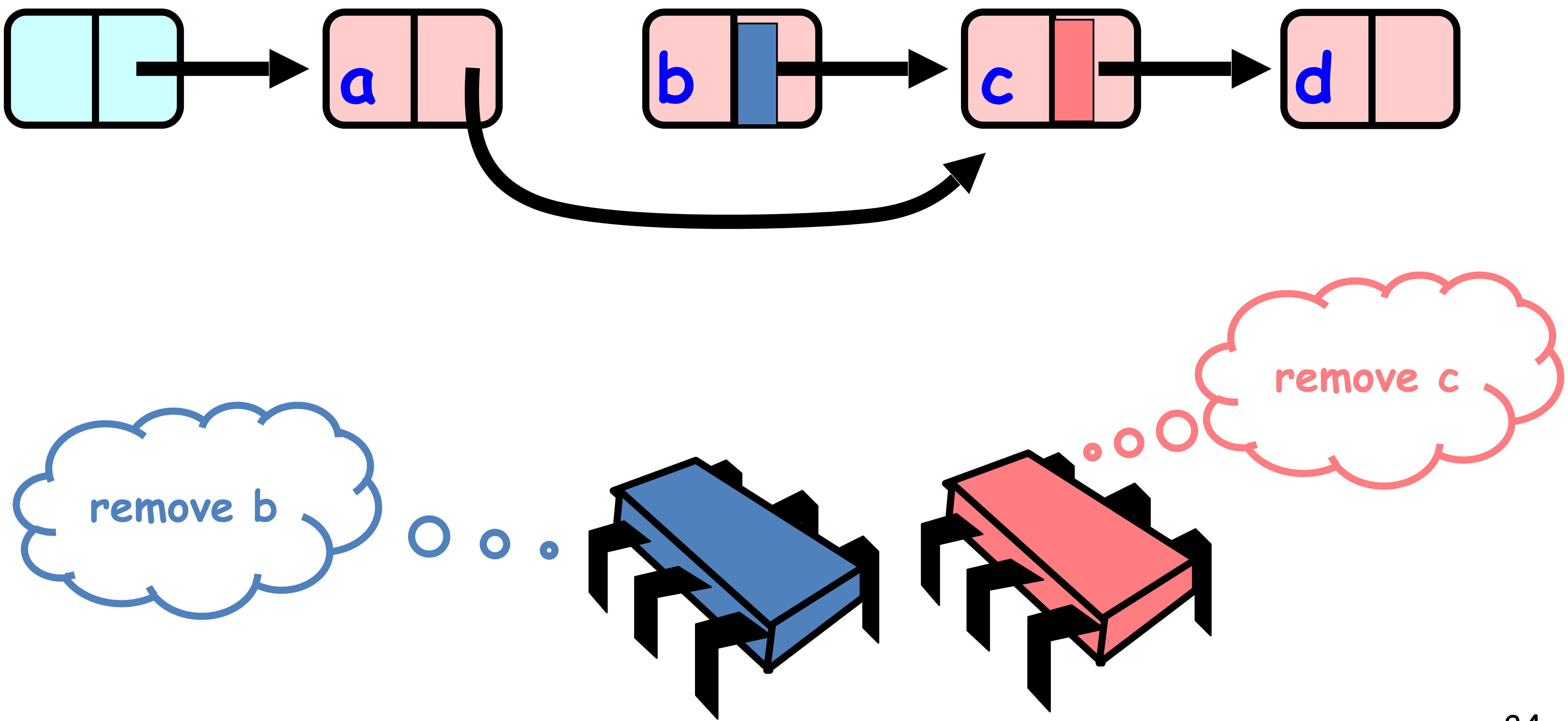


Mark-Bit and Pointer
are CASed together

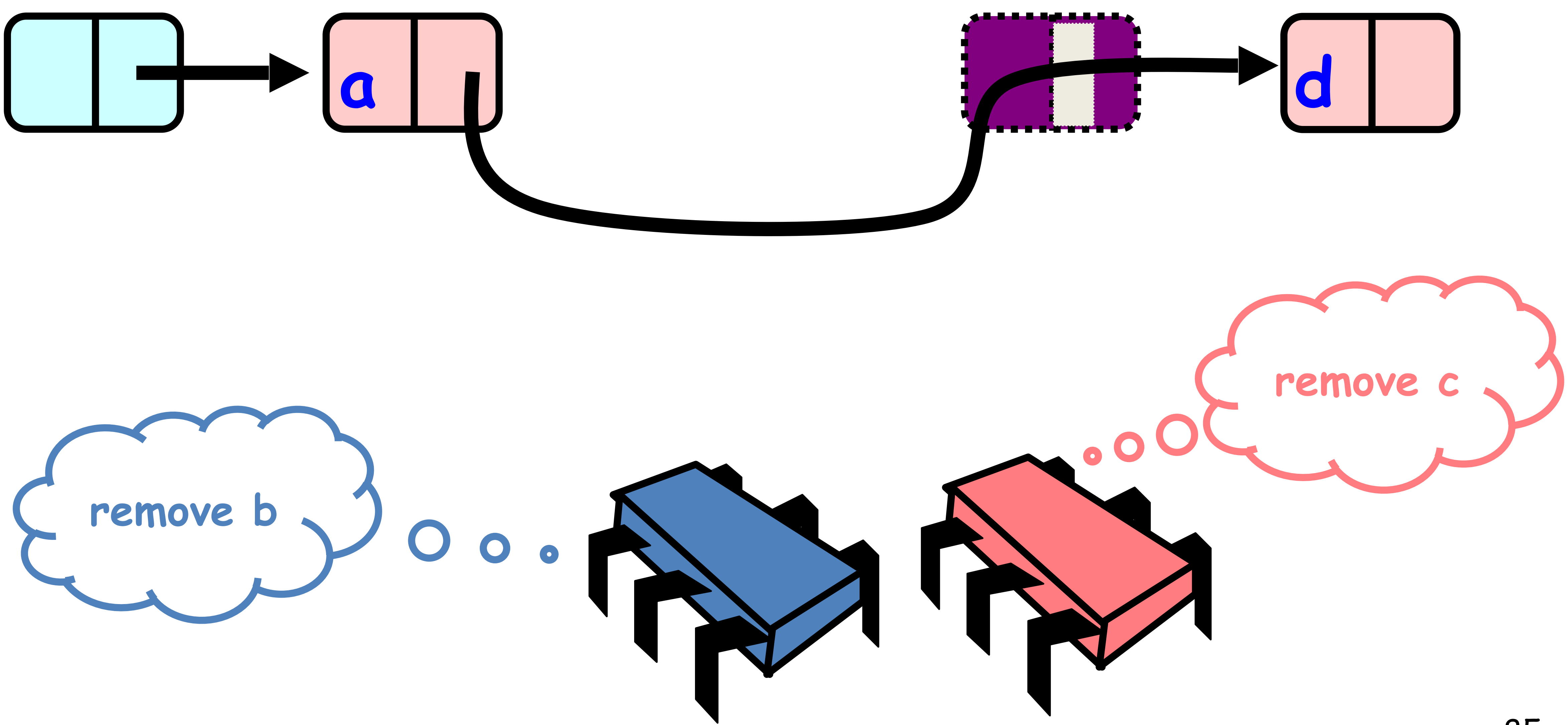
Concurrent Removal



Removing a Node



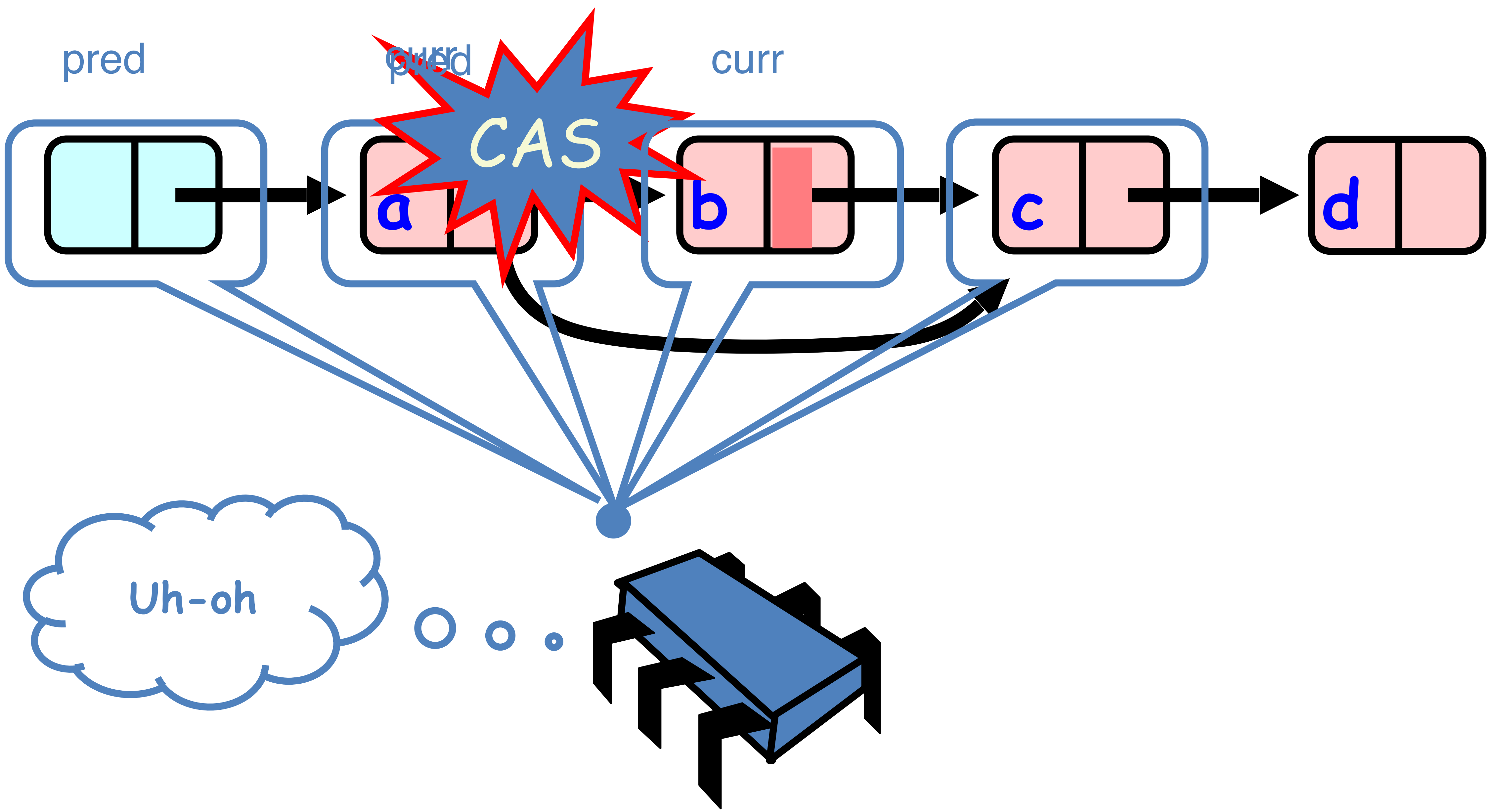
Removing a Node



Traversing the List

- When you find a “logically” deleted node in your path:
  - Finish the job:
    - CAS the predecessor’s next field,
  - Proceed (repeat as needed).

Lock-Free Traversal (only Add and Remove)



CAS Failures

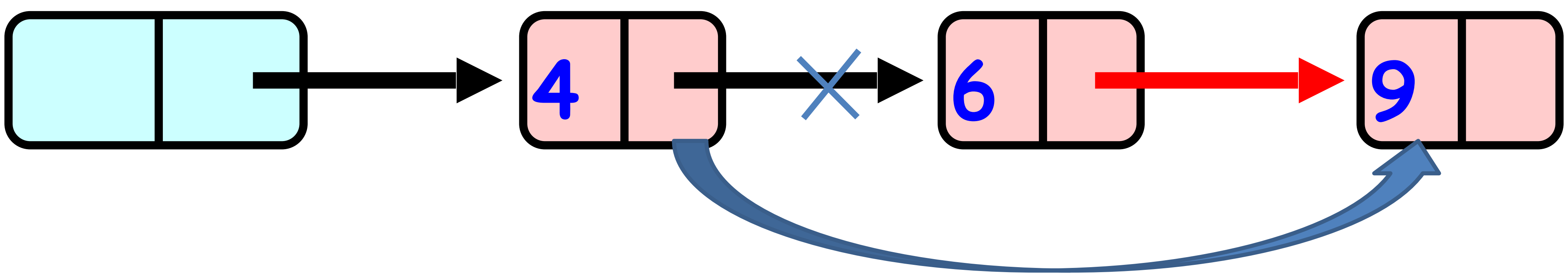
- Node removal:
  - Logical remove fails: start from scratch.
  - Physical remove fails: ignore.
    - Why?
- Node insert:
  - CAS fails: start from scratch.

Why is it Lock-Free?

- Node removal:
  - Logical remove fails:
    either someone else has succeeded to remove this node, or someone else has inserted a node.
  - Logical remove succeeds:
    I succeeded to delete a node (and will finish the operation after trying the physical remove once).
- Node insert:
  - CAS fails: someone else succeeded to insert or delete a node.
  - CAS succeeds: I succeeded in inserting a node.

The Main Intuition

- Logical marking locks the next pointer from being modified.
- But this “lock” can be unlocked by anyone (by trimming the node from the list), so no one is stuck.
- Different from “normal” locking that only the owner can unlock.
- This is the methodology in all lock-free algorithms:
  - Make a change in the data structure, leaving it “unstable”.
  - Anyone can stabilize the data structure and continue to work on it.



Progress Guarantees are good for

- Real-time, OS, interactive systems, service level agreements, etc.
- But it's always good to have.
  - Avoid deadlock, live-lock, convoying, priority inversion, etc.
- Scalability.

Progress Guarantees

Great guarantee!
Until recently considered difficult to achieve and inefficient.

Wait-Freedom

If you schedule enough steps of *any thread*, *it* will make progress.

Lock-Freedom

If you schedule enough steps across *all threads*, one of them will make

Contains is Wait-Free

- Contains(key);
  - curr = head;
  - while (curr.key < key)
    - curr = removeMark (curr.next)
    - succ = removeMark (curr.next)
  - return (curr.key == key && !marked(curr.next))

Contains is important!

Fourth List:

Third (and Best) Fine-Grained Locking:

Lazy List

We discussed hand-over-hand, optimistic, and lock-free.

Lazy Synchronization

[Heller et al. 2005]

- Lock only relevant nodes
- Do not validate reachability
- Instead, leave a mark on deleted nodes, like in lock-free algorithm.

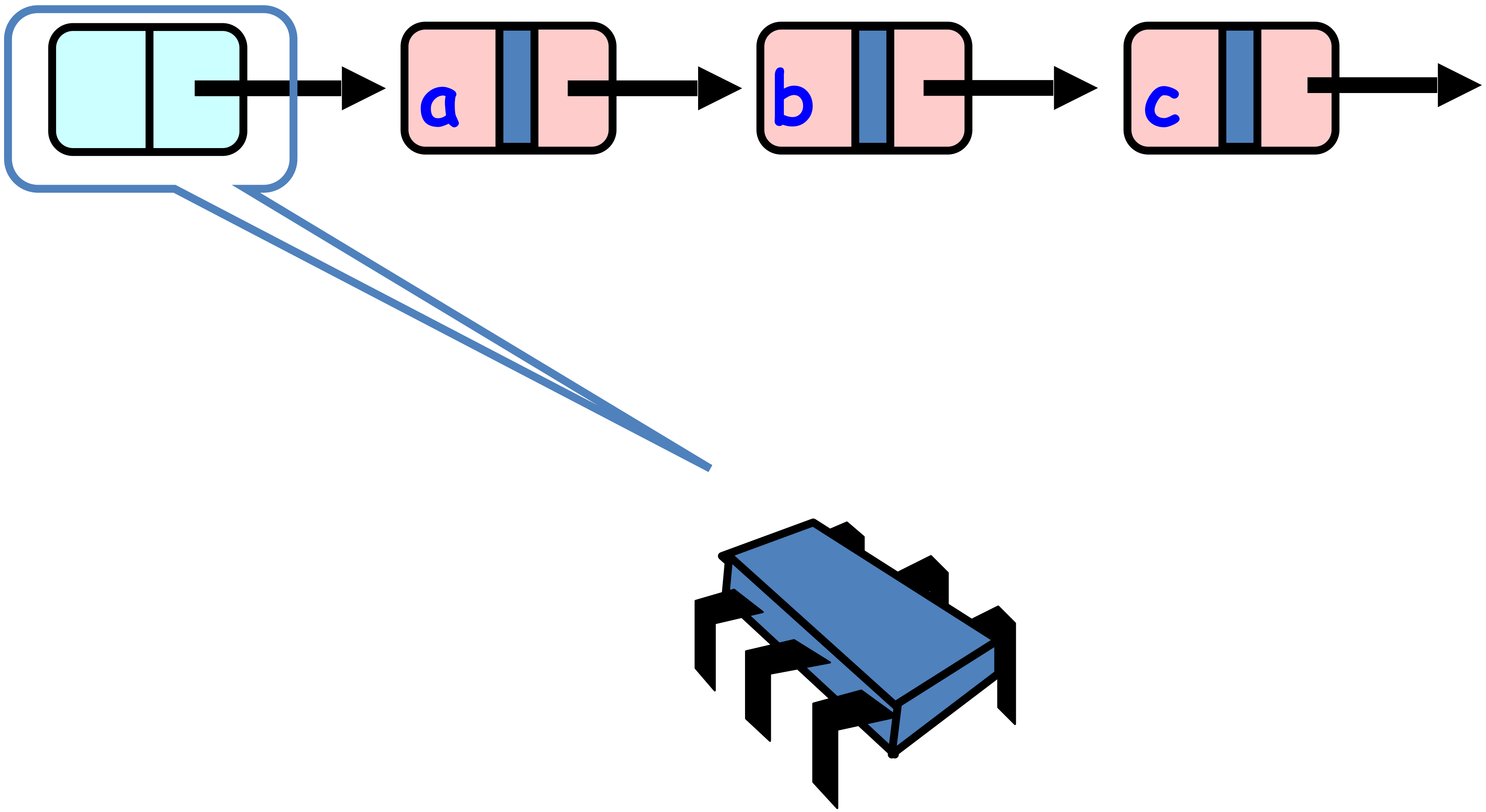
- To remove a node:
  - Logically remove it by marking it “removed”.
  - Physically remove it by unlinking it.

Remove or Add

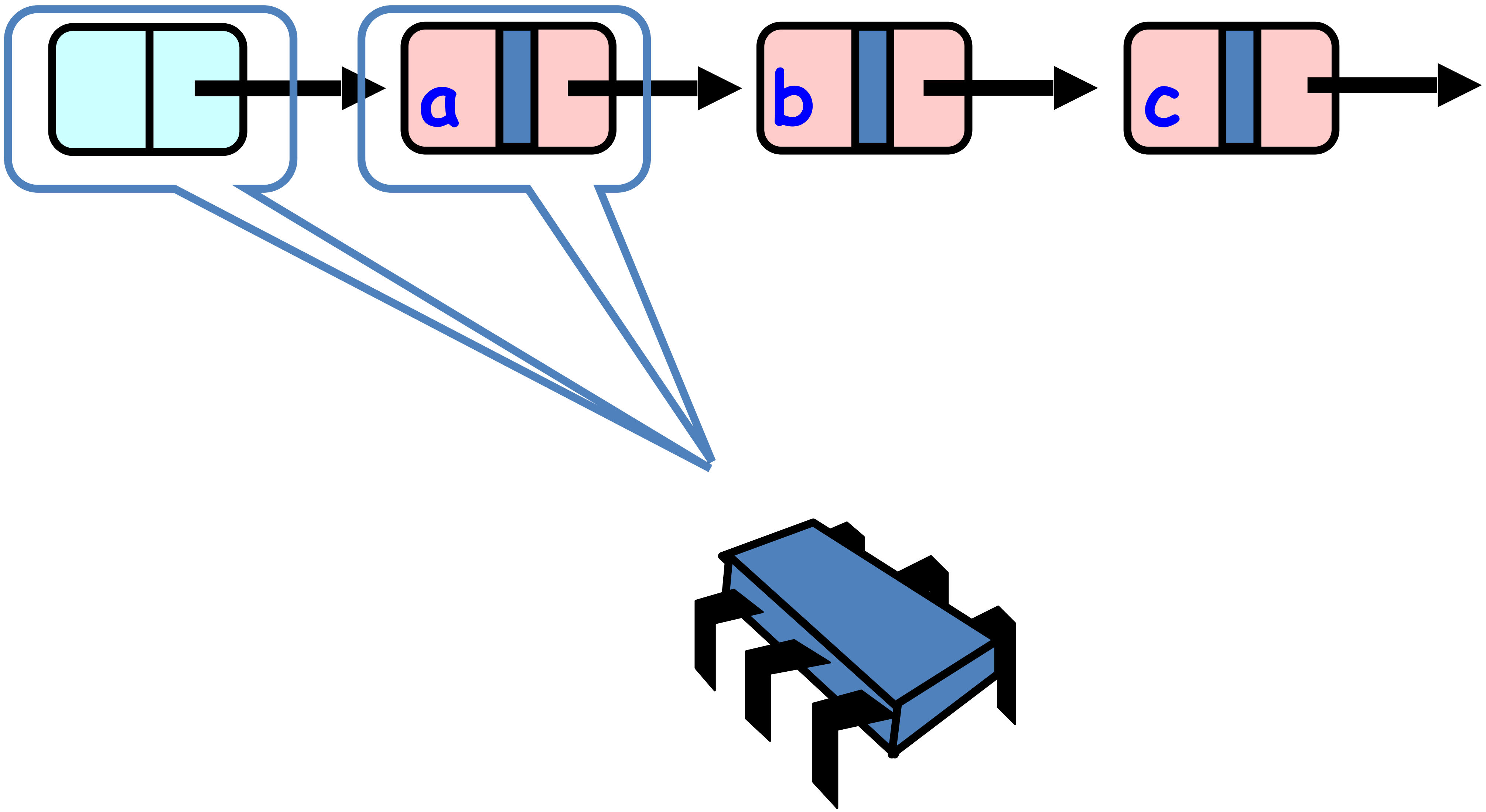
- Scan through the list
- Lock predecessor and current nodes
- validate that
  - both are not deleted, and that
  - predecessor points to current.
- Perform the add or the remove.

- Search can simply traverse the list.

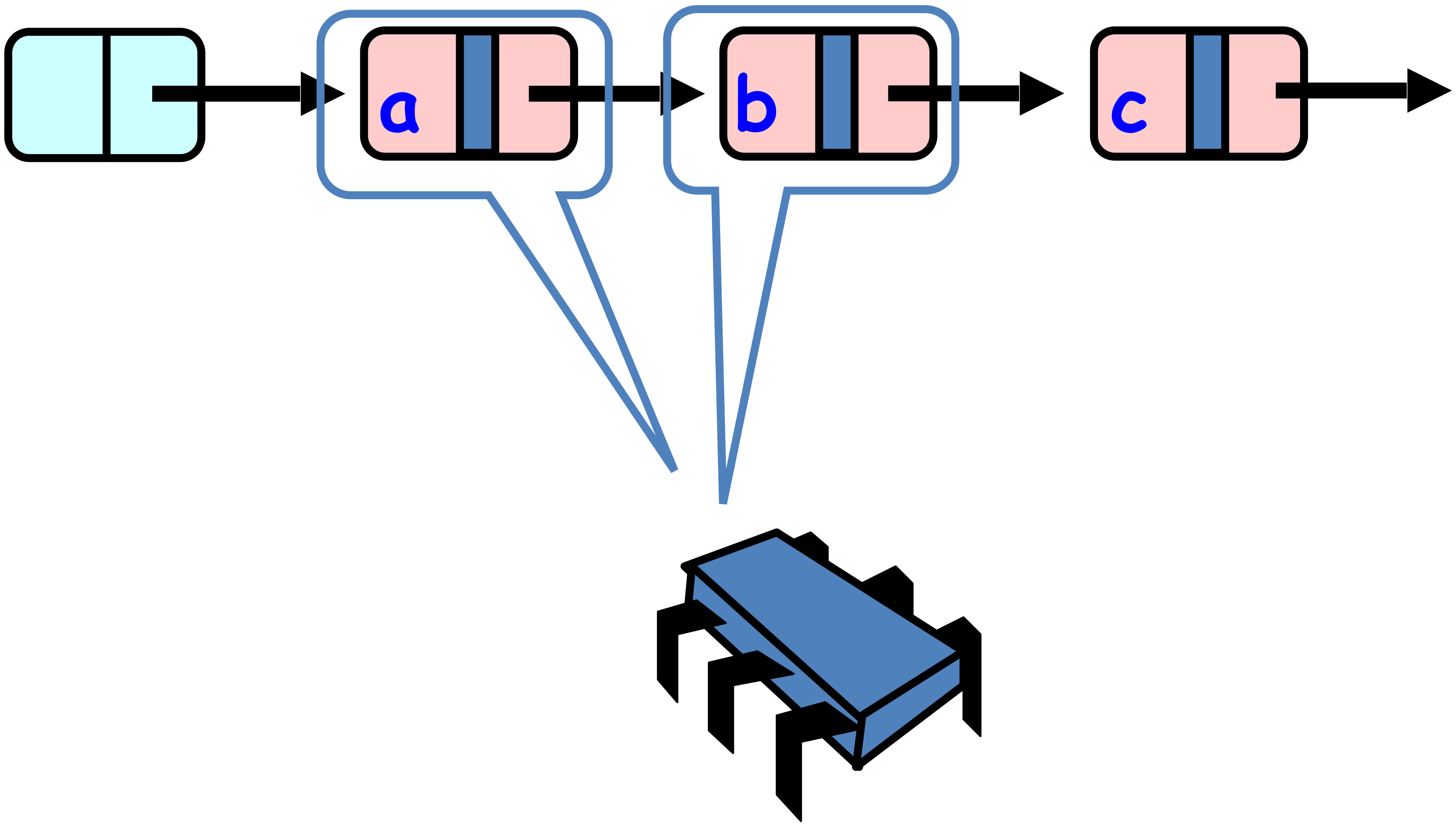
Lazy List



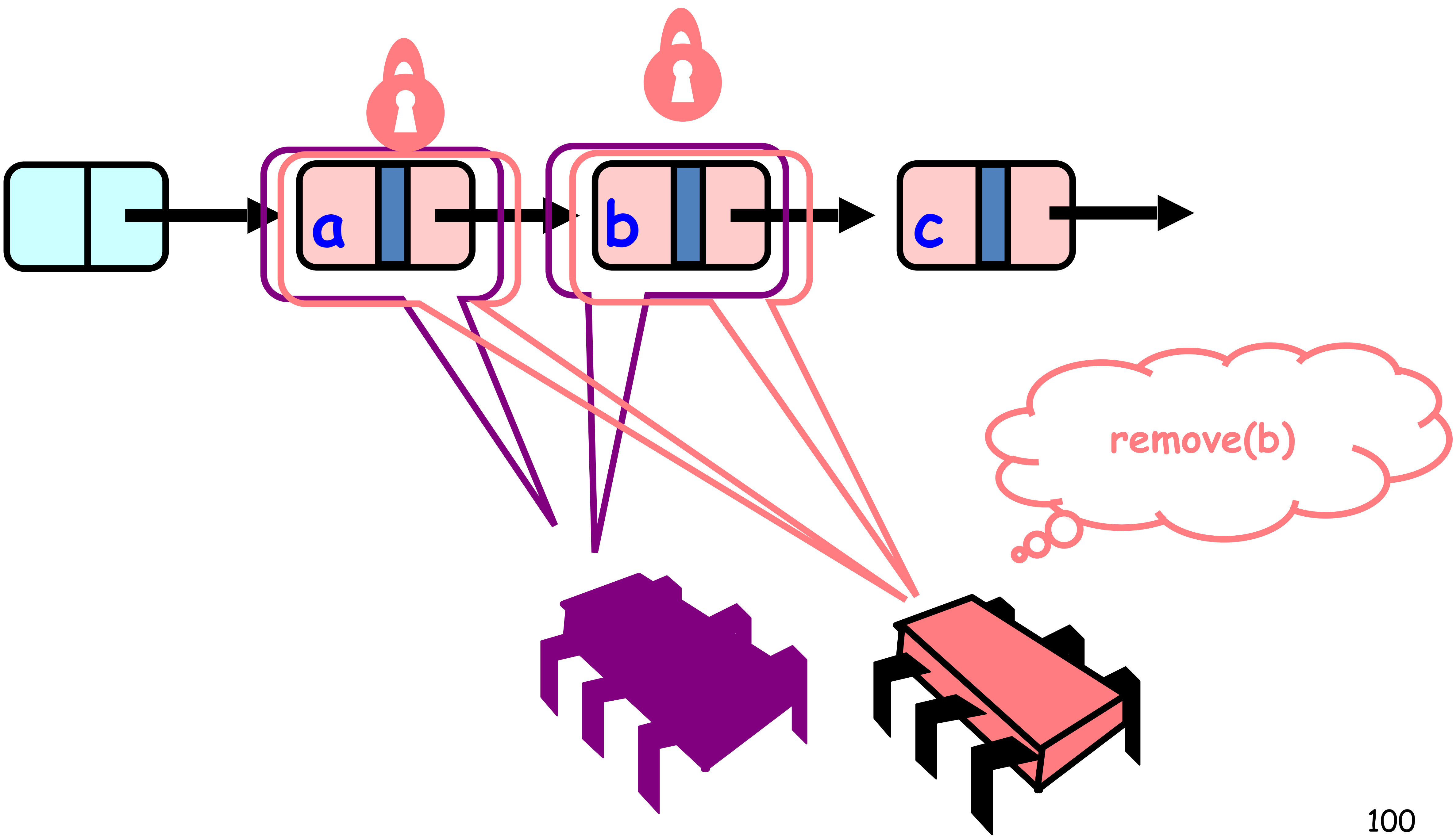
Lazy List



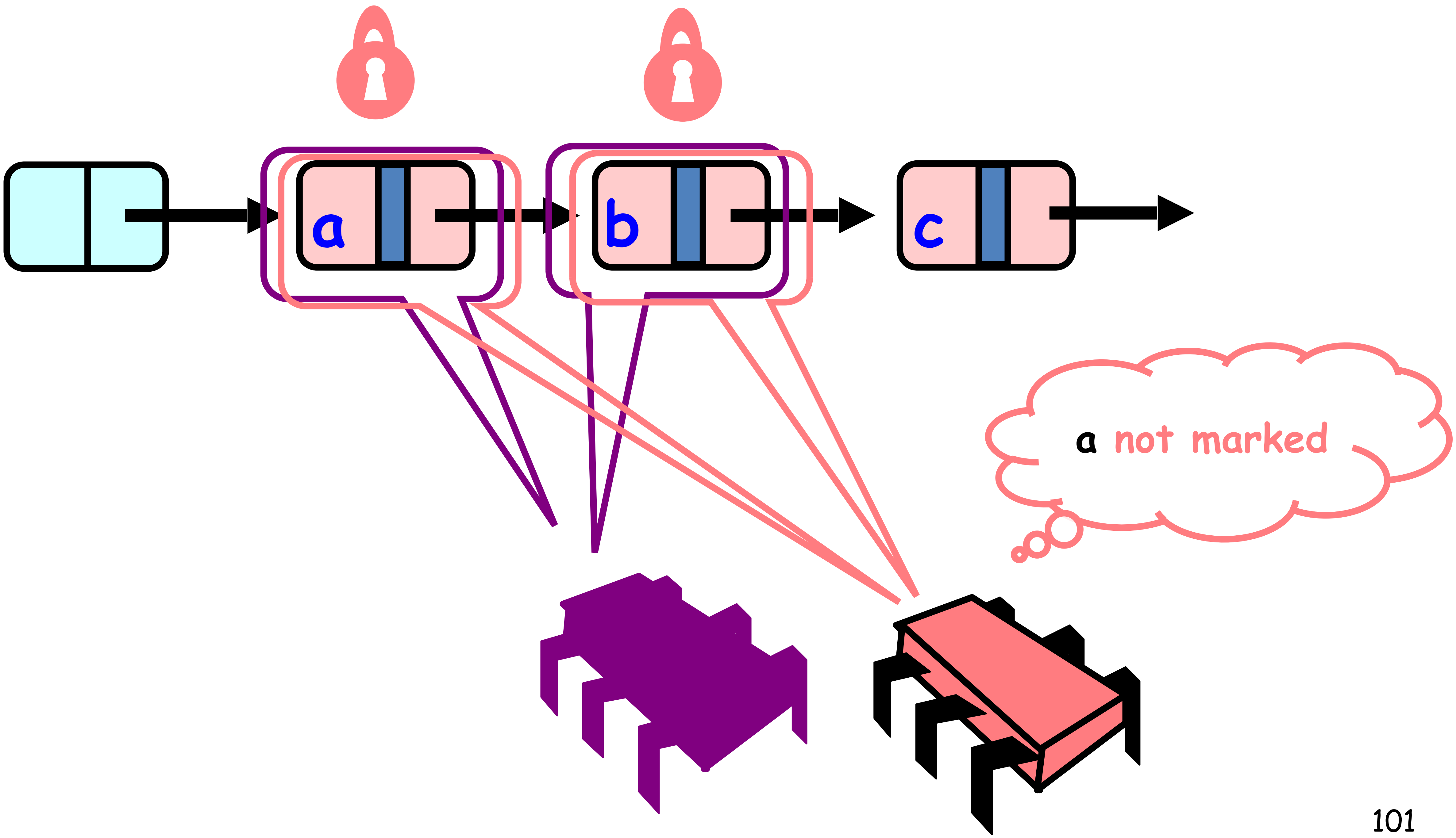
Lazy List



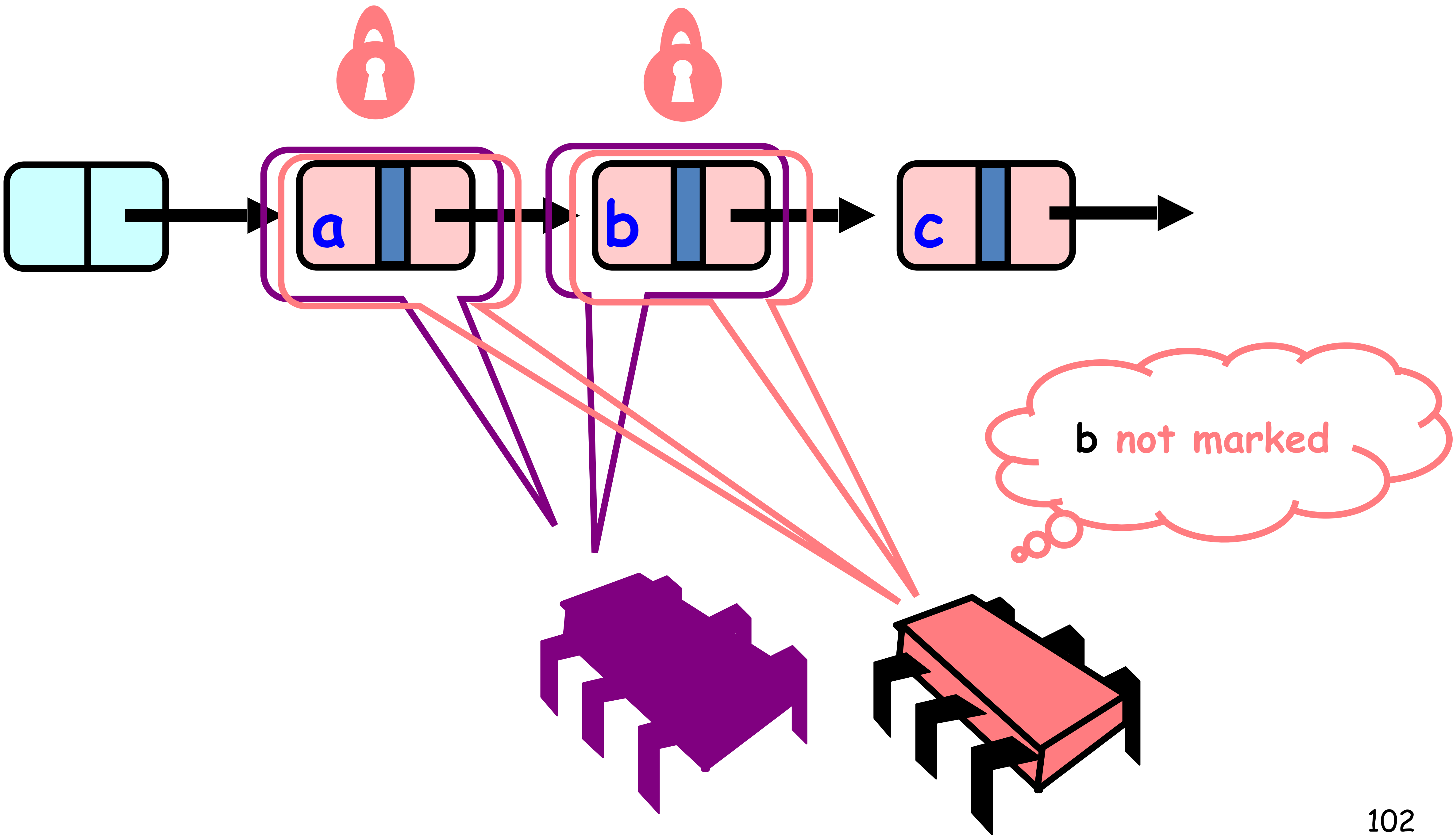
Lazy List



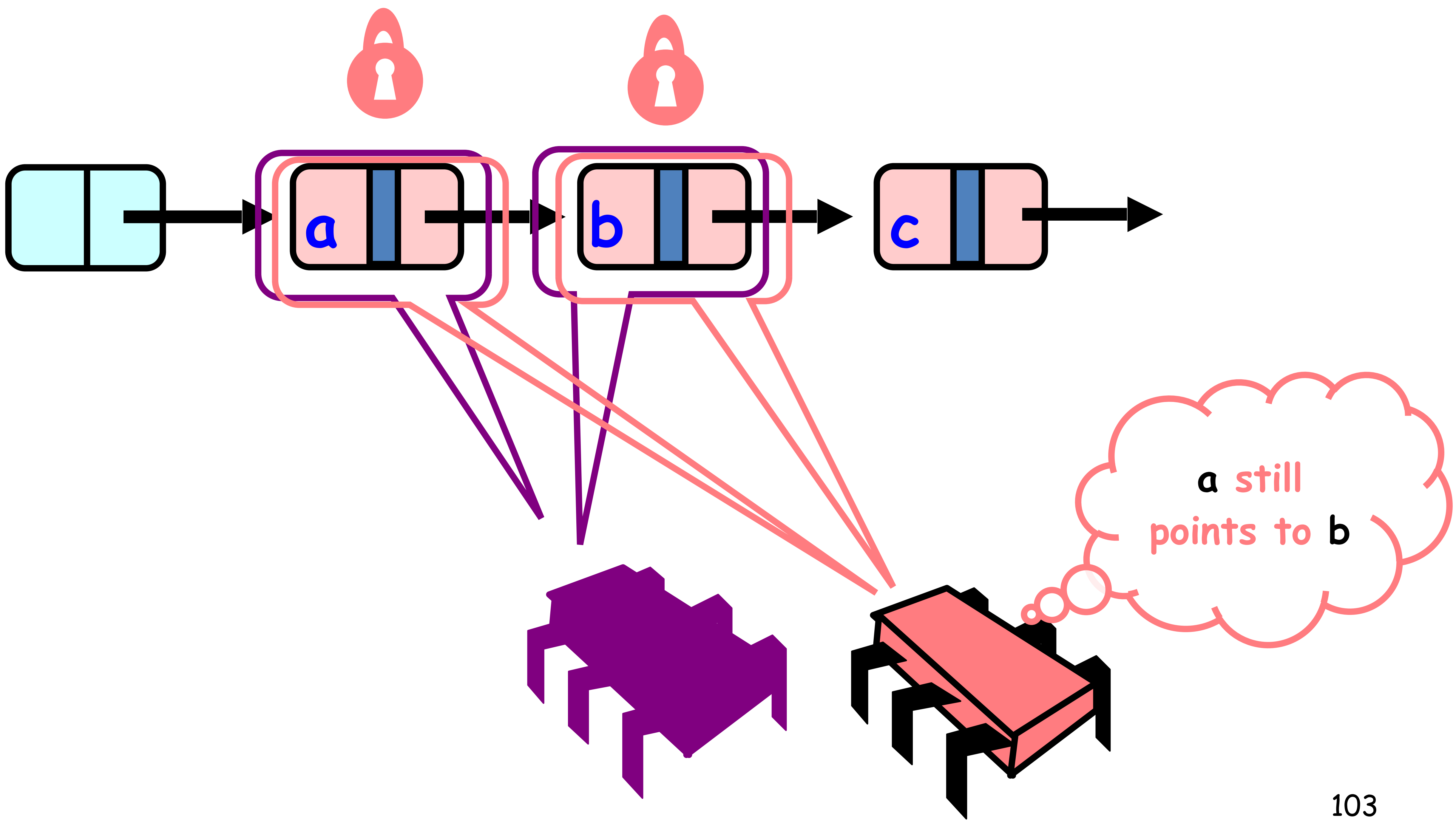
Lazy List



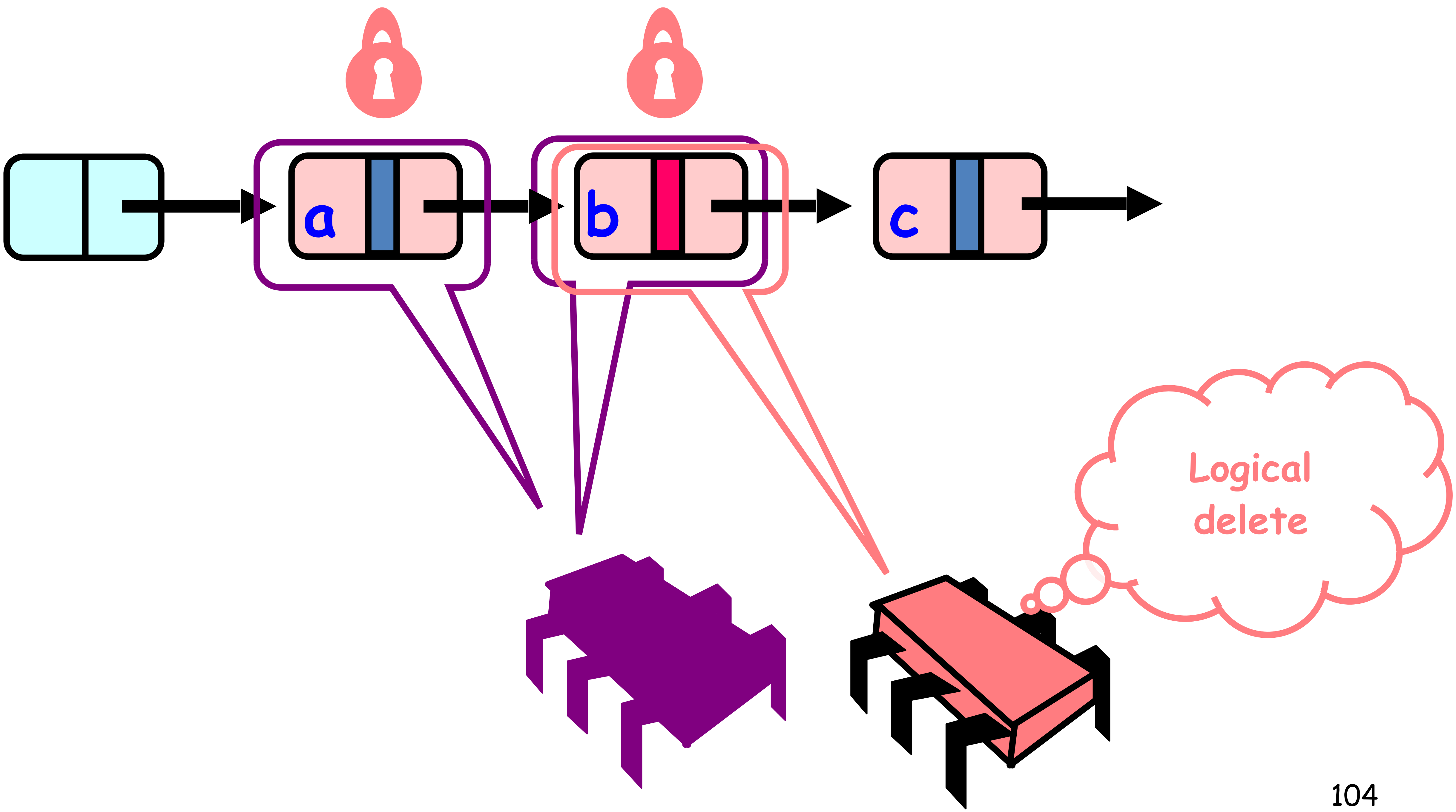
Lazy List



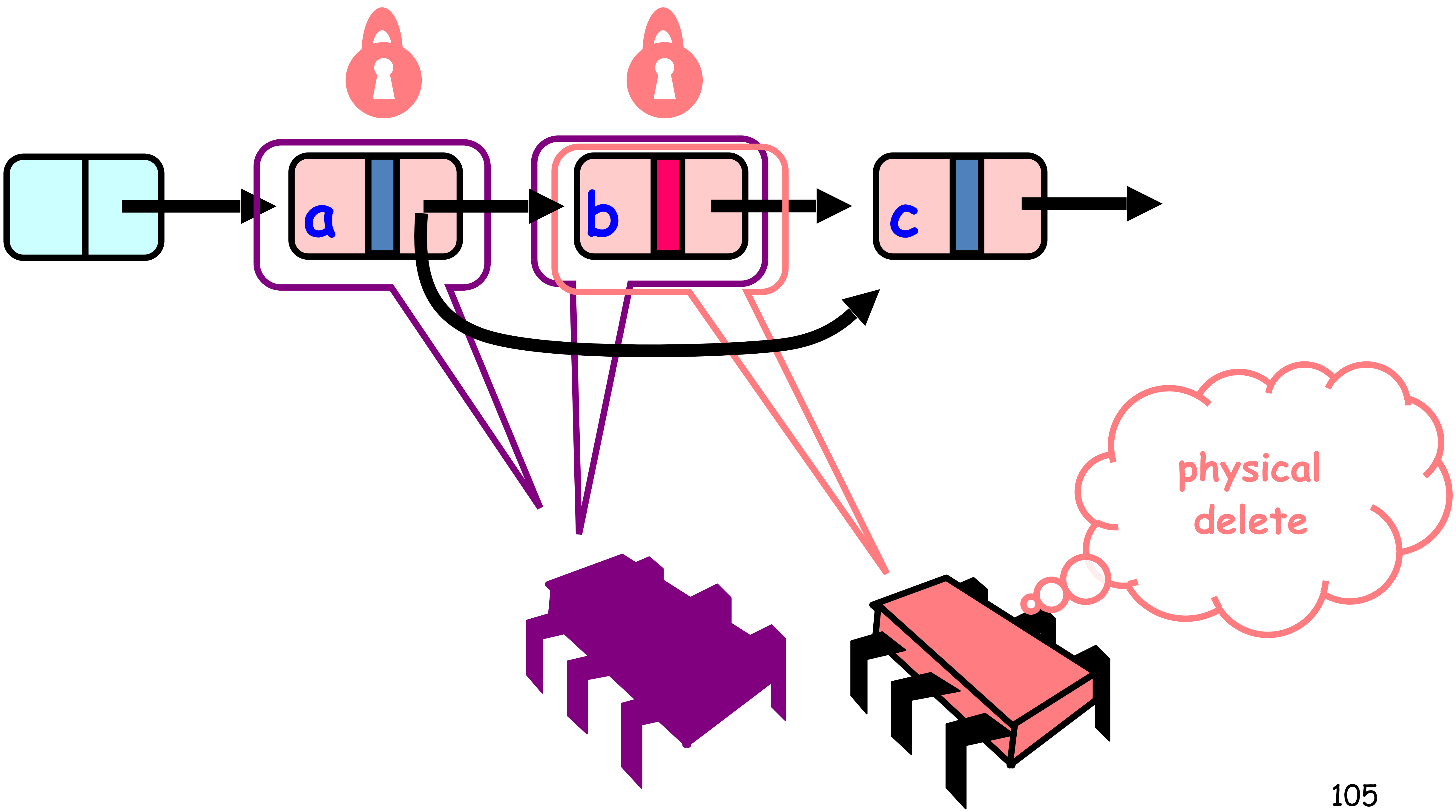
Lazy List



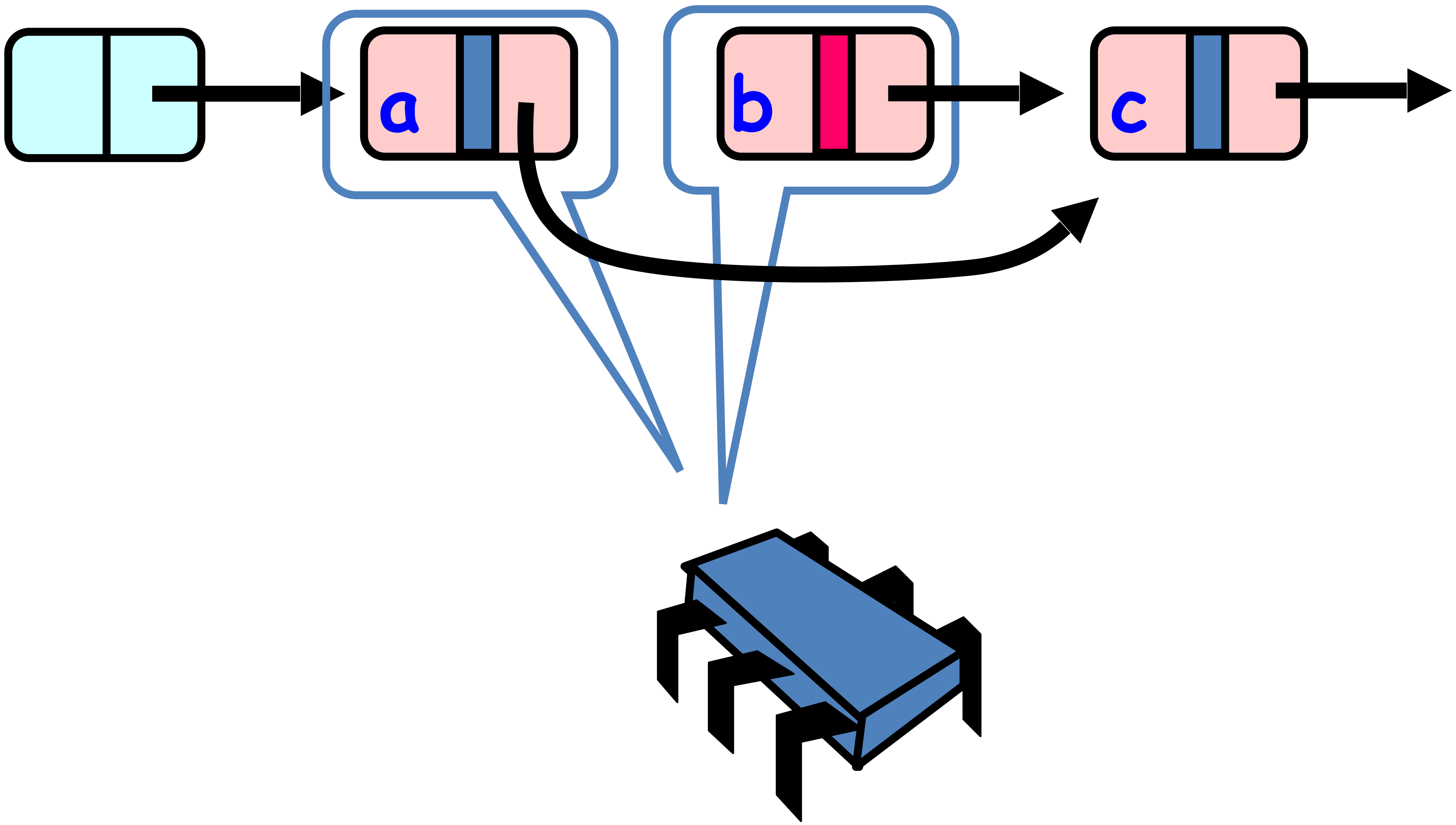
Lazy List



Lazy List



Lazy List



Invariant

- If a node is not marked then its key is in the set
  - and reachable from head

The contains Method

- Simply traverses the list and reports finding.
- Very efficient, progress guaranteed.
  - Wait-free
- Most “popular” method.

Properties of Lazy List

- Good performance
  - no rescanning,
  - a small number of locks,
  - hopefully not too many validation failures
- Good scalability
  - Lock only relevant nodes.
- Still standard locking problems
  - No progress guarantee
  - A thread holding a lock may face a cache-miss, page-fault, swap-out, etc.
  - Worst-case scalability issues, scheduler critical here…

Summary

- Starting data structures
- Locking and Lock-freedom
- Linked list (ordered for sets)
- Parallization problems
- Fine grained locking:
  - Hand-over-hand
  - Optimistic
  - Lazy
- Lock-Free version

Which List Should You Use?

- If little contention: coarse-grained locking.
- To handle contention pretty well: lazy list.
- To handle high contention and provide a progress guarantee: lock-free list.

The End