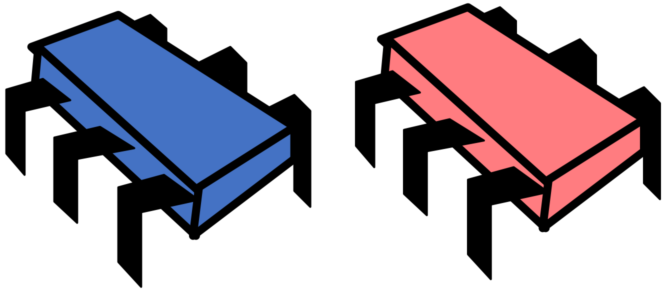
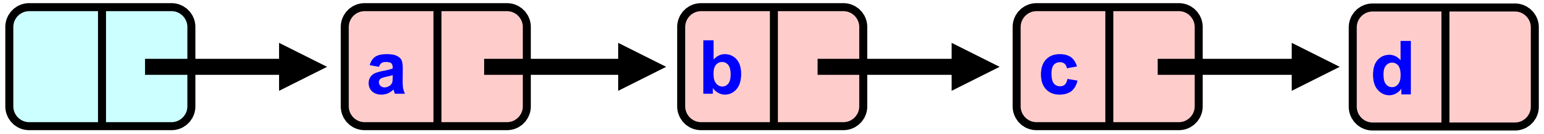
CSE113: Parallel Programming

- **Topics**:
  - Concurrent general set





Announcements

- HW 4 submission by tomorrow.

Announcements

- HW 5 will be released on this week.

Announcements

SETs are out, please do them! It helps us out a lot.

Previous quiz + Review

Previous quiz + Review

The C++ relaxed memory order provides

- ○ no orderings at all
- ○ orderings only between accesses of the same address
- ○ TSO memory behaviors when run on an x86 system
- ○ an easy way to accidentally introduce horrible bugs into your program

Relaxed memory order

language
C++11 (sequential consistency)

	L	S
L	NO	NO
S	NO	NO

language
C++11 (memory_order_relaxed)

	L	S
L	different address	different address
S	different address	different address

basically no orderings except for accesses to the same address

Previous quiz + Review

The C++ relaxed memory order provides

- ○ no orderings at all
- -> ○ orderings only between accesses of the same address
- ○ TSO memory behaviors when run on an x86 system
- ○ an easy way to accidentally introduce horrible bugs into your program

Previous quiz + Review

In terms of memory models, the compiler needs to ensure the following property:

- ○ Any weak behavior allowed in the language is also allowed in the ISA
- ○ Any weak behaviors that are disallowed in the language need to be disallowed in the ISA
- ○ The compilation ensures that the program has sequentially consistent behavior at the ISA level
- ○ The compiler does not need to reason about relaxed memory

C++11 atomic operation compilation

start with both both of the grids for the two different memory models

language
C++11 (sequential consistency)

	L	S
L	NO	NO
S	NO	NO

C++	ISA
x.store(1); →	store(x,1); fence;

or

C++	ISA
z = x.load() →	fence; %z = load(x);

target machine
TSO (x86)

	L	S
L	NO	different address
S	NO	No

Compiling memory order relaxed

language
C++11 (memory_order_relaxed)

	L	S
L	different address	different address
S	different address	different address

lots of mismatches!

But language is more relaxed than machine

so no fences are needed

target machine
TSO (x86)

	L	S
L	NO	different address
S	NO	No

Previous quiz + Review

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- ○ Any weak behavior allowed in the language is also allowed in the ISA
- -> ○ Any weak behaviors that are disallowed in the language need to be disallowed in the ISA
- ○ The compilation ensures that the program has sequentially consistent behavior at the ISA level
- ○ The compiler does not need to reason about relaxed memory

Previous quiz + Review

A program that uses mutexes and has no data conflicts does not have weak memory behaviors for which of the following reasons?

- ○ Mutexes prevent memory accesses from happening close enough in time for weak behaviors to occur
- ○ The OS has built in support for Mutexes that disable architecture features, such as the store buffer
- ○ A correct mutex implementation uses fences in lock and unlock to disallow weak behaviors

Previous quiz + Review

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- -> ○ A correct mutex implementation uses fences in lock and unlock to disallow weak behaviors

Previous quiz + Review

Assuming you had a sequentially consistent processor, any C/++ program you ran on it would also be sequentially consistent, regardless of if there are data-conflicts or not.

- ○ True
- ○ False

Previous quiz + Review

Assuming you had a sequentially consistent processor, any C/++ program you ran on it would also be sequentially consistent, regardless of if there are data-conflicts or not.

- ○ True
- -> ○ False

In addition to processor, the compiler can reorder instruction as well.

Previous quiz + Review

If you put a fence after every memory instruction, would that be sufficient to disallow all weak behaviors on a weak architecture? Please write a few sentences explaining your answer.

Previous quiz + Review

If you put a fence after every memory instruction, would that be sufficient to disallow all weak behaviors on a weak architecture? Please write a few sentences explaining your answer.

It is sufficient but makes execution slower.

General Concurrent Set

Set Interface

- Unordered collection of items
- No duplicates

- We will implement set as a sorted linked list.

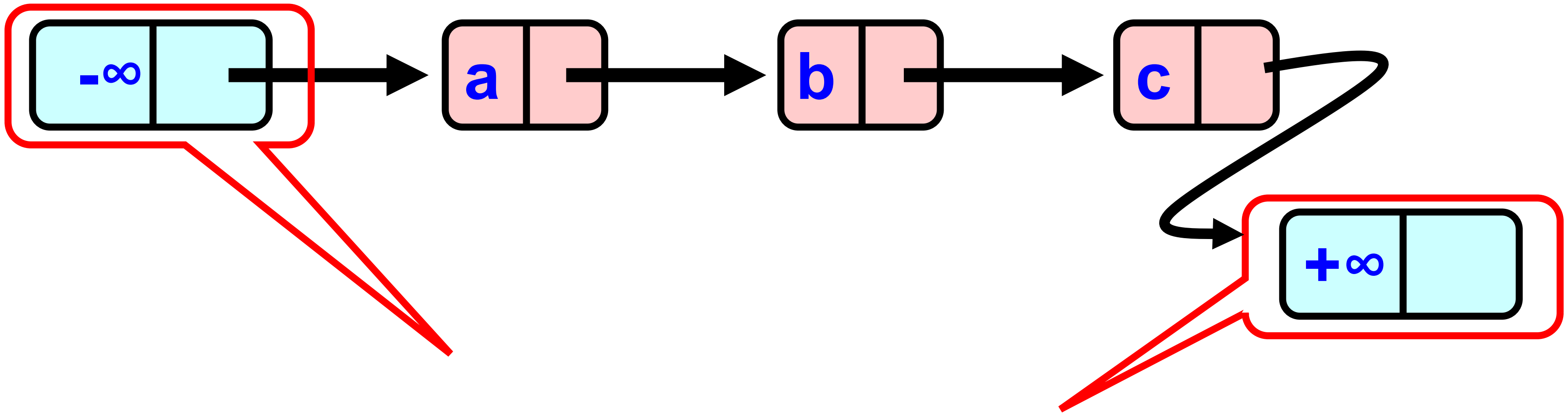
Set Interface

- Methods
  - **`add(x)`** put **`x`** in set
  - **`remove(x)`** take **`x`** out of set
  - **`contains(x)`** tests if **`x`** in set

List Node

```
class Node {
 public:
   Value v;
   int key;
   Node *next;
}
```

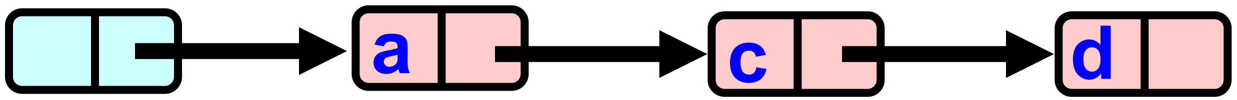
The List-Based Set



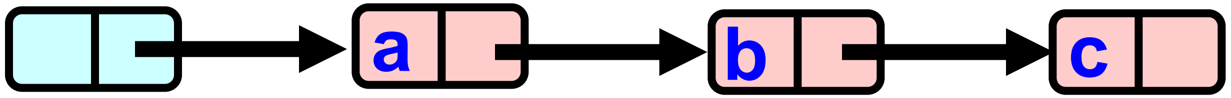
Sorted with Sentinel nodes
(min & max possible keys)

Sequential List Based Set

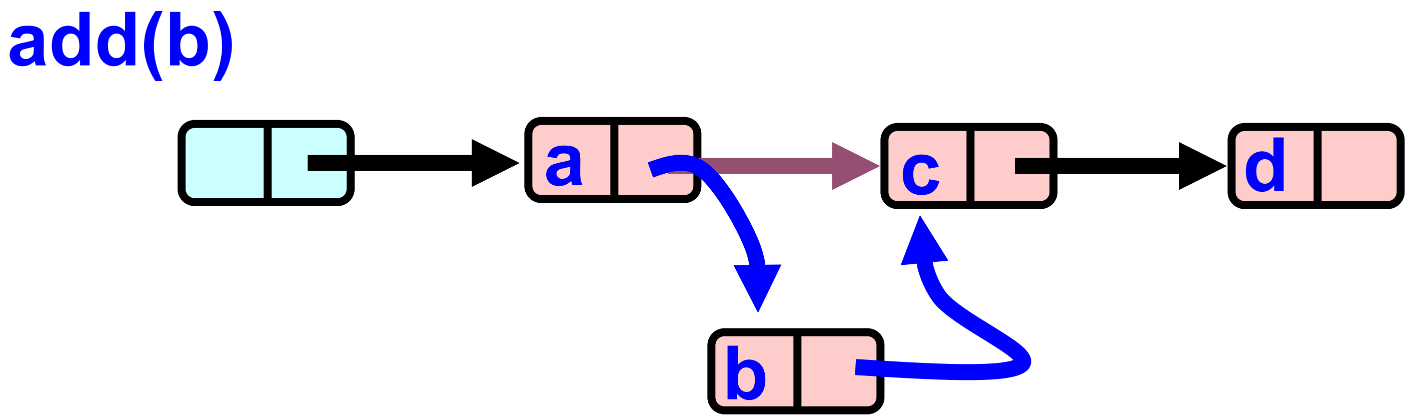
add(b)

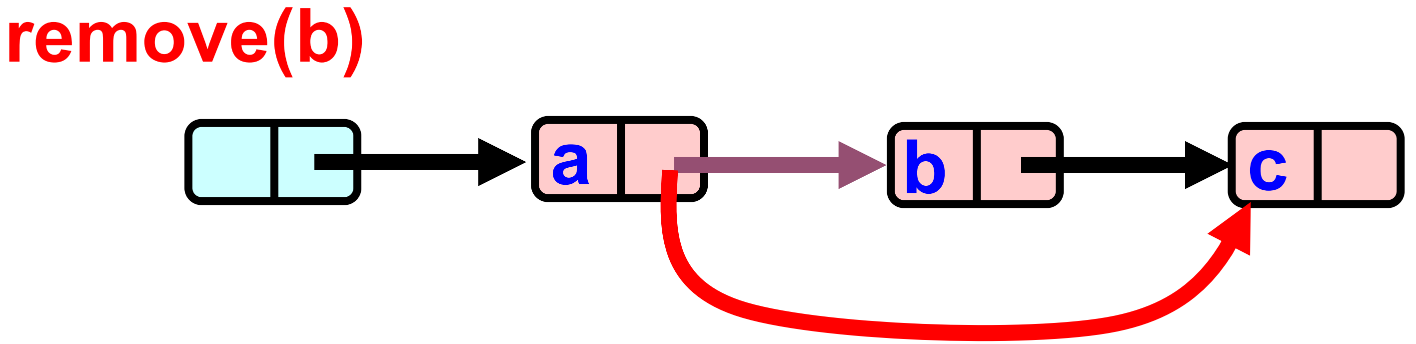


remove(b)

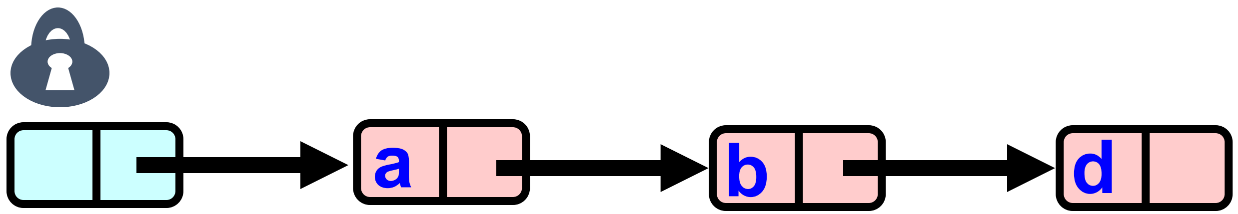


Sequential List Based Set





Coarse-Grained Locking



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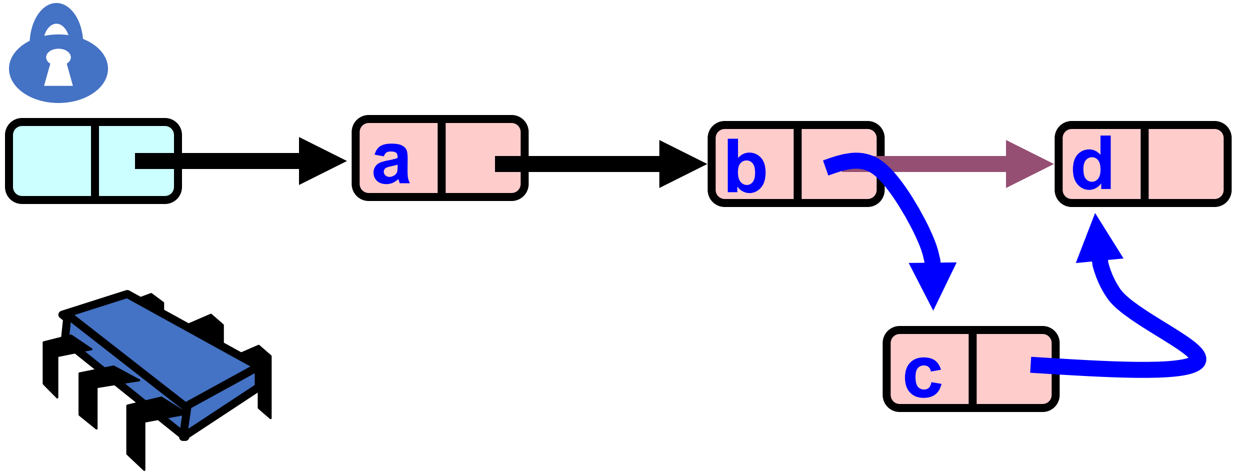
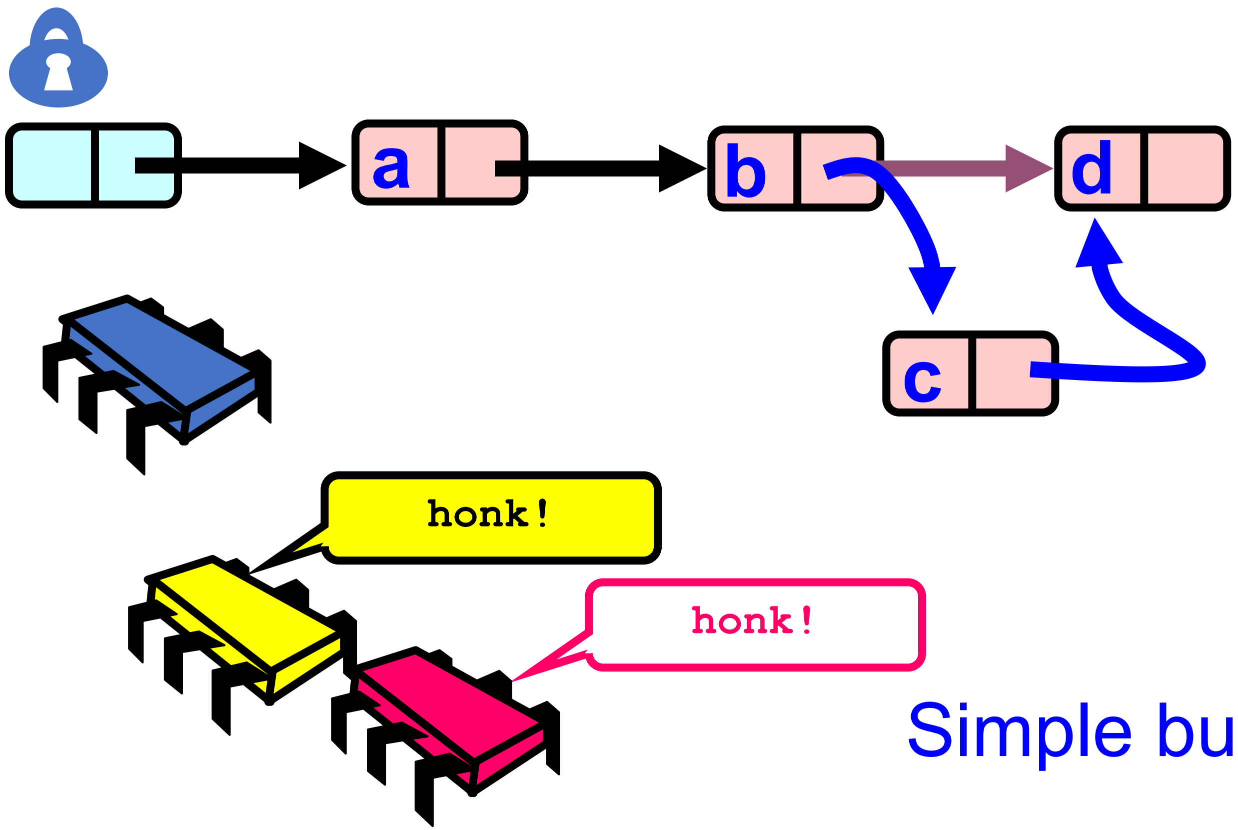


Coarse-Grained Locking



Simple but inefficient!

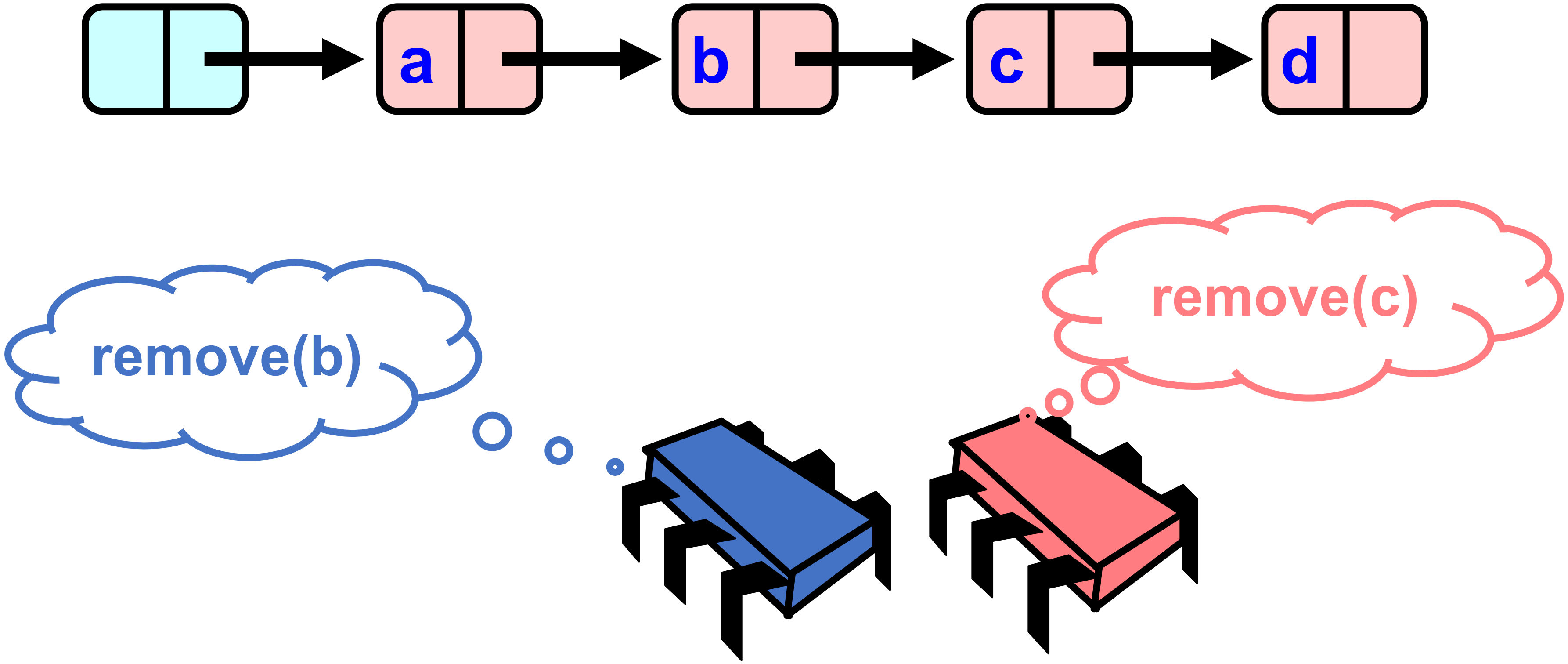
Schedule

- Concurrent set
  - Coarse-grained lock
  - **fine-grained lock**
  - optimistic locking

Fine-grained Locking

- Split object into pieces
  - Each piece has own lock
  - Methods that work on disjoint pieces need not exclude each other
- Requires **careful** thought
  - Acquire all required locks
  - Acquire them in the same order

Concurrent Removes



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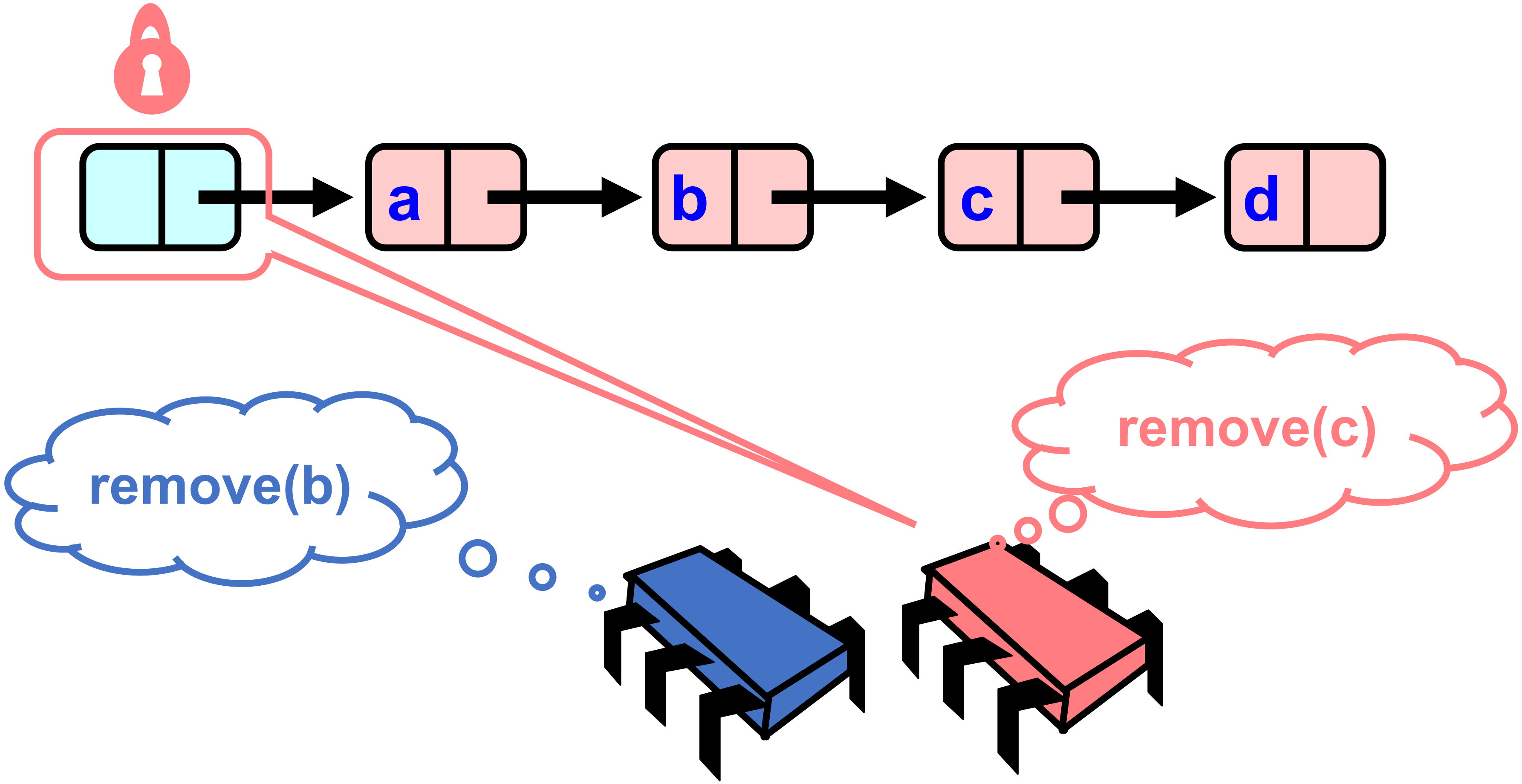

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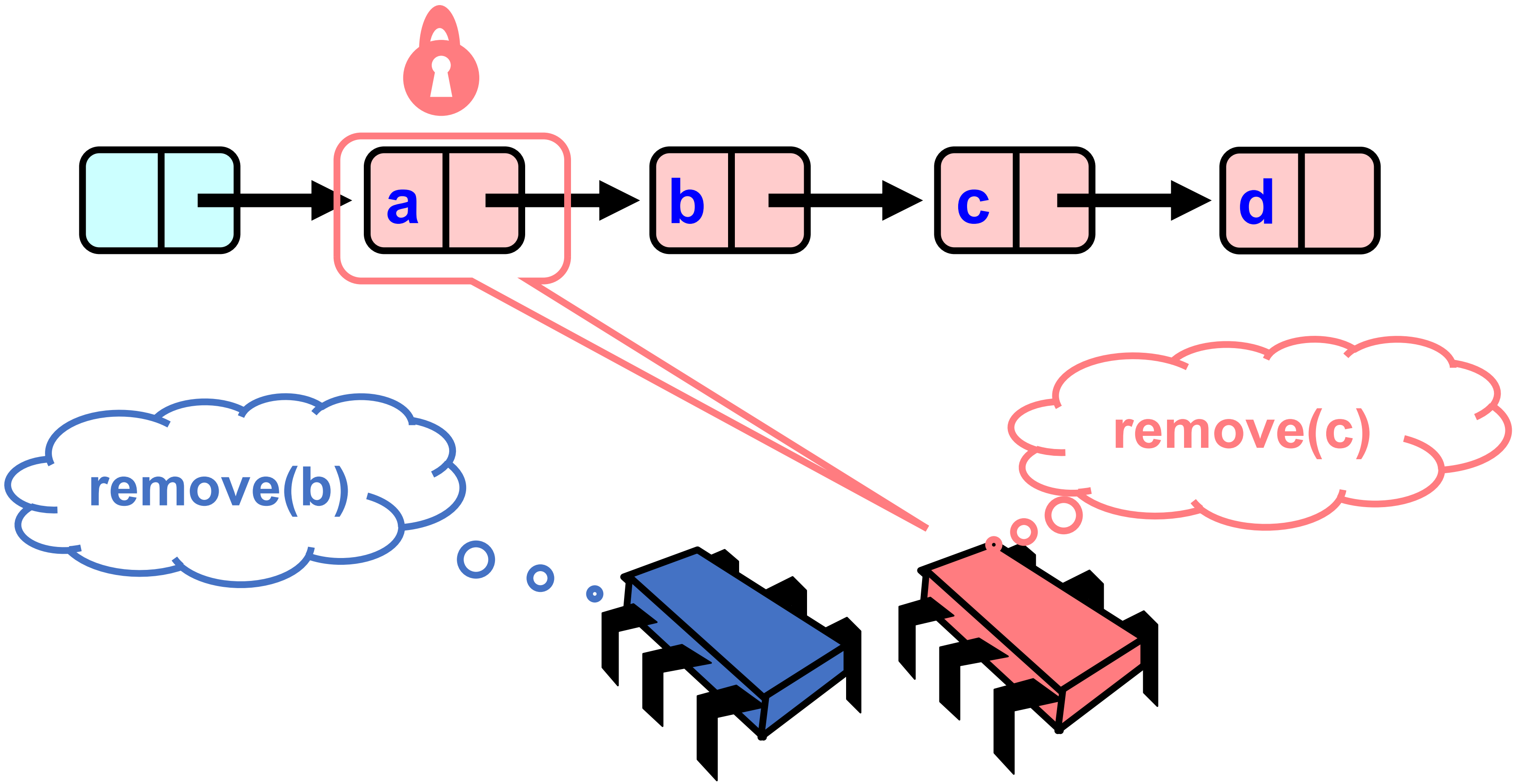

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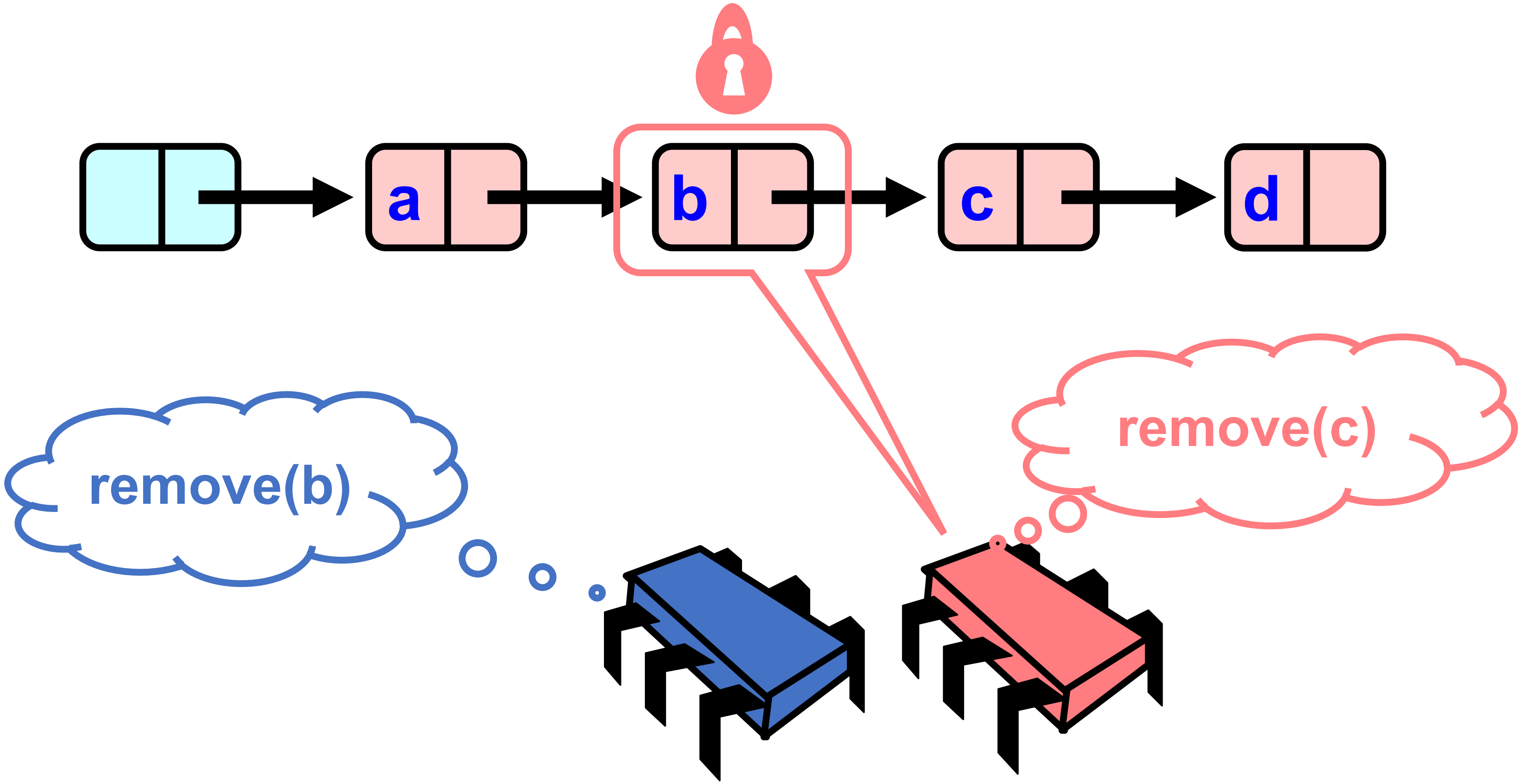

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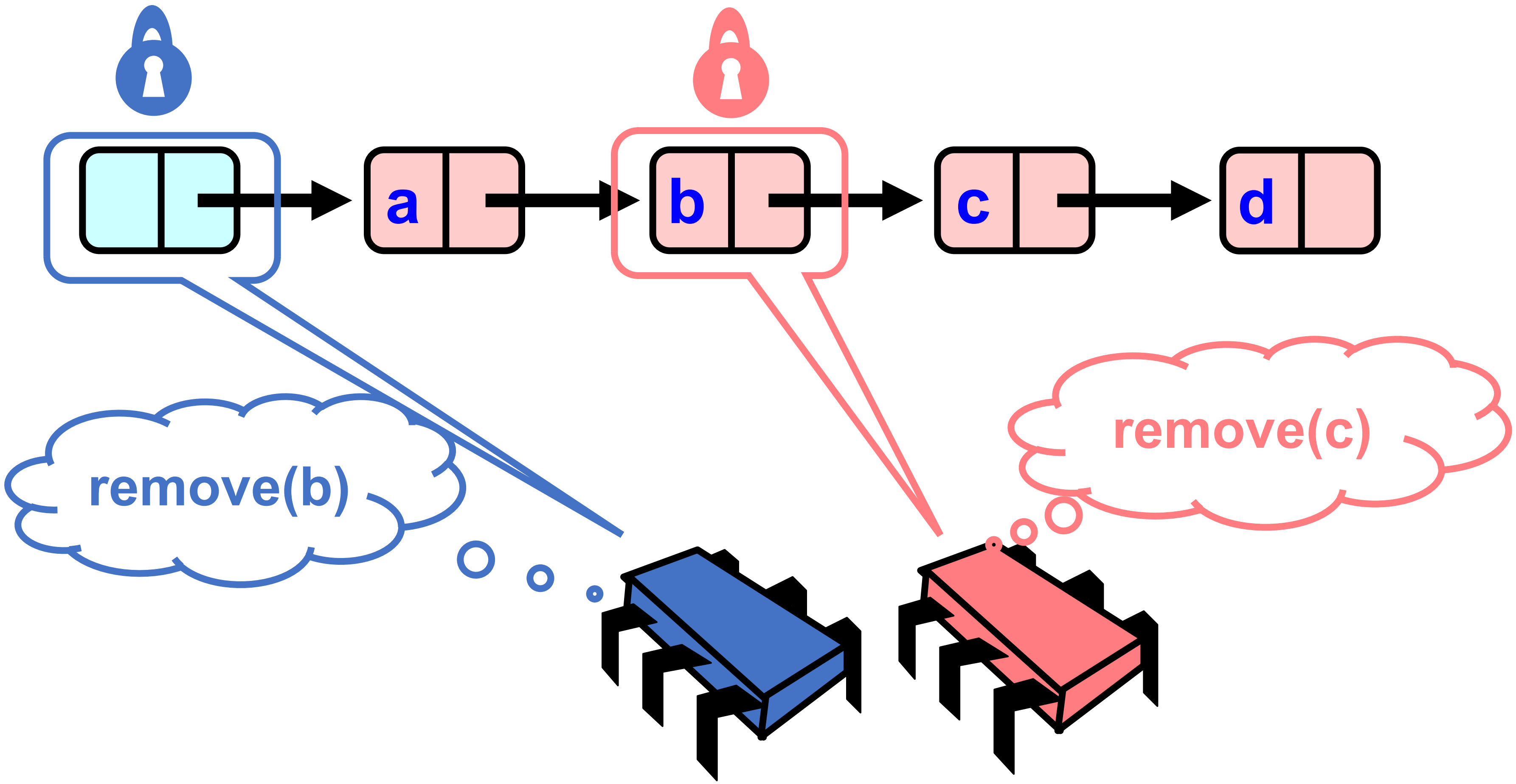

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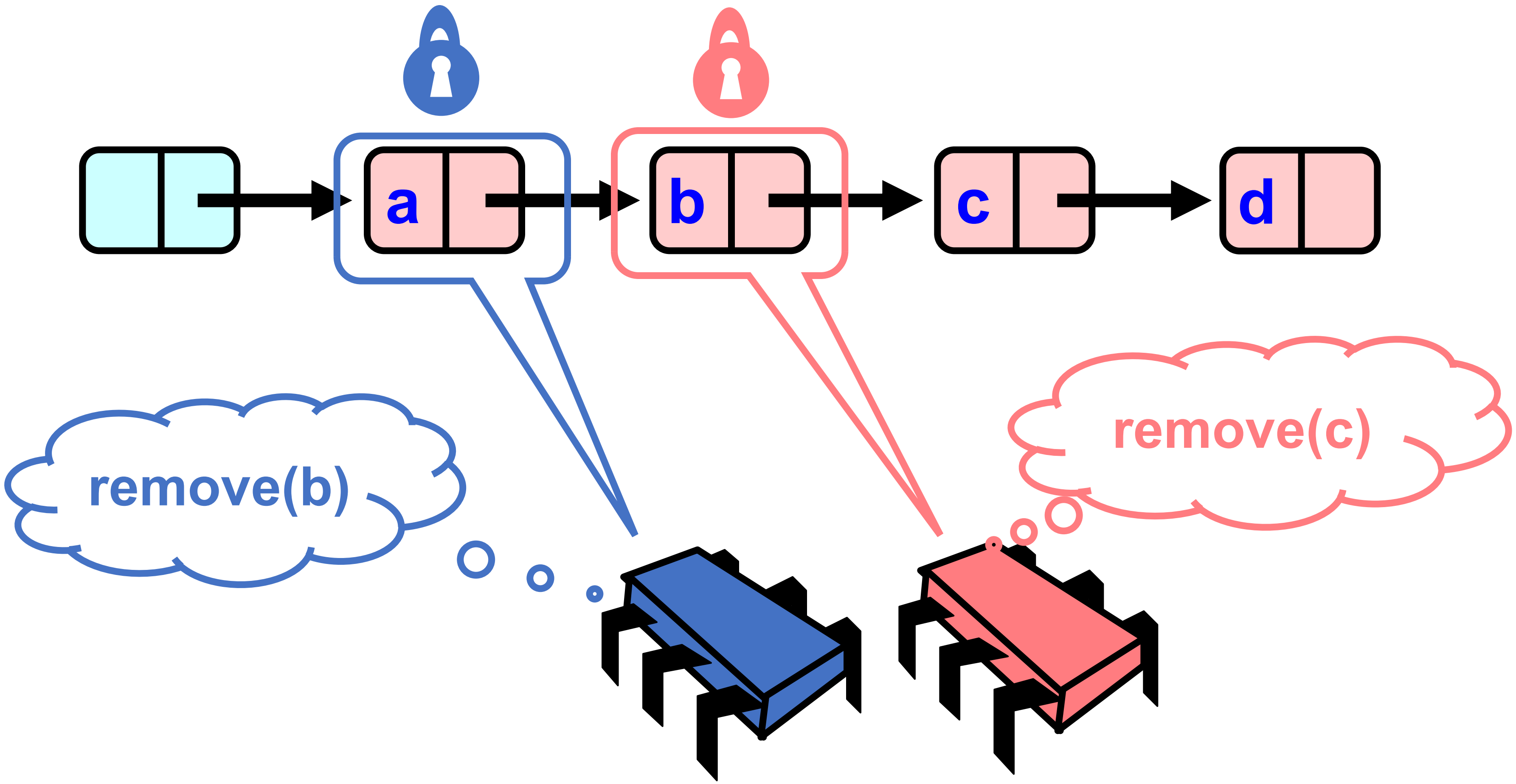

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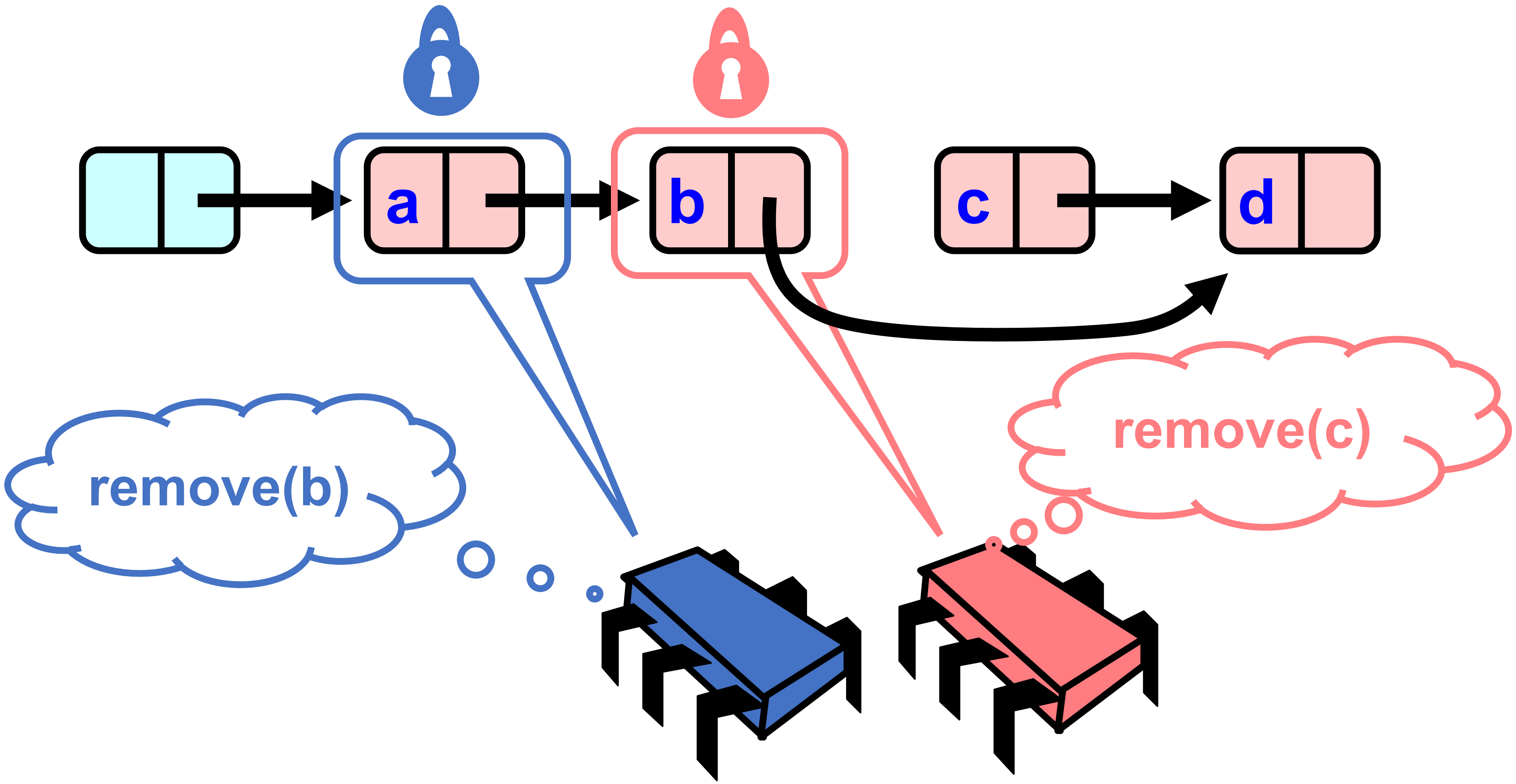

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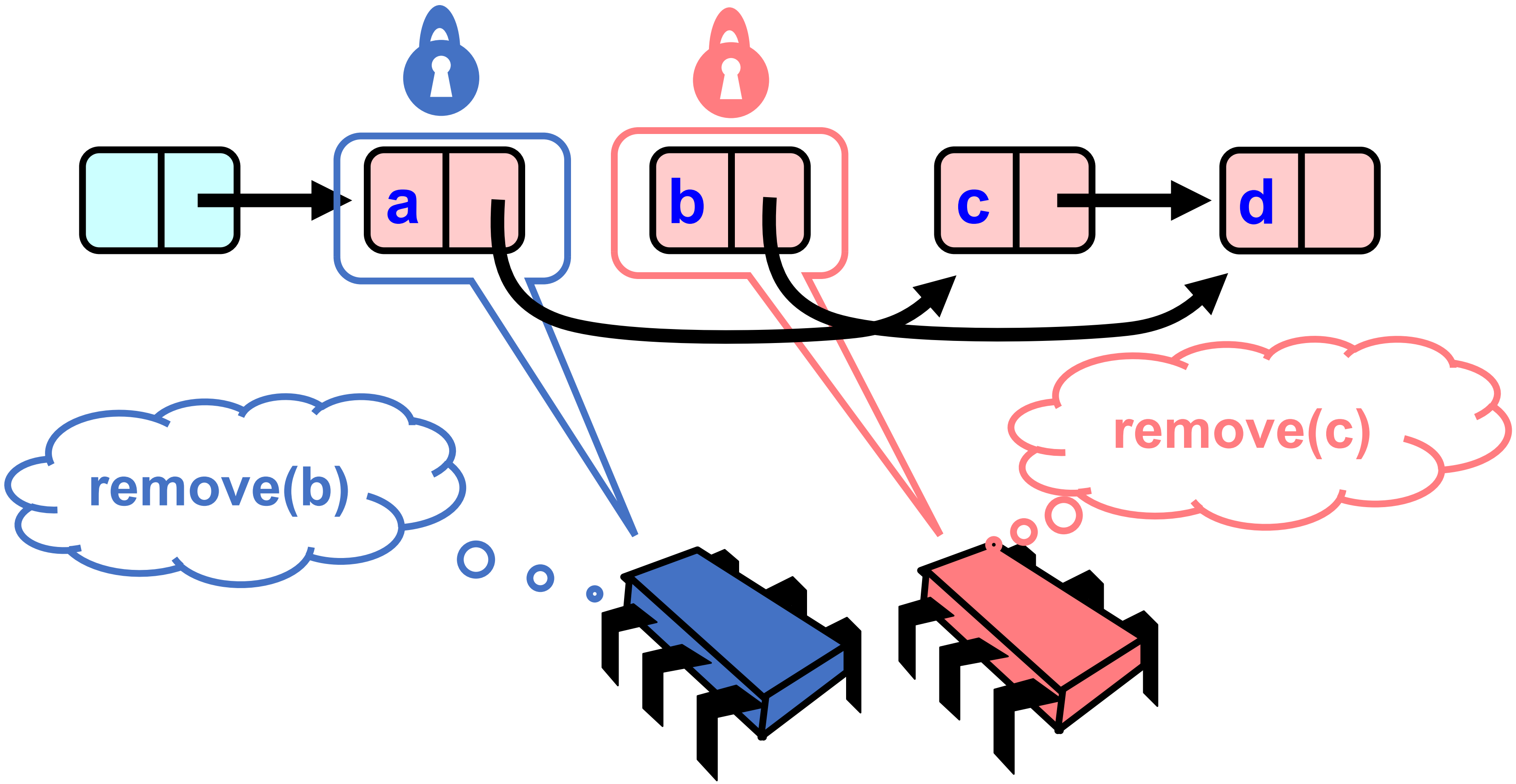
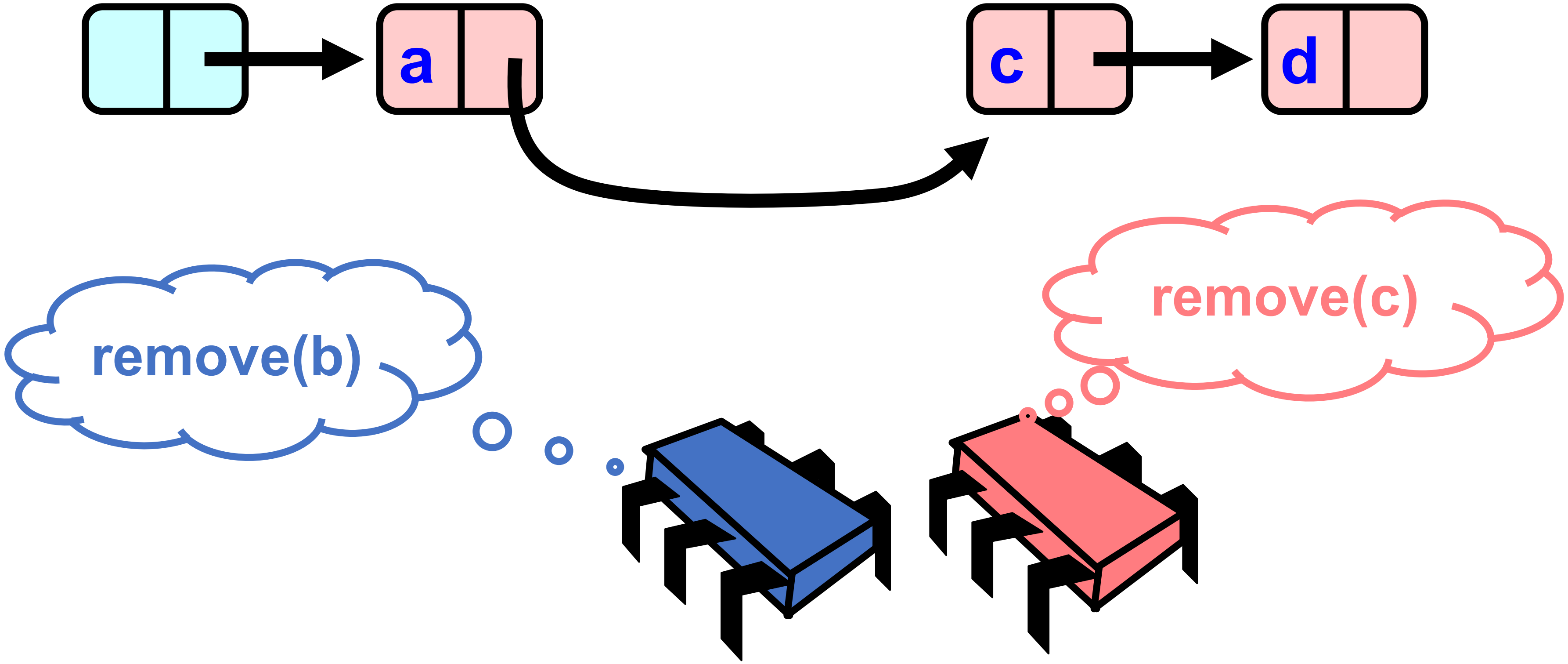


Uh, Oh



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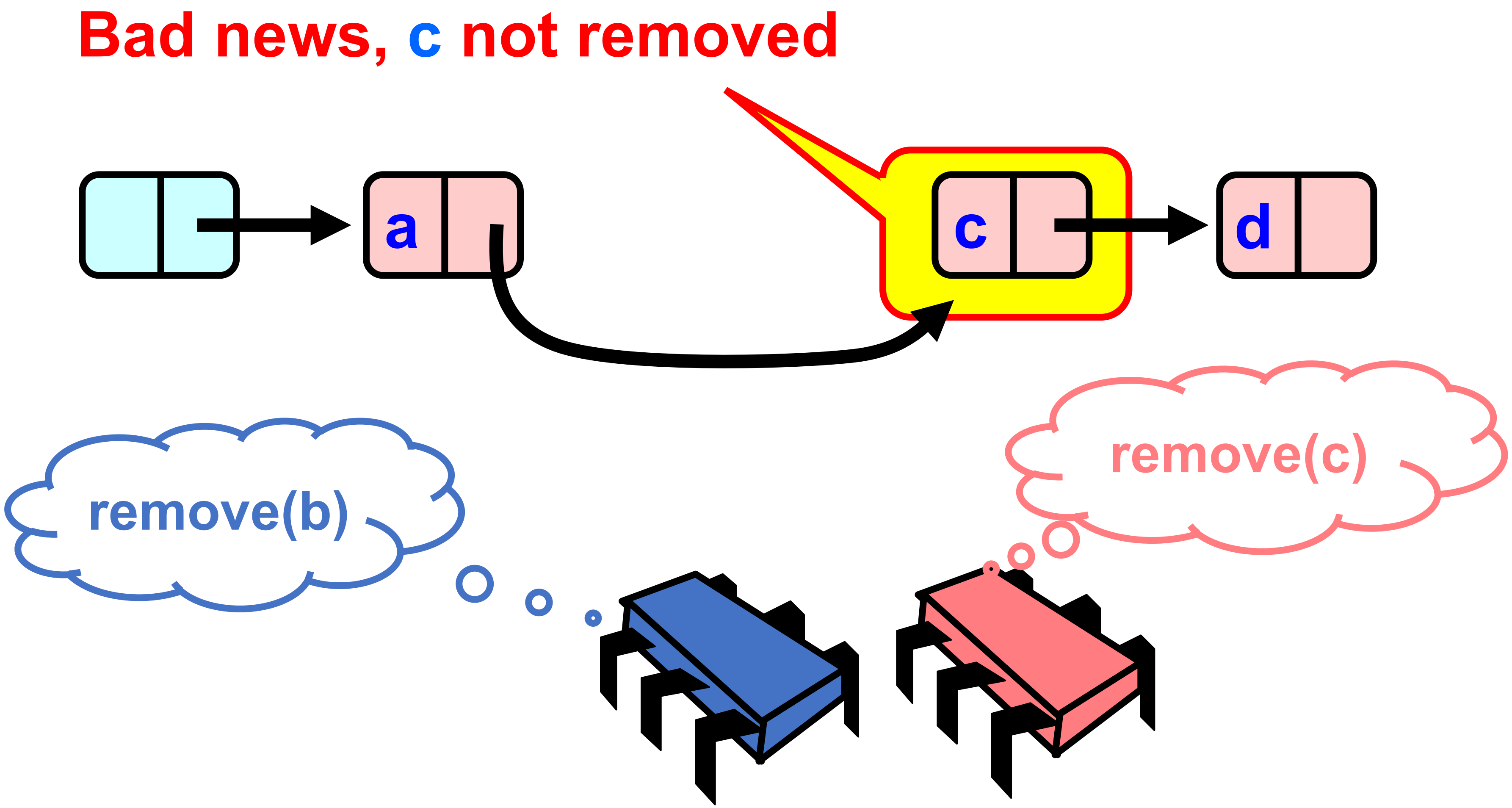
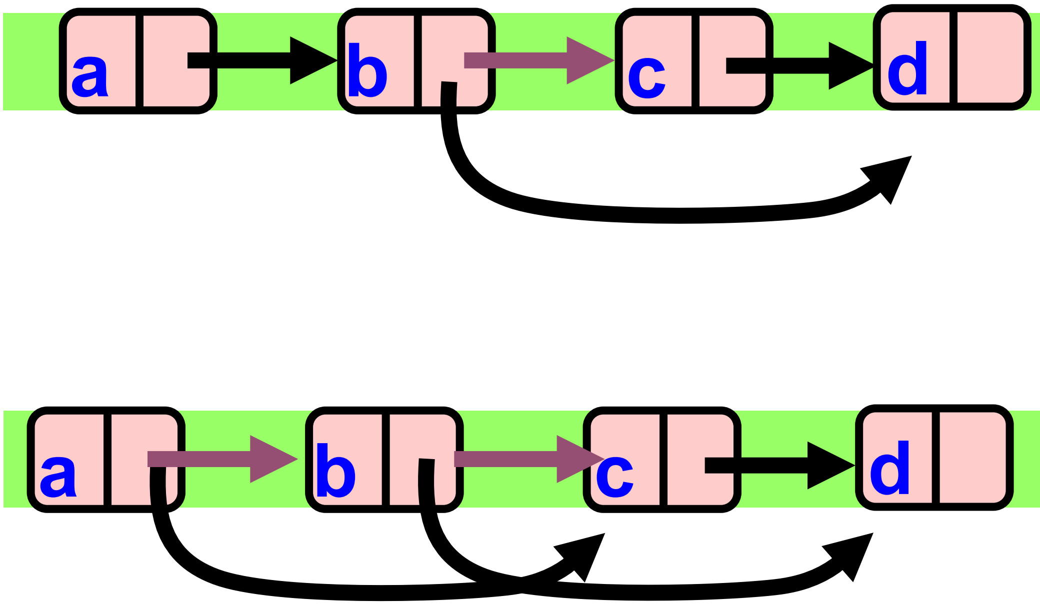
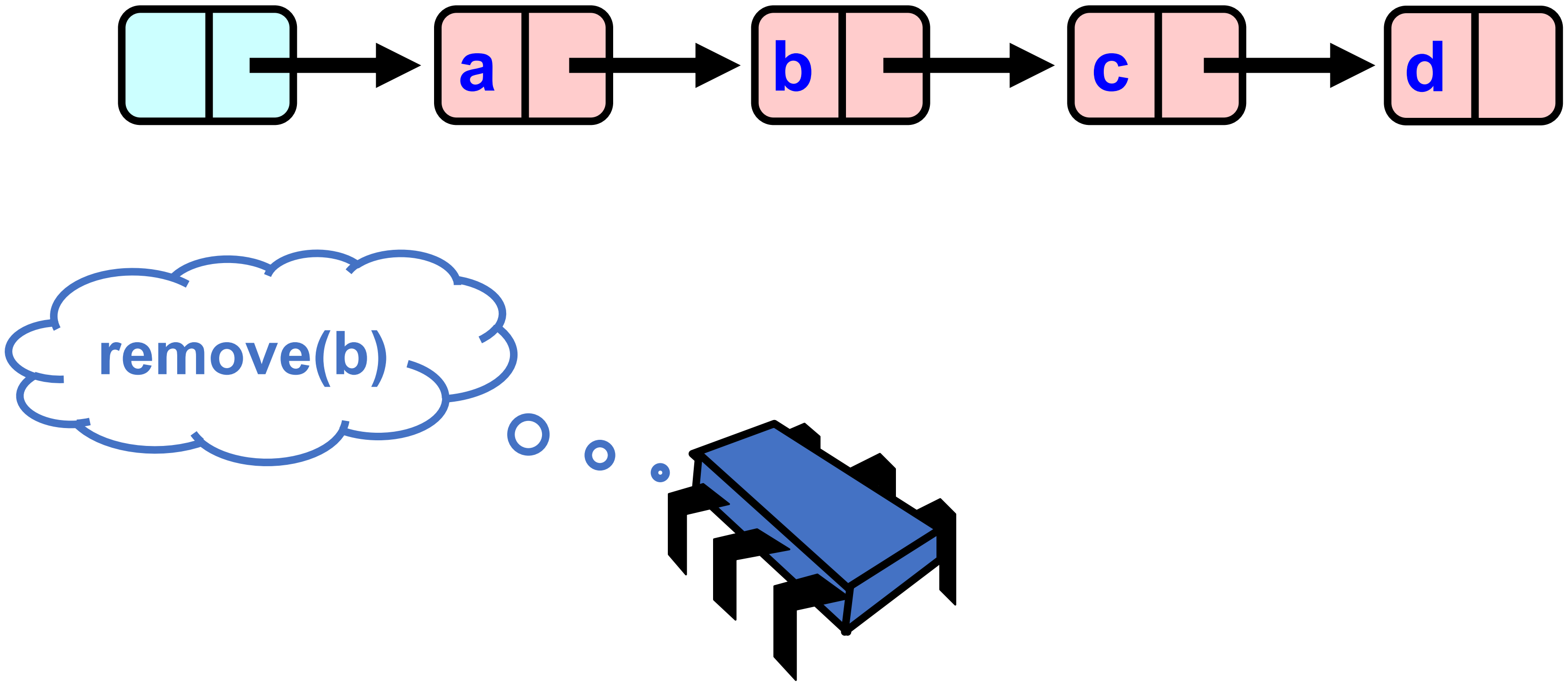


Problem

- 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 Again



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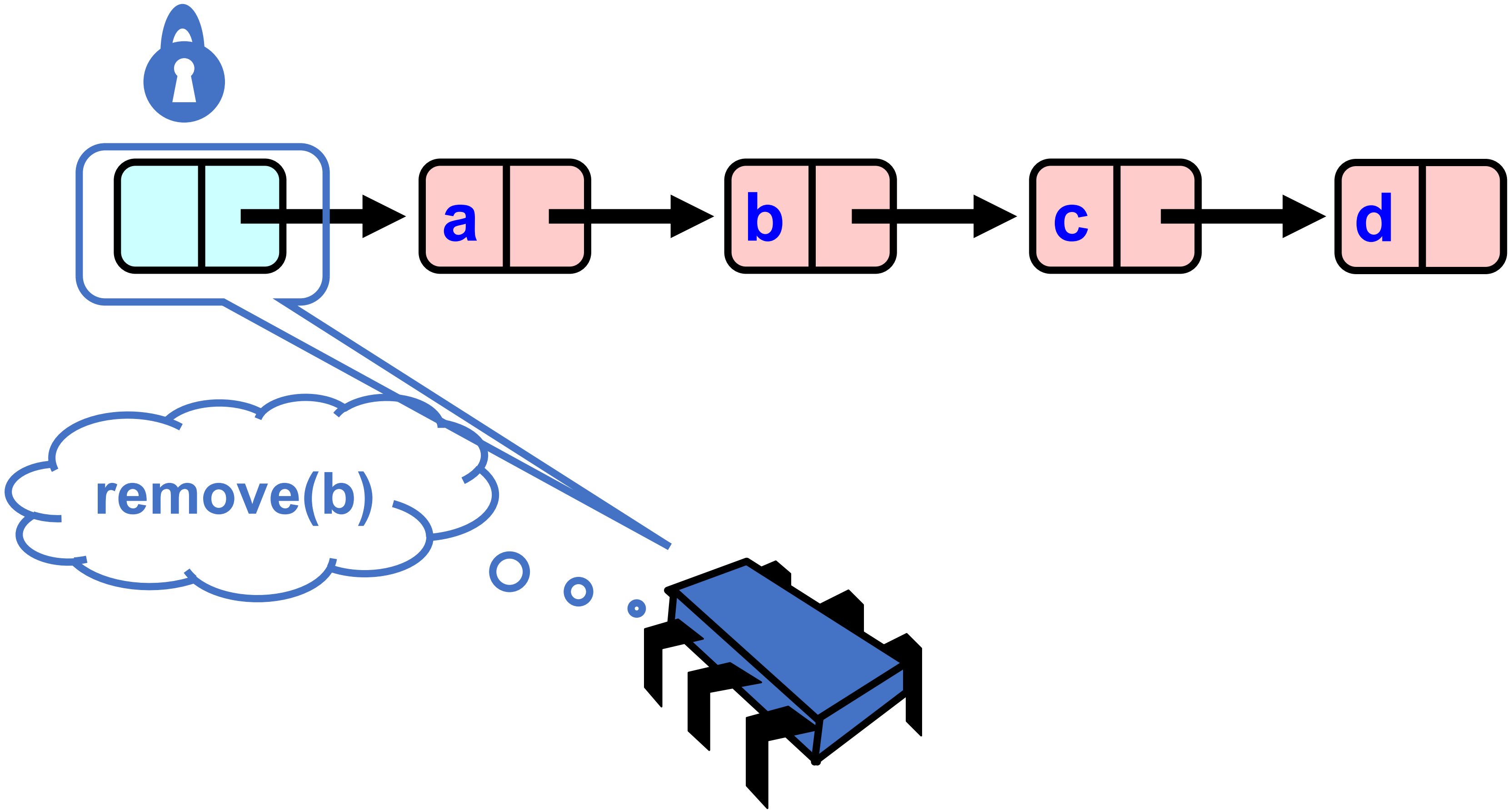

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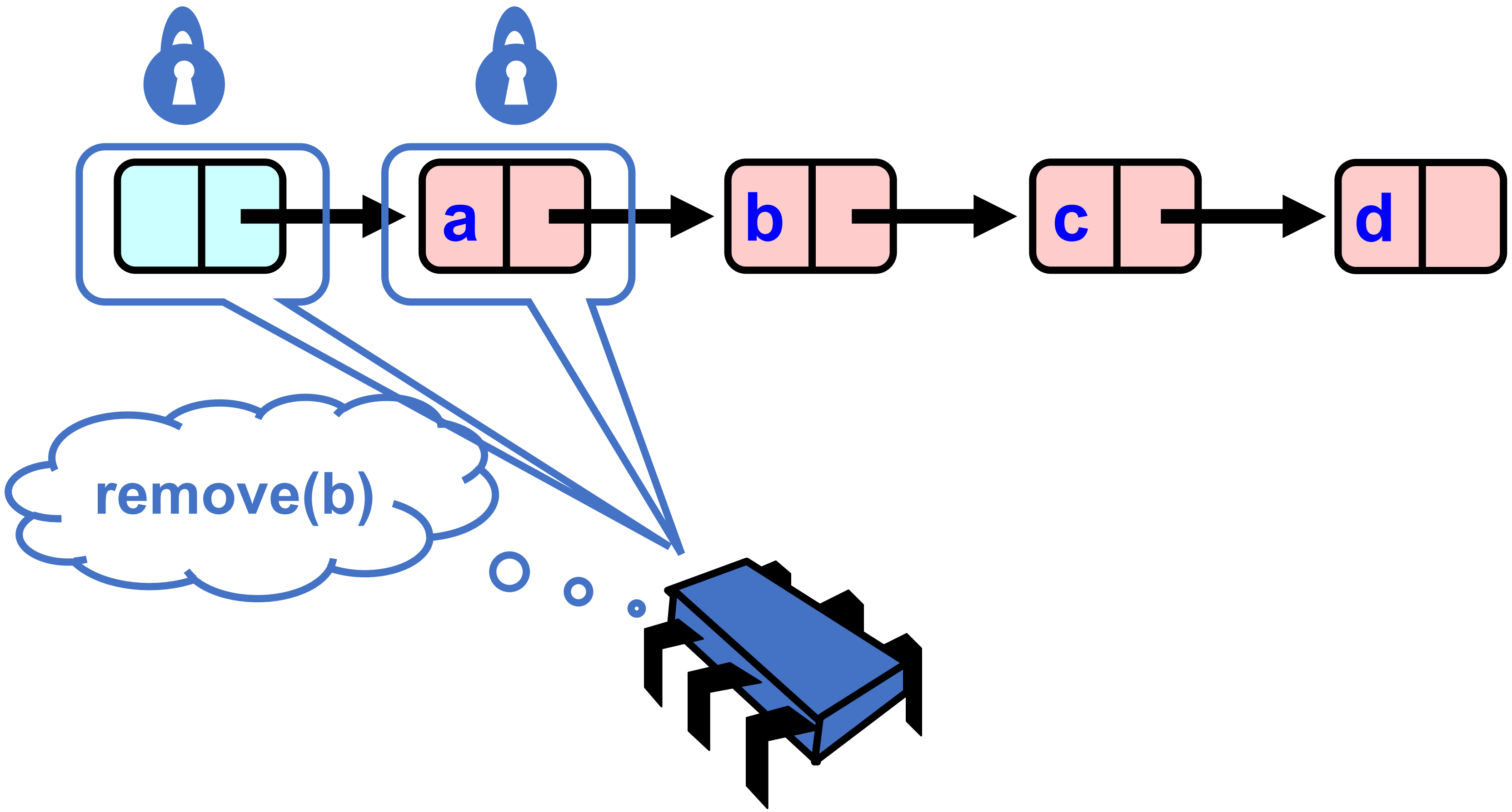

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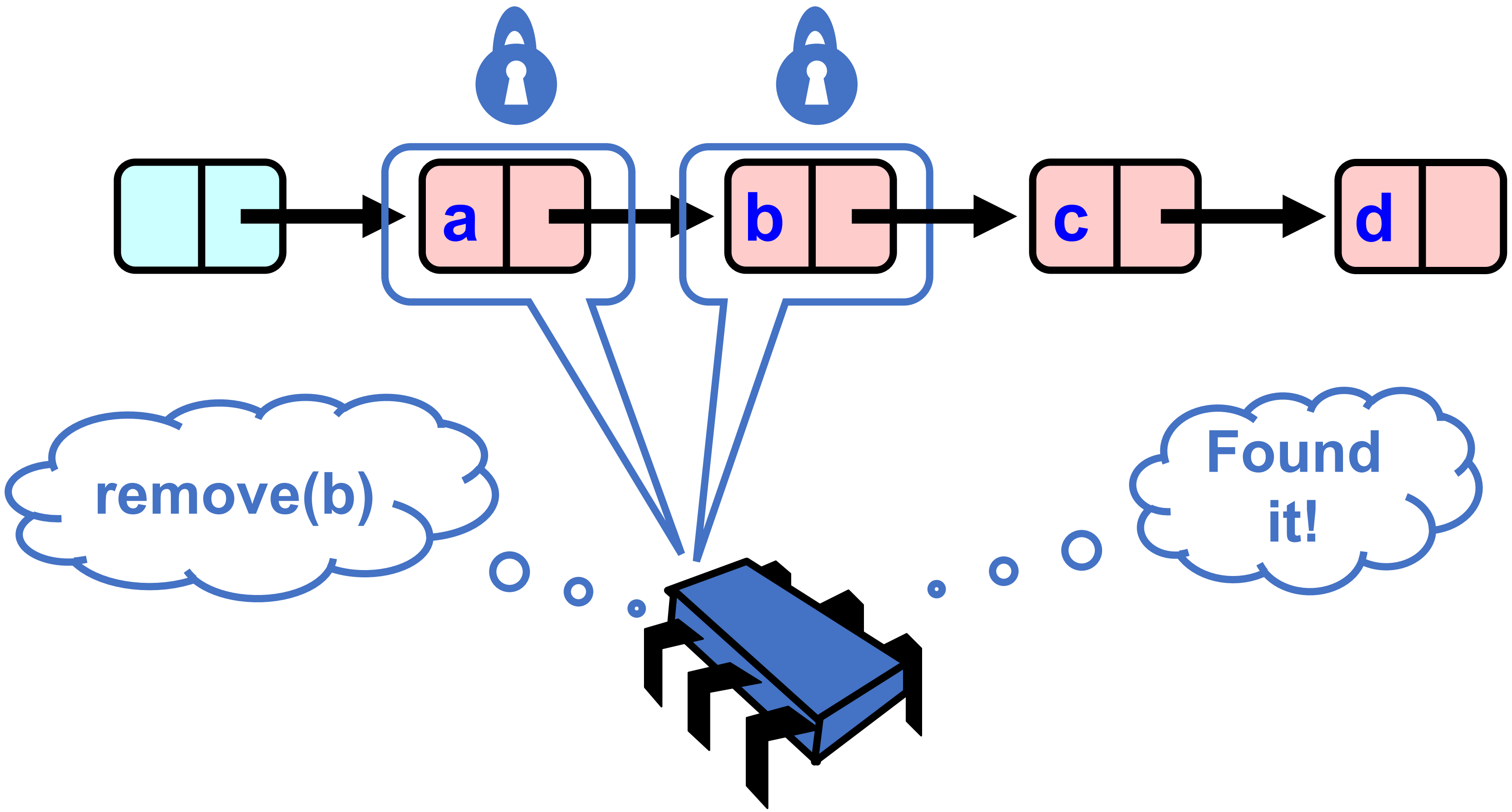

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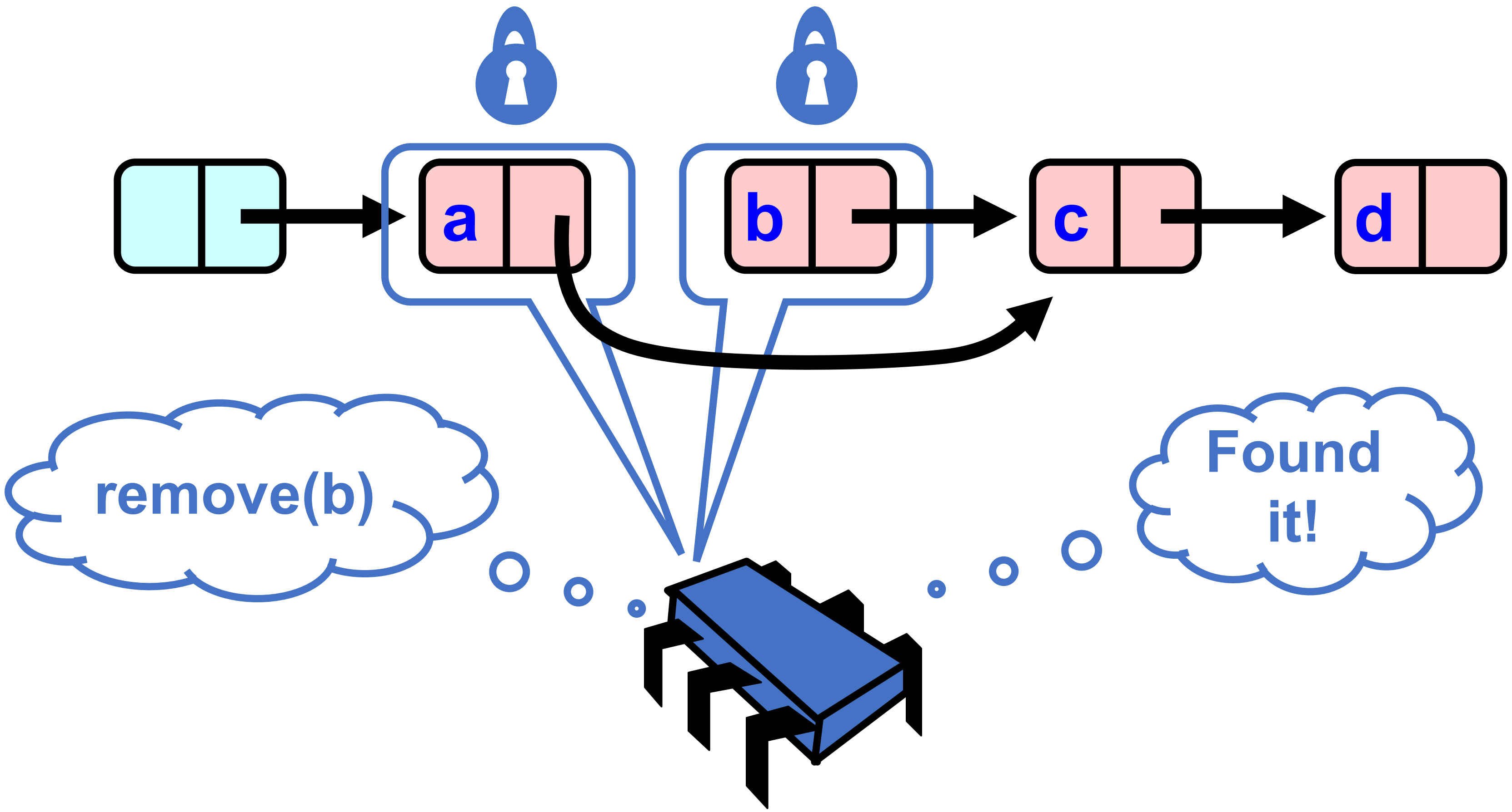

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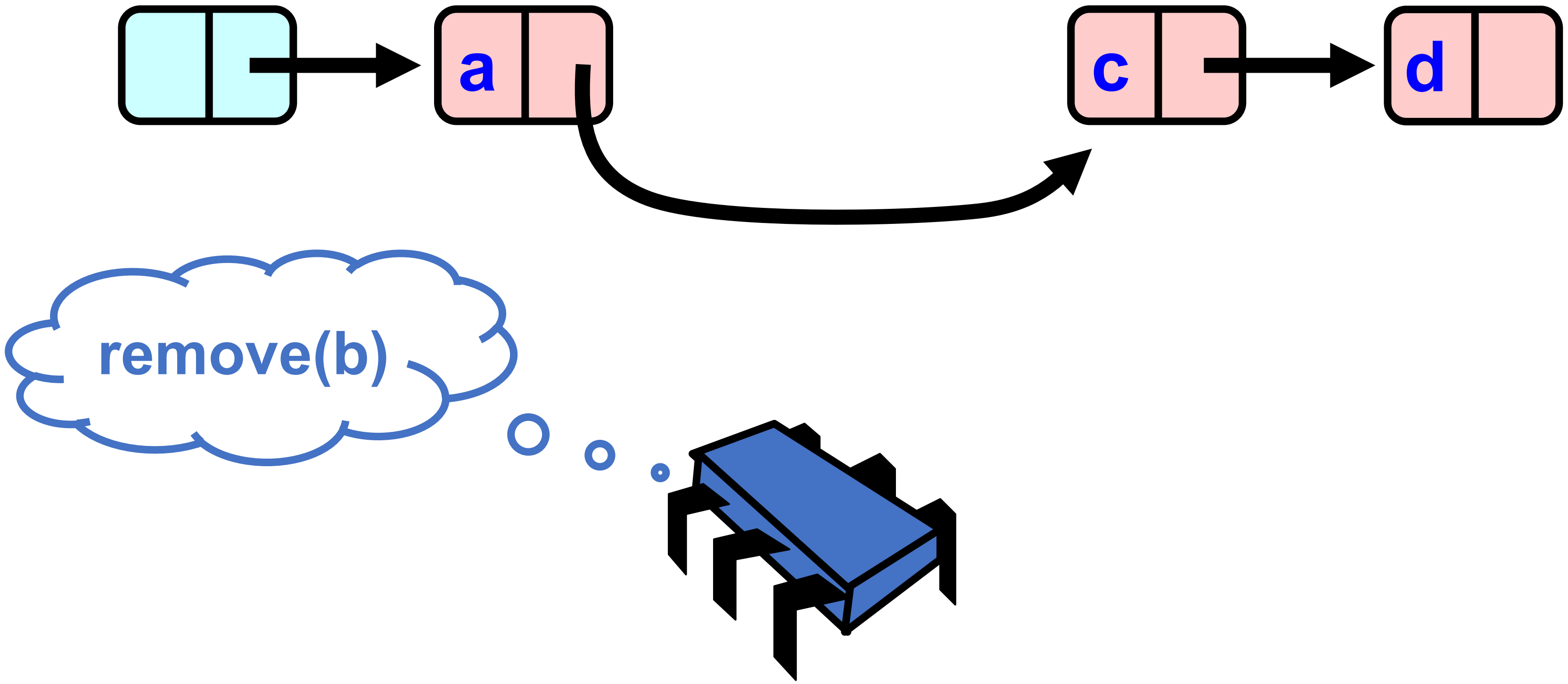
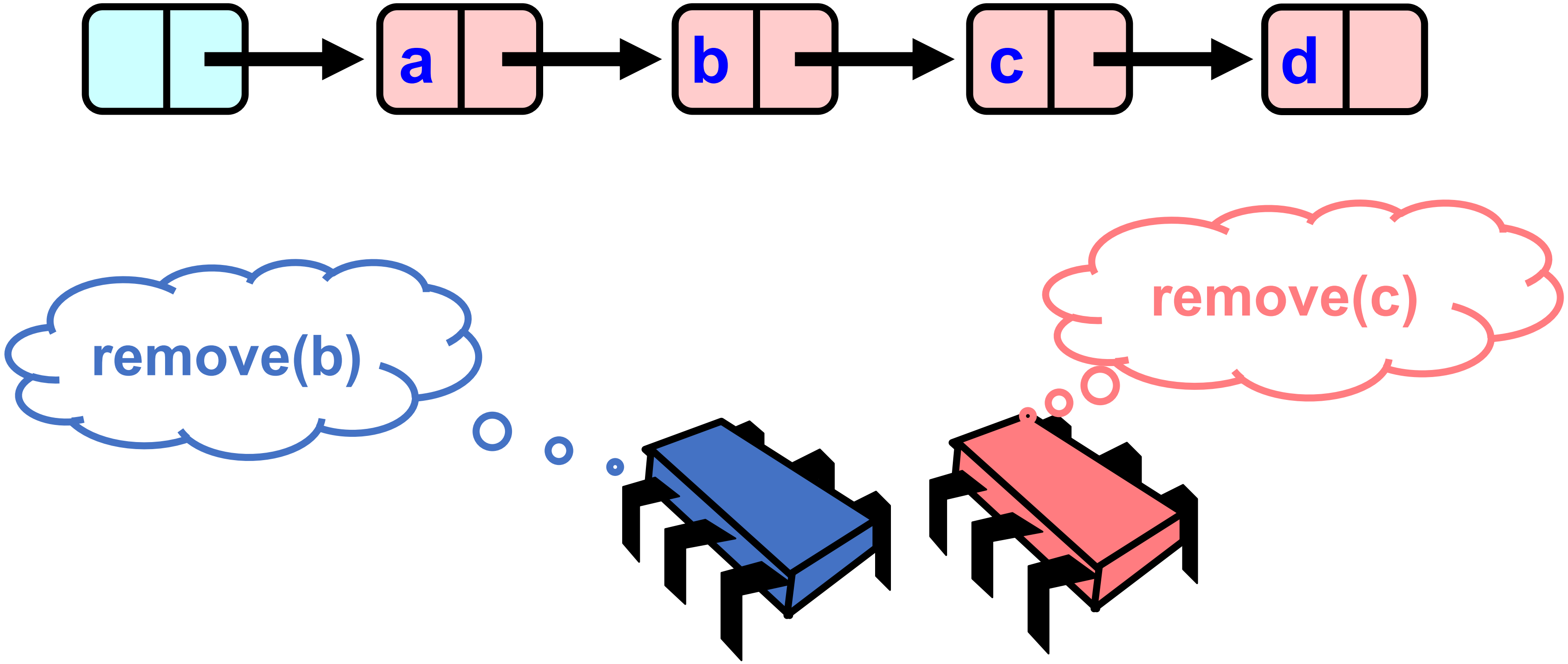


Removing a Node



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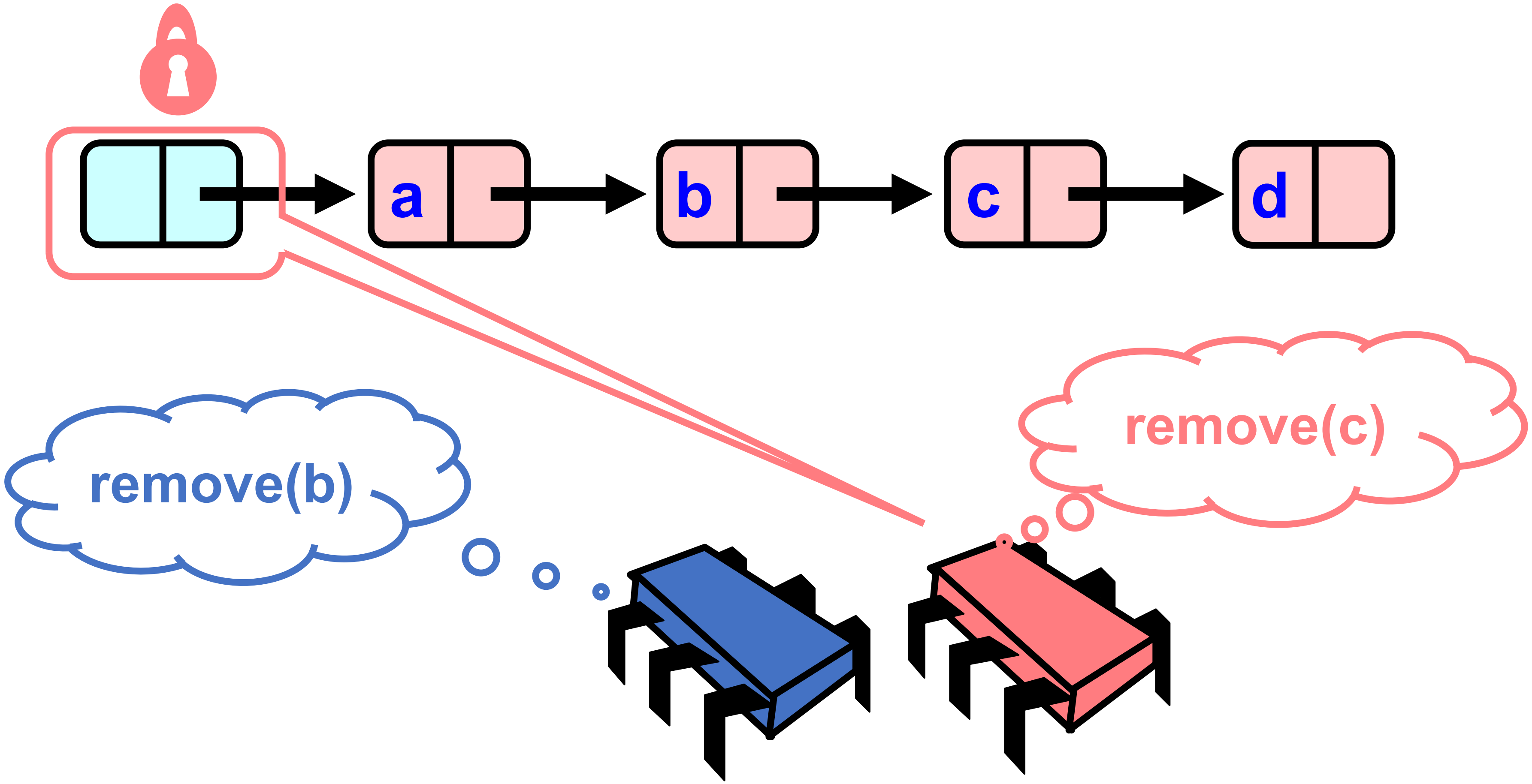

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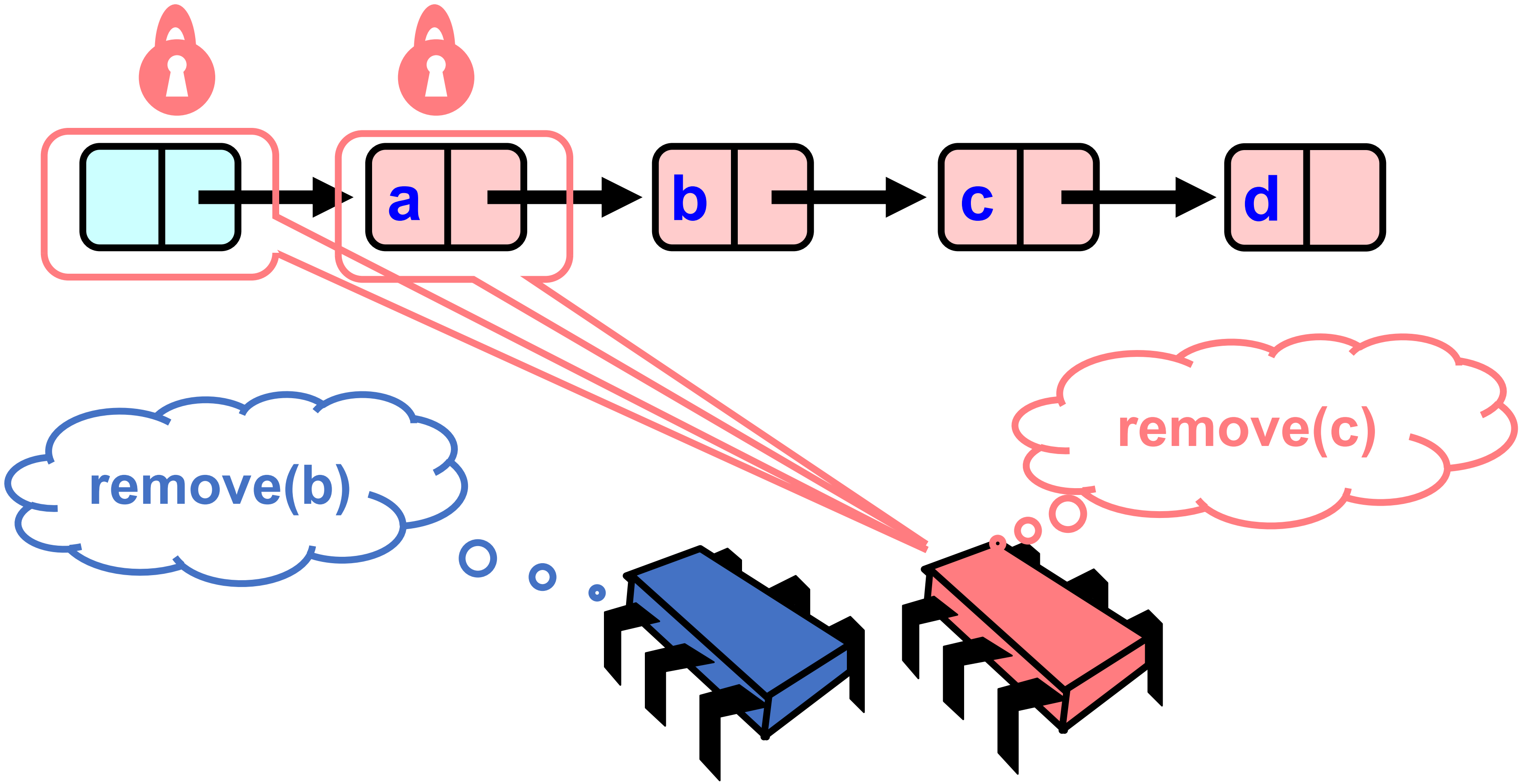

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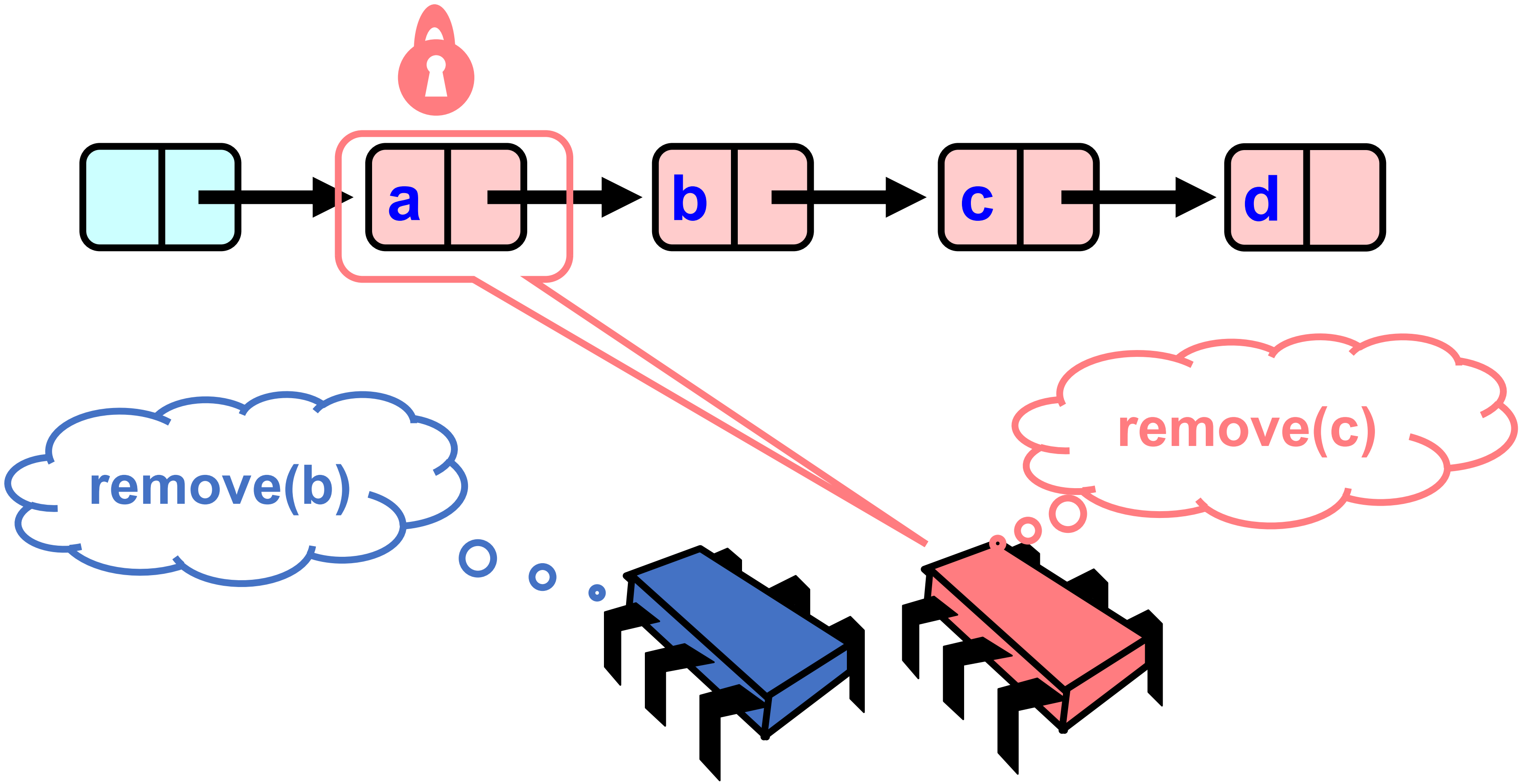

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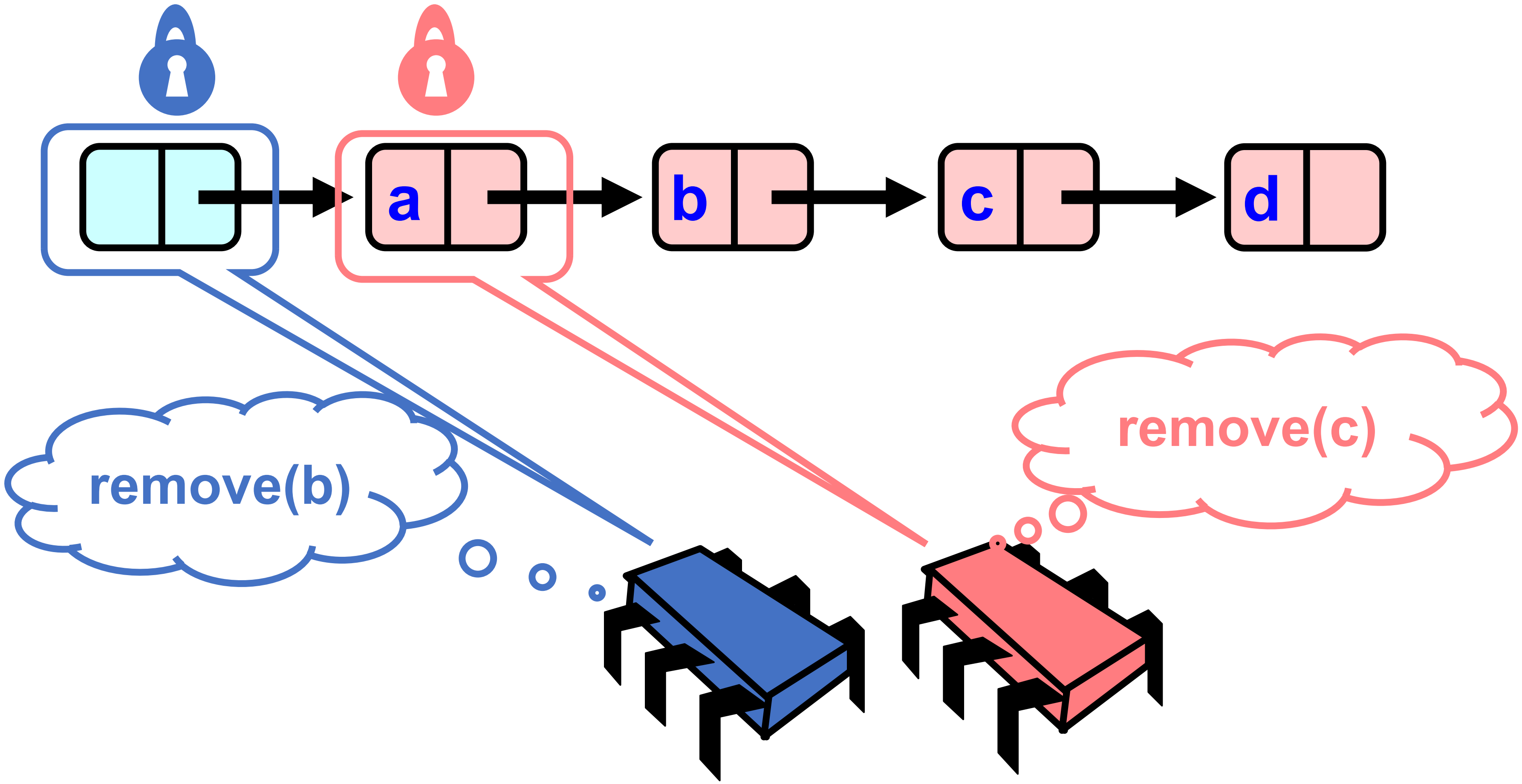

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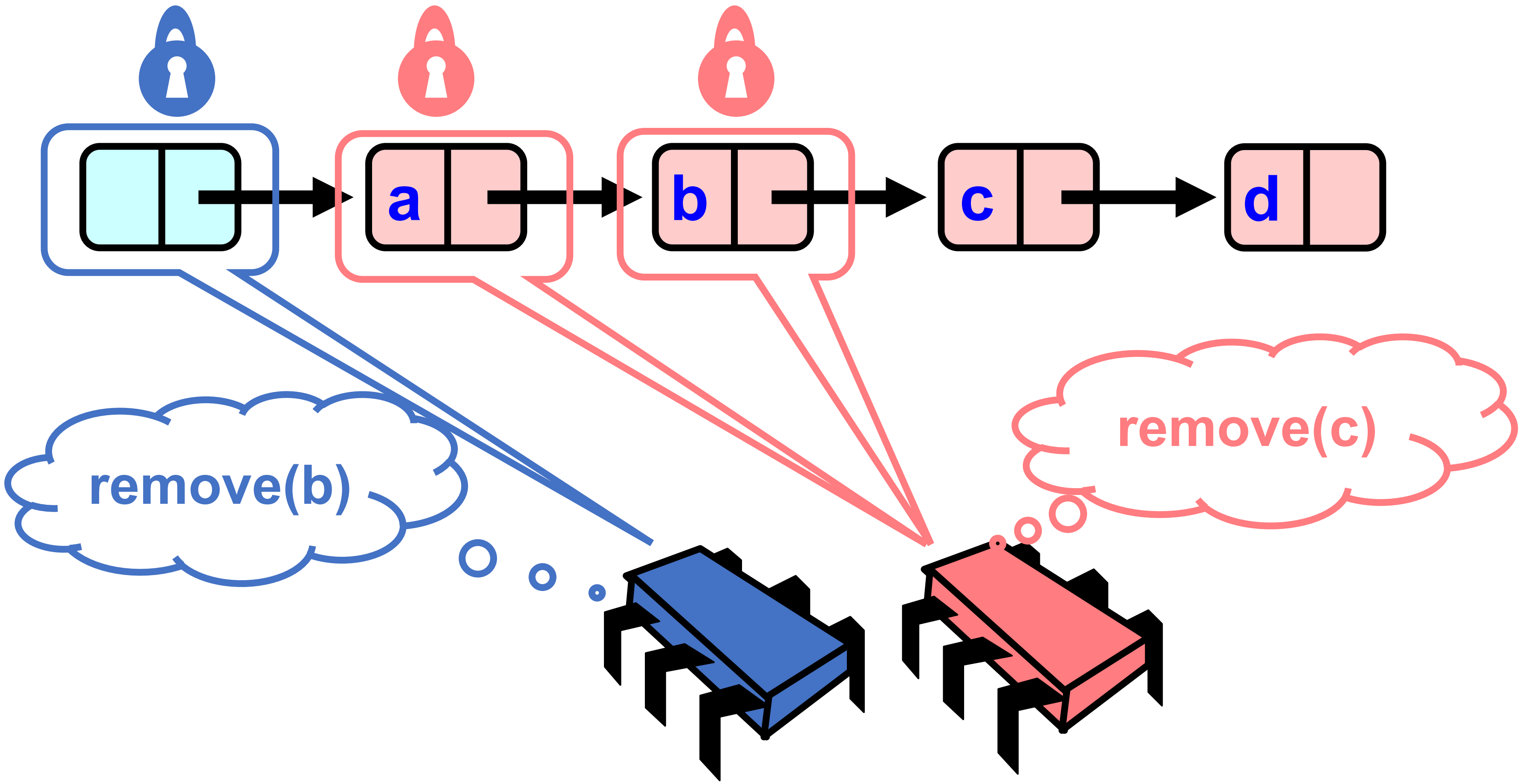

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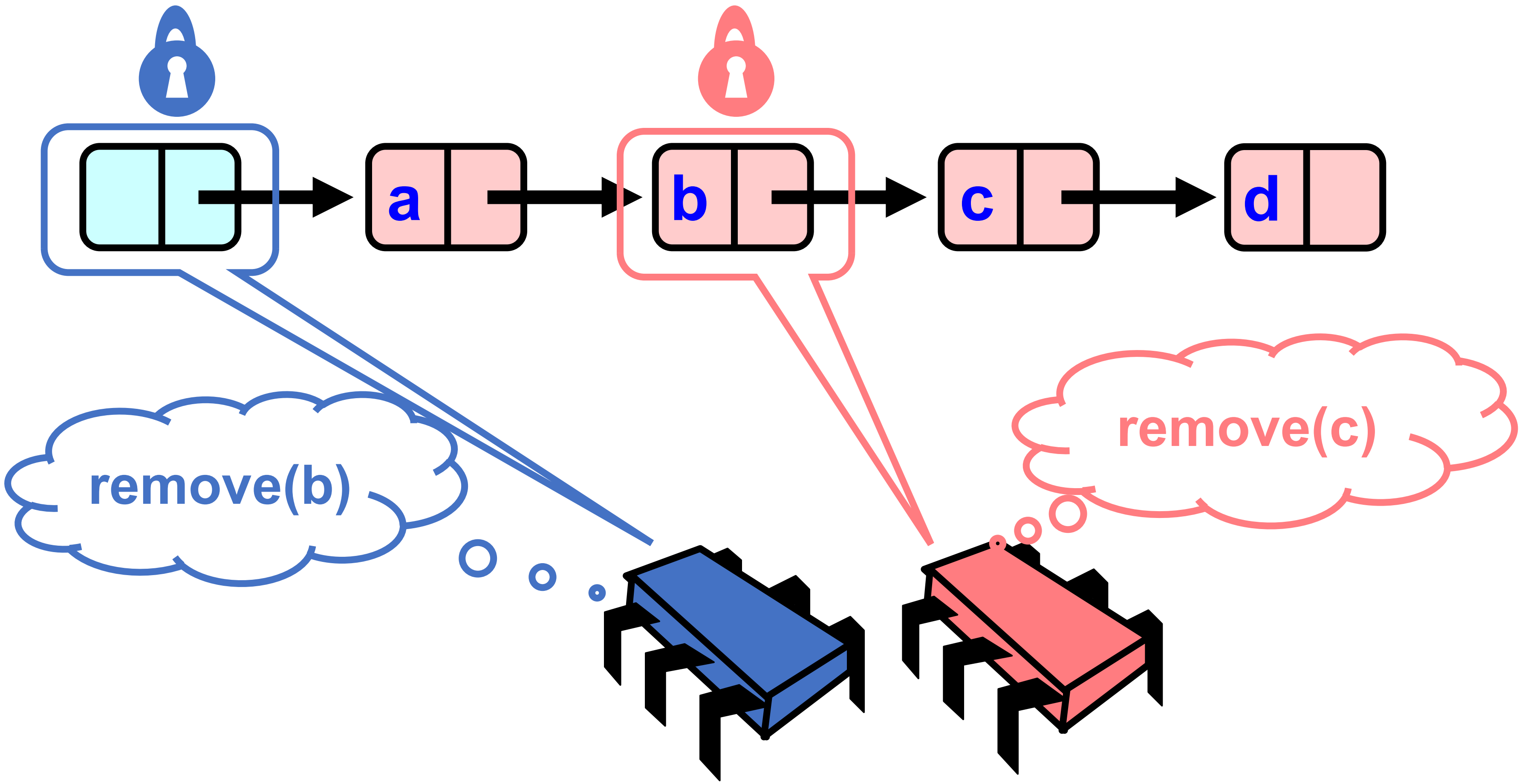

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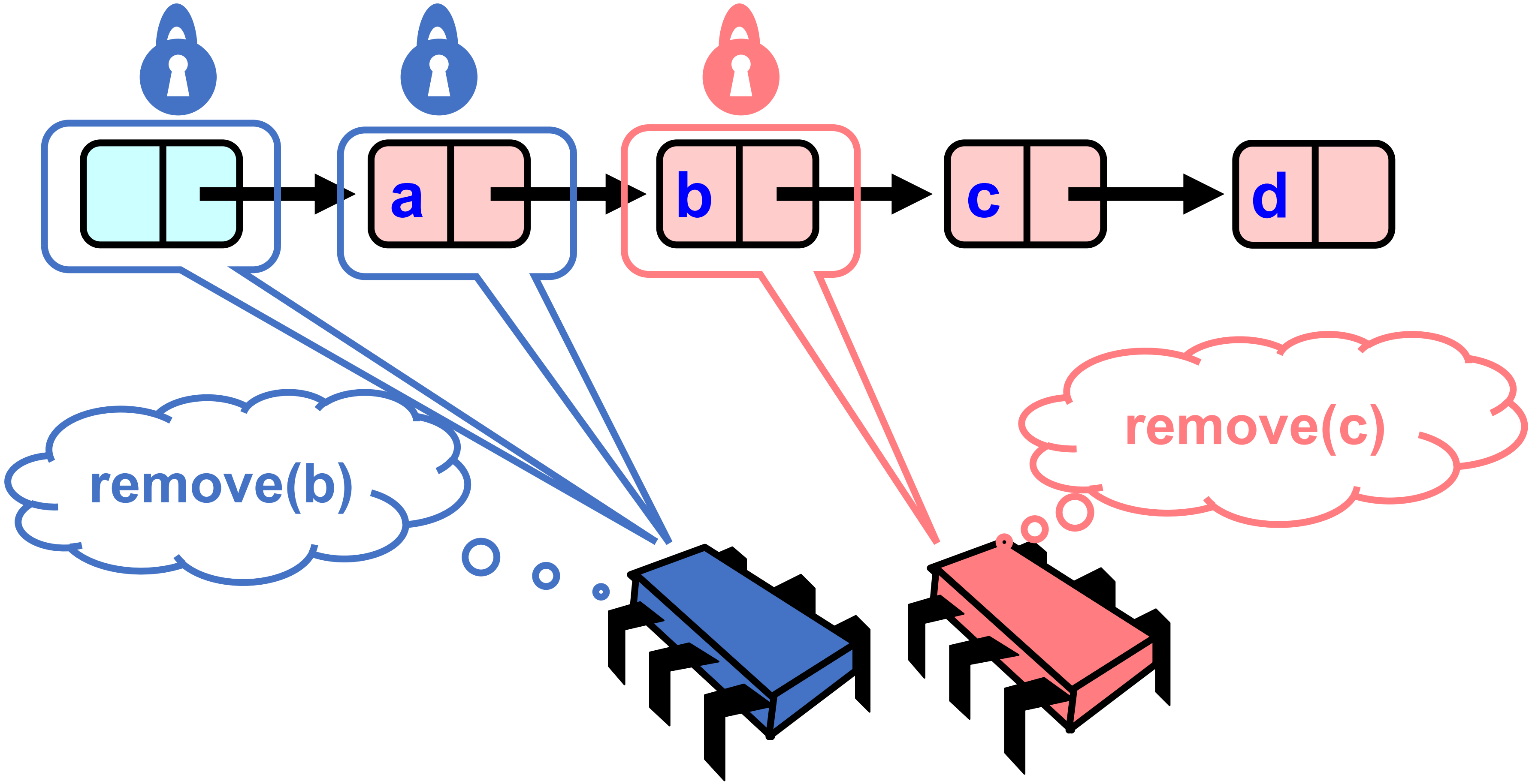

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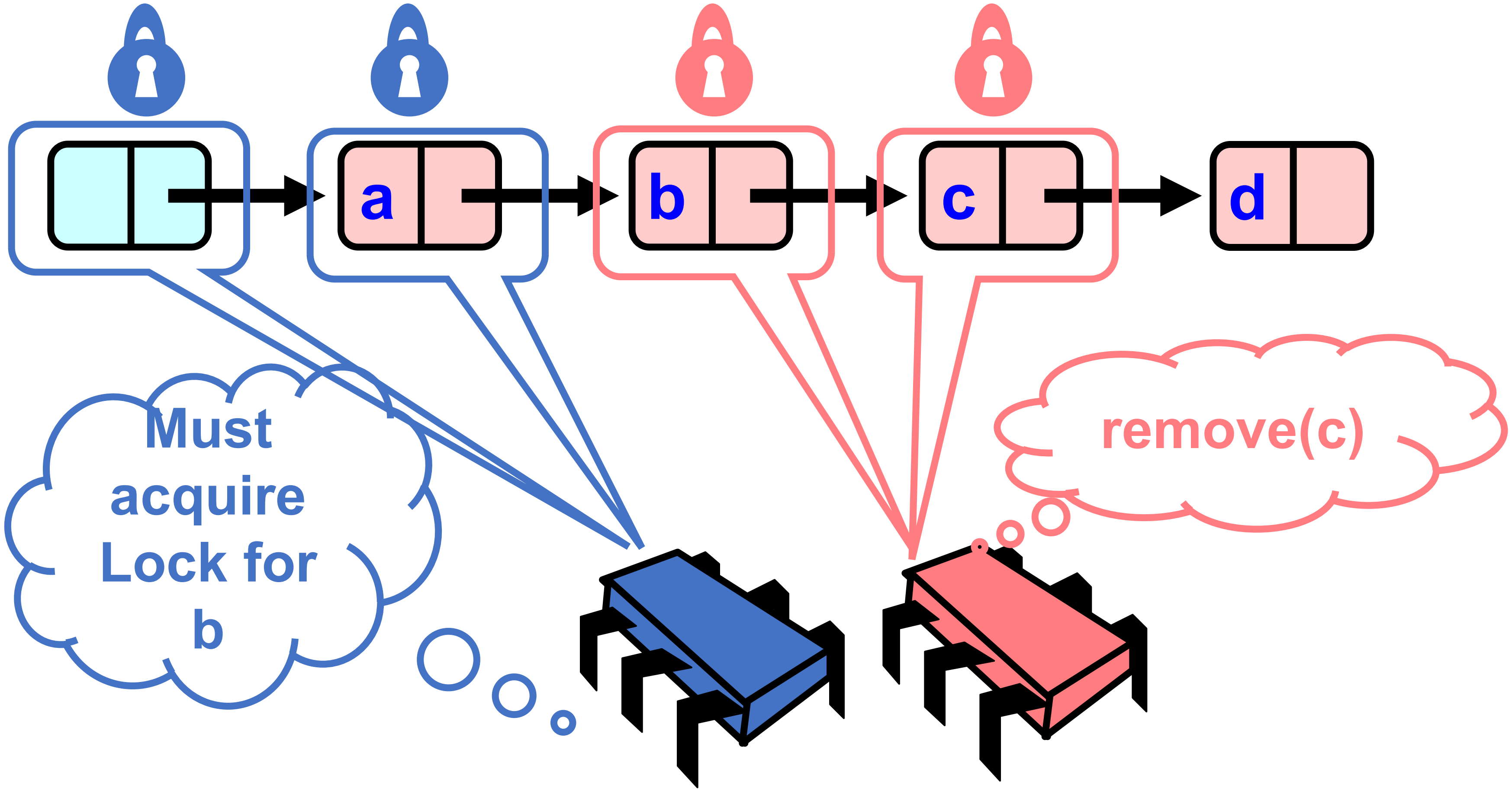

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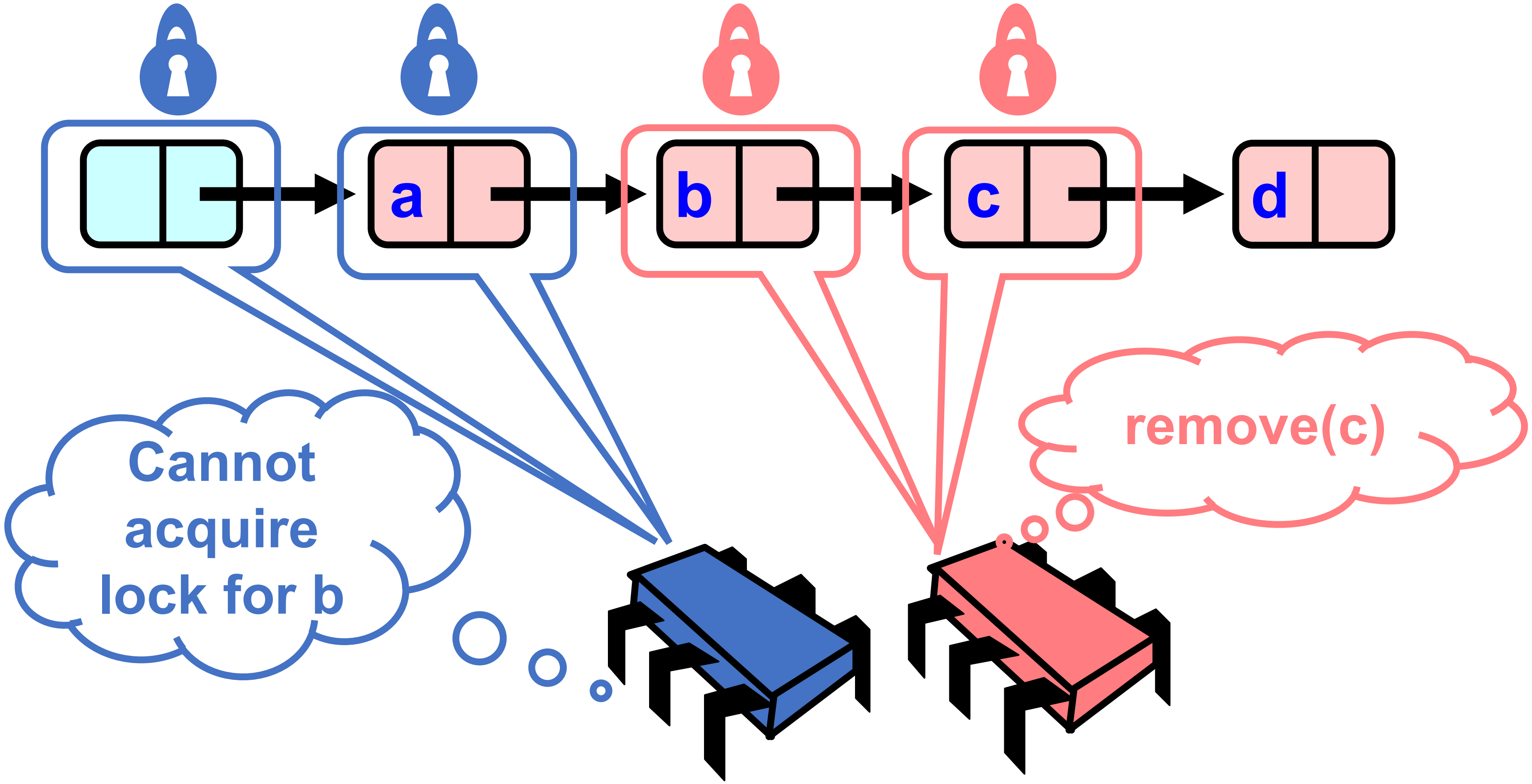

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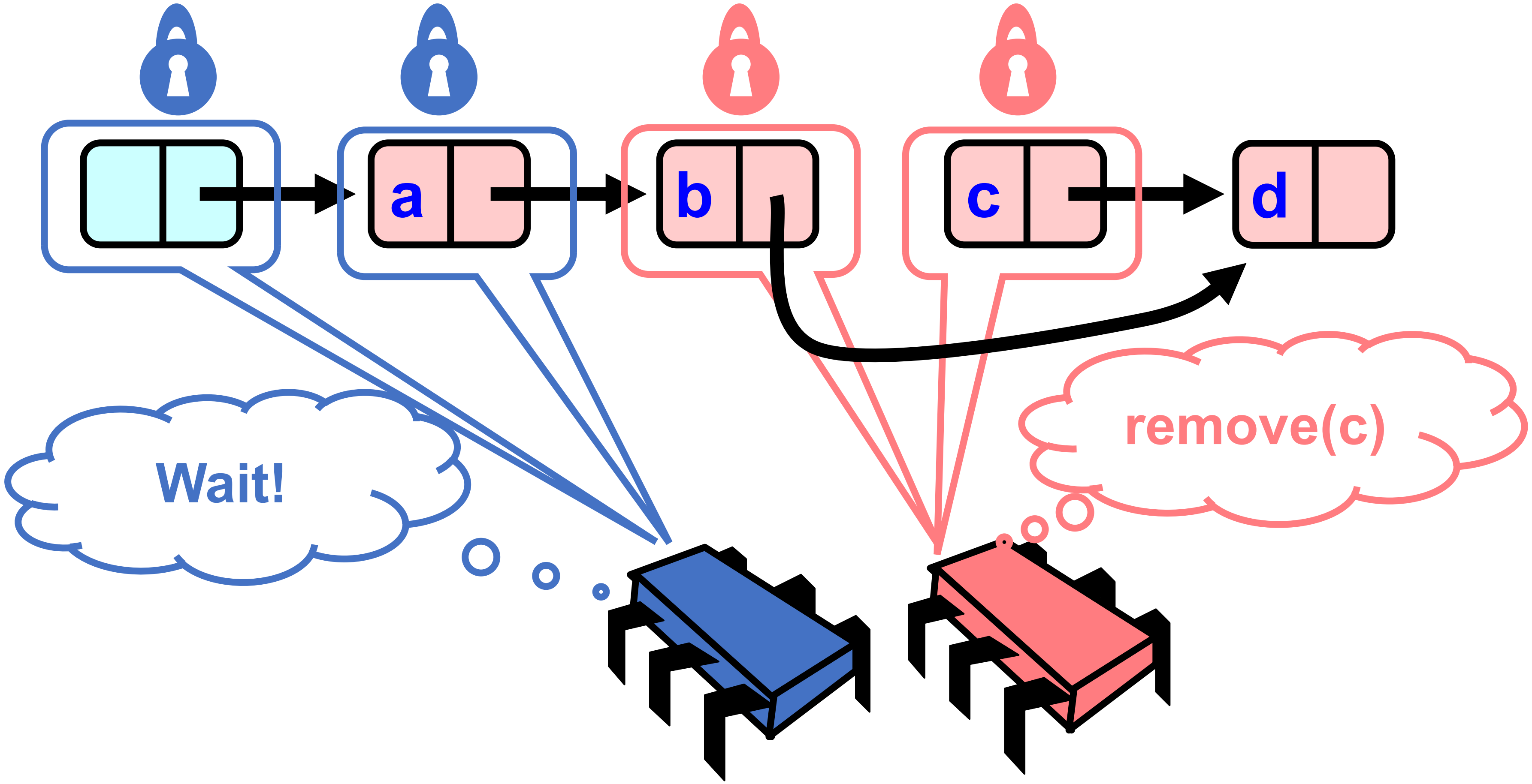

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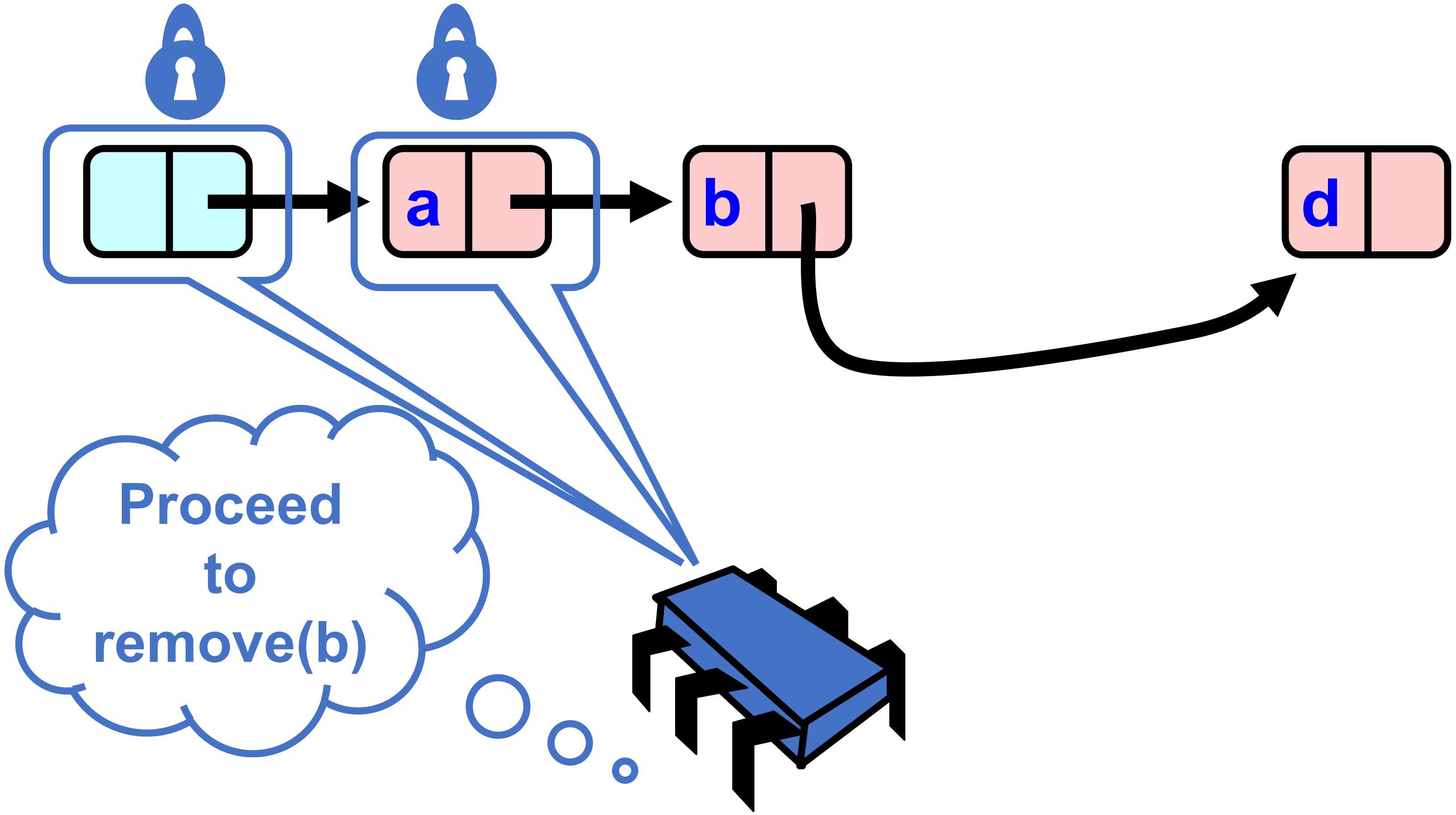

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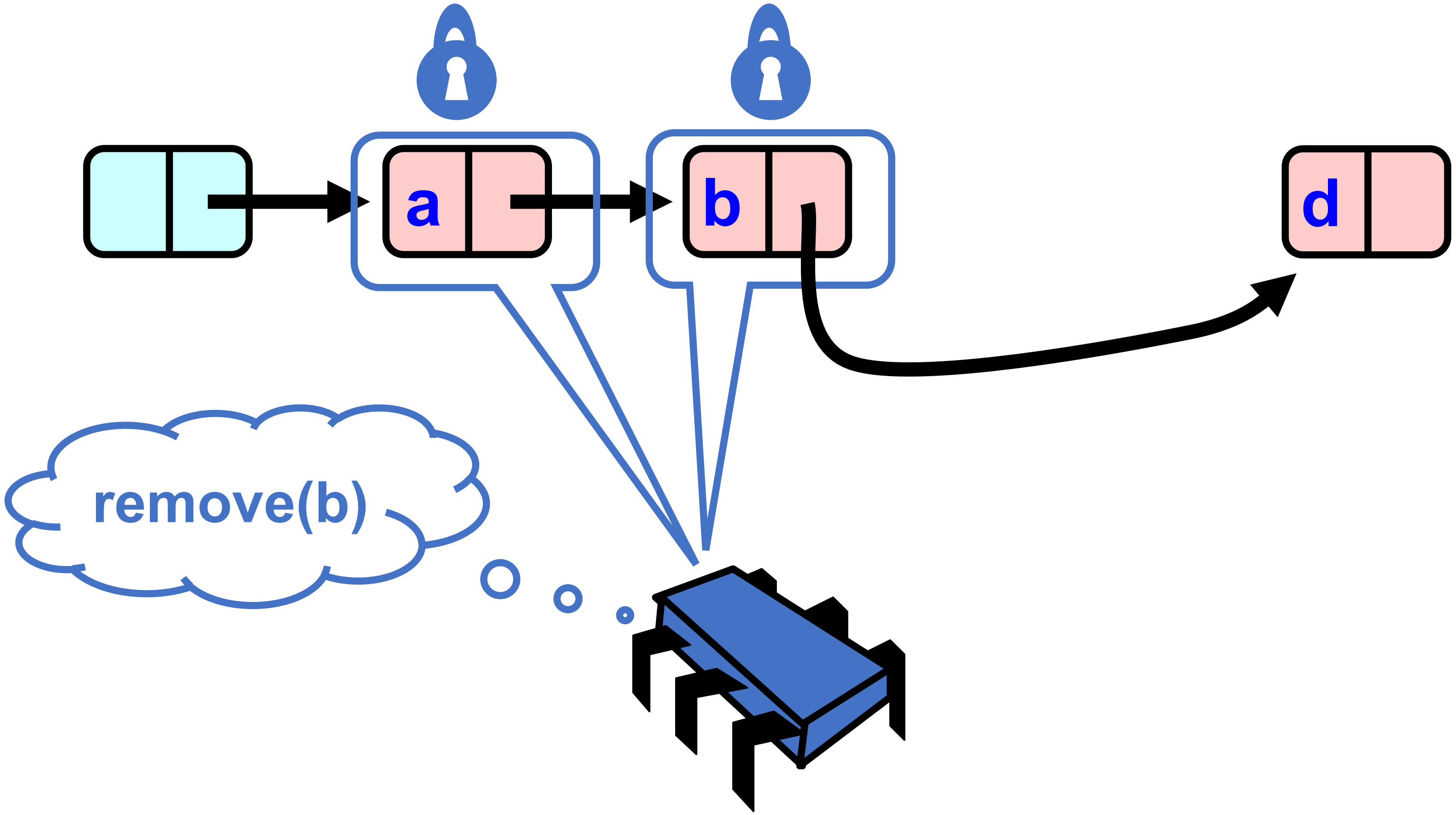

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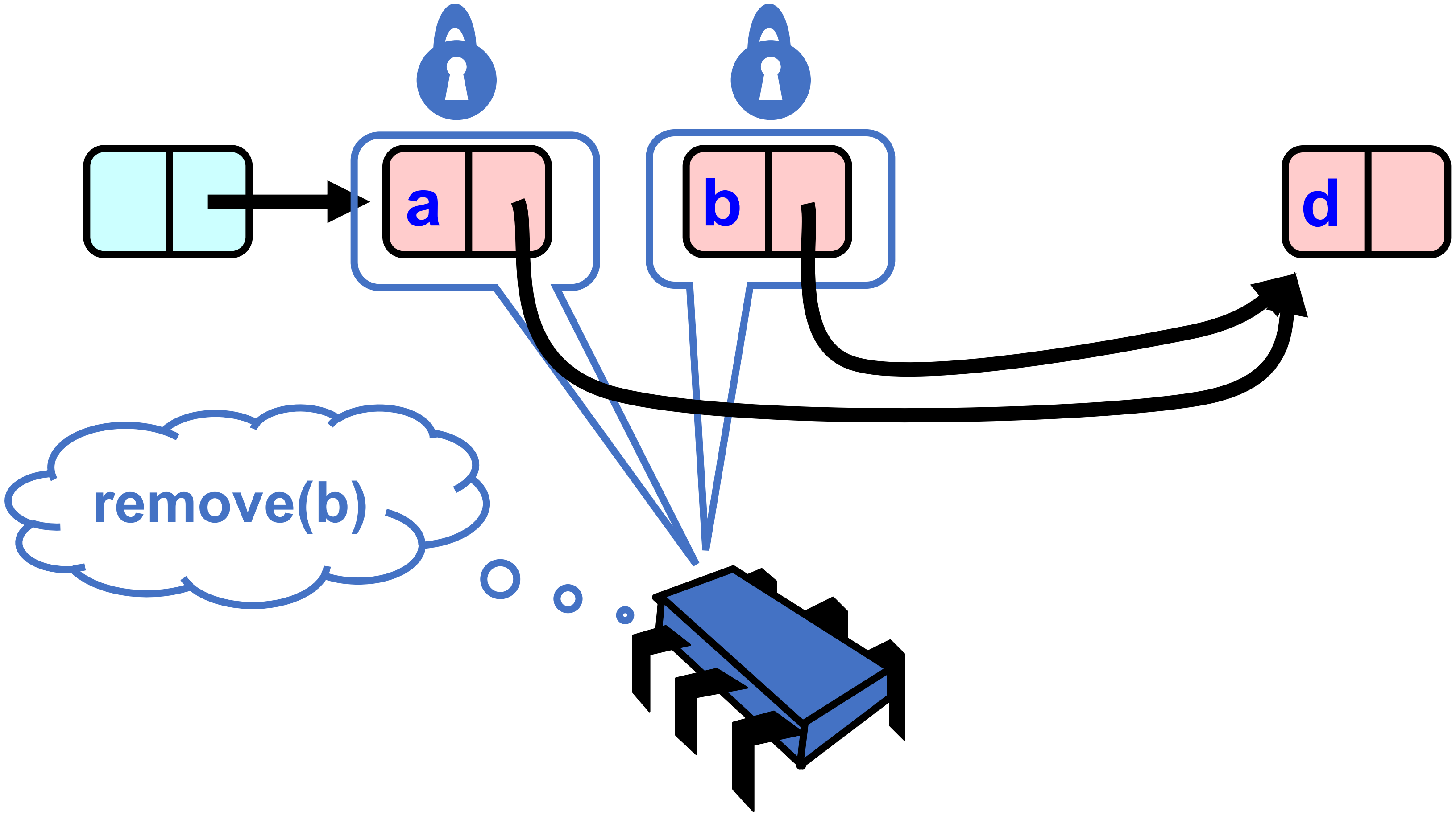

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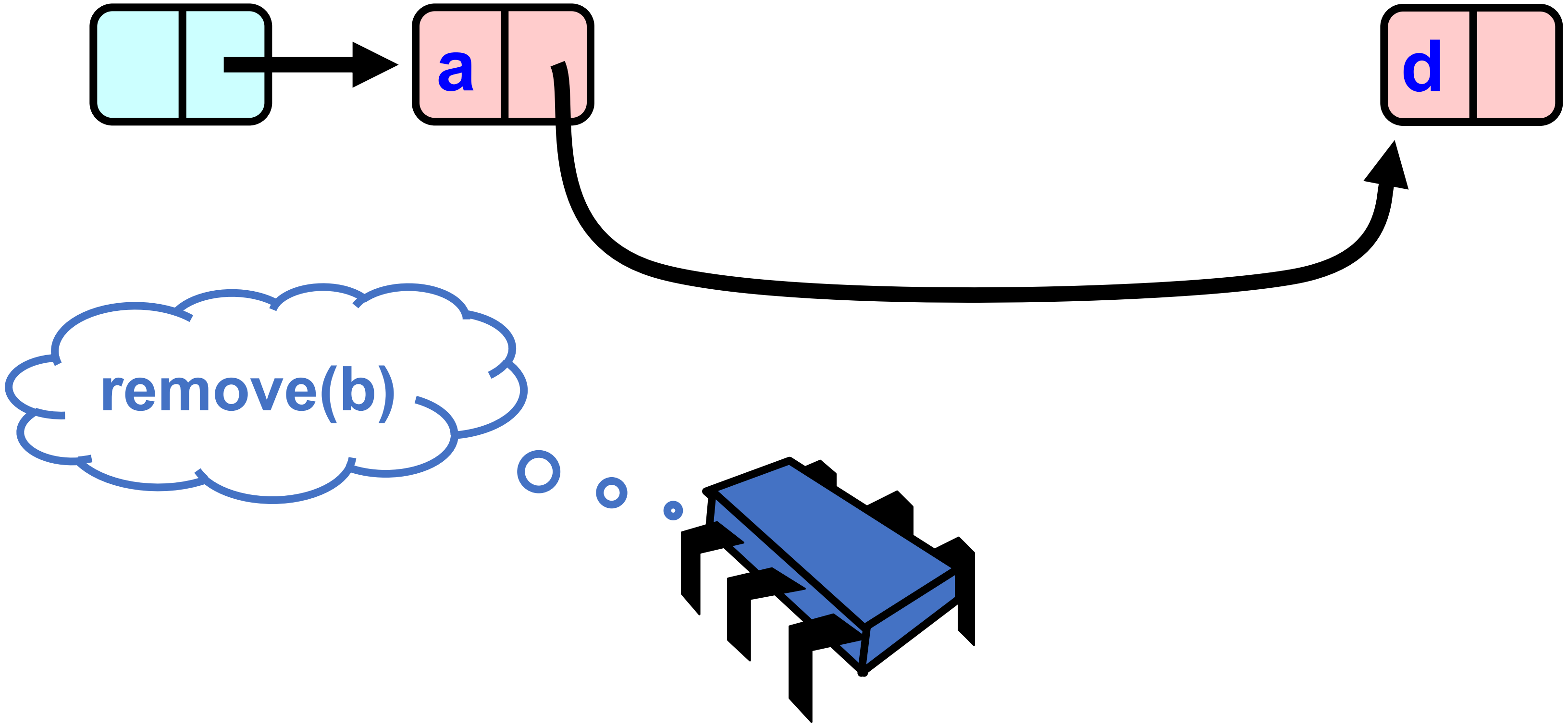

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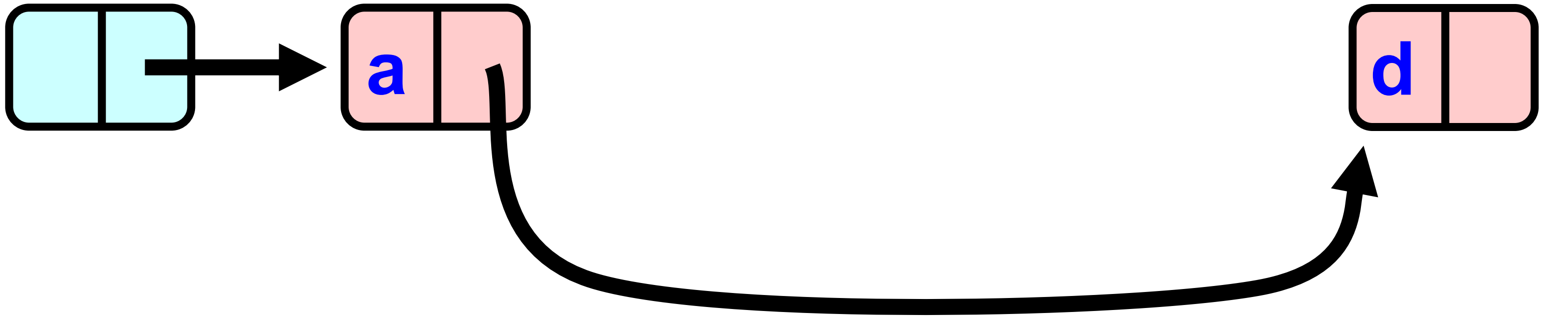


Adding Nodes

- Similar hand-over-hand locking
- To add node e
  - Must lock predecessor
  - Must lock successor
- Neither can be deleted

Drawbacks of fine-grained locking

- Better than coarse-grained lock
  - Threads can traverse in parallel
- Still not ideal
  - Acquires and releases lock for every node traversed. Long chain of acquire/release.
  - Reduces concurrency (traffic jams). Inefficient.

Optimistic Synchronization

- Assume there will be no conflicts.
- Check before committing.
- If there was a conflict, try again.

Optimistic Synchronization

- Find nodes without locking. Then, lock the two nodes.

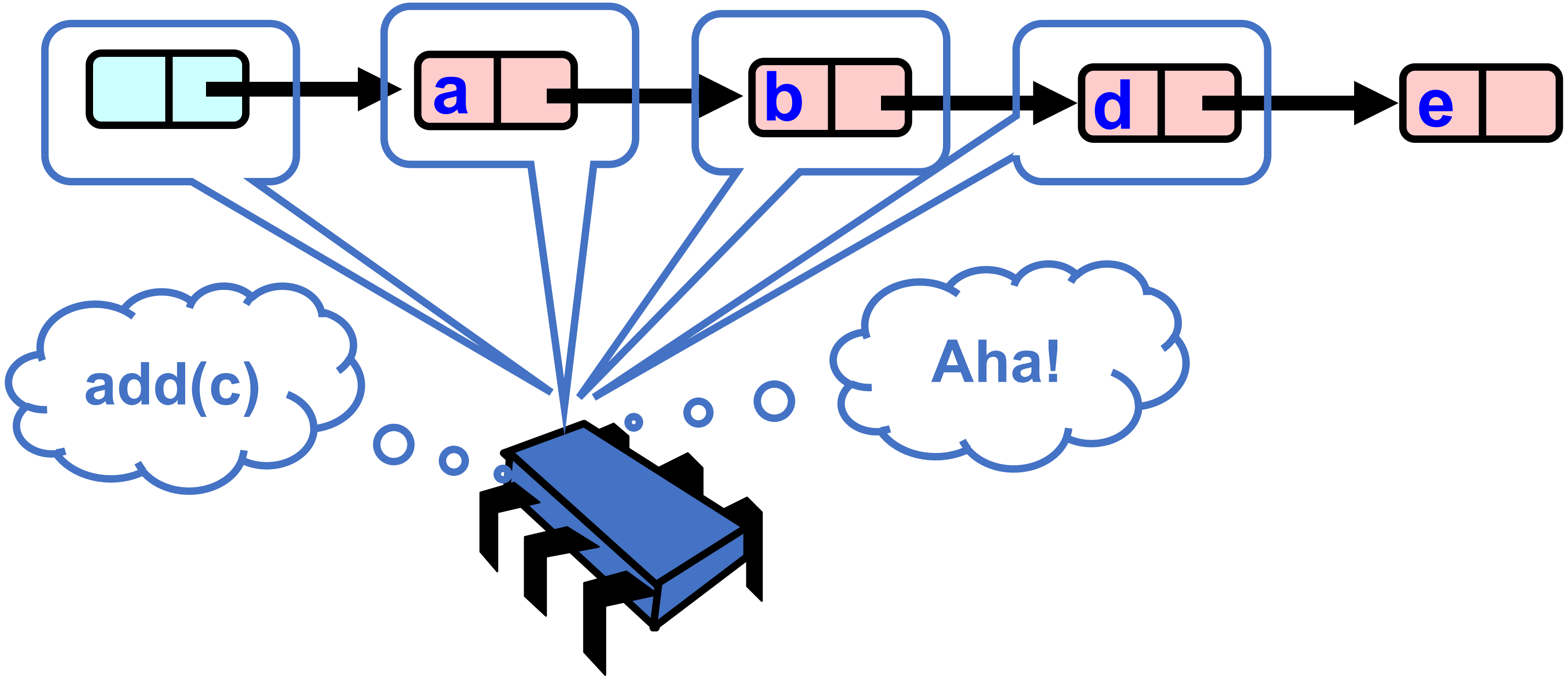
Optimistic Synchronization

- Find nodes without locking. Then, lock the two nodes.
- Check that the two nodes area still reachable.

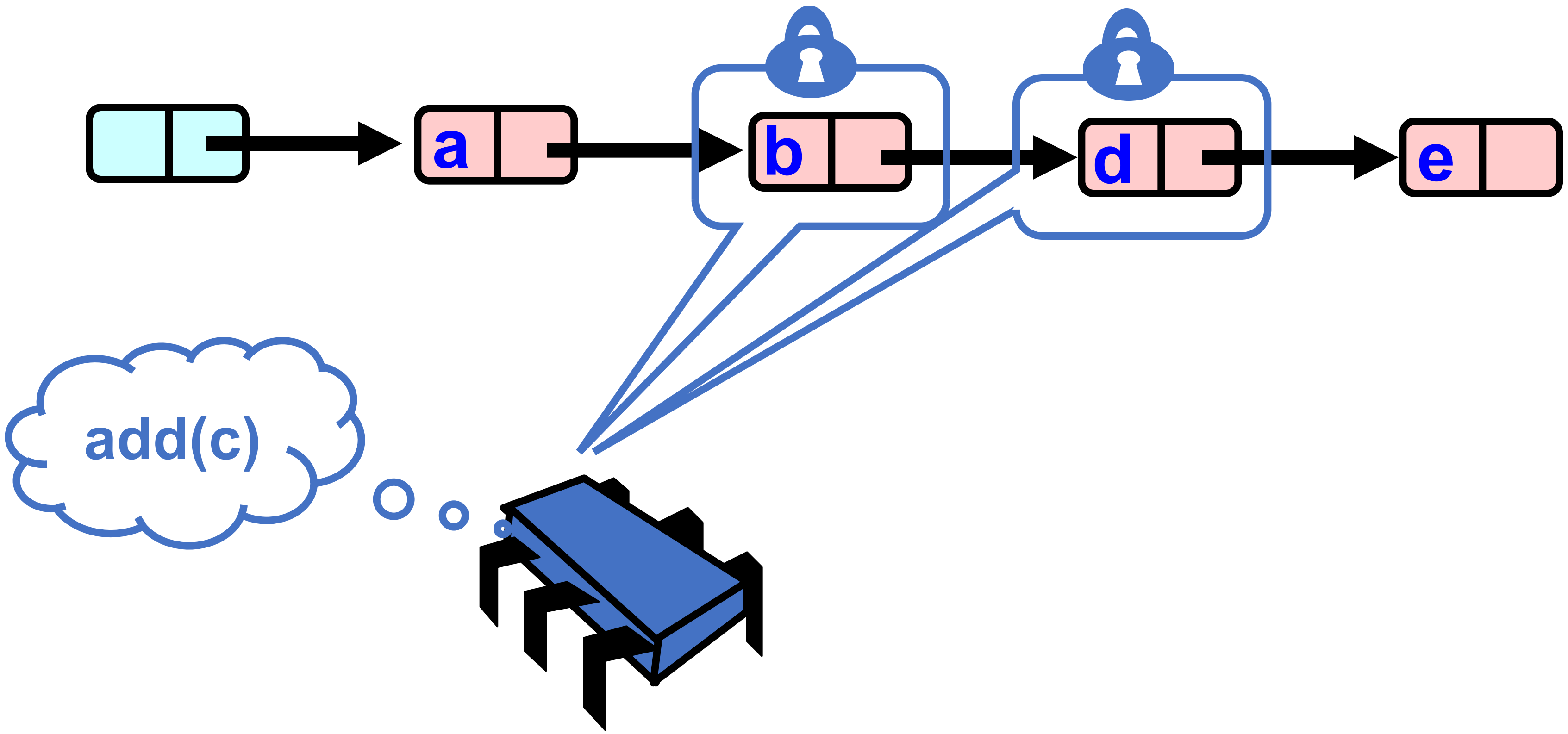
Optimistic Synchronization

- Find nodes without locking. Then, lock the two nodes.
- Check that the two nodes area still reachable.
- If they are not, search again from the beginning of the list.

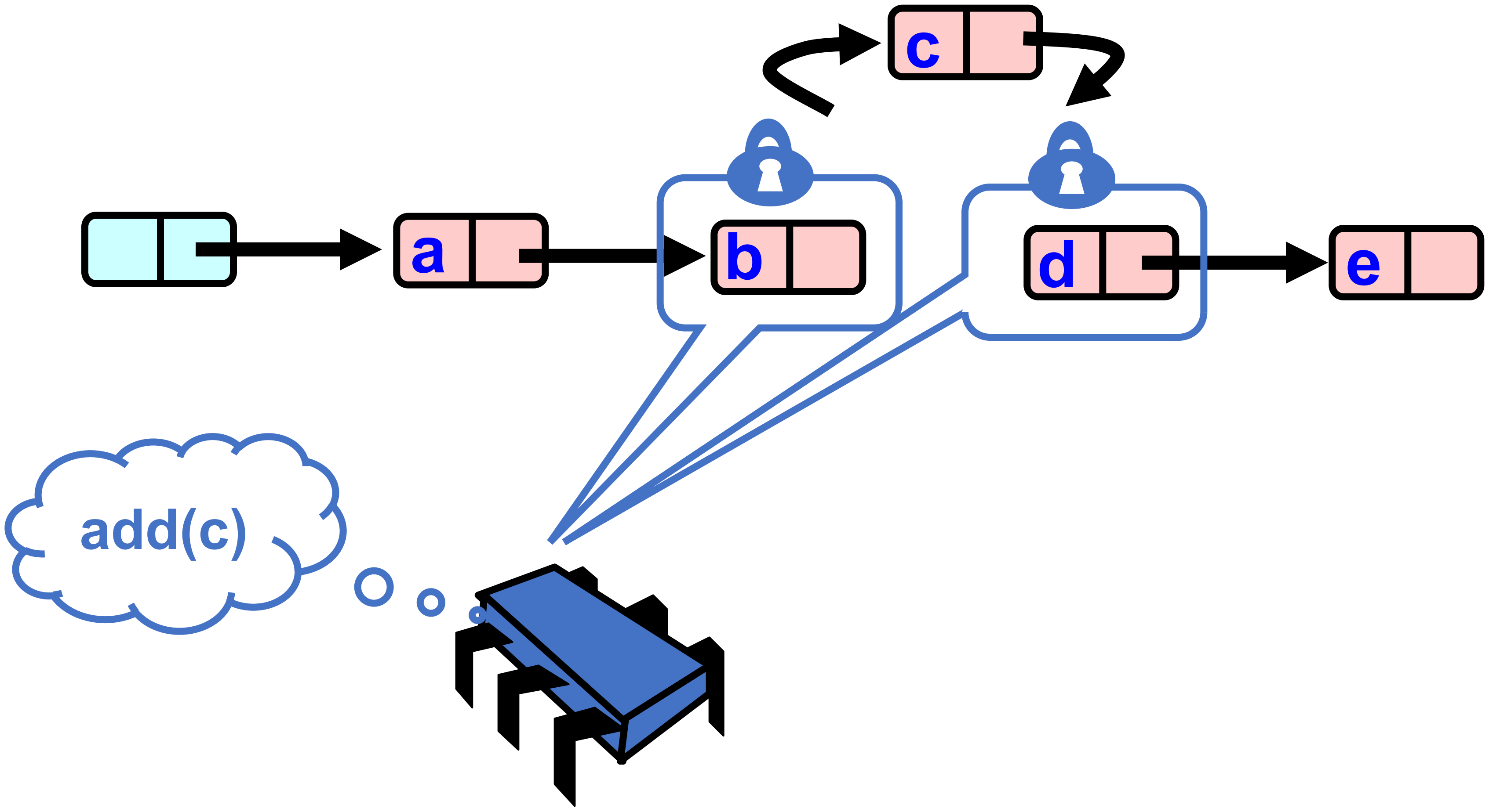
Optimistic: Traverse without Locking



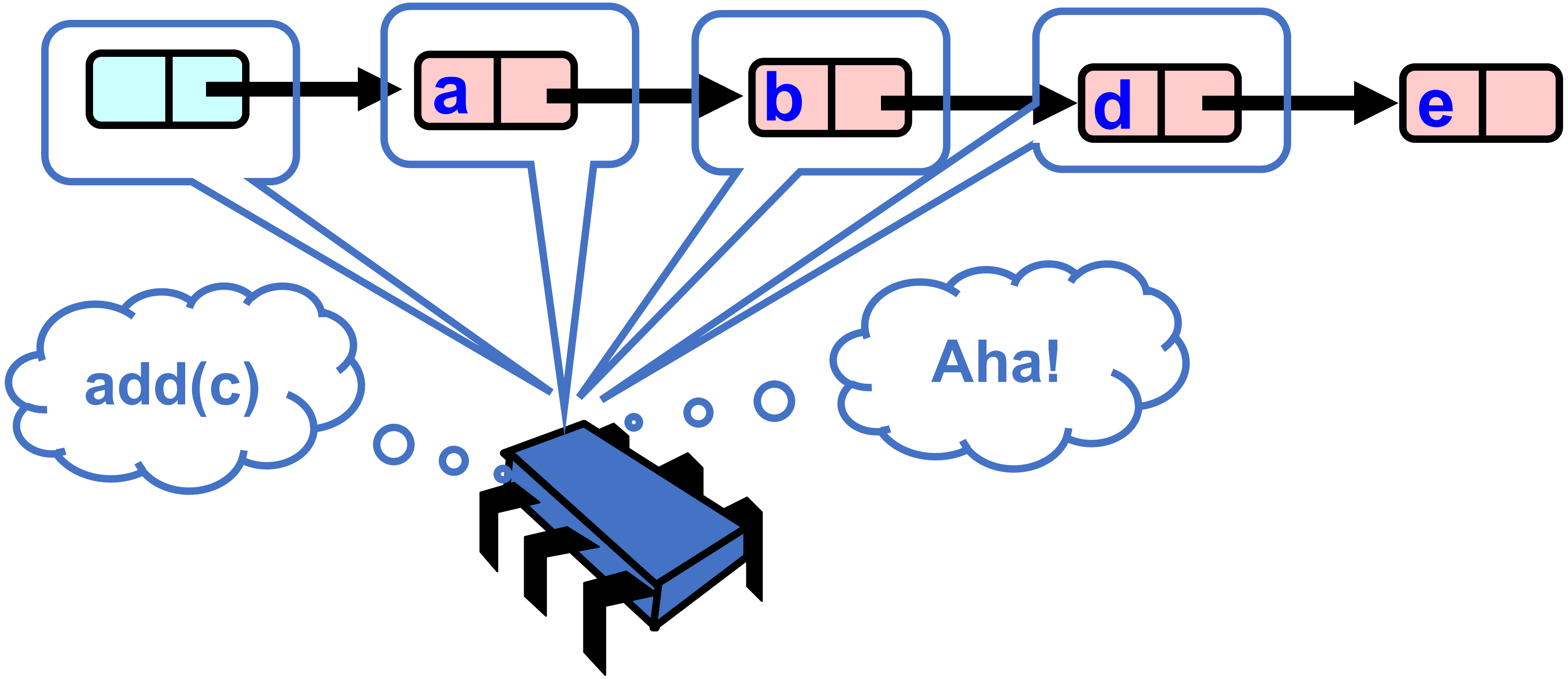
Optimistic: Lock



Optimistic: Insert without checking



What could go wrong?



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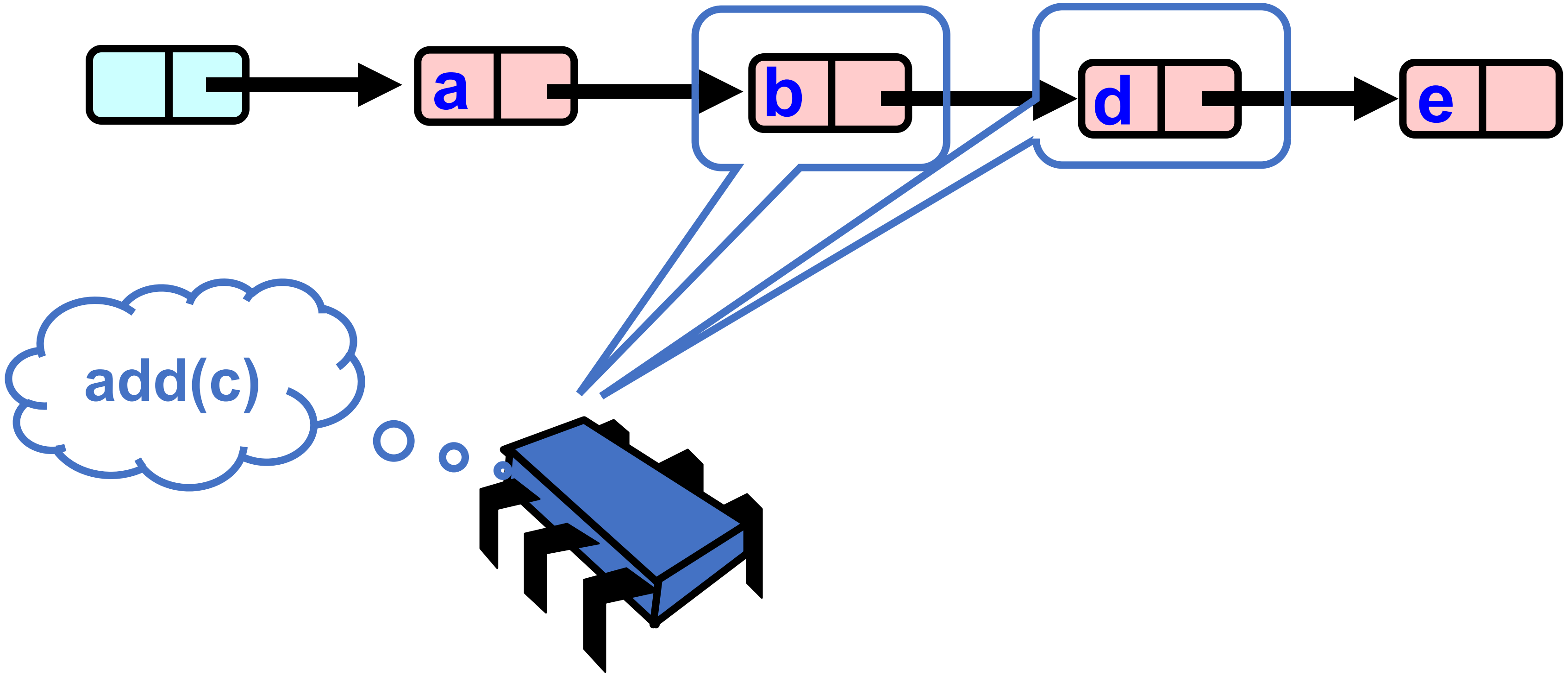

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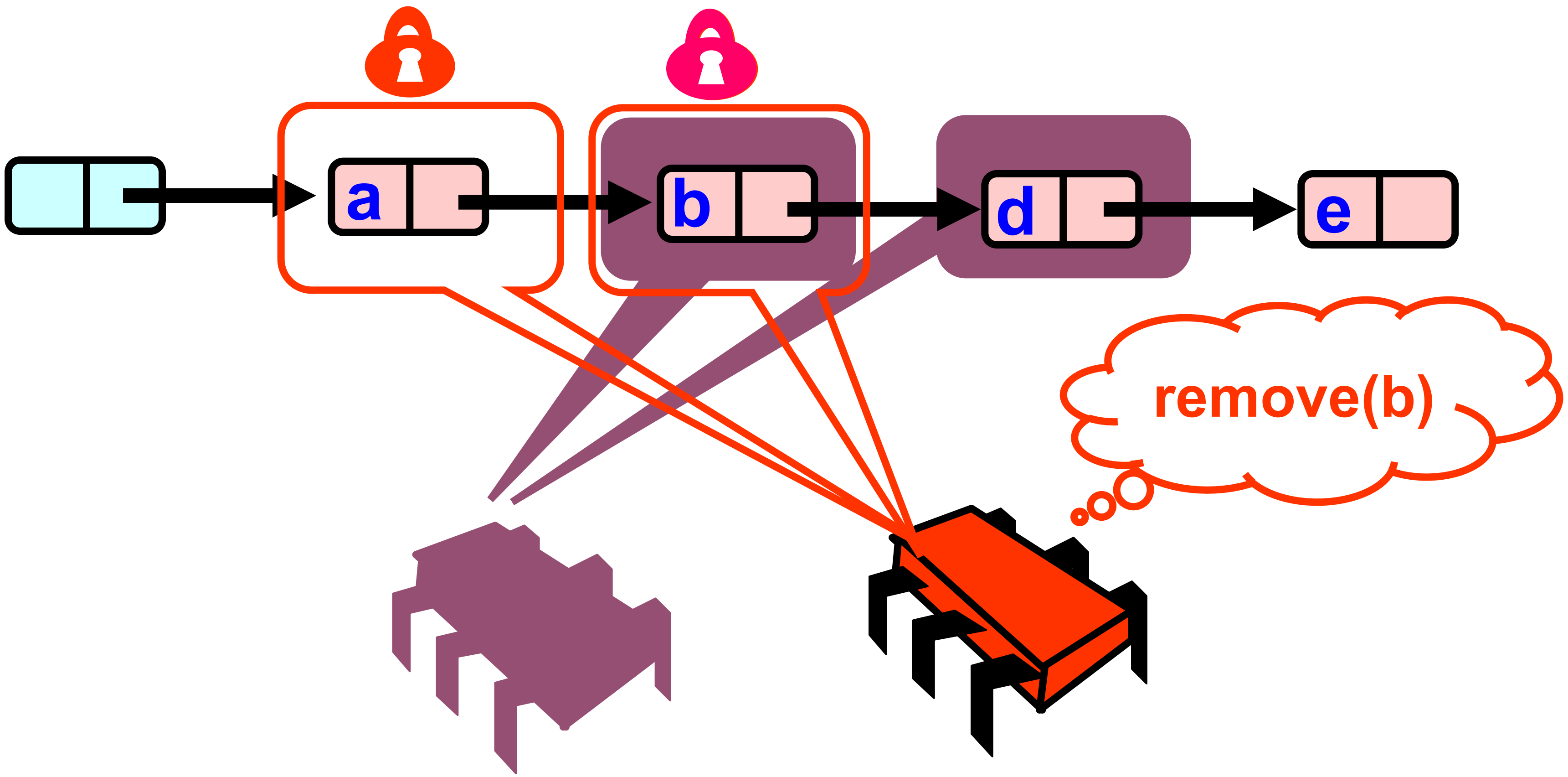


Data conflict (Race)!

- Red thread has the lock on a node (so it can modify the node)
- Blue thread is traversing without locks

- What do we do?

Race-freedom

- We can use atomic variables

Race-freedom

```
class Node {
 public:
   Value v;
   int key;
   Node *next;
}
```

Race-freedom

```
class Node {
 public:
   Value v;
   int key;
   atomic<Node*> next;
}
```

Create an atomic pointer type using C++ templates

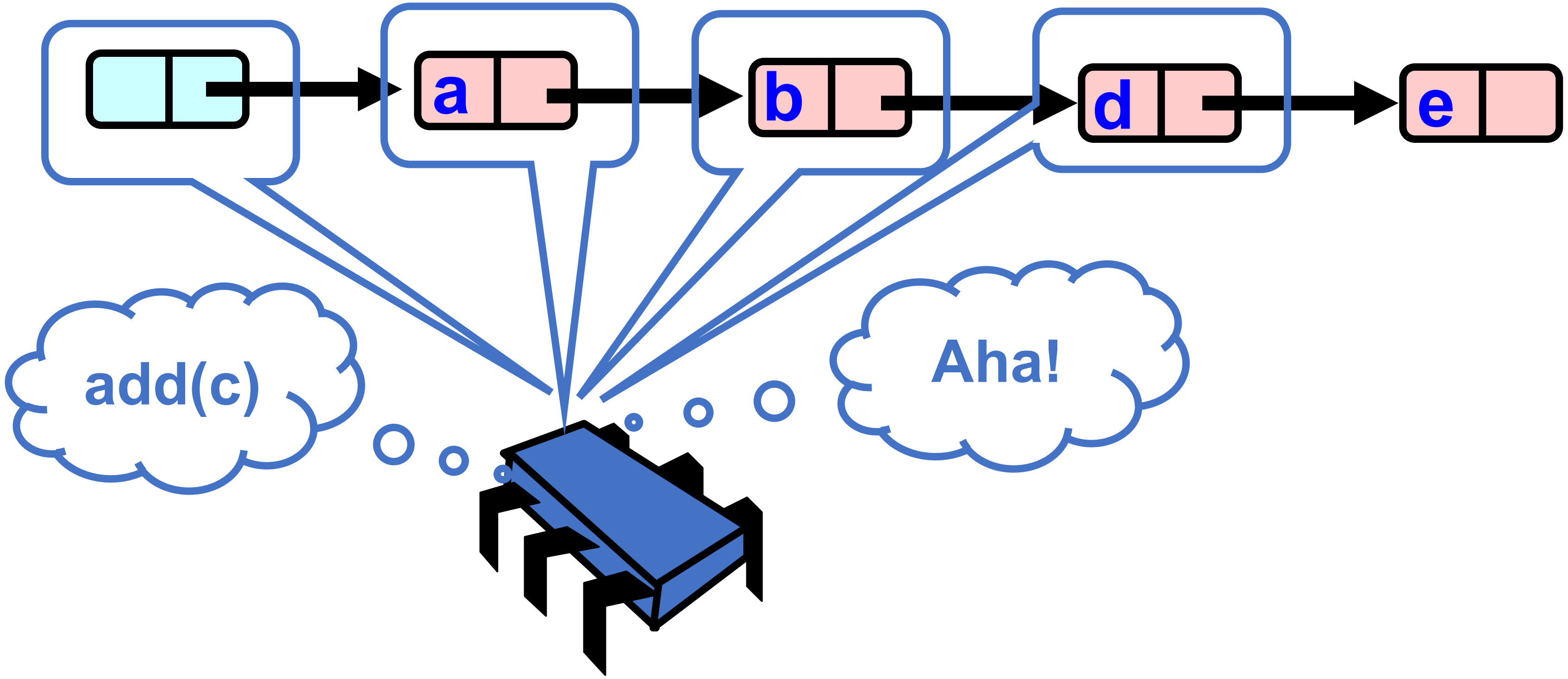
Race-freedom

```
void traverse(node *n) {
  while (n->next != NULL) {
    n = n->next;
  }
}
```

Race-freedom

```
void traverse(node *n) {
  while (n->next.load() != NULL) {
    n = n->next.load();
  }
}
```

What could go wrong?



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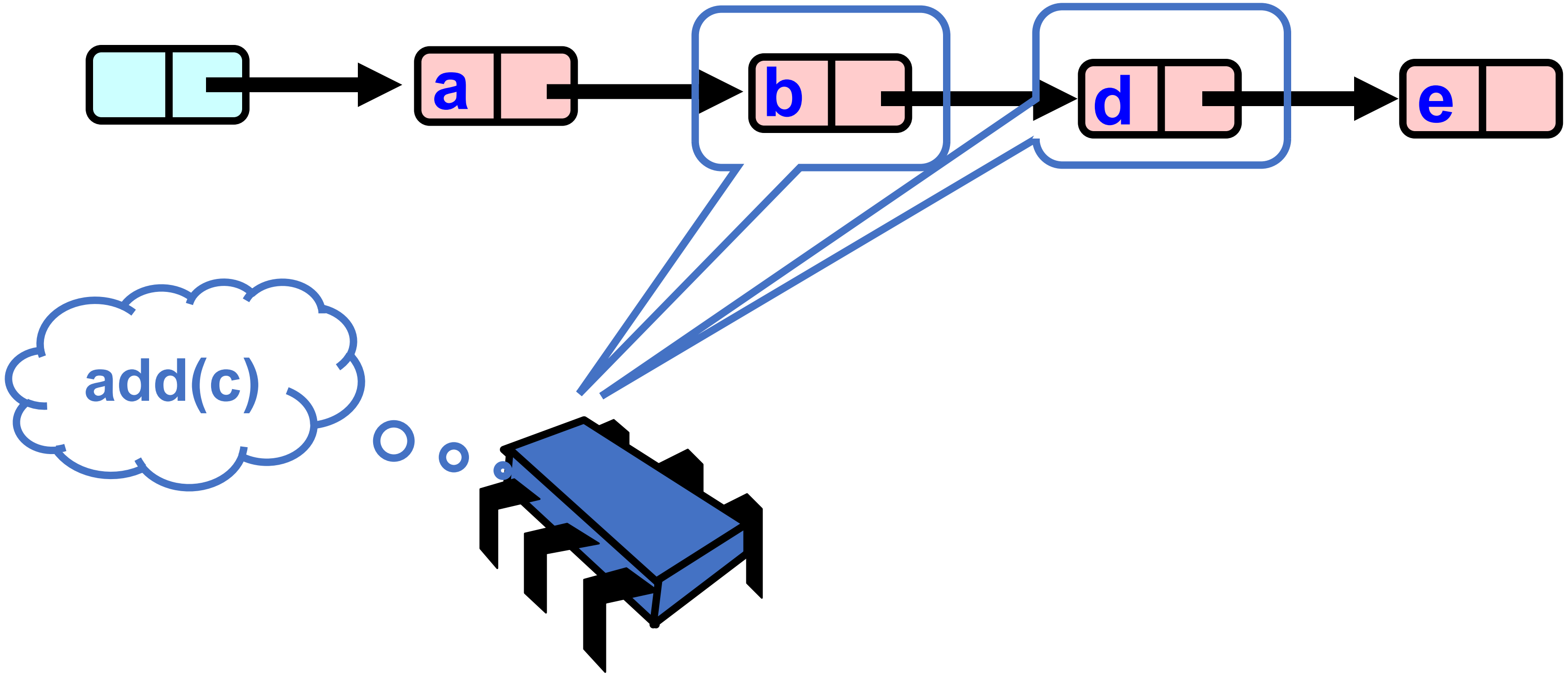

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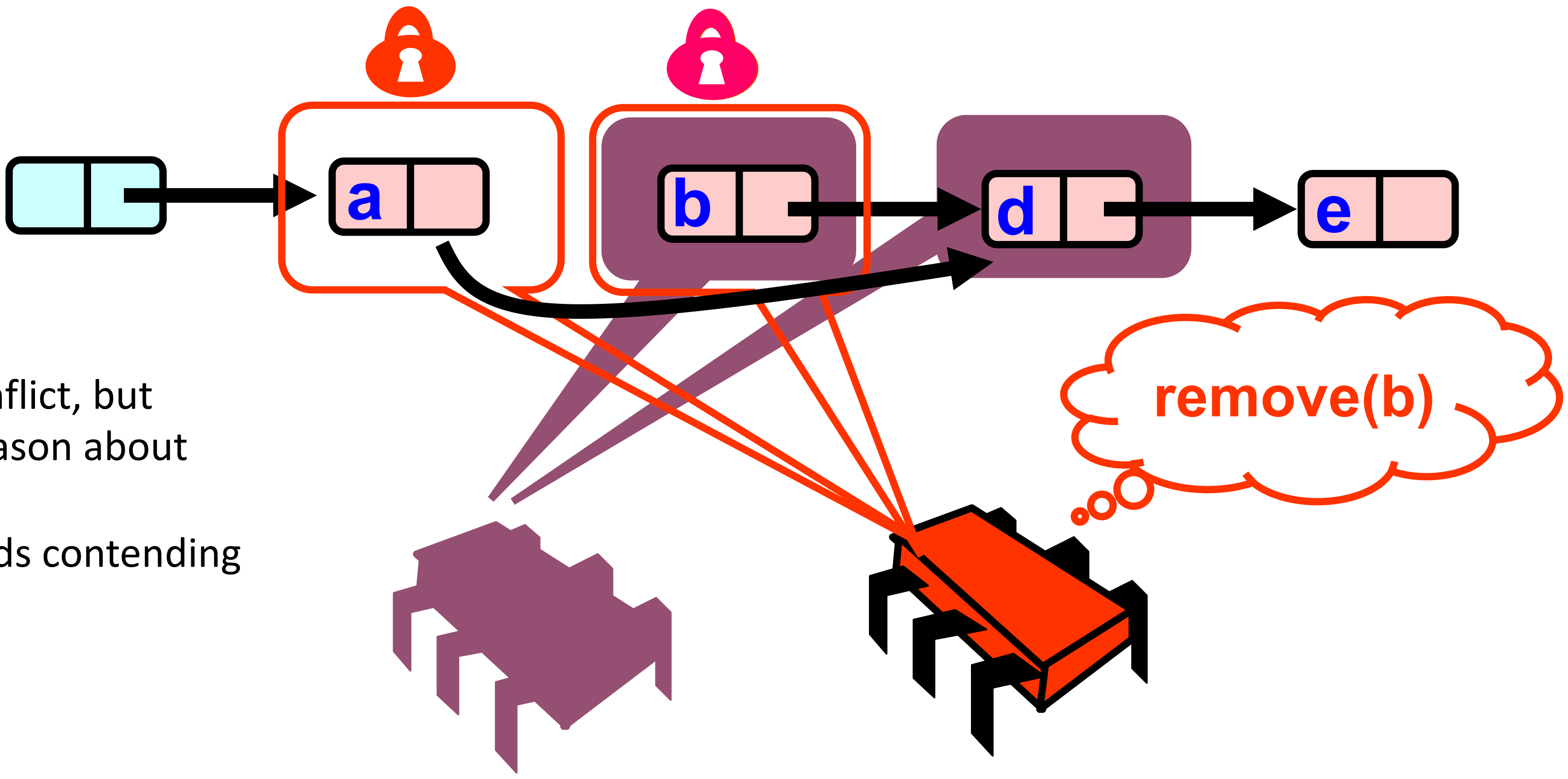
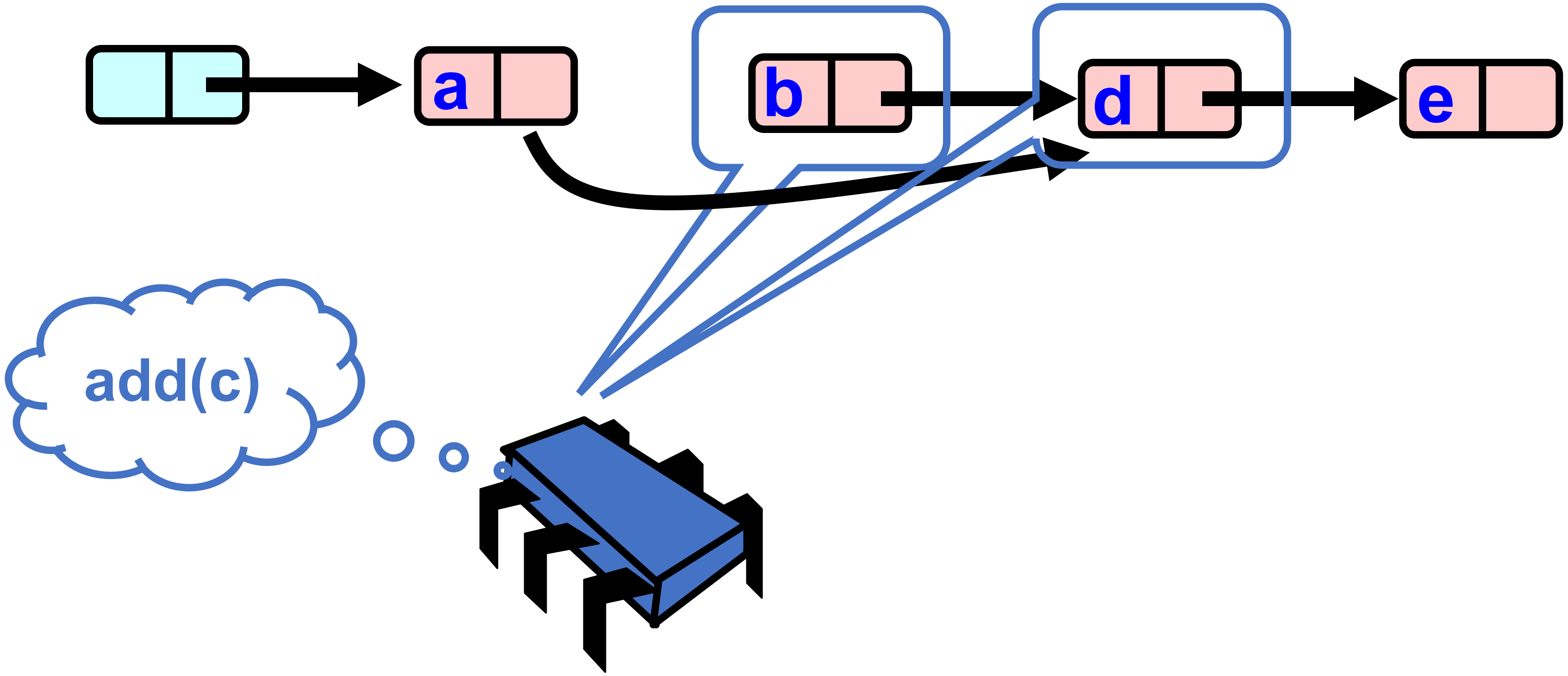


No more data conflict, but we do need to reason about interleavings.
Concurrent threads contending for values.

What could go wrong?



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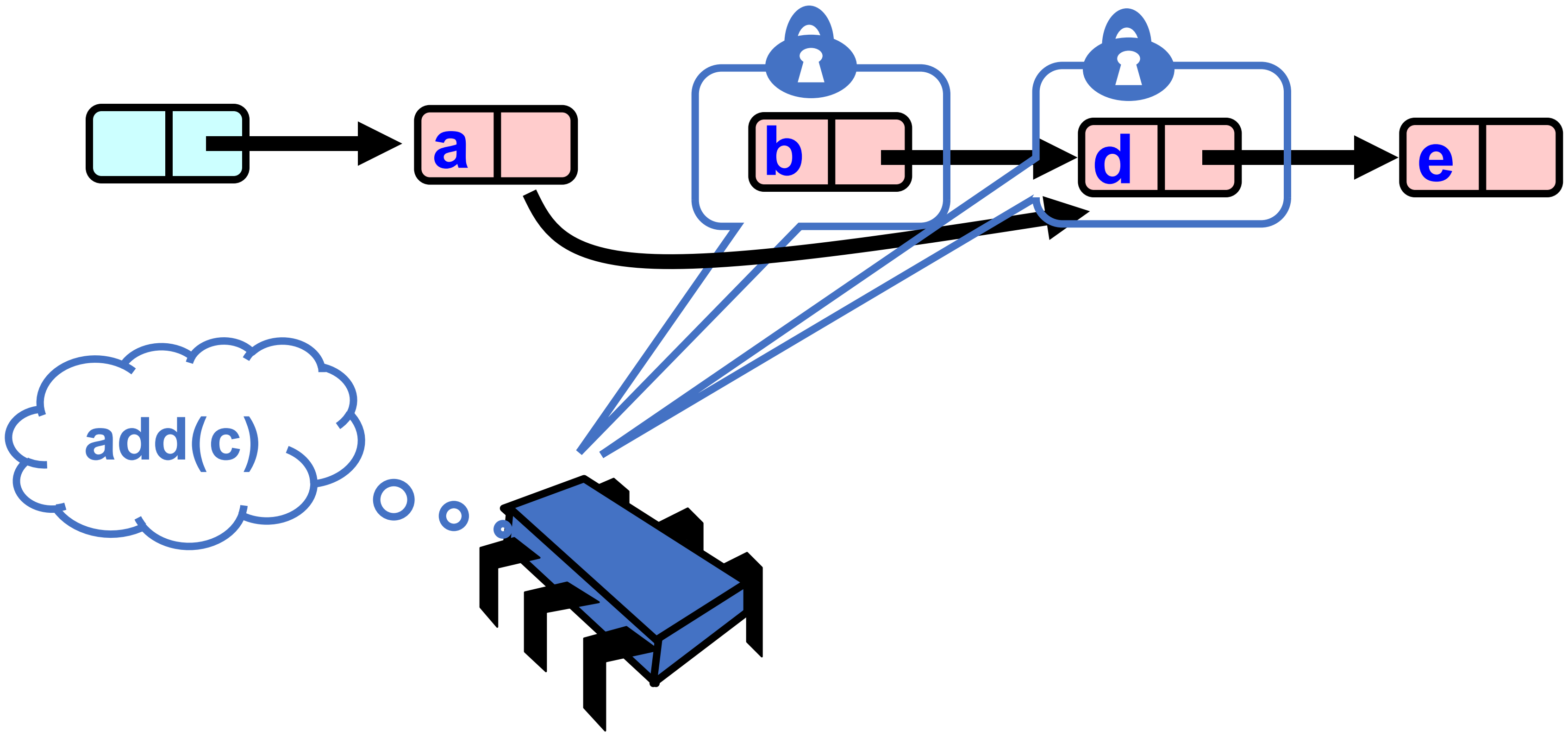
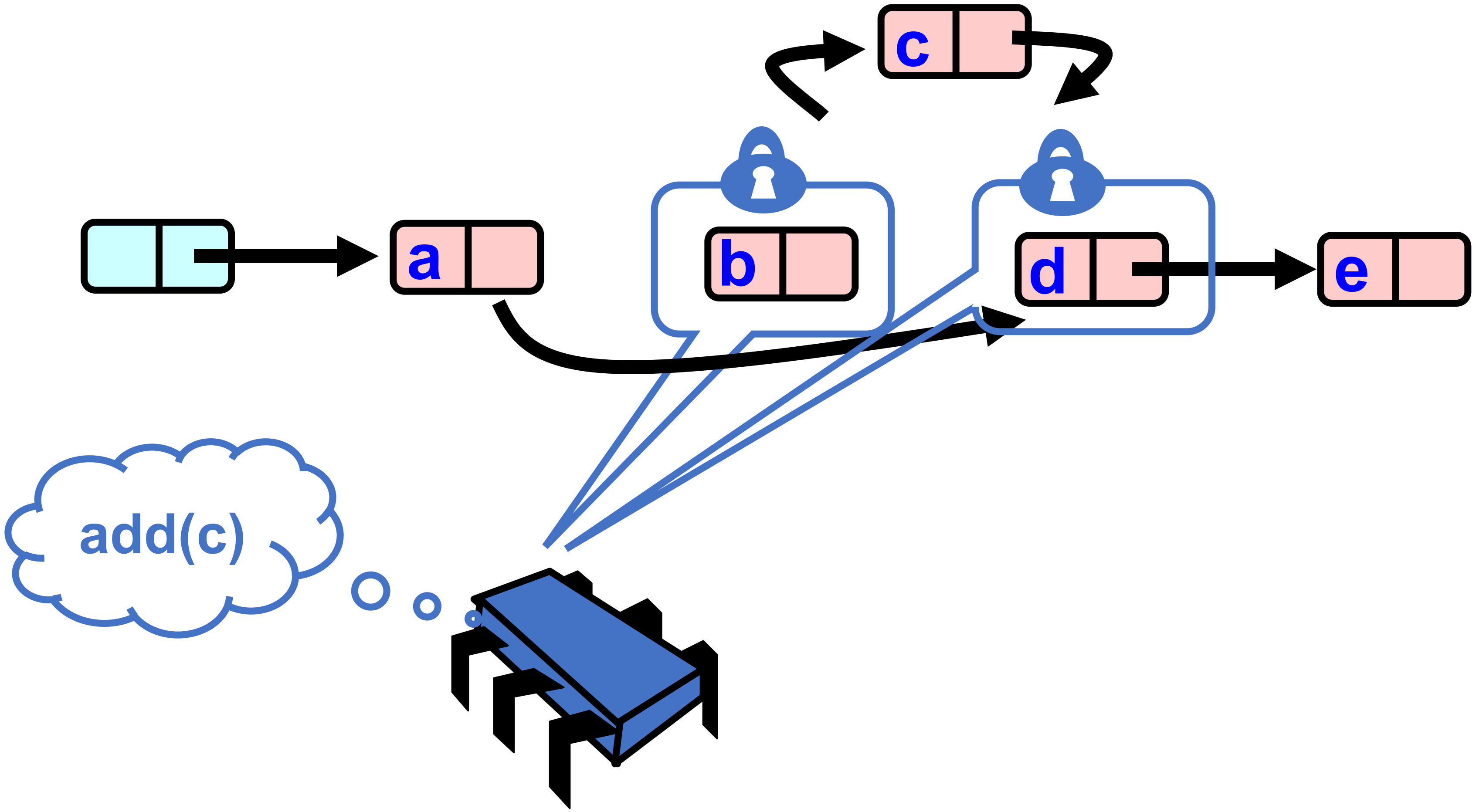


What could go wrong?



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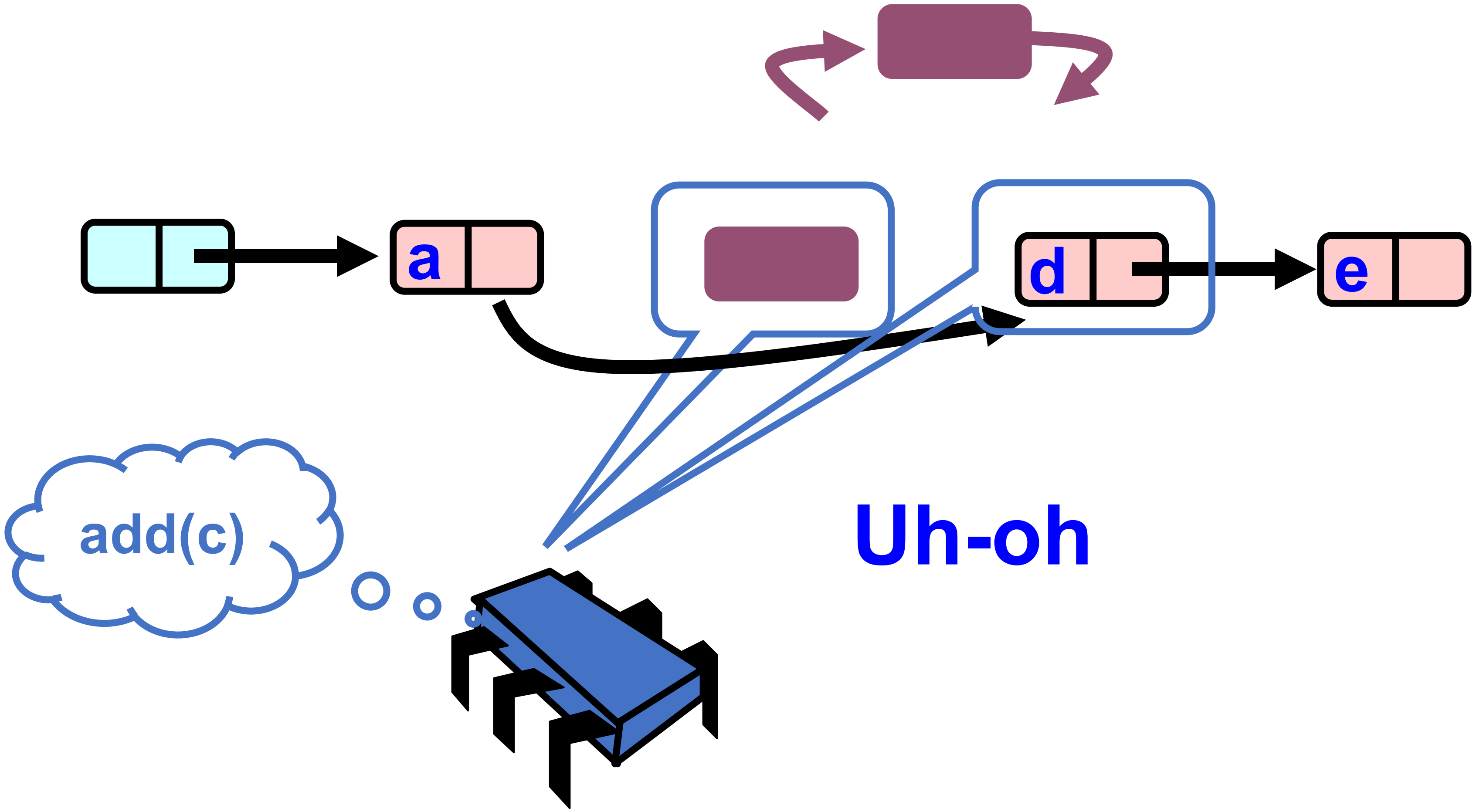
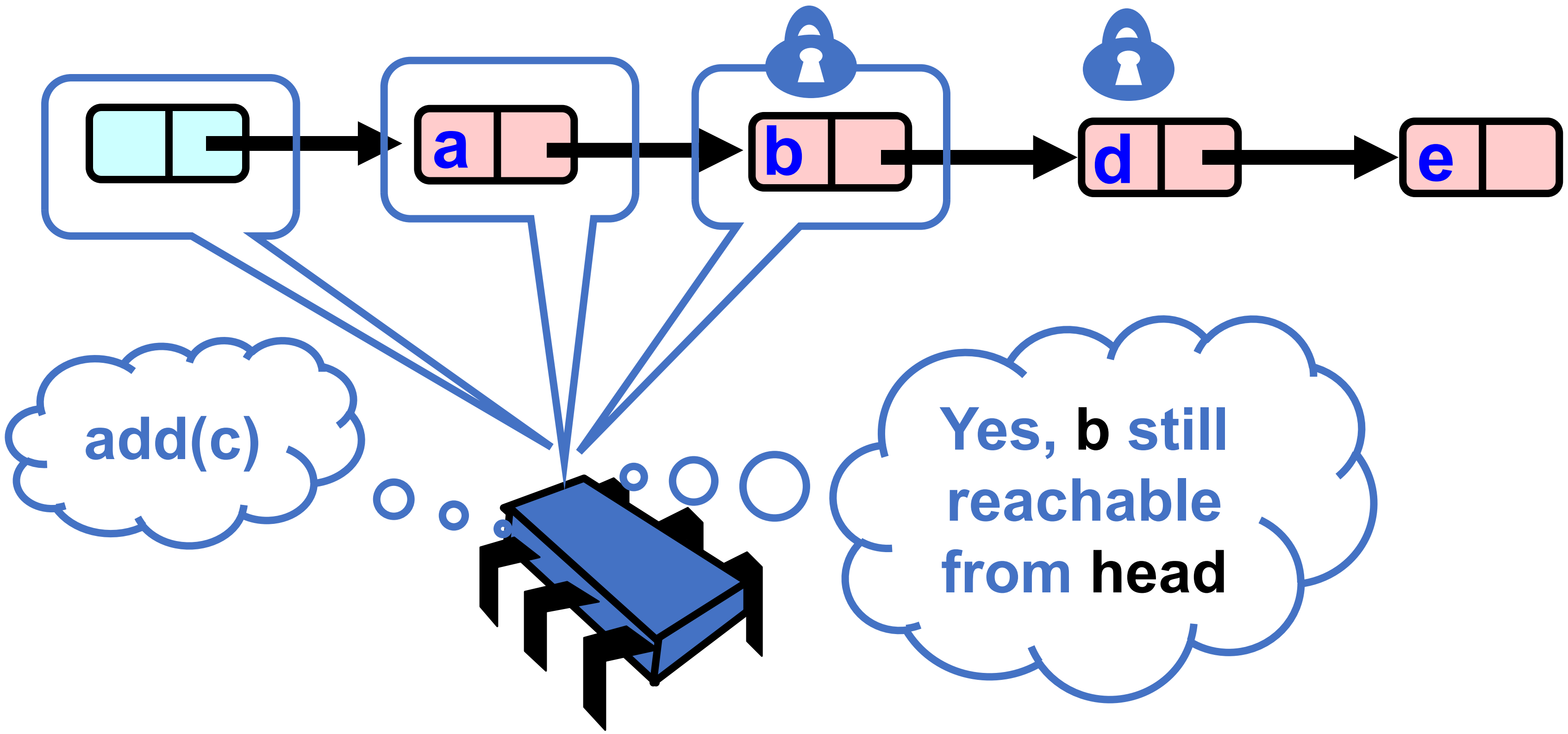


Validate – Part 1



What happens if failure?

- Ideas?

What happens if failure?

- Could try to recover? Back up a node?
  - Very tricky!
  - Just start over!

What happens if failure?

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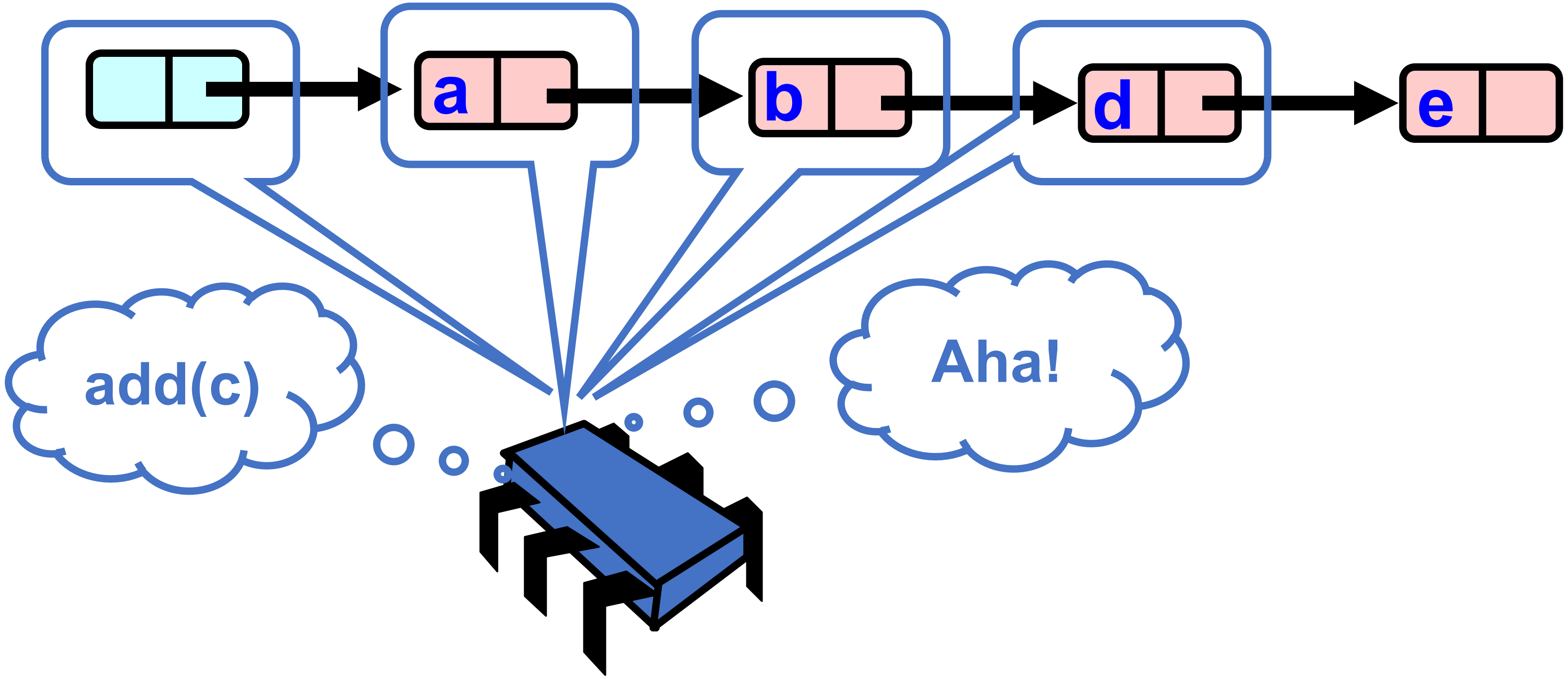
  - Very tricky!
  - Just start over!

- Private method:
  - try_remove
  - remove loops on try_remove until it succeeds

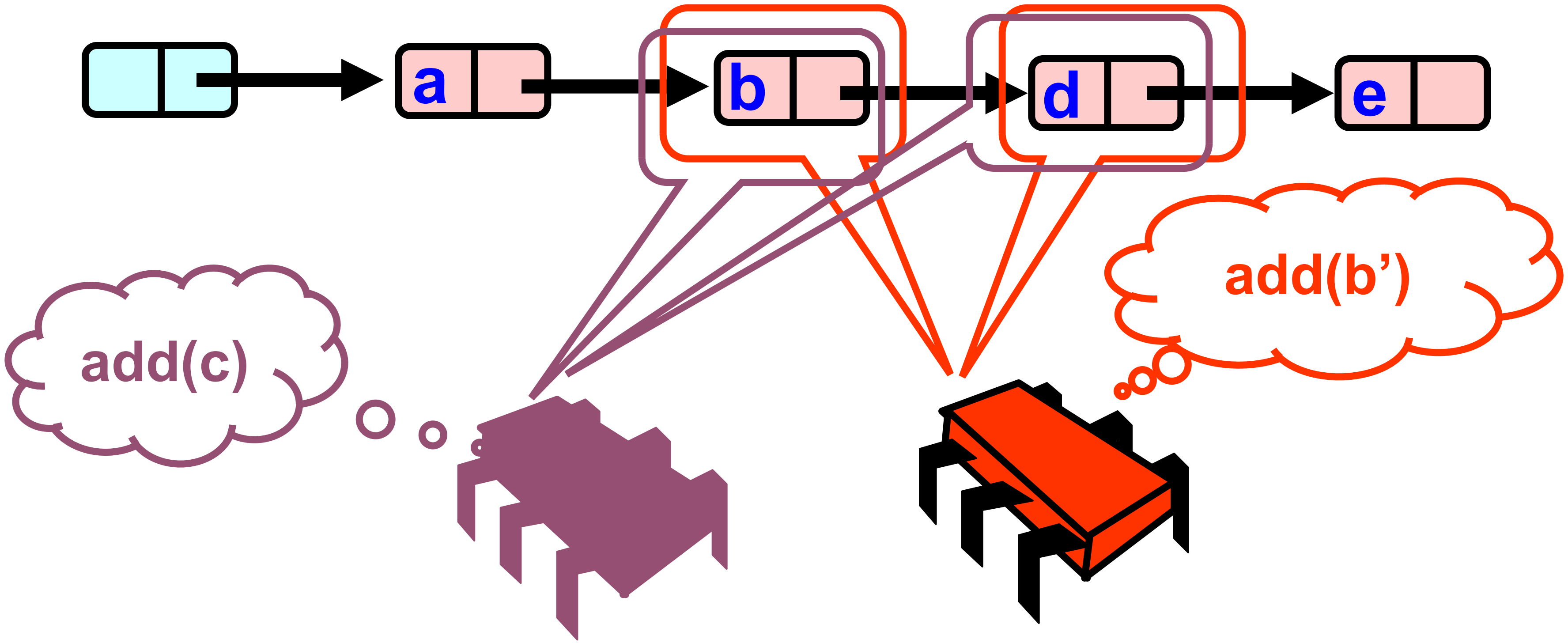
What about concurrent adds?

What if 2 threads try to add a node in the same position?

What Else Could Go Wrong?



What Else Coould Go Wrong?



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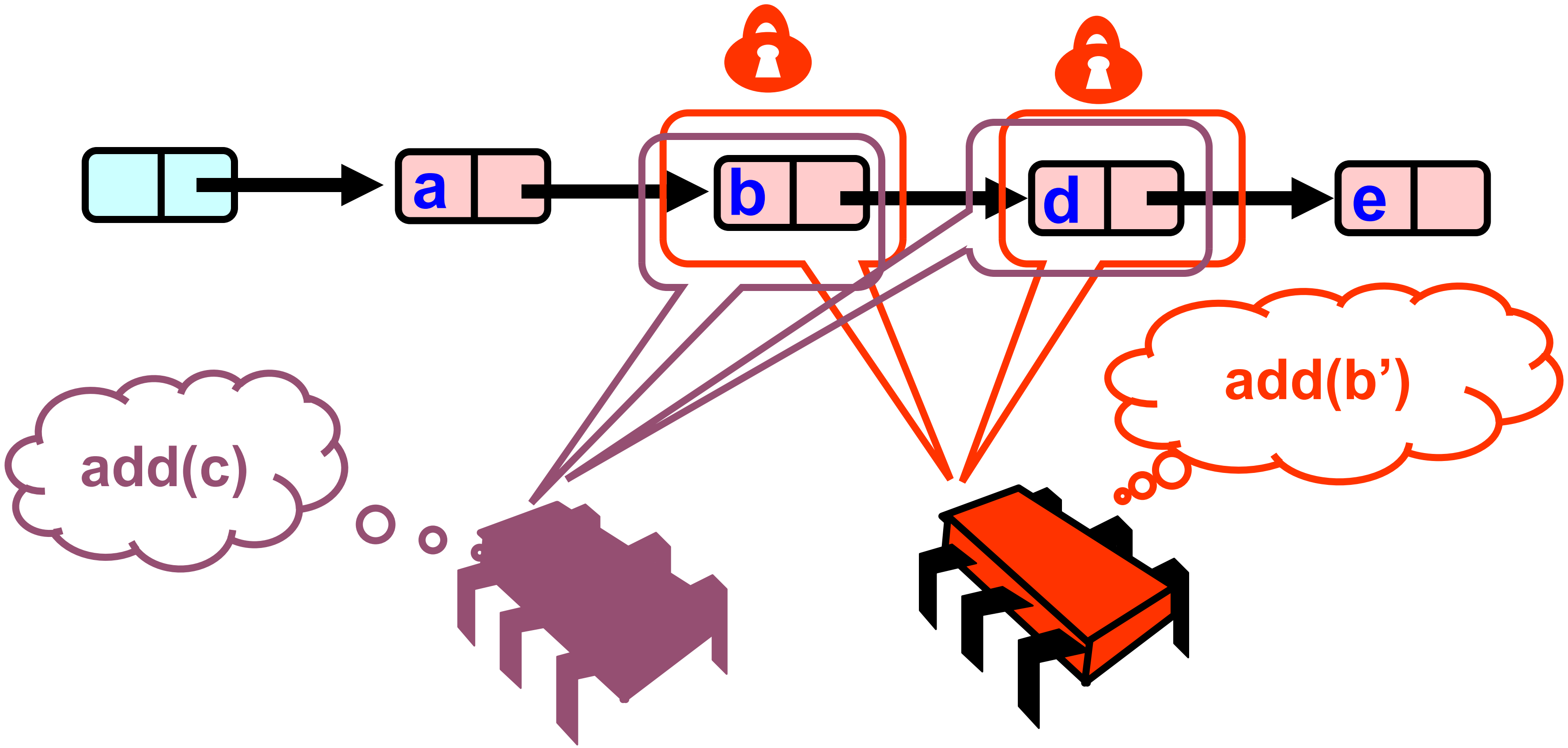

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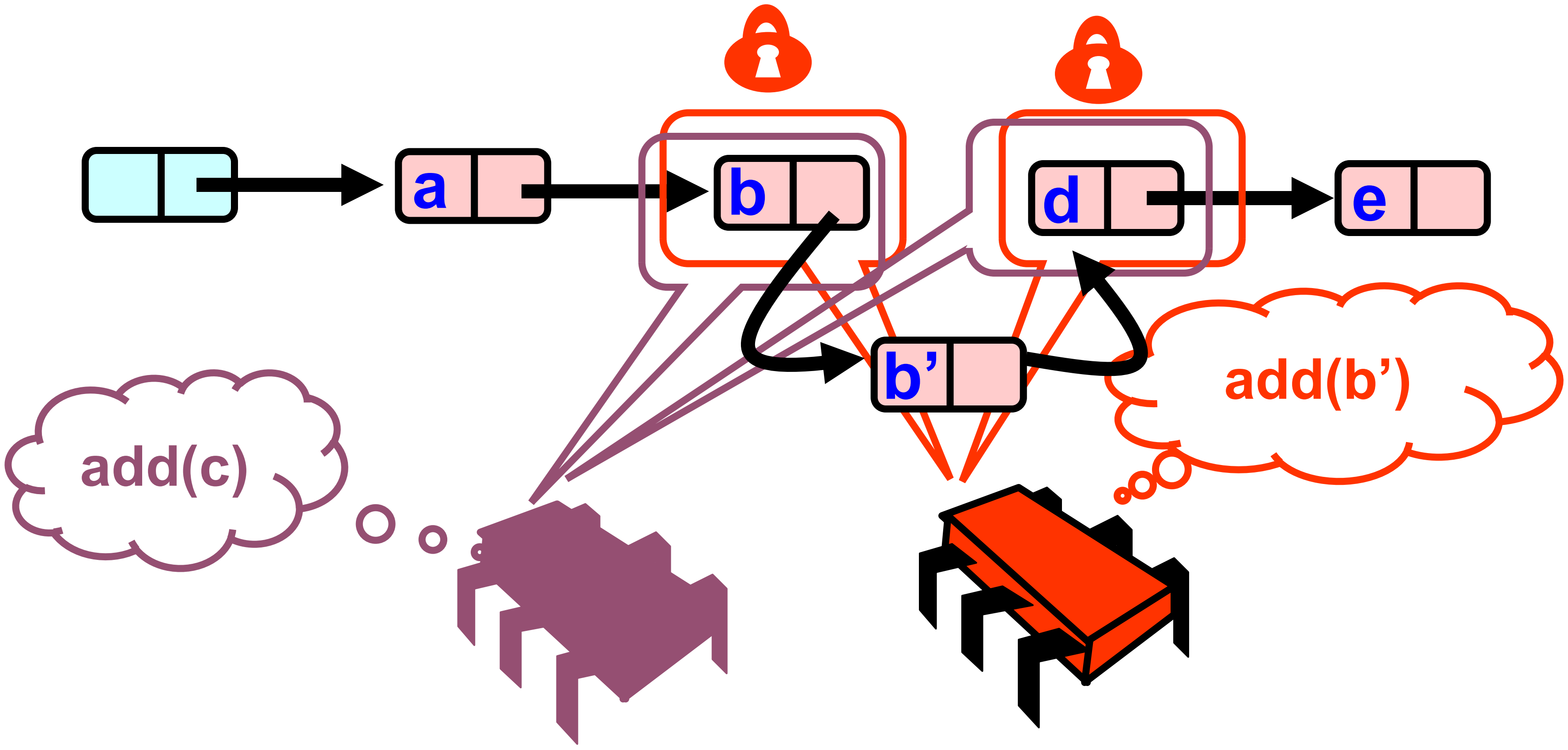

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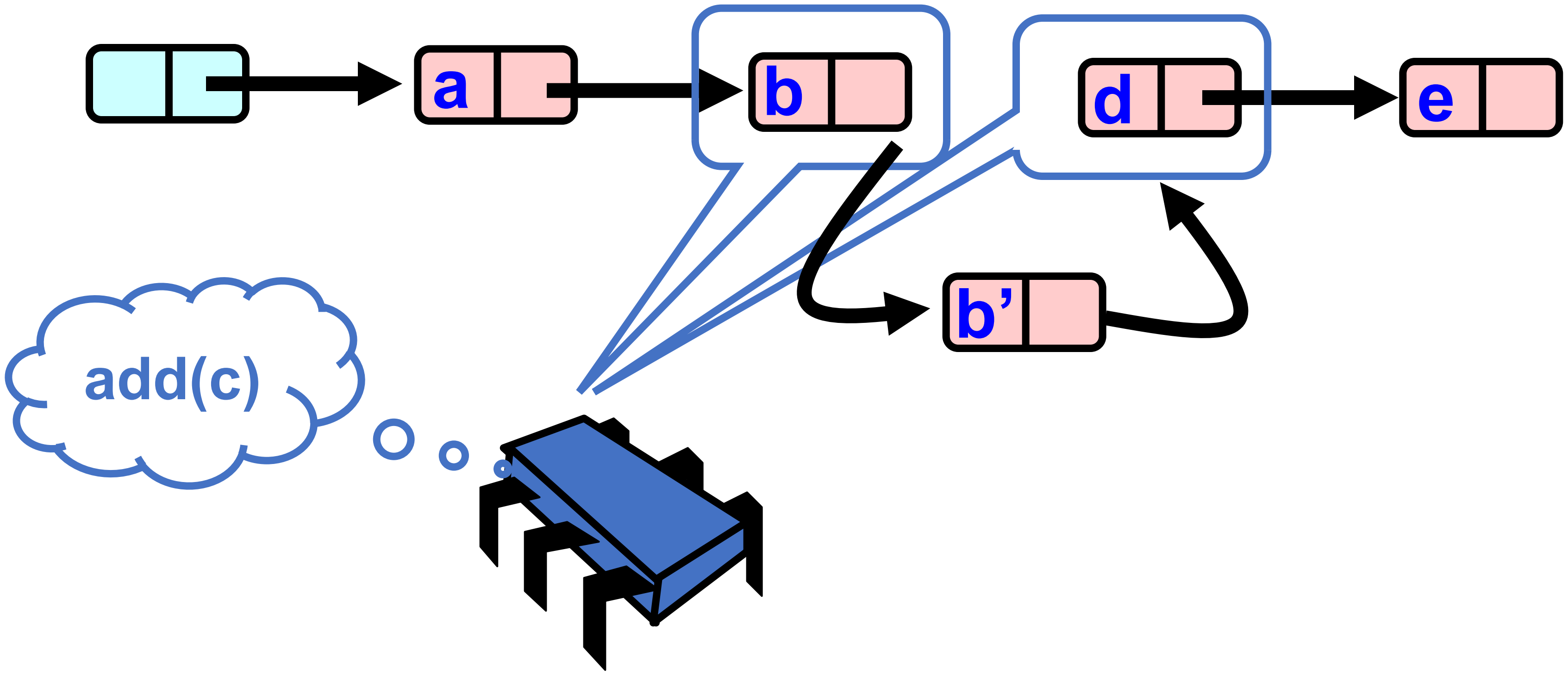

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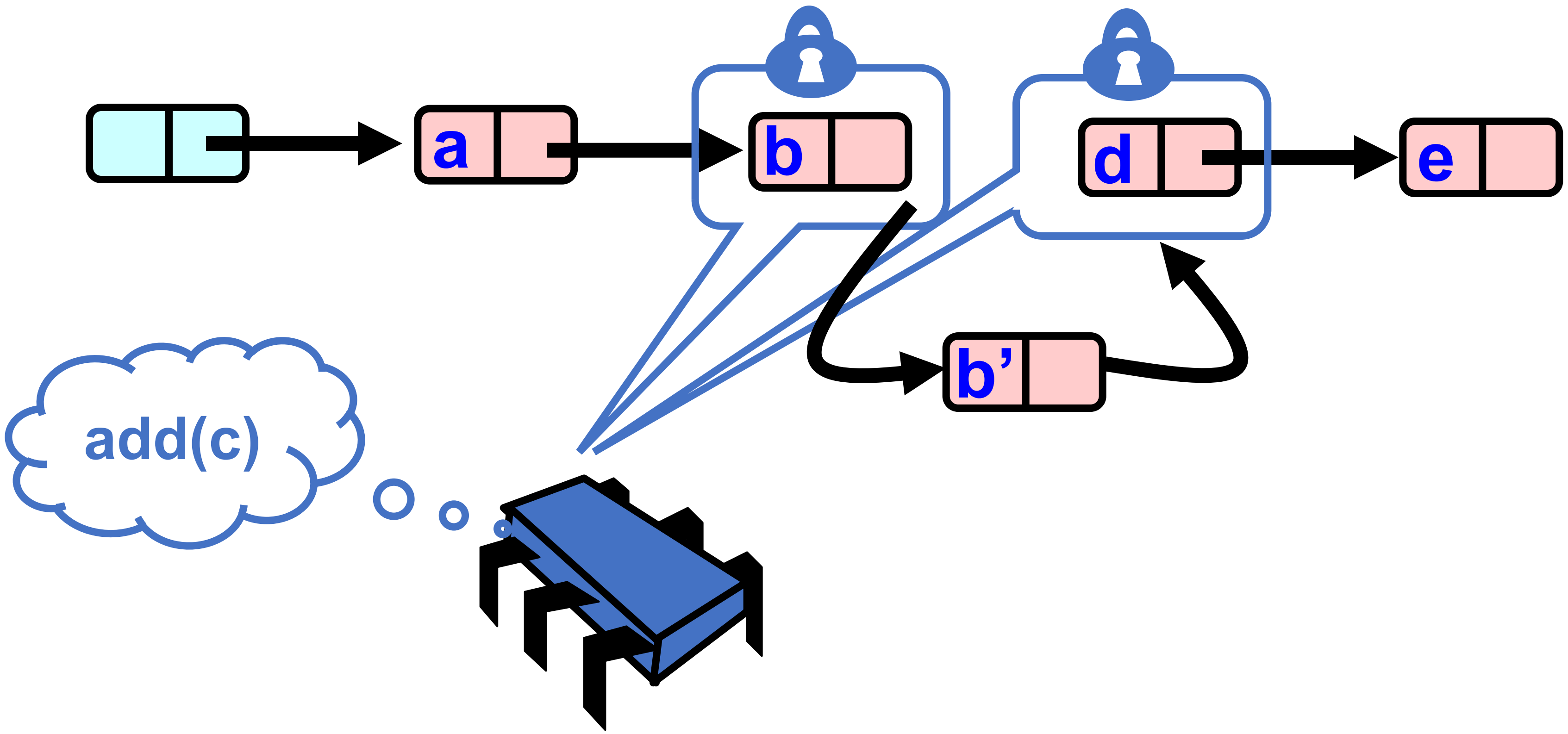
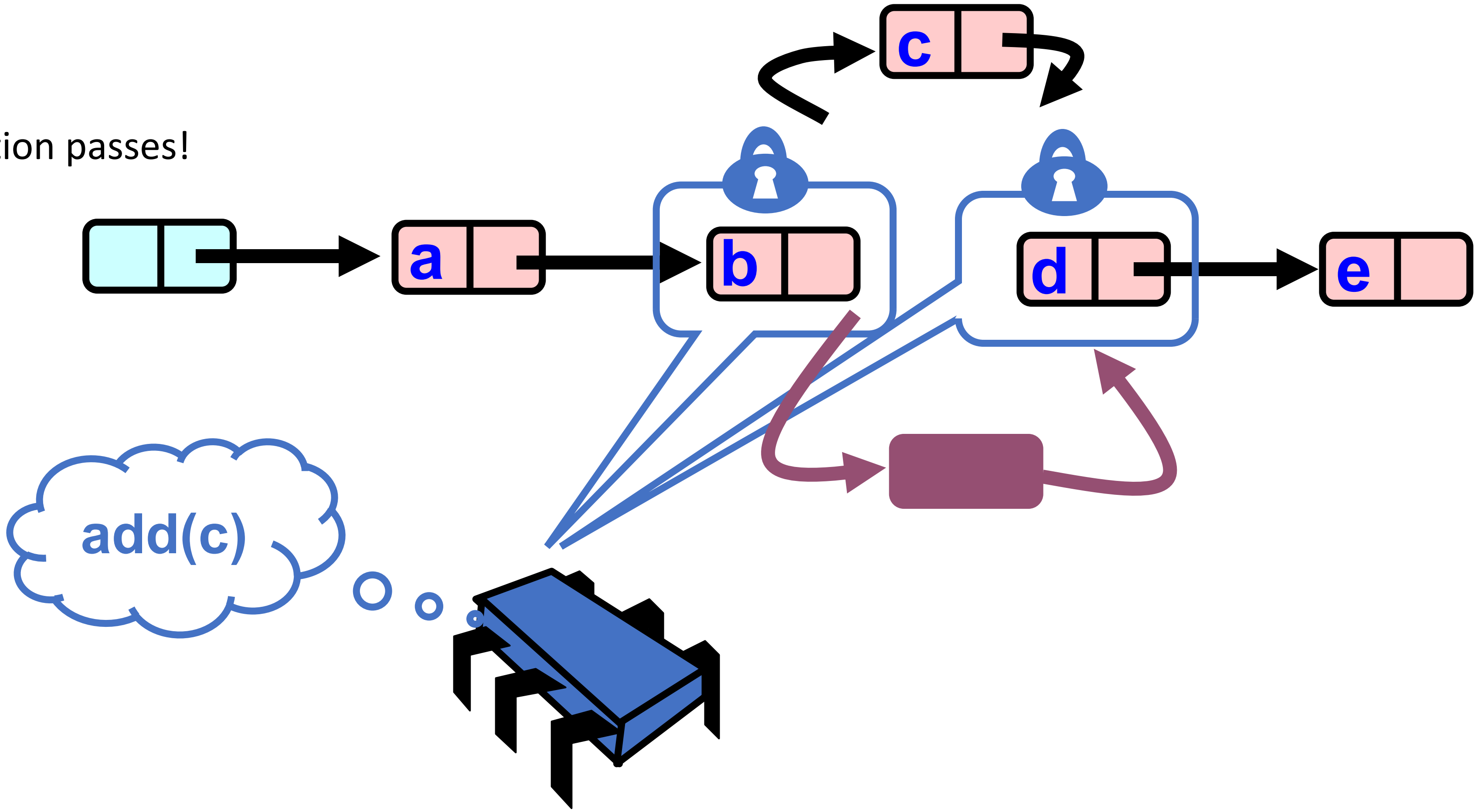
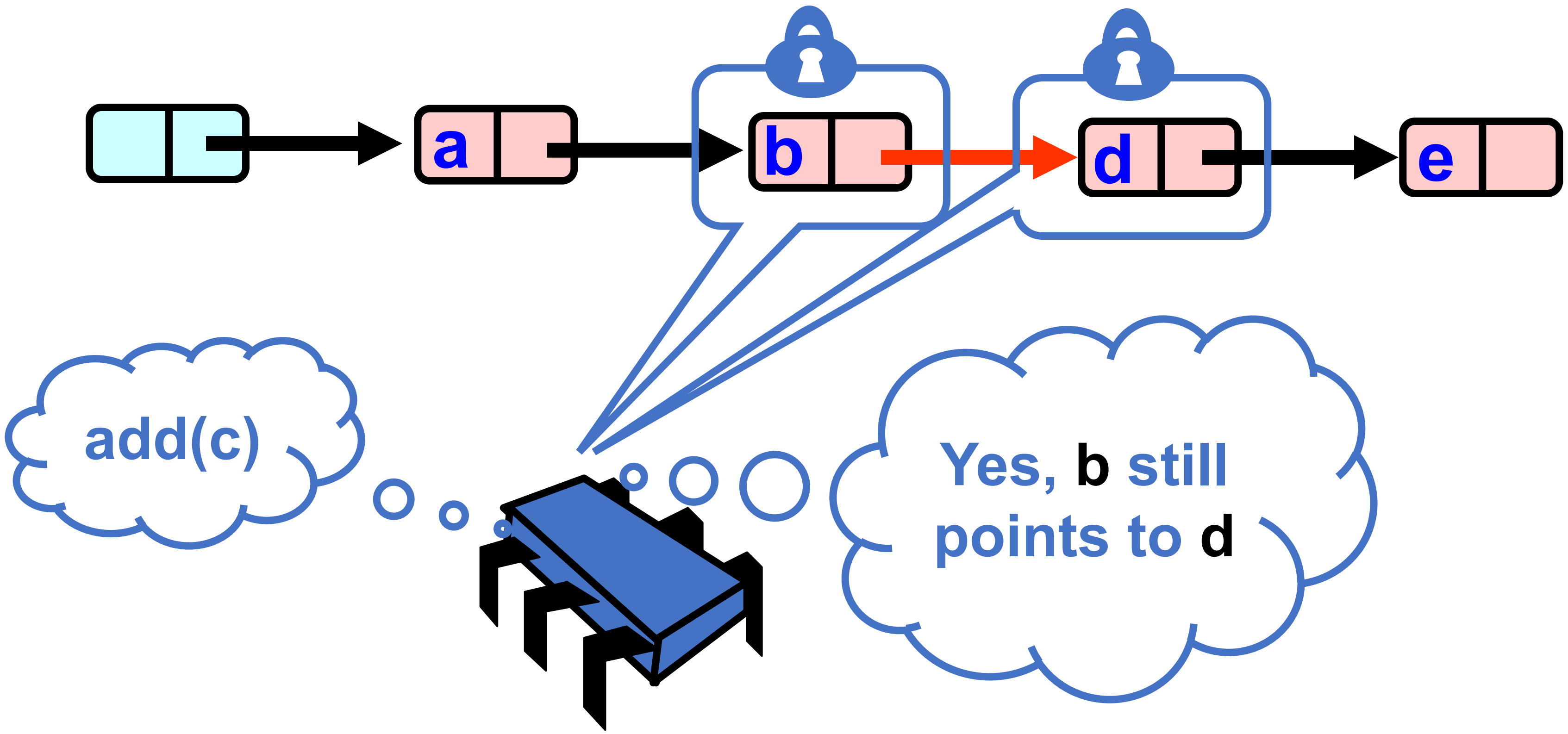


What Else Could Go Wrong?

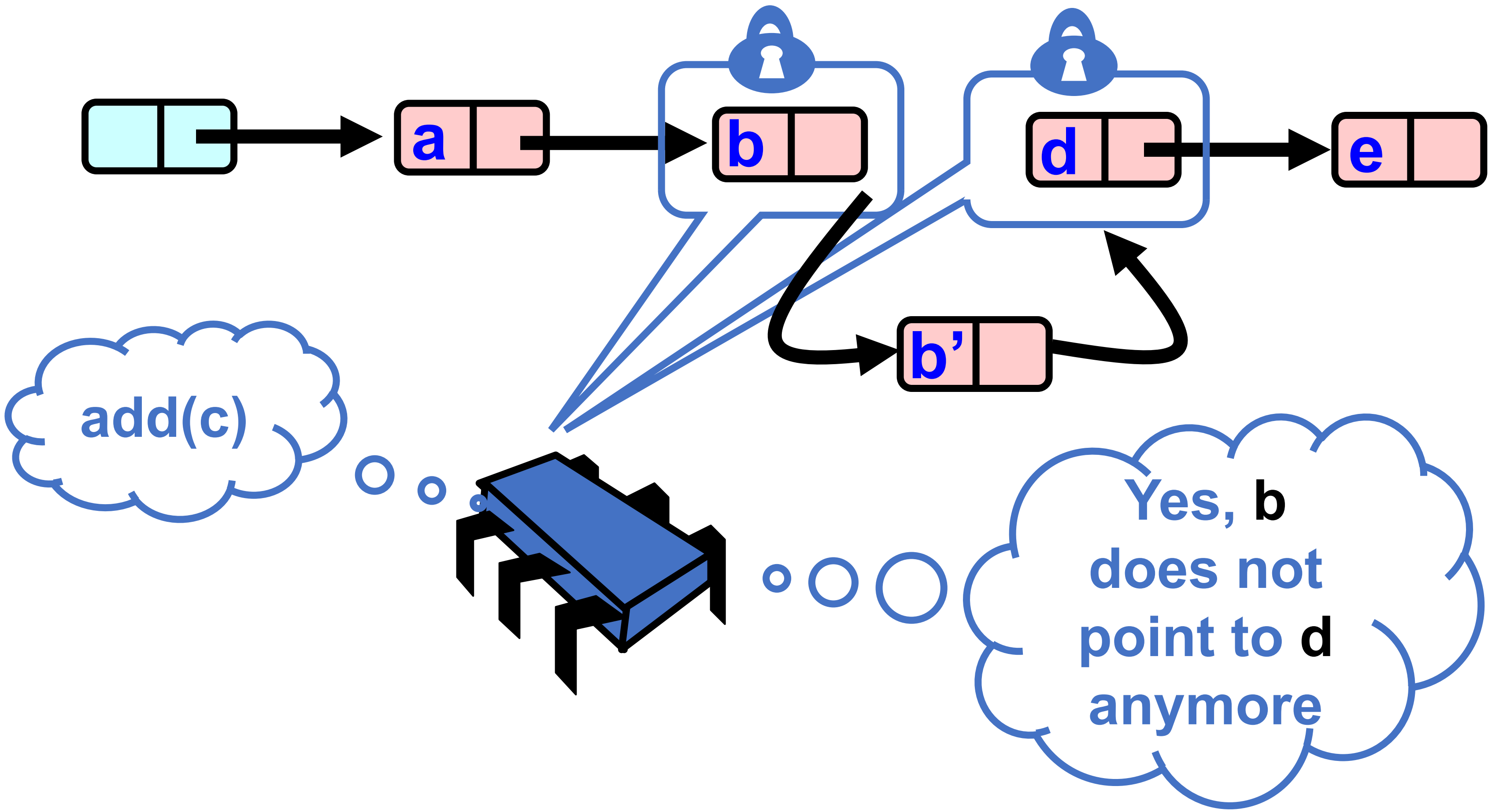
Validation passes!



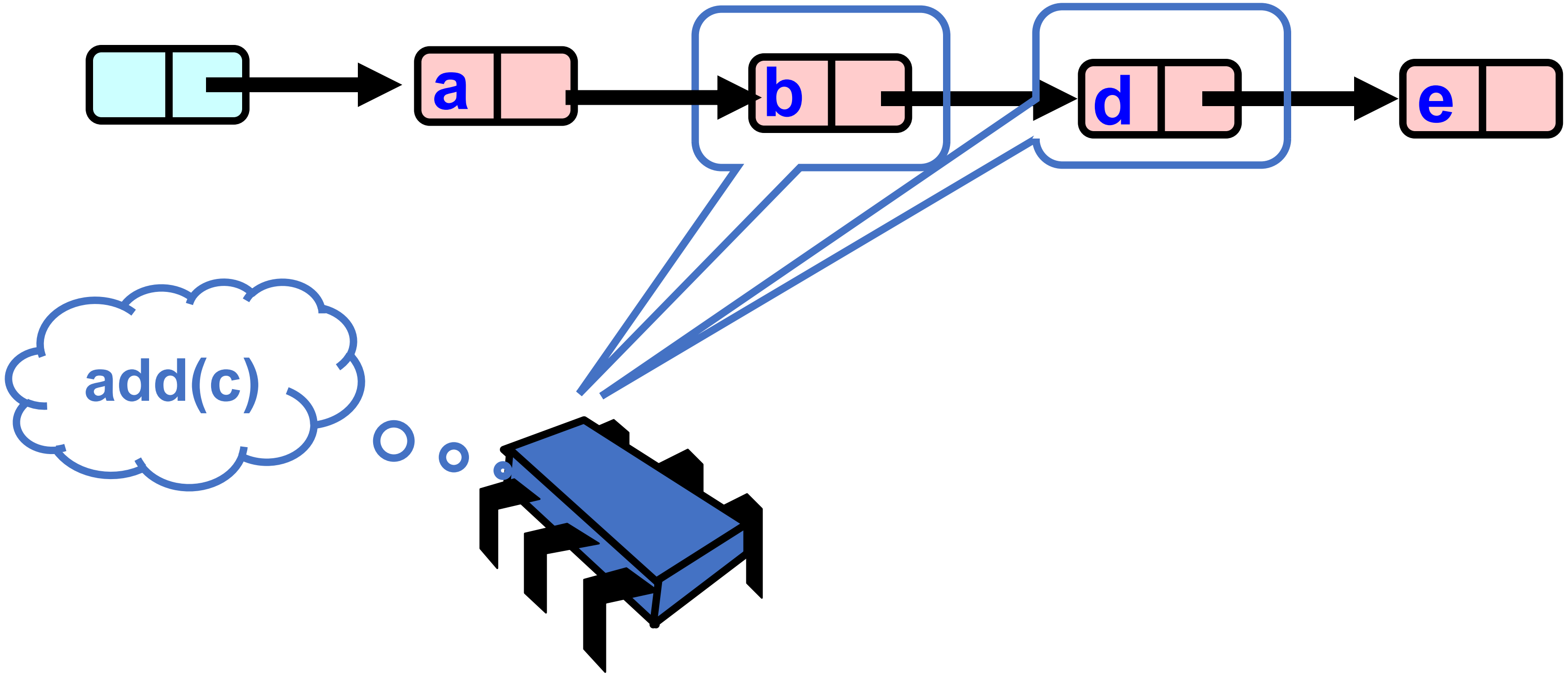
Validate Part 2
(while holding locks)



What Else Could Go Wrong?



Can threads that remove a node delete (free) it?



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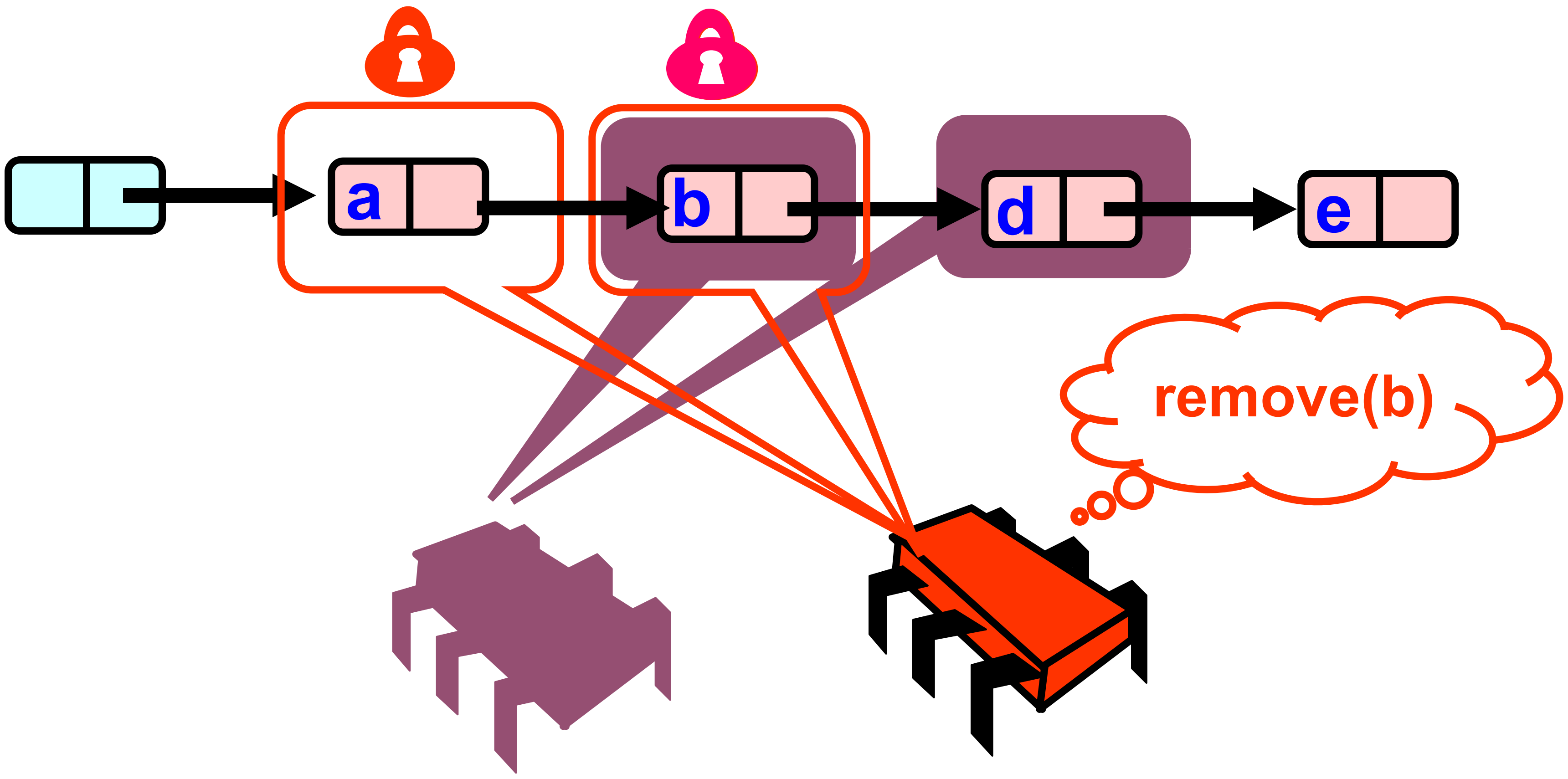
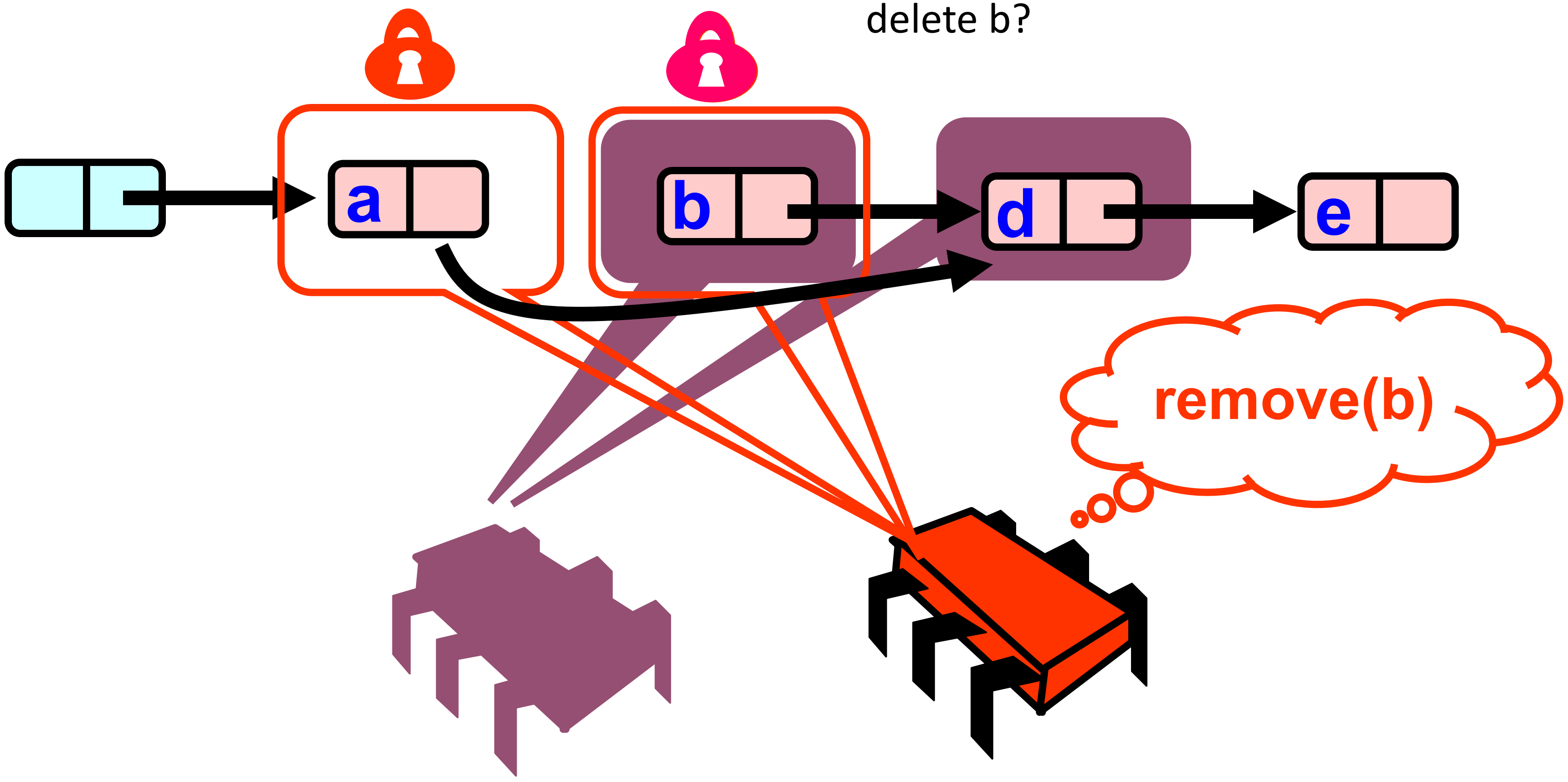


Can threads that remove a node delete it?

delete b?



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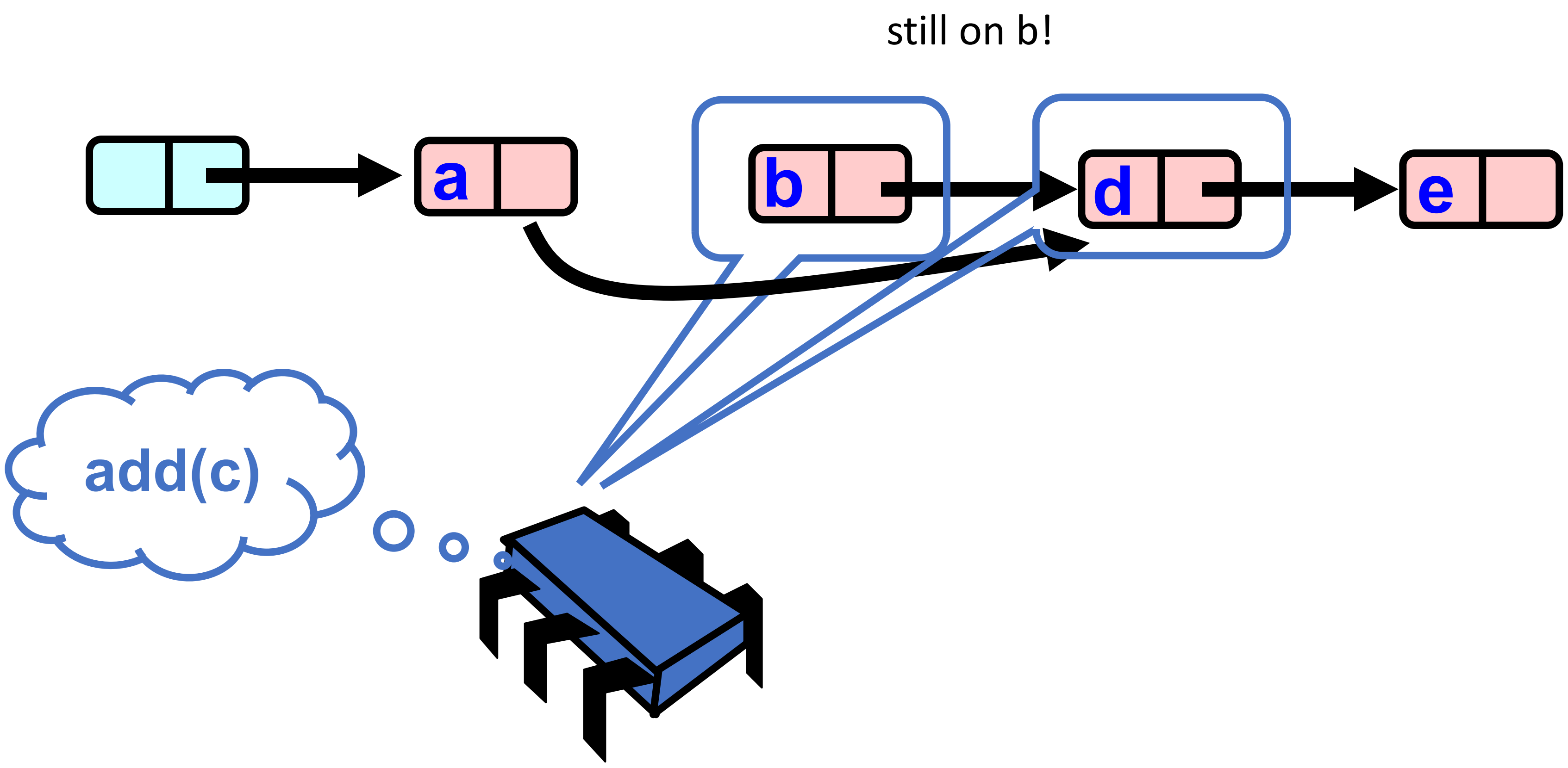
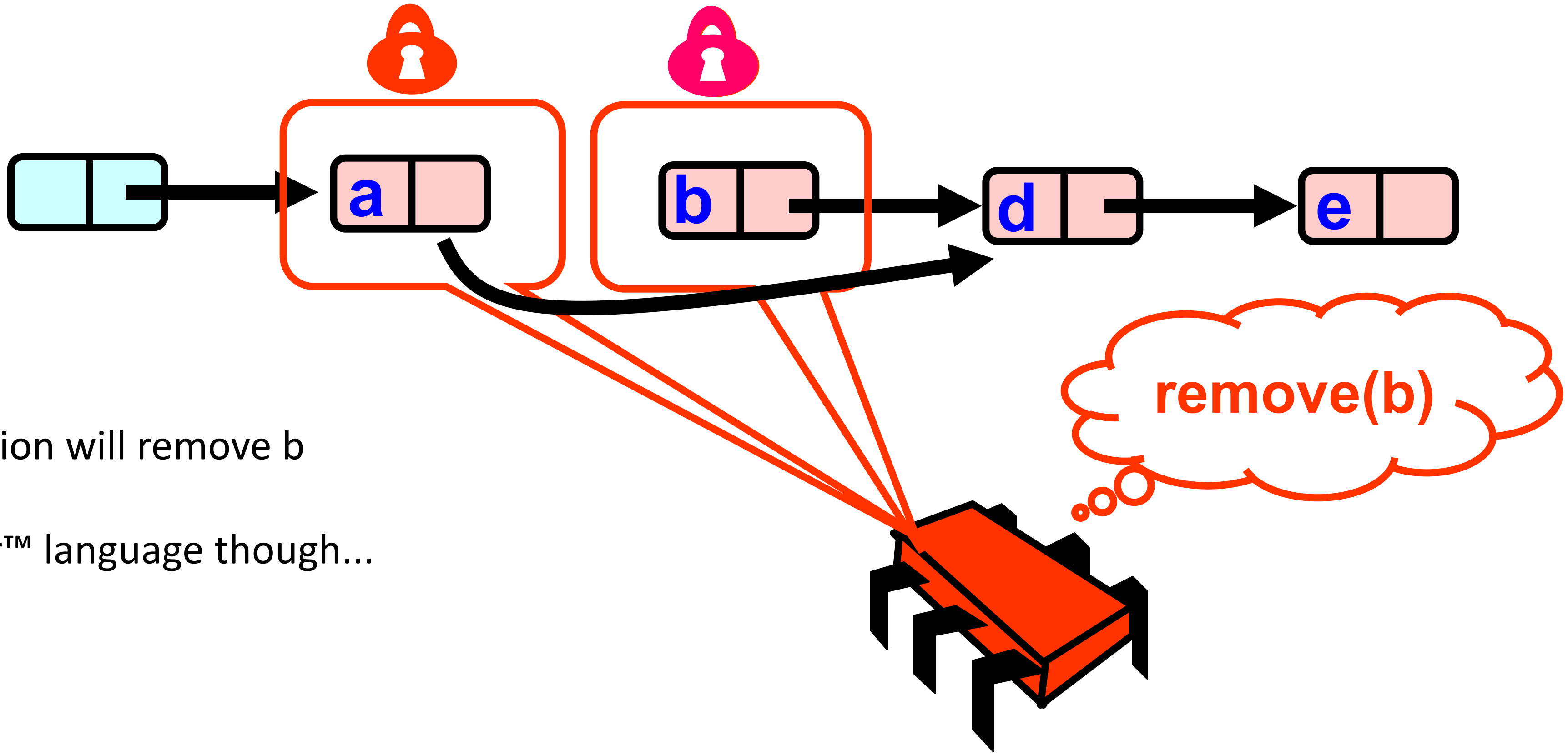


Our own garbage collector



Java's garbage collection will remove b

We are using a better™ language though...

maintain a list to delete:

Our own garbage collector

Java's garbage collection will remove b

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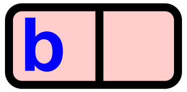
maintain a list to delete: 

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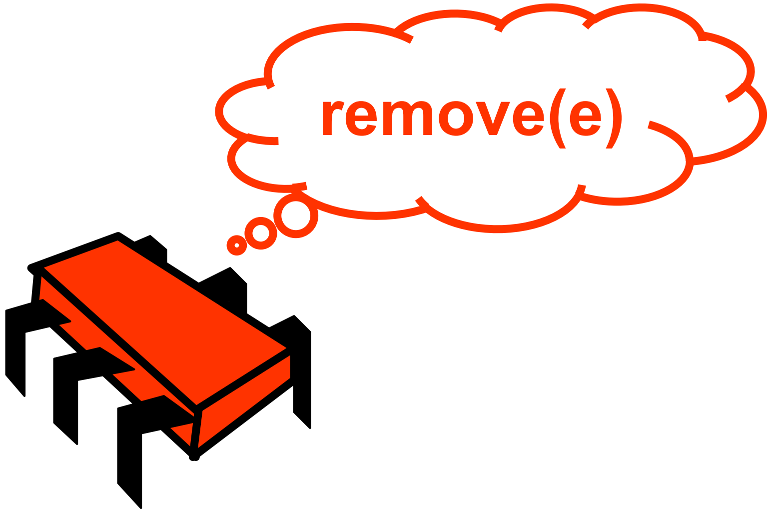
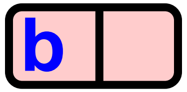


maintain a list to delete:
can be thread-local



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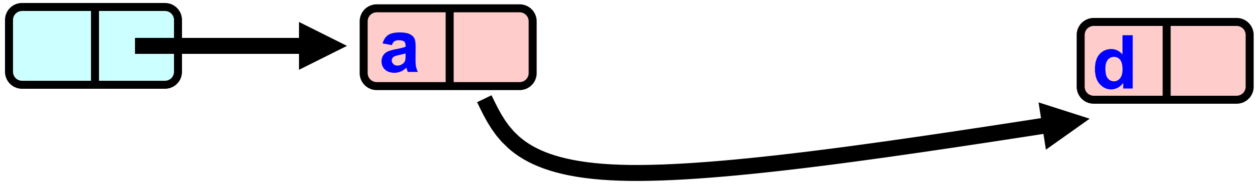

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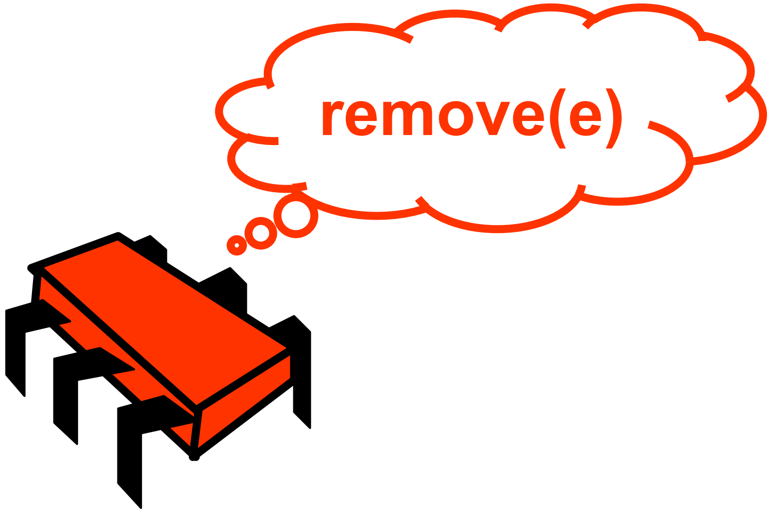

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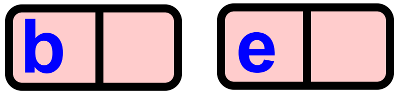
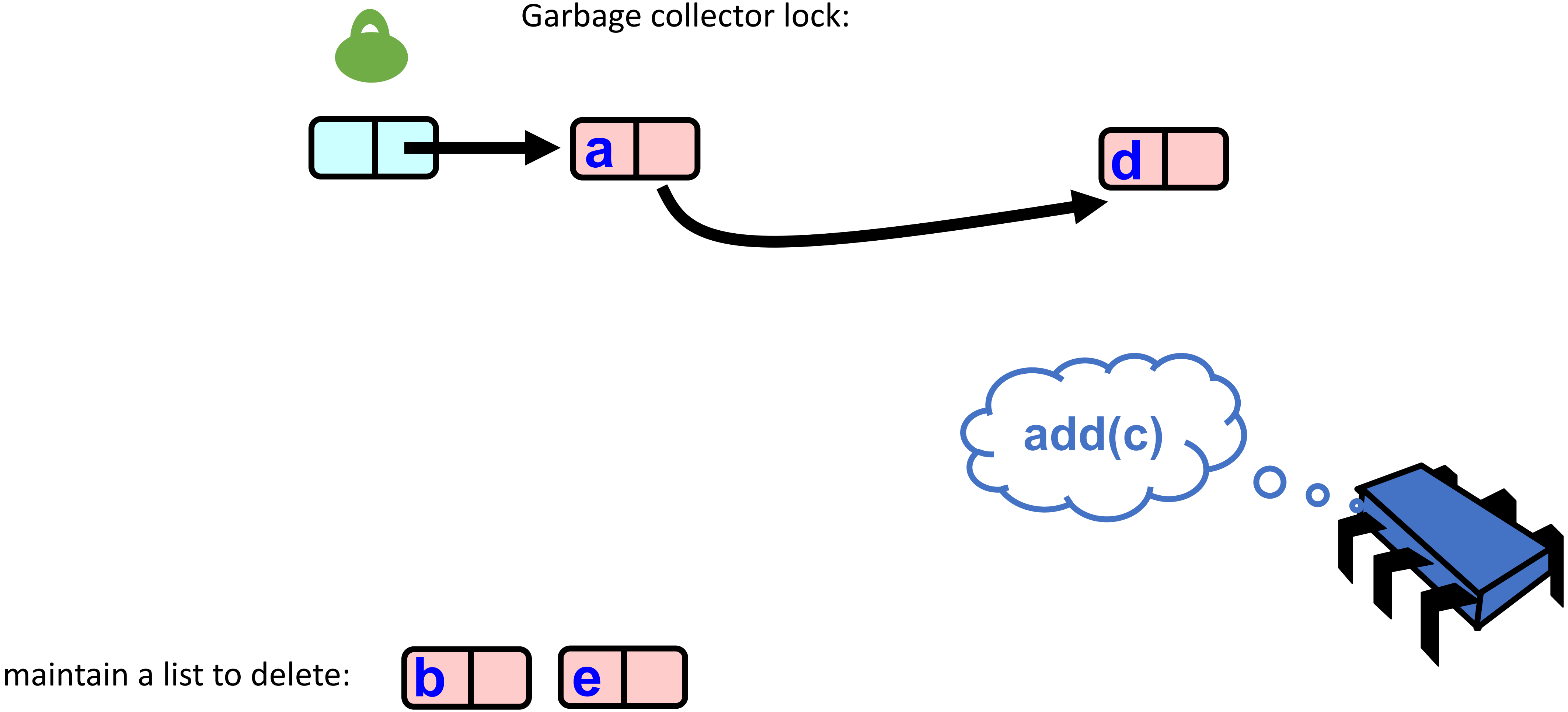
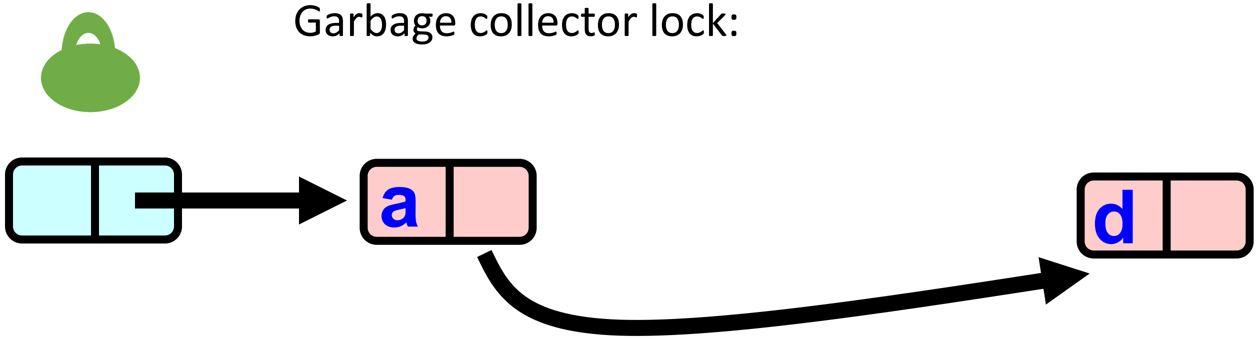


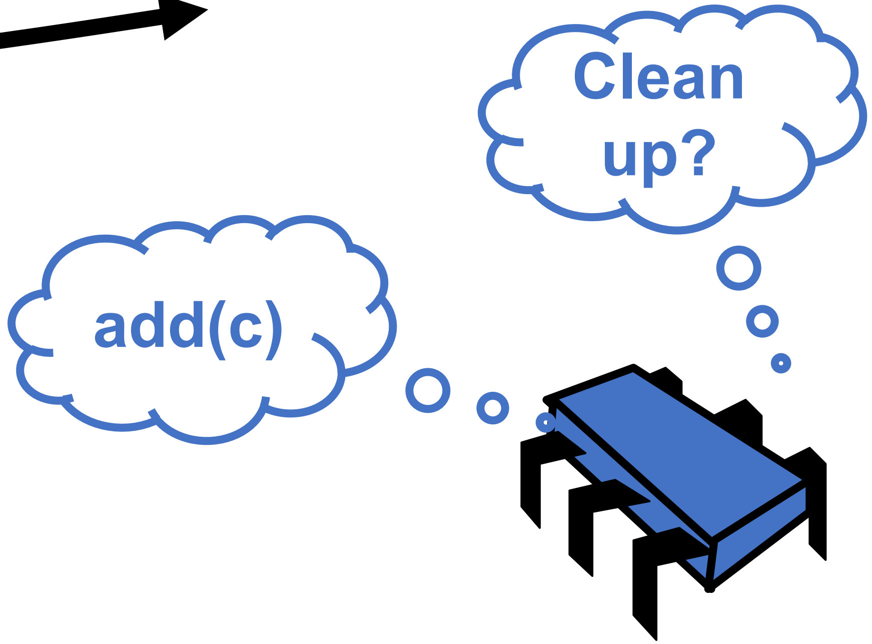
Our own garbage collector



Our own garbage collector

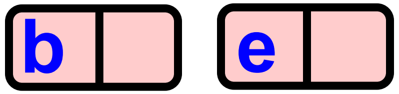
Garbage collector lock:





Similar to a reader/writer lock:
Allows an arbitrary number of threads that operate on the list
Only 1 garbage collector thread erases the list of nodes

maintain a list to delete:



Garbage collector lock

- Many strategies!
  - A big research area ~10 years ago
- **Strat 1:** Threads always try once to take the garbage collector lock:
  - if failed, no worries, the next operation will get a chance
  - can starve garbage collection
- **Strat 2:** Wait until size grows to a threshold:
  - Wait on the lock
  - Can cause performance spikes

Summary

- We traverse without lock
  - Traversal may access nodes that are locked
  - Its okay because we have atomic pointers!
- We avoid traversing the old structure
  - We validate after we obtain locks.
    - Our node is still reachable (it was not deleted)
    - Our insertion point is still valid (no thread has inserted in the meantime)
- To free nodes
  - We put them in a list to be freed later.