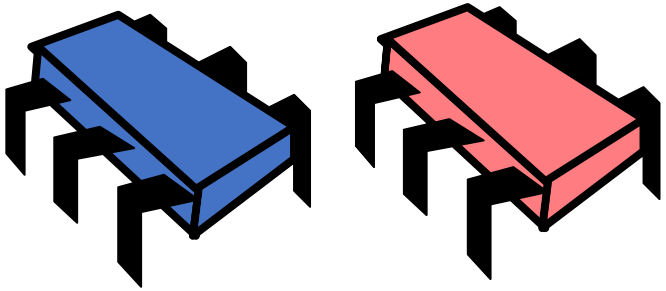
CSE113: Parallel Programming

Feb. 24, 2023

- **Topics**:
  - General concurrent sets



Announcements

- Midterm was due last Friday
  - Everyone got it in on time; thanks!
  - We are planning to release grades either today or Monday
  - Let us know ASAP if there are issues; you have 1 week
    - make a private piazza post
- HW 2 has 2 extra free late days
  - get it in by Wednesday
- Because we canceled class, HW 3 will be released Wednesday as well

Previous Quiz

Previous Quiz

Which one of the following is NOT a drawback of a global workstealing parallel schedule

- ○ Requires a concurrent data structure
- ○ Contention on shared cache lines
- ○ Contention on a single location with RMWs

Previous Quiz

Which of the following is NOT an overhead of the local worklist workstealing parallel schedule (that we studied in class)

- ○ Initialization of the queues
- ○ Checking a global variable to ensure all work is completed
- ○ Managing concurrent enqueues to the worklists

Previous Quiz

Which of the following solutions can guarantee that a static schedule will not be out of bounds?

- ◯ The last thread always checks to get the minimum between the end of the array or the value allocated
- ◯ The last thread always get the end of the array
- ◯ The last thread never receives more than N tasks

Previous Quiz

Write a few sentences about the pros and cons of using local workstealing queues over the global implicit worklist

New material

C++ Atomic template

- C++ lets you wrap custom objects/types as an atomic type
- included in `<atomic>`
- use like this:
  - `atomic<int> i;`
  - `atomic<float> f;`

C++ Atomic template

- Lets you:
  - `load`
  - `store`
  - `exchange`
  - `compare_and_swap`

- It may use a lock behind the scenes!

- *Examples*

C++ Atomic template

- If you do this to a class, you will lose access to your methods!

- Pattern:
  - load the class atomically into a non atomic variable
  - operate on it
  - store it back. Be careful (others may have updated it!)

Schedule

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

Thanks to Roberto Palmieri (Lehigh University) and material from the text book for some of the slide content/ideas.

Set Interface

- Unordered collection of items
- No duplicates

- We will implement this as a sorted linked list

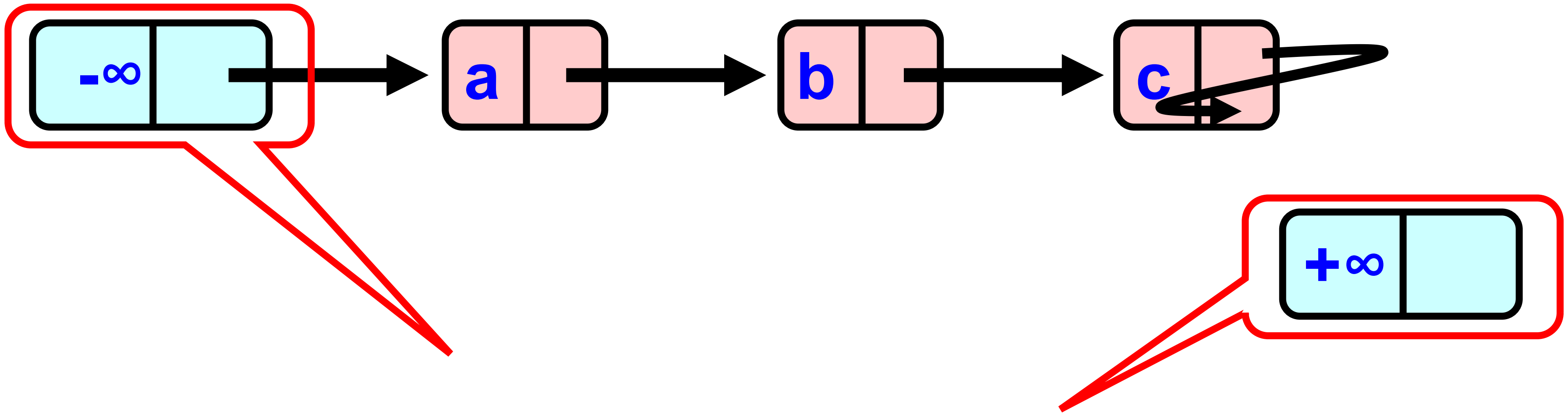
Set Interface

- 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

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

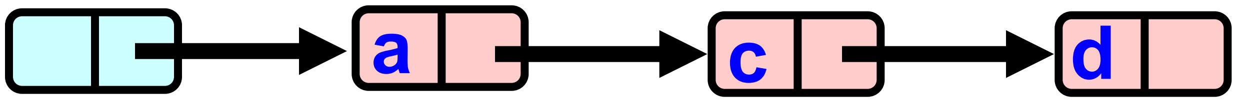
The List-Based Set



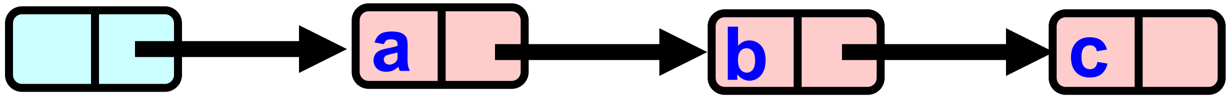
Sorted with Sentinel nodes
(min & max possible keys)

Sequential List Based Set

add(b)



remove(b)



Sequential List Based Set

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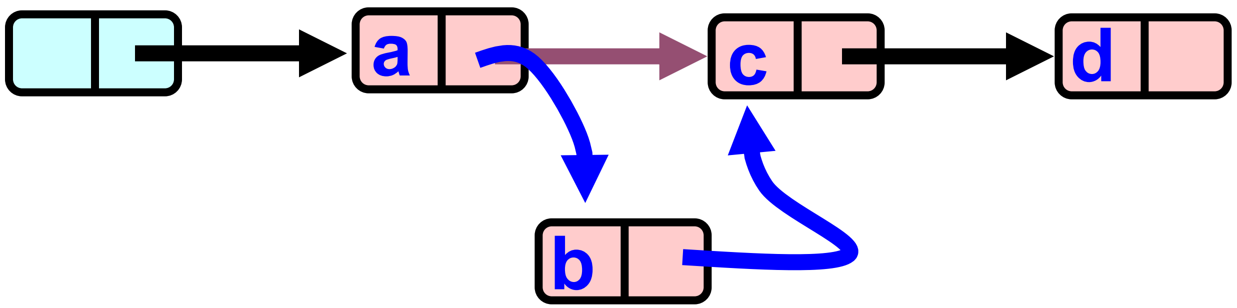

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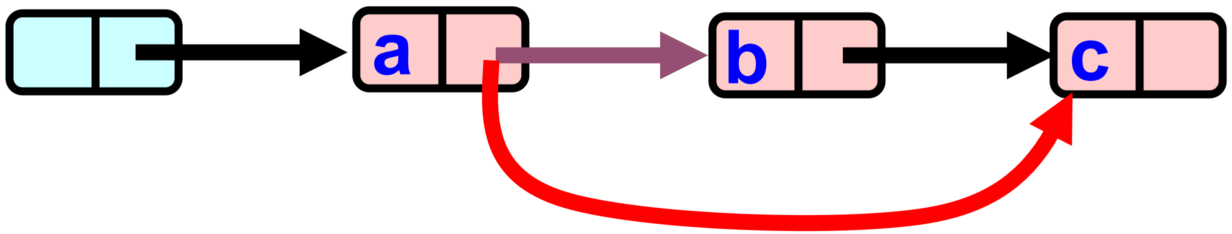
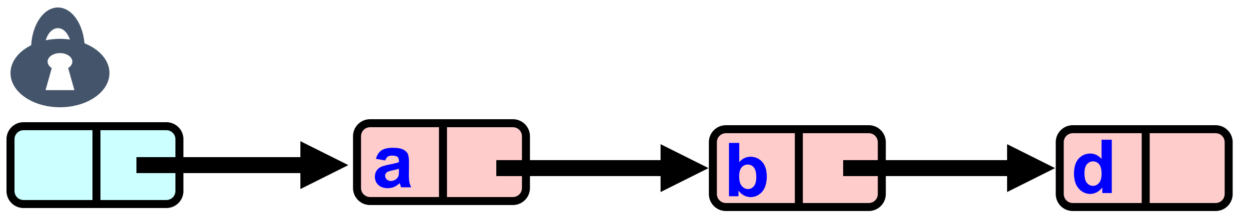


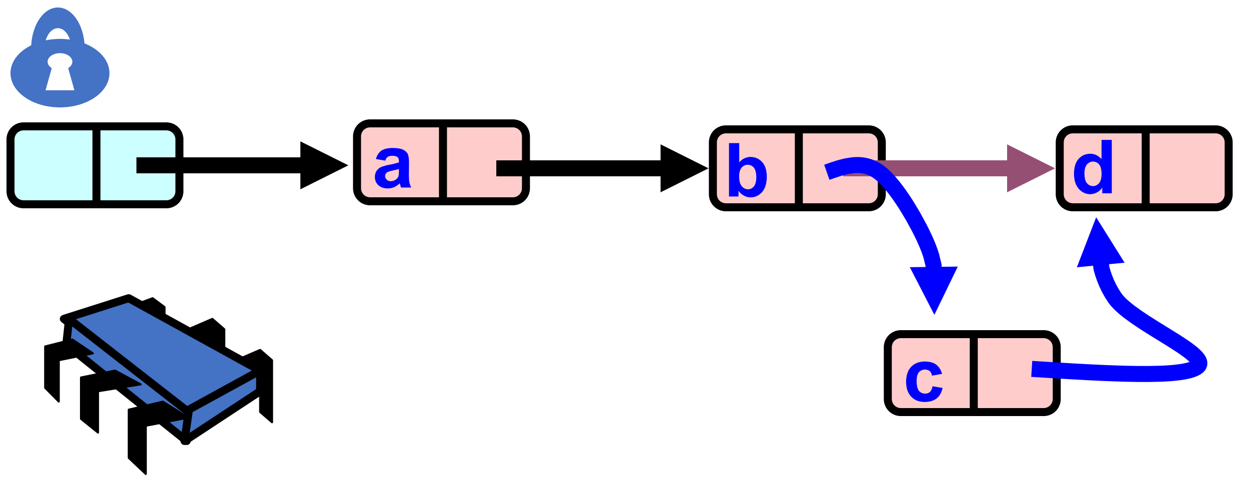
Schedule

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

Coarse-Grained Locking



Coarse-Grained Locking



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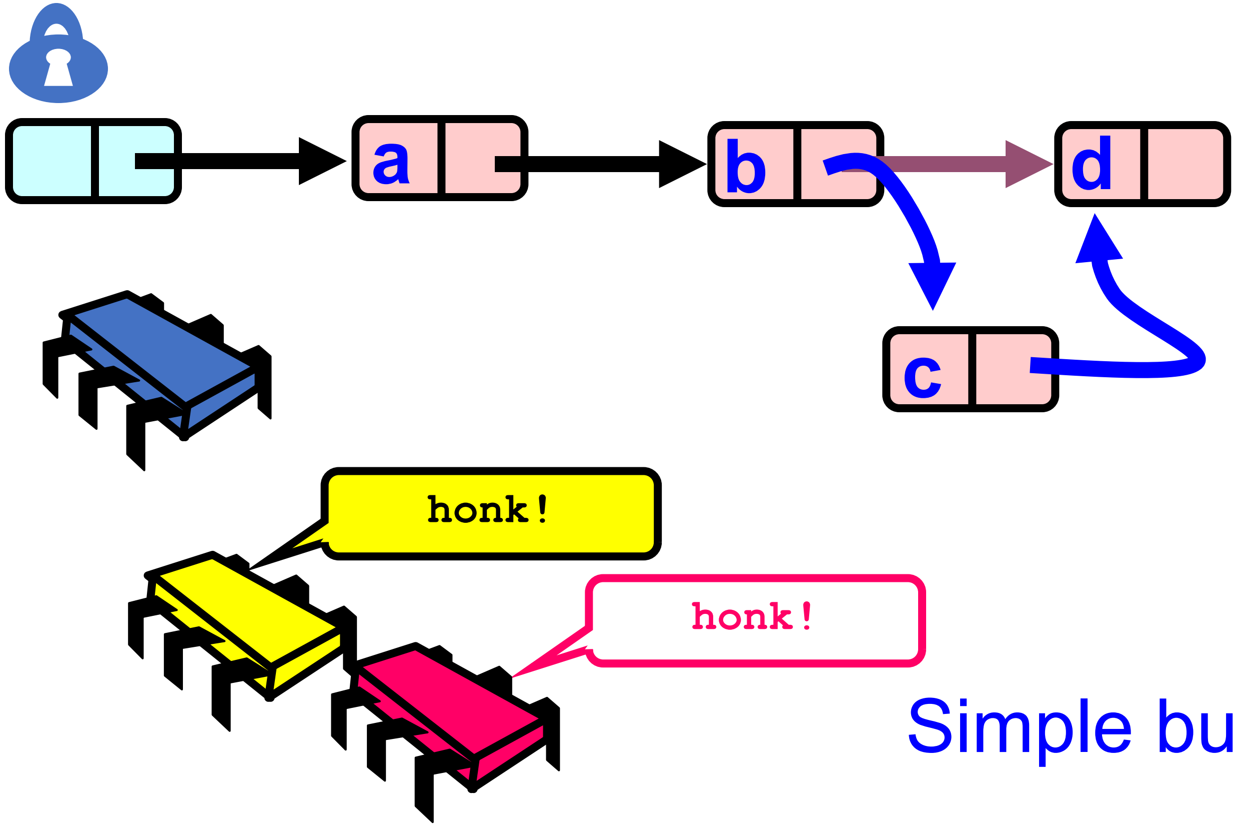


Simple but inefficient!

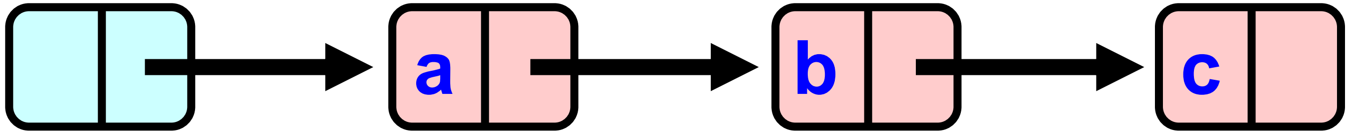
Schedule

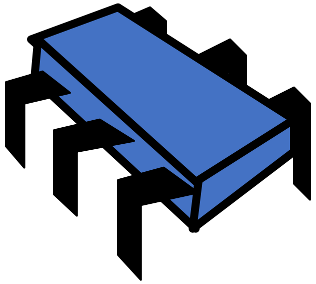
- Concurrent set
  - Coarse-grained lock
  - **fine-grained lock**
  - optimistic locking

Fine-grained Locking

- Requires **careful** thought
- 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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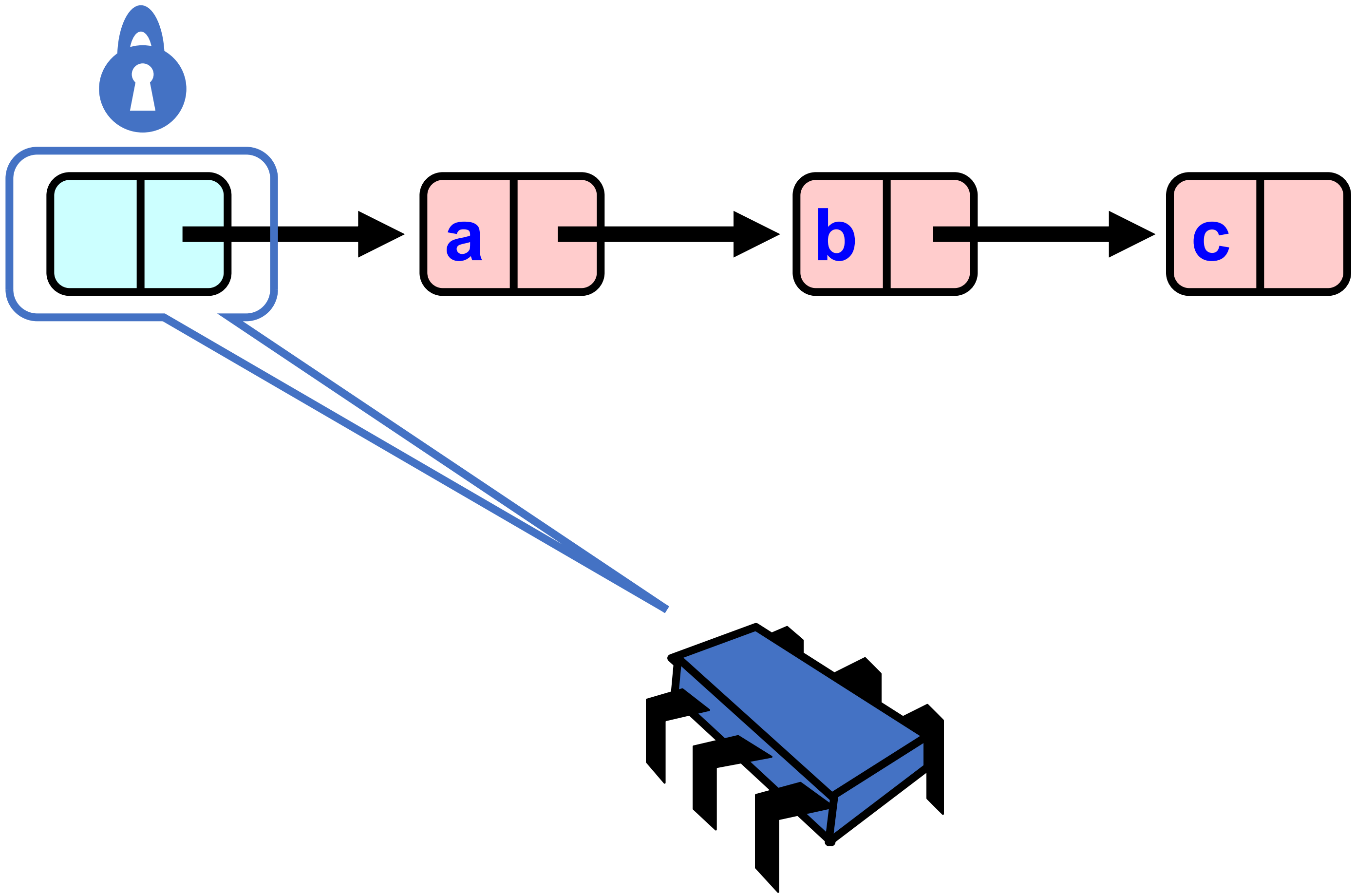

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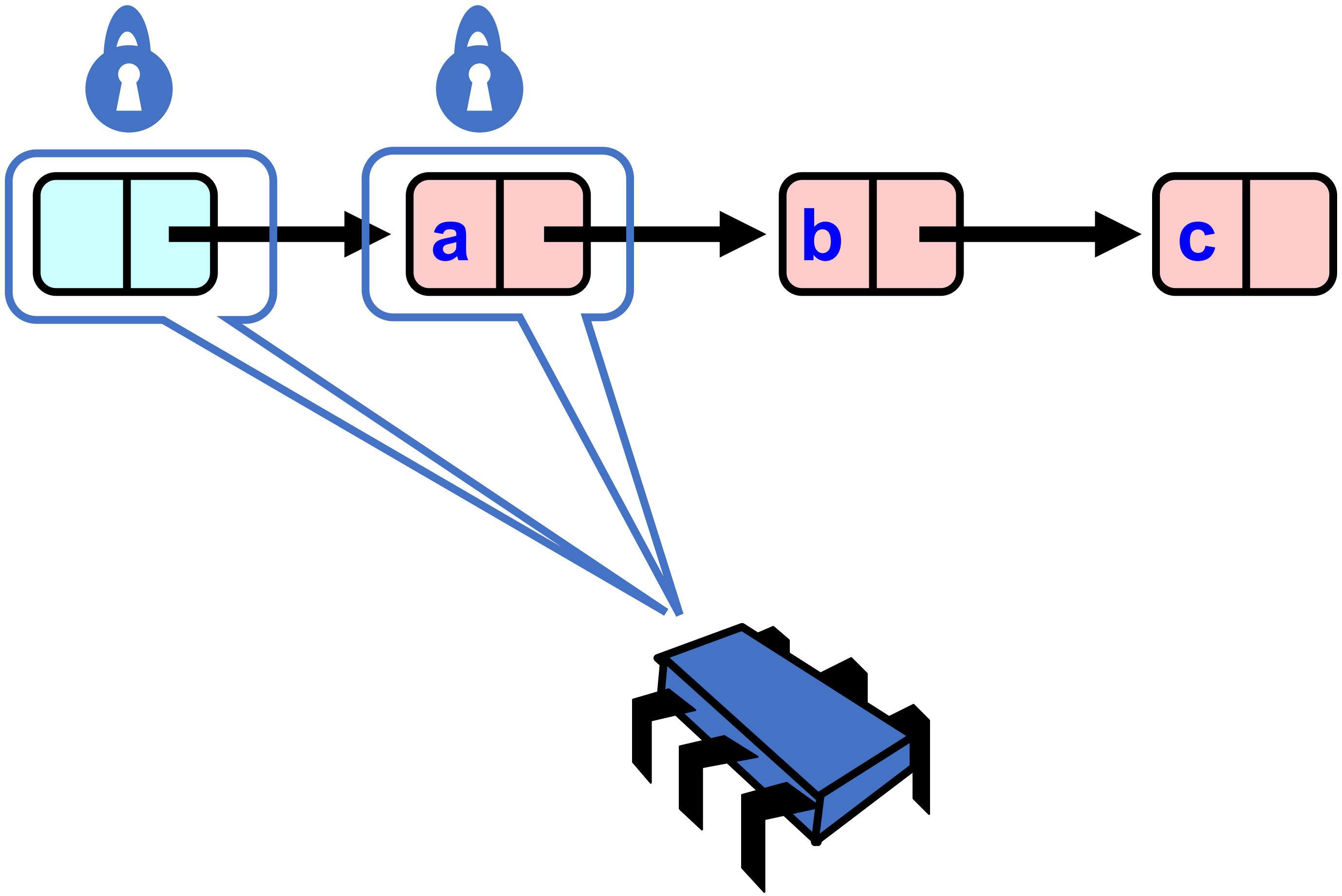

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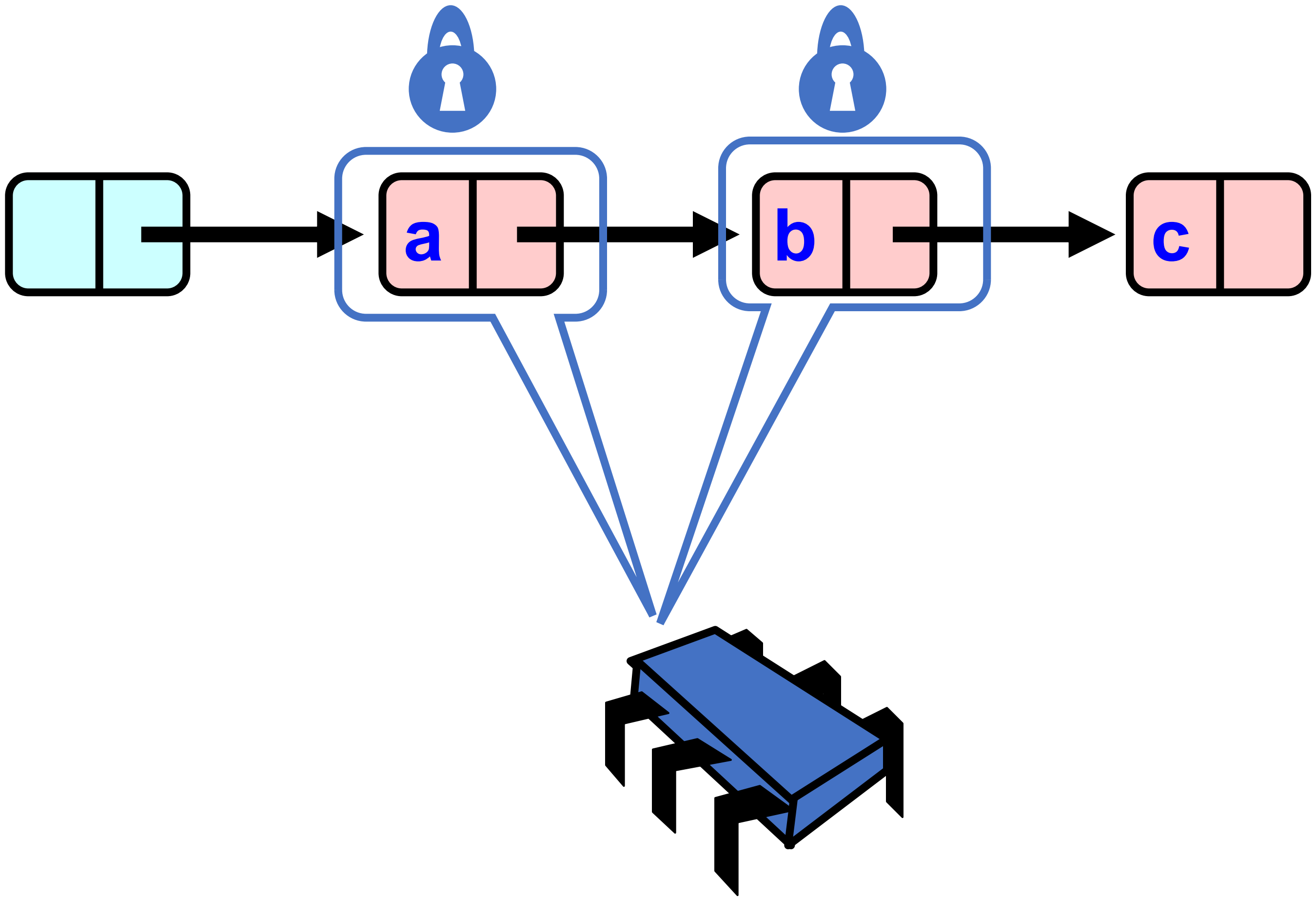

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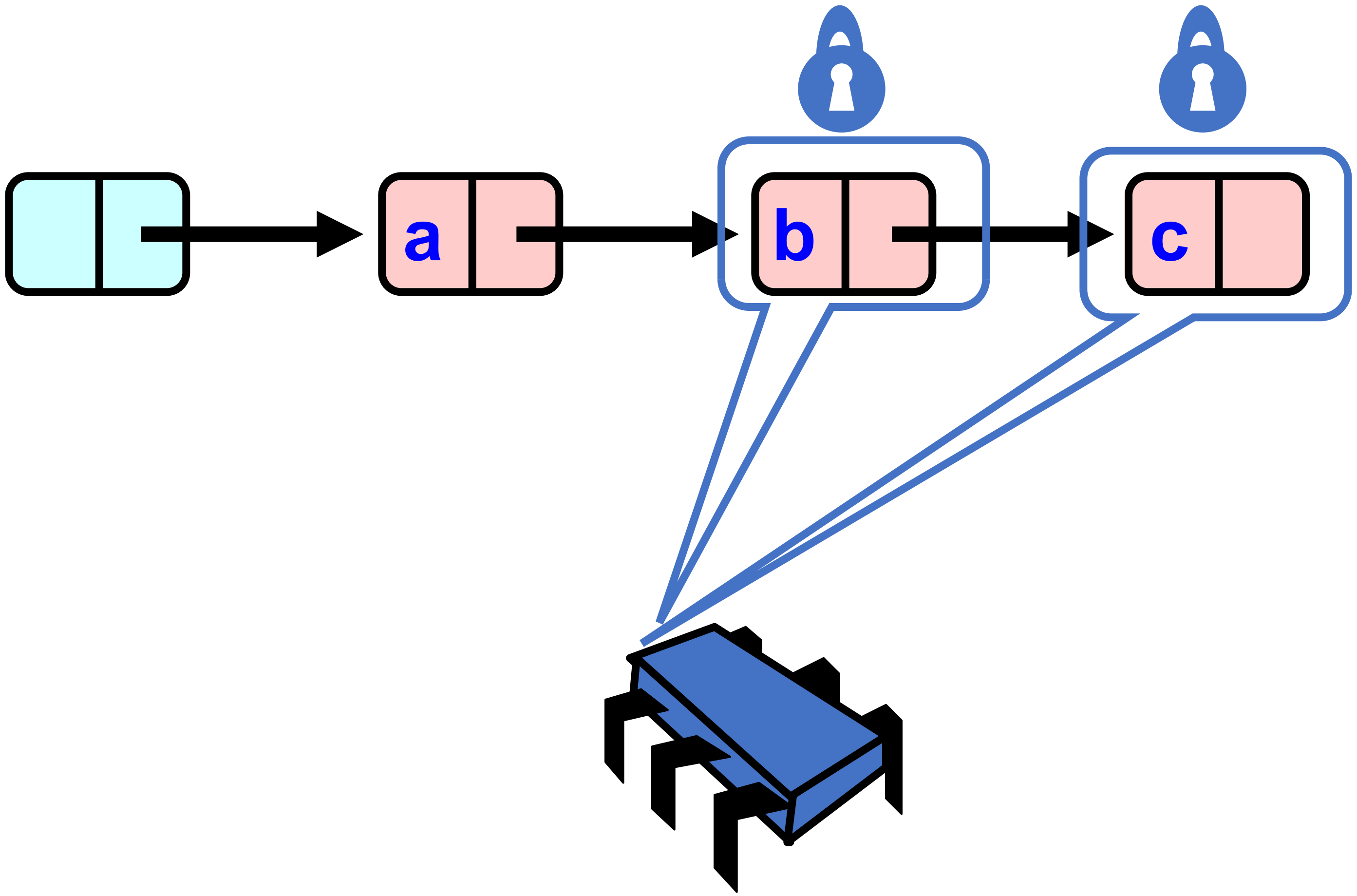
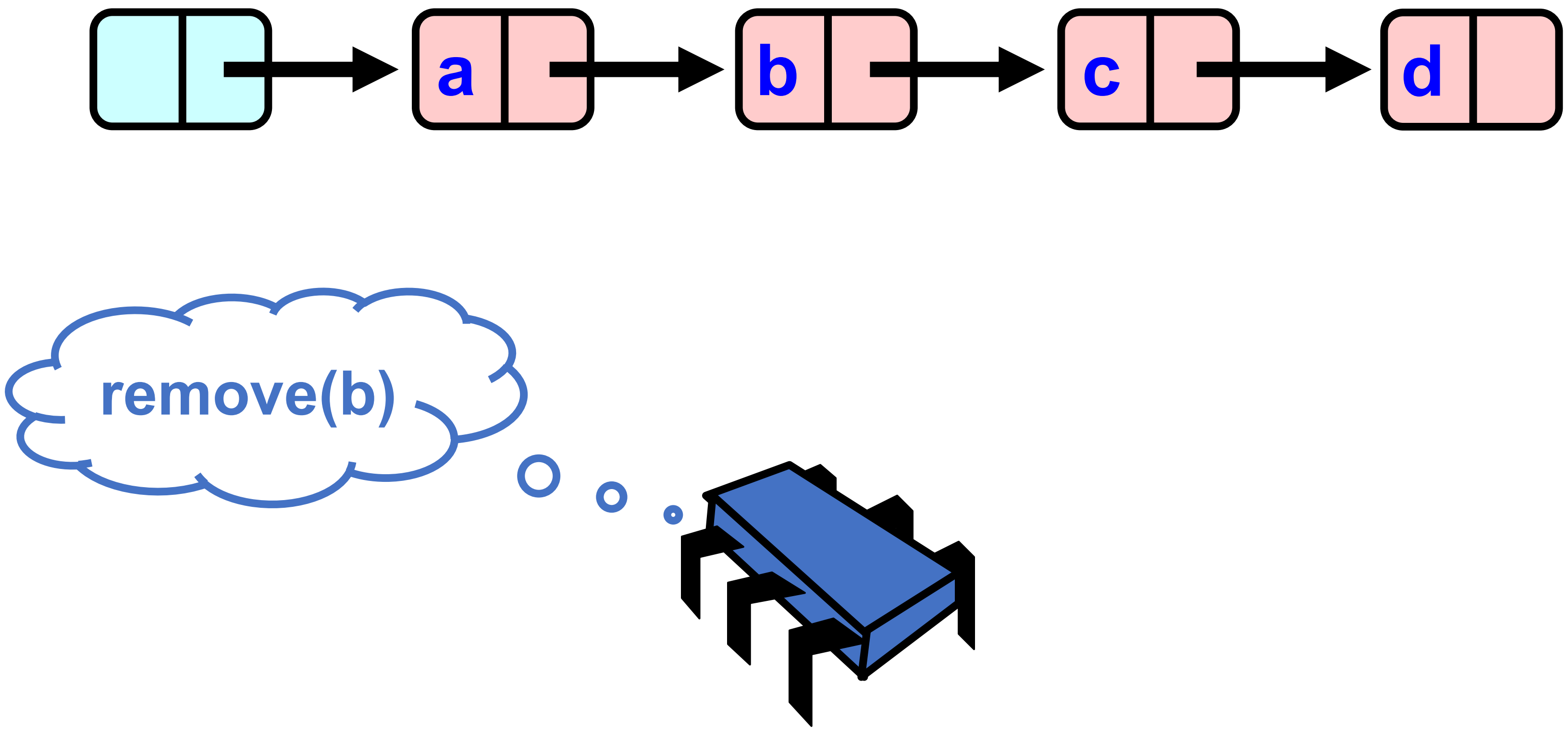


Removing a Node



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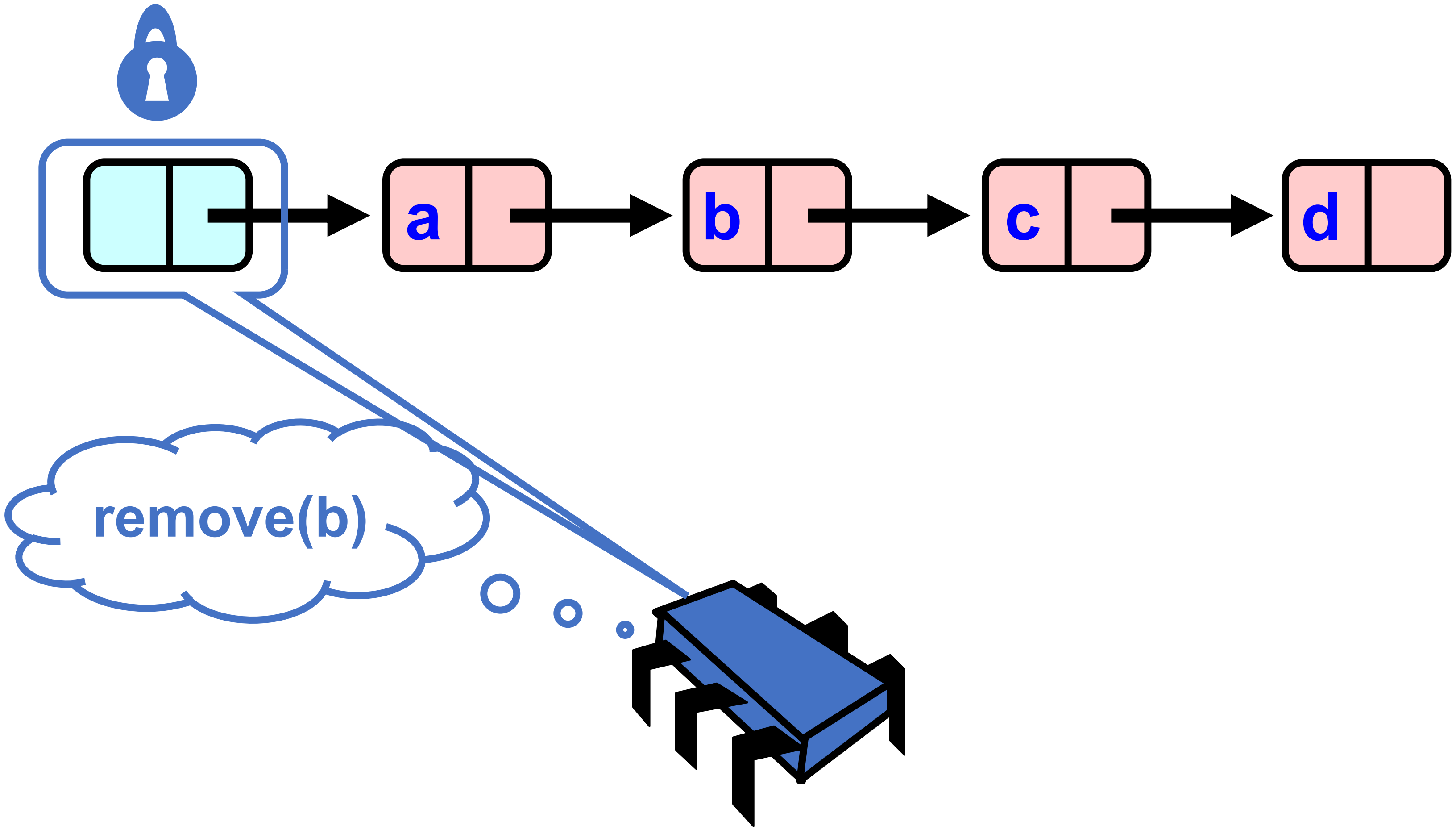

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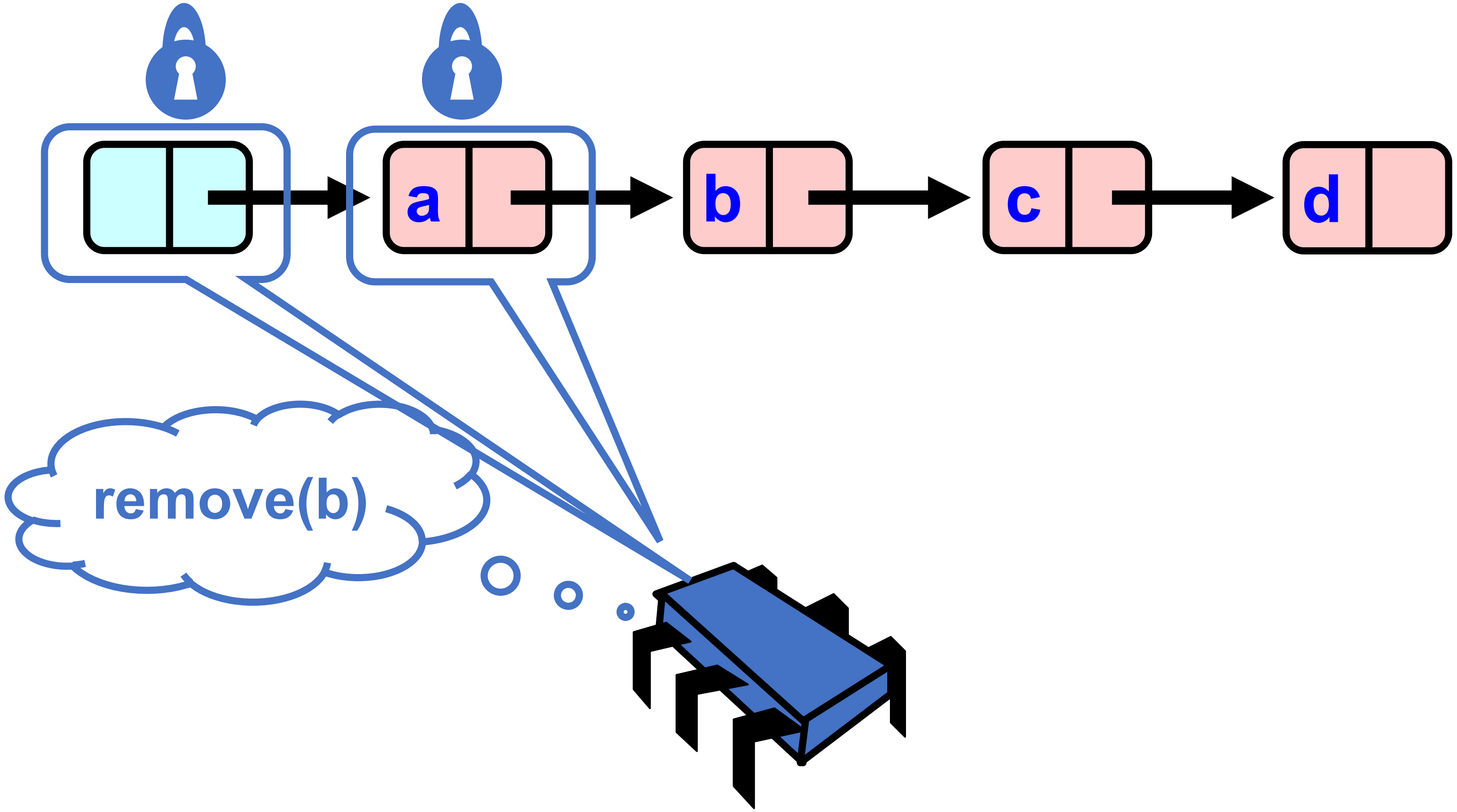

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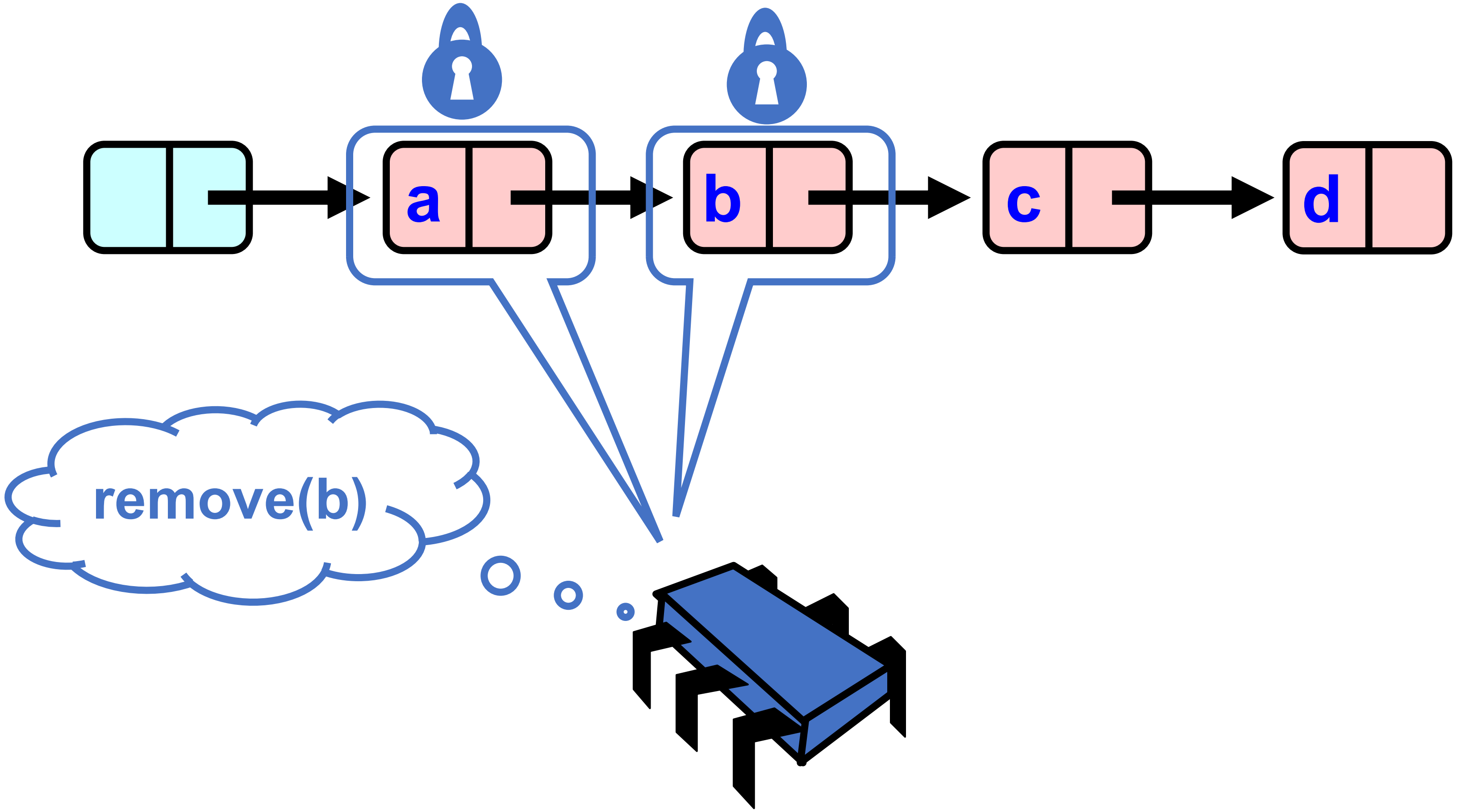

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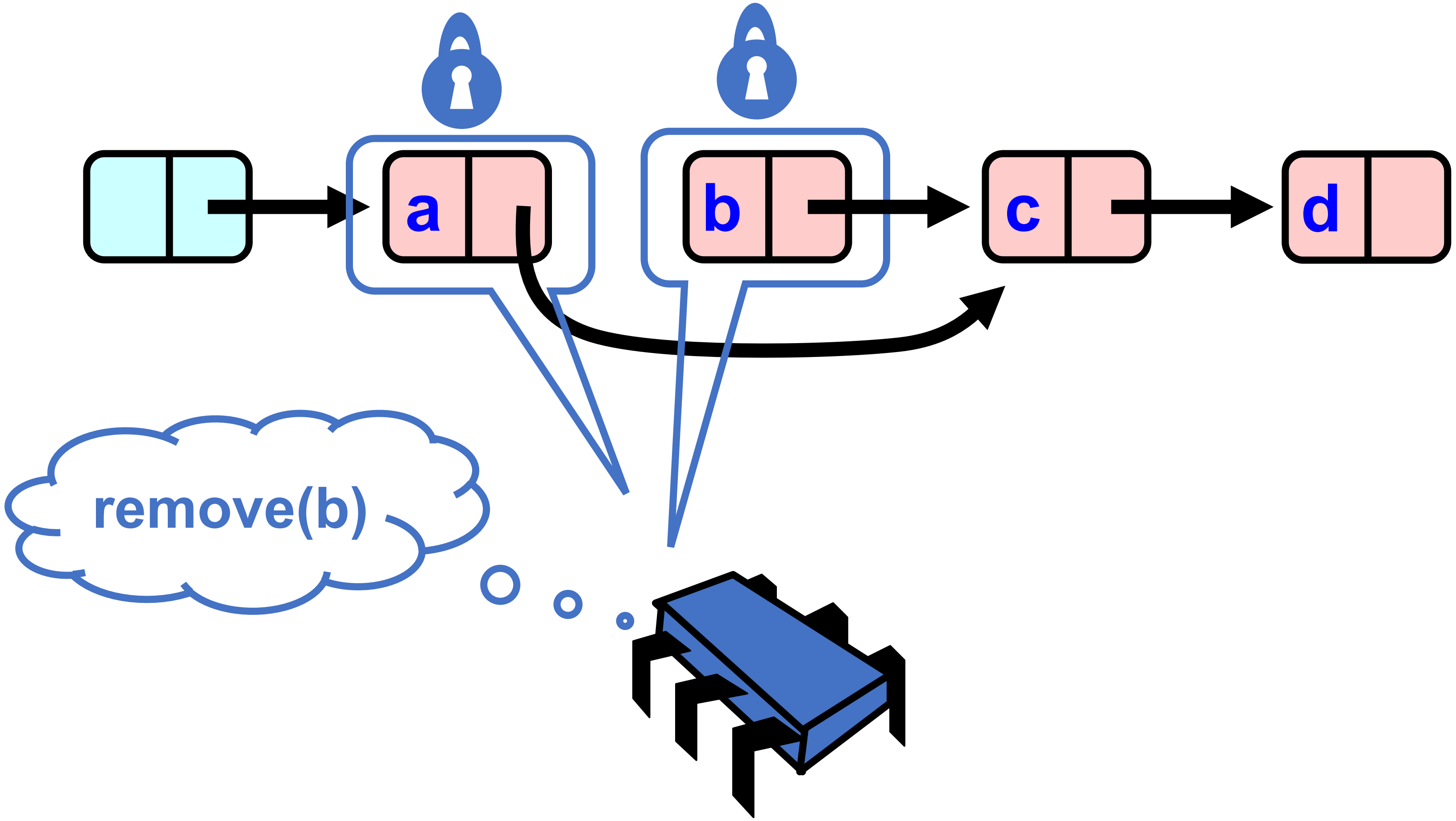

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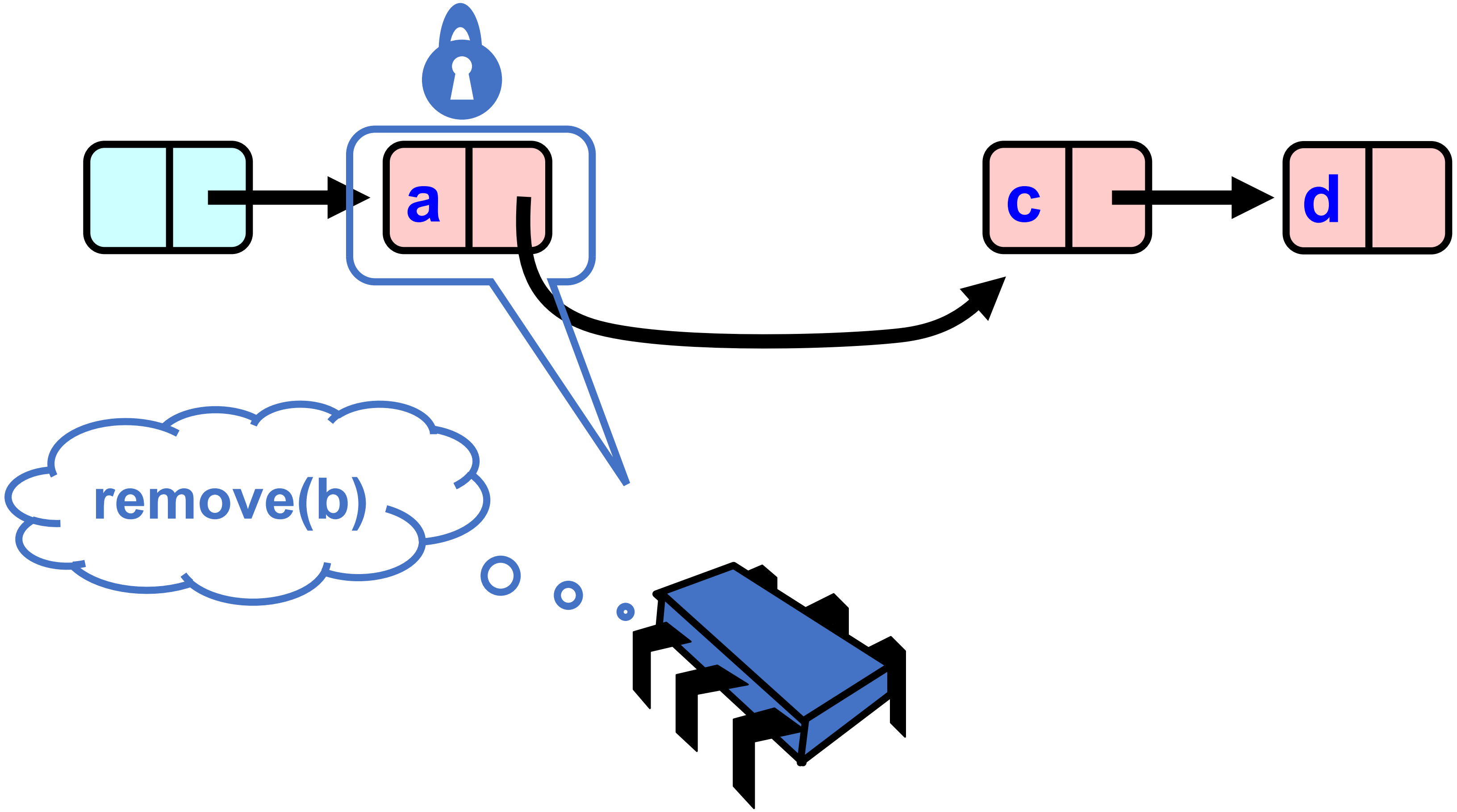

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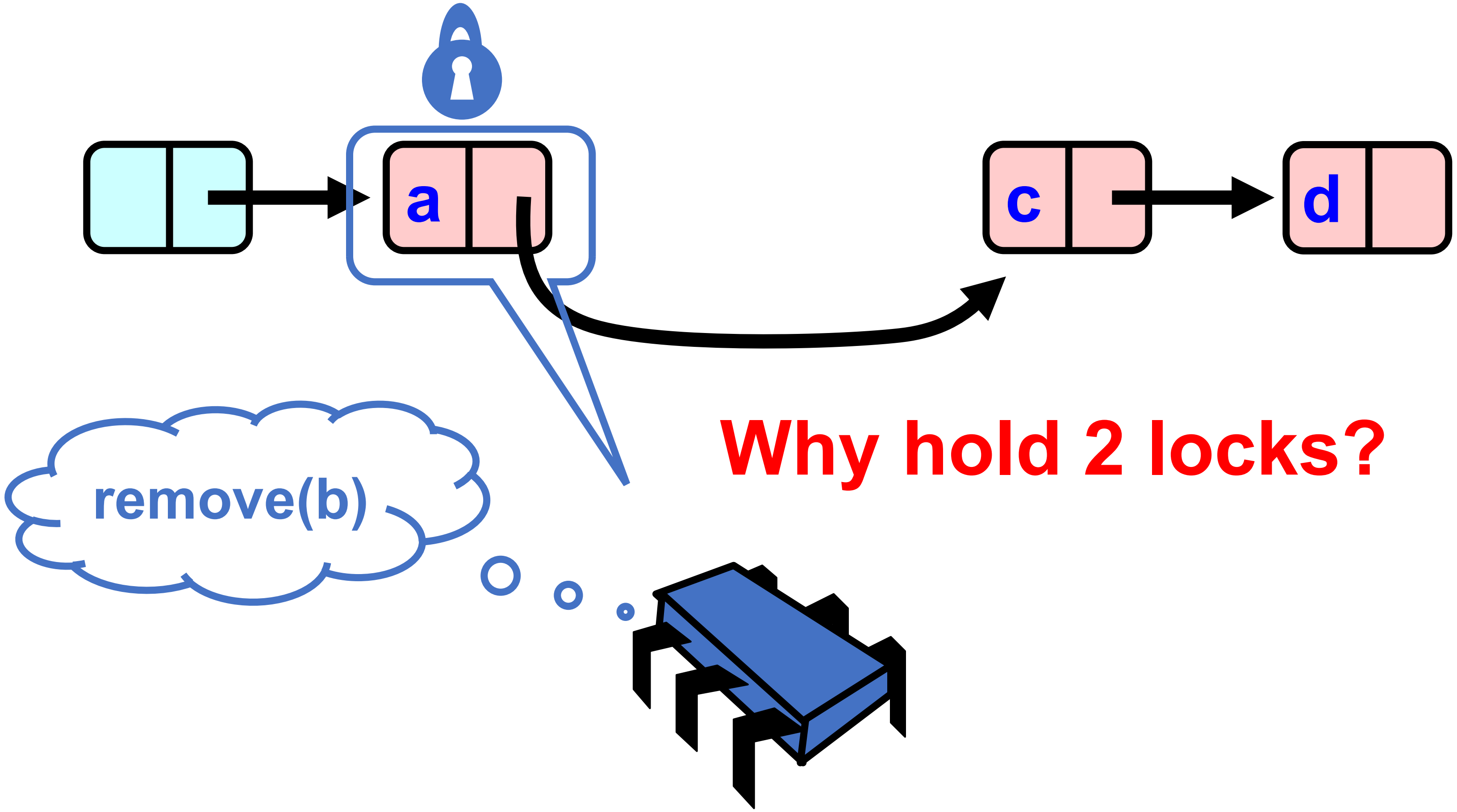
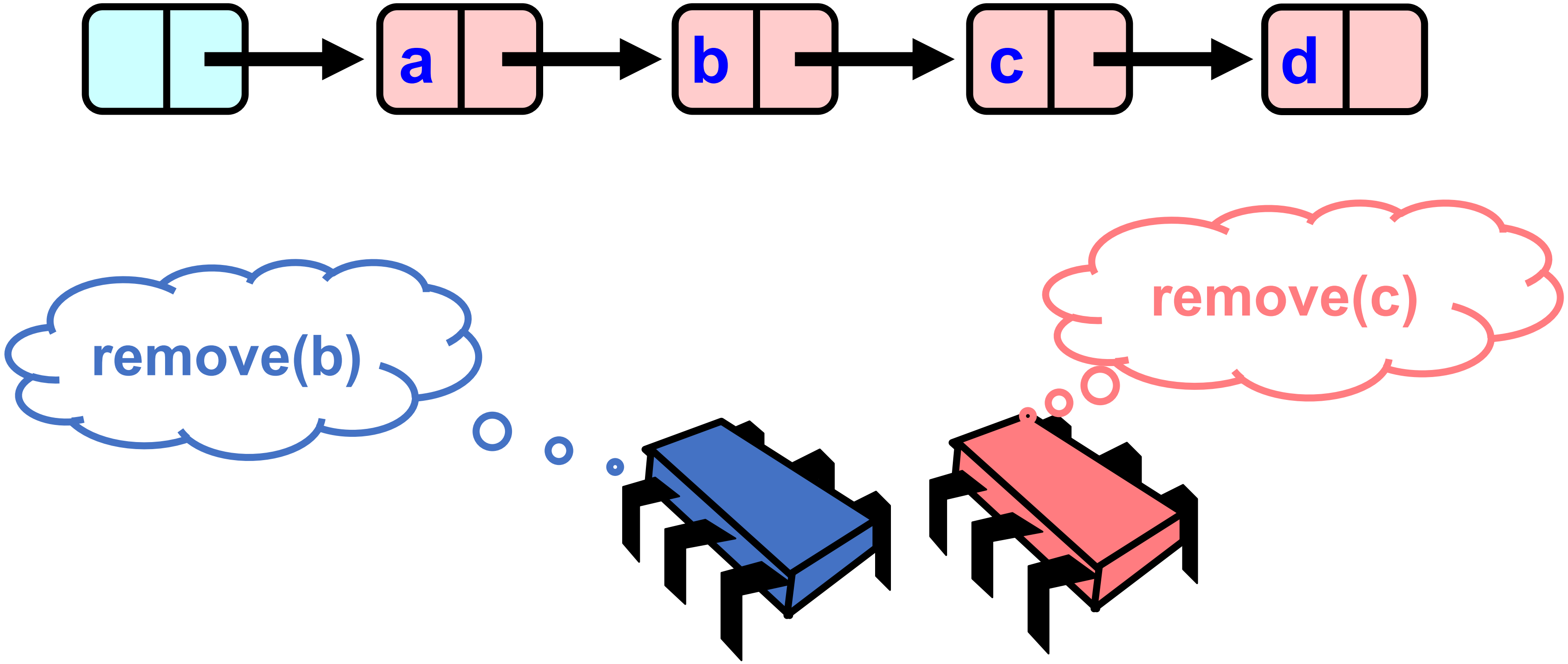
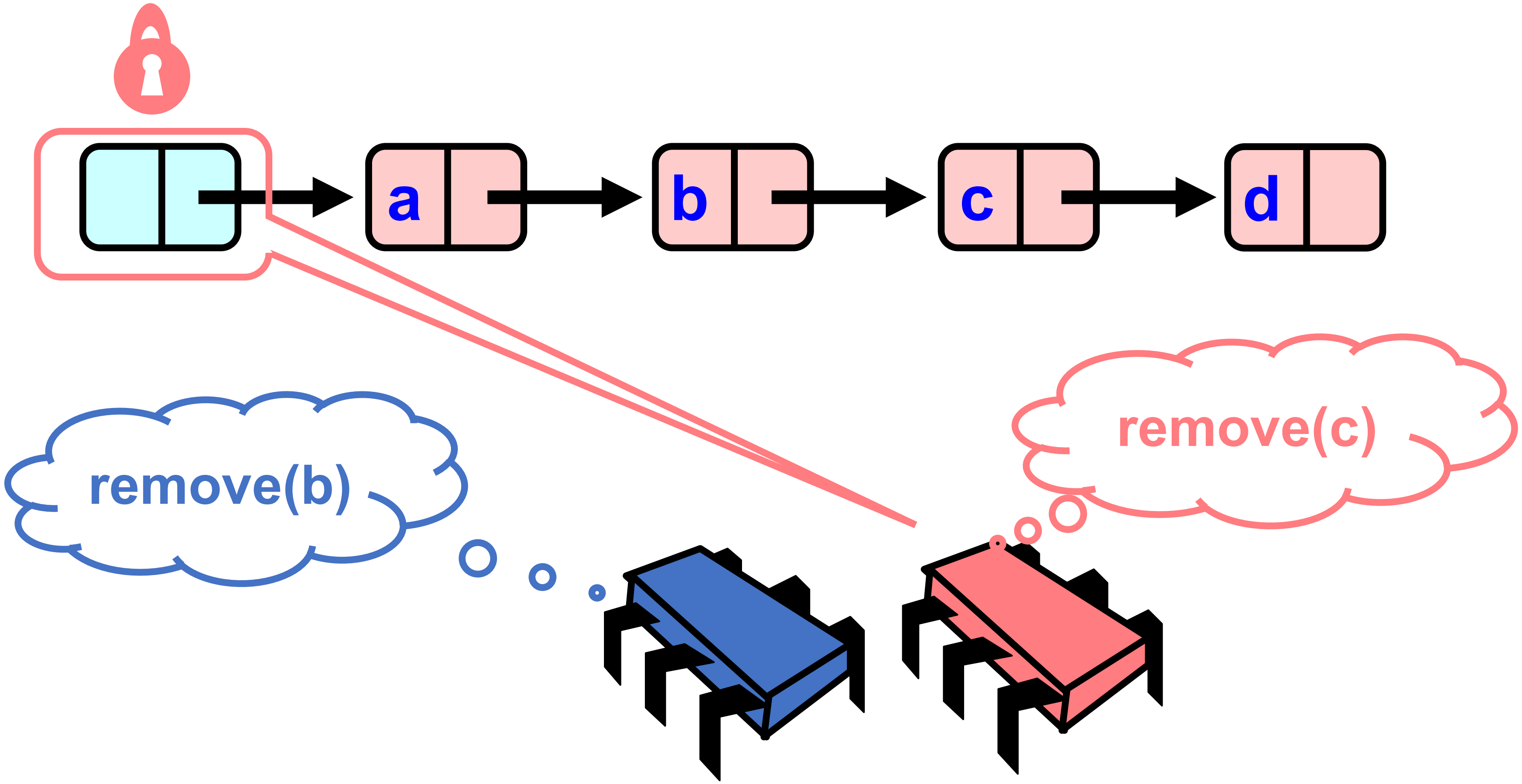


Why hold 2 locks?

Concurrent Removes



Concurrent Removes



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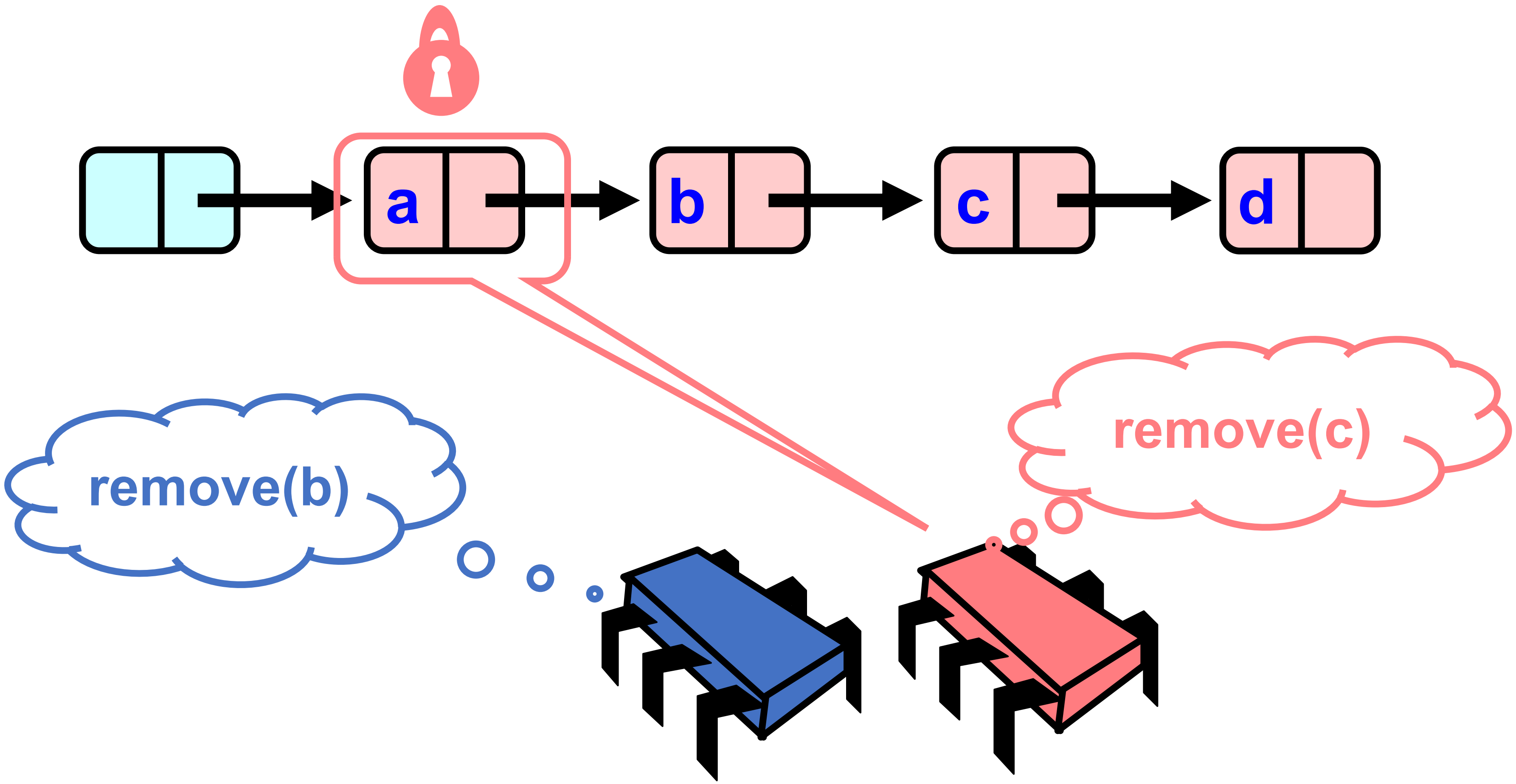

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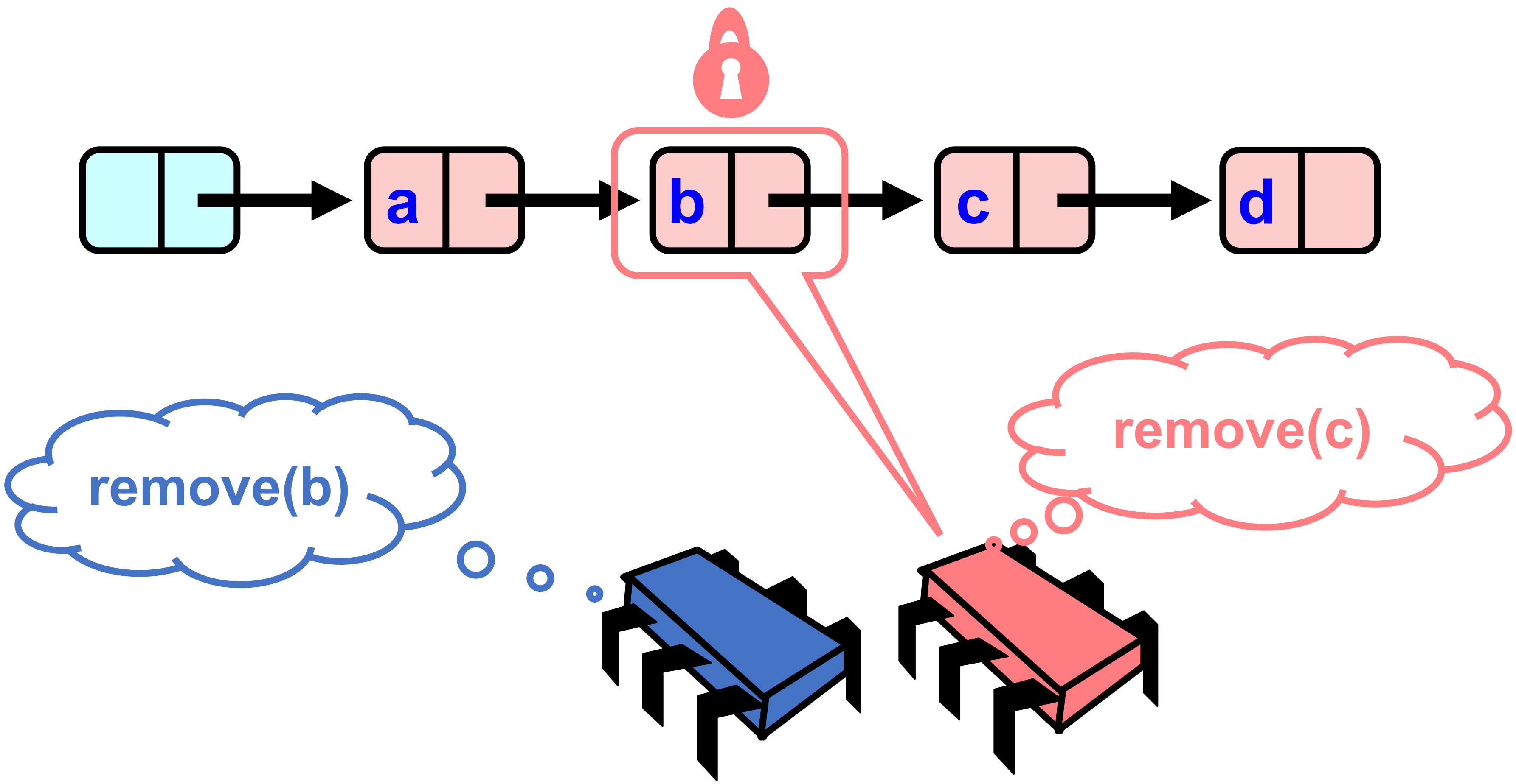

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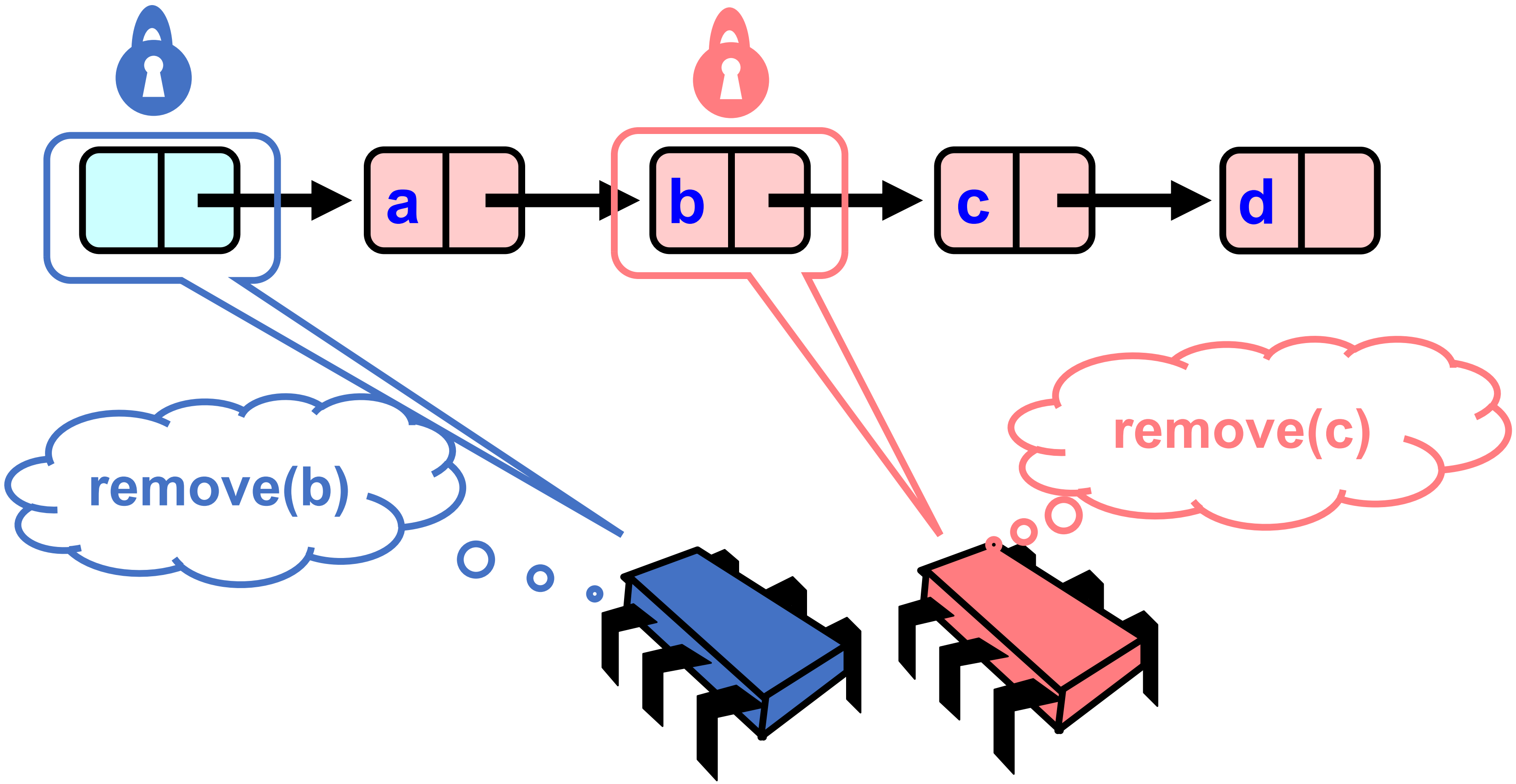

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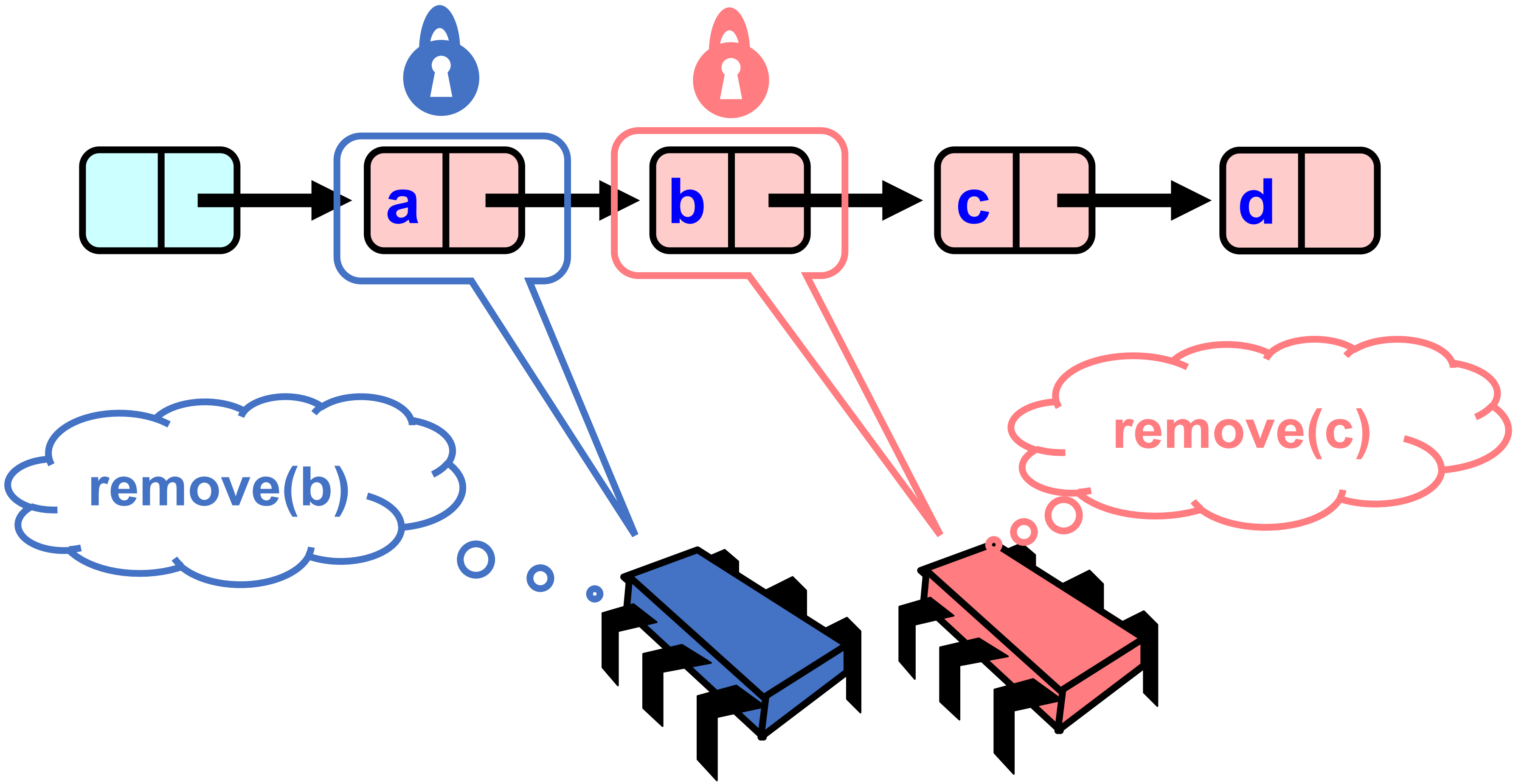

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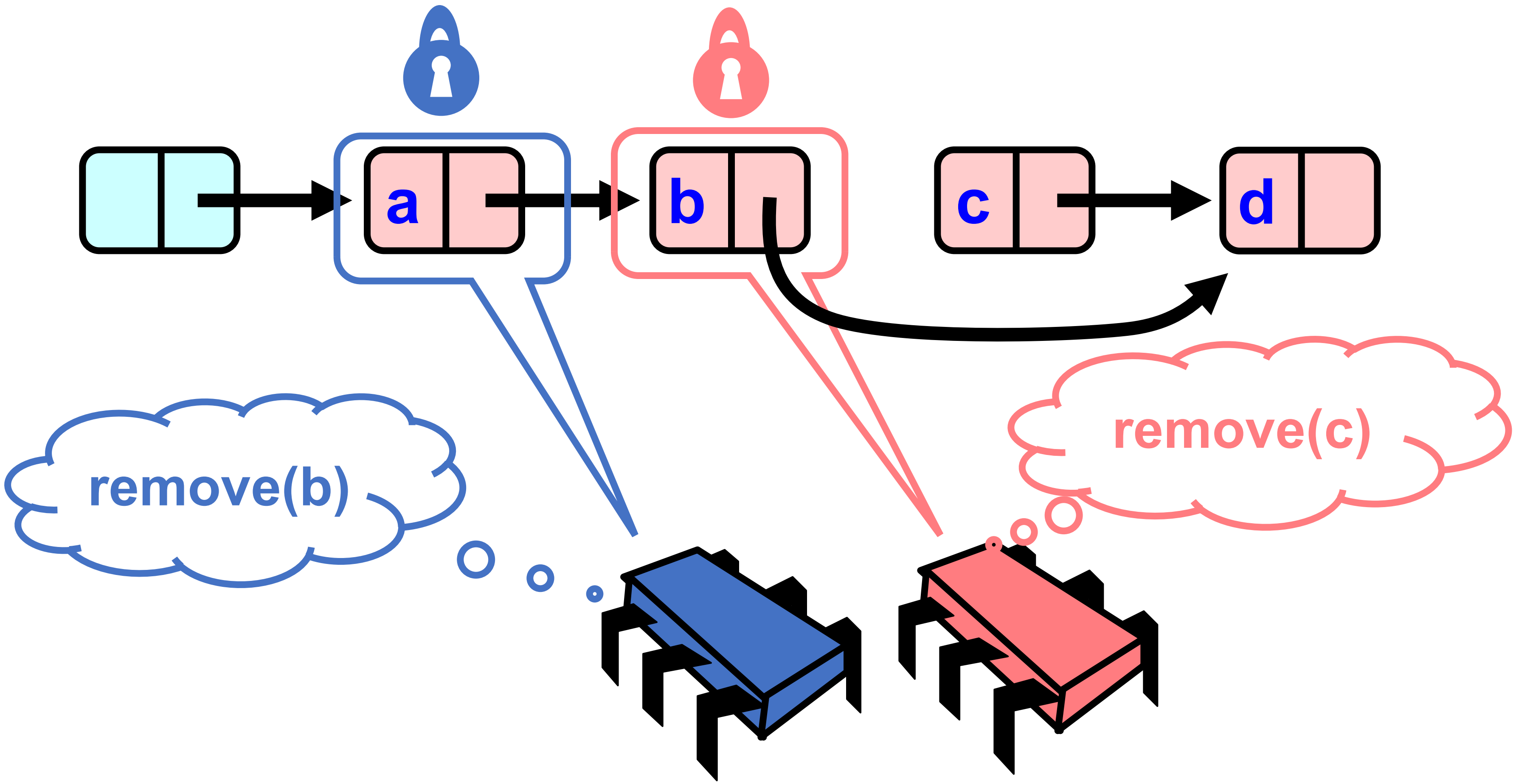

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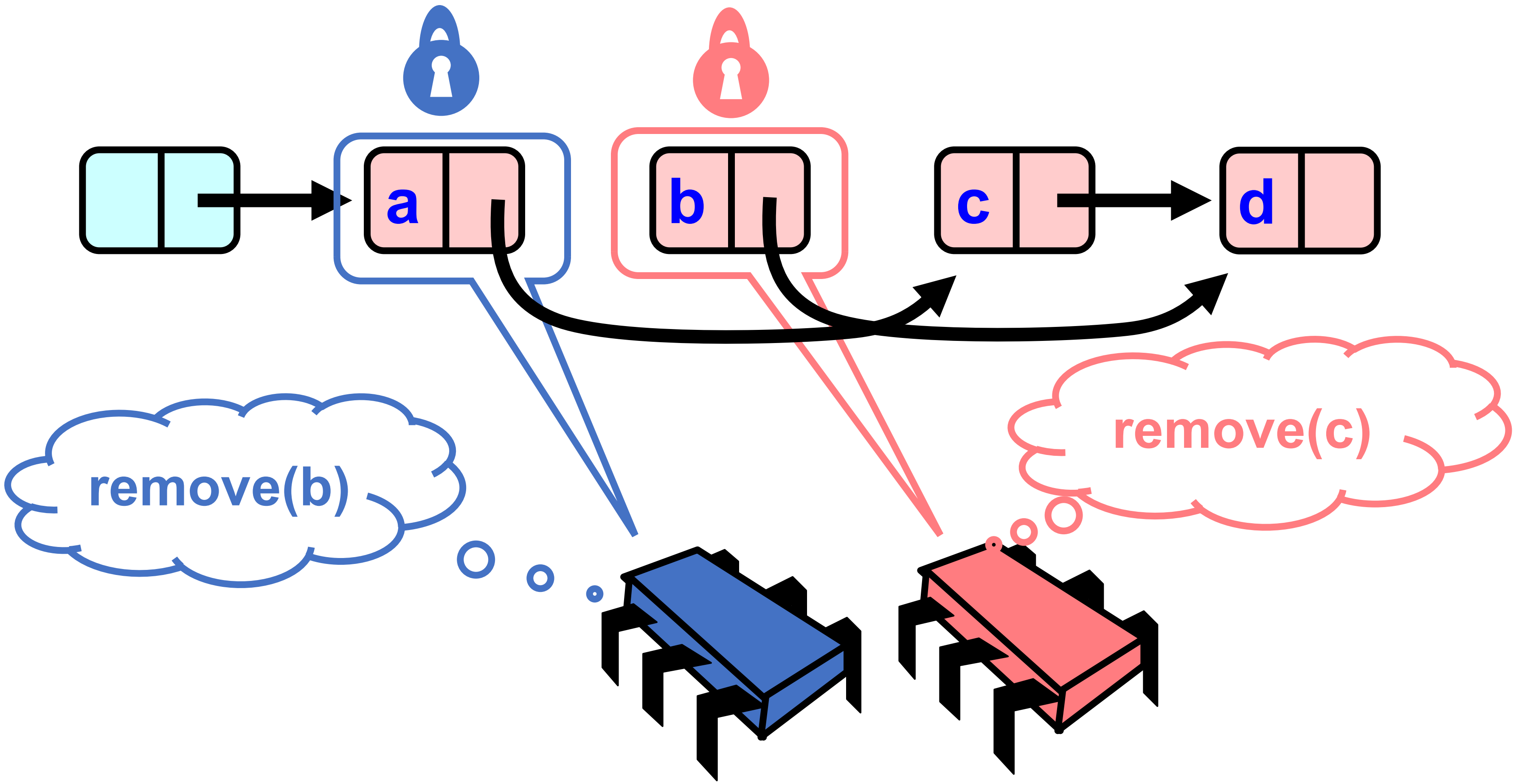
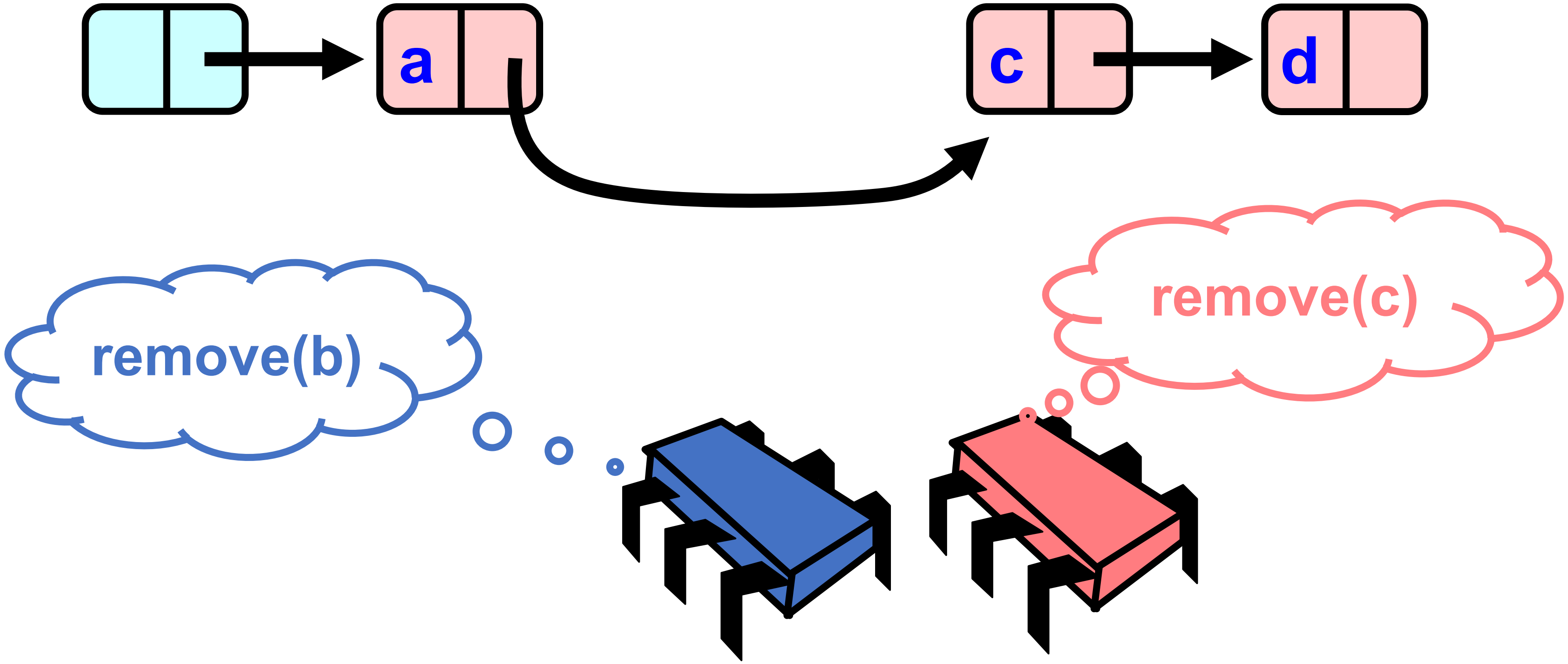


Uh, Oh



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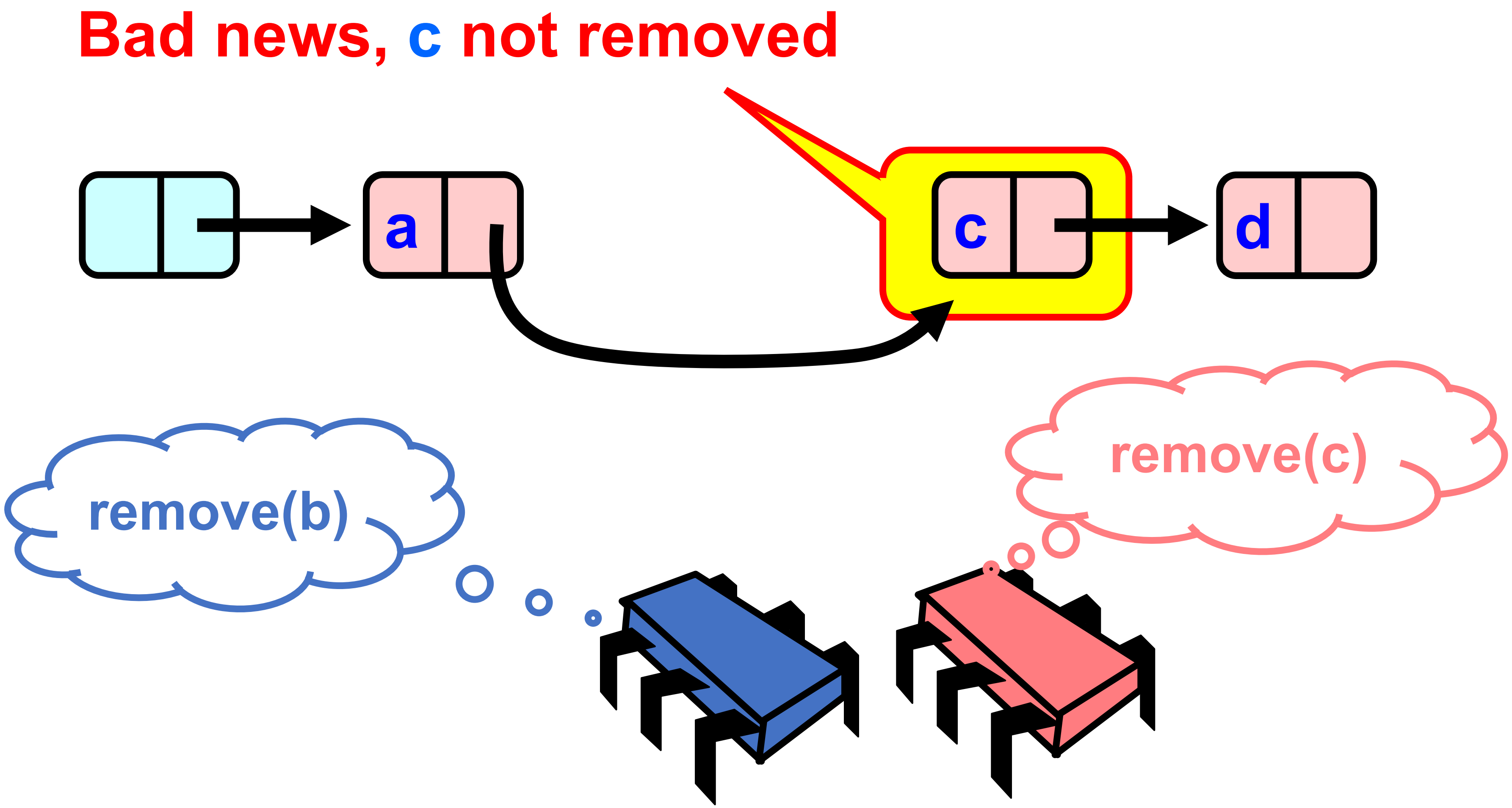
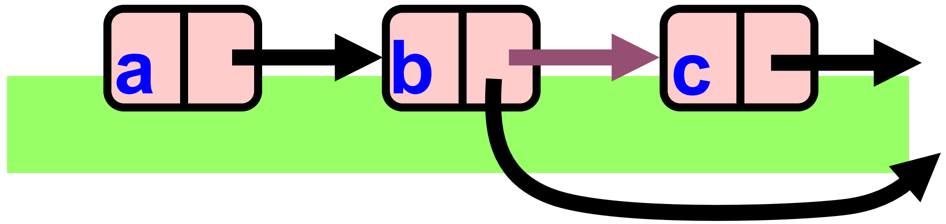
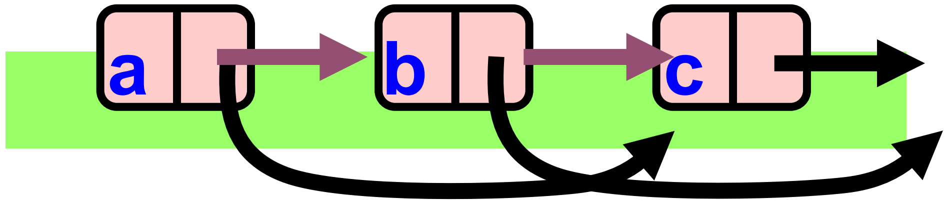


Problem

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



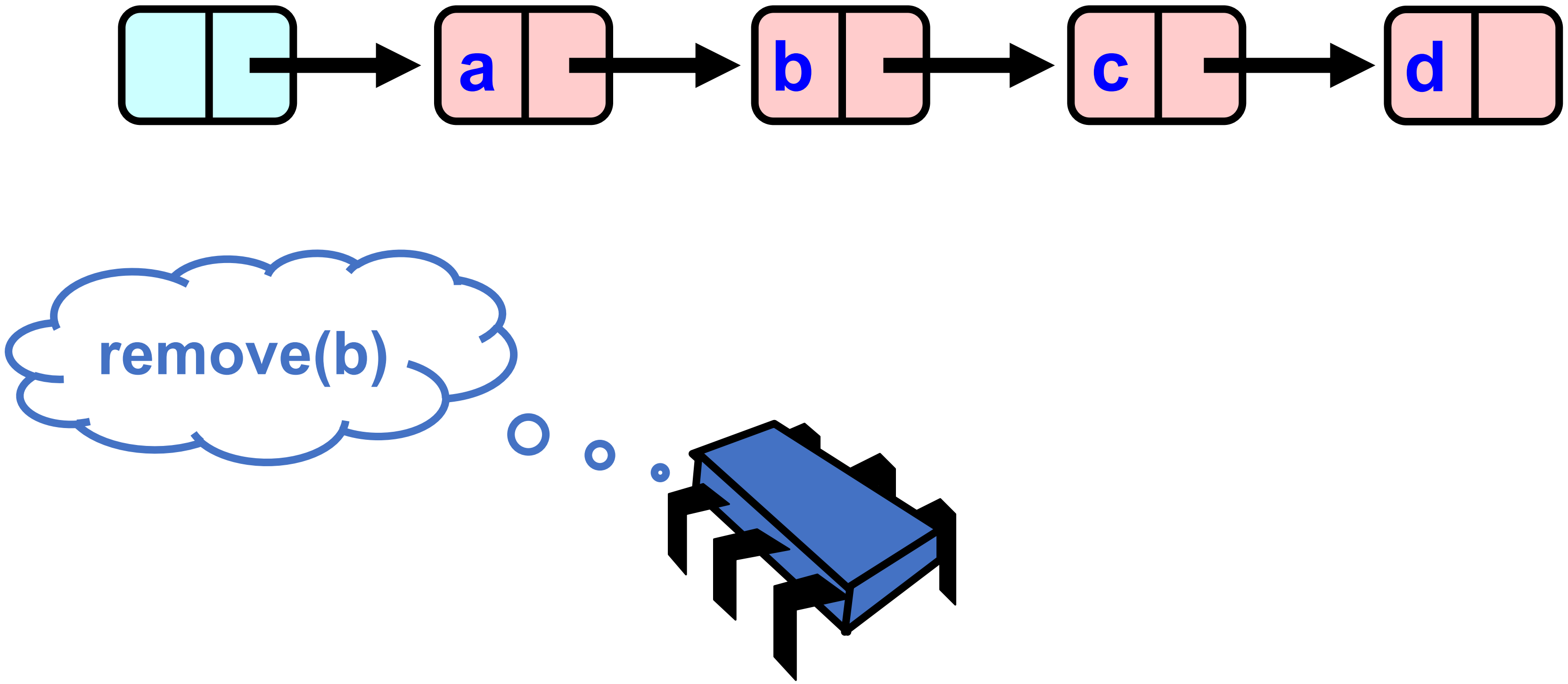
- Problem is,
  - ***Data conflict:***
  - Someone deleting b concurrently could direct a pointer to C



Insight

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

Hand-Over-Hand Again



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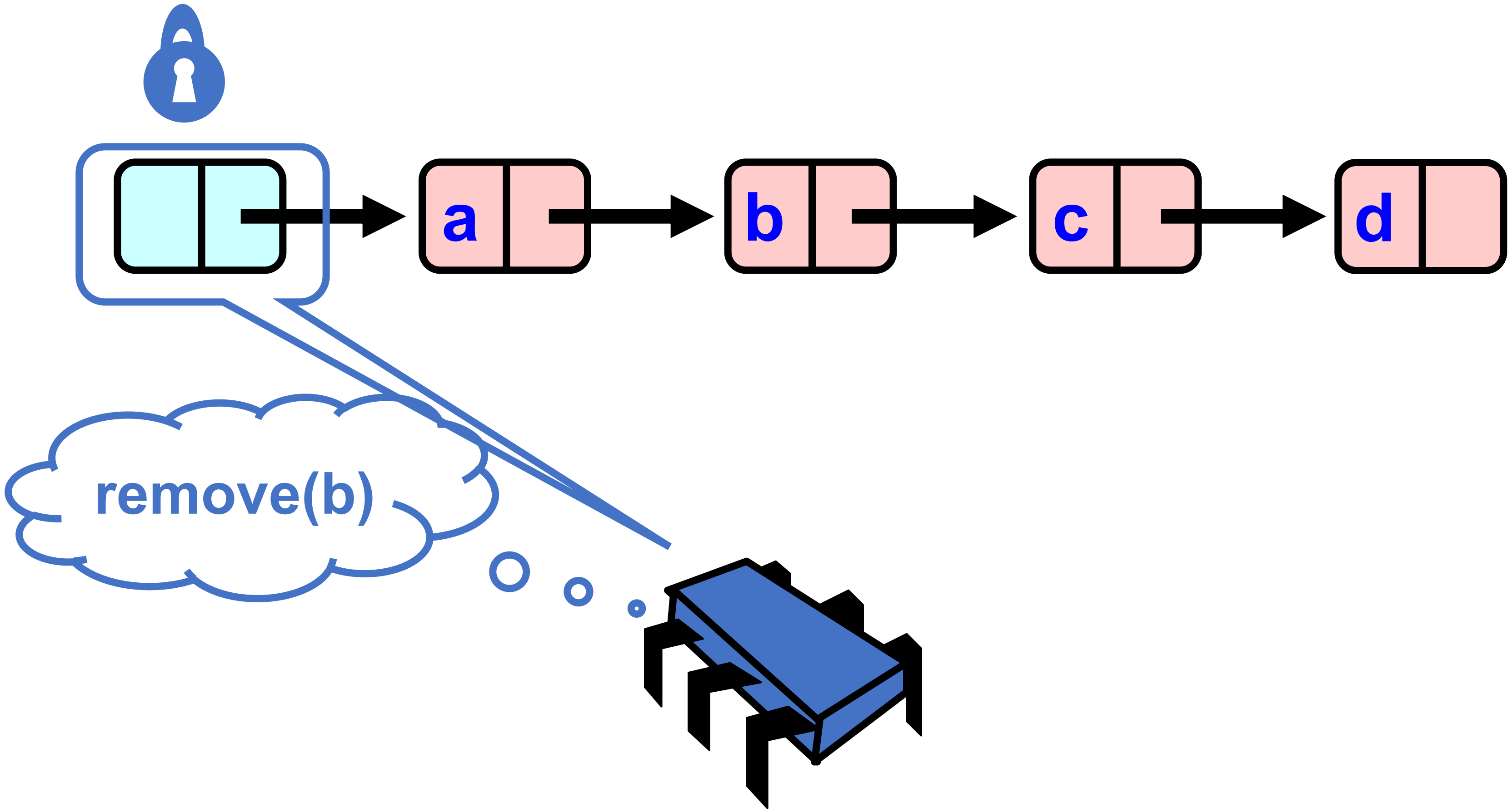

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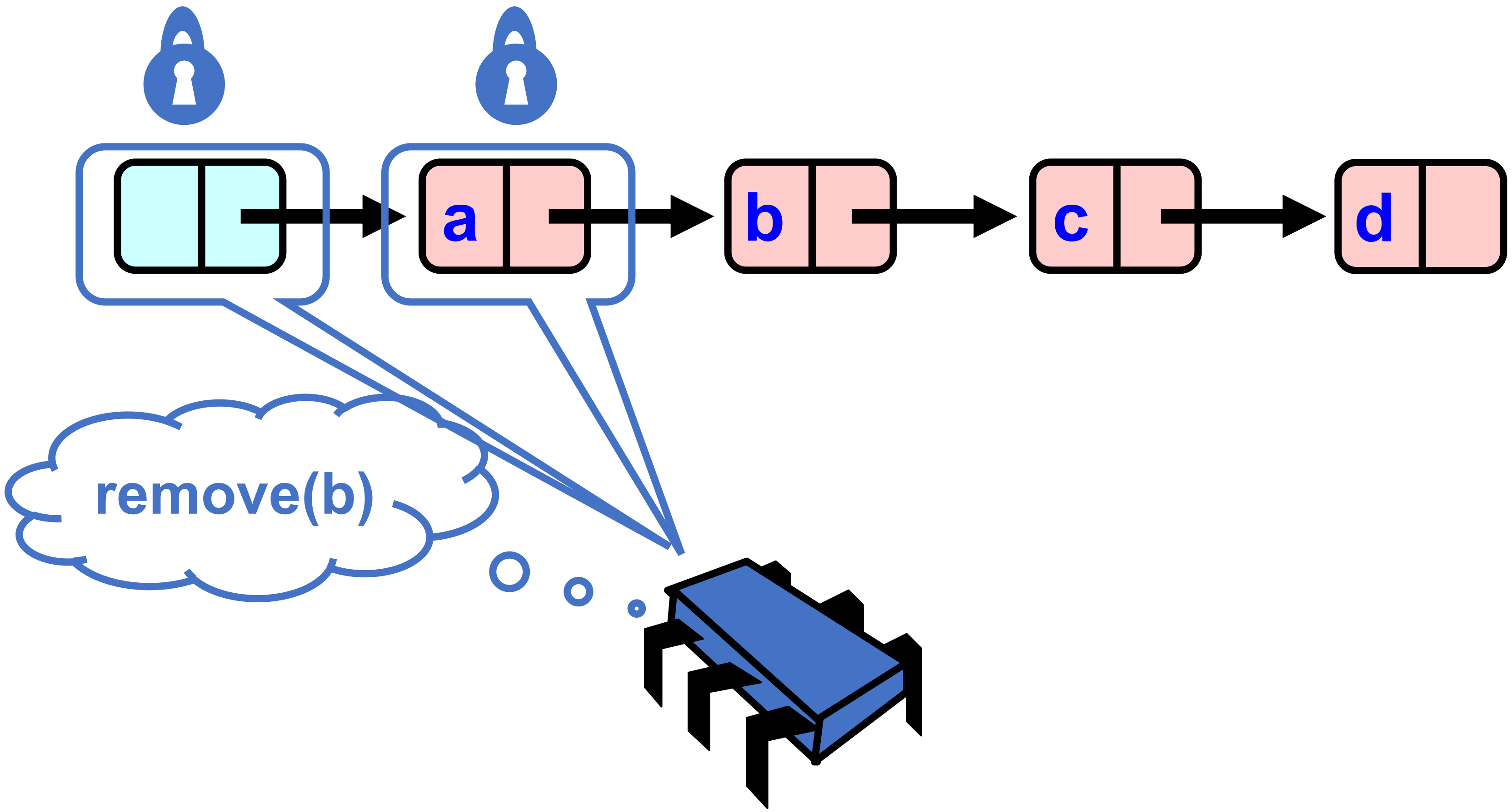

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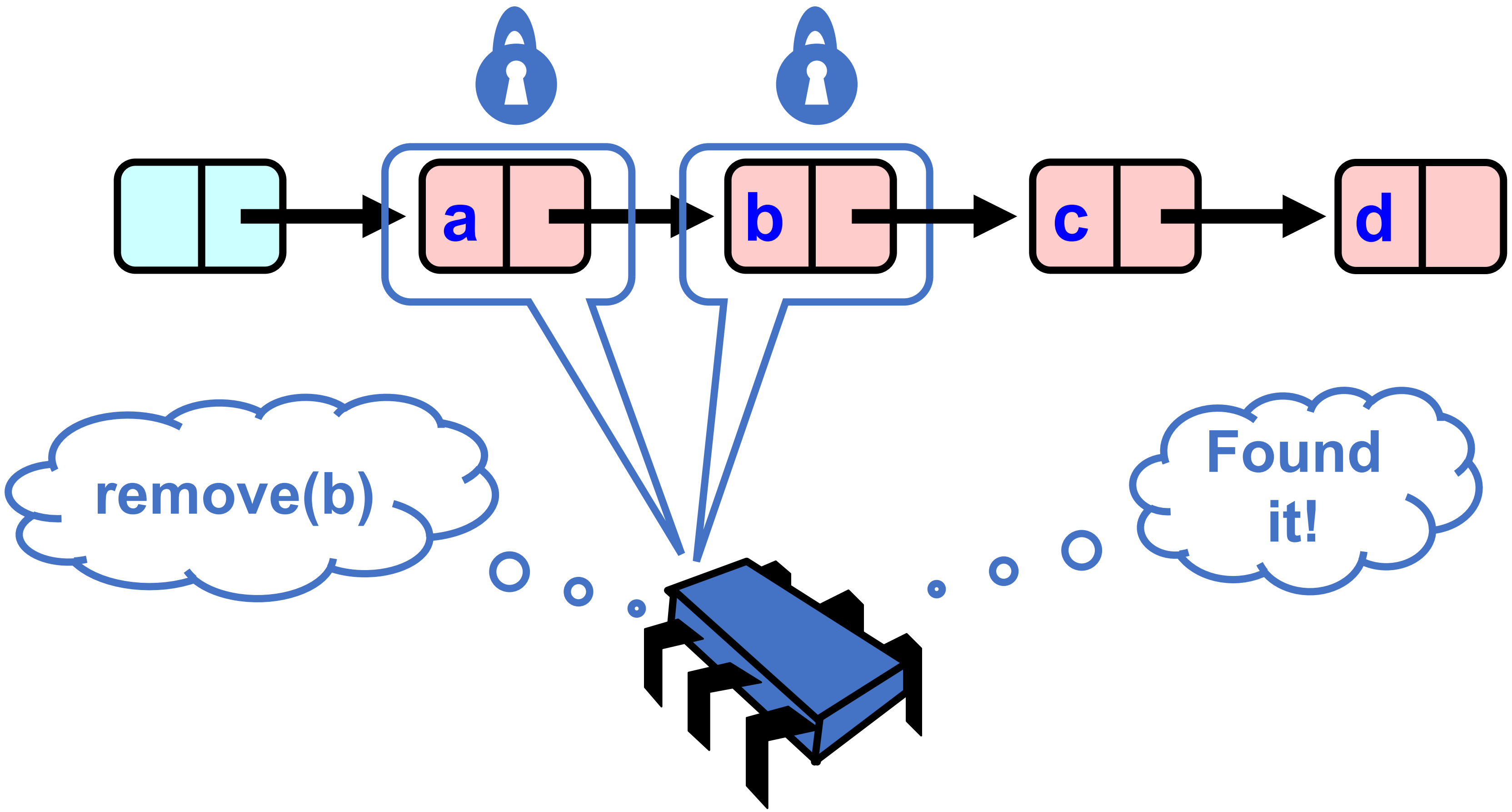

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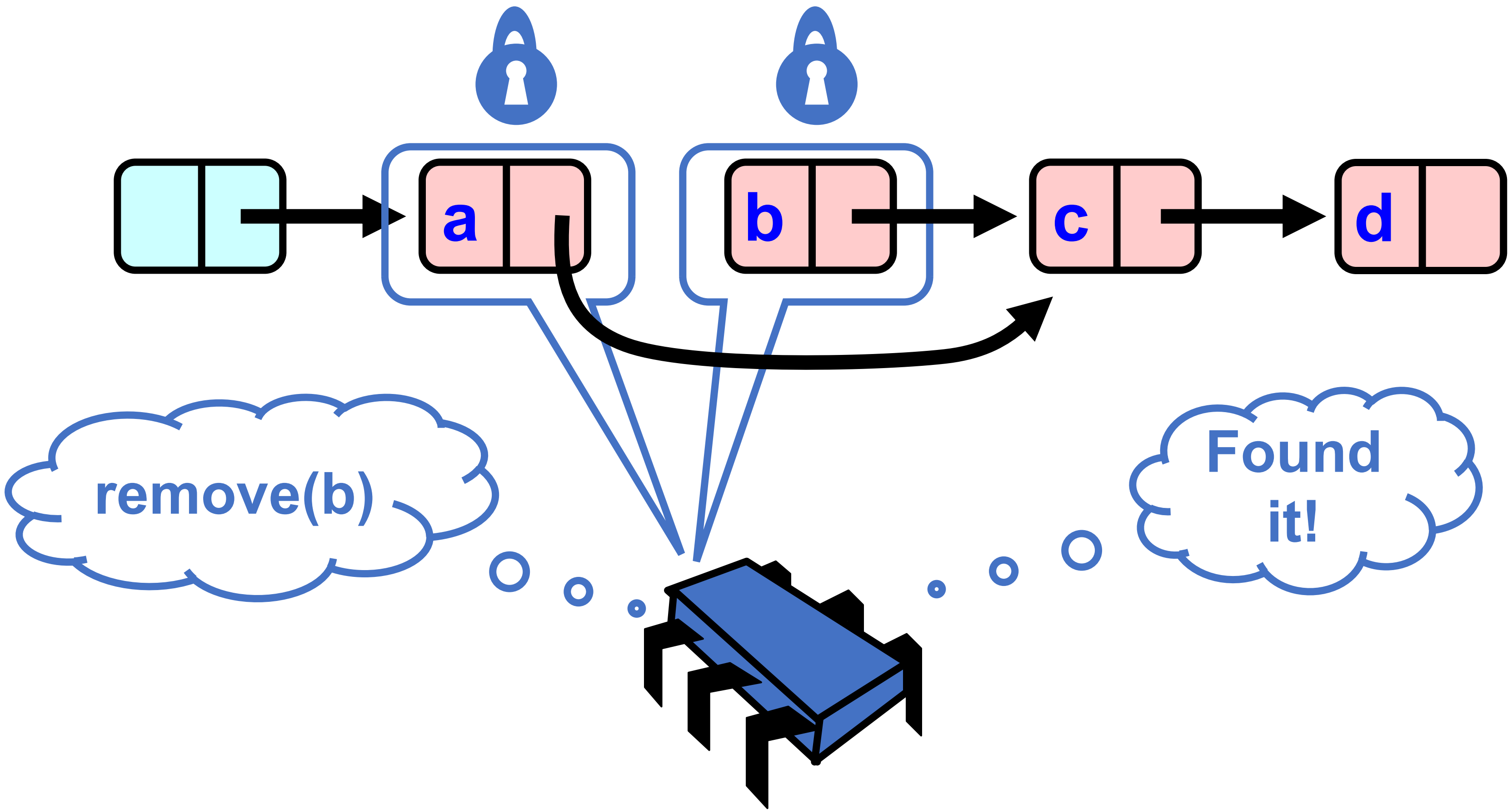

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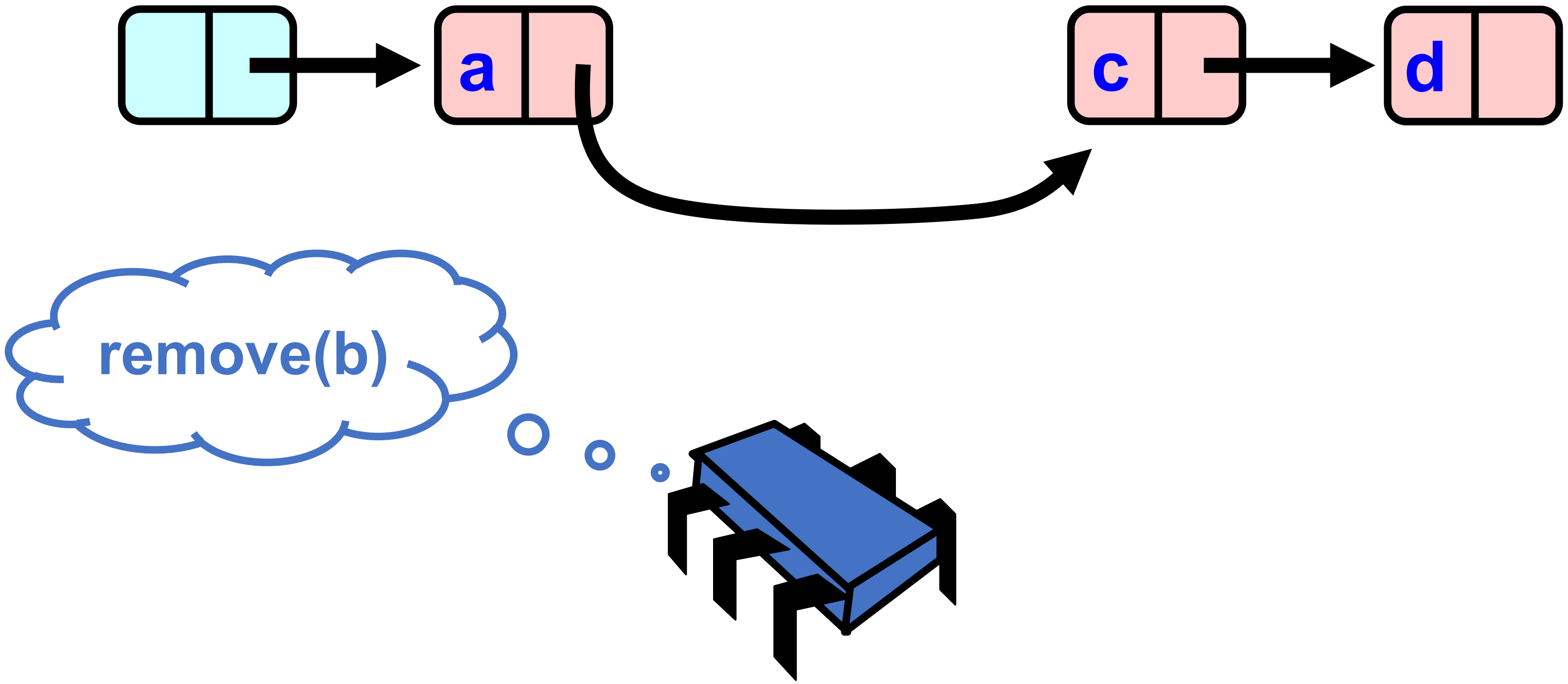
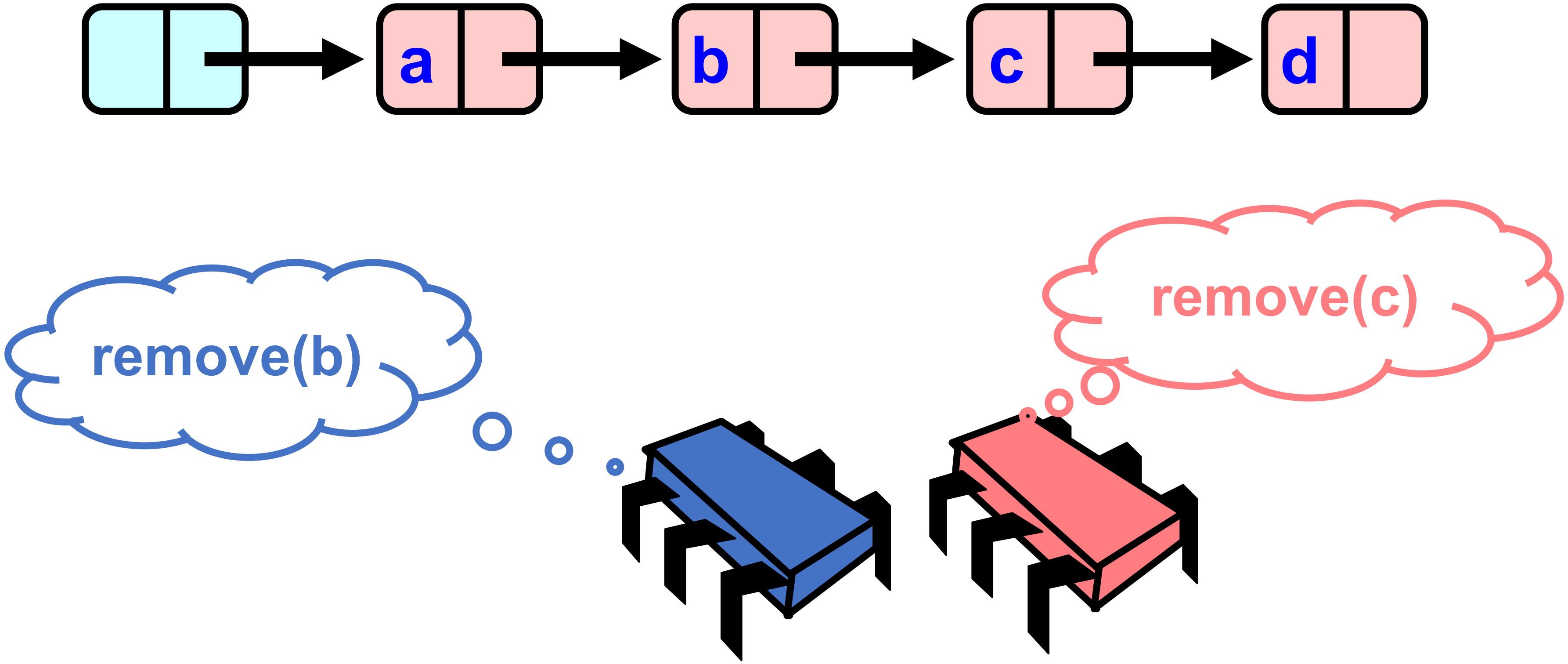


Removing a Node



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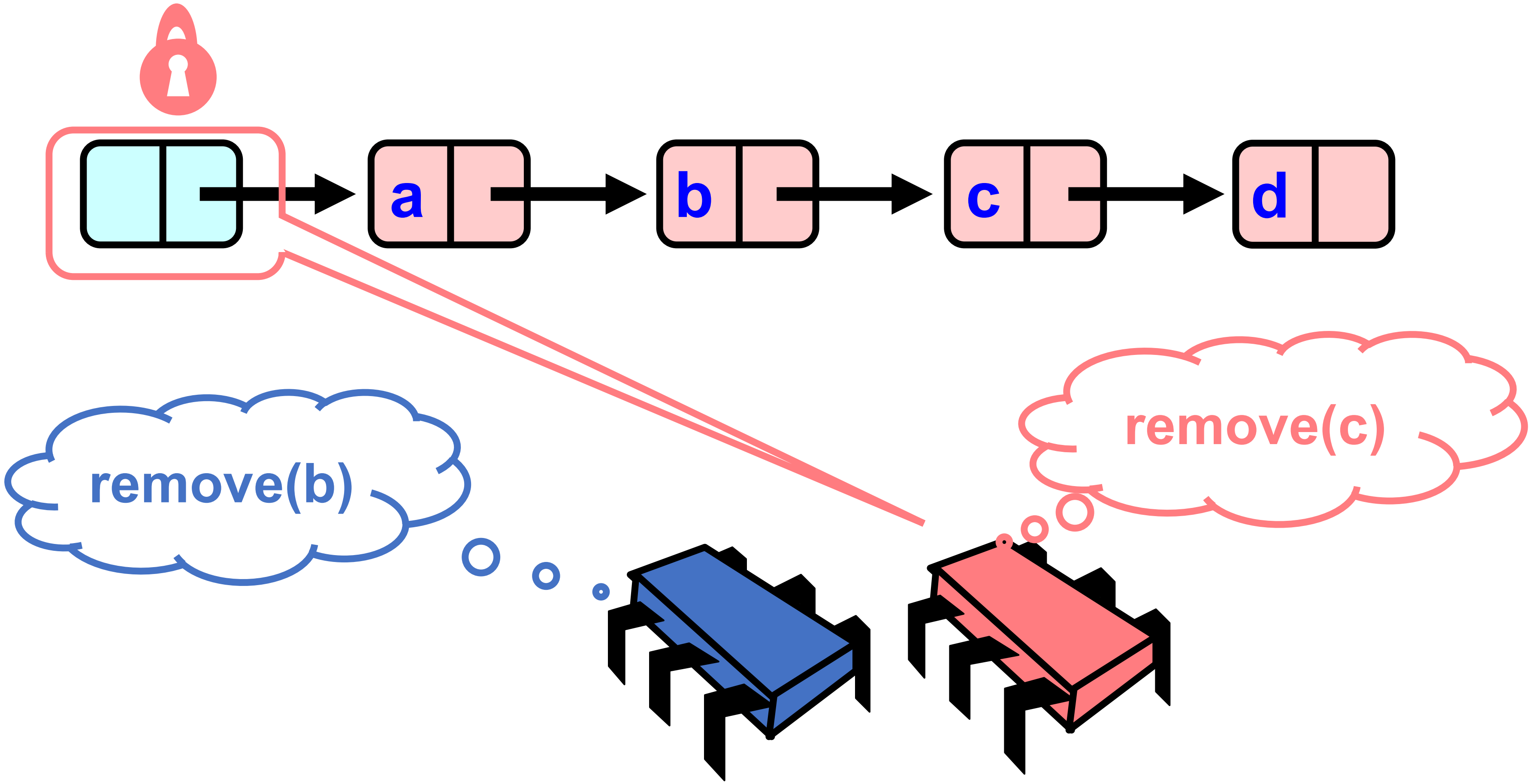

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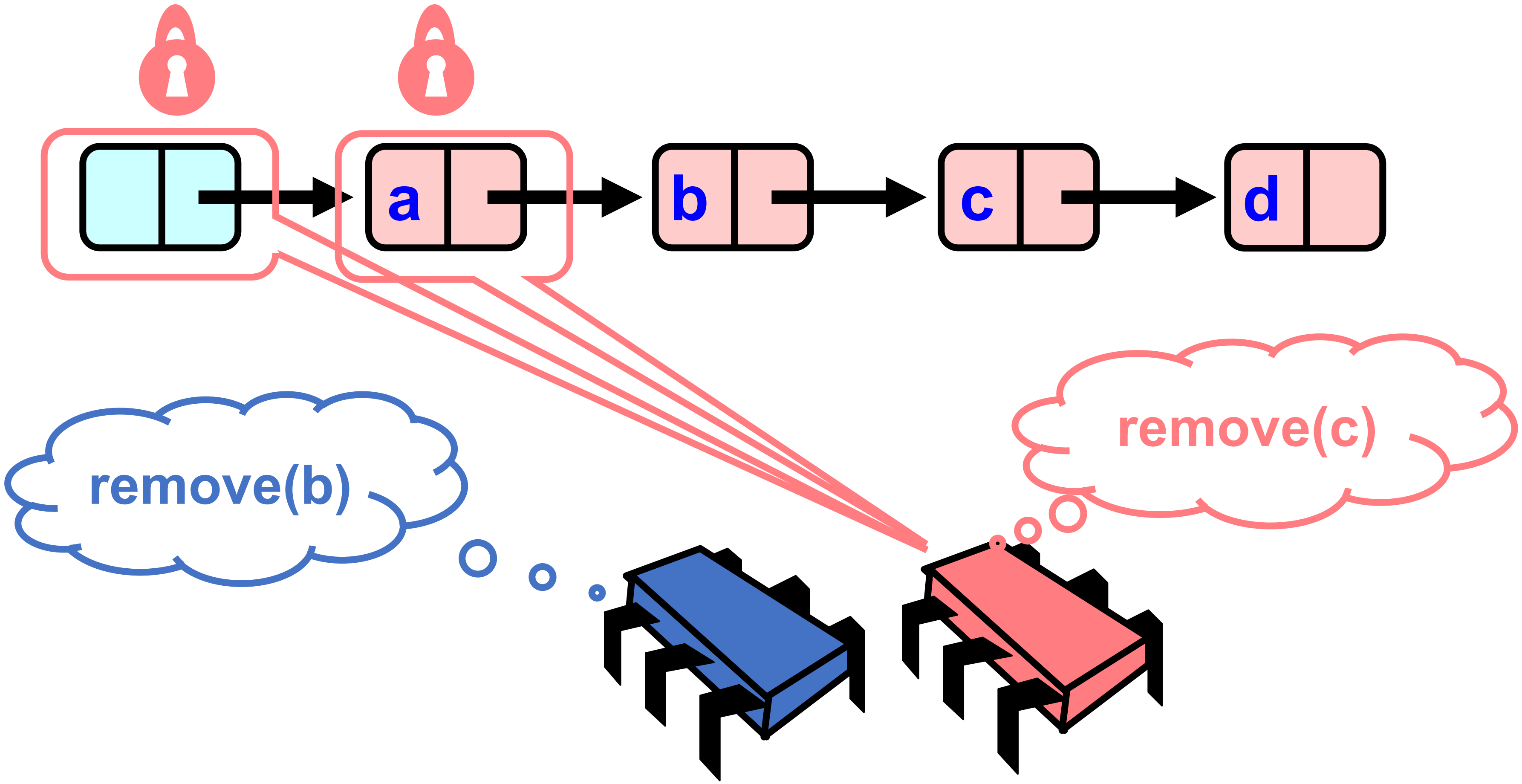

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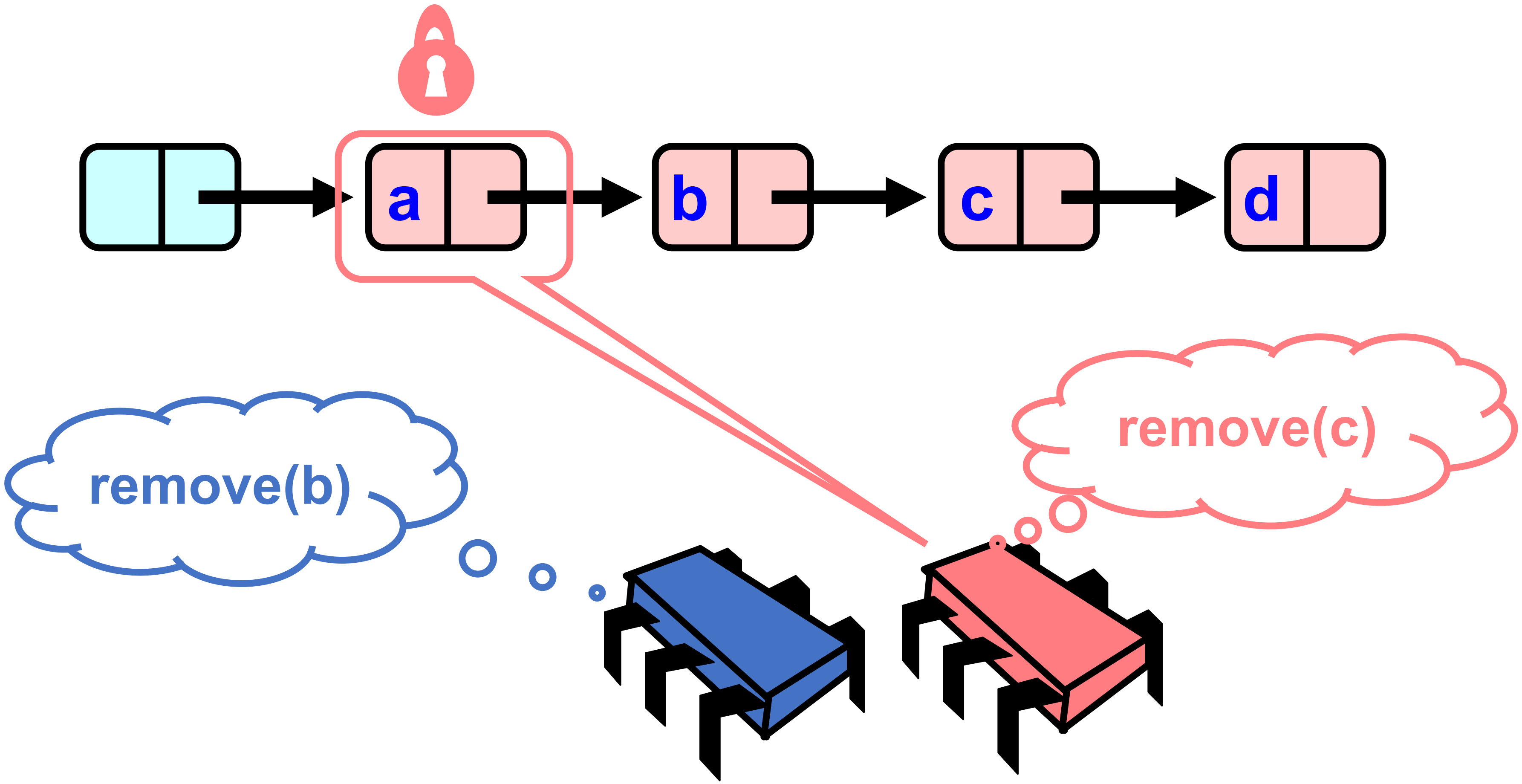

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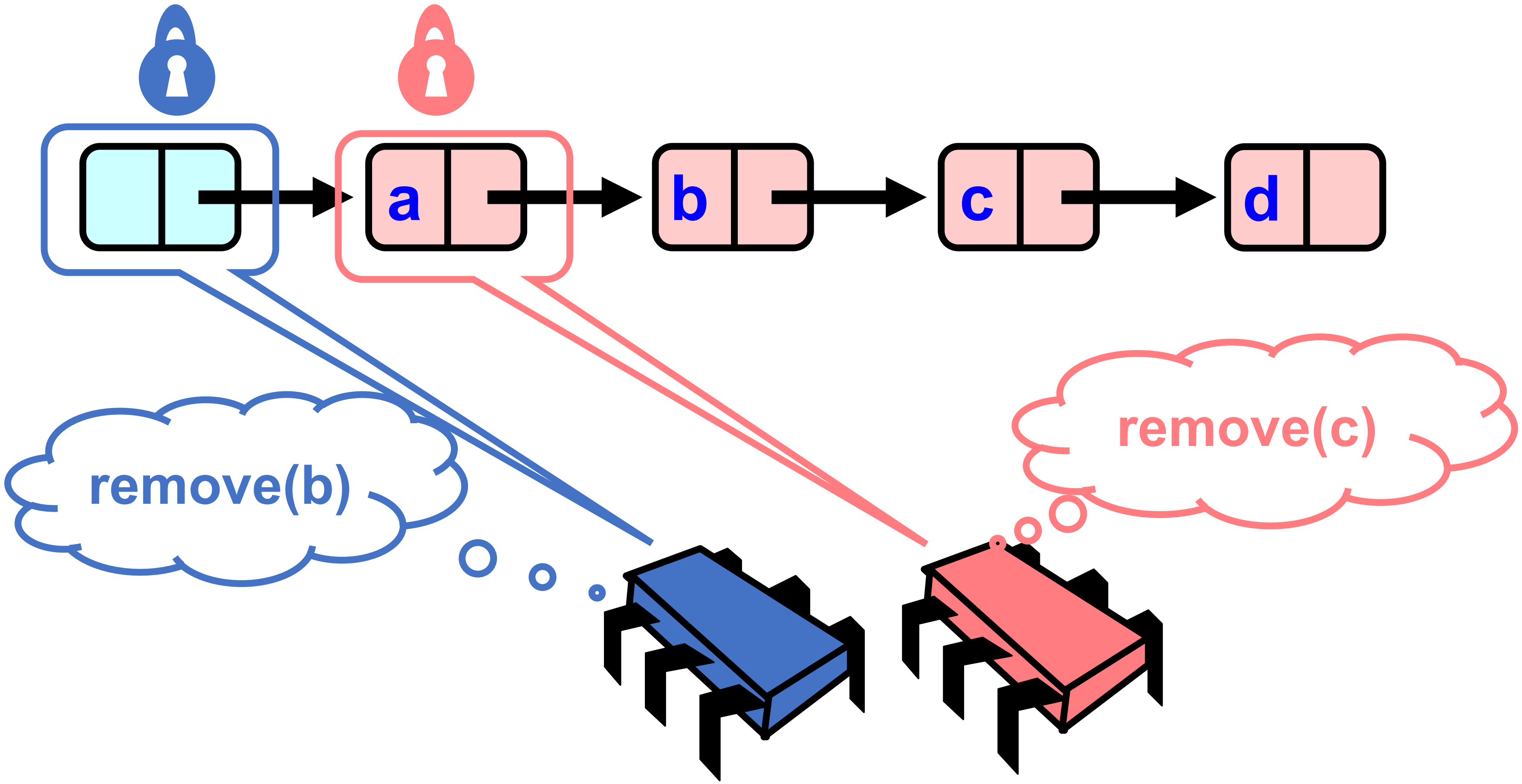

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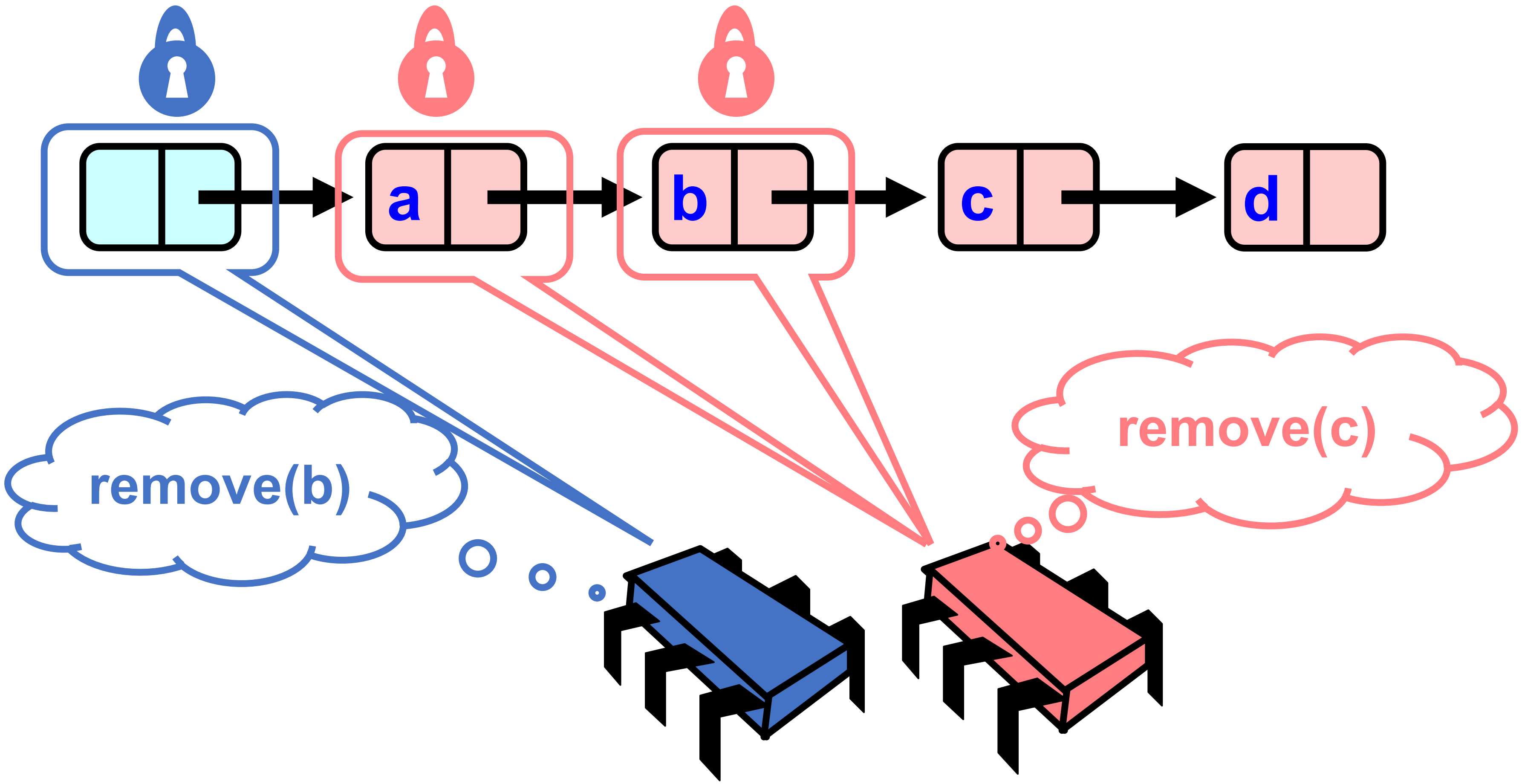

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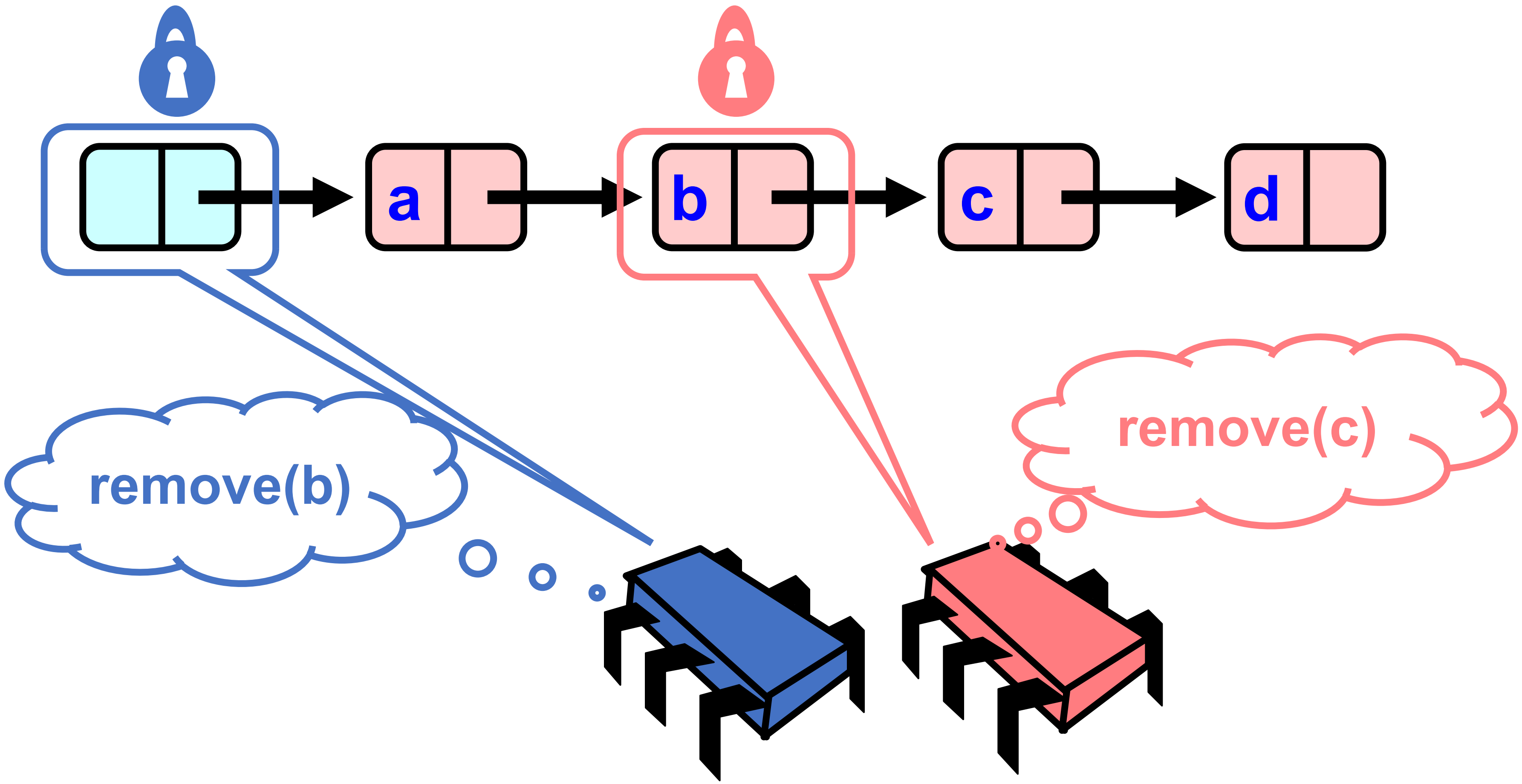

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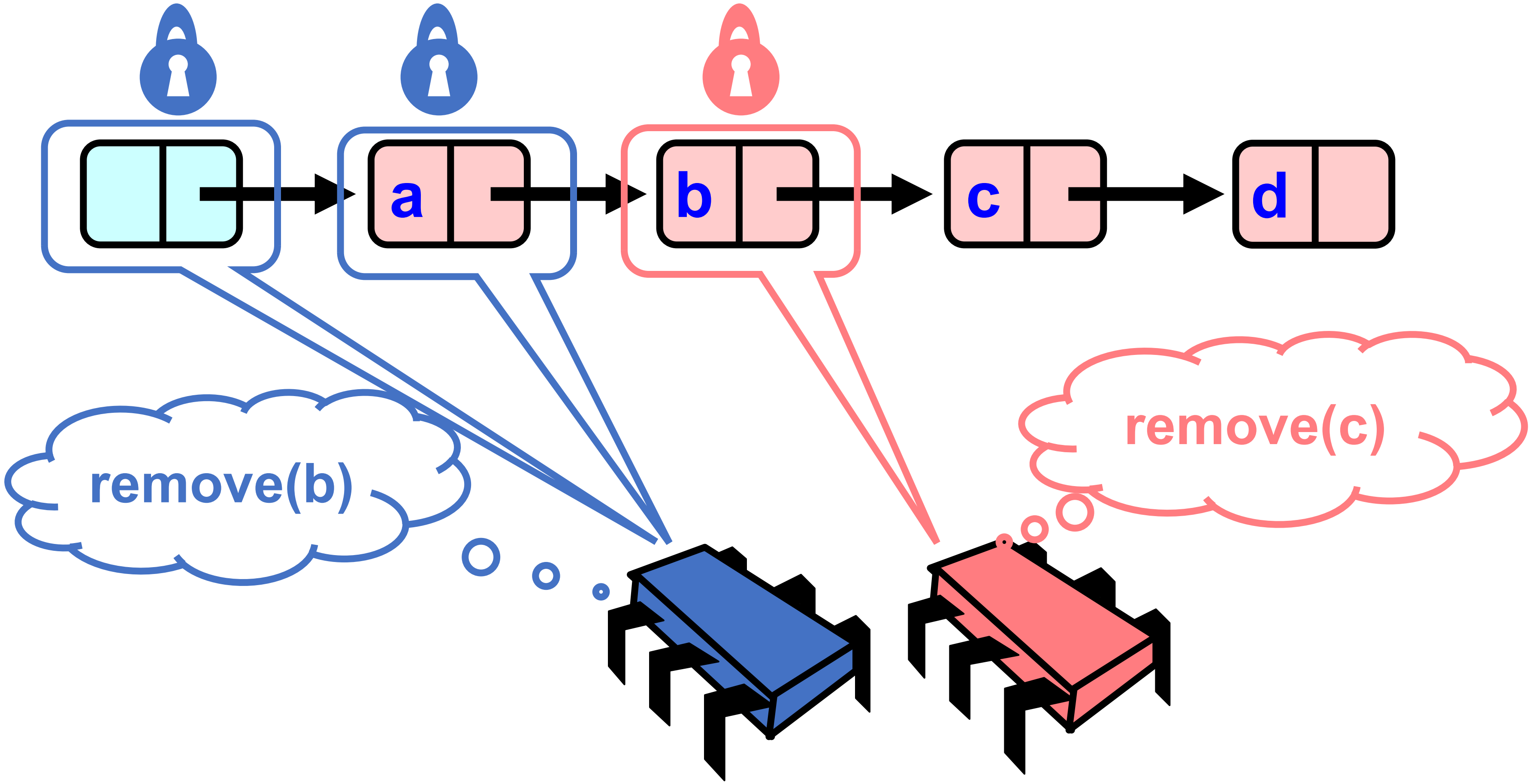

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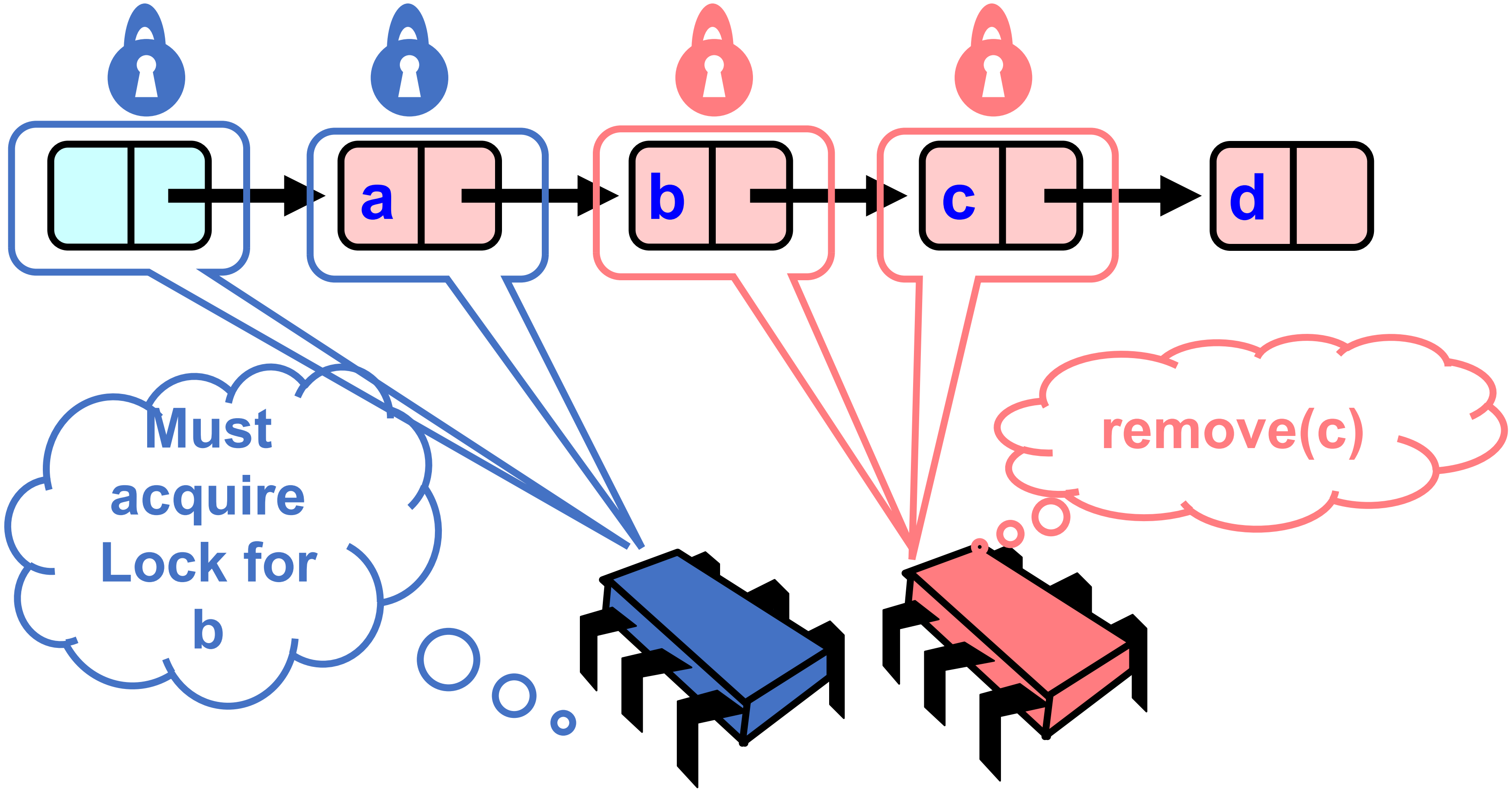

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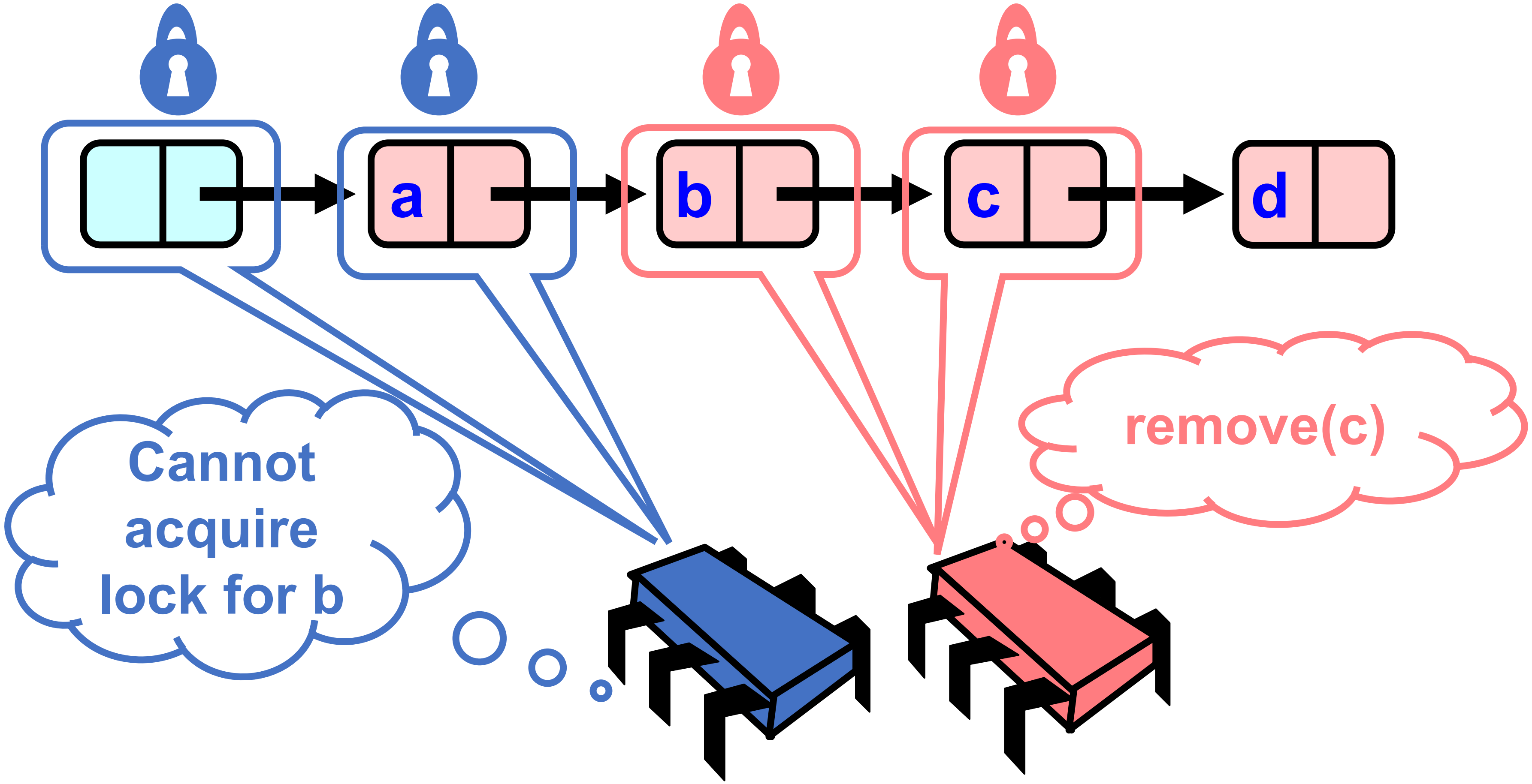

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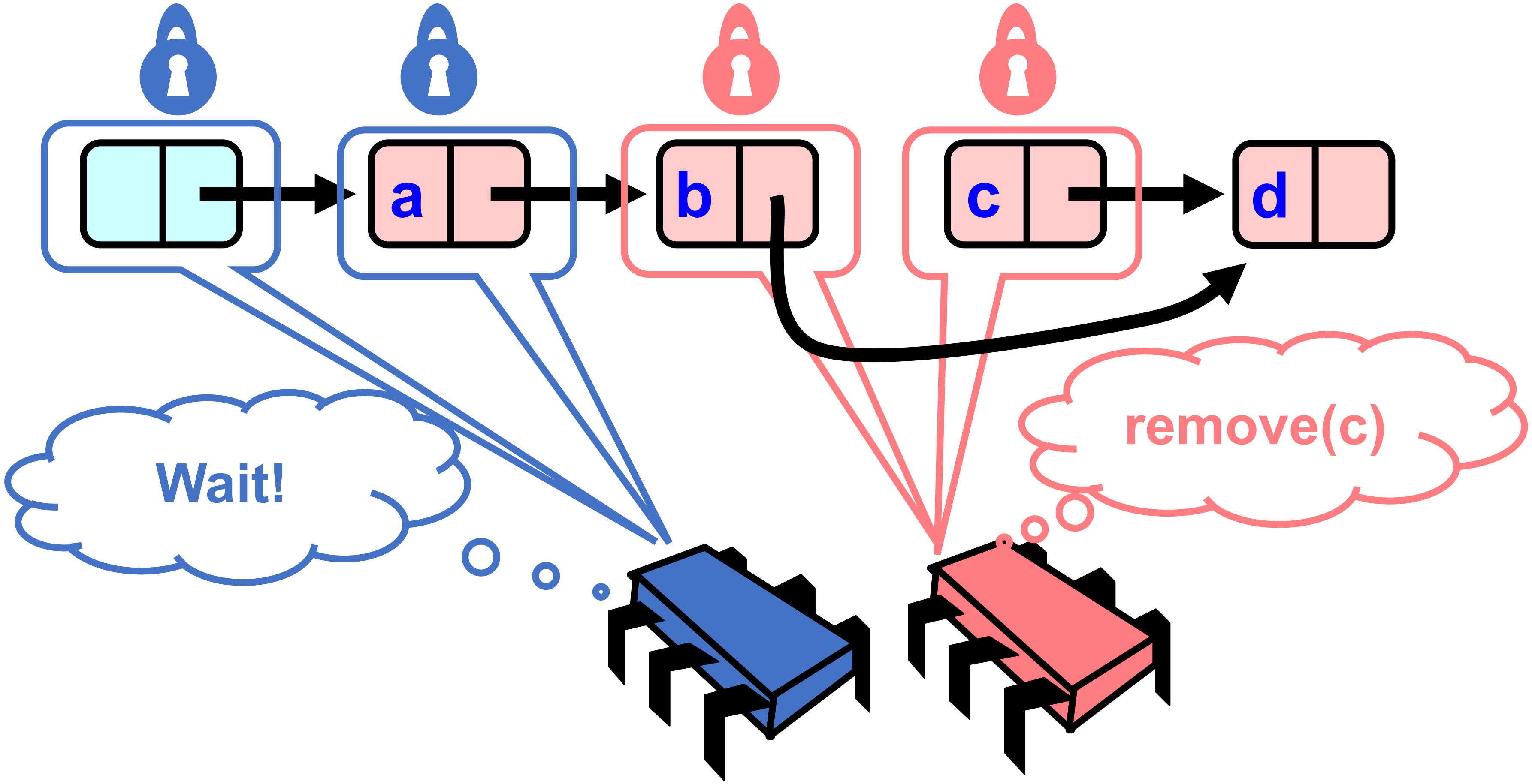

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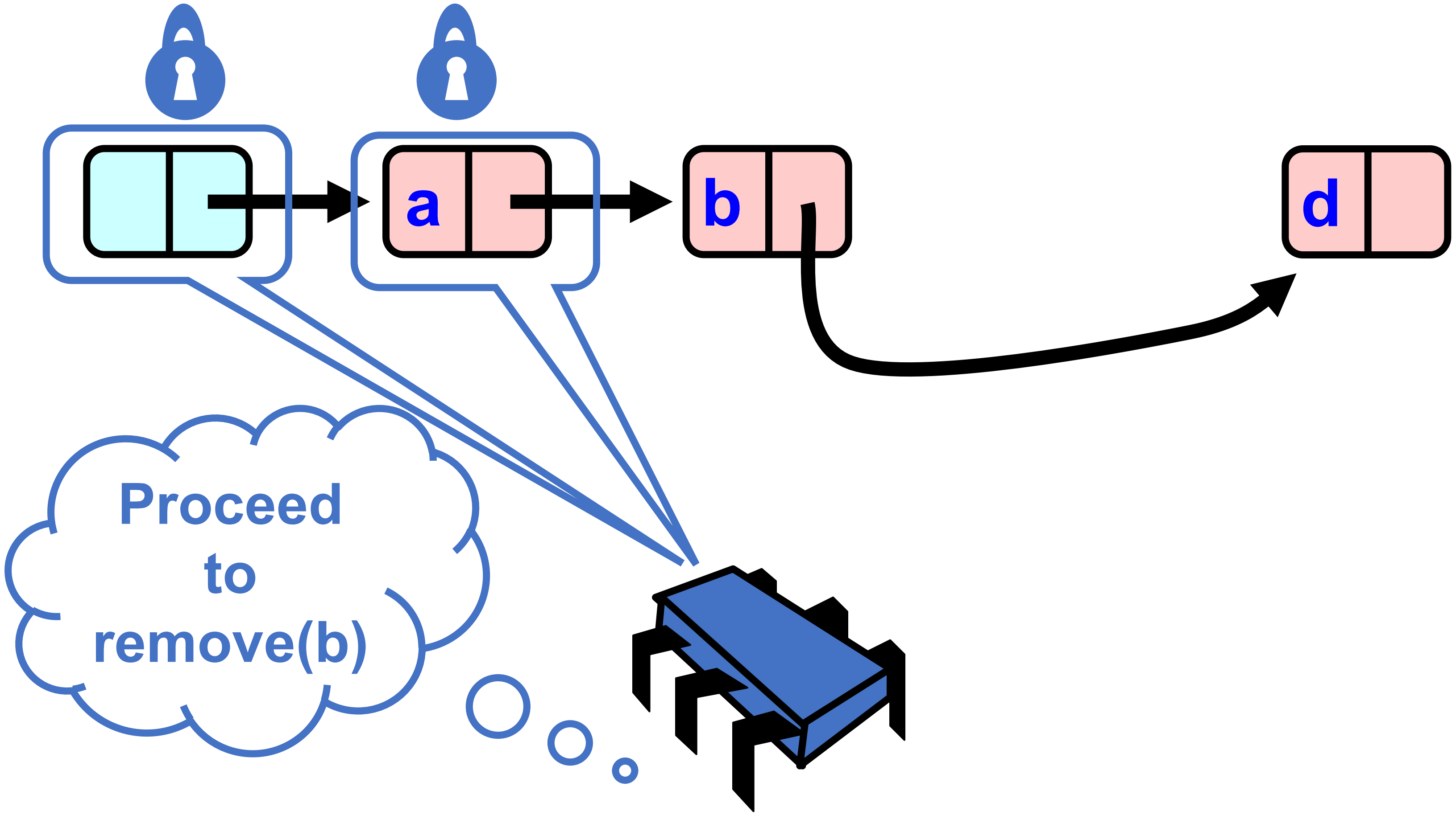

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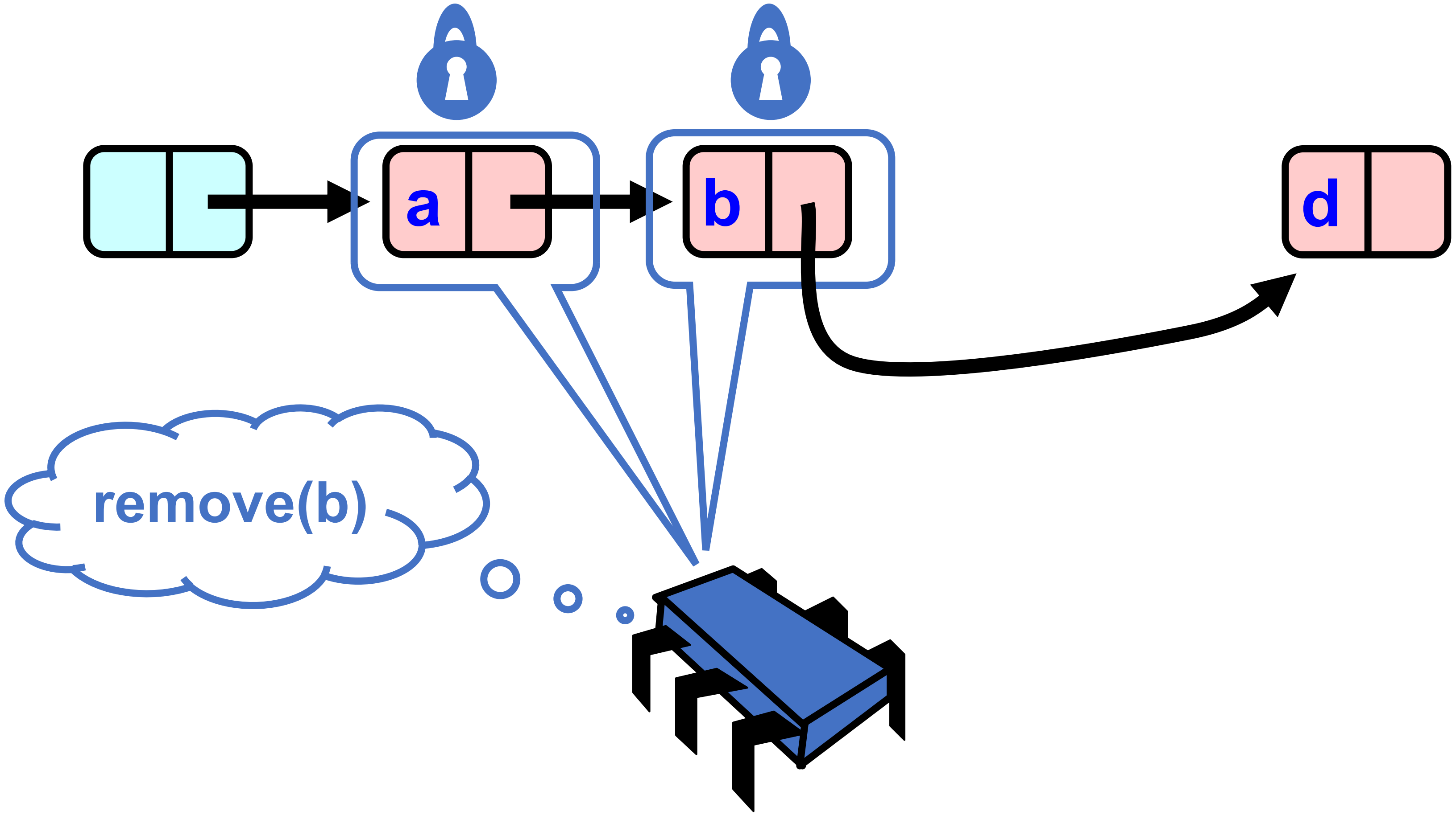

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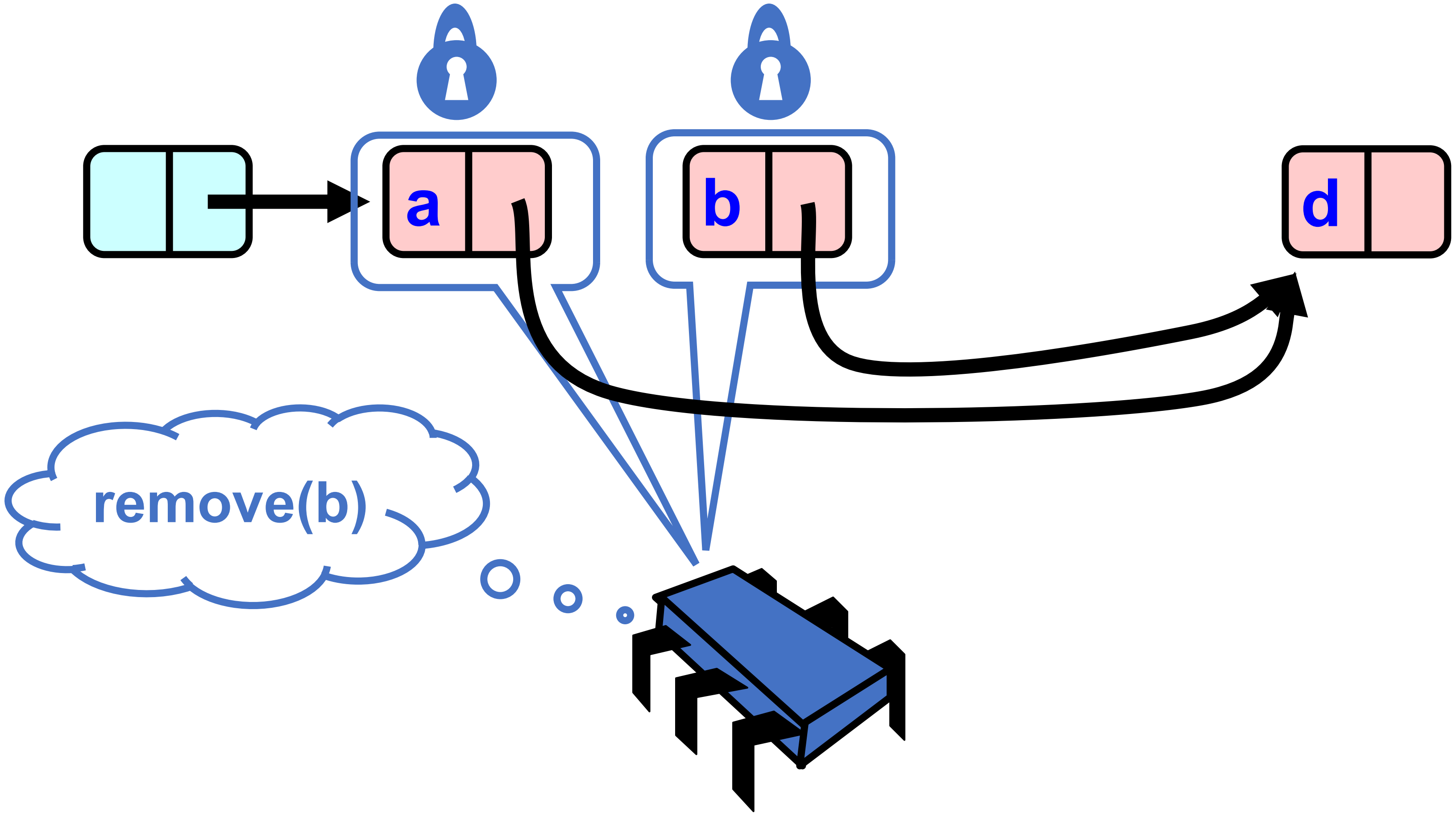

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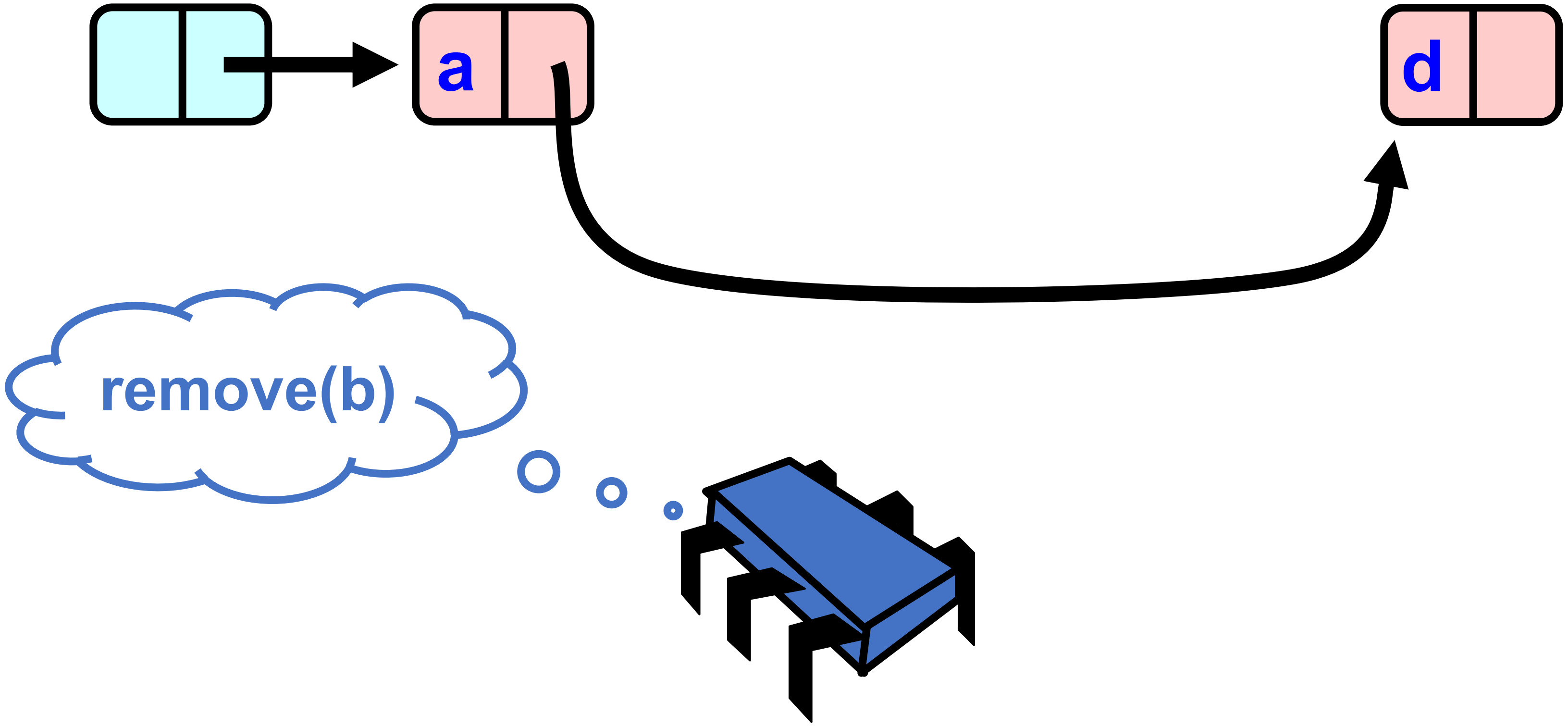

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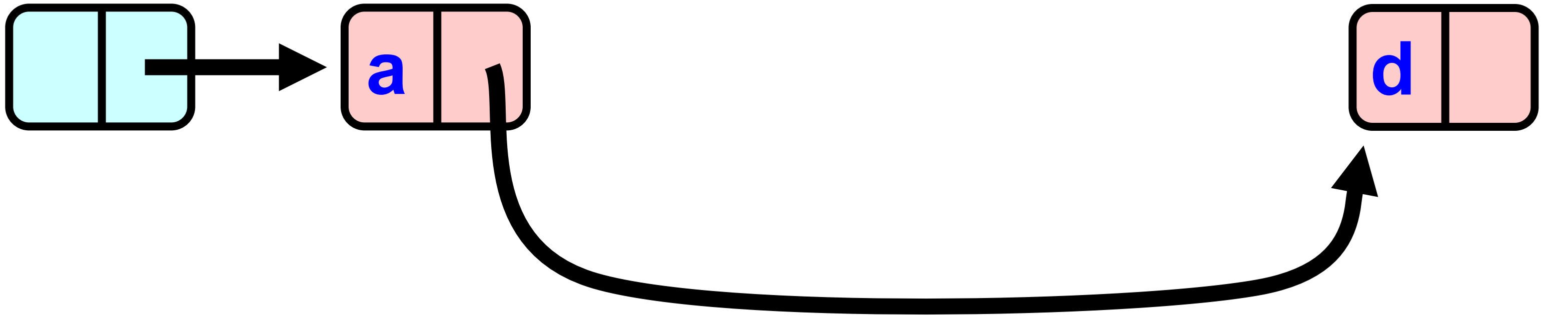

Adding Nodes

- To add node e
  - Must lock predecessor
  - Must lock successor
- Neither can be deleted

Drawbacks

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

```
void remove(Value v) {
  Node* pred = NULL, *curr = NULL;
  head.lock();
  pred = head;
  curr = pred.next();
  curr.lock();
  while (curr.value != v) {
    pred.ulock();
    pred = curr;
    curr = curr.next();
    curr.lock();
  }
  pred.next = curr.next;
  curr.unlock();
  pred.unlock();
}
```

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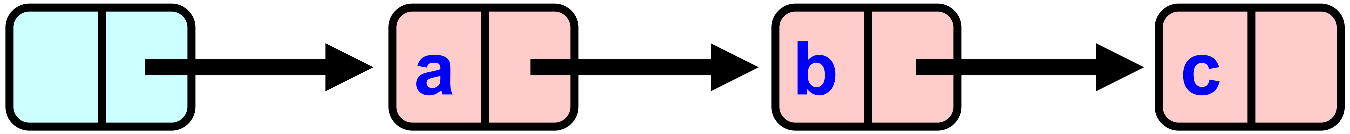

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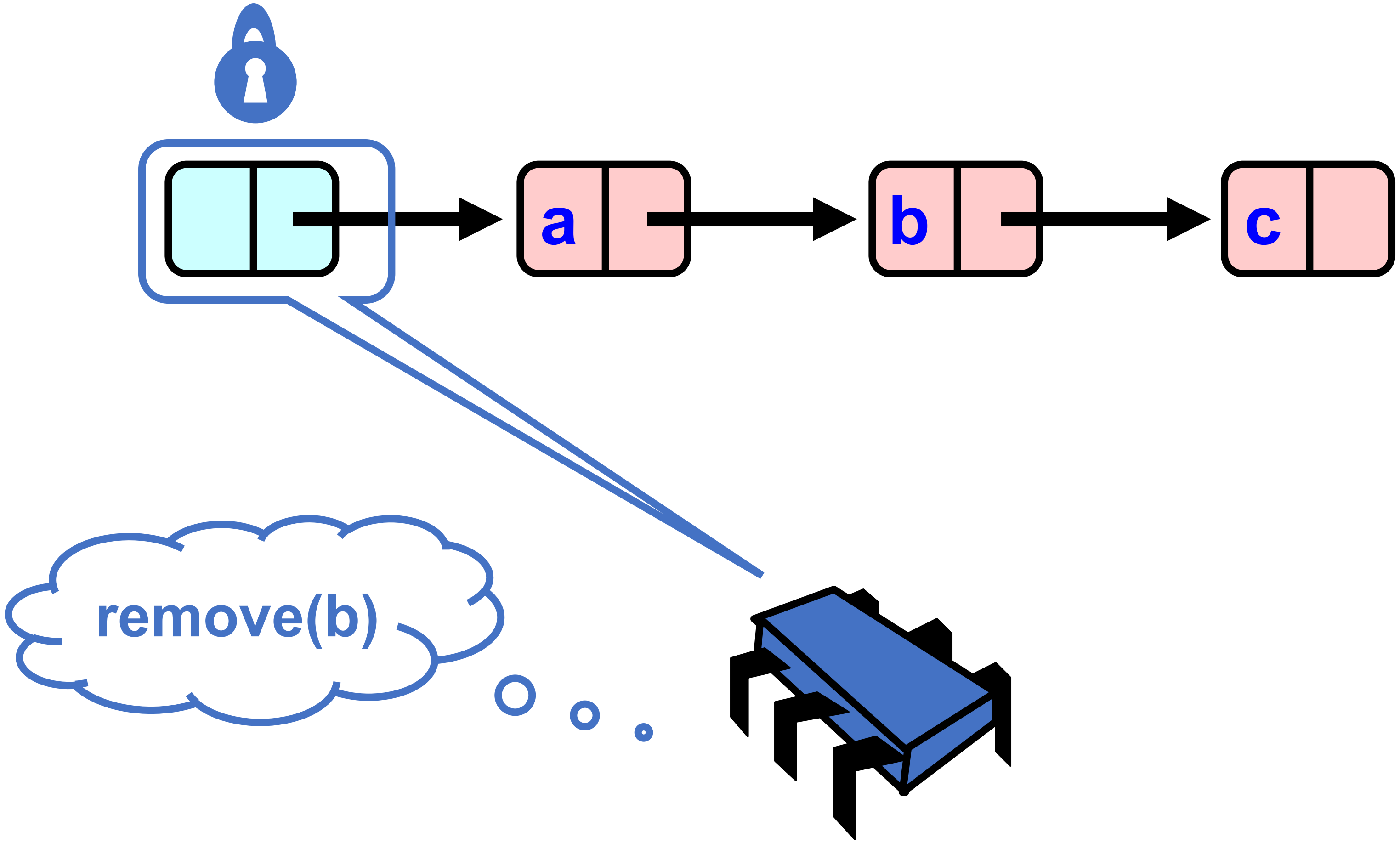

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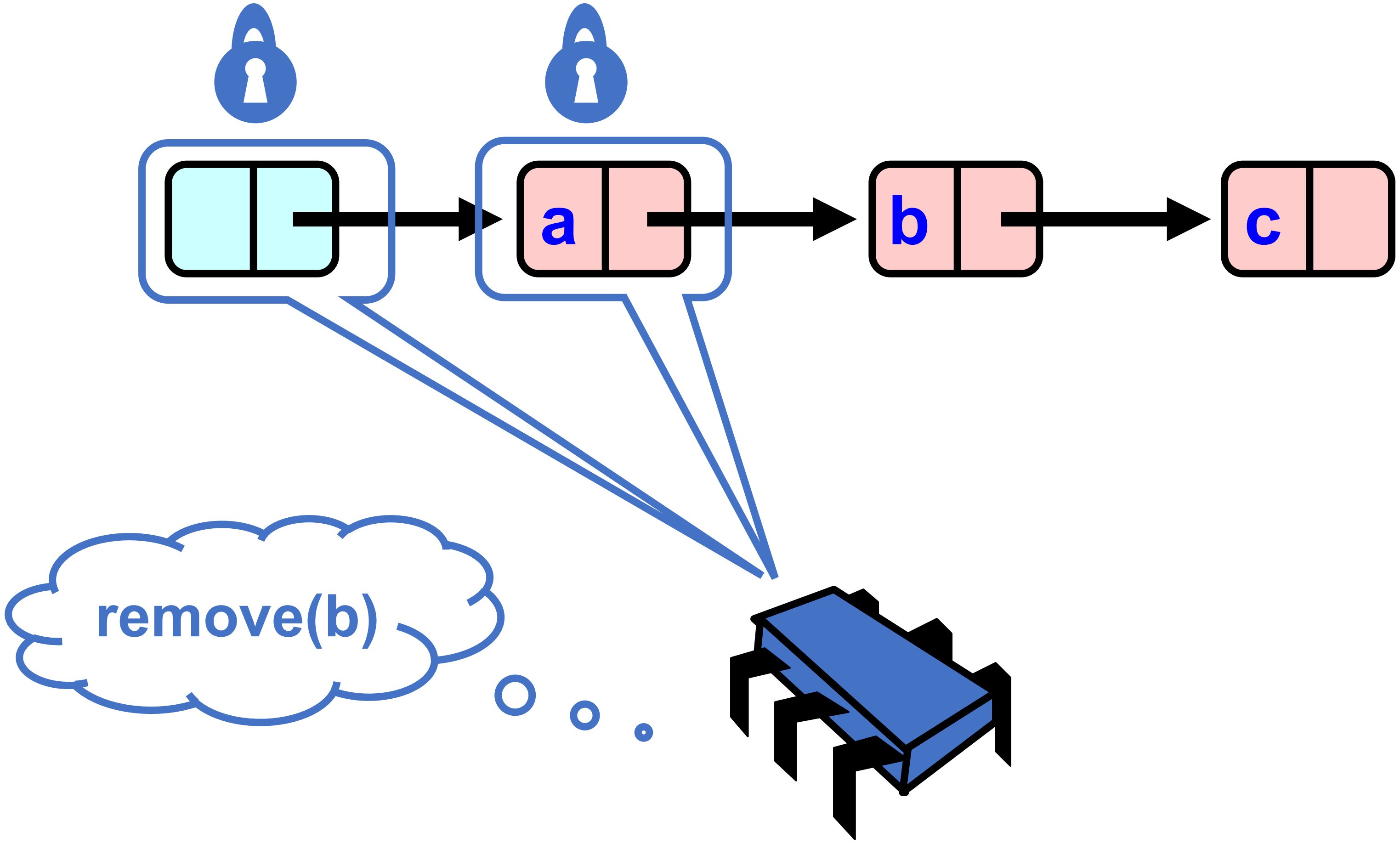
}
```



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void remove(Value v) {
  Node* pred = NULL, *curr = NULL;
  head.lock();
  pred = head;
  curr = pred.next();
  curr.lock();
  while (curr.value != v) {
    pred.ulock();
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    curr = curr.next();
    curr.lock();
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  pred.next = curr.next;
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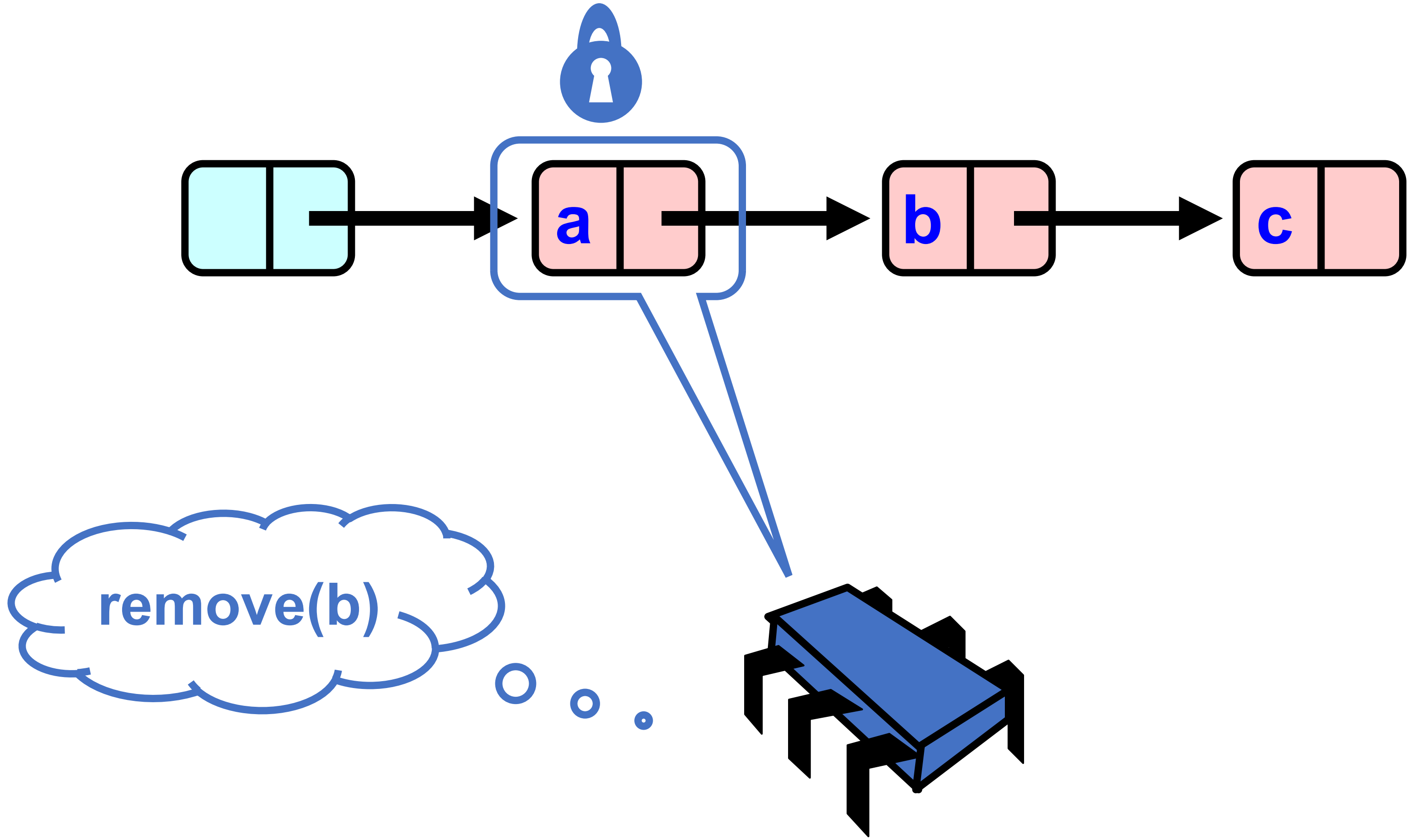

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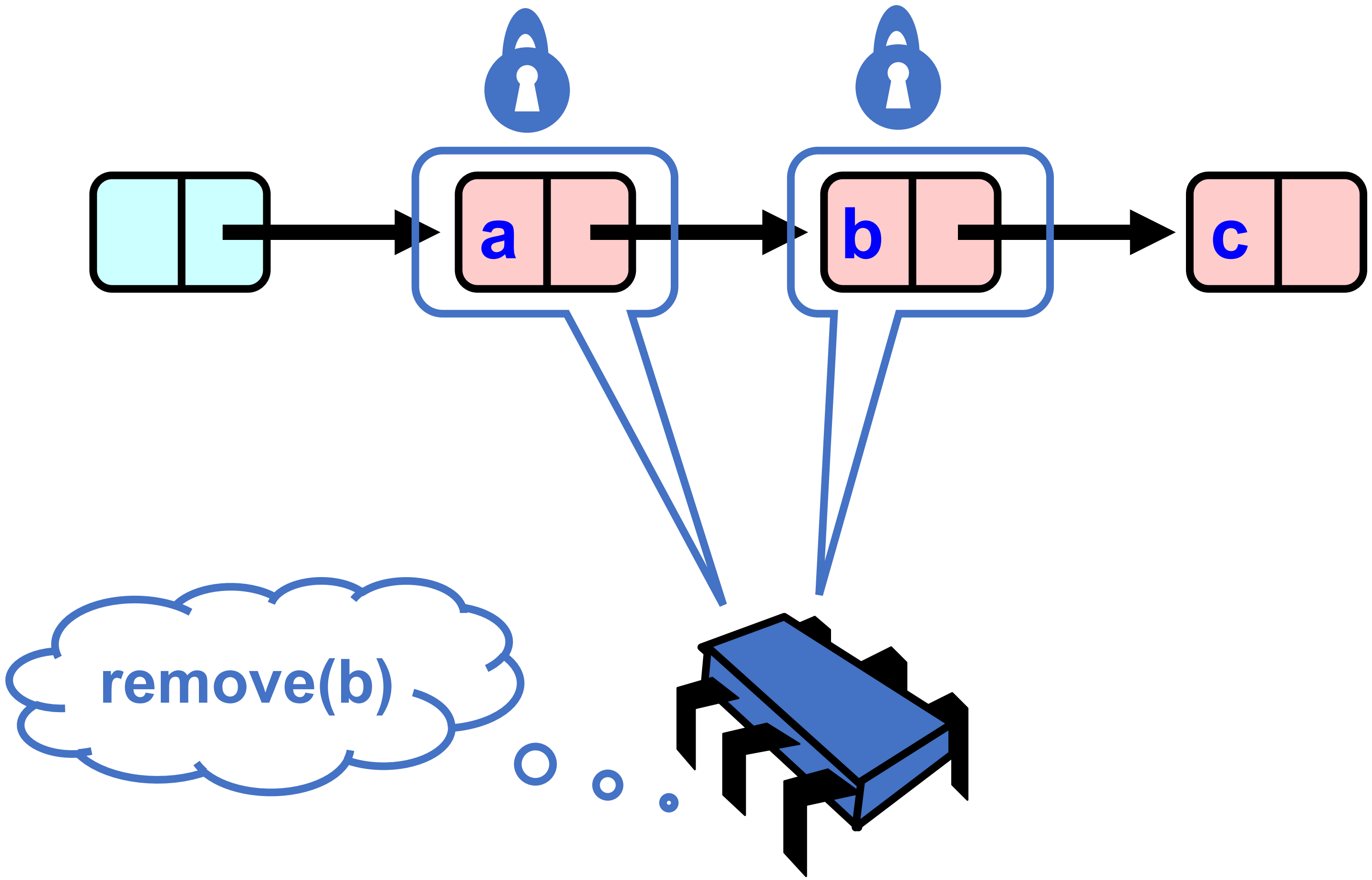

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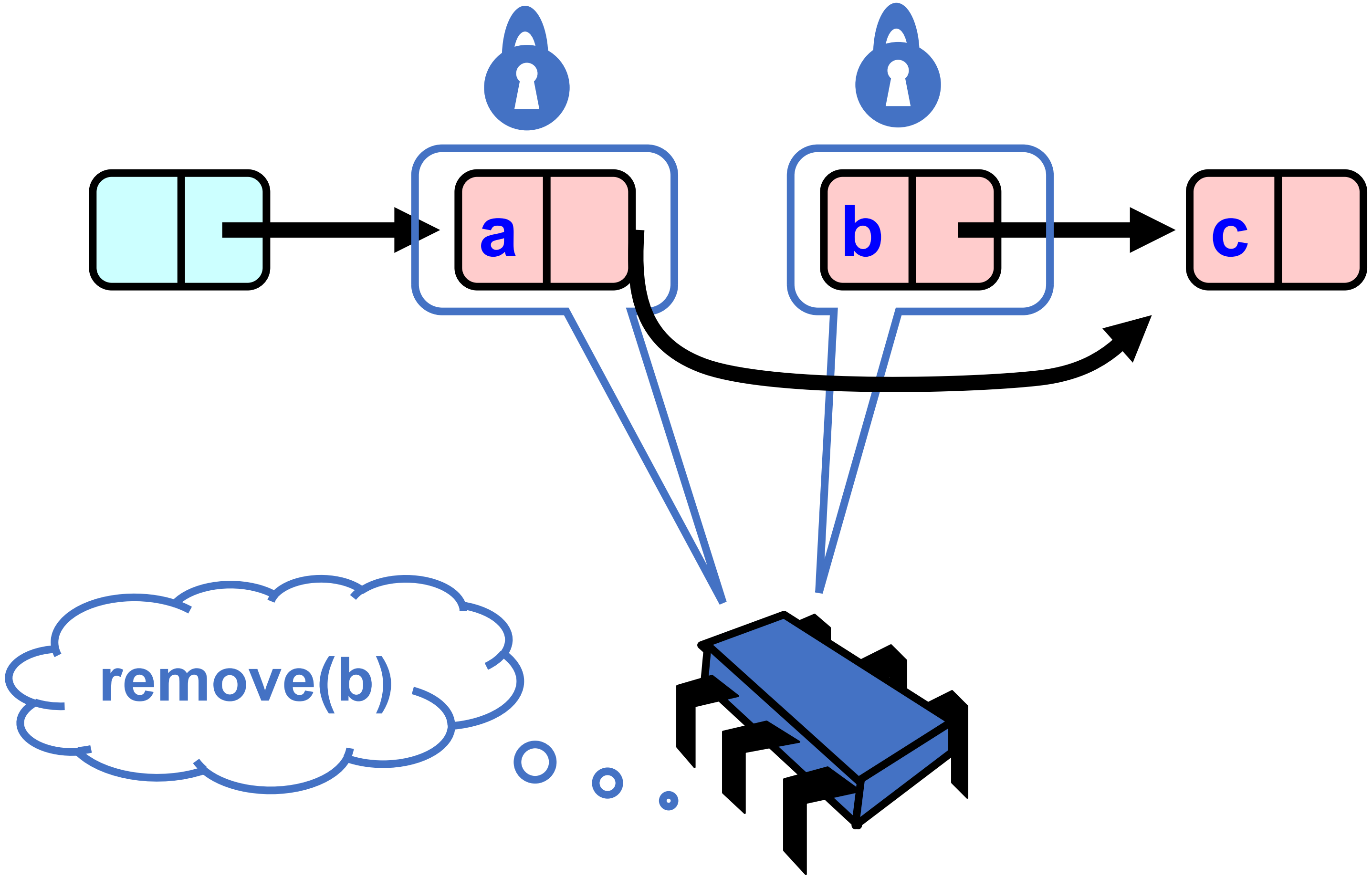

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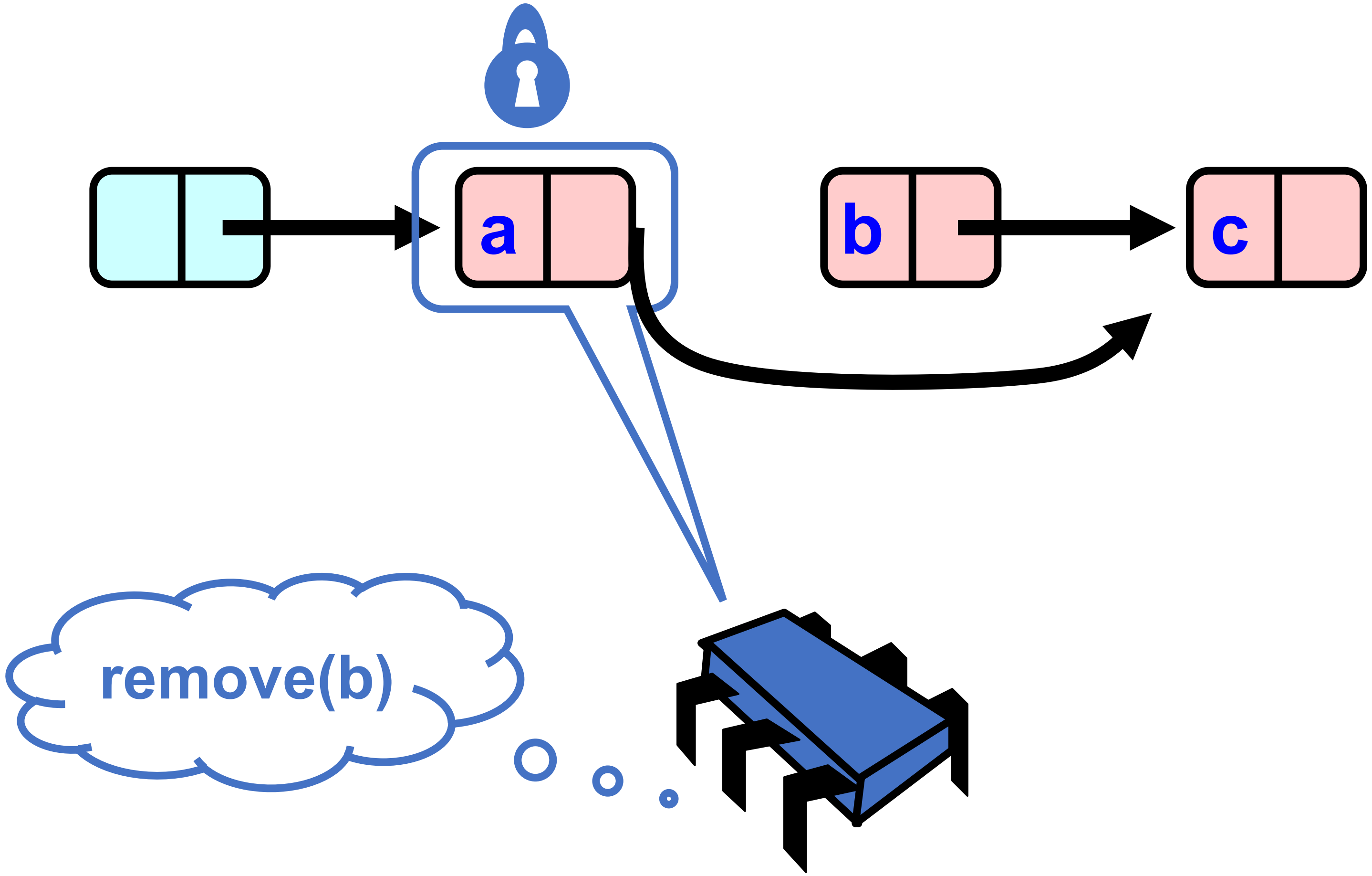

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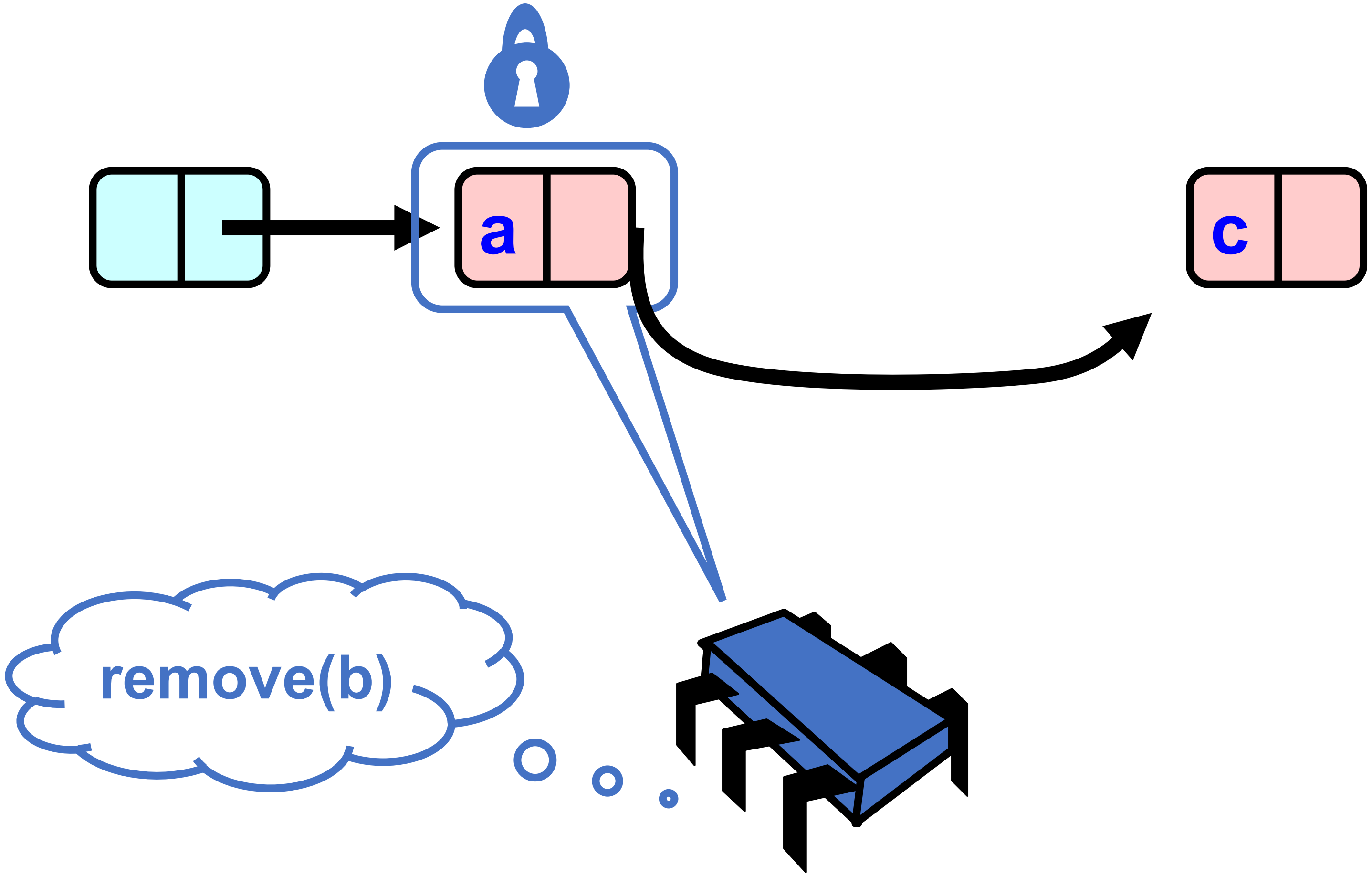

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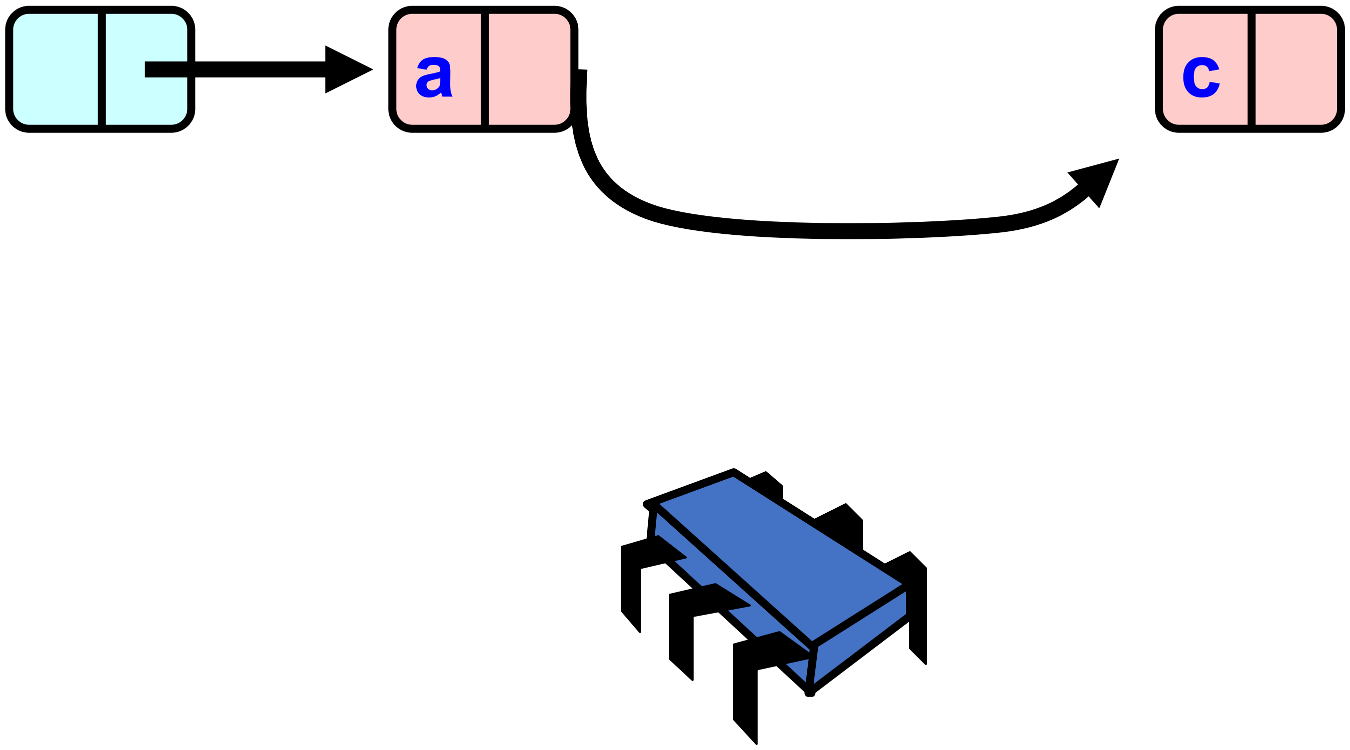


Schedule

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

How can we improve

- Acquires and releases lock for every node traversed
  - If we have a long list to search, it can be bad!
  - reduces concurrency (traffic jams)

Optimistic Synchronization

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

Optimistic Synchronization

- Find nodes without locking

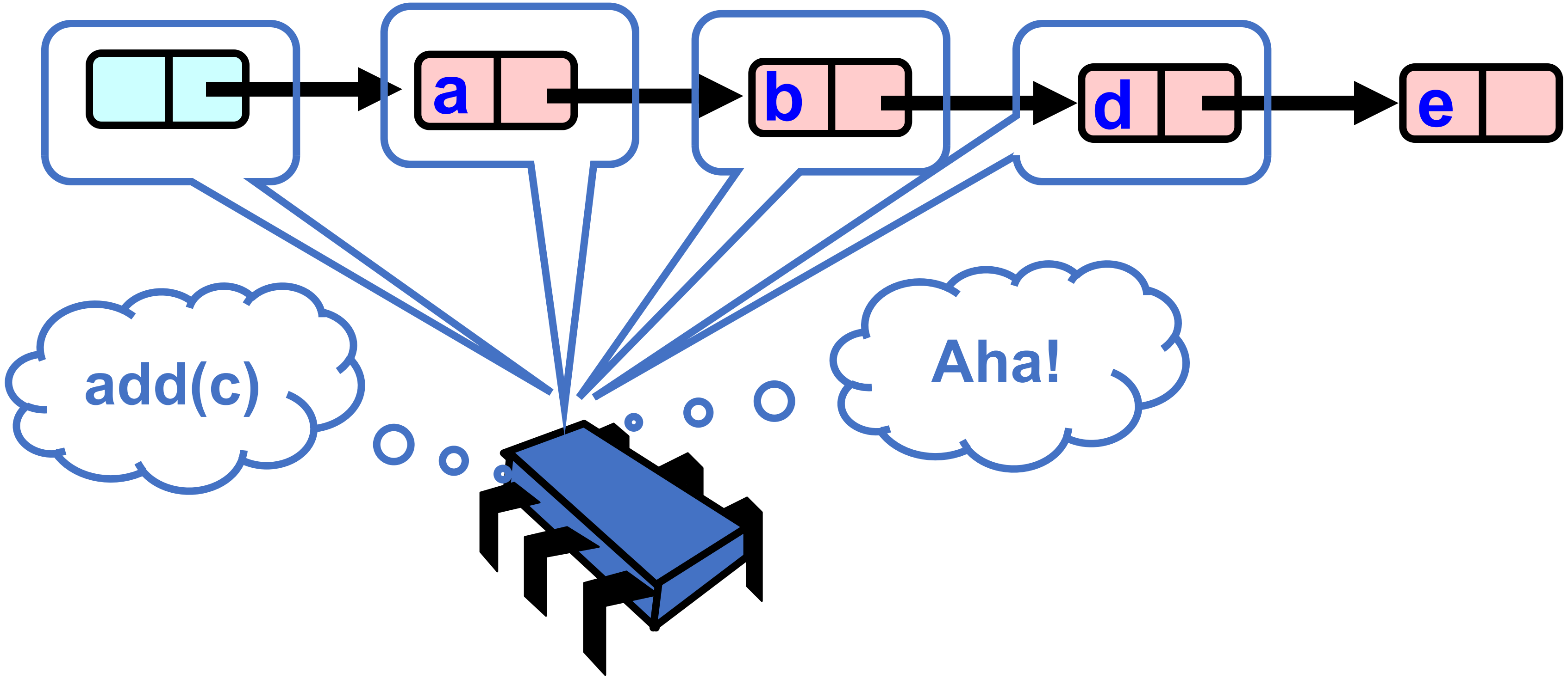
Optimistic Synchronization

- Find nodes without locking
- Lock nodes

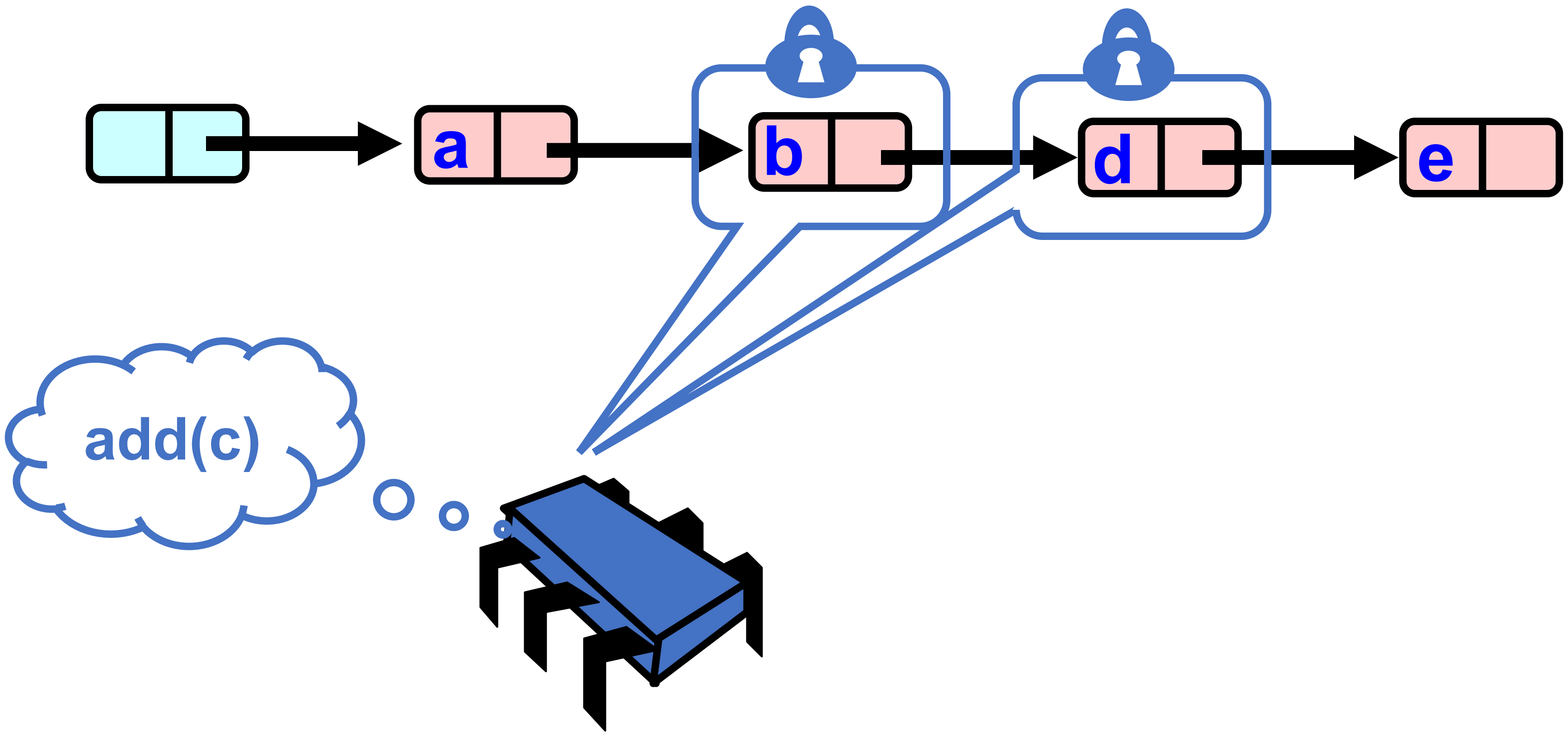
Optimistic Synchronization

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

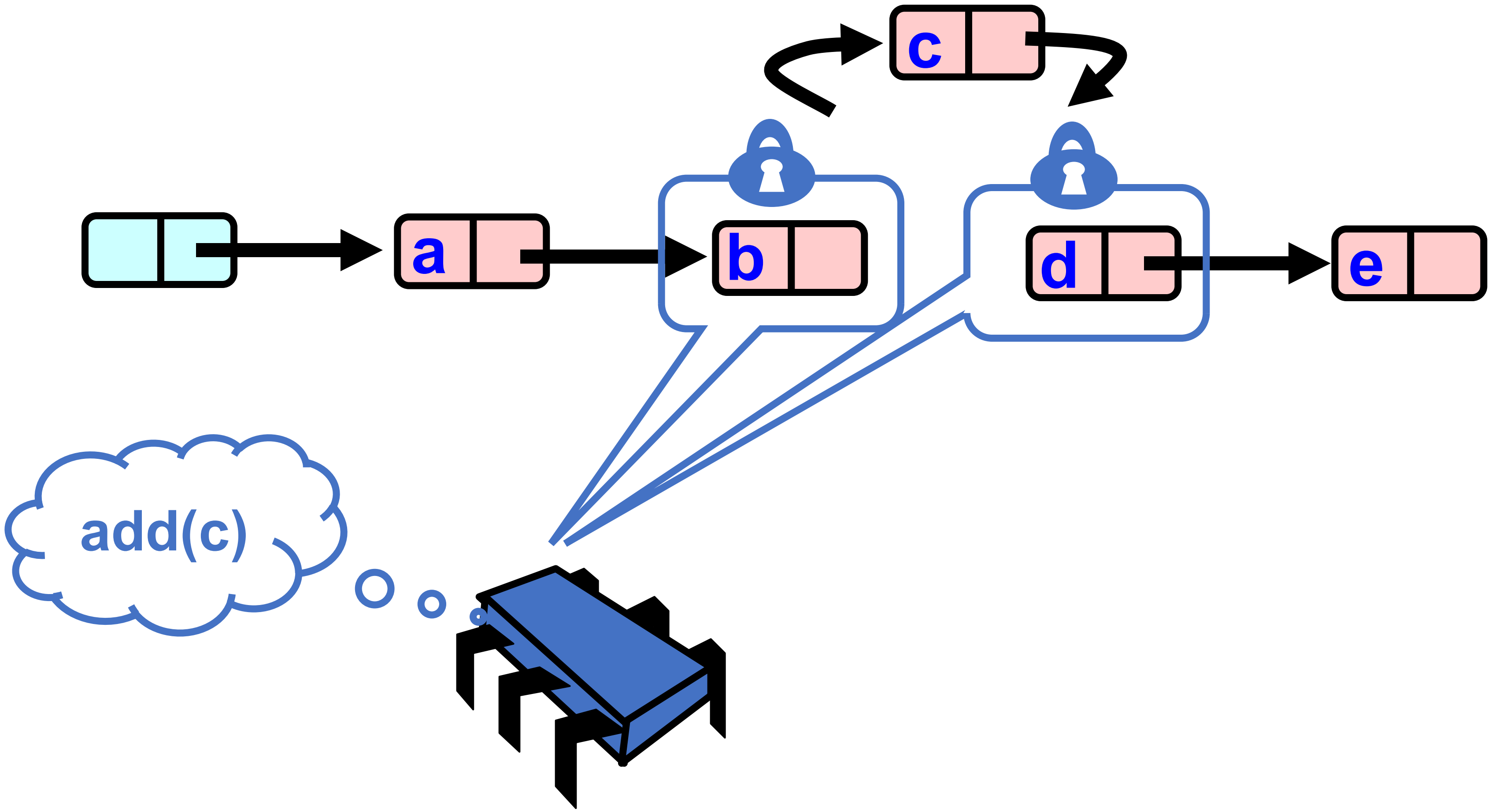
Optimistic: Traverse without Locking



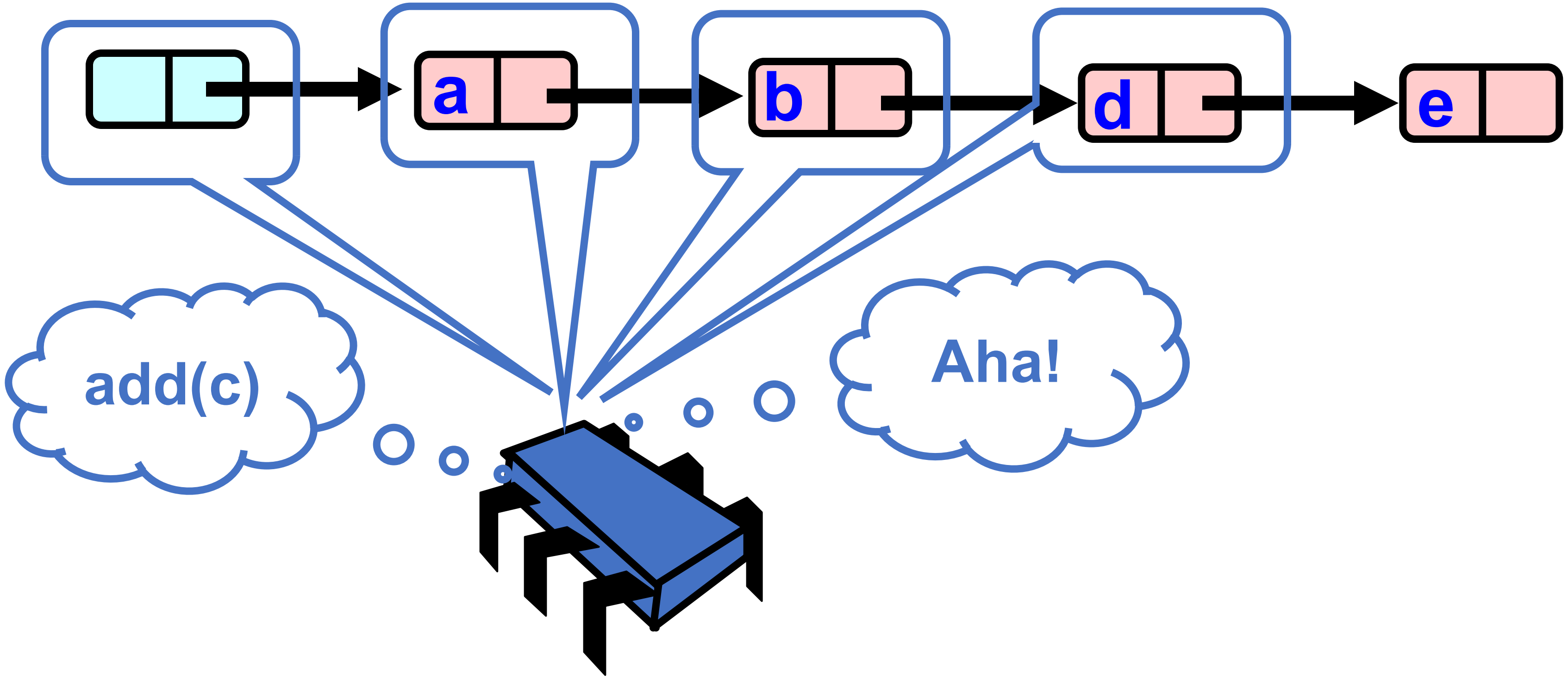
Optimistic: Lock and Load



Optimistic: Lock and Load



What could go wrong?



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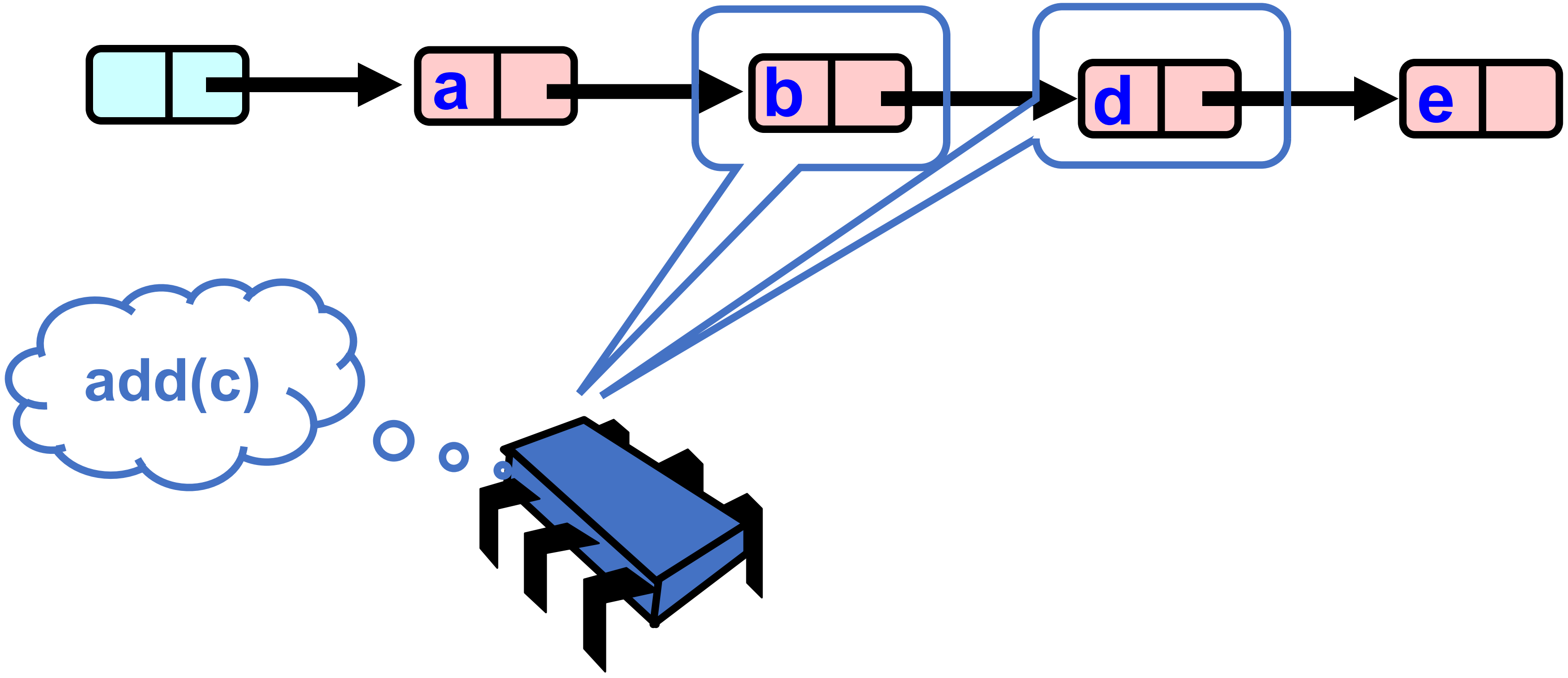

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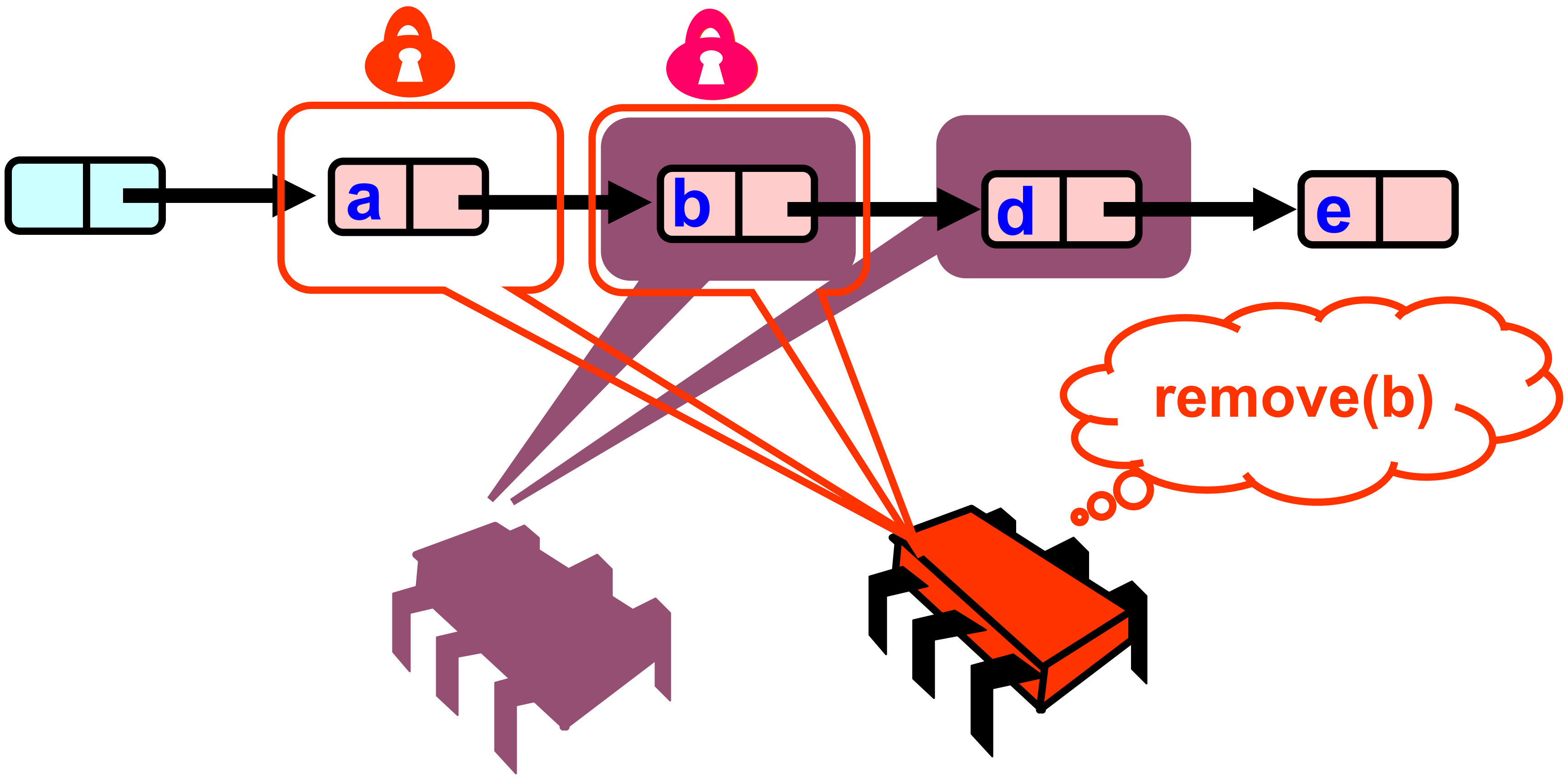


Data conflict!

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

- What do we do?

Data conflict!

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

- What do we do? We decided that locking when traversing is too expensive.

Lock-free reasoning

- We can use atomic variables

Lock-free reasoning

- Default atomic accesses are documented to be sequentially consistent.

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

Lock-free reasoning

- Default atomic accesses are documented to be sequentially consistent.

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

Create an atomic pointer type using C++ templates

Lock-free reasoning

- Default atomic accesses are documented to be sequentially consistent.

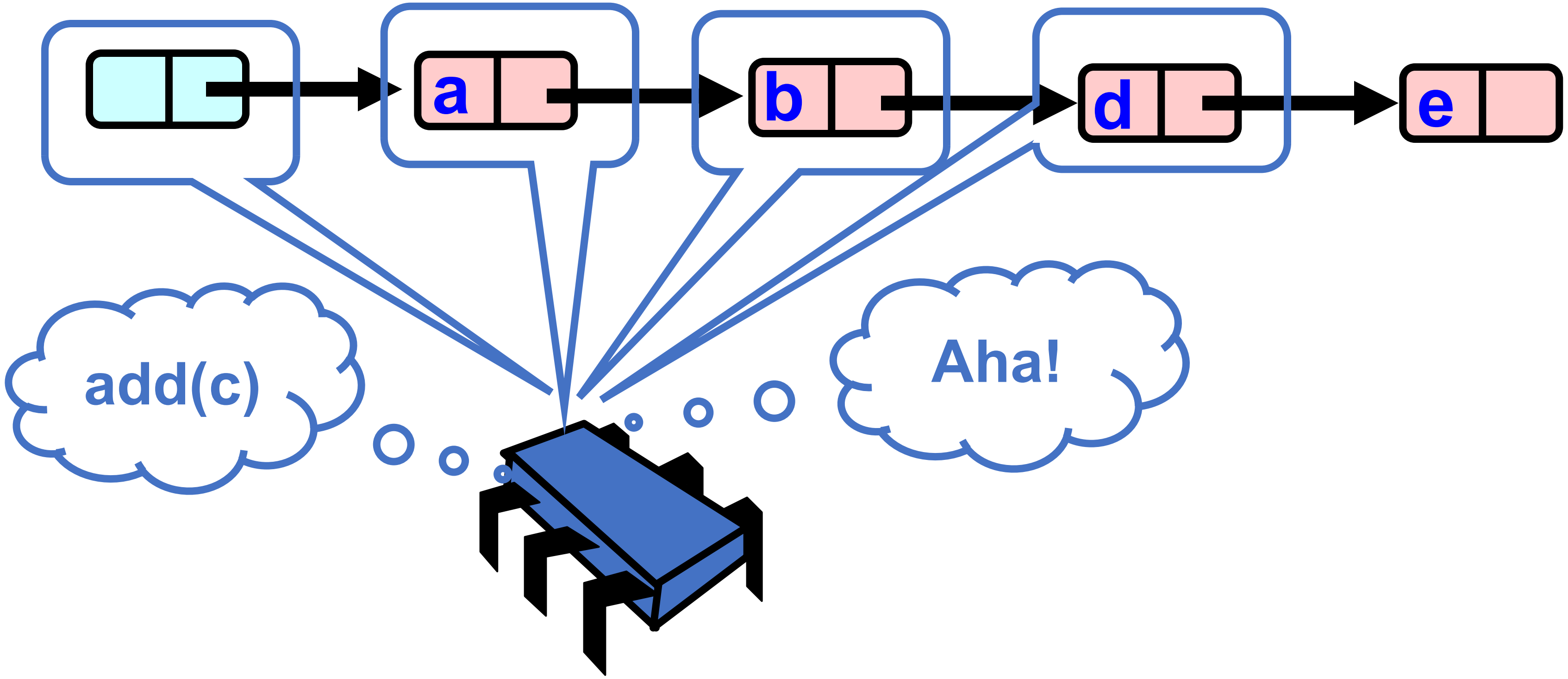
```
void traverse(node *n) {
  while (n->next != NULL) {
    n = n->next;
  }
}
```

Lock-free reasoning

- Default atomic accesses are documented to be sequentially consistent.

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

What could go wrong?



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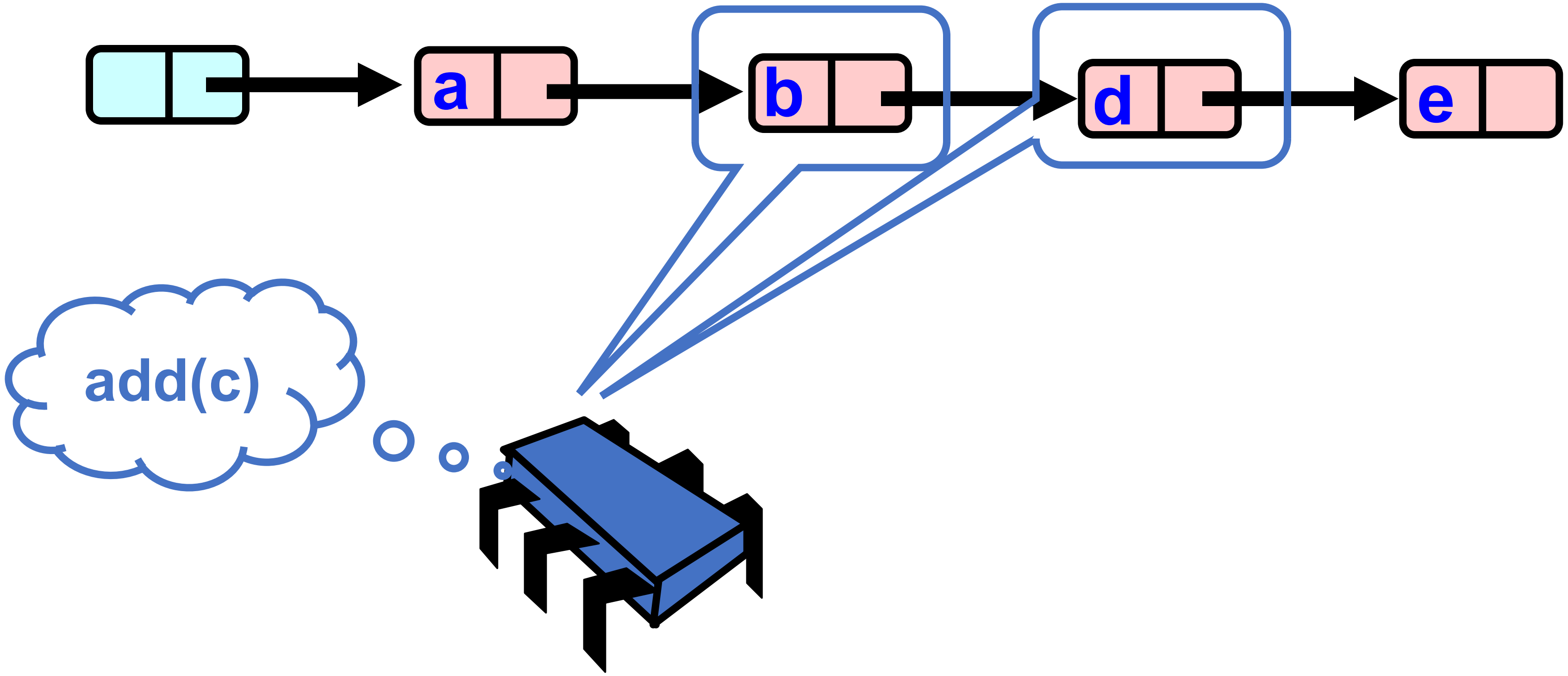

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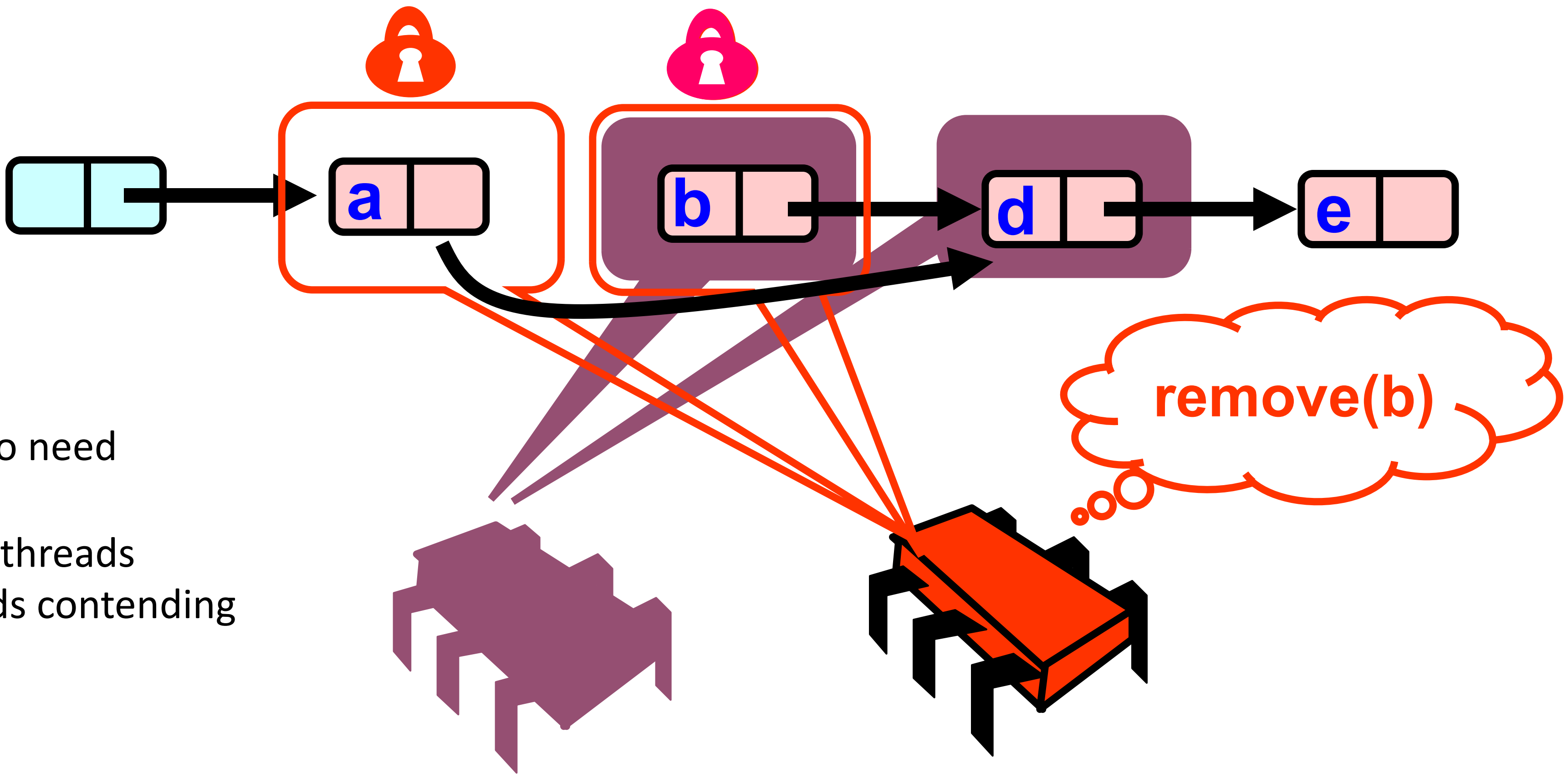
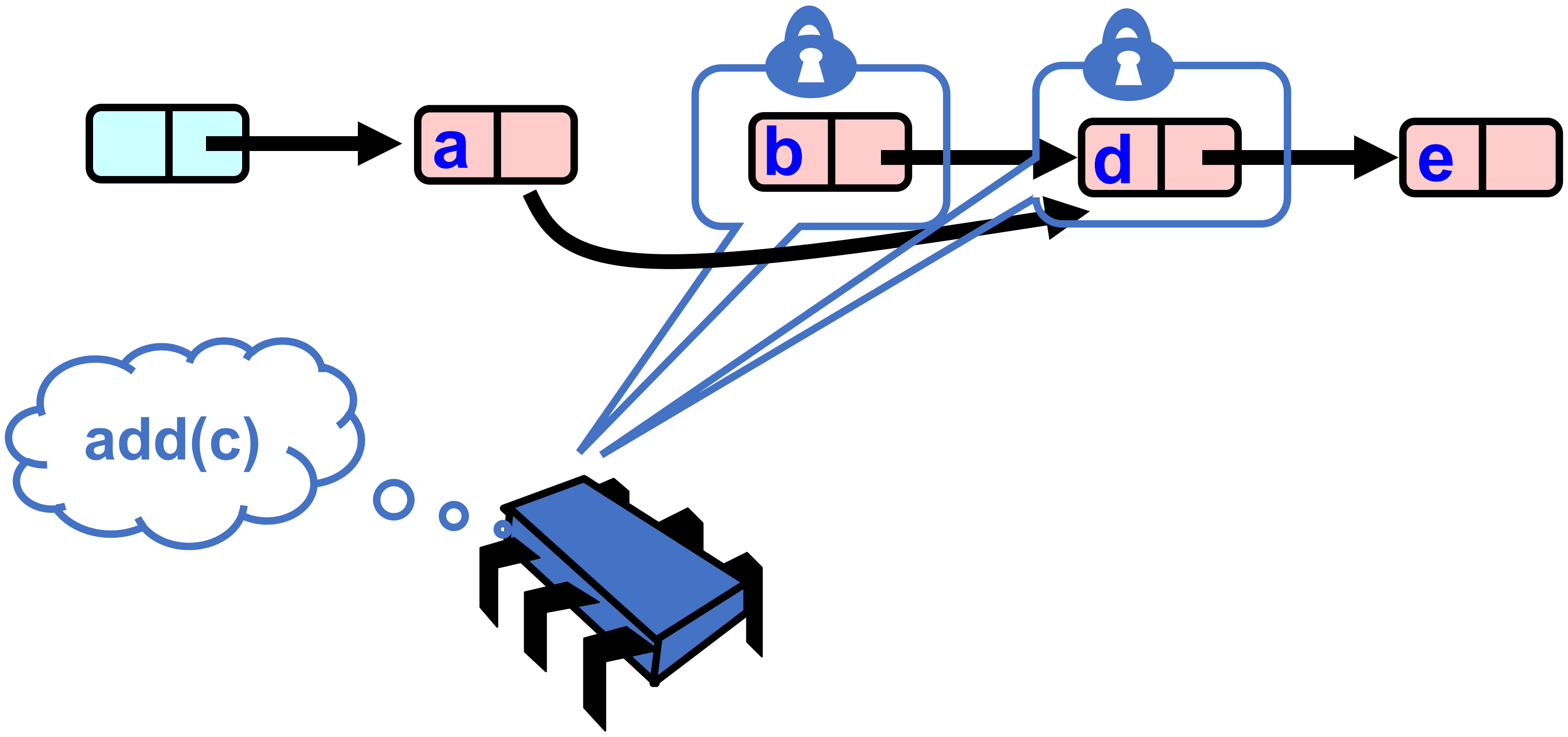


No more data conflict, but we do need to reason about interleavings and threads concurrent threads contending for values.

What could go wrong?



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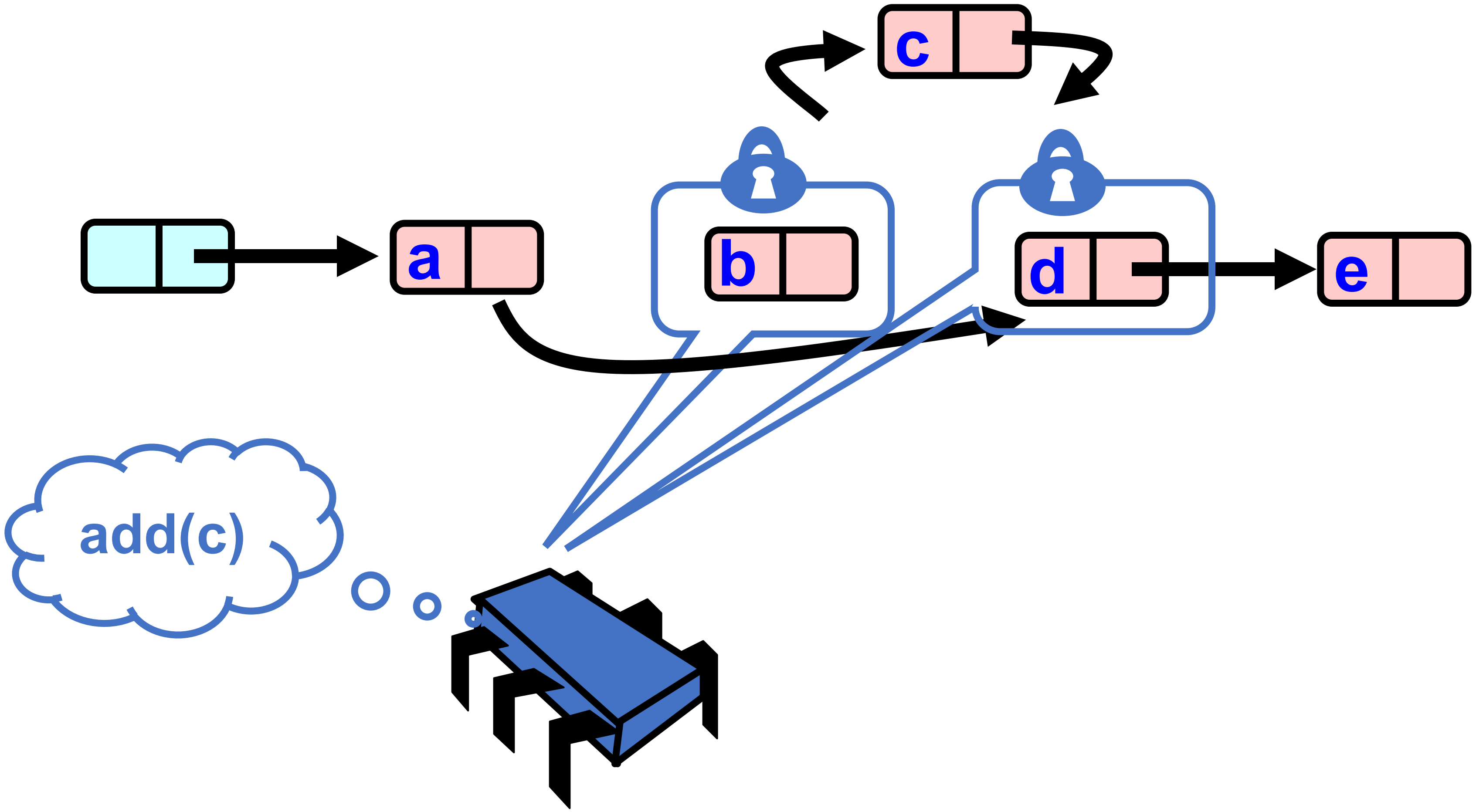

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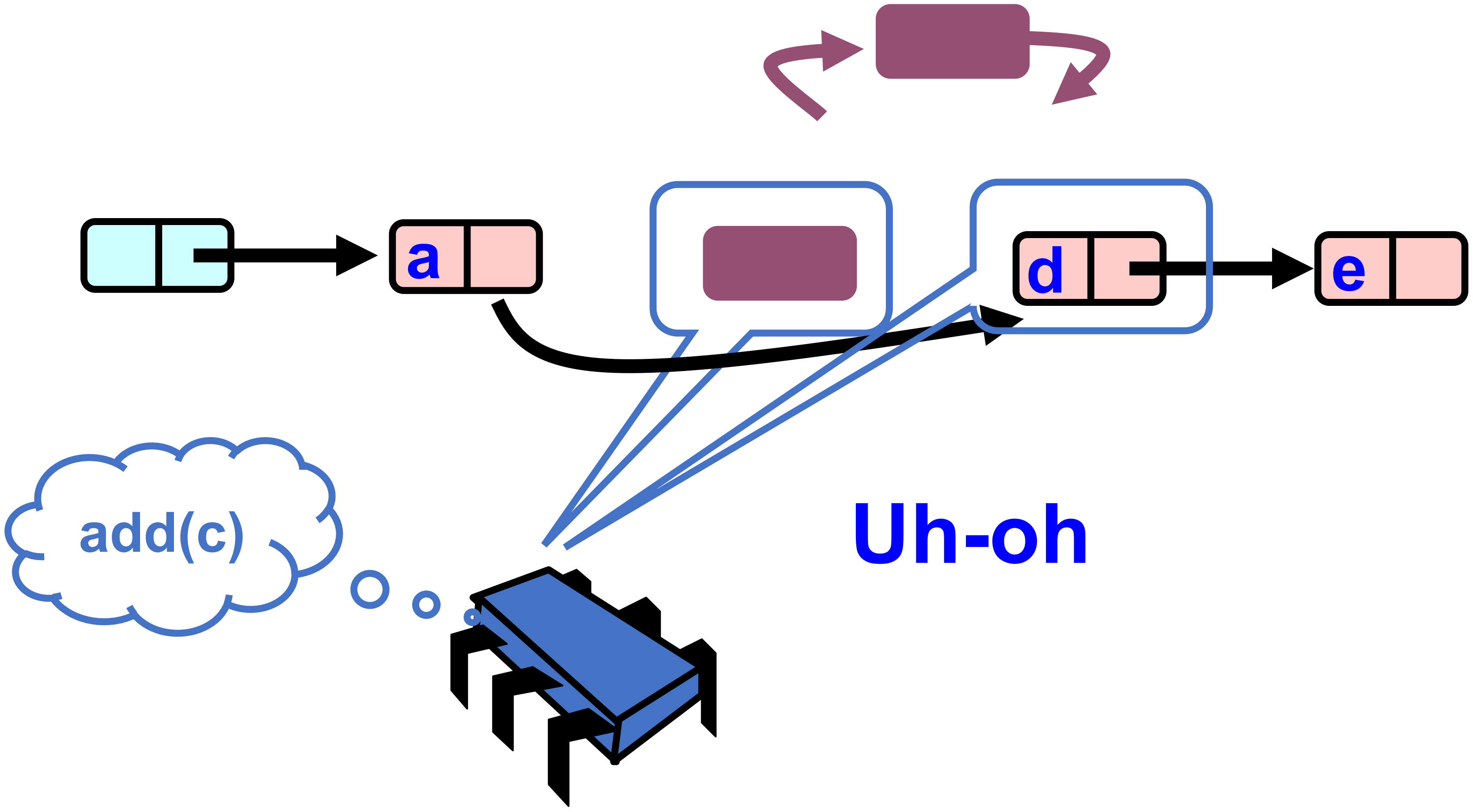
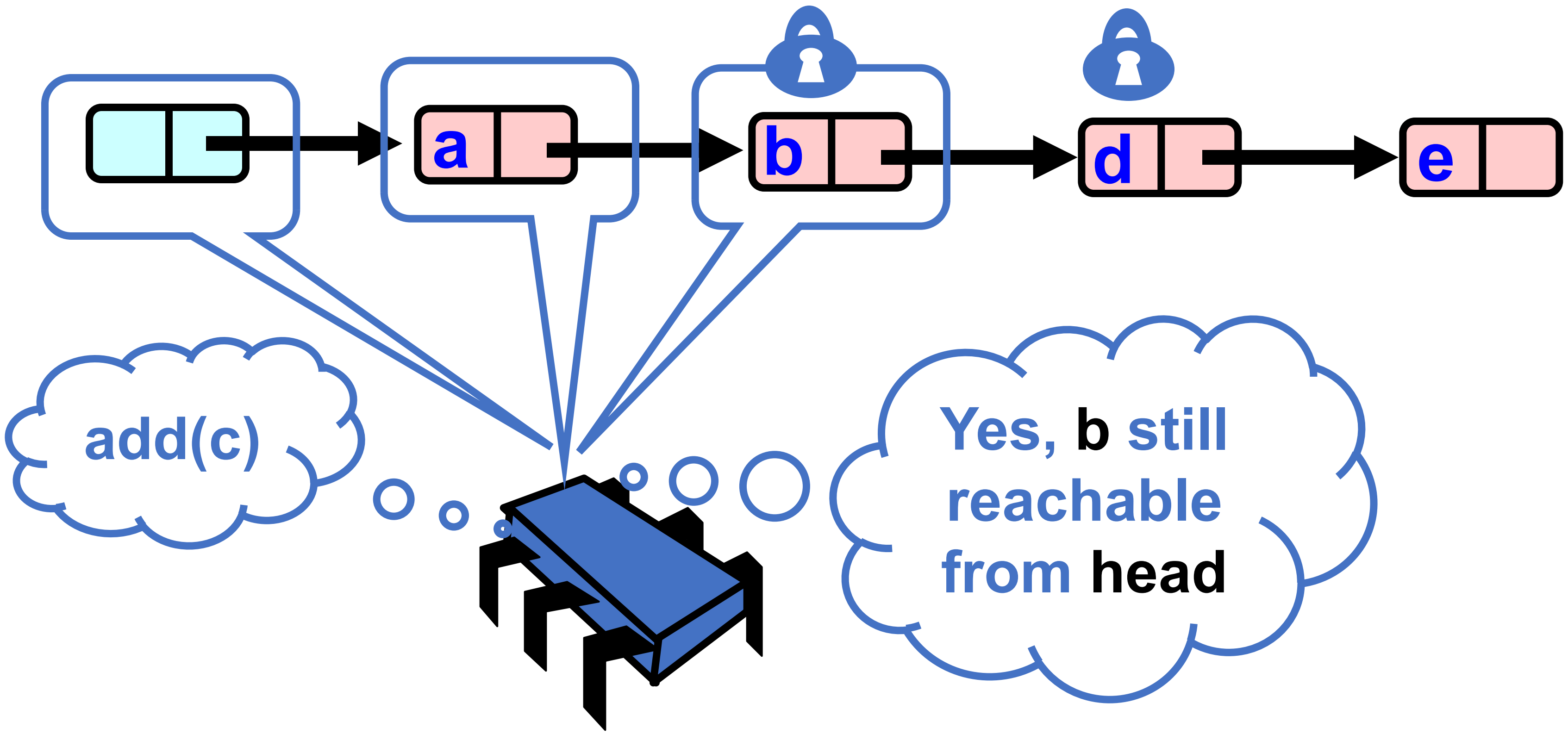


Validate – Part 1



What happens if failure?

- Ideas?

What happens if failure?

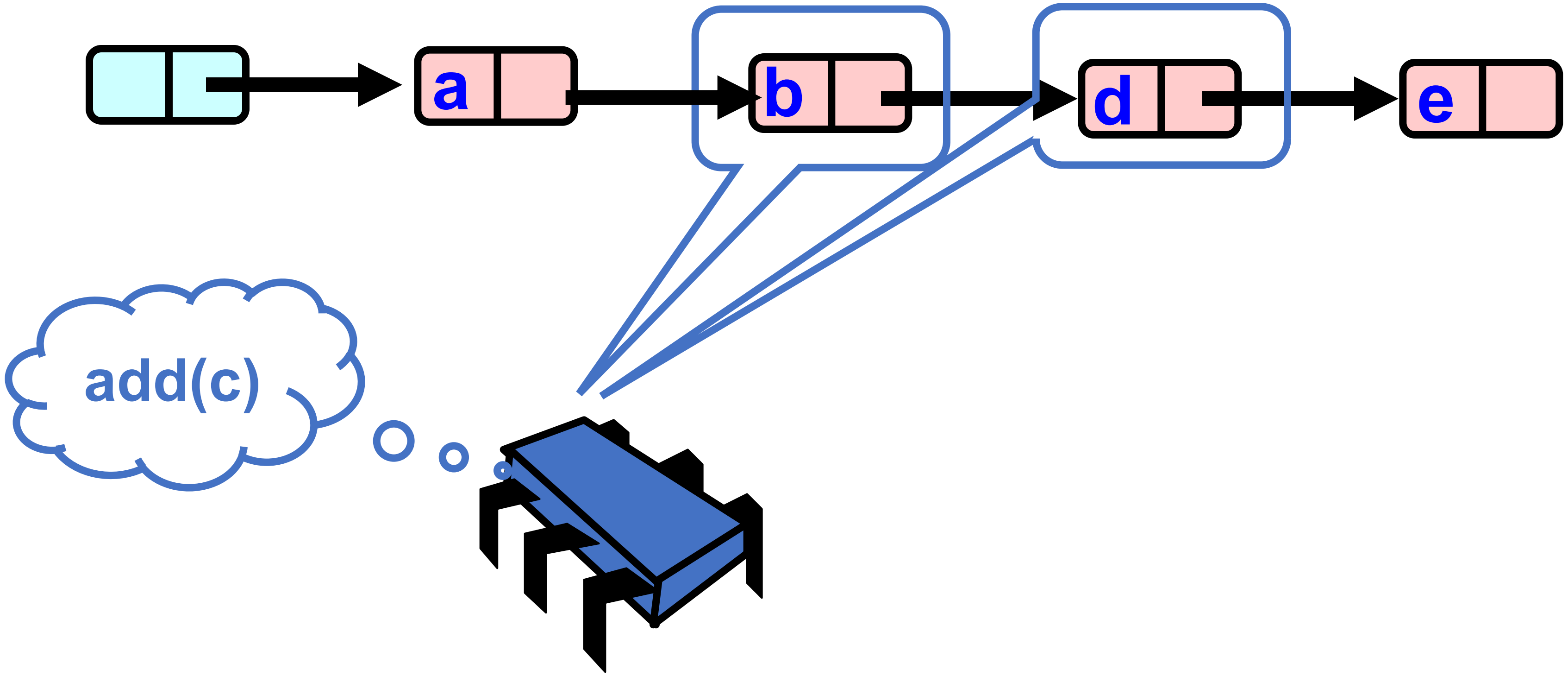
- Could try to recover? Back up a node?
  - Very tricky!
  - Just start over!

What happens if failure?

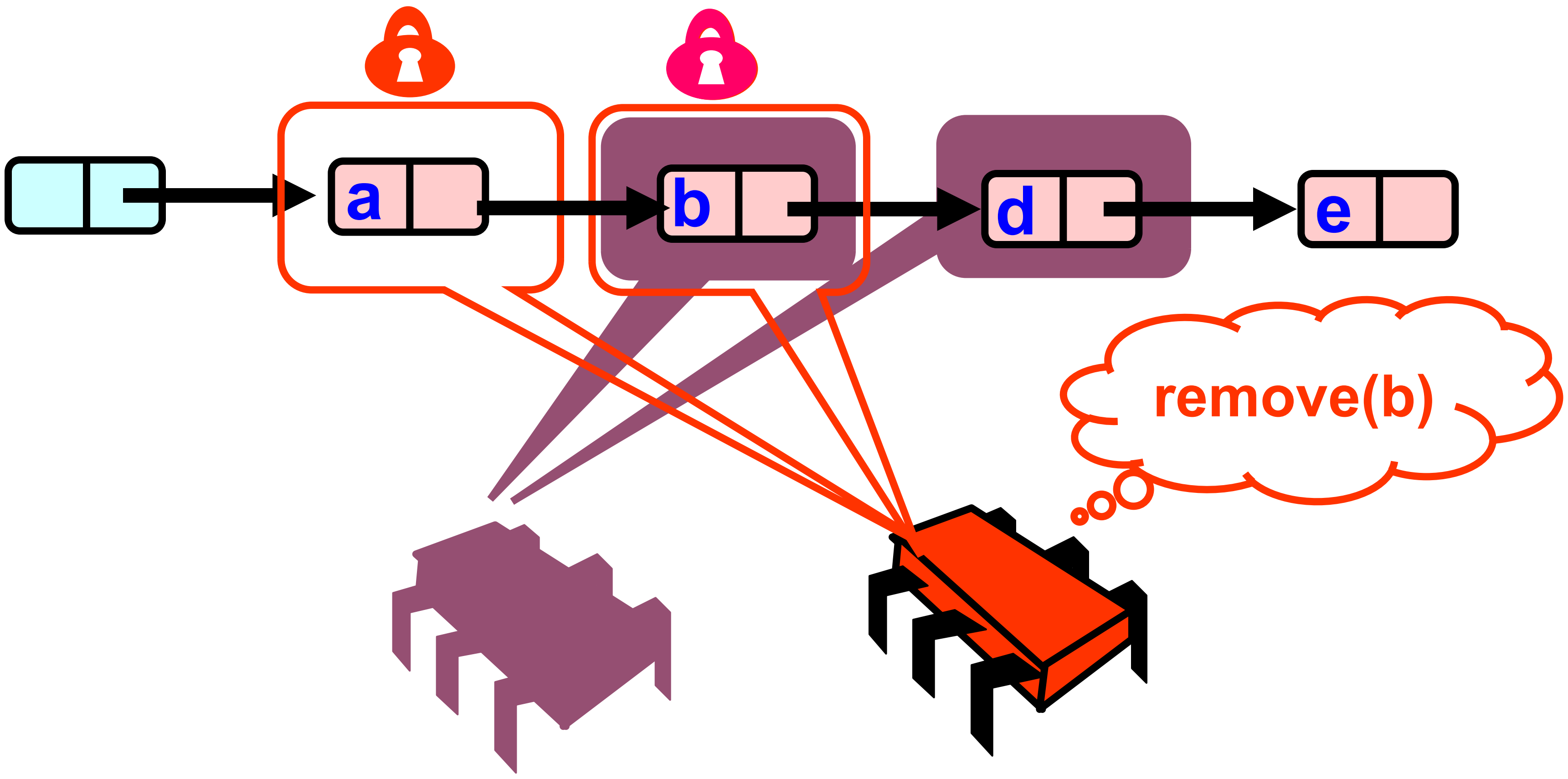
- Could try to recover? Back up a node?
  - Very tricky!
  - Just start over!
- Private method:
  - try_remove
  - remove loops on try_remove until it succeeds

What about deletion?

Can threads that remove a node delete it?



Can threads that remove a node delete it?



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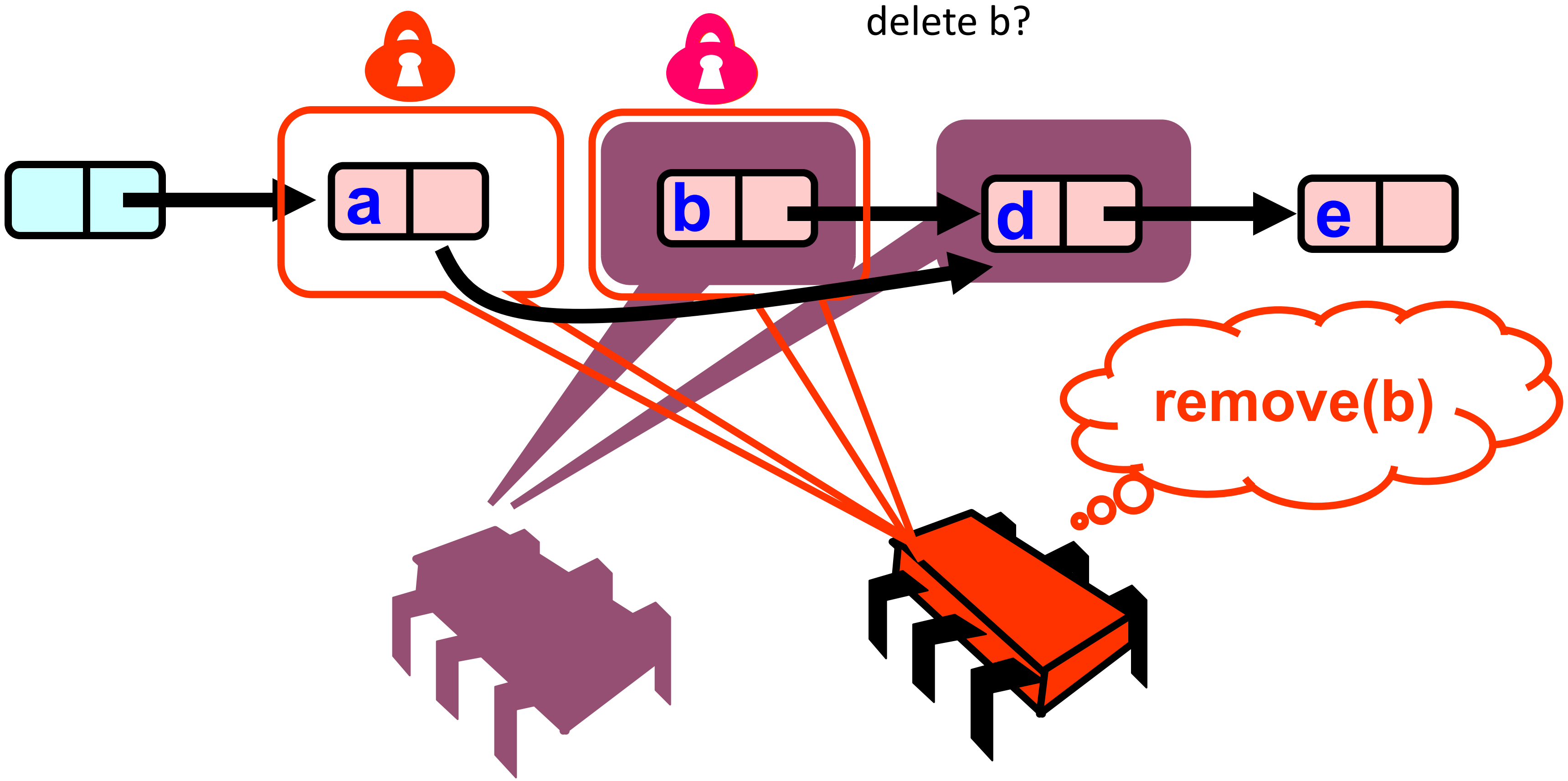

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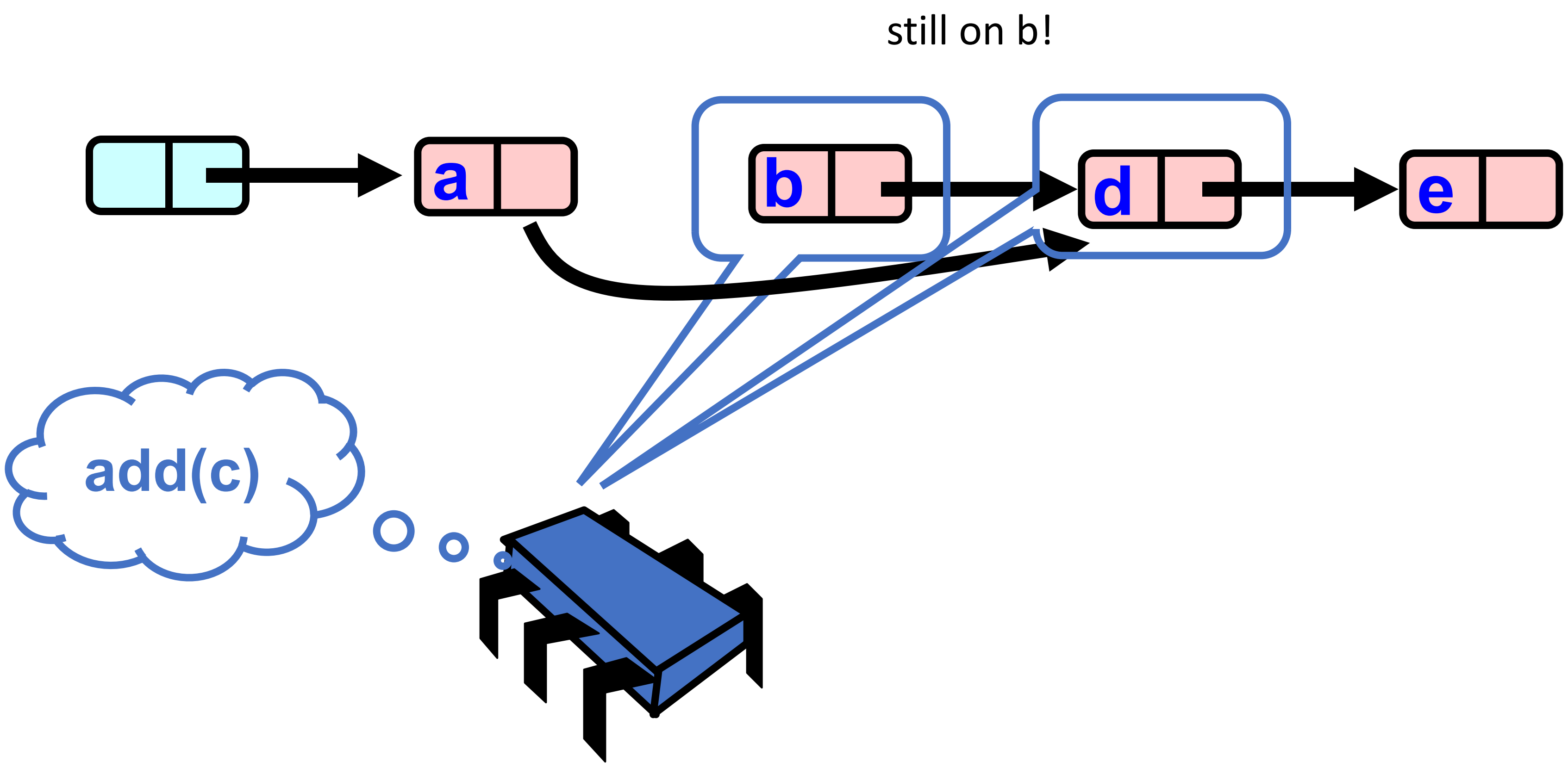
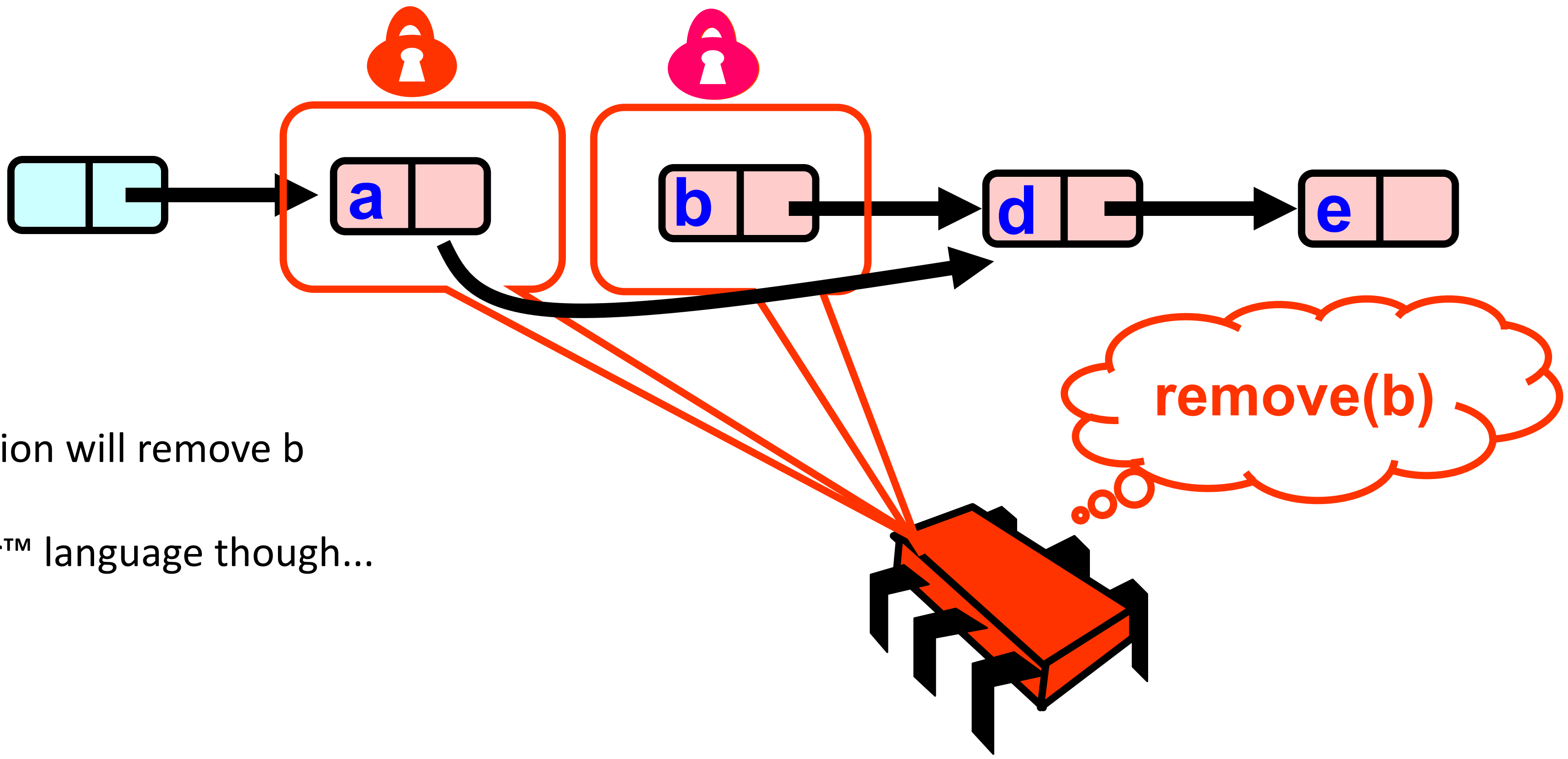


Our own garbage collector



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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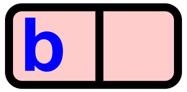

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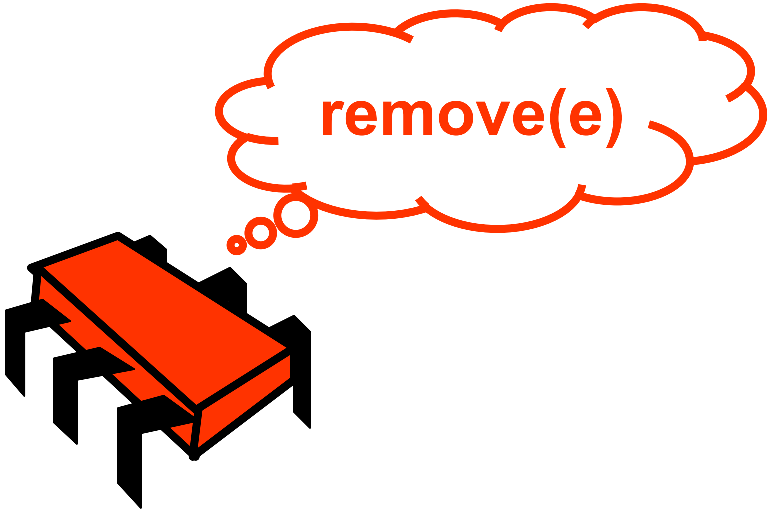

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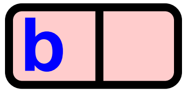

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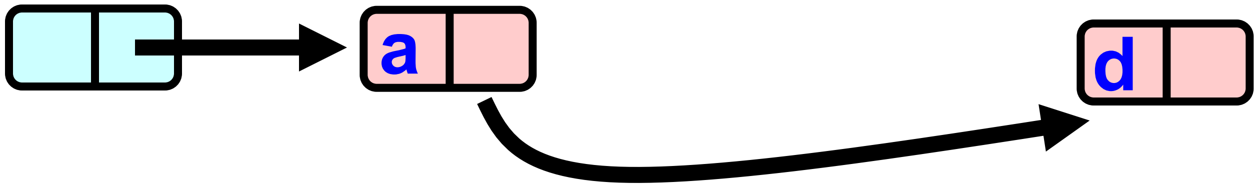

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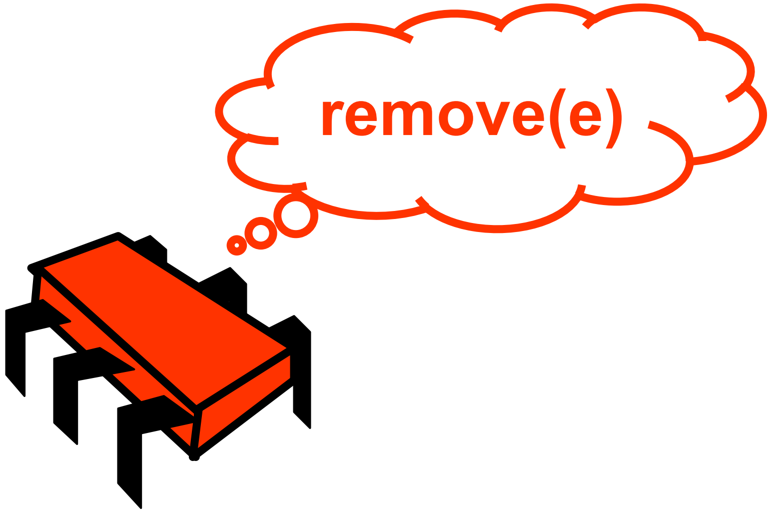

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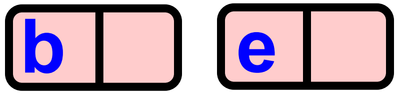
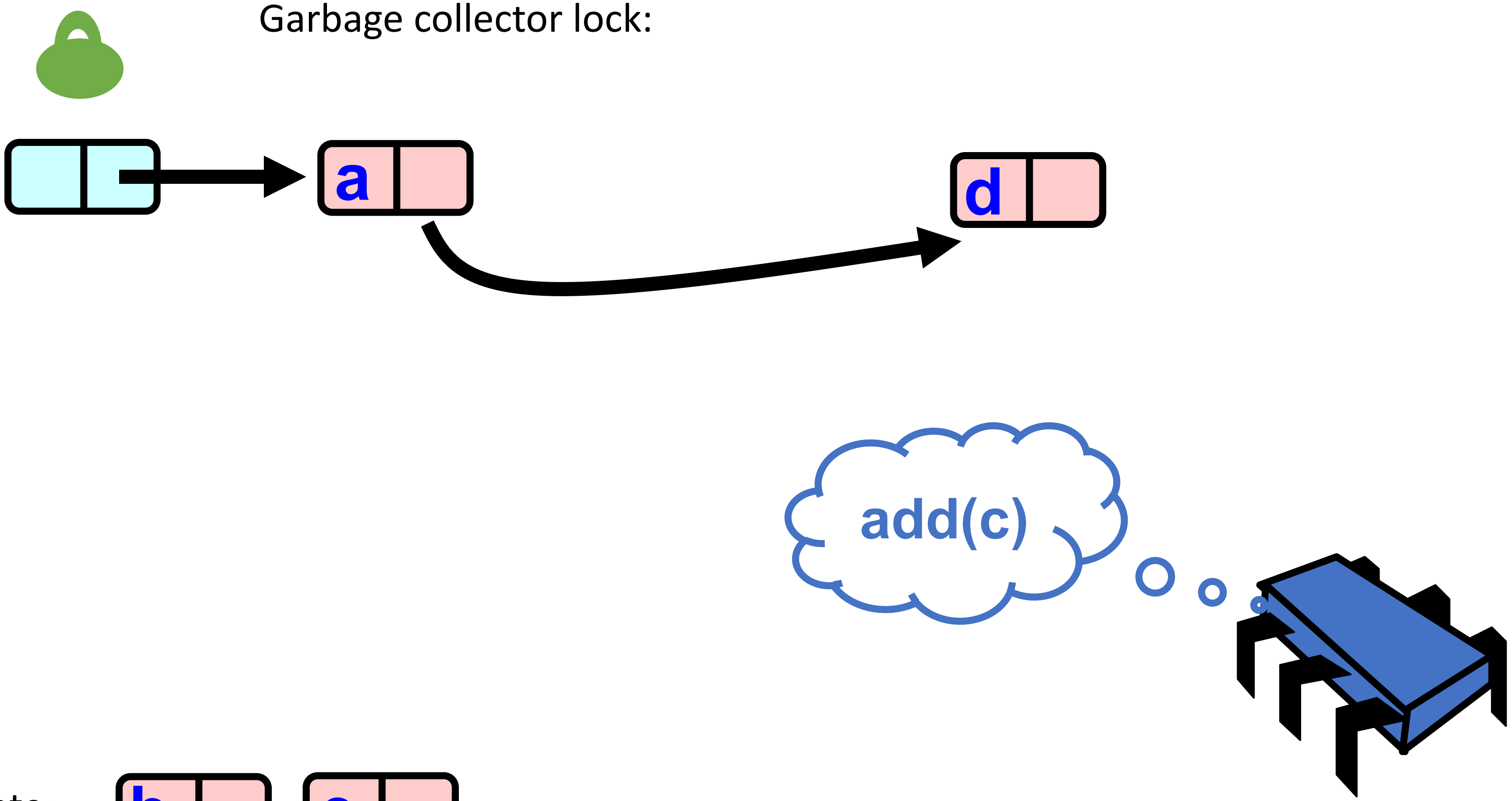


Our own garbage collector

Garbage collector lock:



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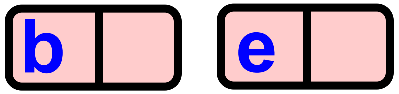

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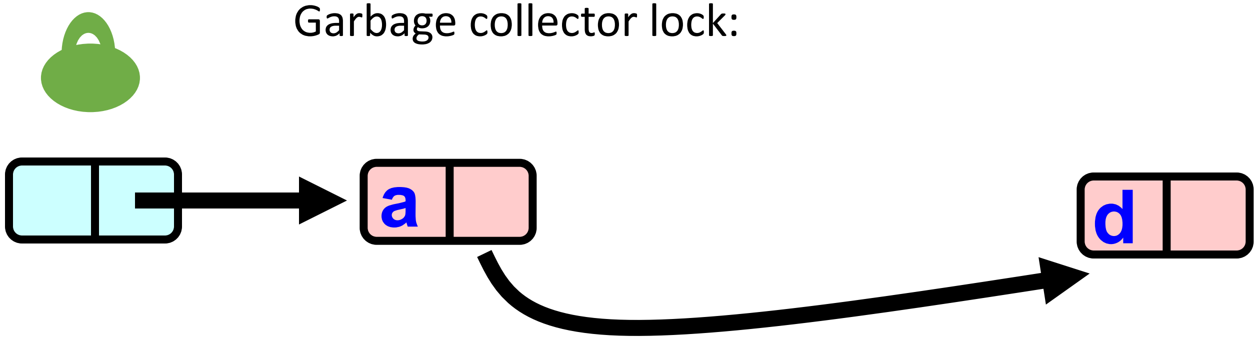
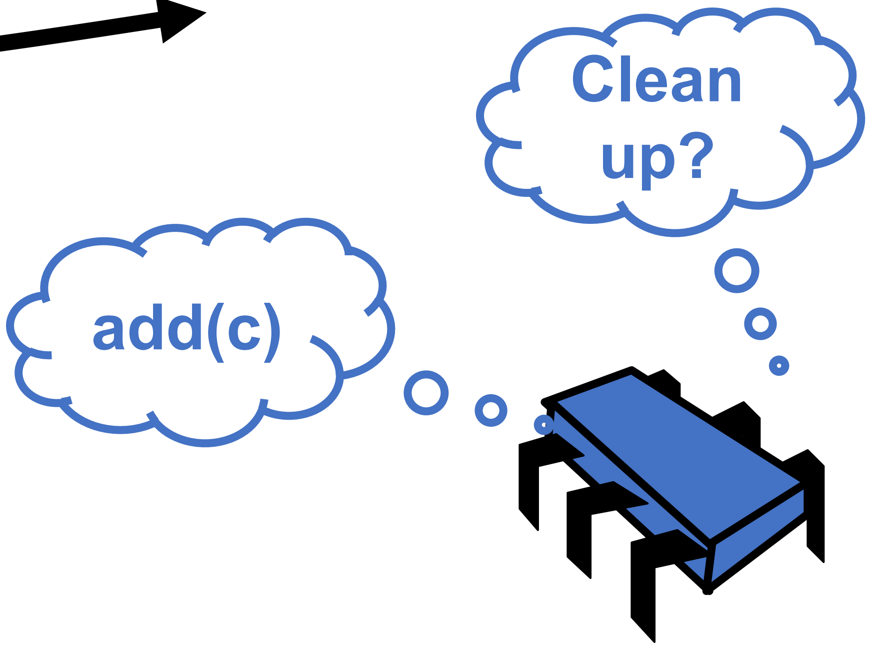
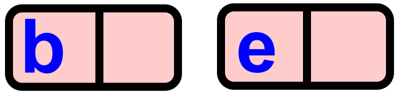




Similar to a reader/writer lock:
Allows an arbitrary number of threads that operate on the list
Only 1 garbage collector thread
Erases the list of nodes

maintain a list to delete:



Garbage collector lock

- Many strategies!
  - A big research area ~10 years ago

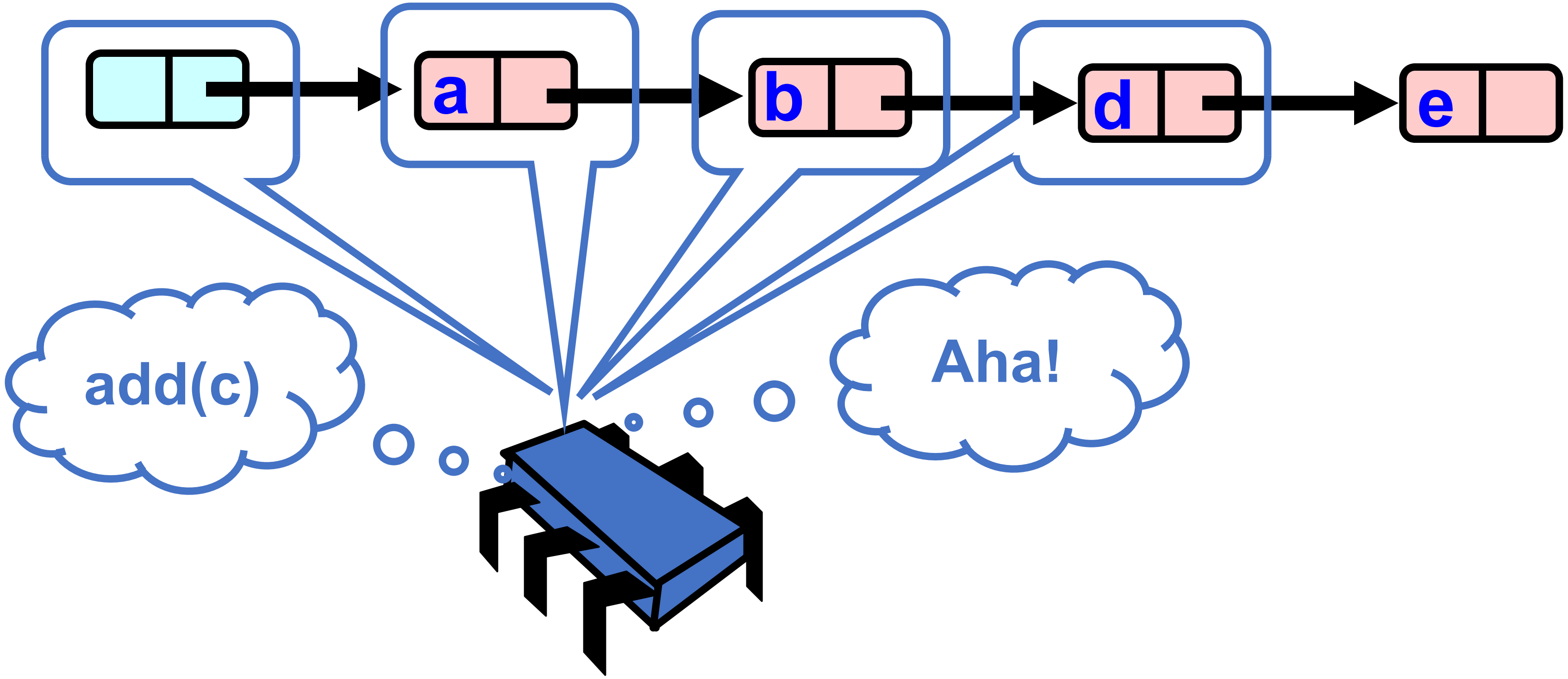
- **Strat 1:** Threads always try once to take the garbage collector lock:
  - if failed, no worries, the next operation will get a chance
  - if succeeded, then there was no contention
  - can starve garbage collection

- **Strat 2:** Wait until size grows to a threshold:
  - Wait on the lock (hope for a fair implementation!)
  - Can cause performance spikes

Back to the linked list

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

What Else Could Go Wrong?



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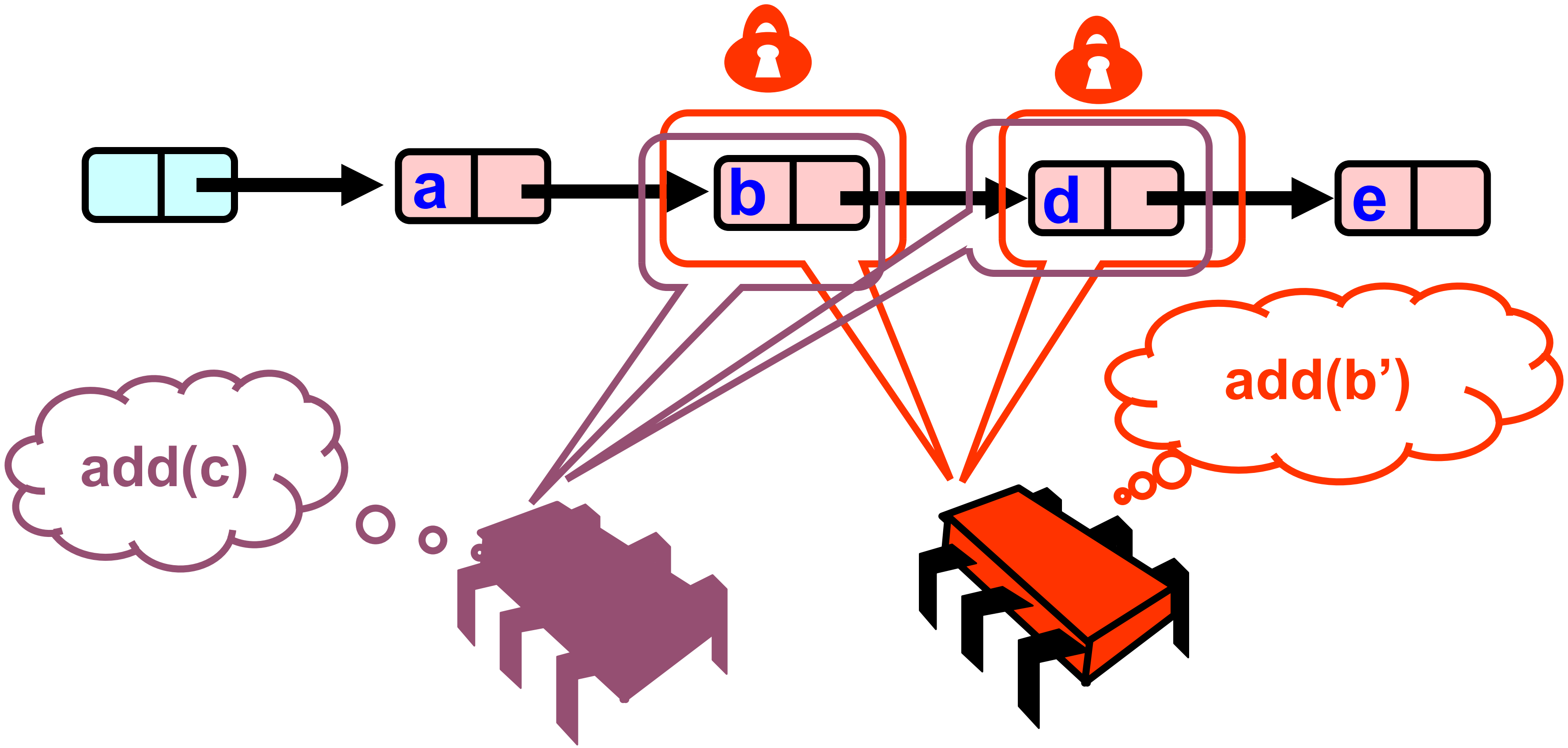

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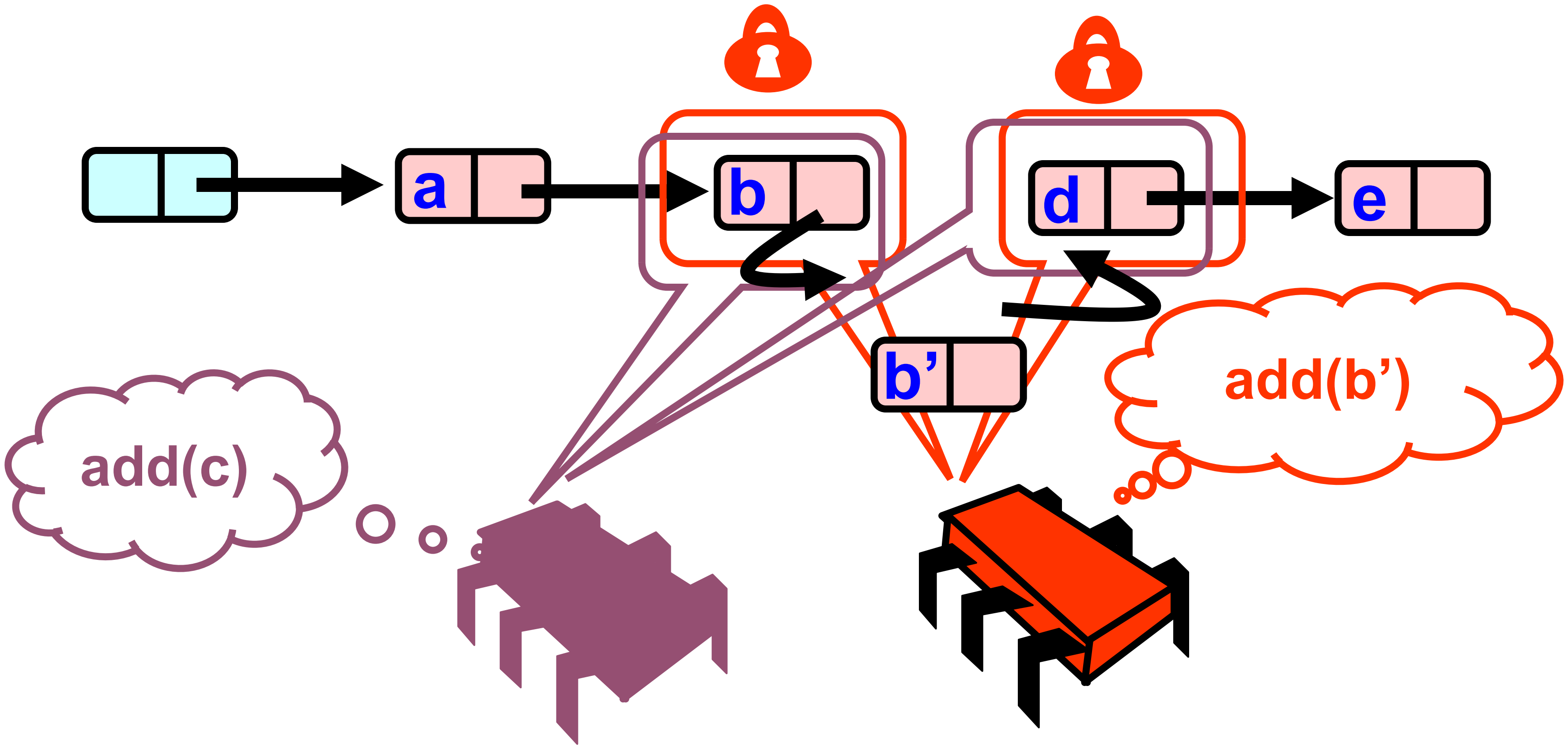

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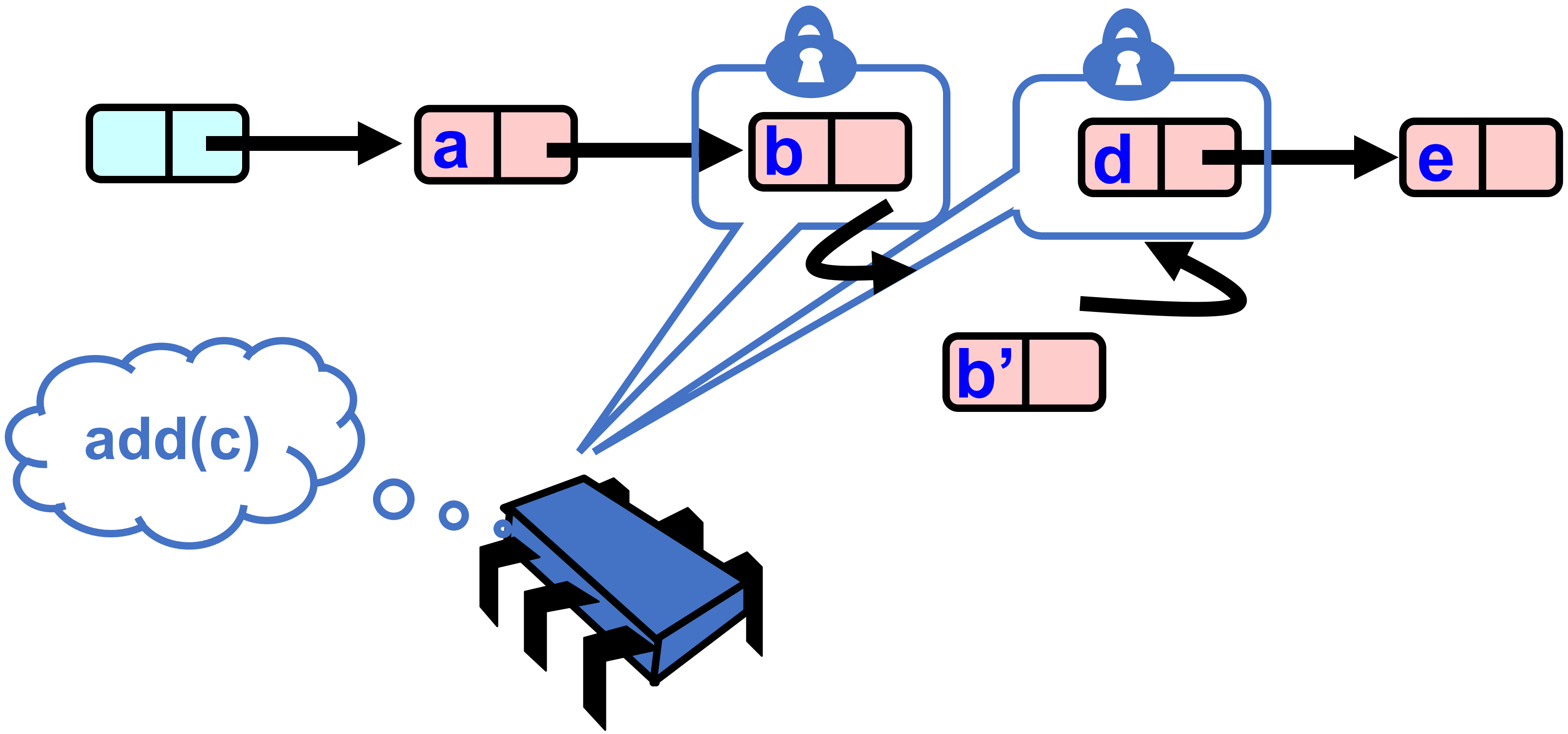
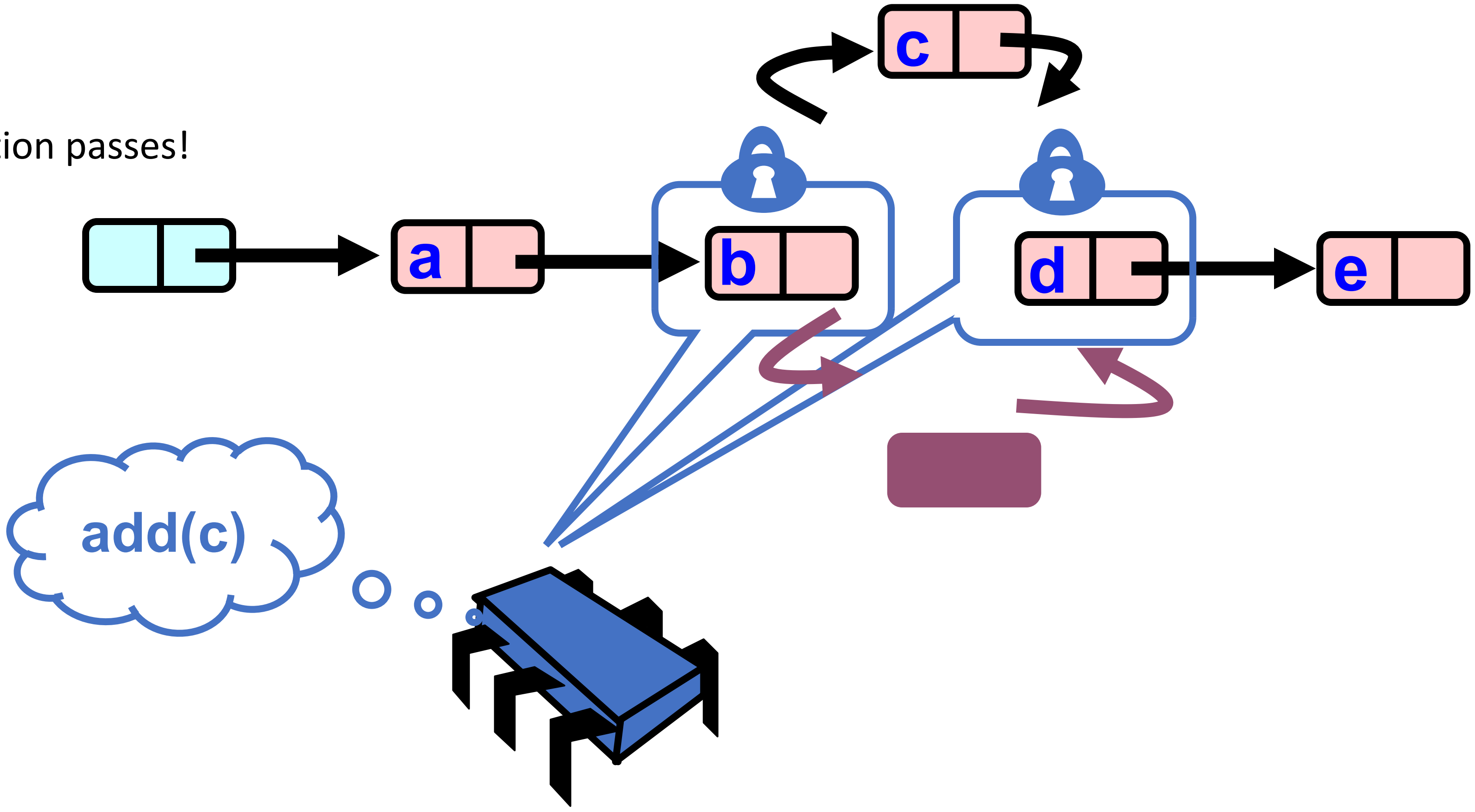
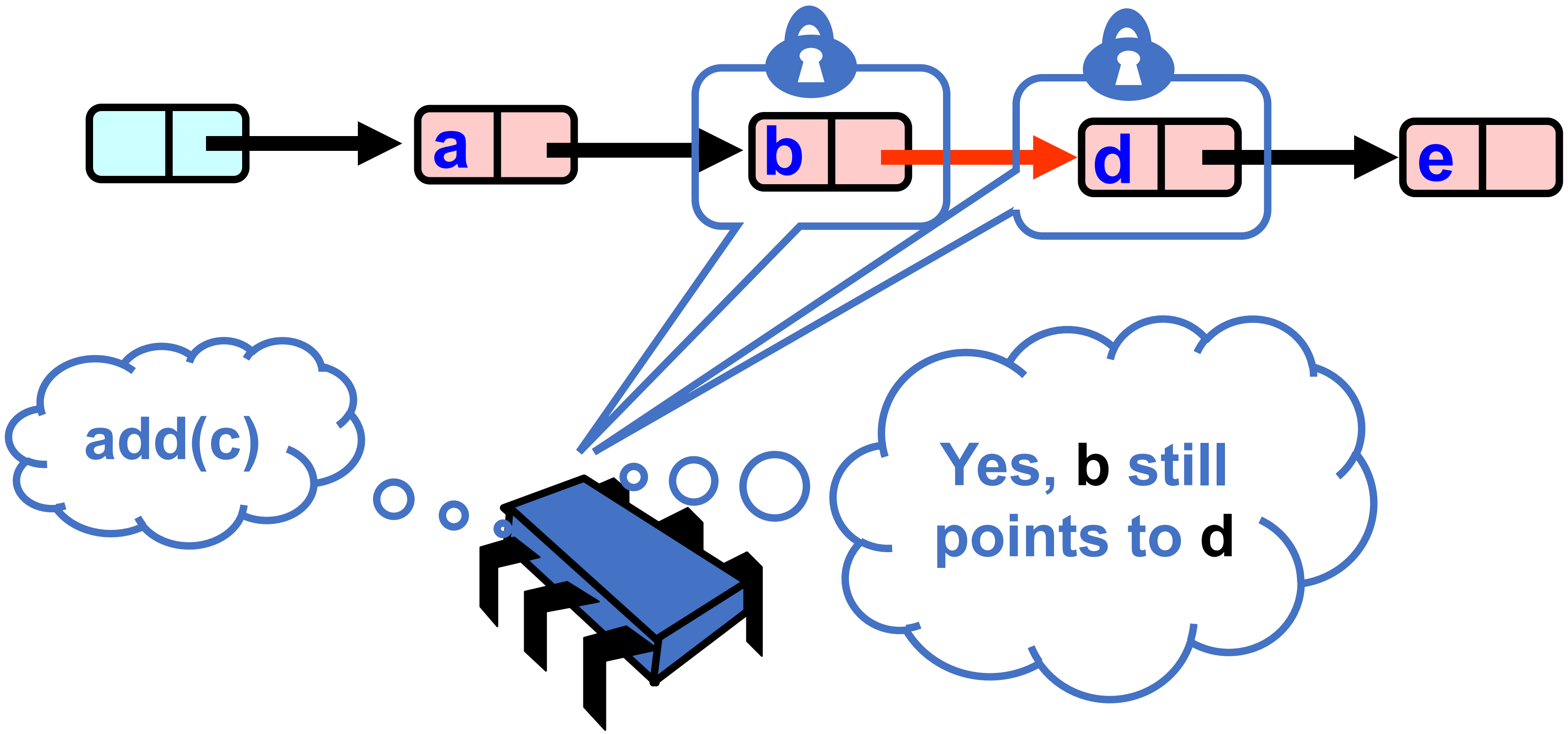


What Else Could Go Wrong?

Validation passes!



Validate Part 2
(while holding locks)



Summary

- We traverse without lock
  - Traversal may access nodes that are locked
  - Its okay because we have atomic pointers!
- We might traverse deleted nodes
  - Its okay because we validate after we obtain locks
  - Two validations:
    - our node is still reachable (it was not deleted)
    - Our insertion point is still valid (no thread has inserted in the meantime)
- We don’t actually free node memory, but we put them in a list to be freed later

Enjoy your weekend!

- On Monday: making the list lock-free!
- Get HW 2 in and look for midterm grades