CSE113: Parallel Programming

Feb. 11, 2022

- **Topics**:
  - General concurrent sets

Announcements

- Midterm is out!
  - You have until next Monday at midnight to do it.
  - Do not discuss with your classmates
  - Do not google specific questions or ask on online forums
  - Ask any clarifying questions as a private post on piazza
  - Late tests will not be accepted (prioritize the midterm!)
  - You can ask me or Reese about the midterm, not Tim or Sanya

Don’t expect help on Piazza on the weekend or after 5 PM

- Homework 3 is out
  - You should have everything you need by end of today
  - Due next Friday by midnight
- Grades for HW 1 are released
  - You have until next Tuesday to discuss any issues

Announcements

- You can start sharing results for HW 3 on Monday

Today’s Quiz

- Due Monday by class time. Please do it!

Previous quiz

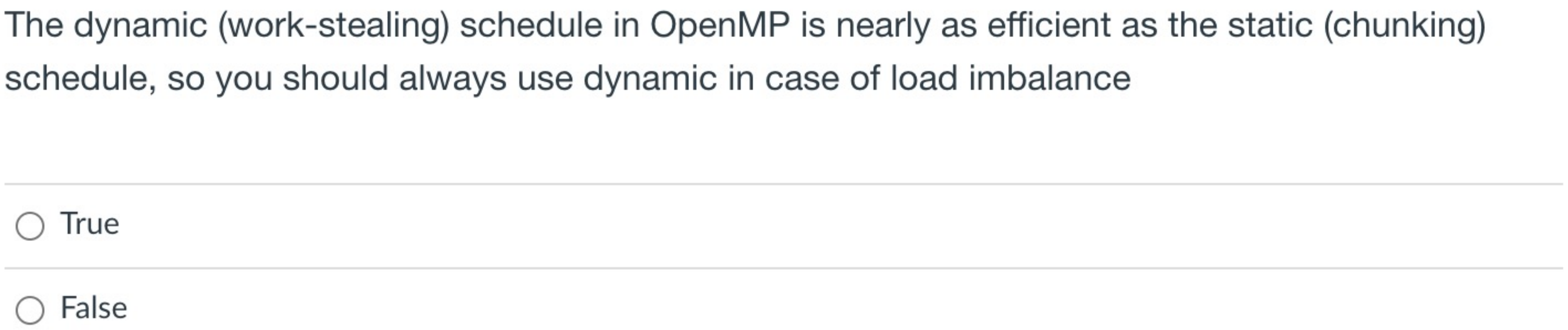
OpenMP does NOT allow you to specify the following properties when specifying that a DOALL loop should be executed in parallel

○ Number of threads

○ whether to use a fair mutex

○ what parallel schedule

Previous quiz

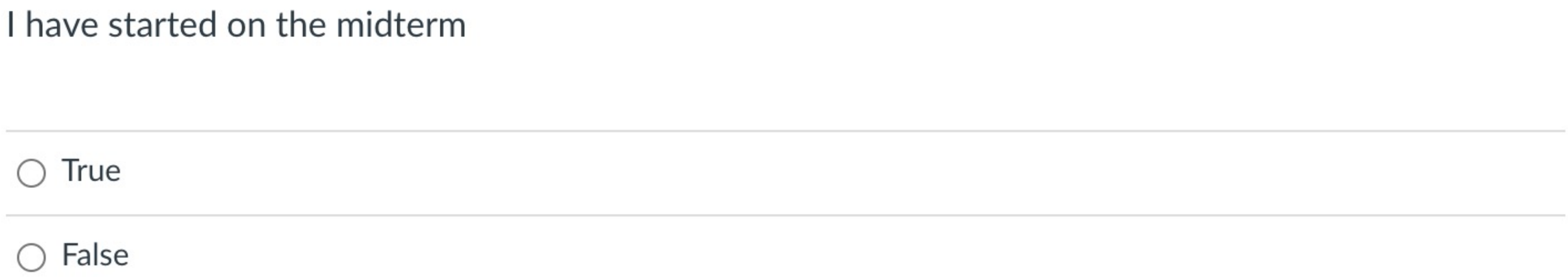


The dynamic (work-stealing) schedule in OpenMP is nearly as efficient as the static (chunking) schedule, so you should always use dynamic in case of load imbalance

○ True

○ False

Previous quiz

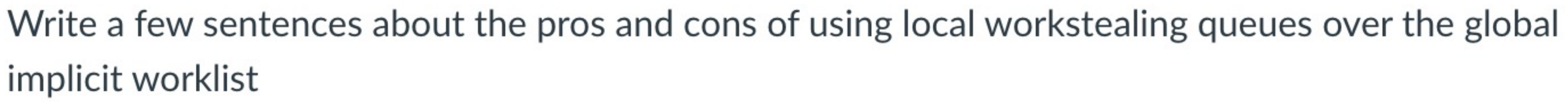


I have started on the midterm

○ True

○ False

Previous quiz



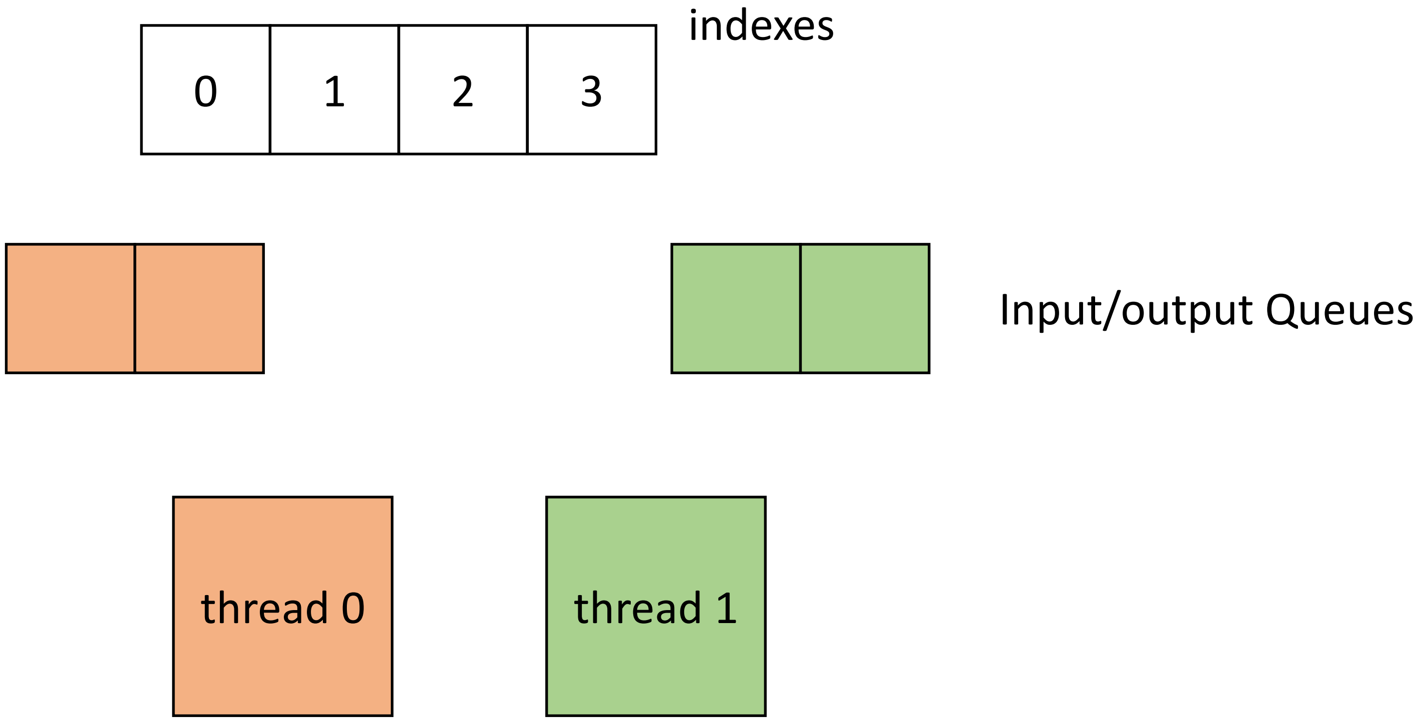
Write a few sentences about the pros and cons of using local workstealing queues over the global implicit worklist

Review

Local worklists

Work stealing - local worklists

- local worklists: divide tasks into different worklists for each thread



0	1	2	3

indexes

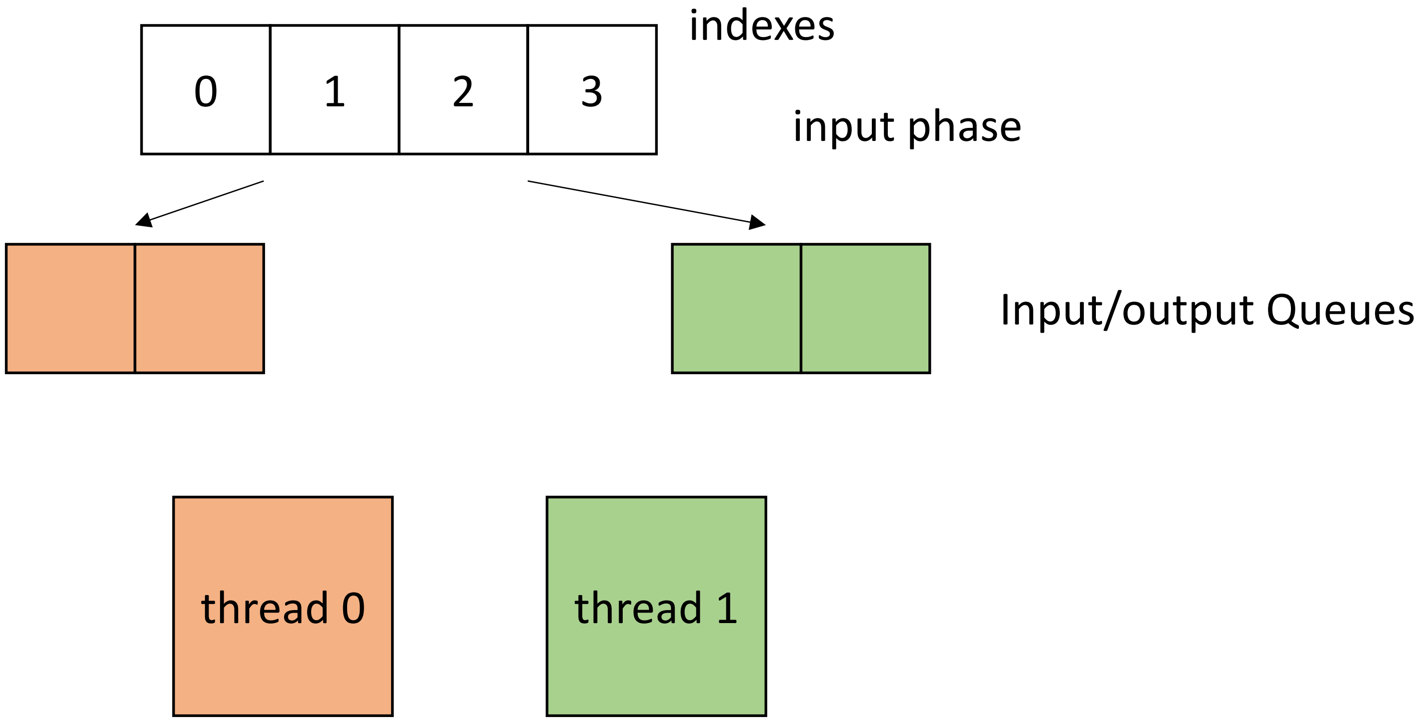
Input/output Queues

thread 0

thread 1

Work stealing - local worklists

- local worklists: divide tasks into different worklists for each thread



Work stealing - local worklists

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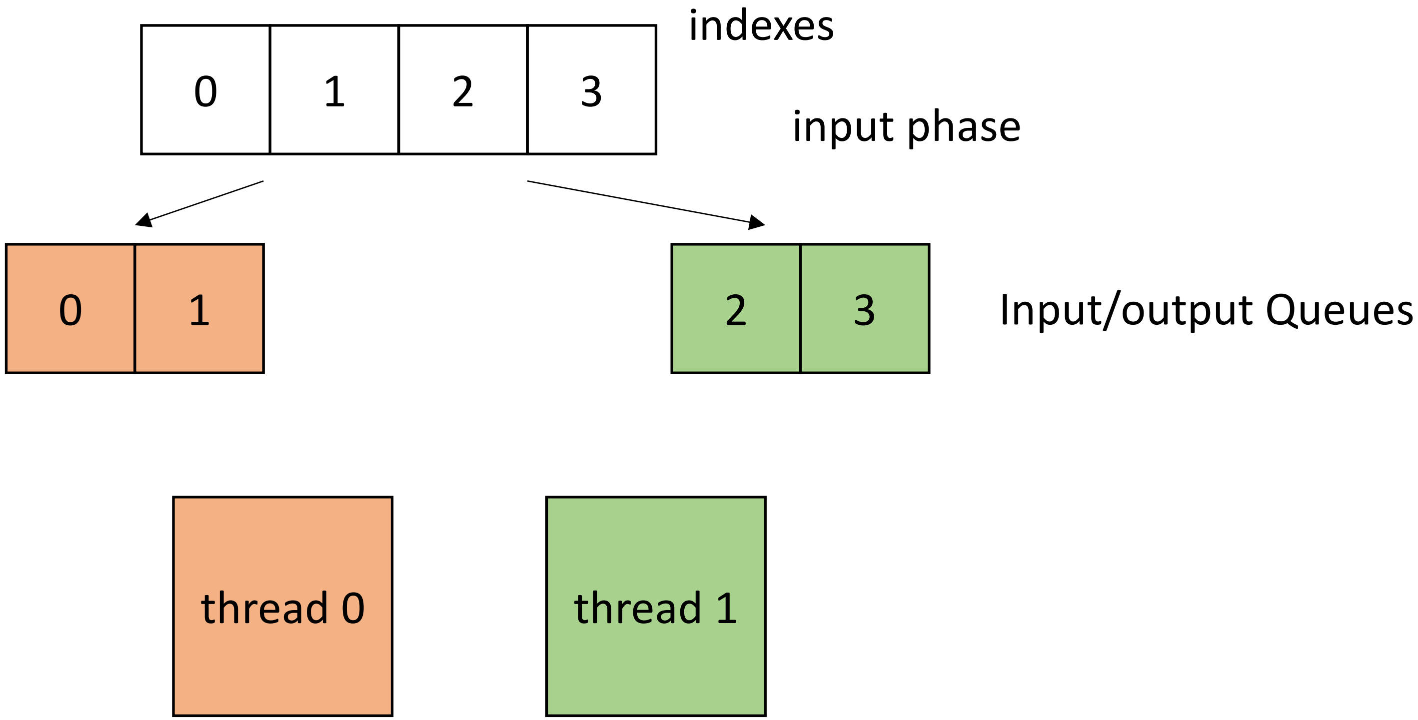
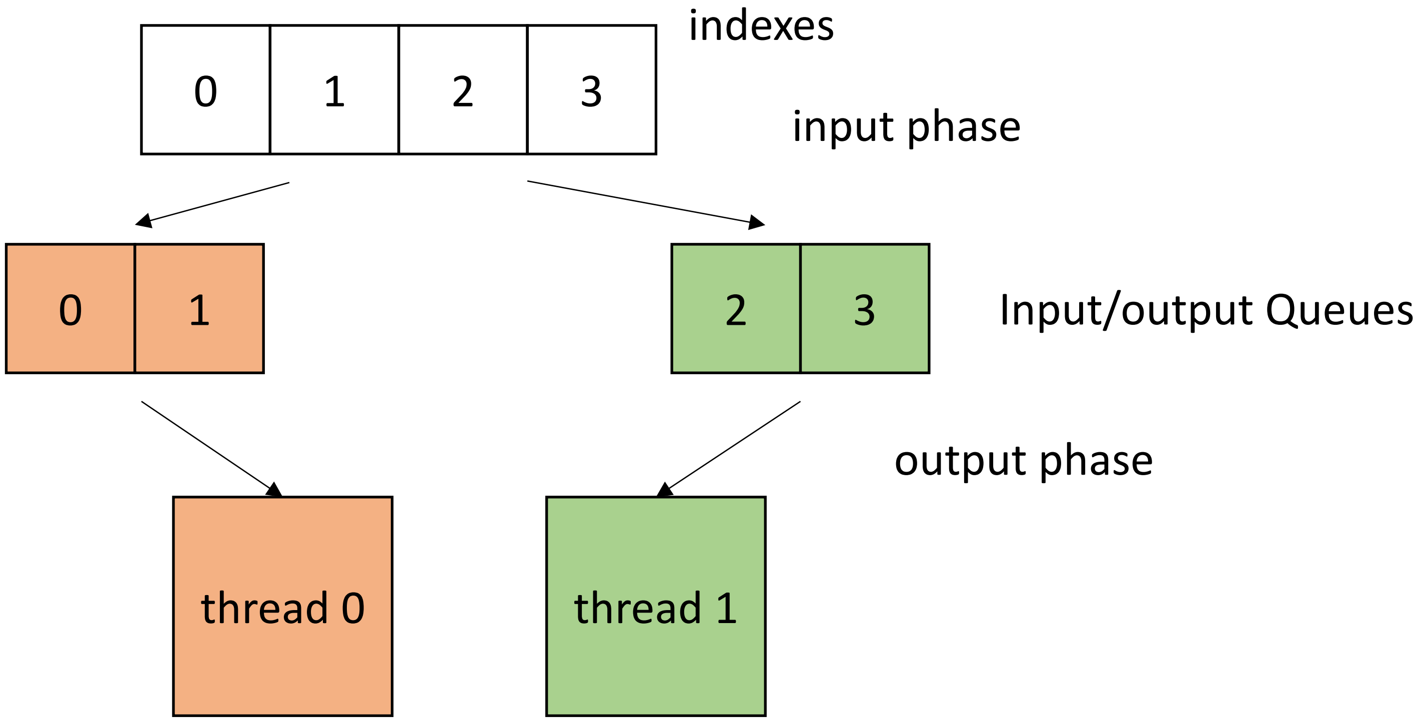
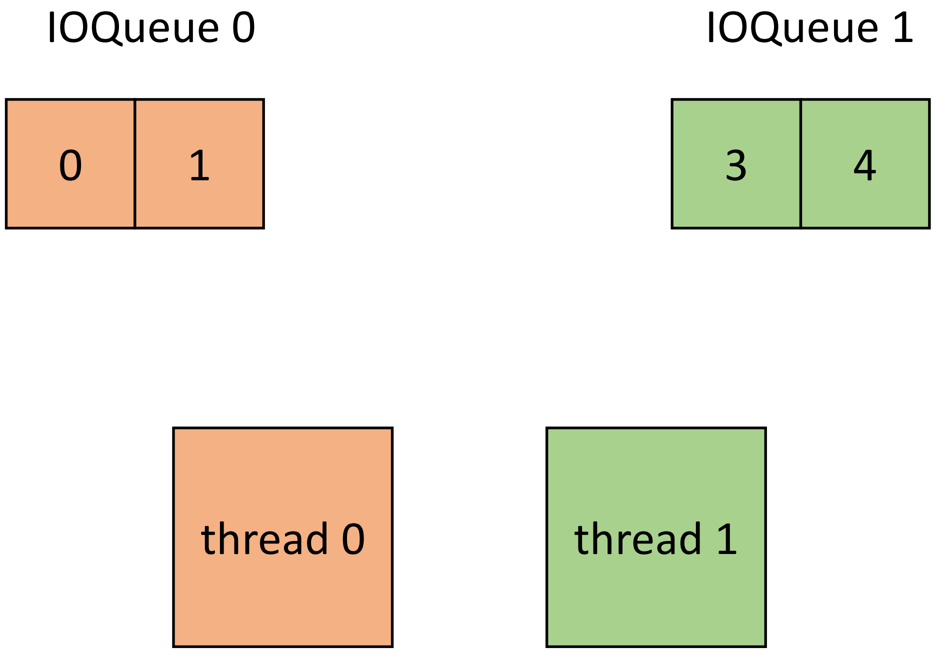


Work stealing - local worklists

- local worklists: divide tasks into different worklists for each thread



Work stealing - local worklists



```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

  for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
  {
    // dynamic work based on task
  }
  atomic_fetch_add(&finished_threads,1);
  while (finished_threads.load() != num_threads) {
    int target = // pick a thread to steal from
    int task = cq[target].deq();
    if (task != -1) {
       // perform task
    }
  }
}
```

OpenMP

OpenMP

- Pragma based extension to C/C++/Fortran

```
#pragma omp parallel for
for (int i = 0; i < SIZE; i++) {
  c[i] = a[i] + b[i];
}
// add -fopenmp to compile line
```

launches threads to perform loop in parallel. Joins threads afterward

OpenMP

- Pragma based extension to C/C++/Fortran

```
#pragma omp parallel for schedule(dynamic)
for (x = 0; x < SIZE; x++) {
  for (y = x; y < SIZE; y++) {
    a[x,y] = b[x,y] + c[x,y];
  }
}
```

What about irregular loops?

Schedule keyword

different types of schedules

New material

Schedule

- C++ Atomic Template

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

C++ Atomic template

Schedule

- C++ Atomic Template

- **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

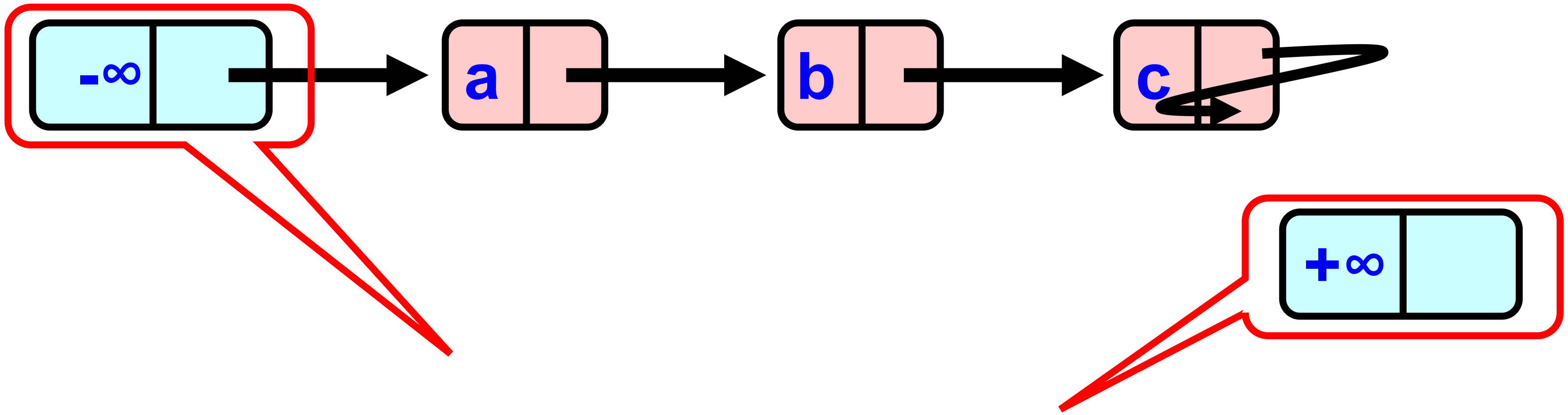
Set Interface

- 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;
}
```

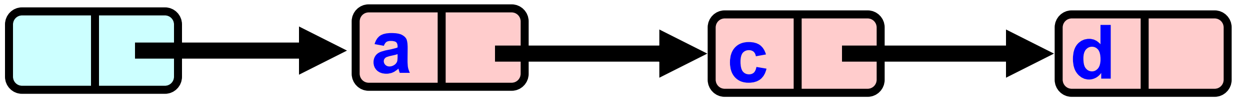
The List-Based Set



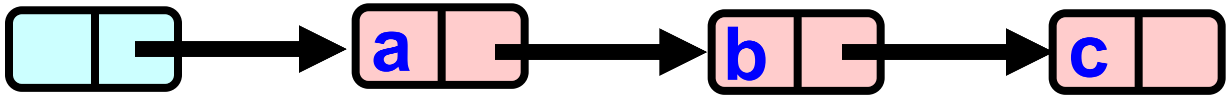
Sorted with Sentinel nodes
(min & max possible keys)

Sequential List Based Set

add(b)



remove(b)



Sequential List Based Set

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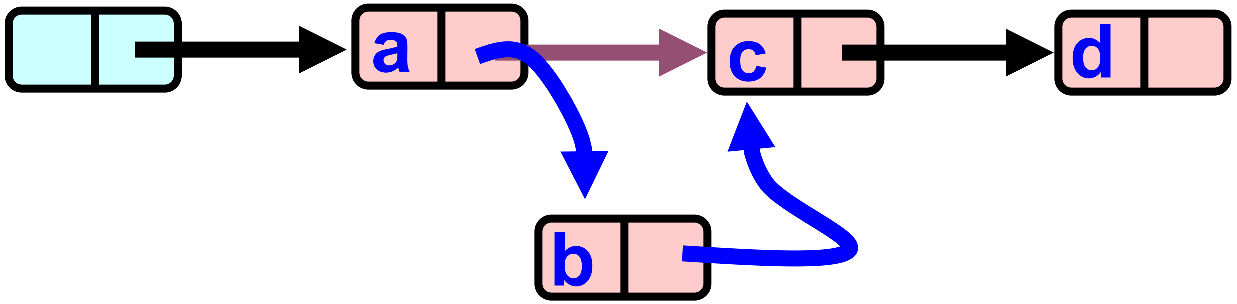
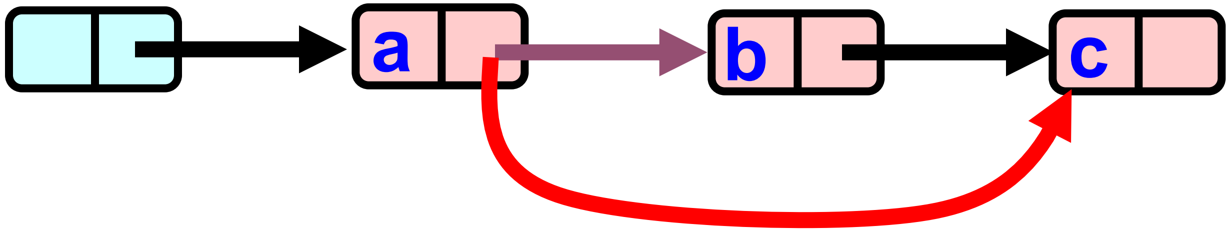


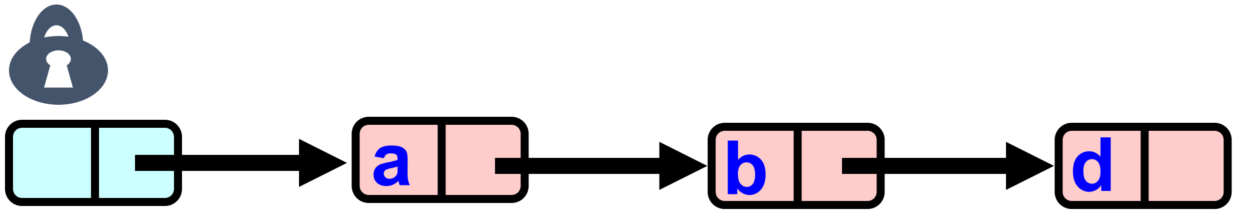
remove(b)



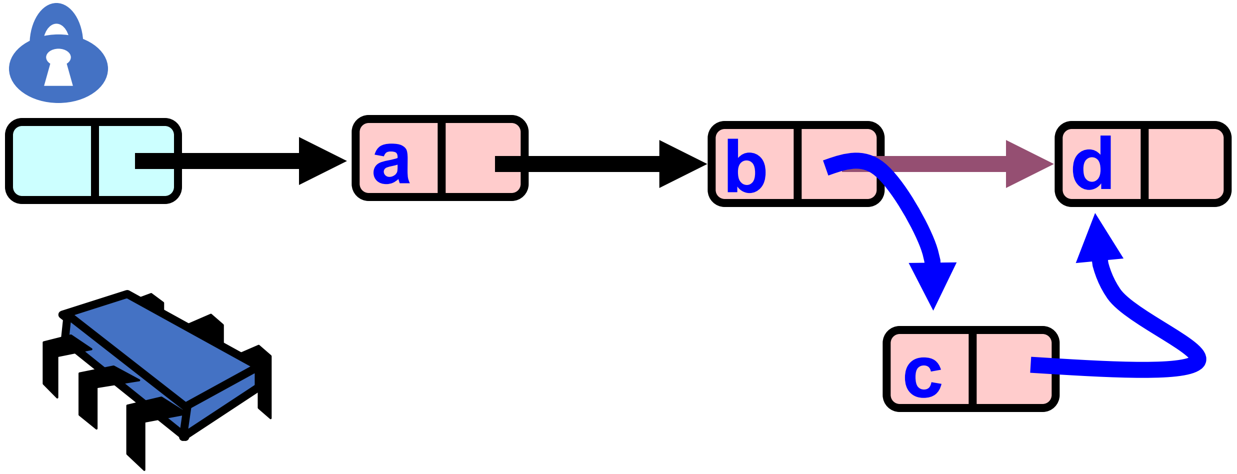
Schedule

- C++ Atomic Template
- Concurrent set
    - **Coarse-grained lock**
    - fine-grained lock
    - optimistic locking

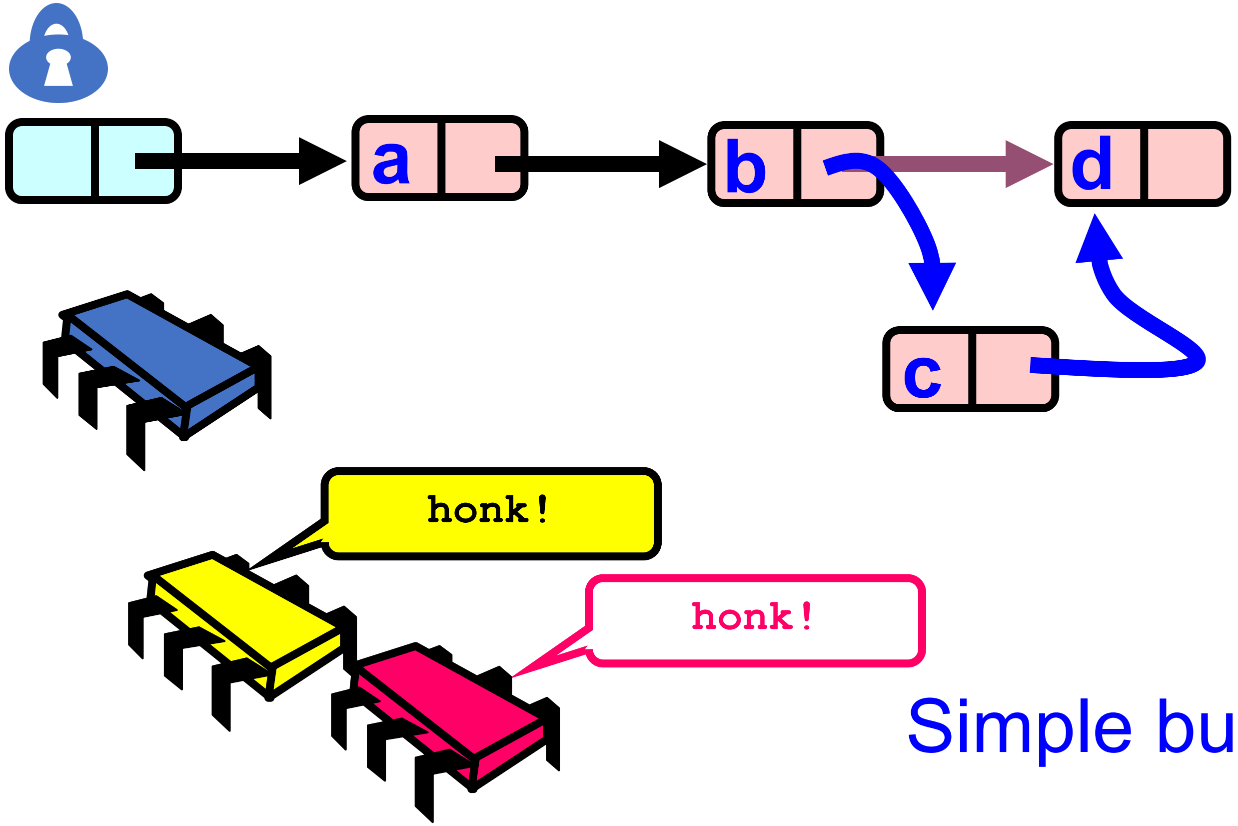
Coarse-Grained Locking



Coarse-Grained Locking



Coarse-Grained Locking



Simple but inefficient!

Schedule

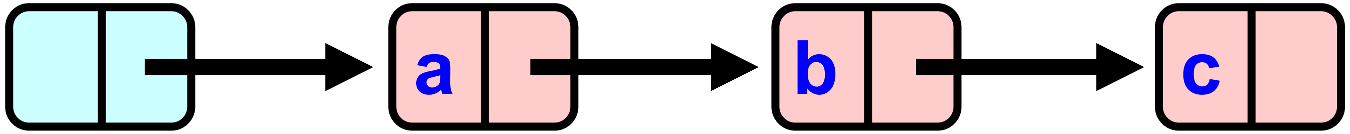
- C++ Atomic Template

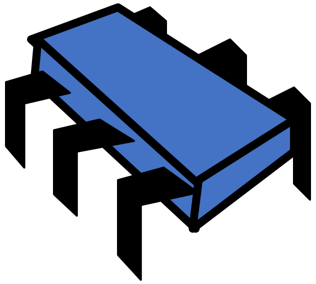
- Concurrent set
    - Coarse-grained lock
    - **fine-grained lock**
    - optimistic locking

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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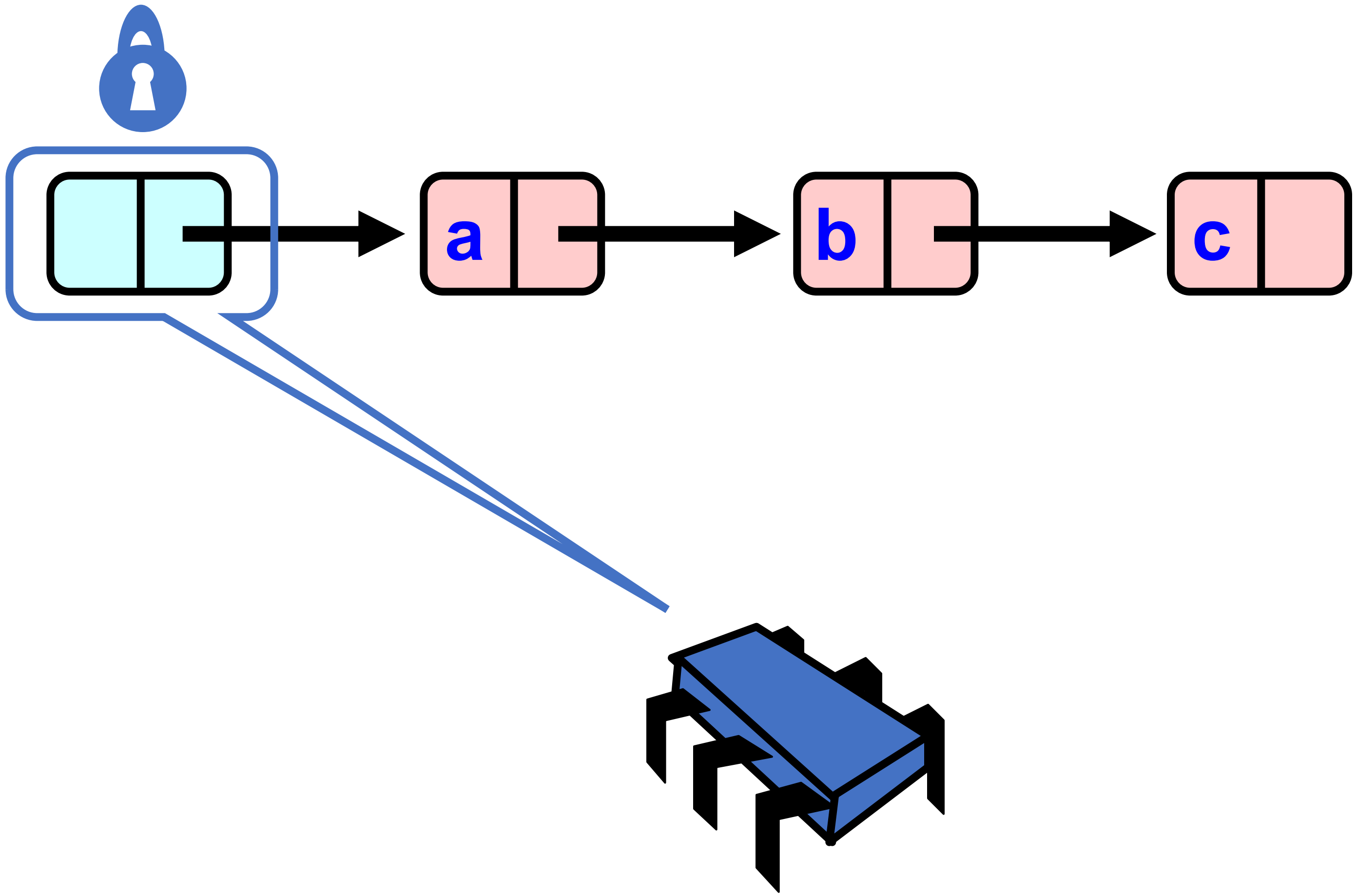

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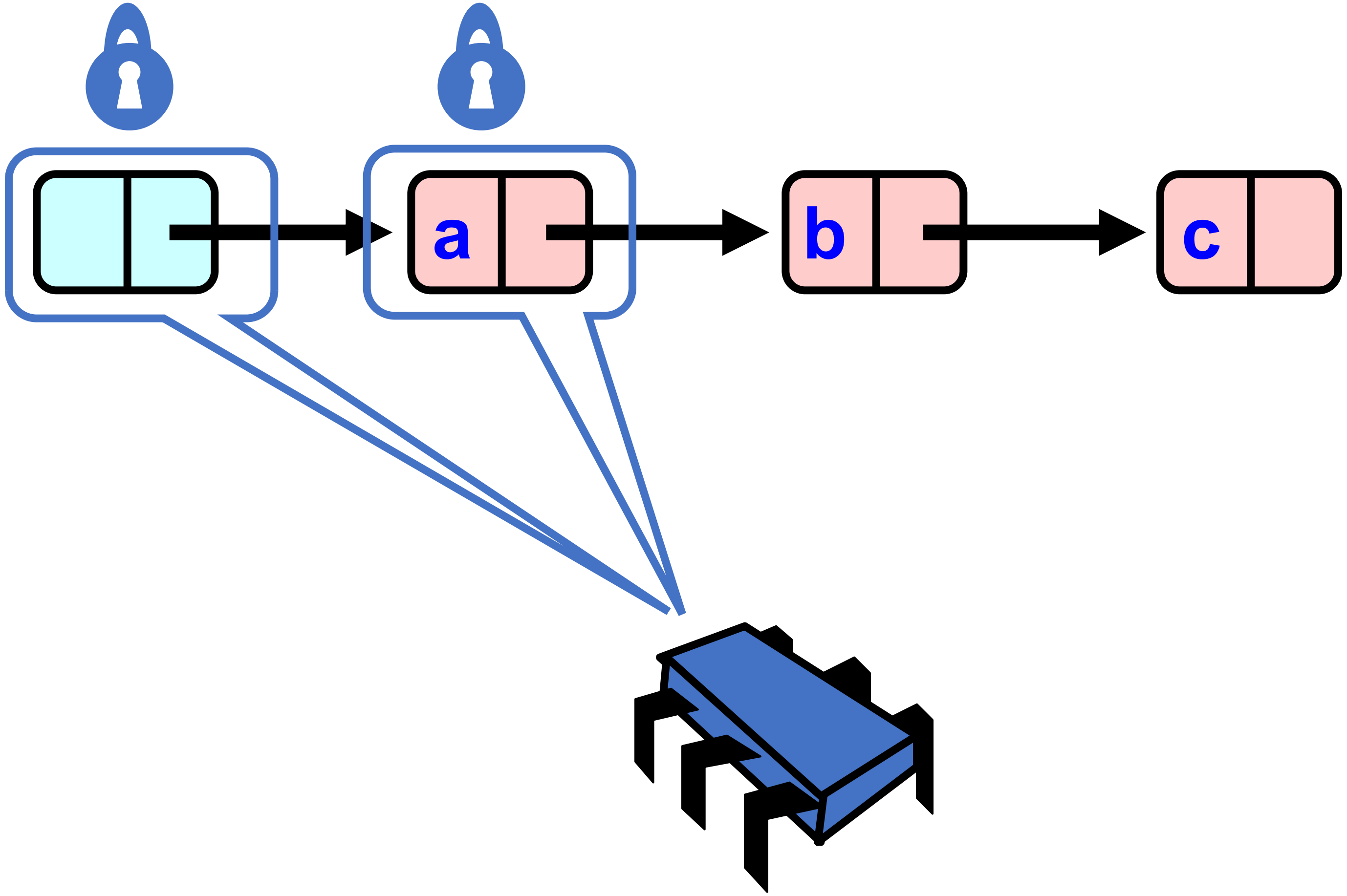

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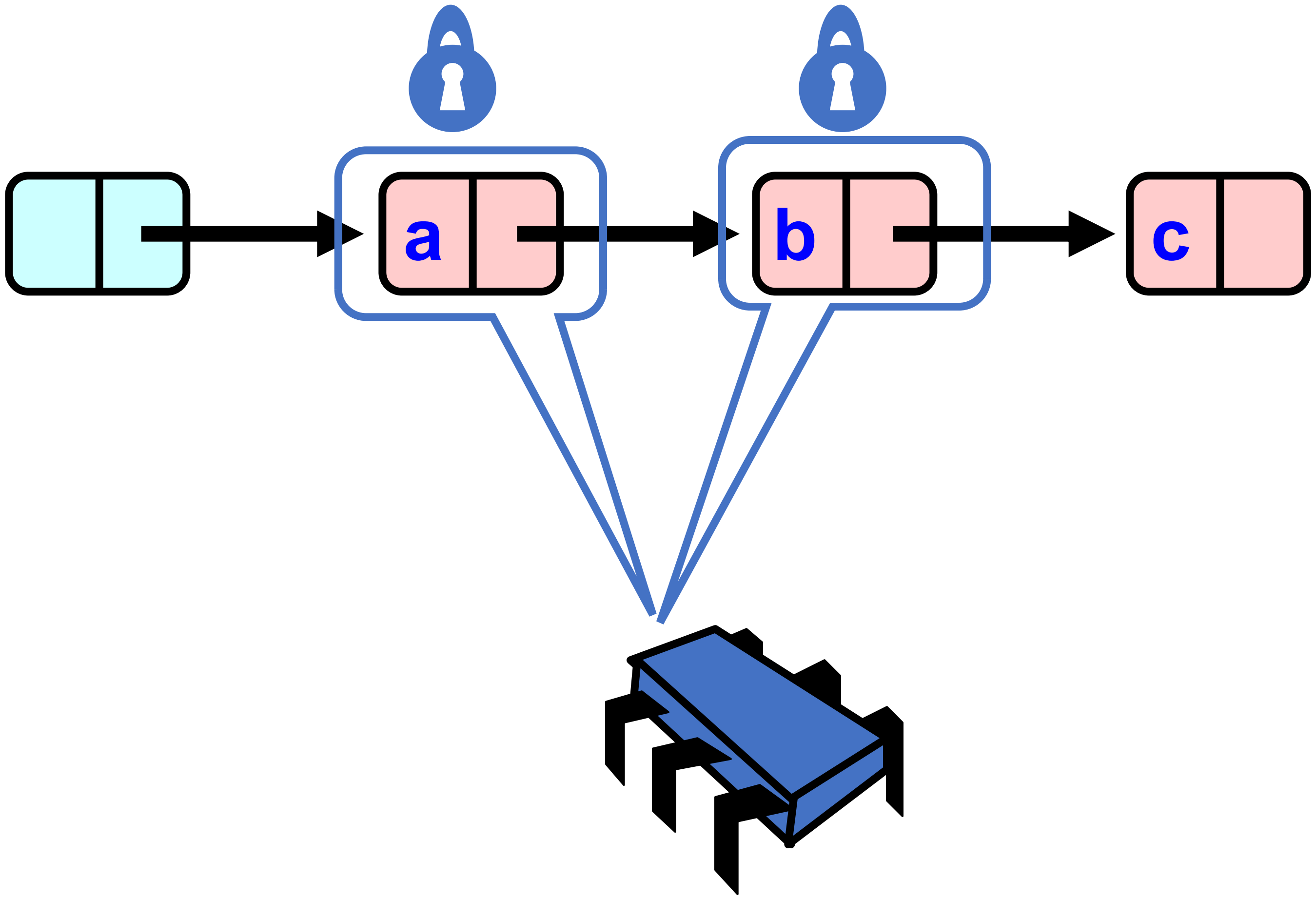

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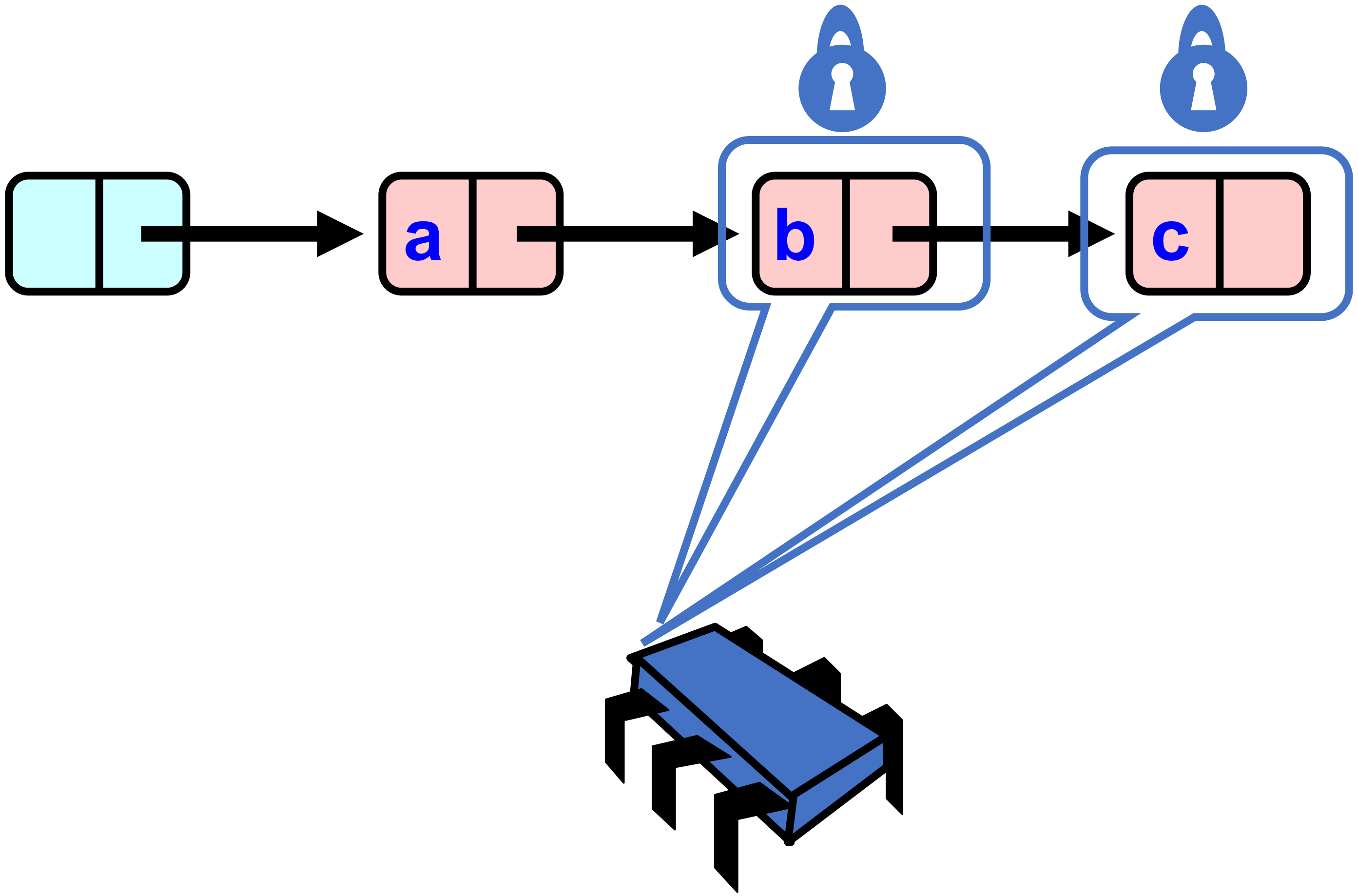
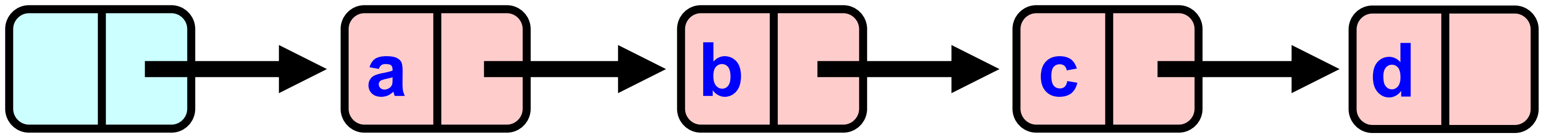
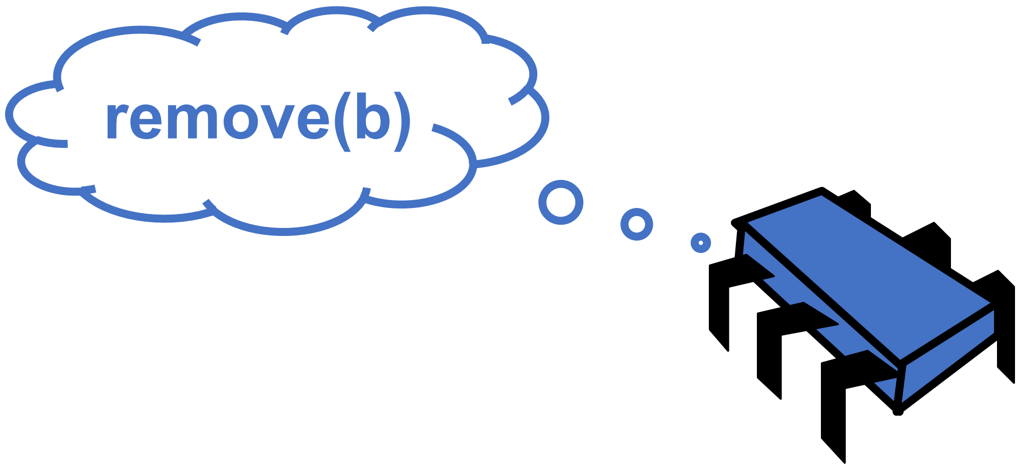


Removing a Node





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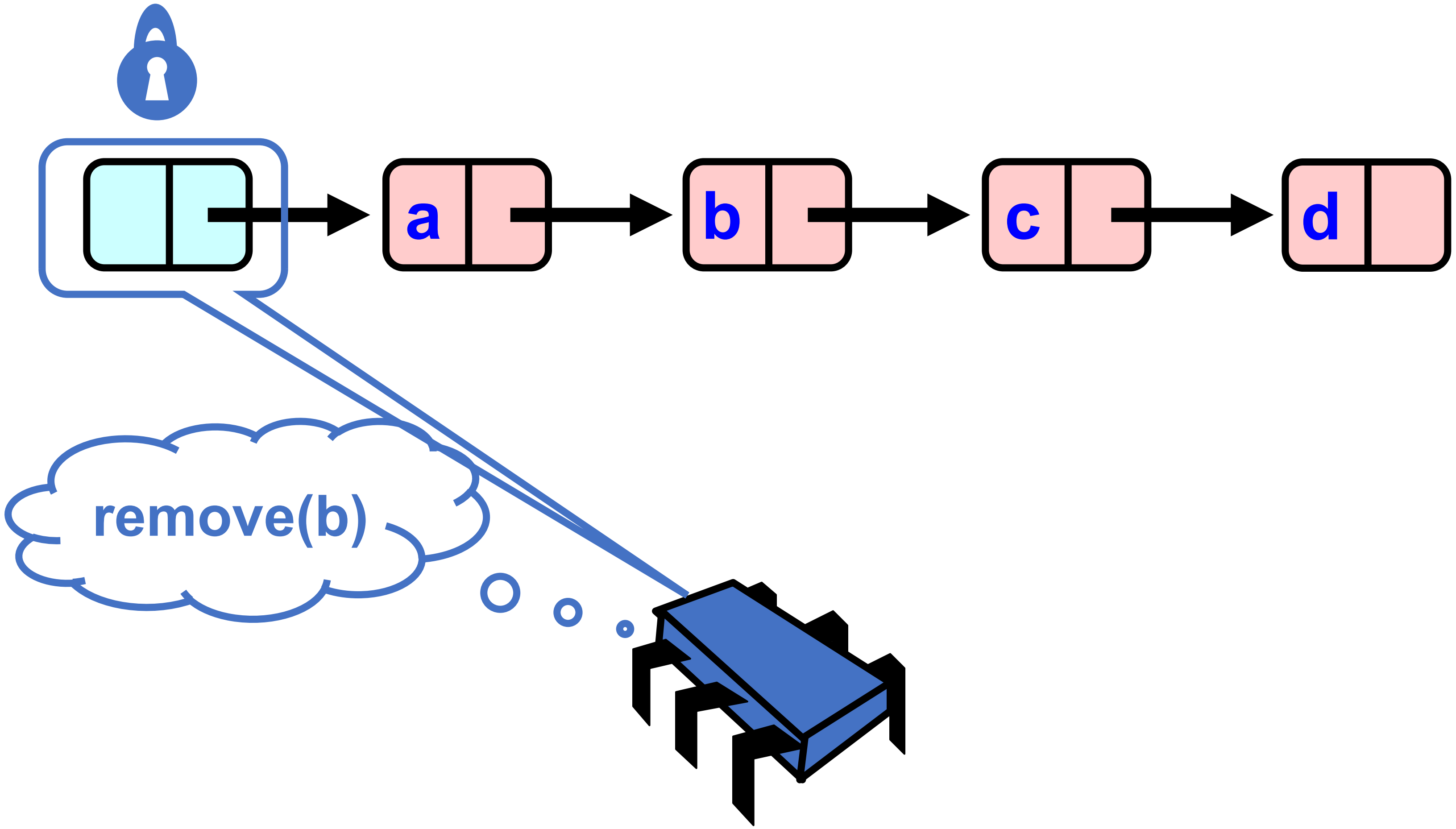

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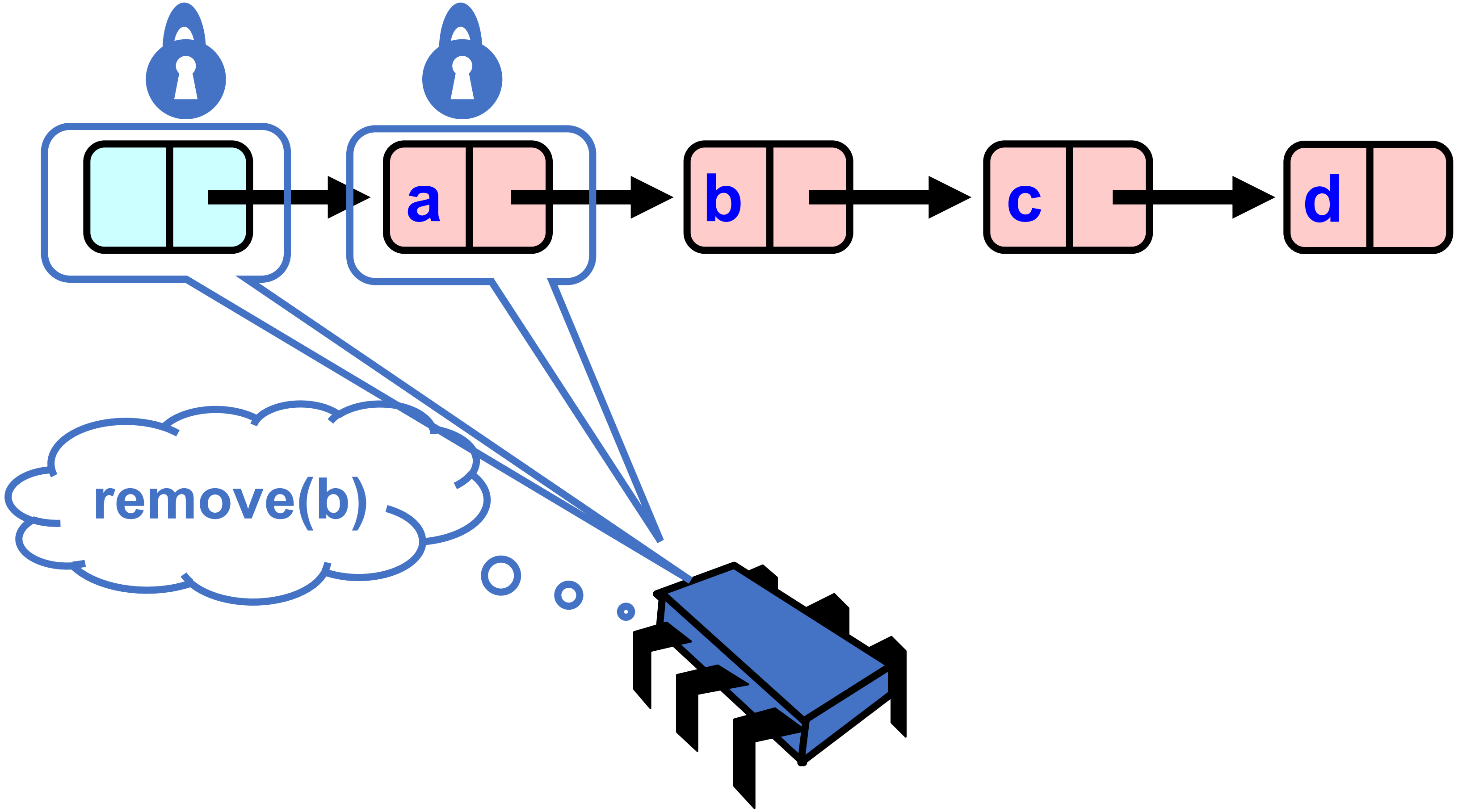

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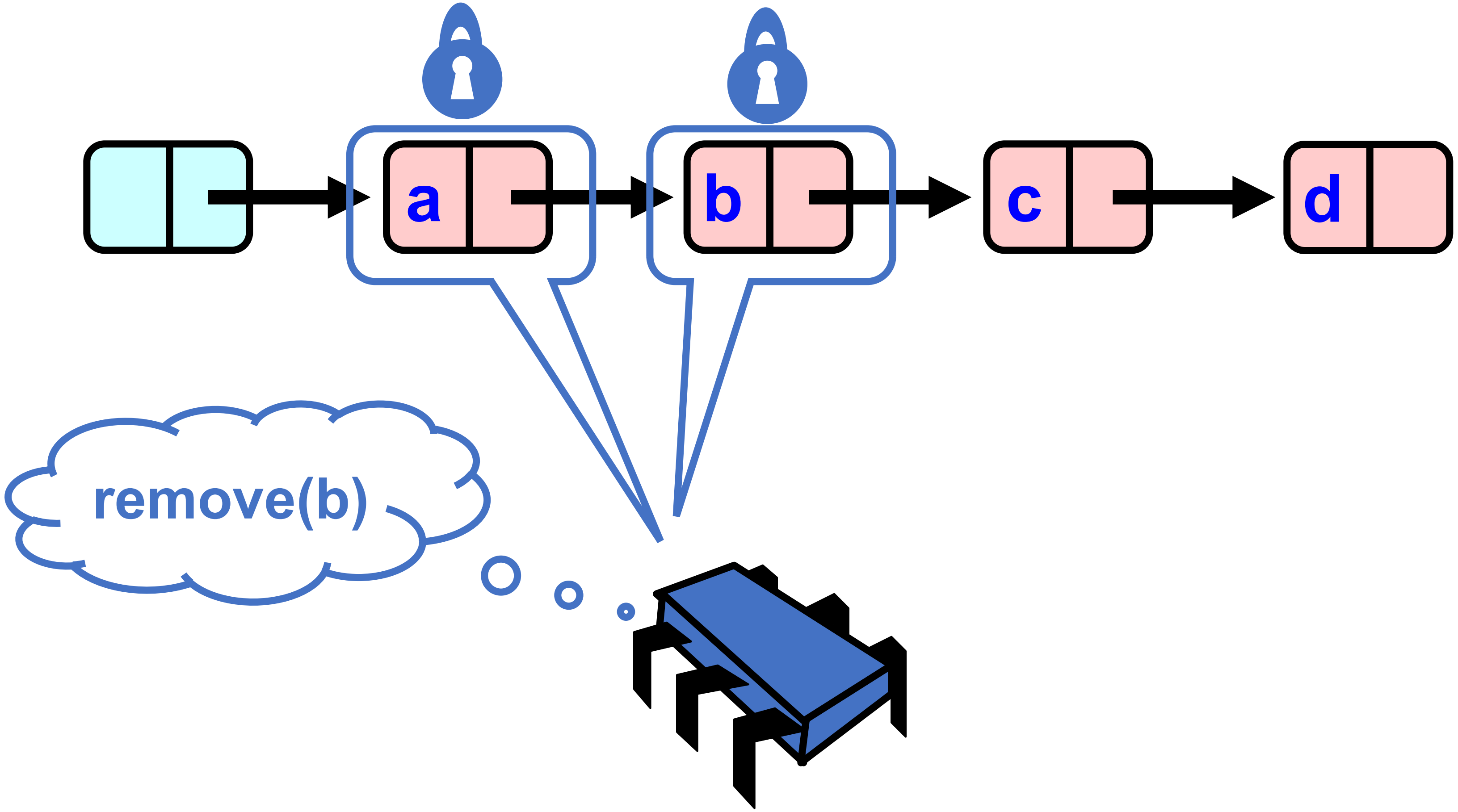

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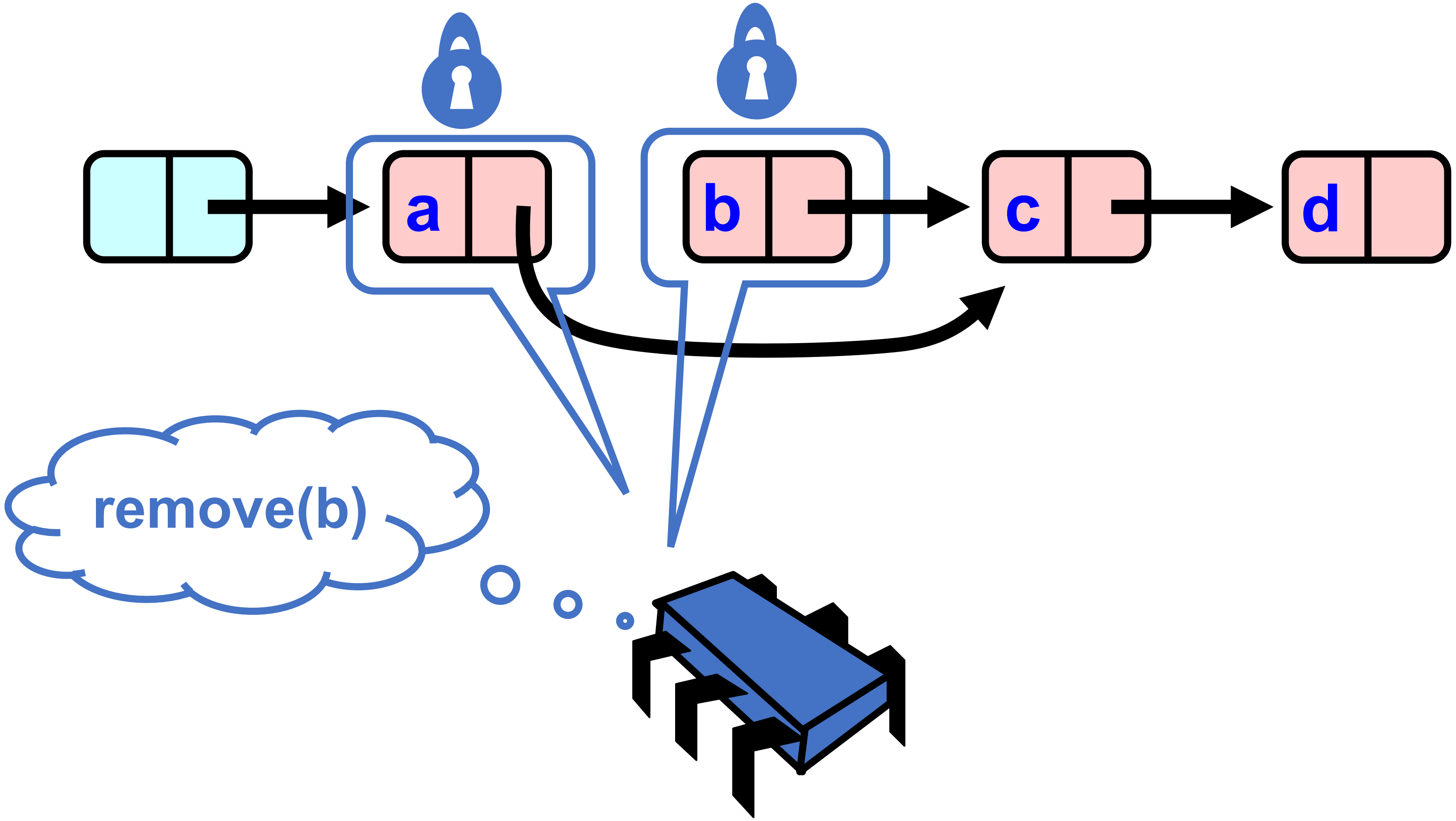

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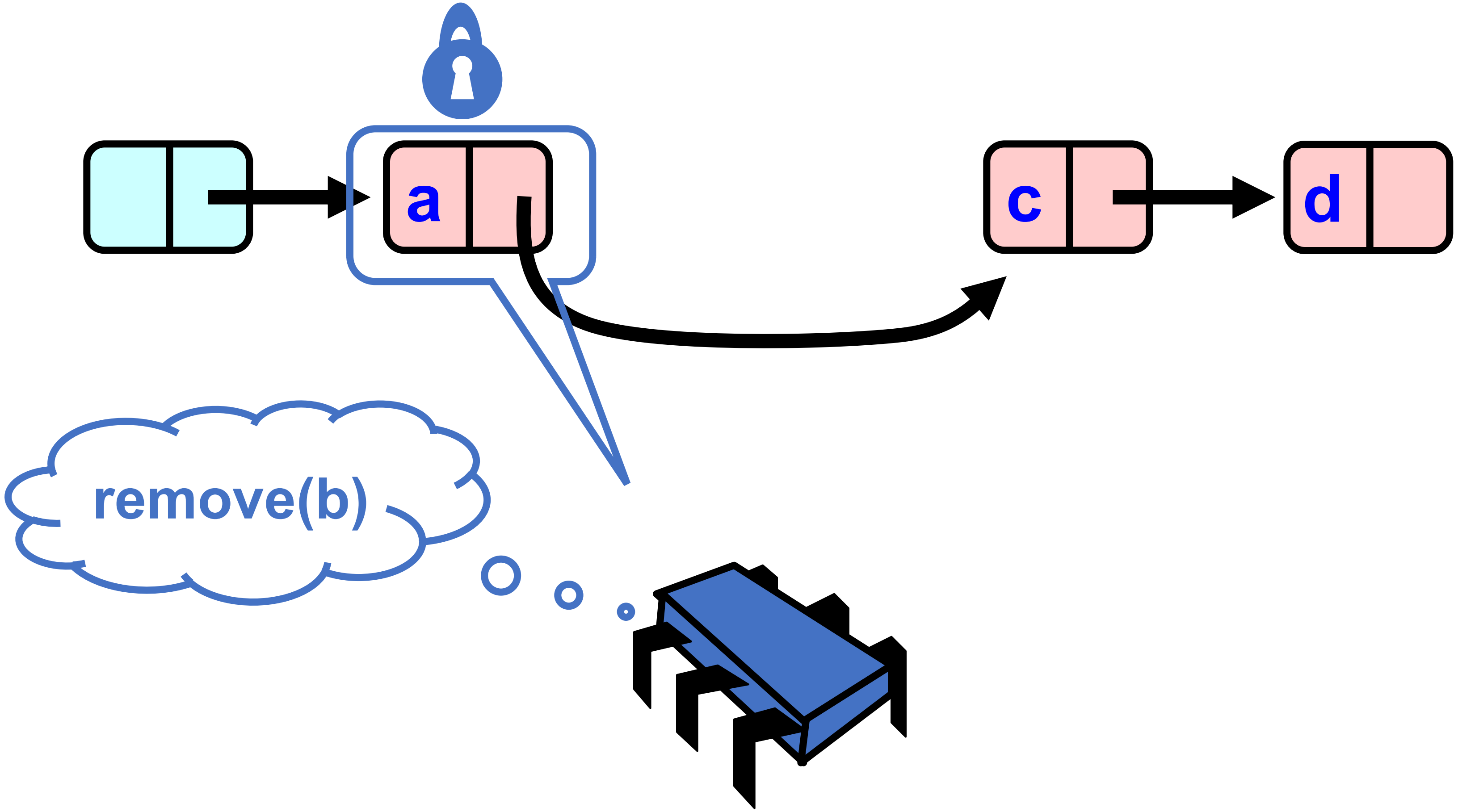

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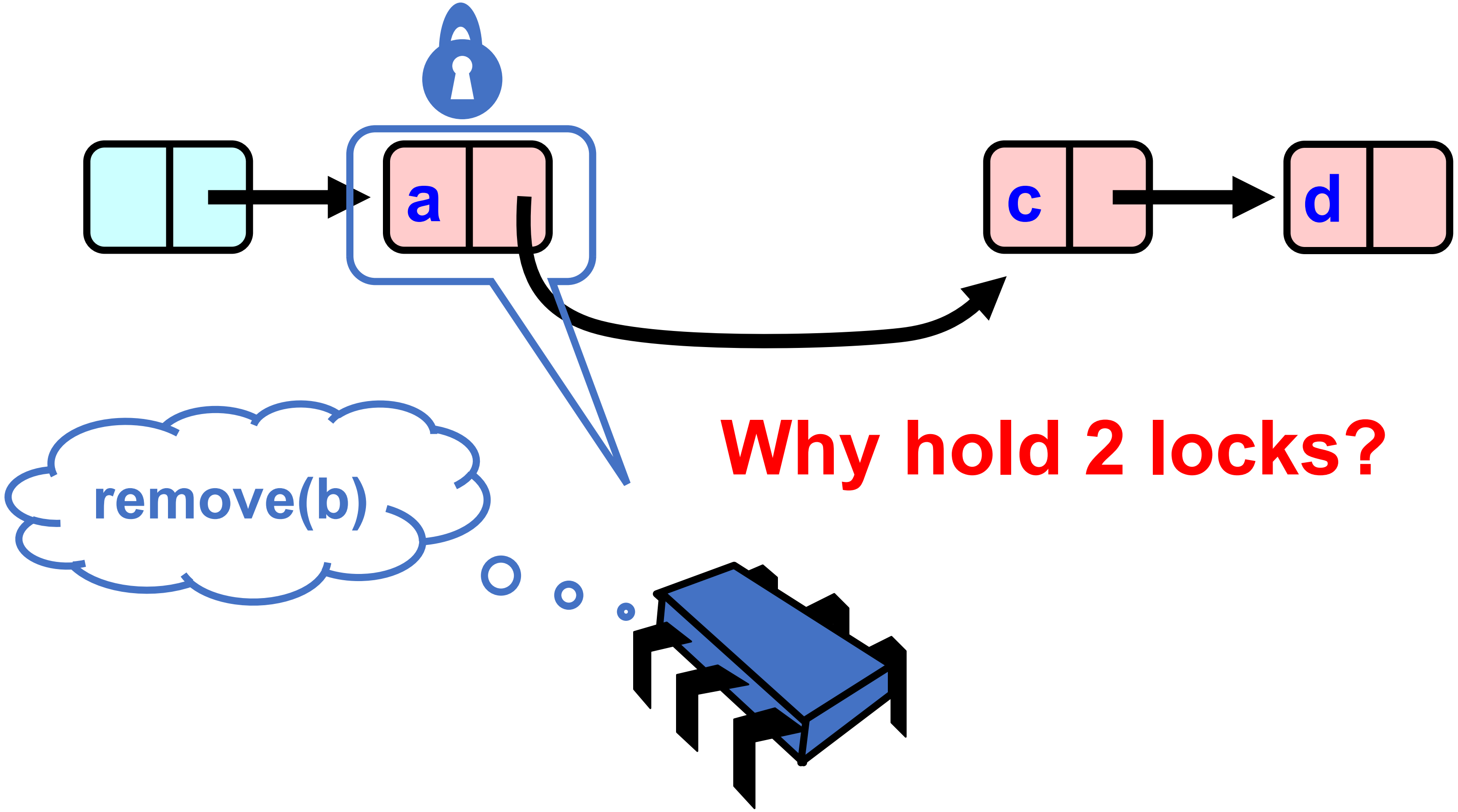
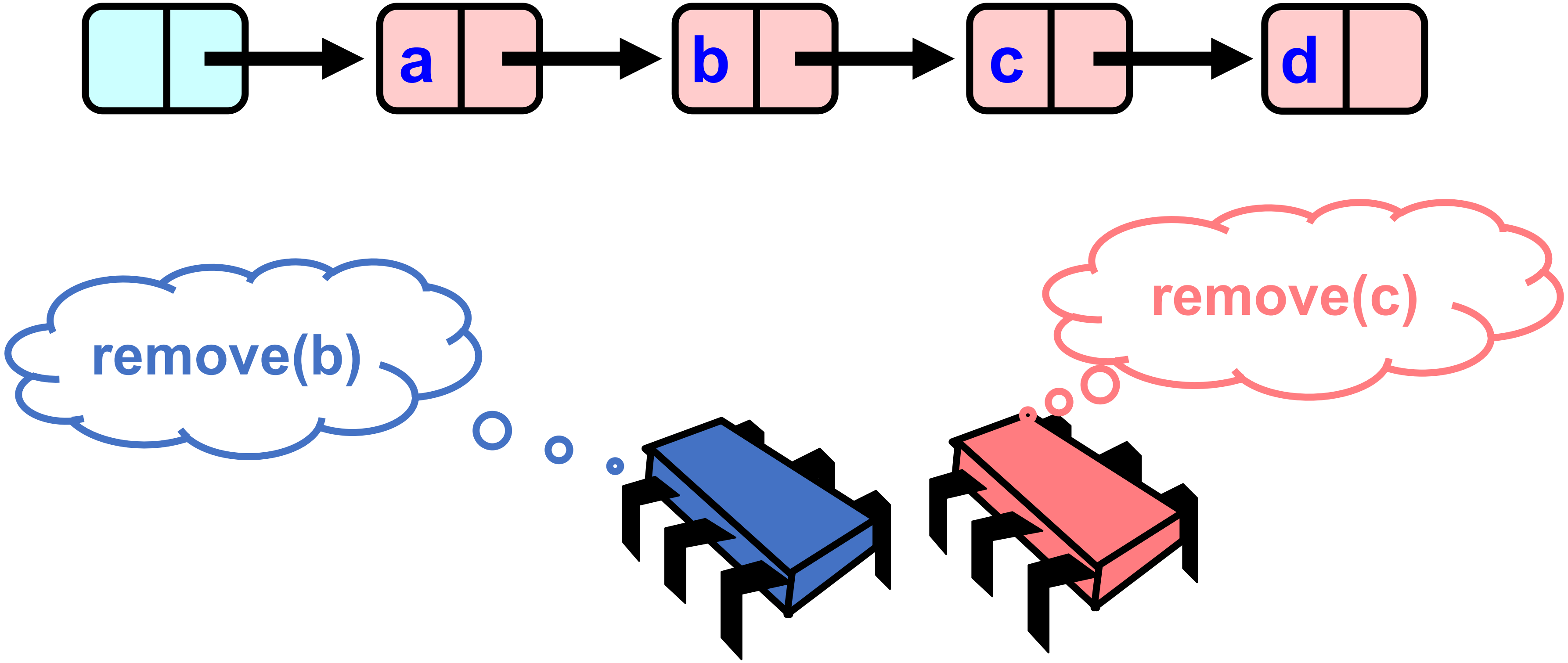


Why hold 2 locks?

Concurrent Removes



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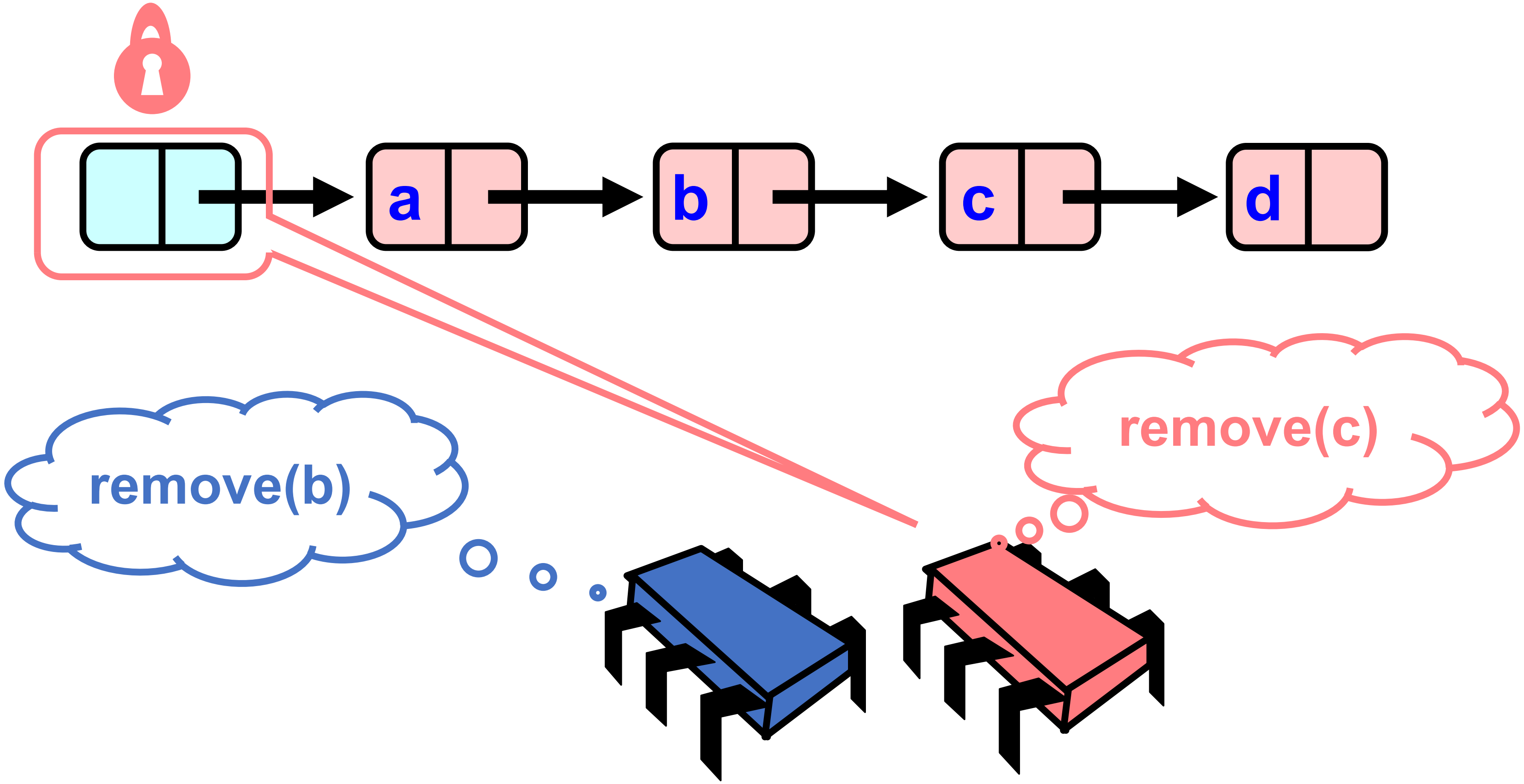

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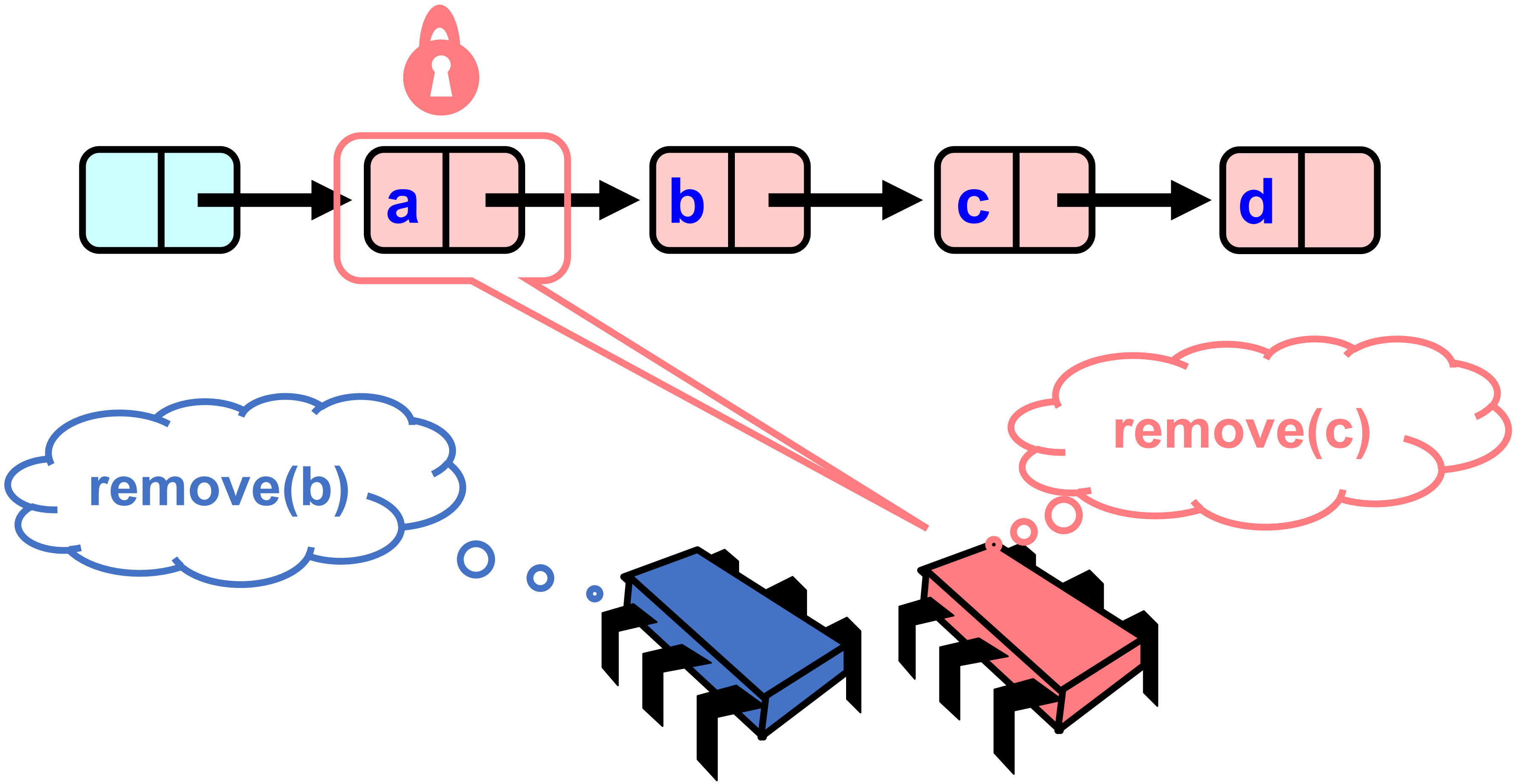

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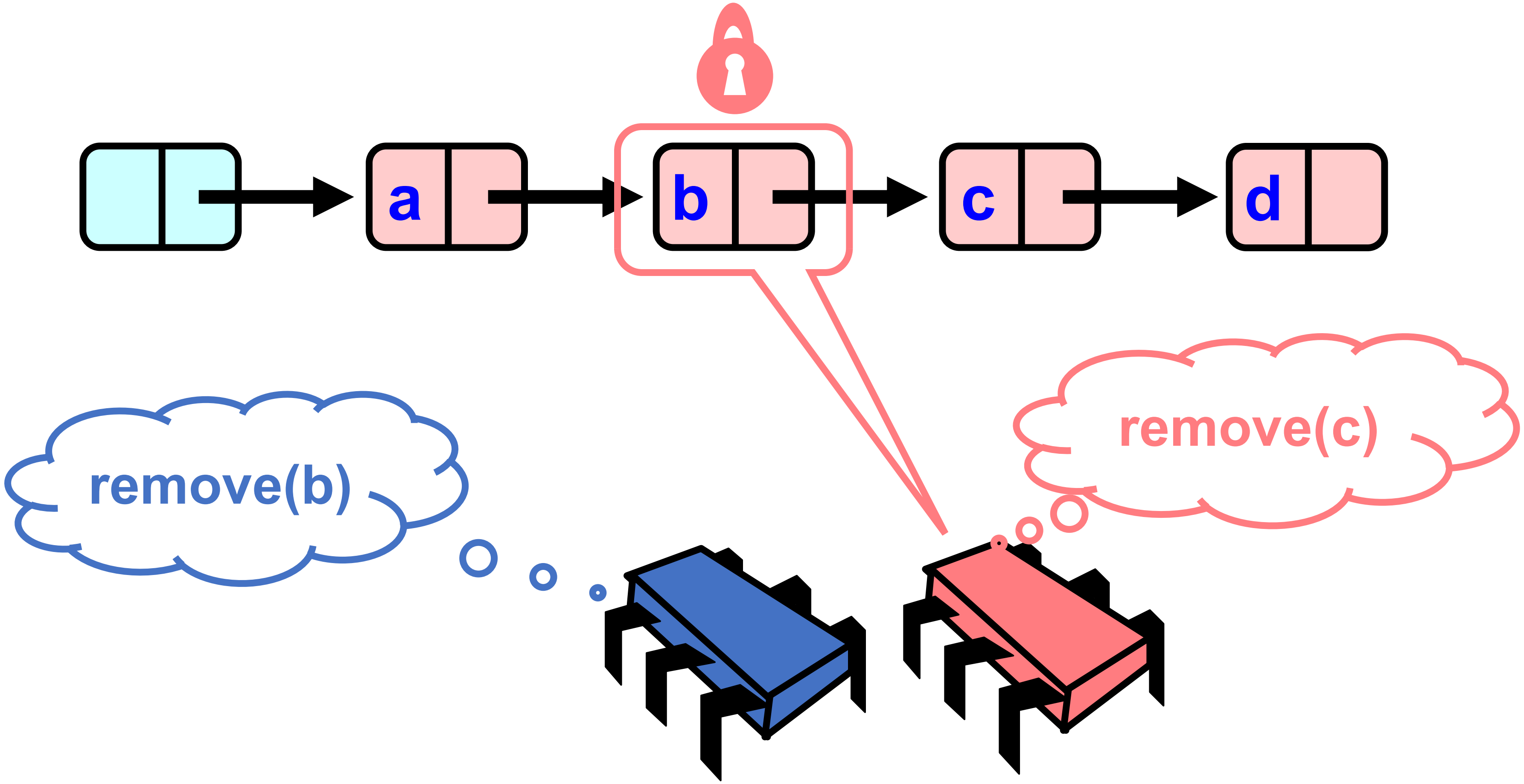

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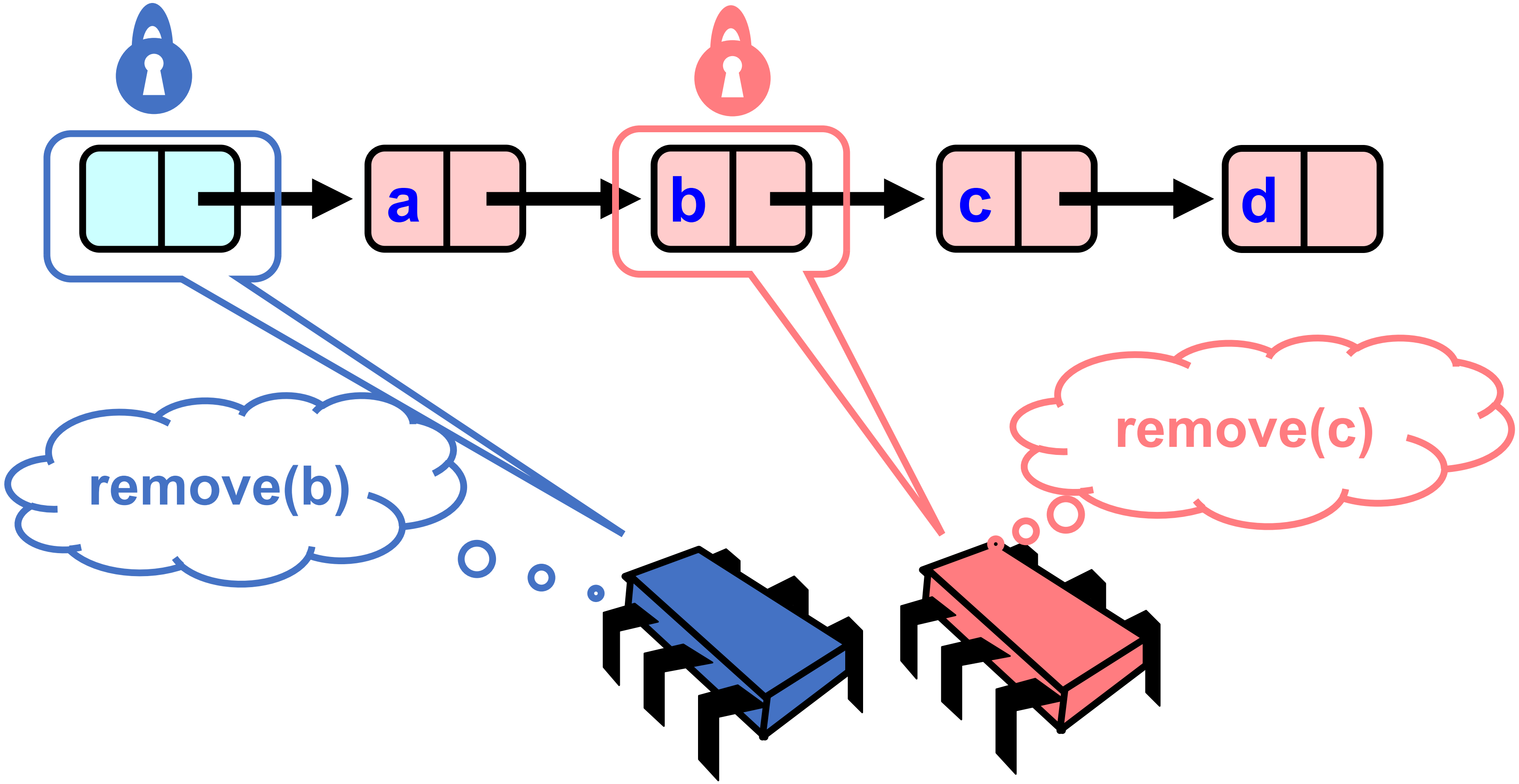

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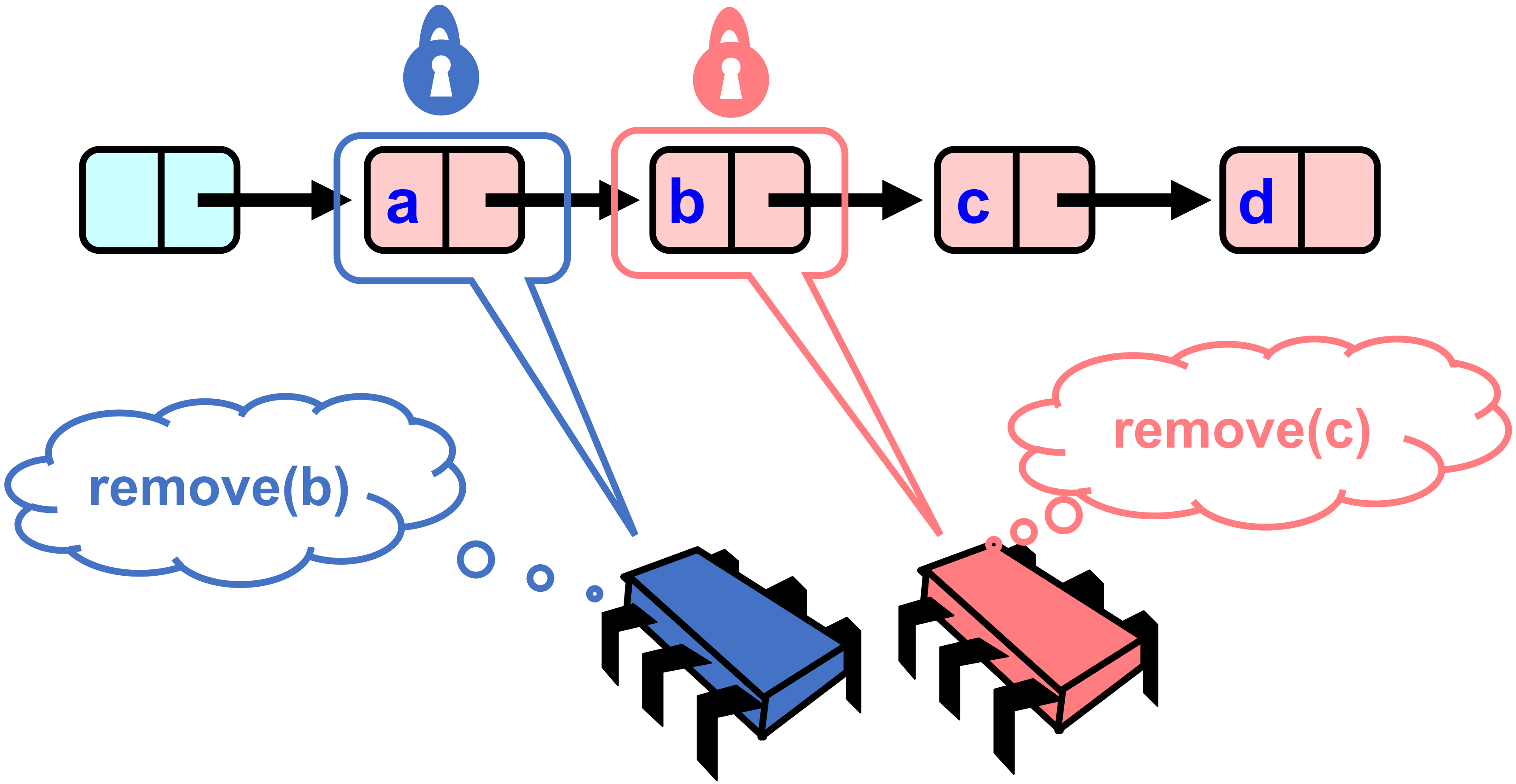

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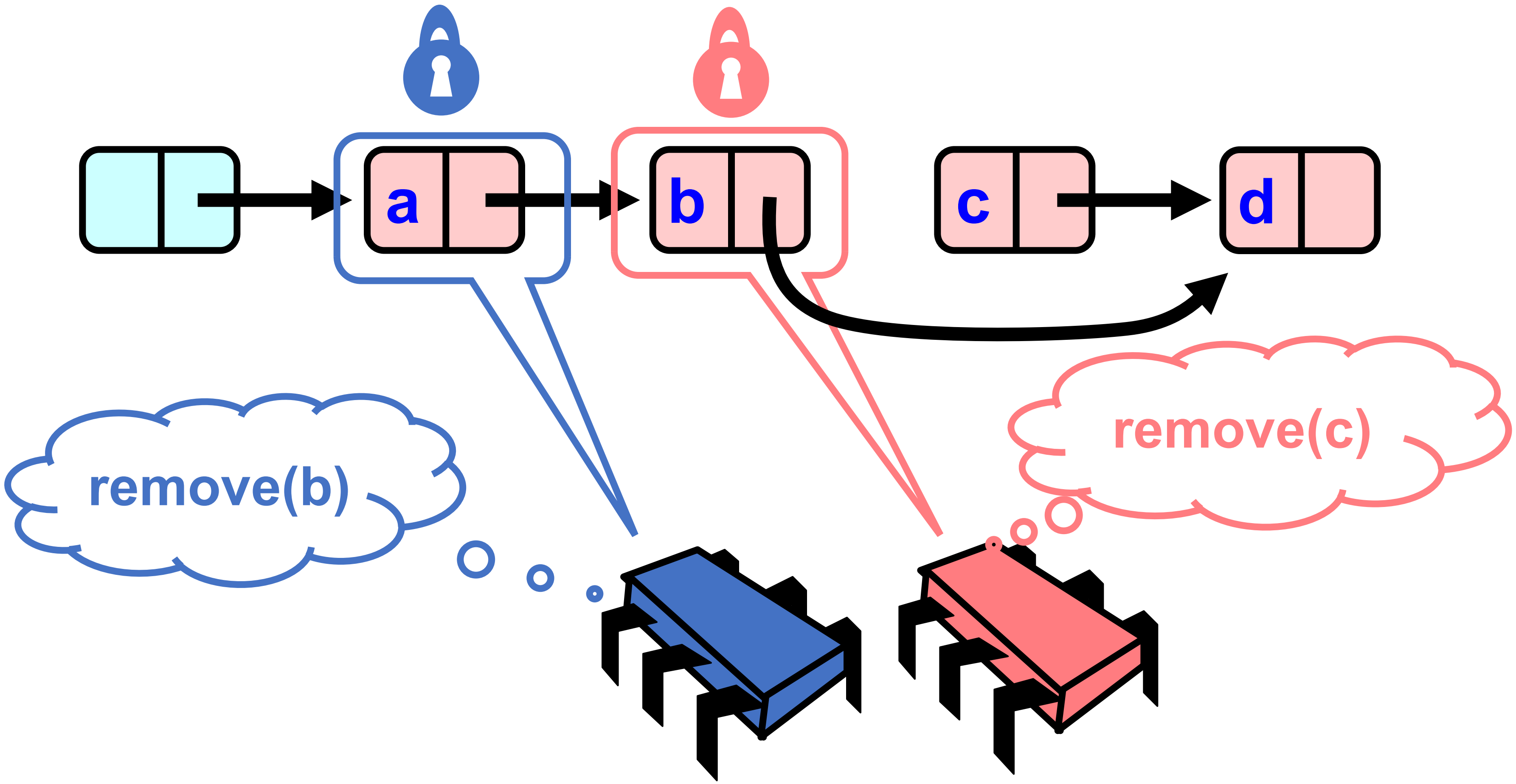

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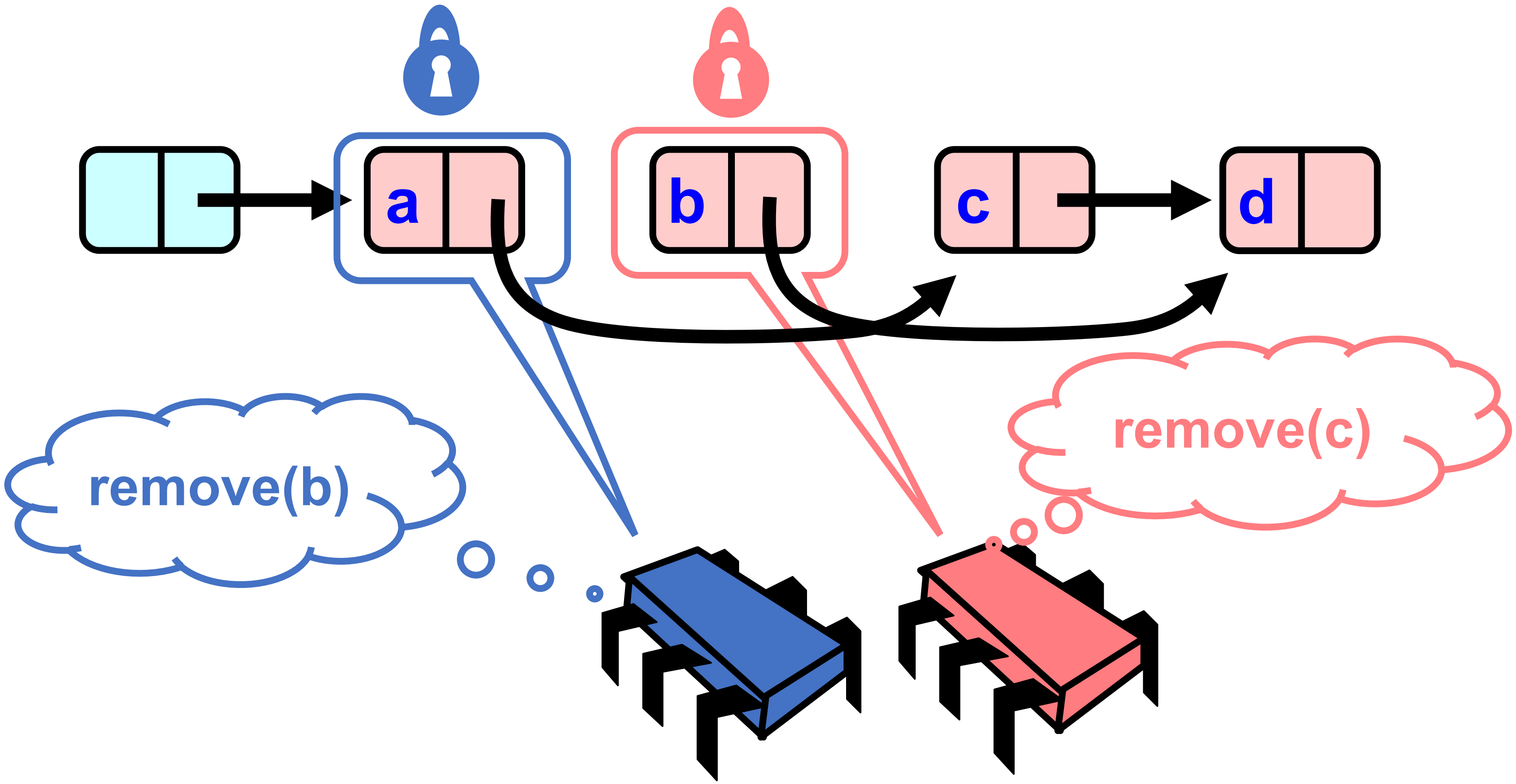
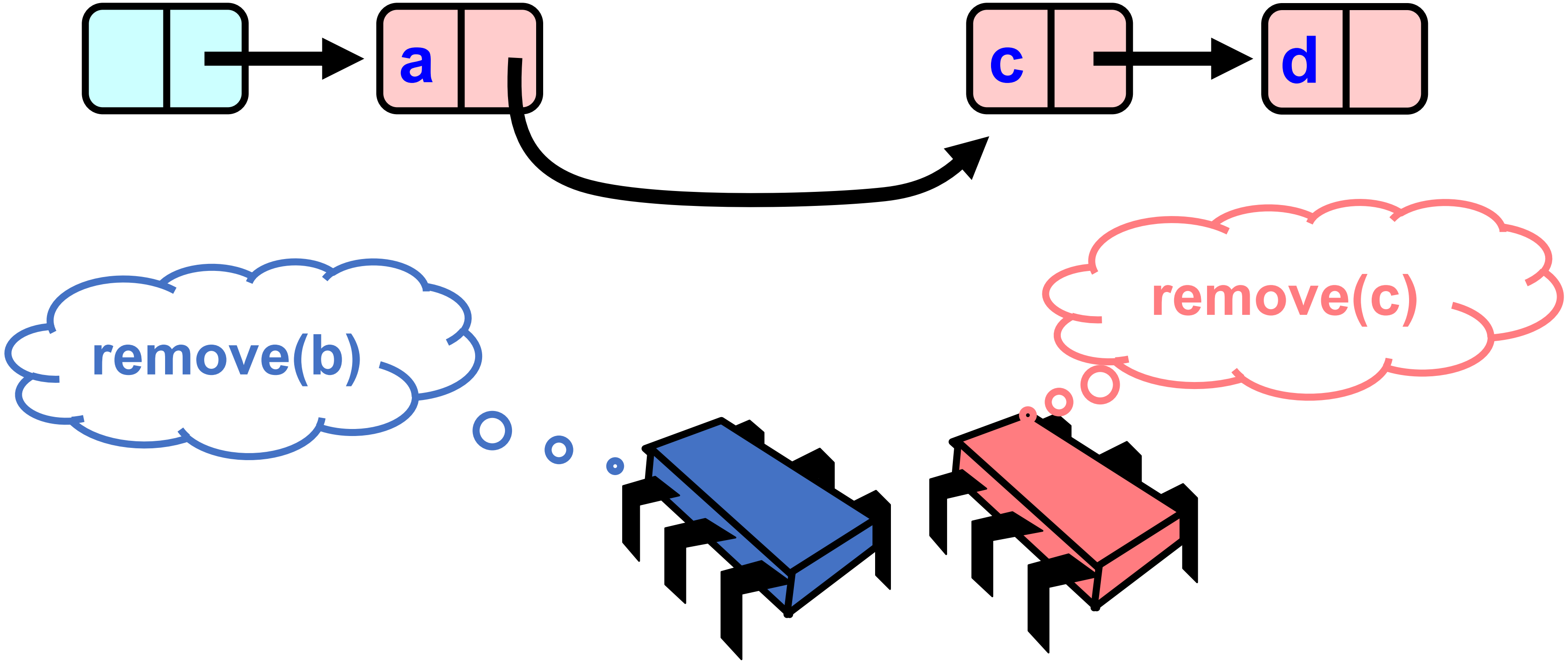


Uh, Oh



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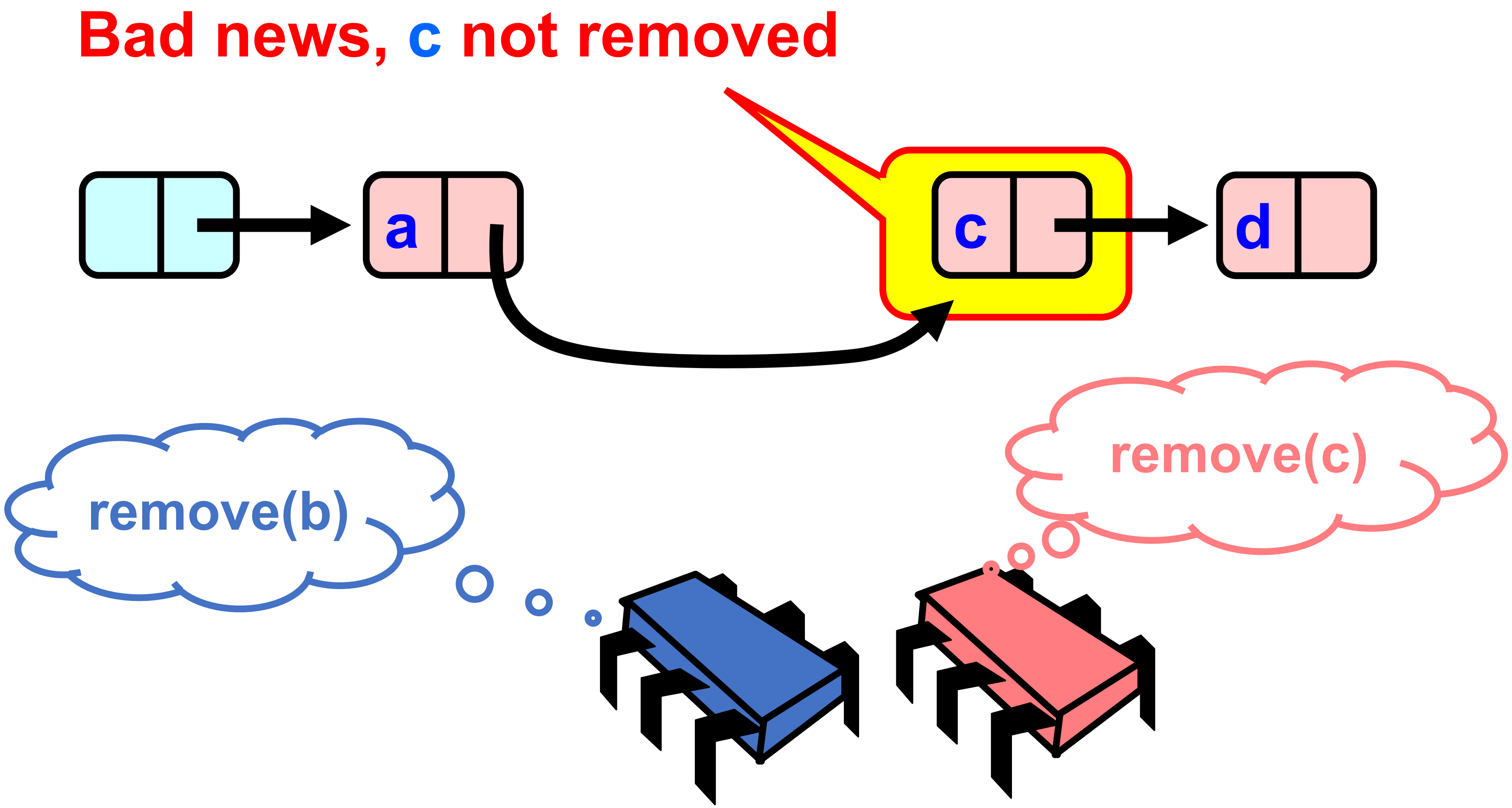
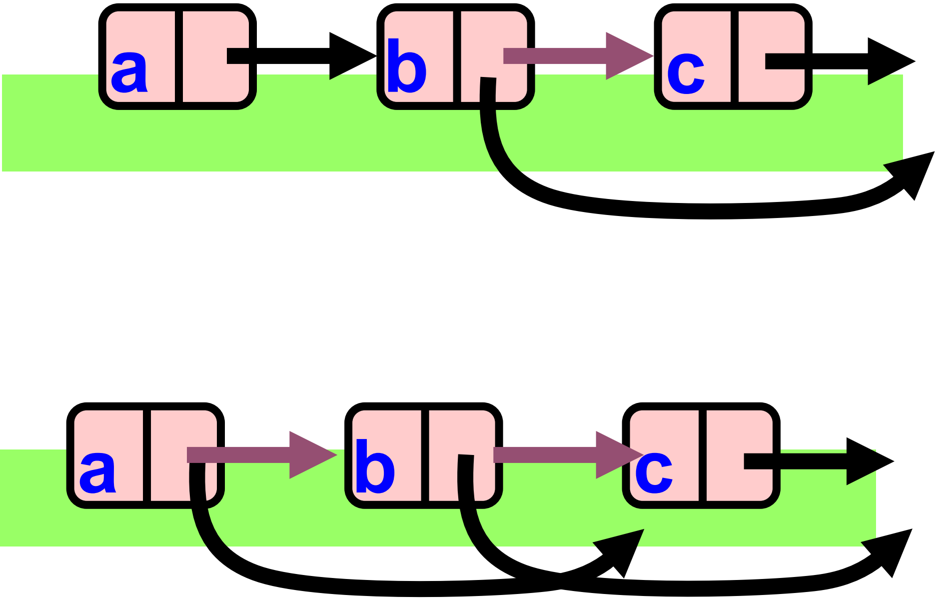


Problem

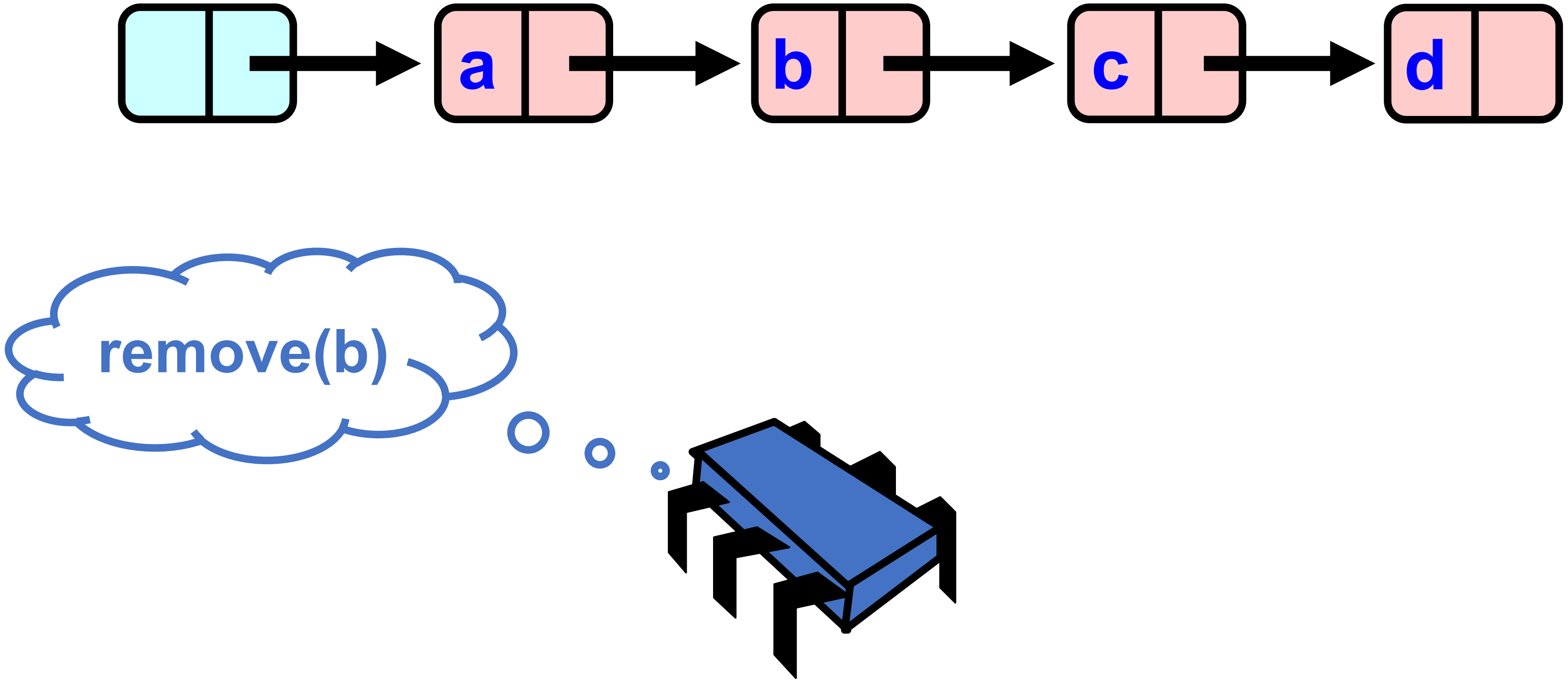
- To delete node c
  - Swing node b's next field to d
- Problem is,
  - ***Data conflict:***
  - Someone deleting b concurrently could direct a pointer to C



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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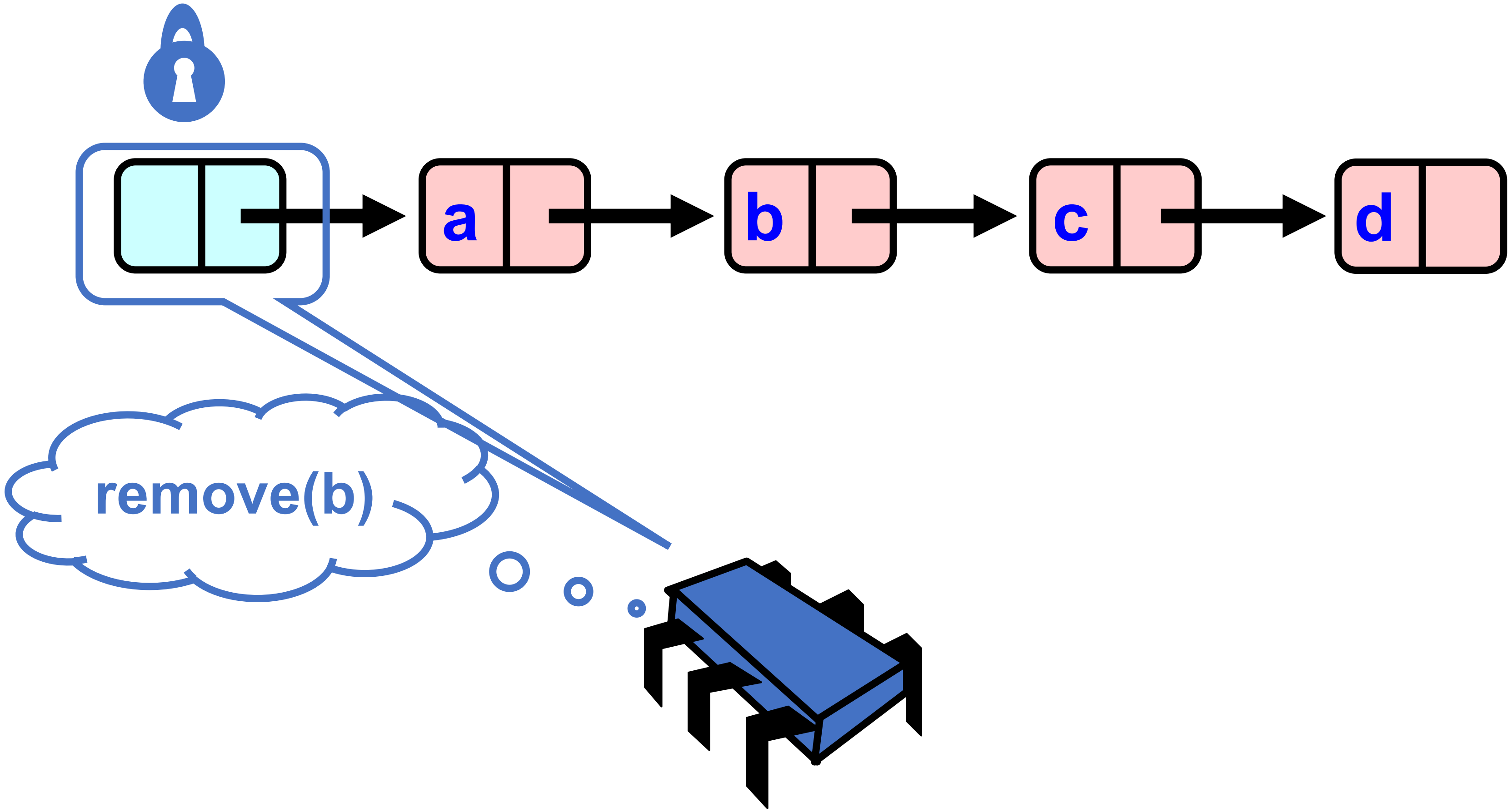

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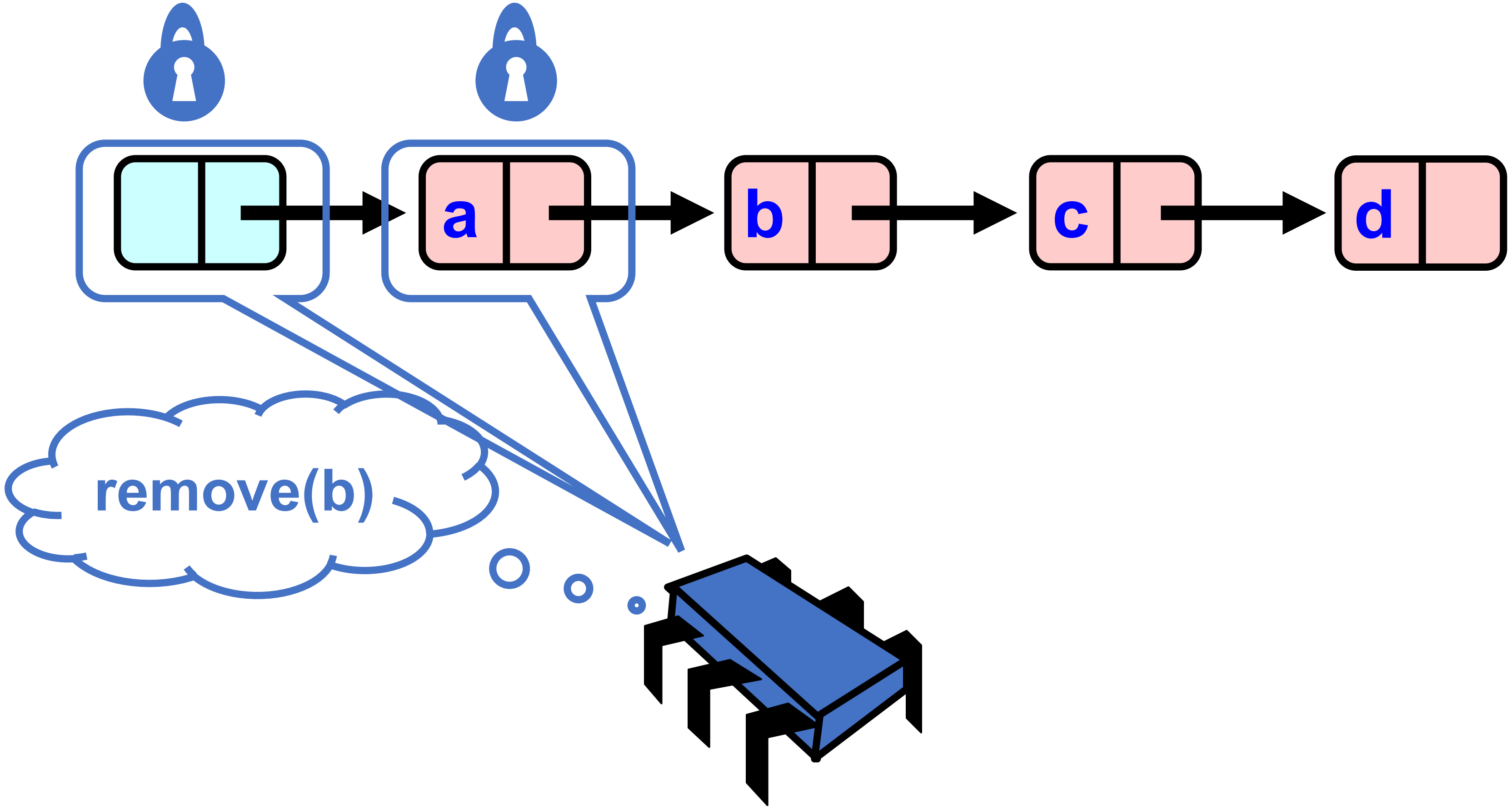

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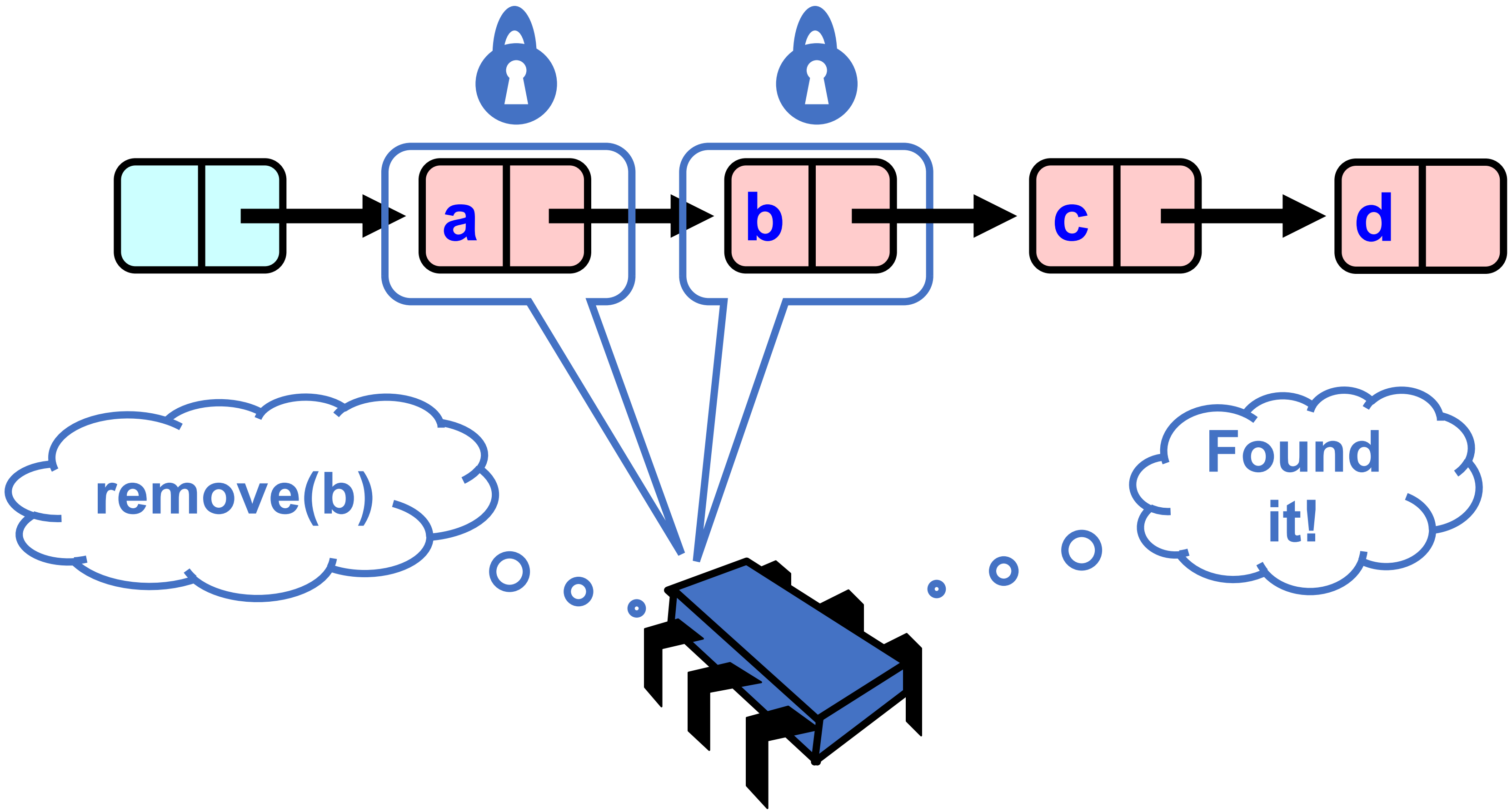

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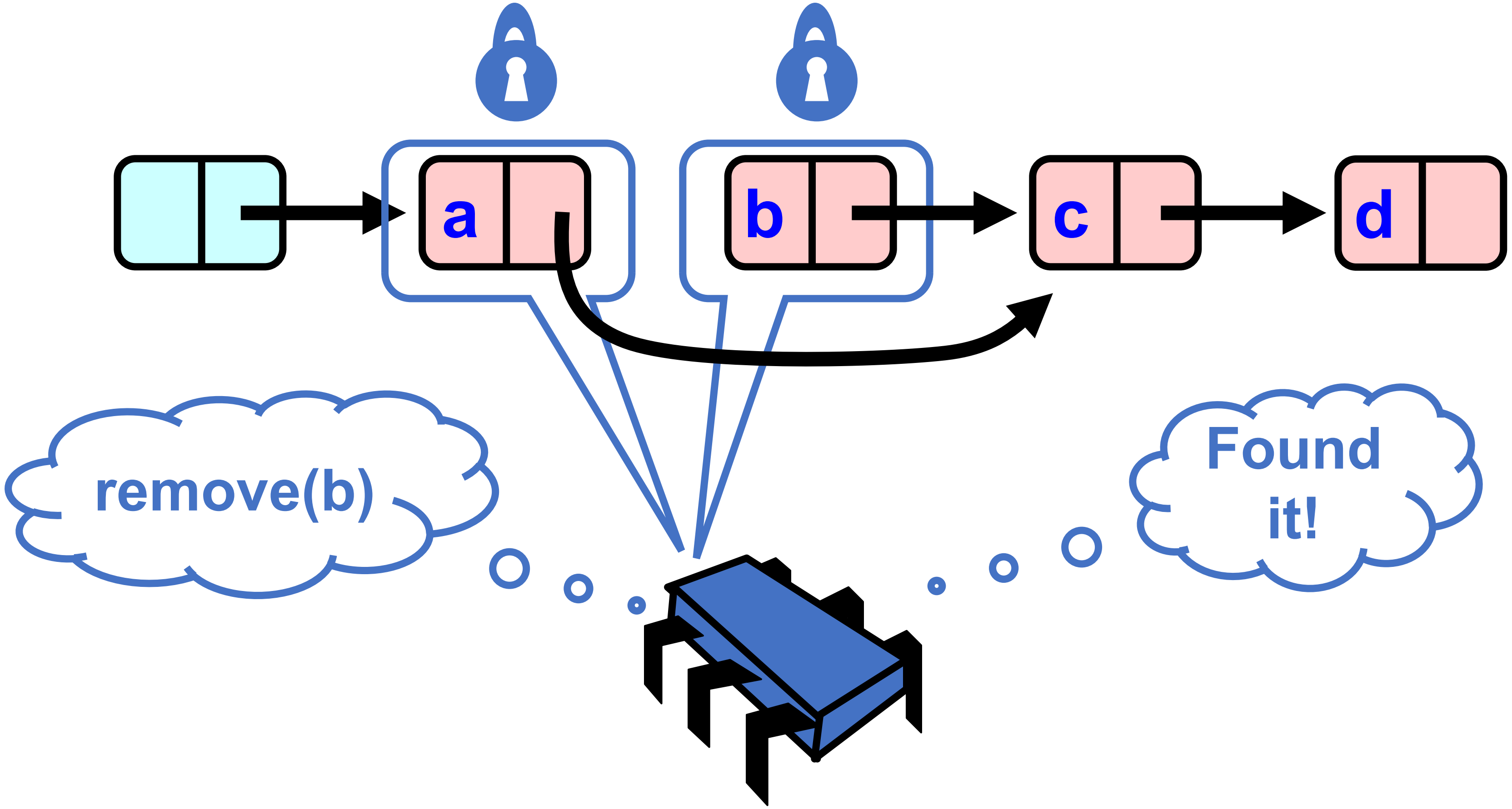

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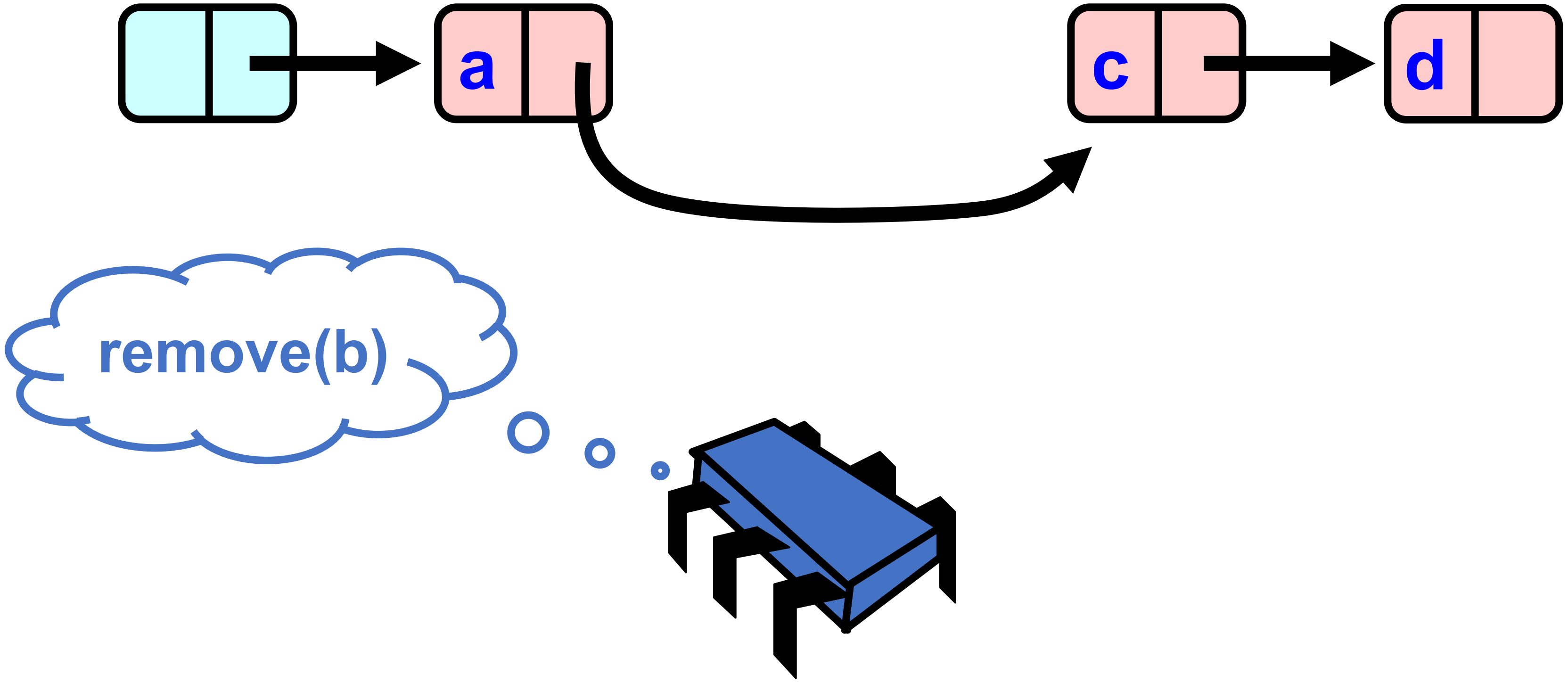
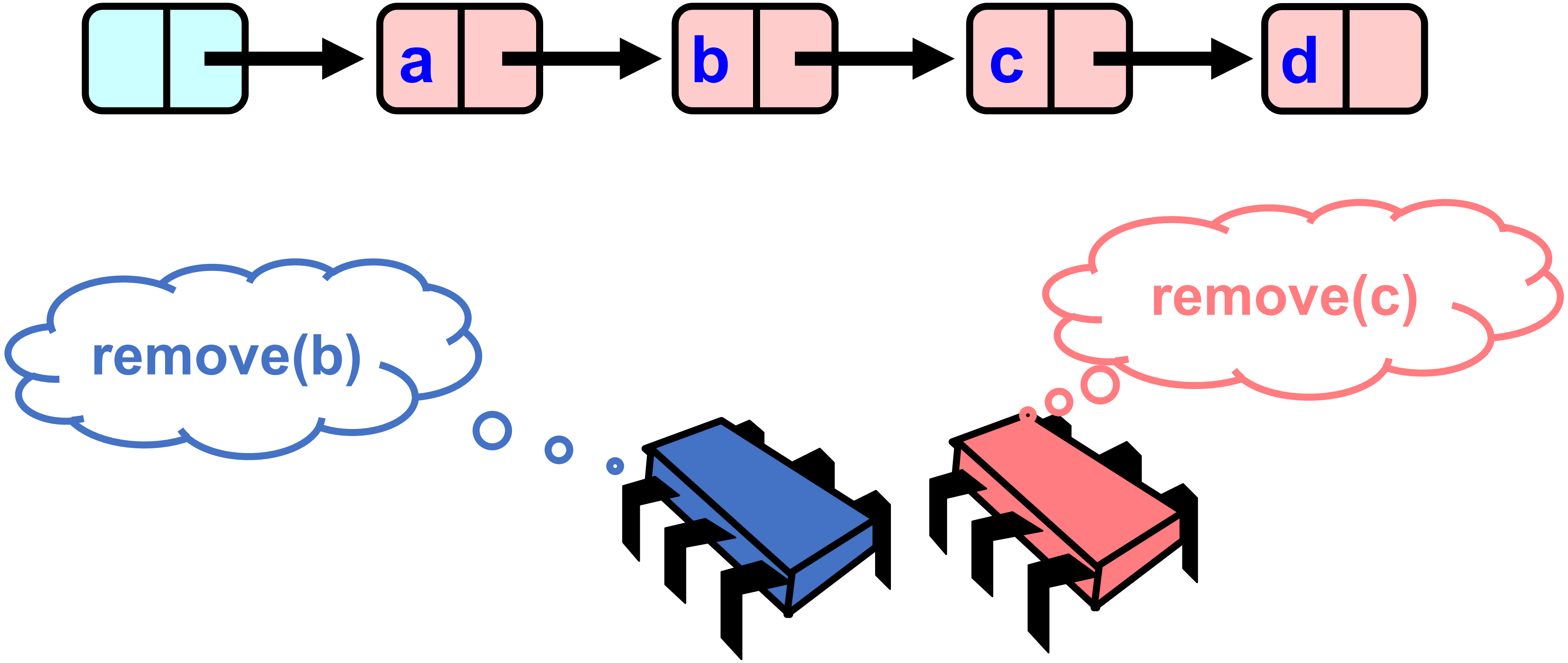


Removing a Node



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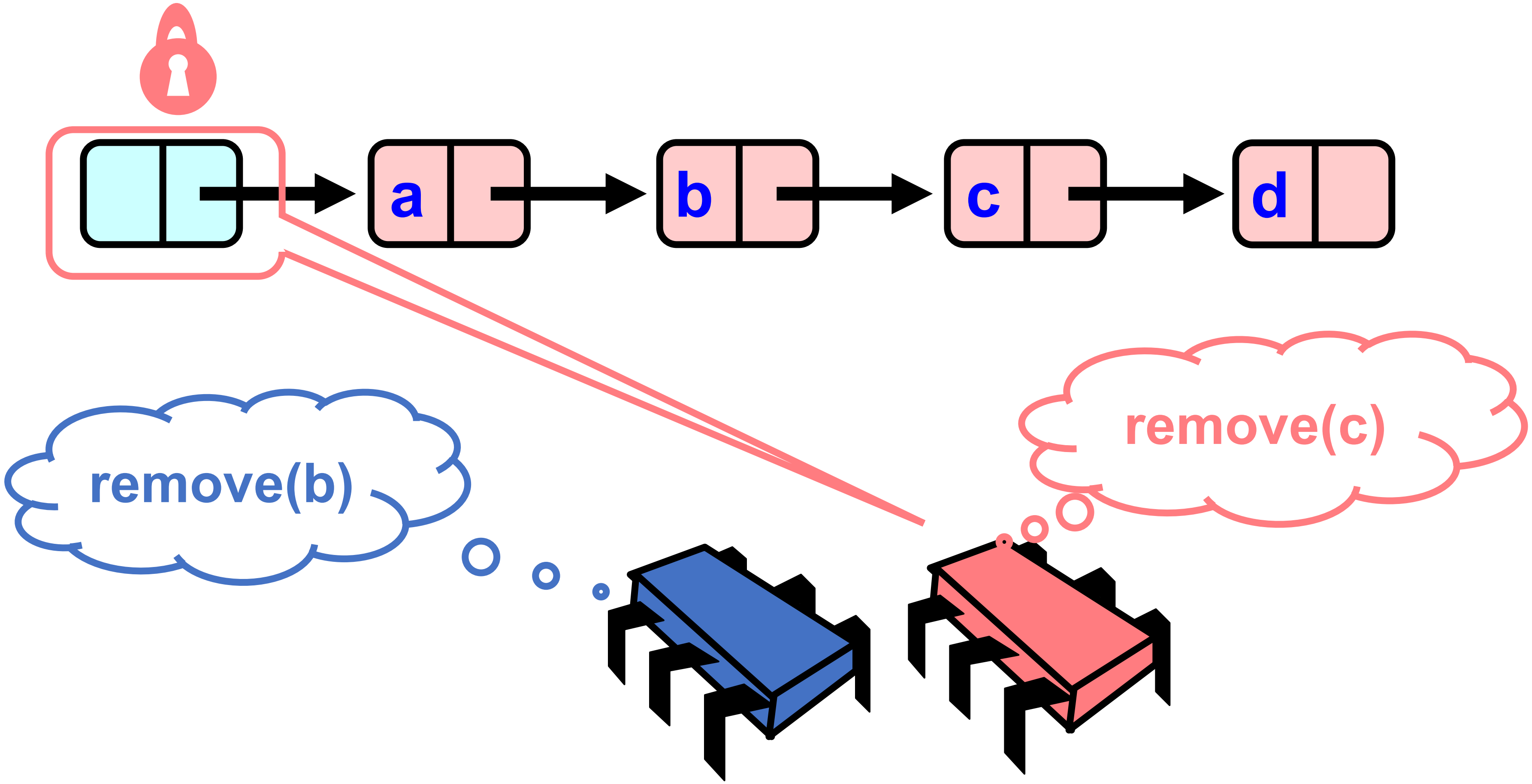

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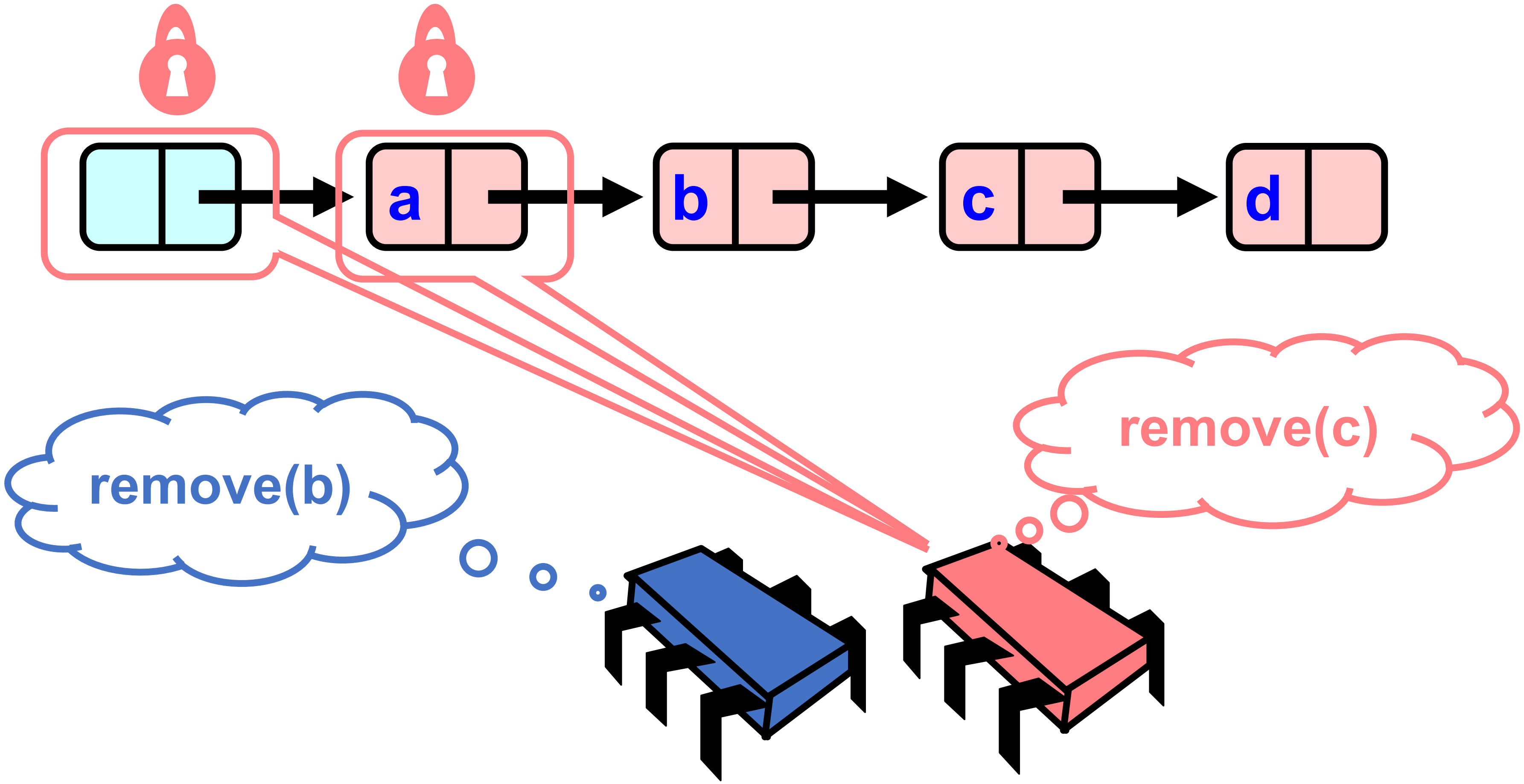

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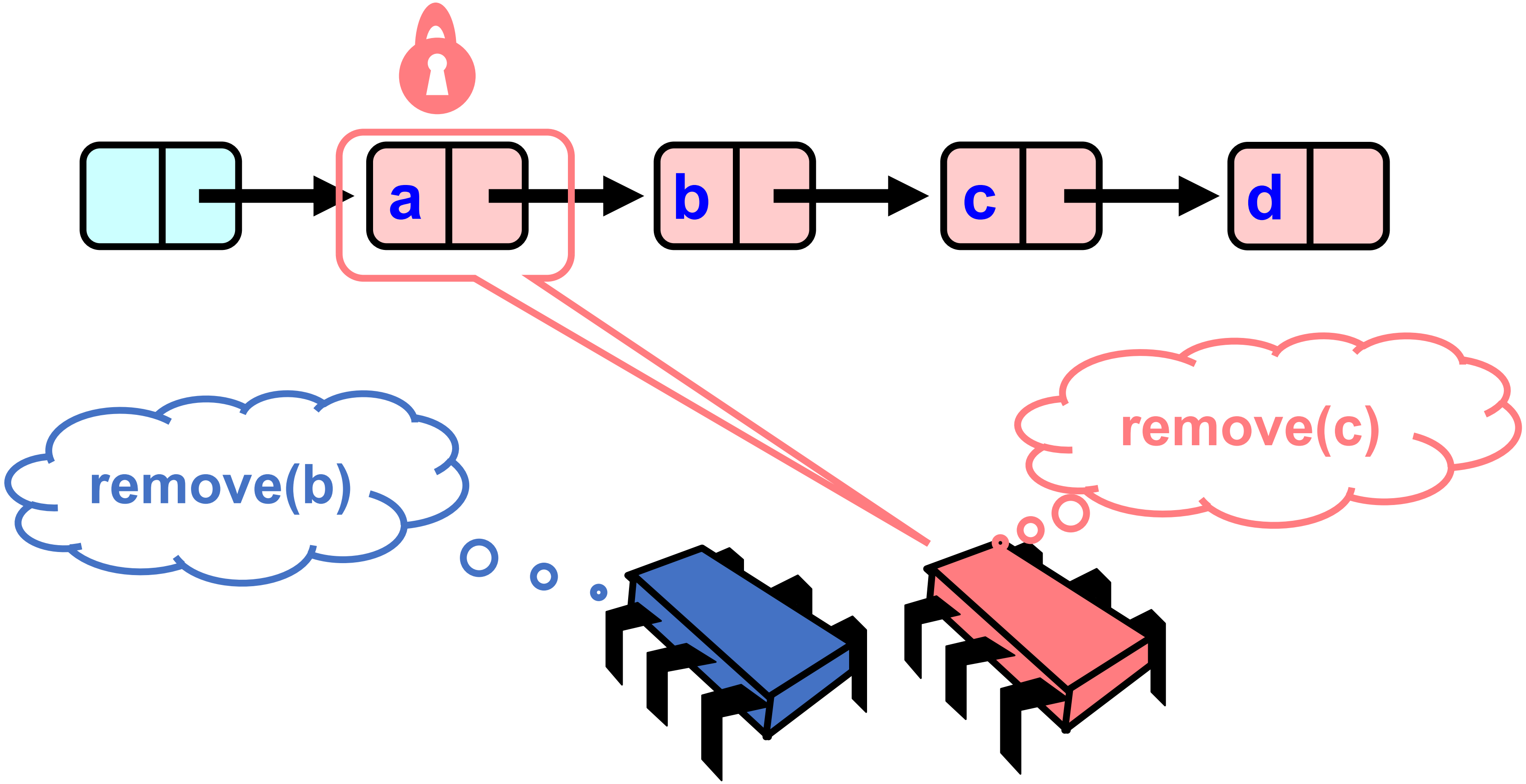

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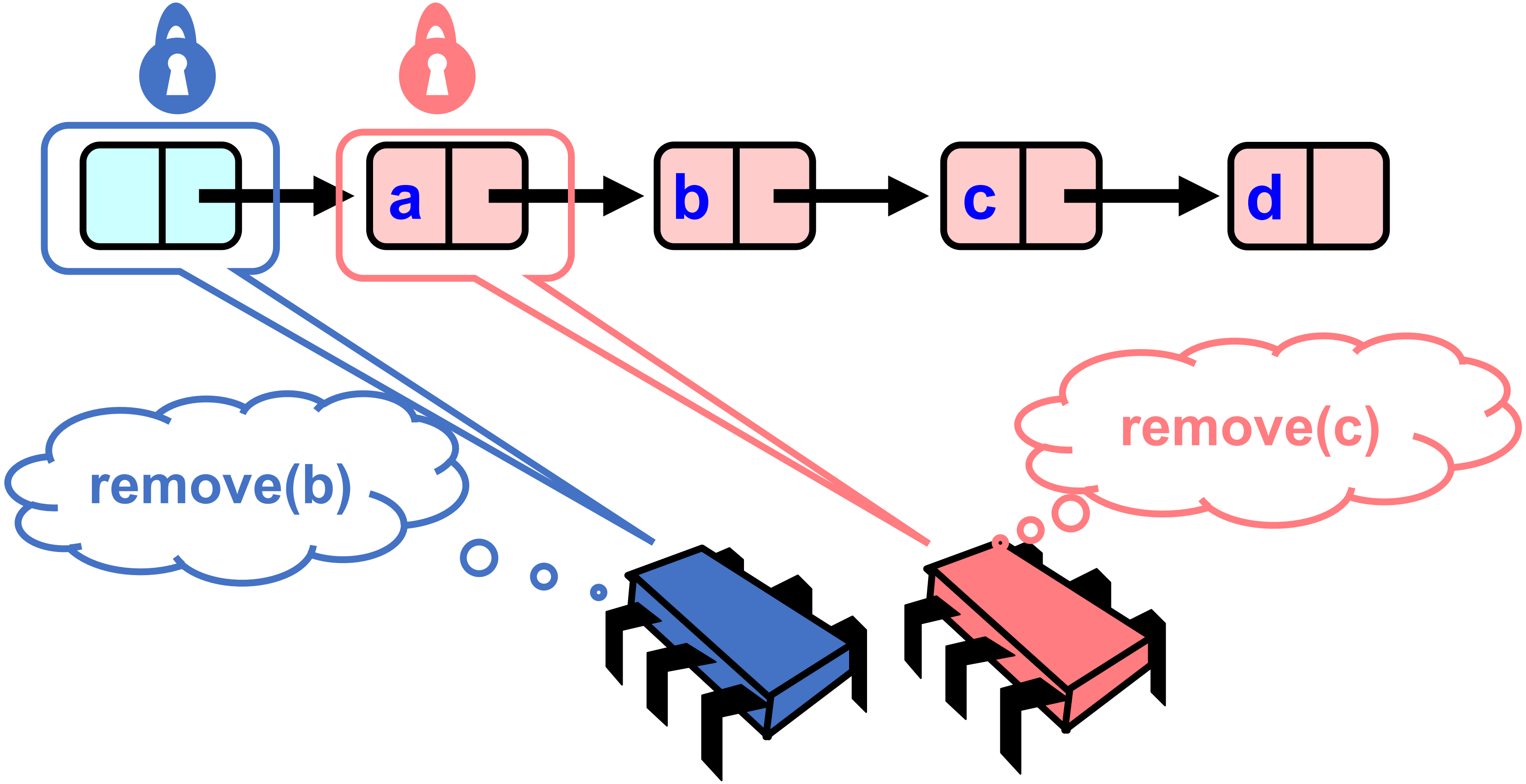

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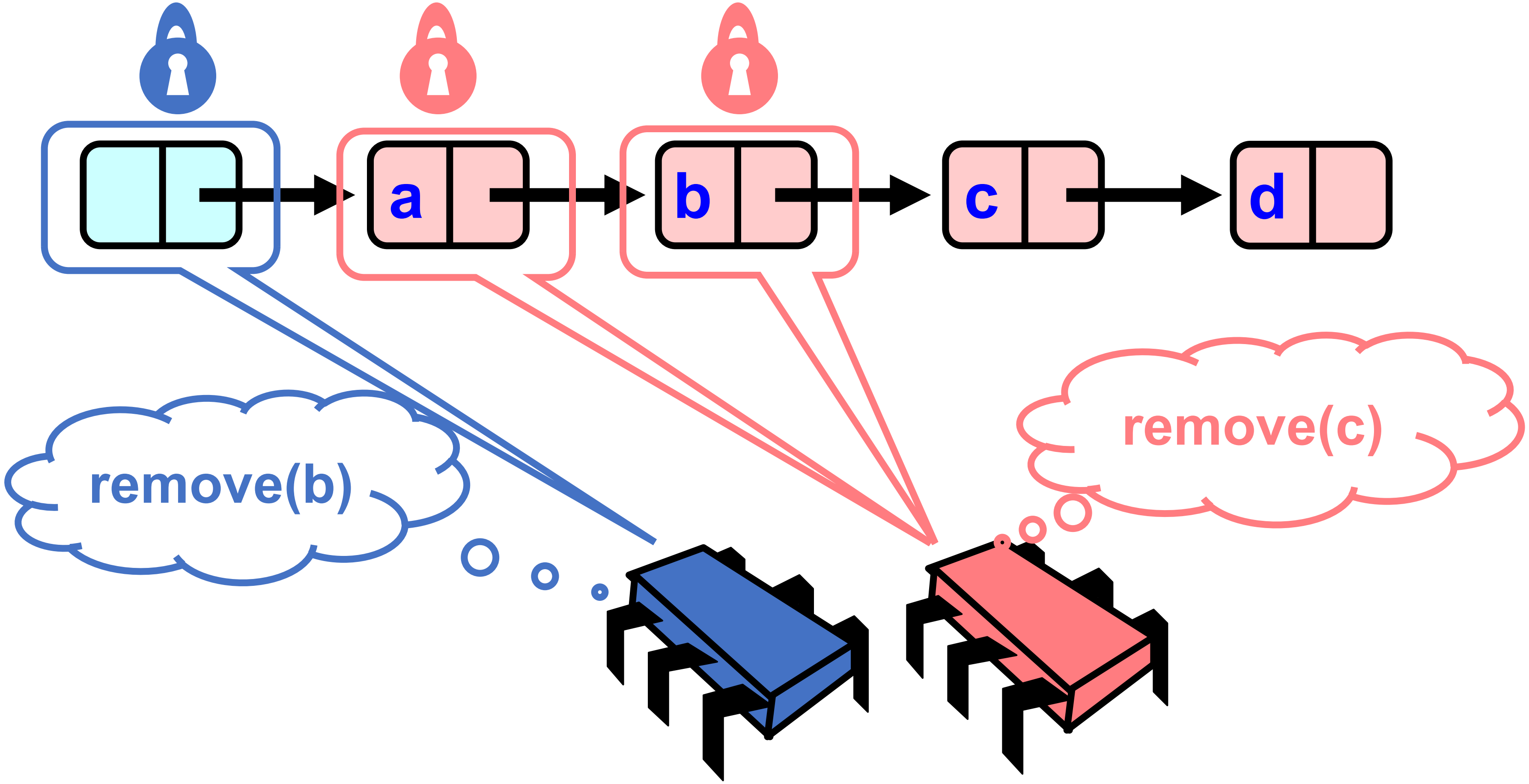

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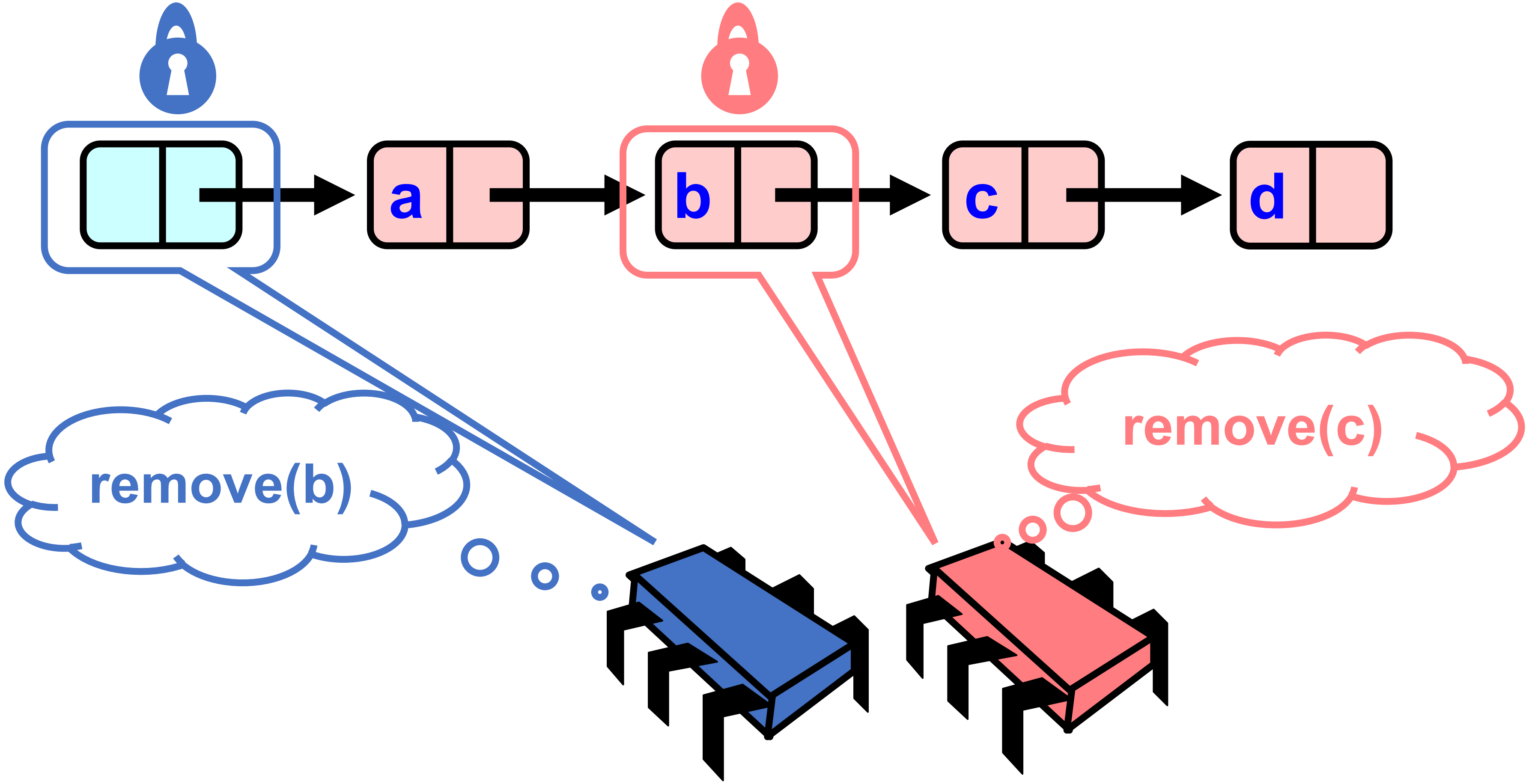

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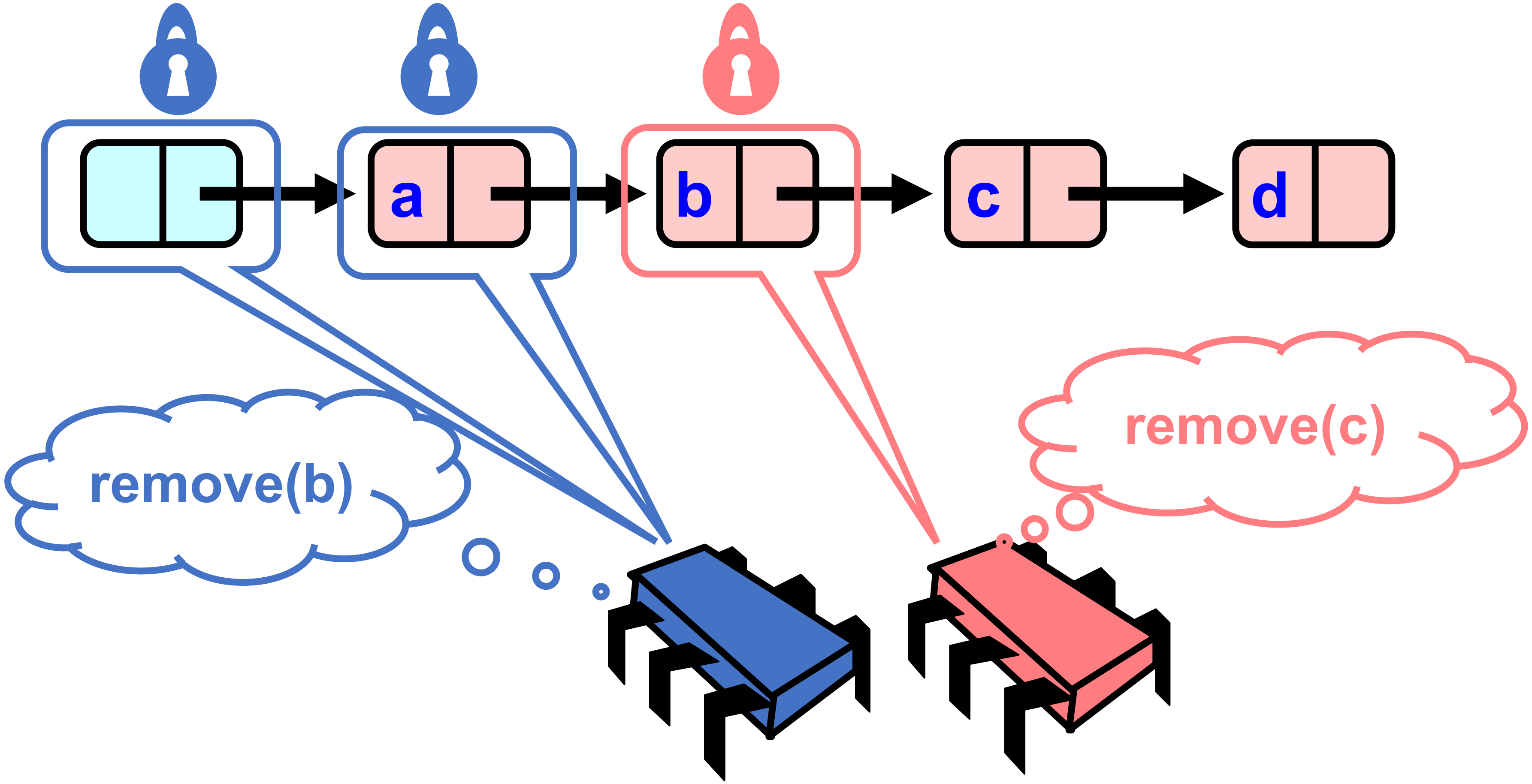

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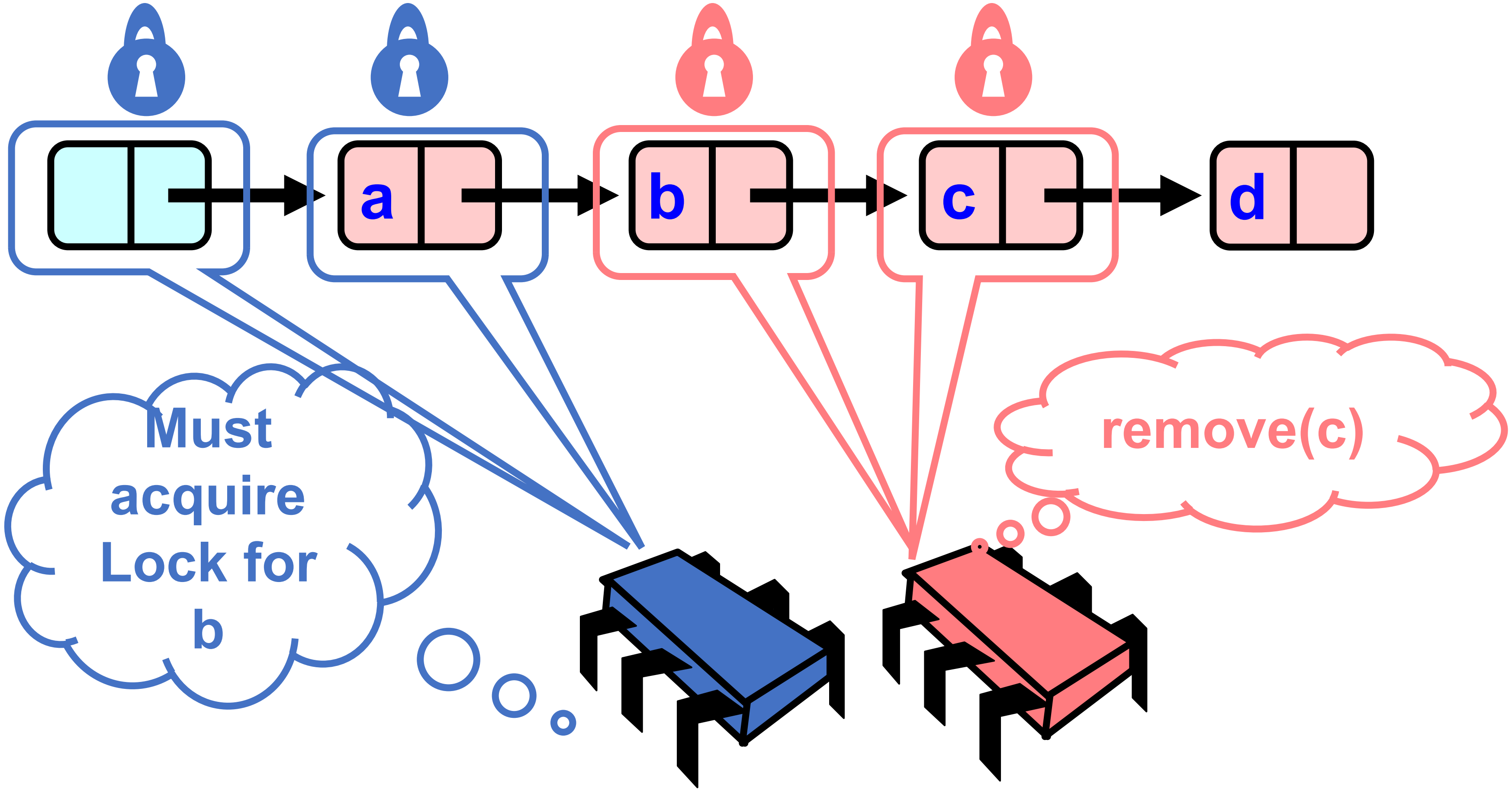

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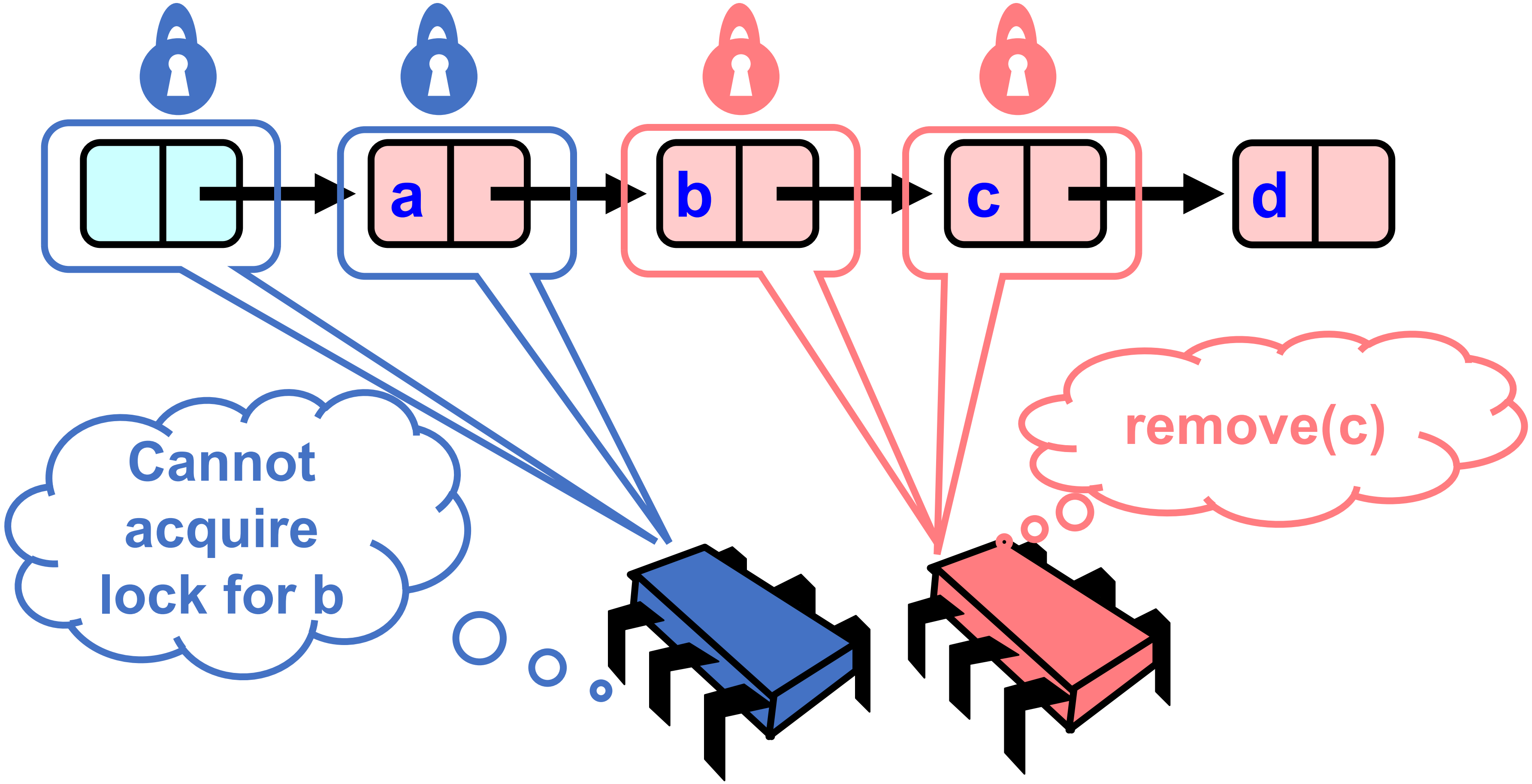

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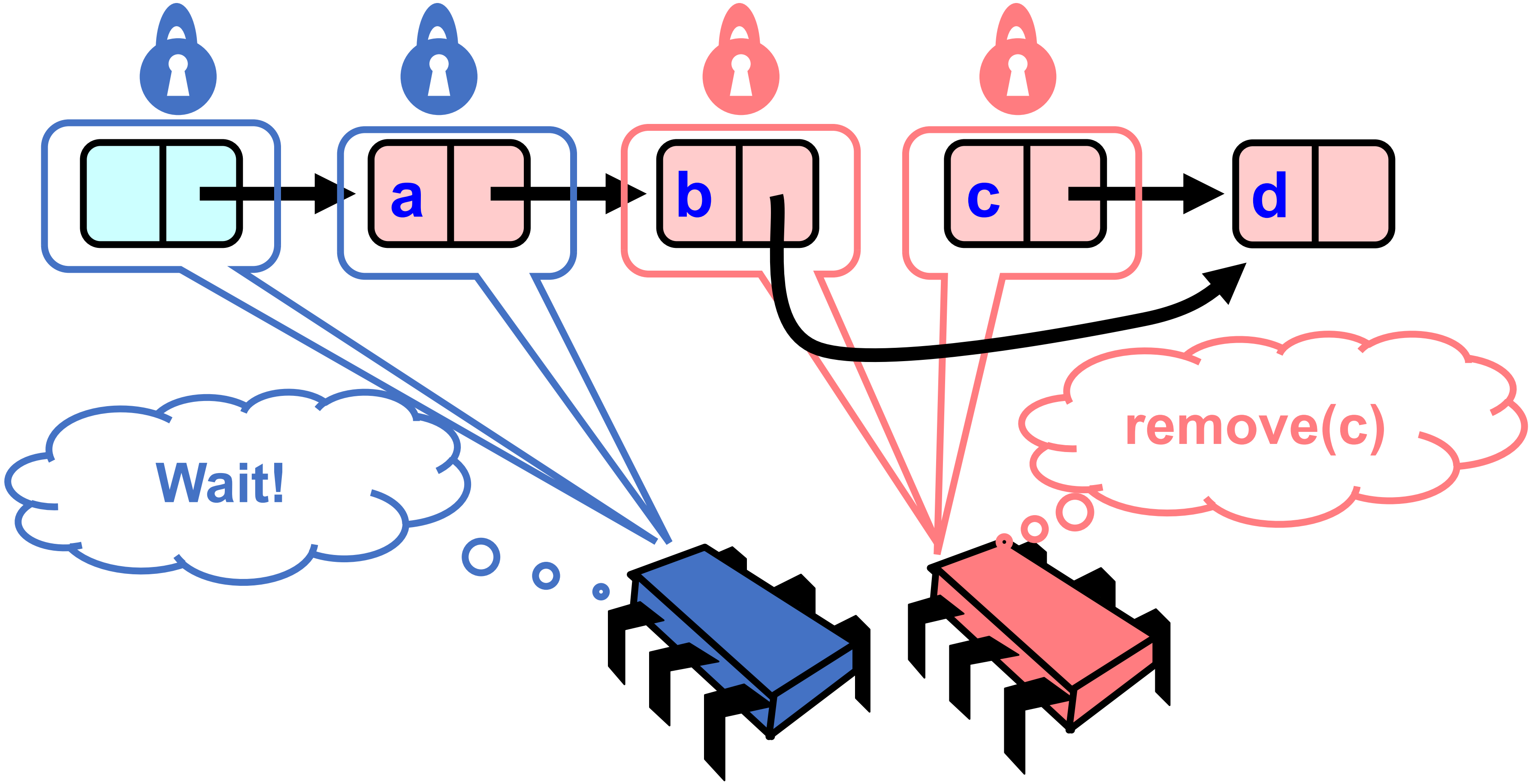

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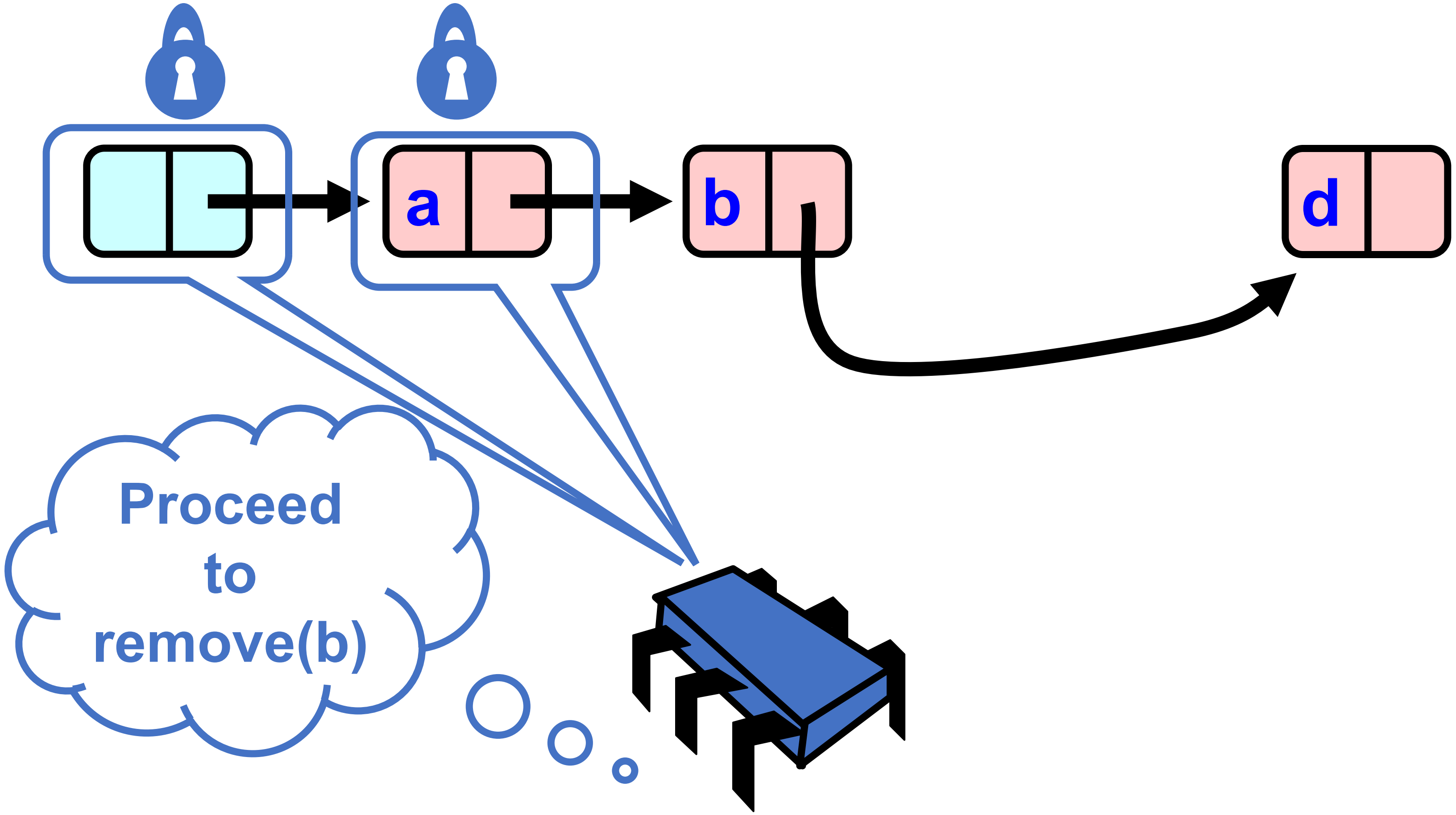

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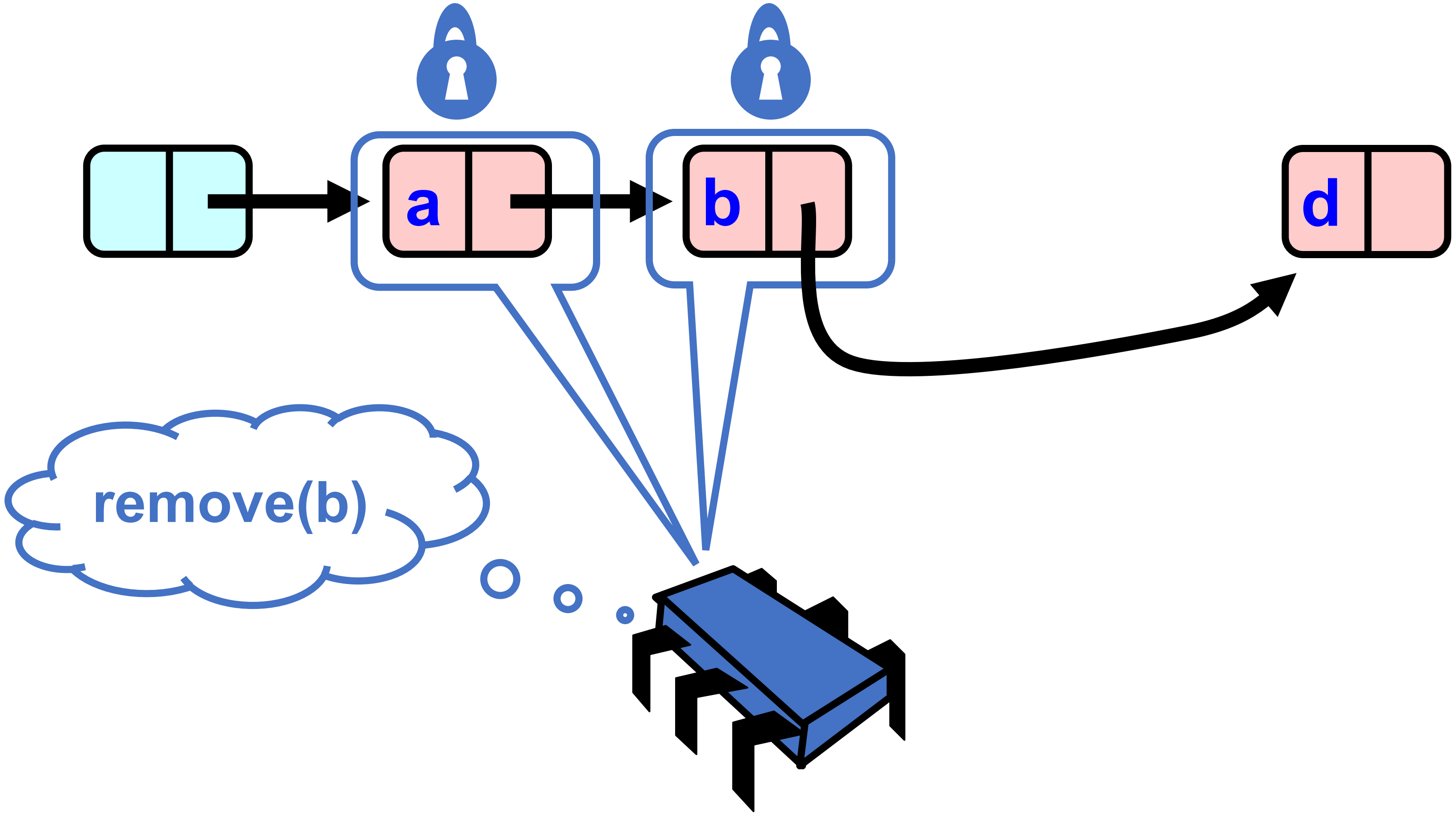
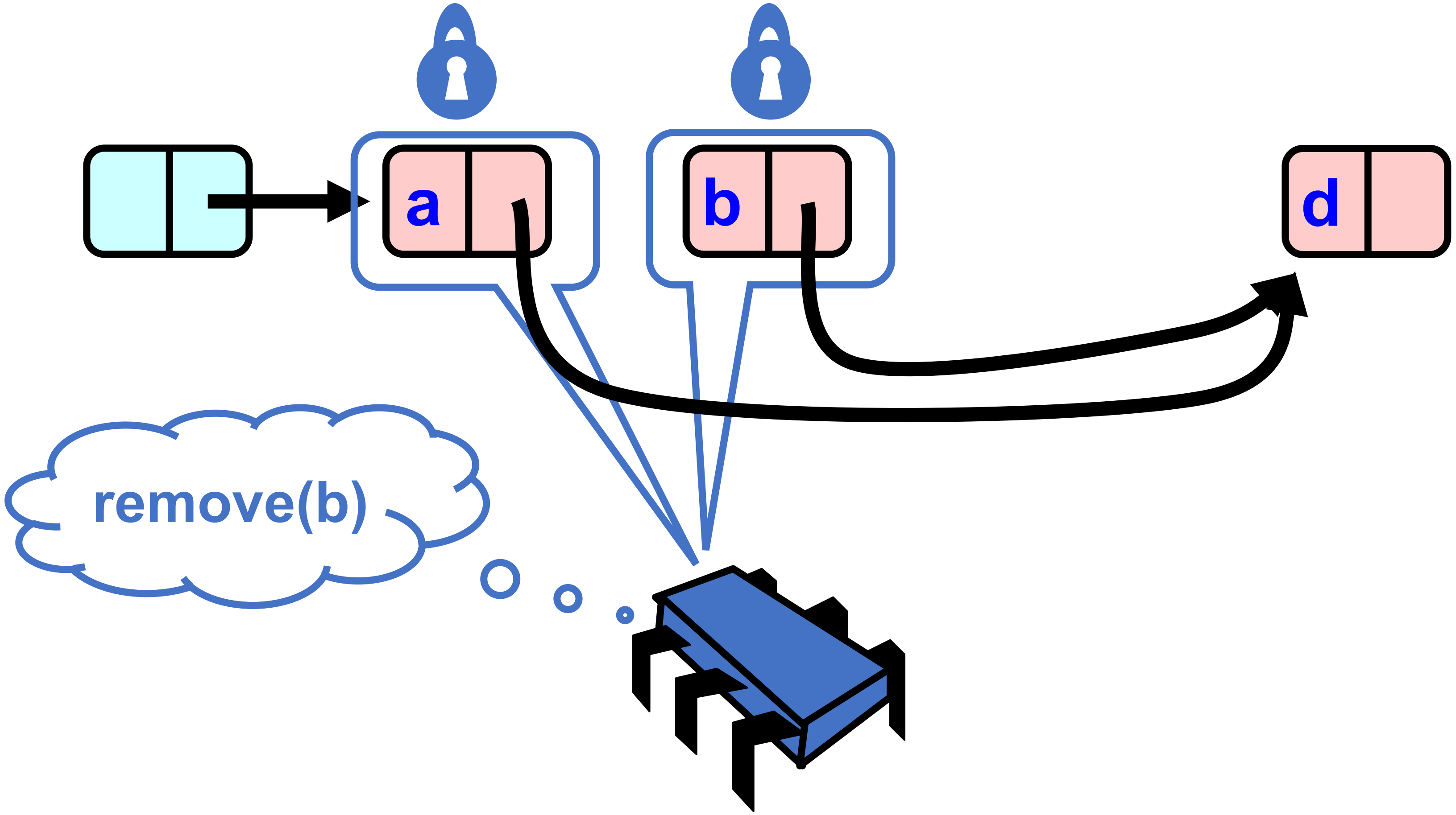
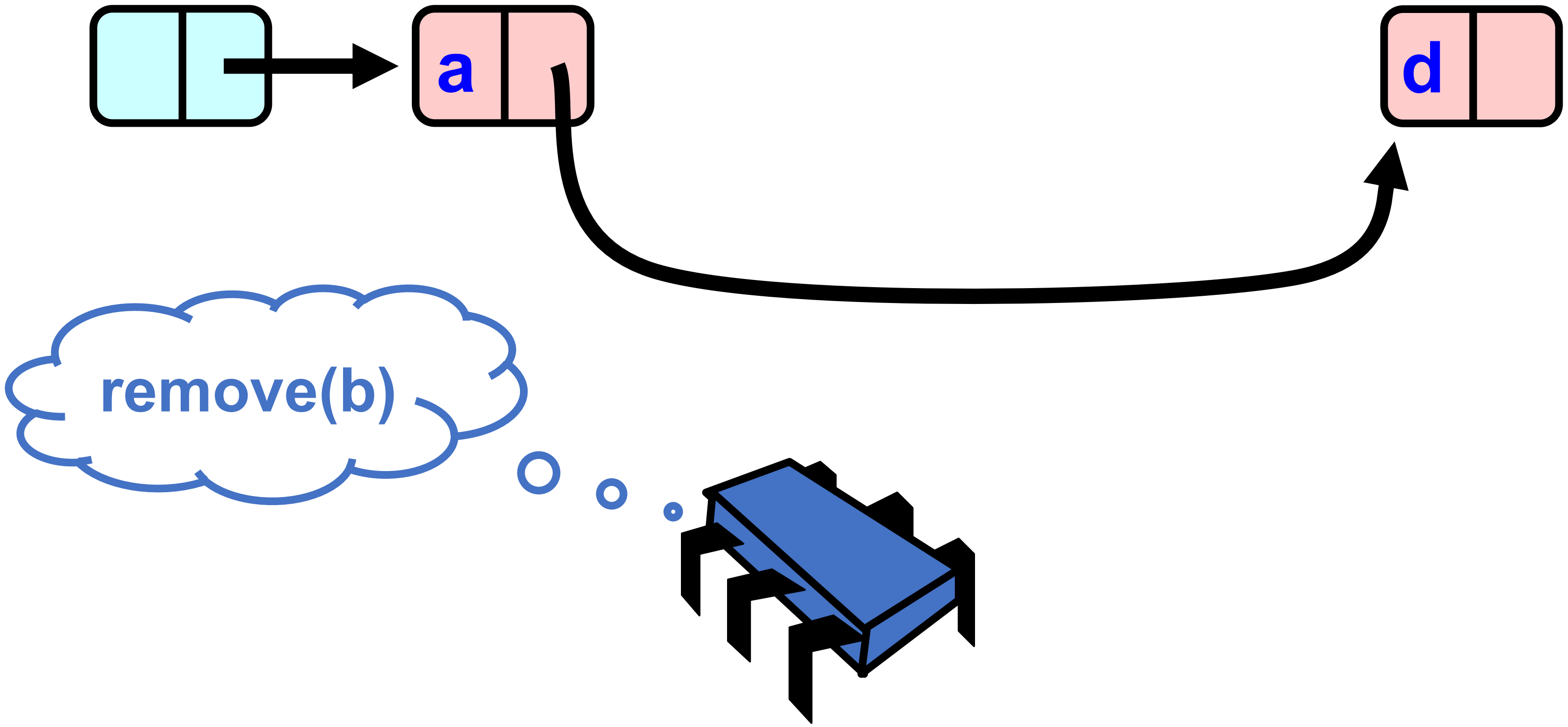


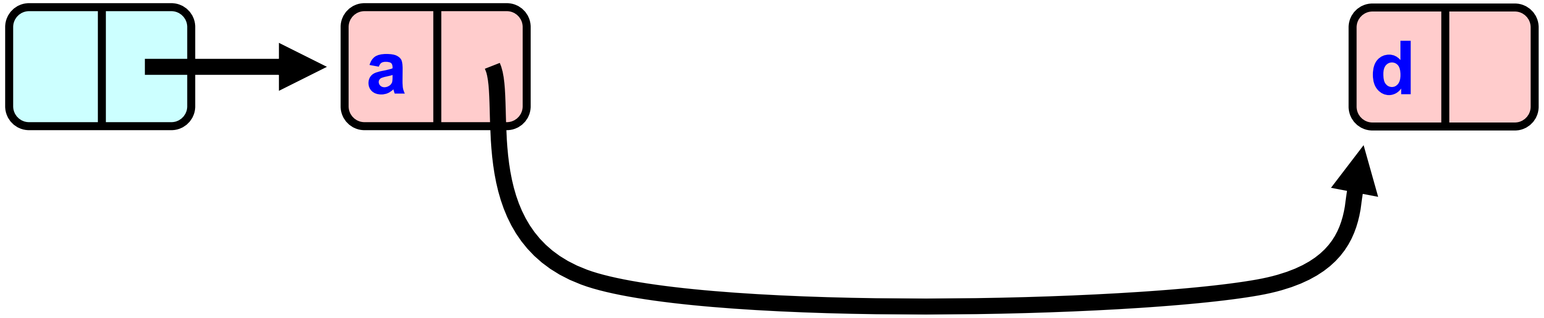
Removing a Node



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?

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();
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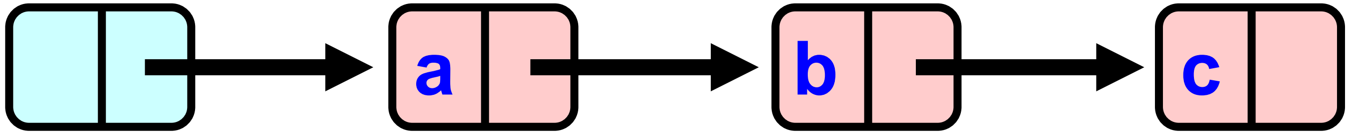

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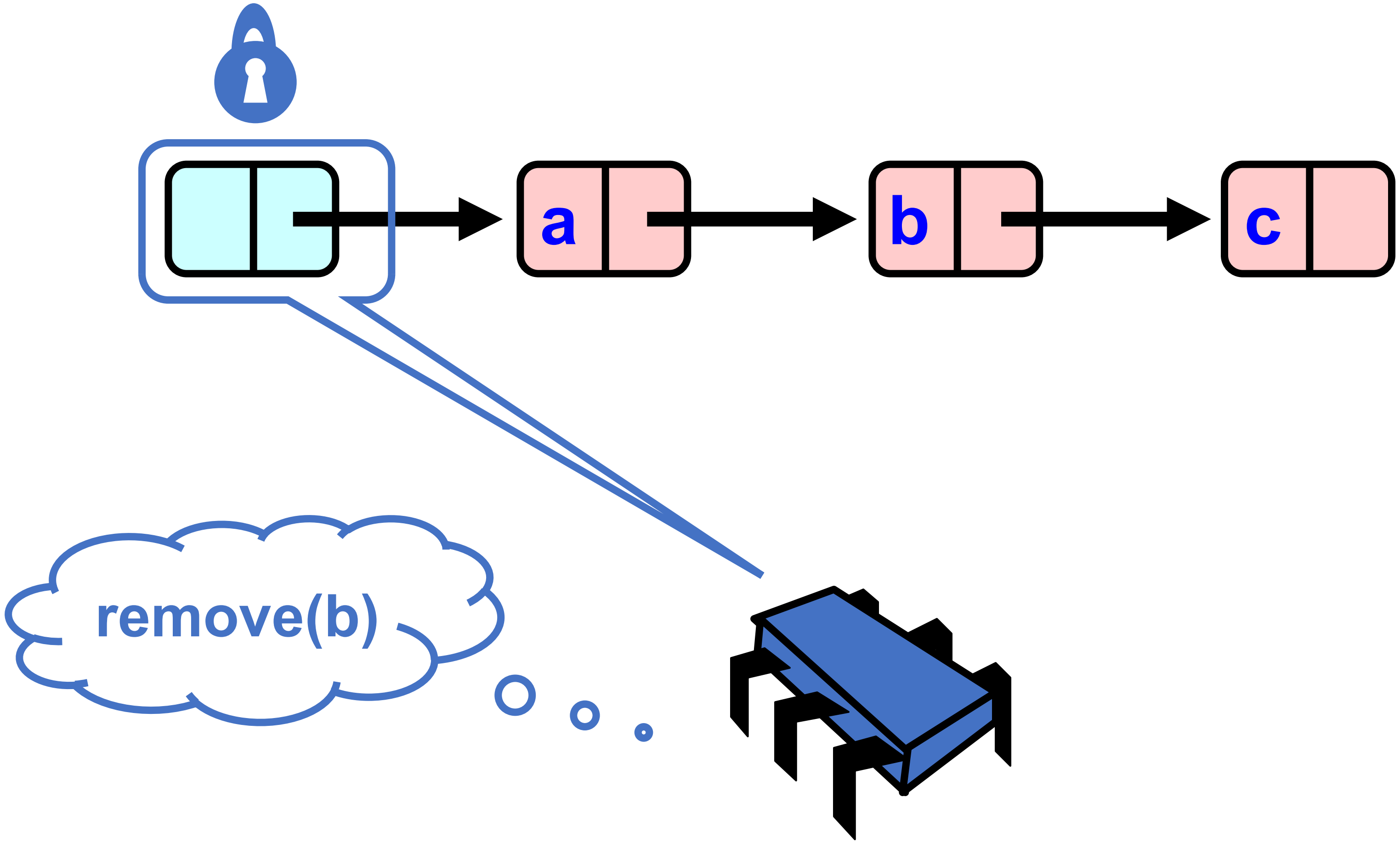

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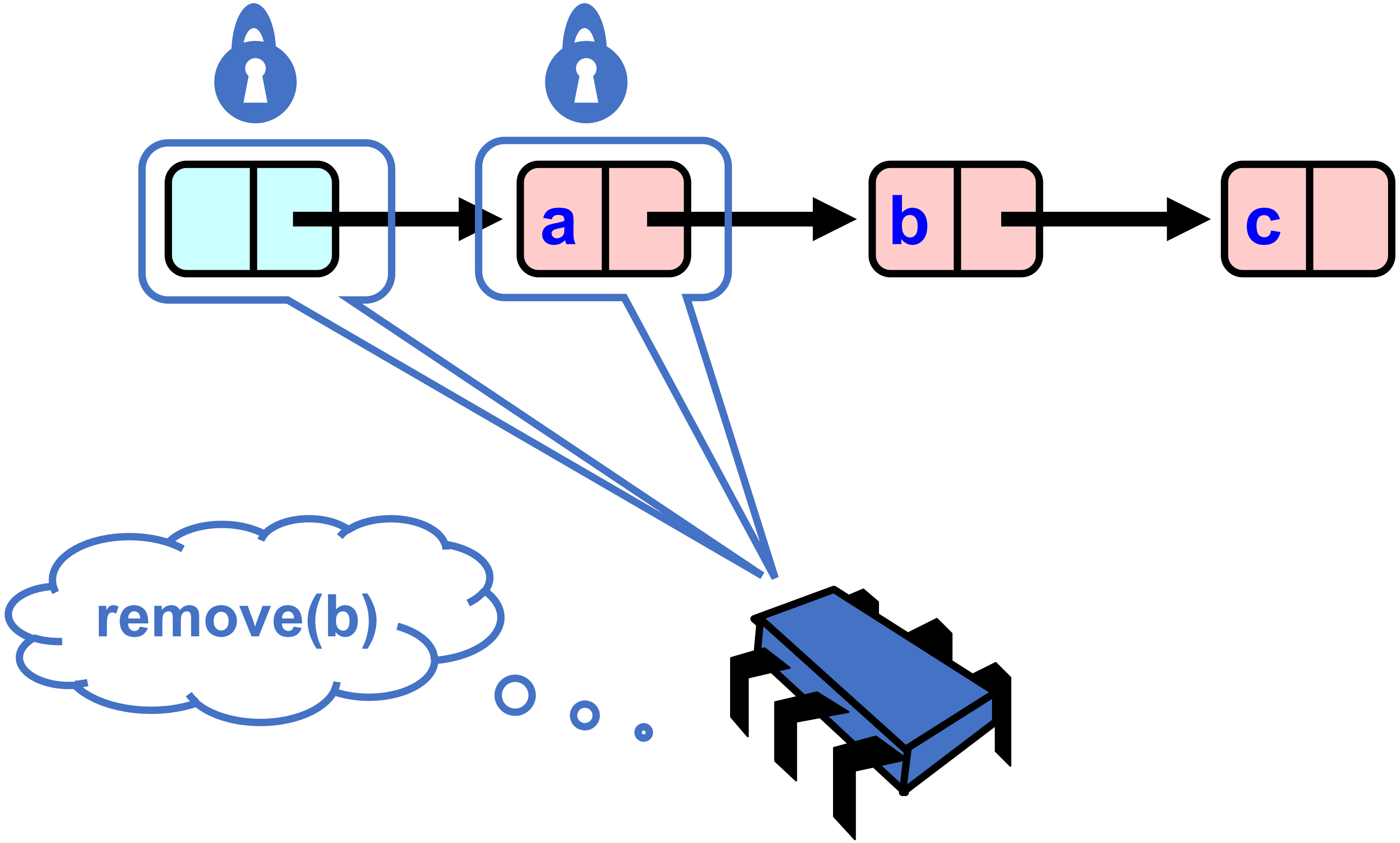

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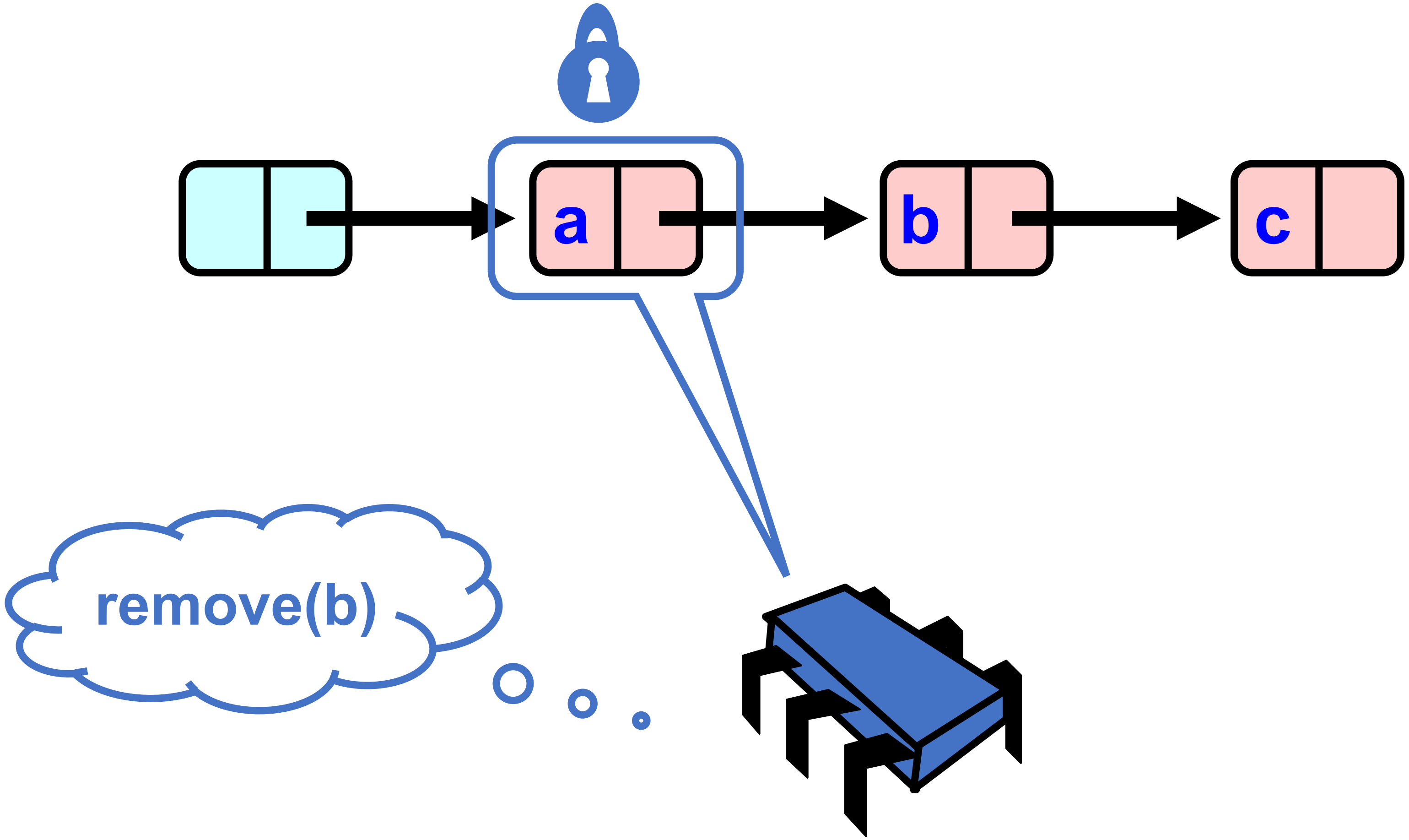

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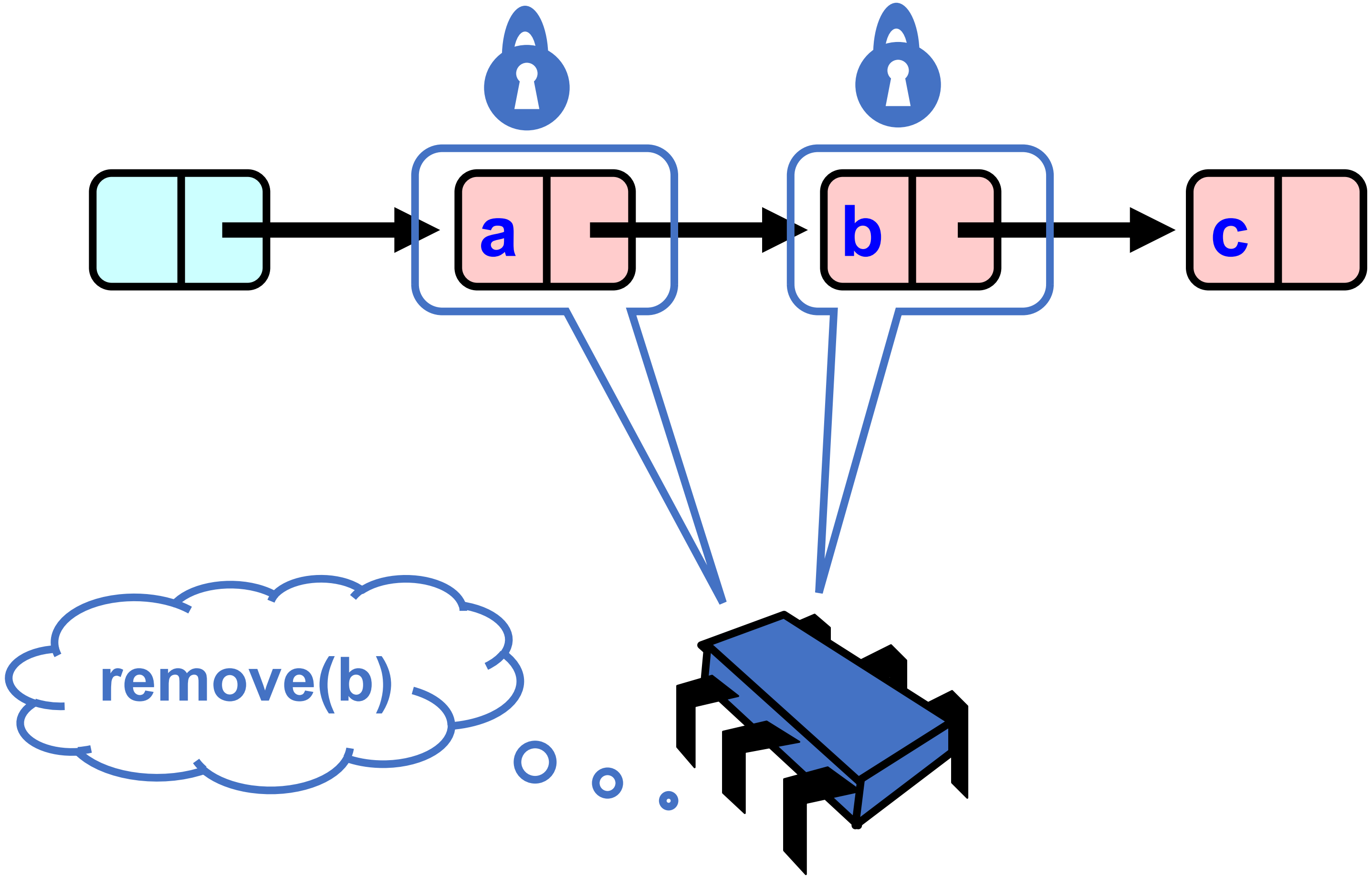

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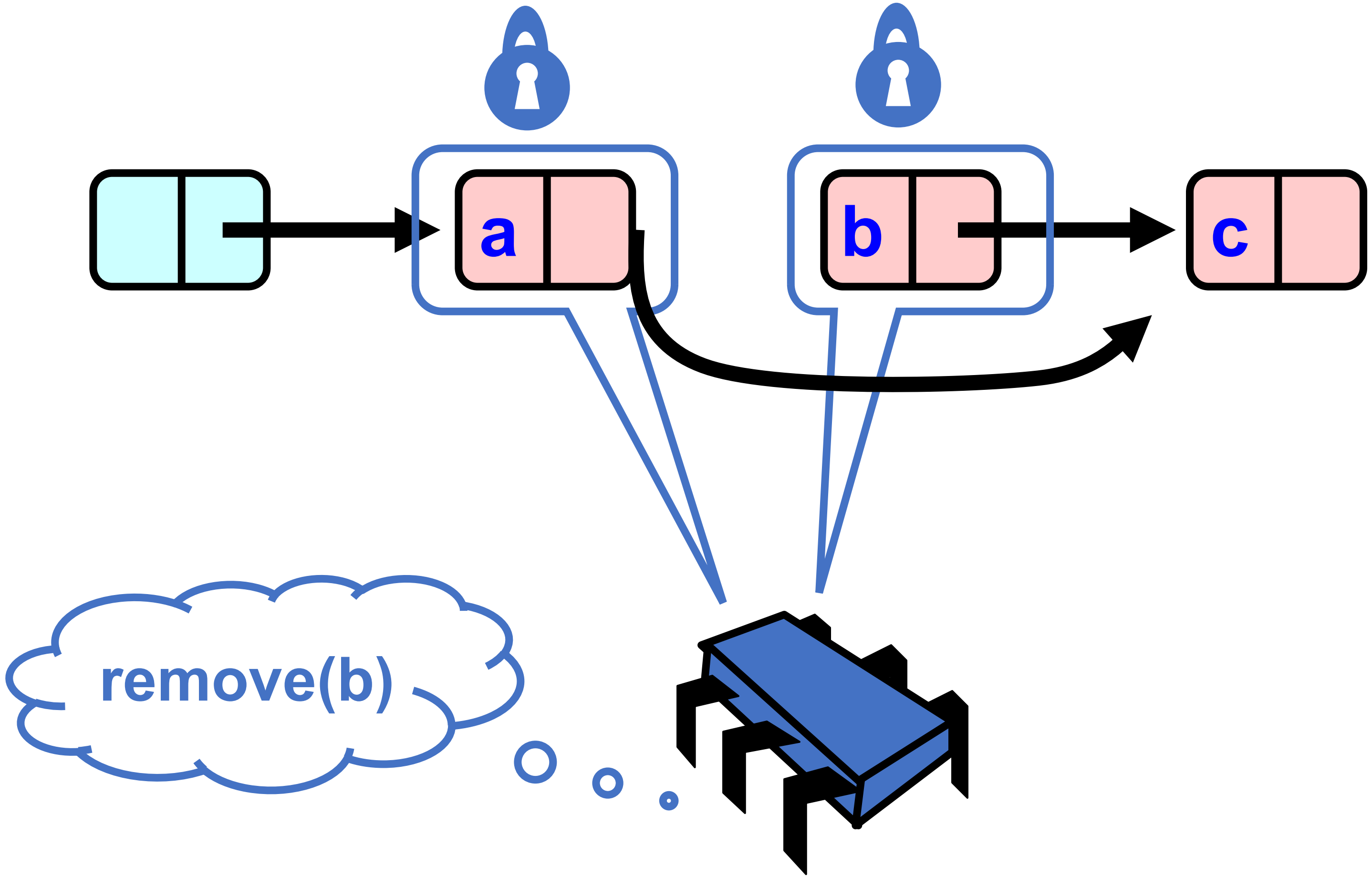

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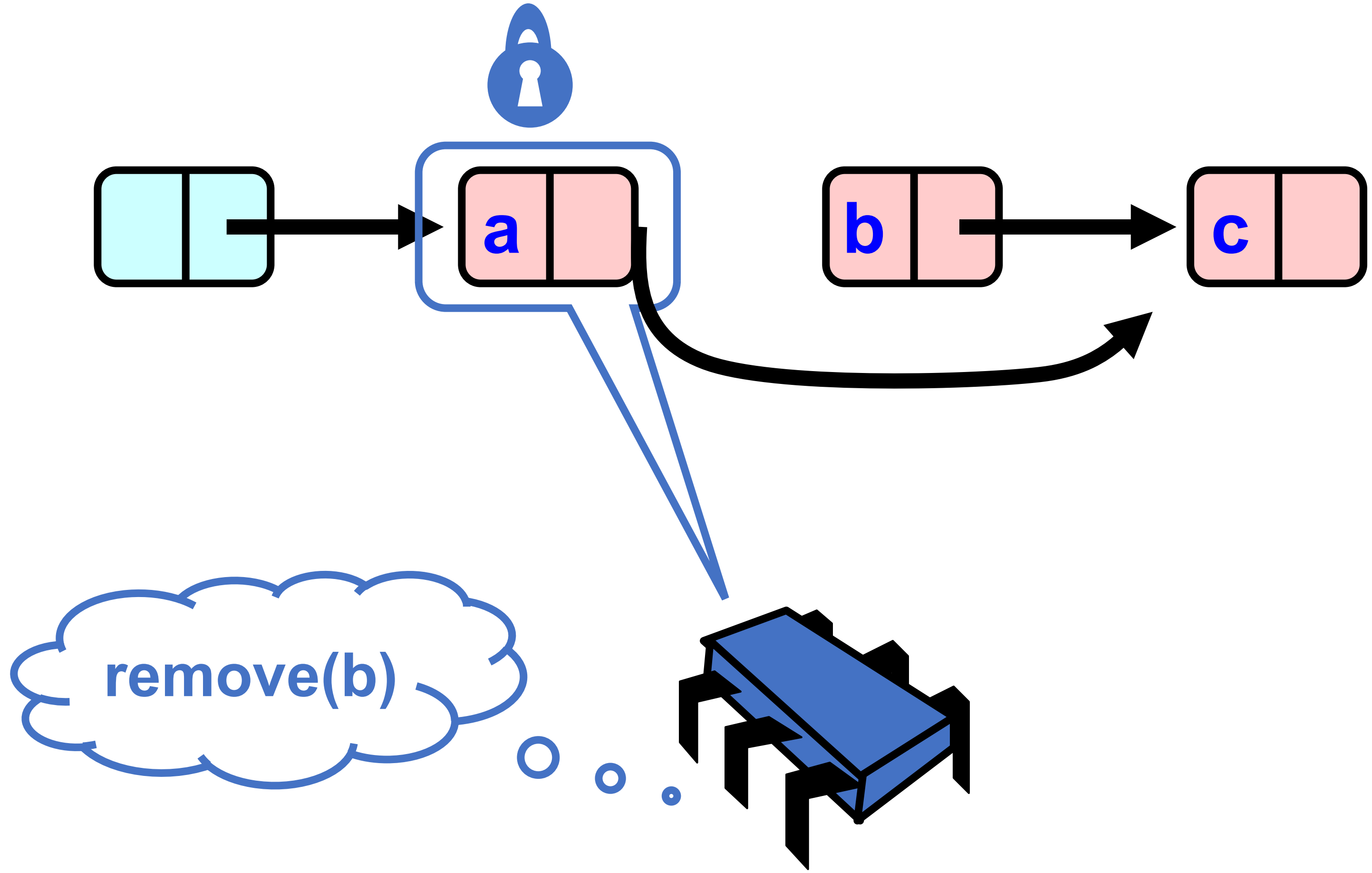

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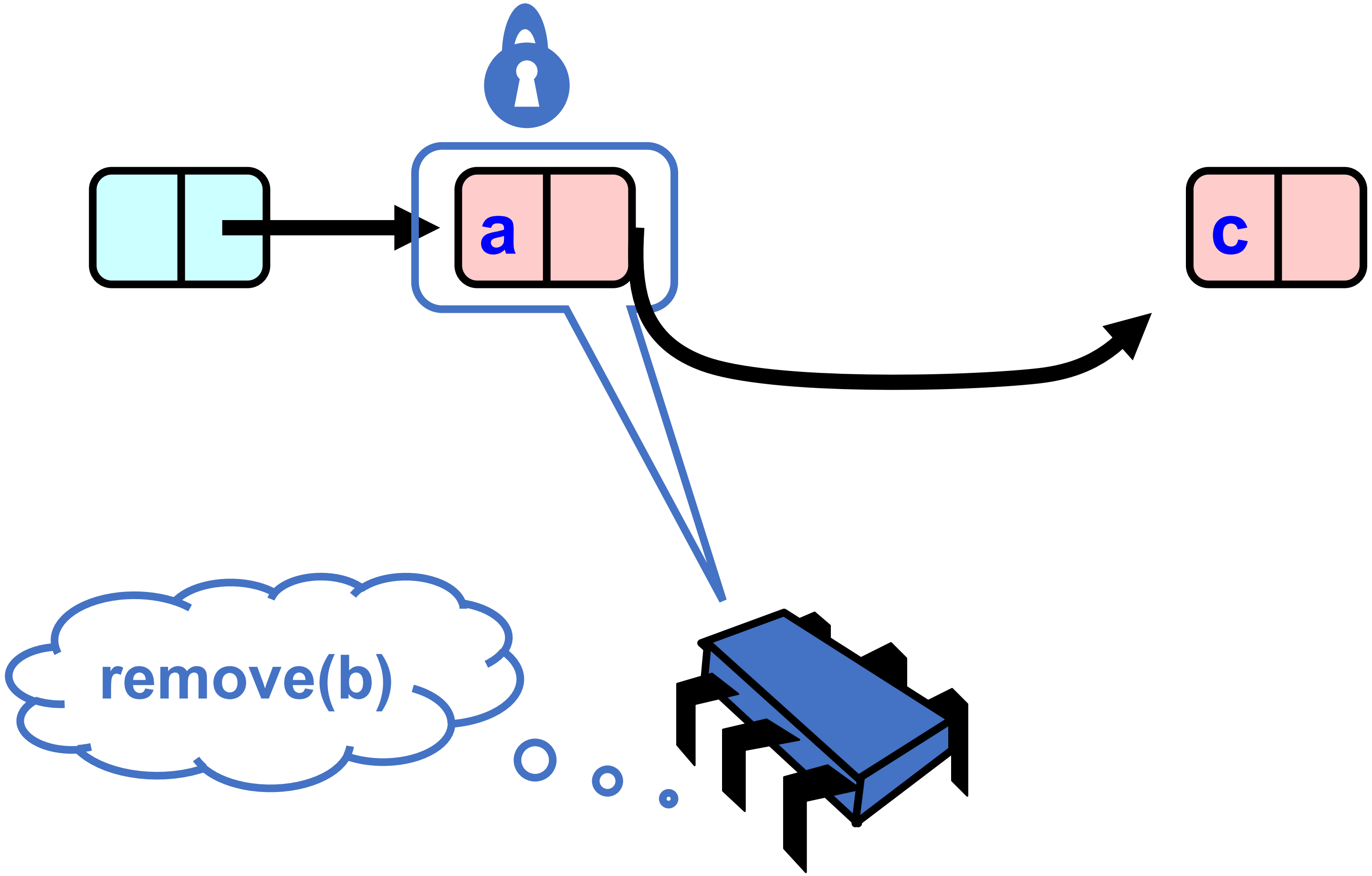

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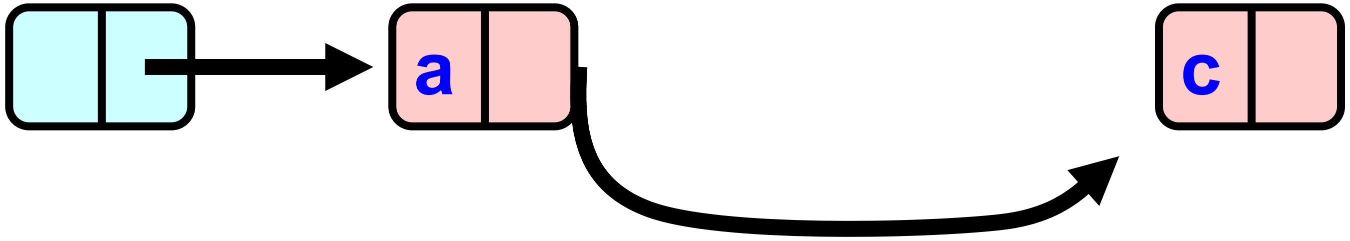
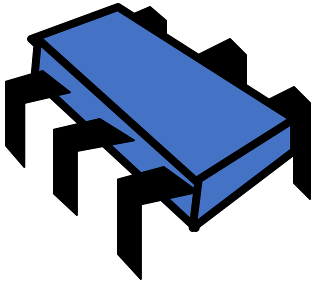




Schedule

- C++ Atomic Template

- 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

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

What was the alternative?

Optimistic Synchronization

- Find nodes without locking

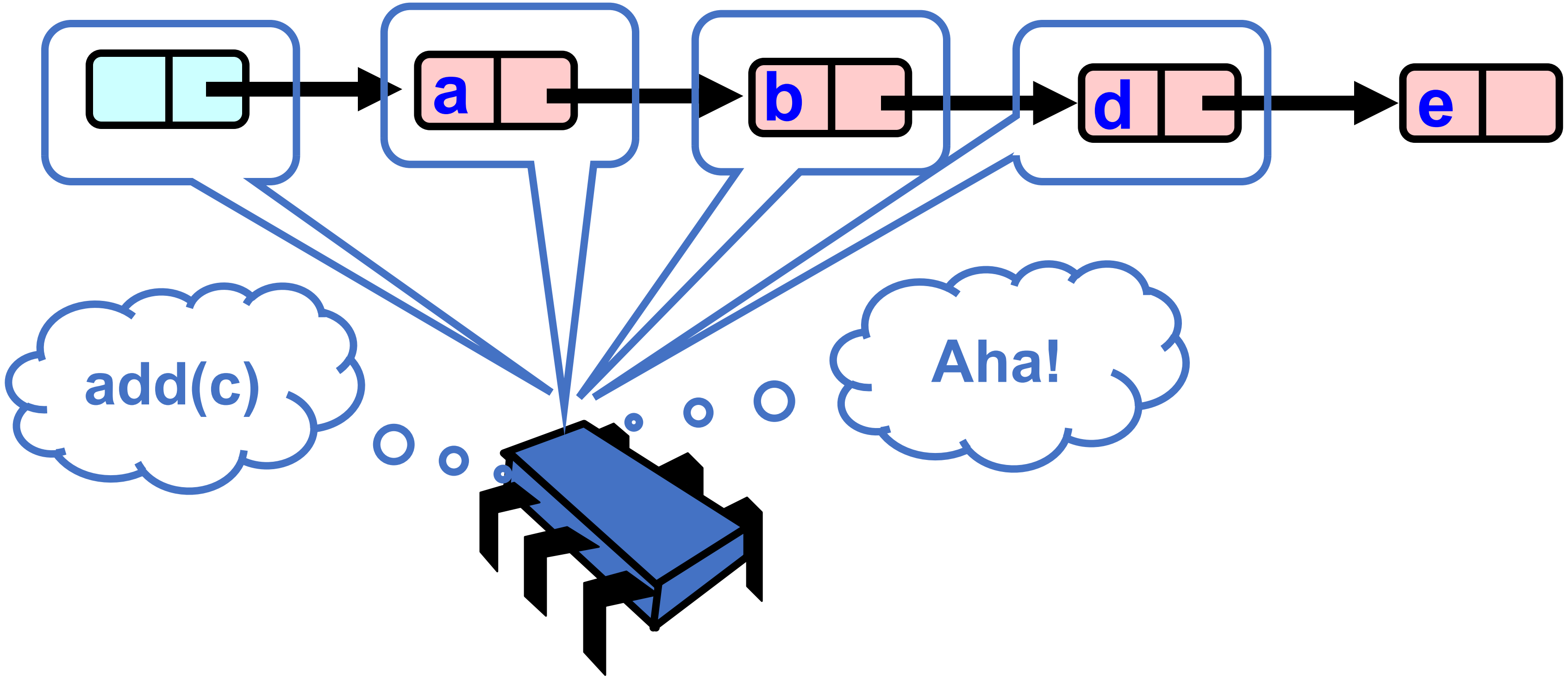
Optimistic Synchronization

- Find nodes without locking
- Lock nodes

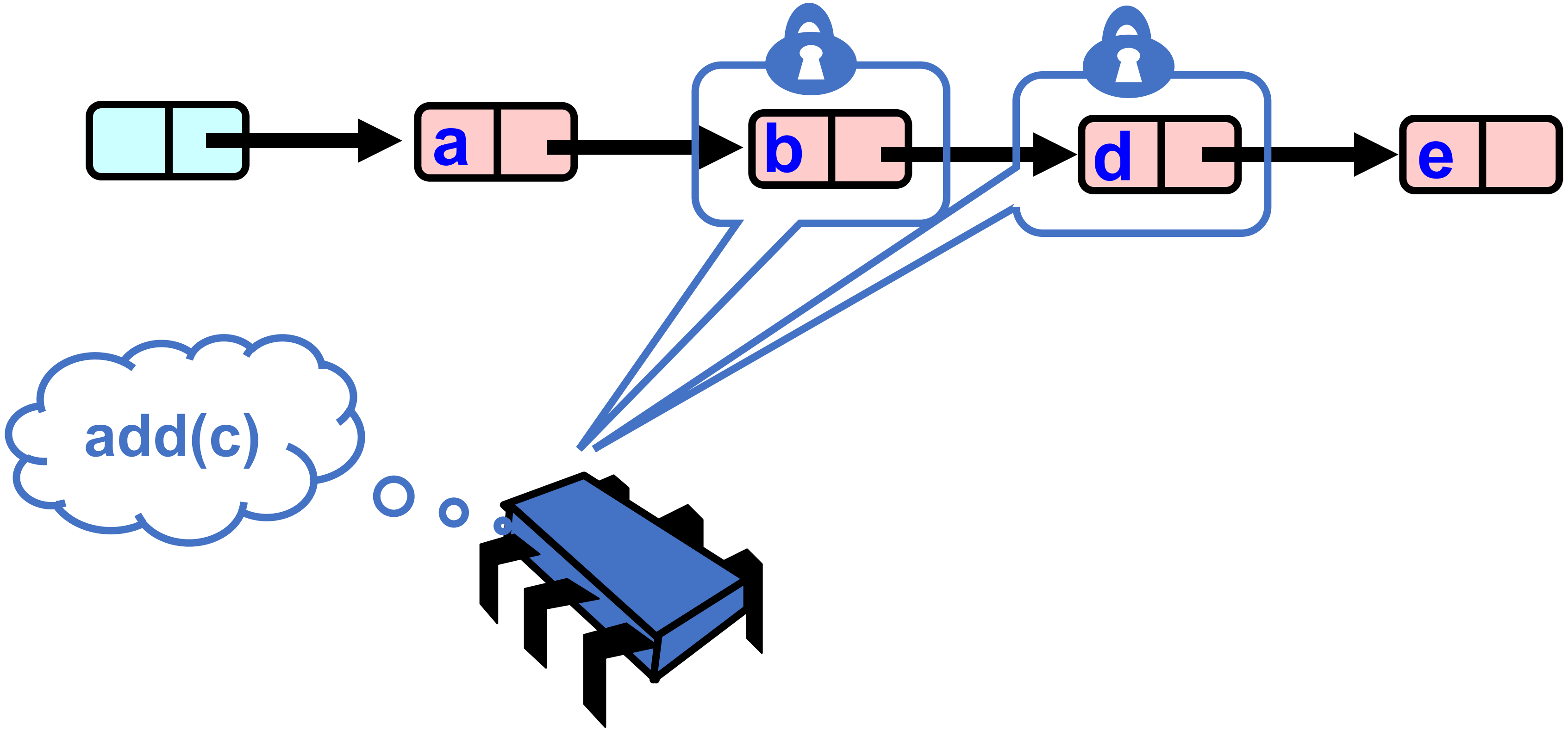
Optimistic Synchronization

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

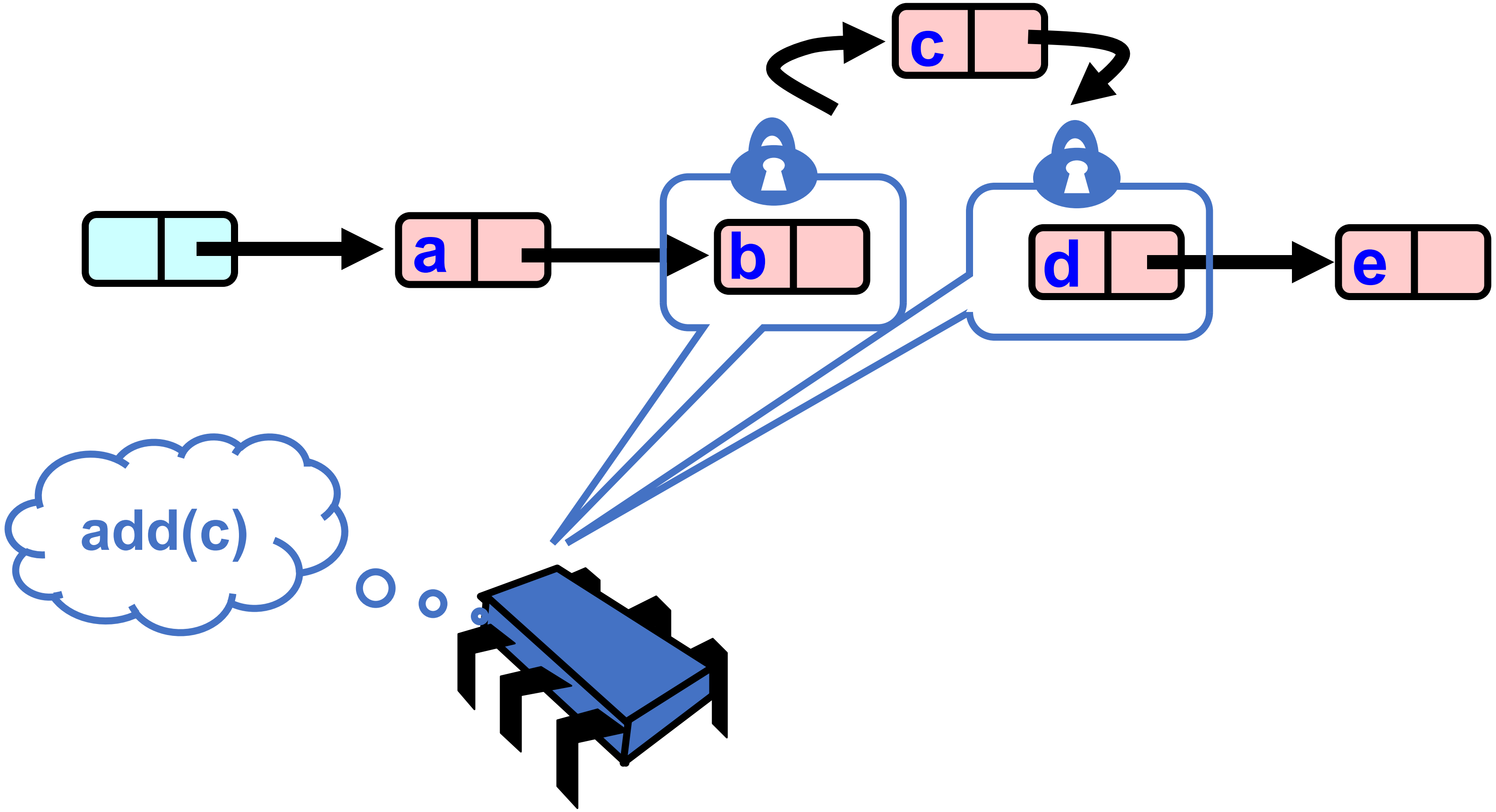
Optimistic: Traverse without Locking



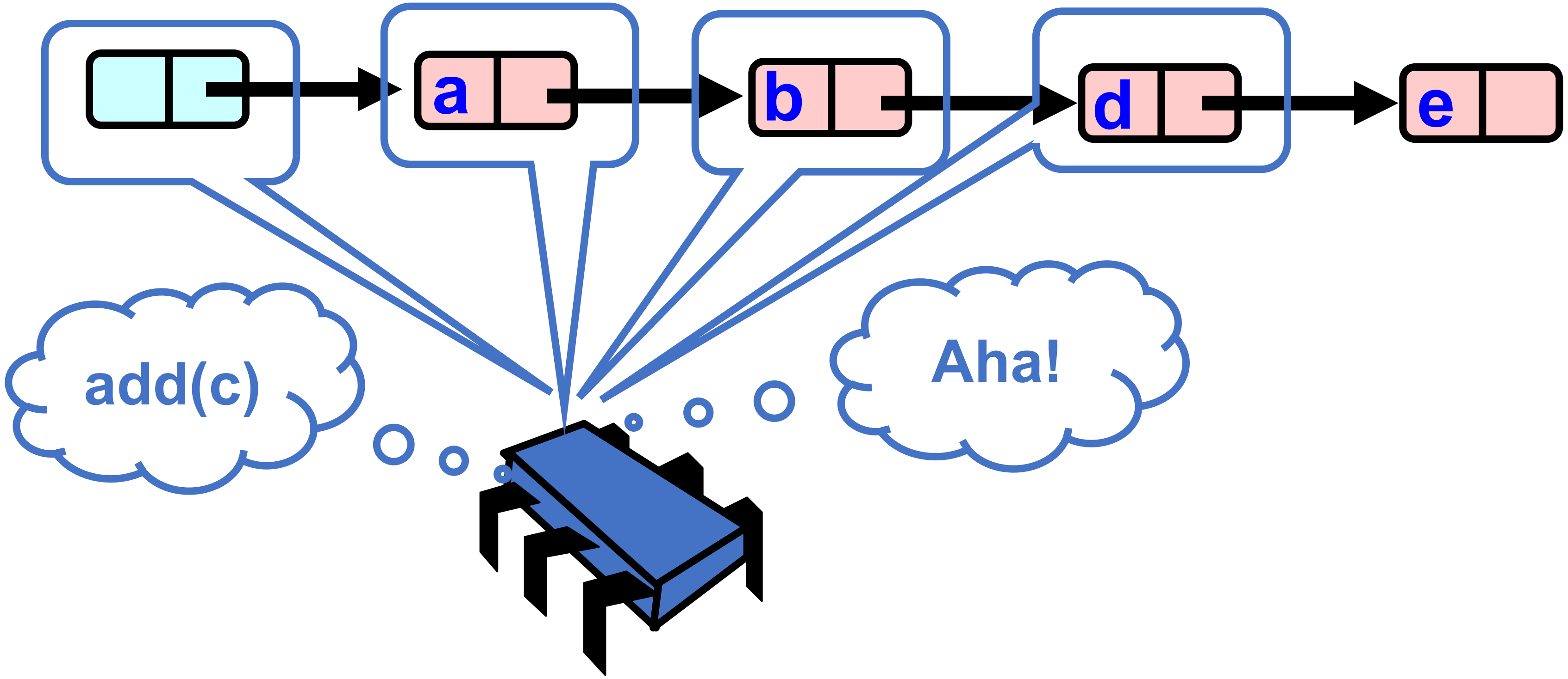
Optimistic: Lock and Load



Optimistic: Lock and Load



What could go wrong?



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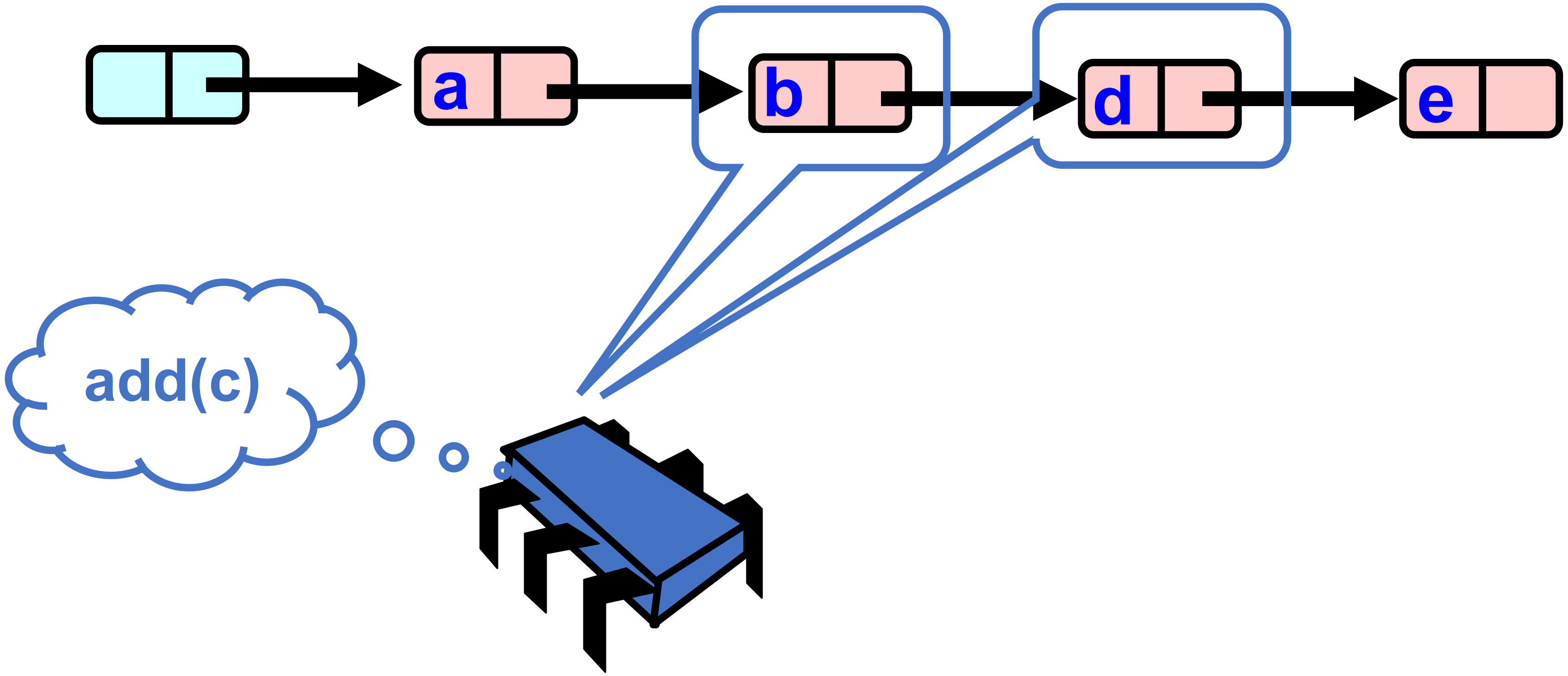

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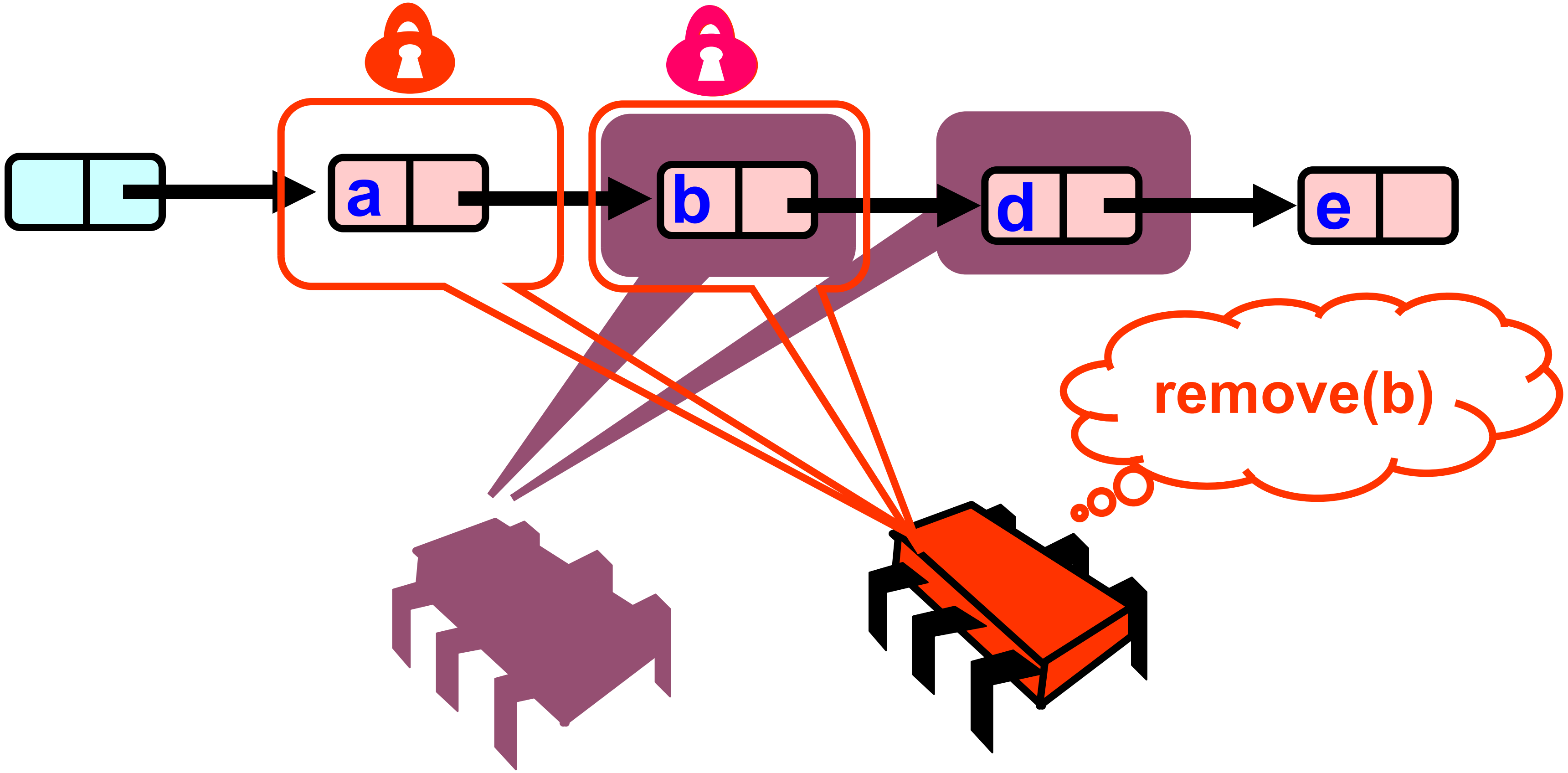


Data conflict!

- 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.

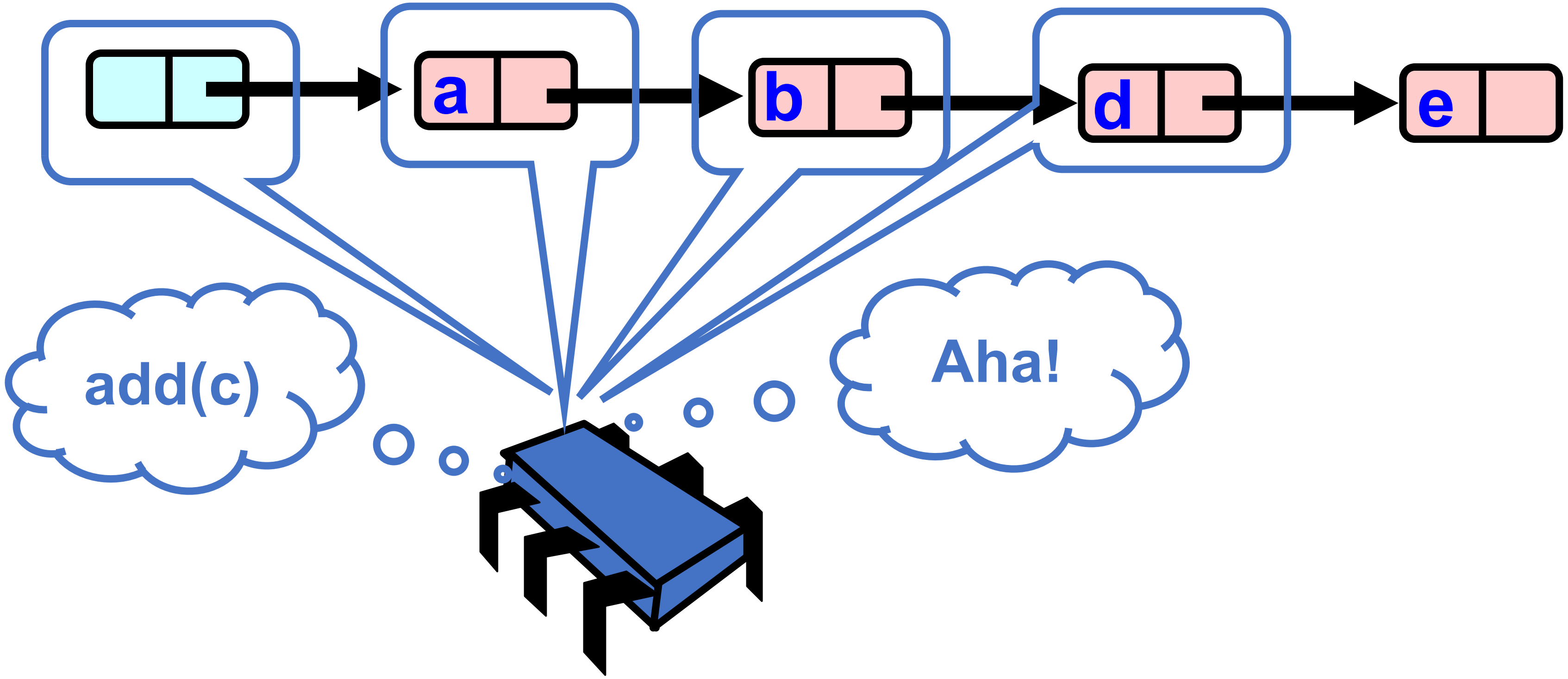
```
void traverse(node *n) {
  while (n->next != NULL) {
    n = n->next;
  }
}
```

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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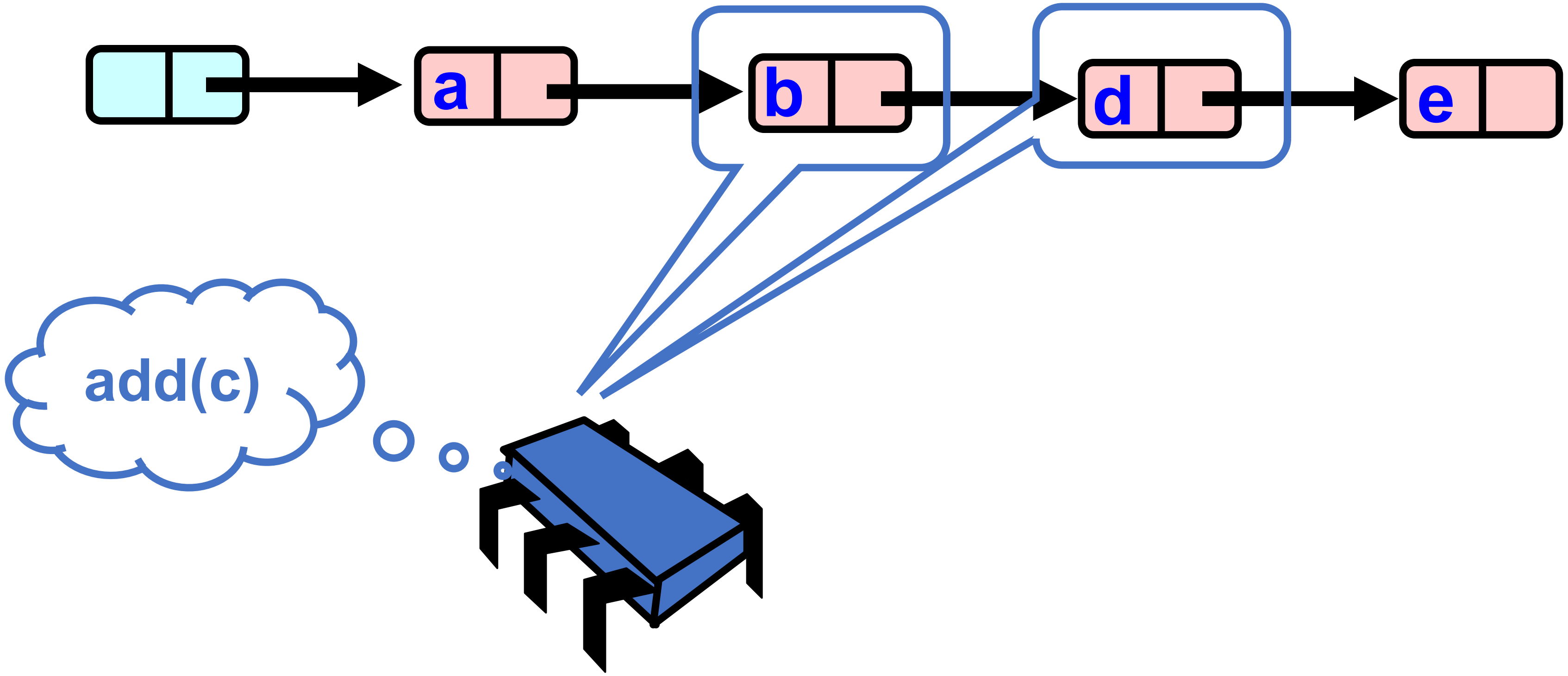

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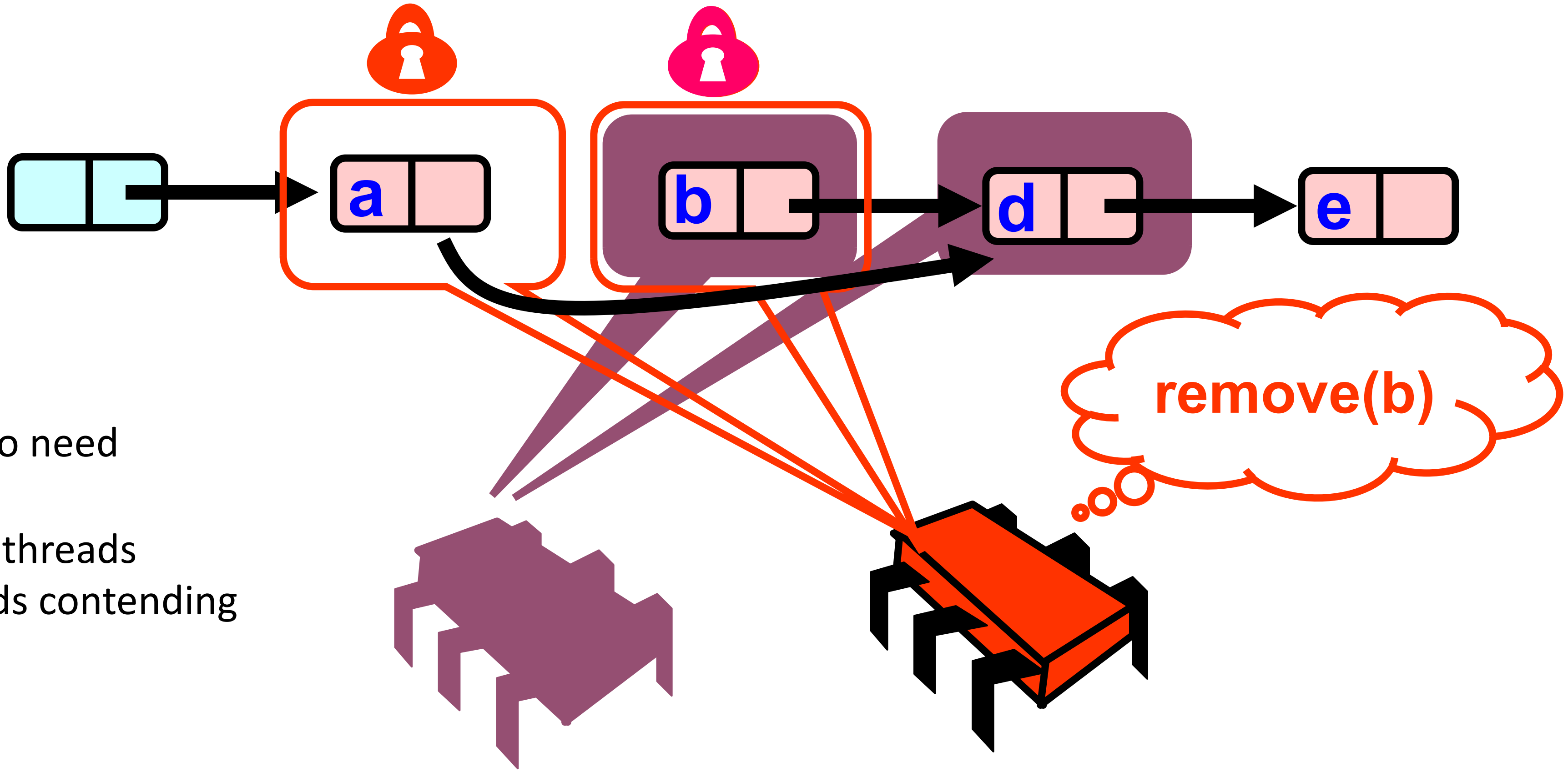
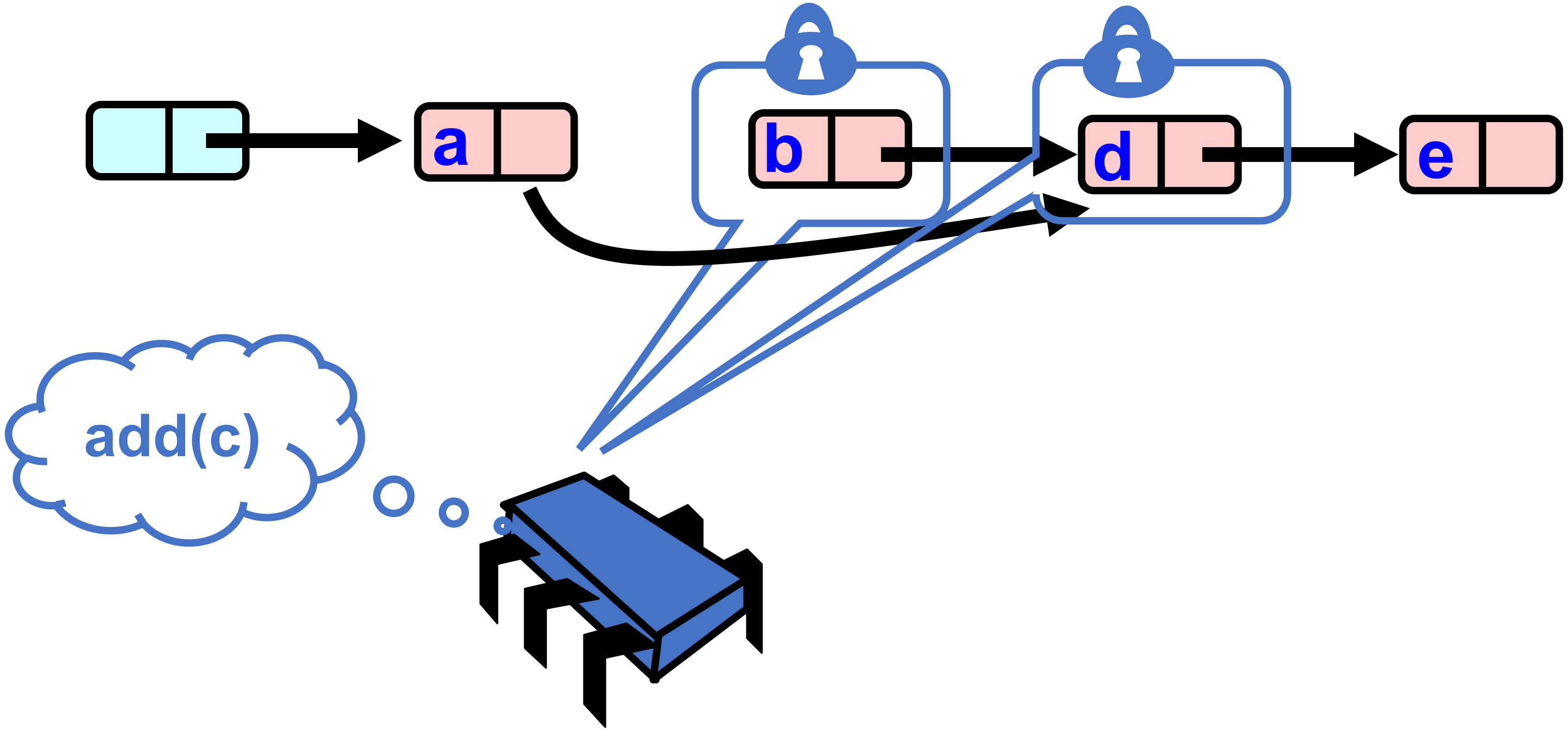


No more data conflict, but we do need to reason about interleavings and threads concurrent threads contending for values.

What could go wrong?



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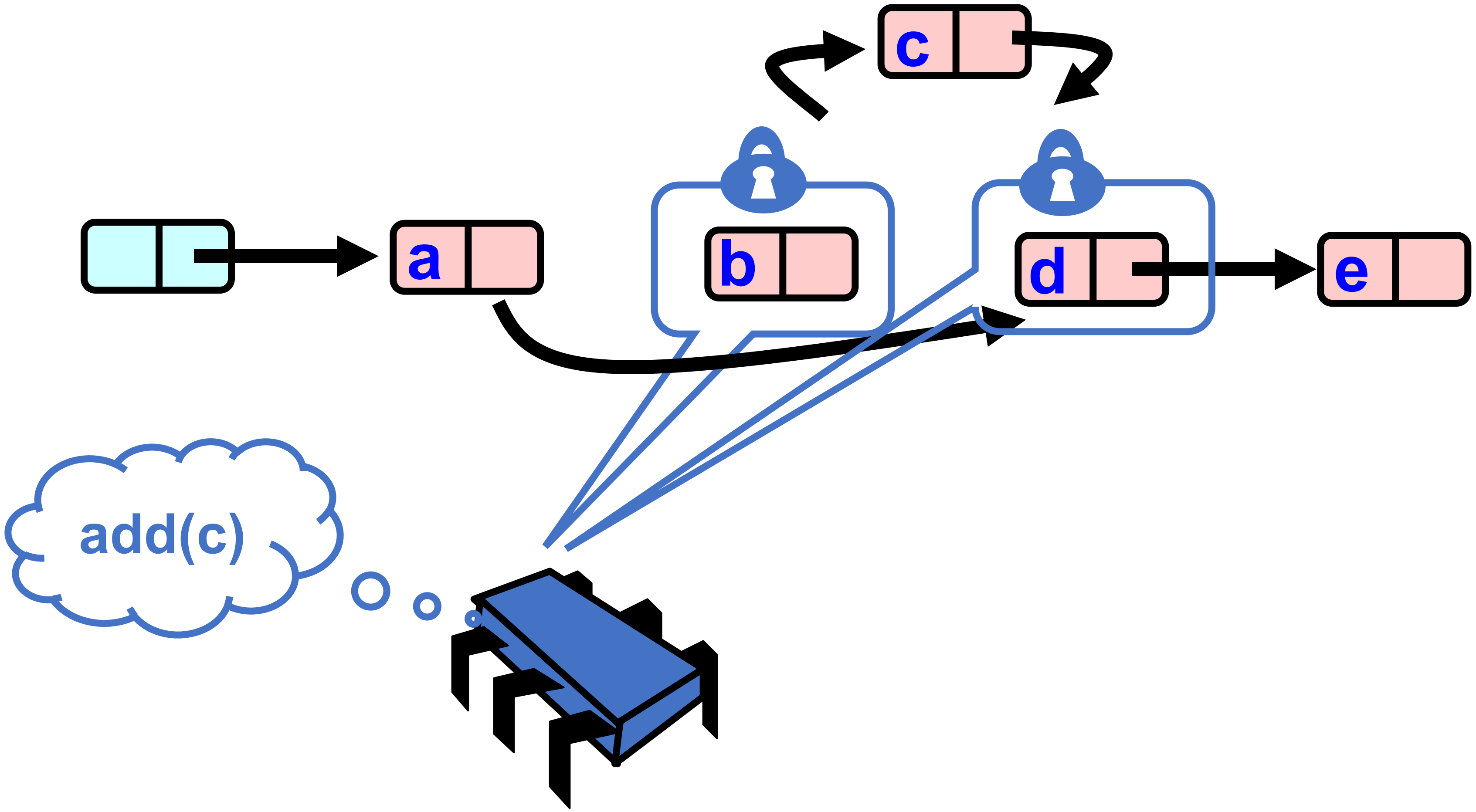

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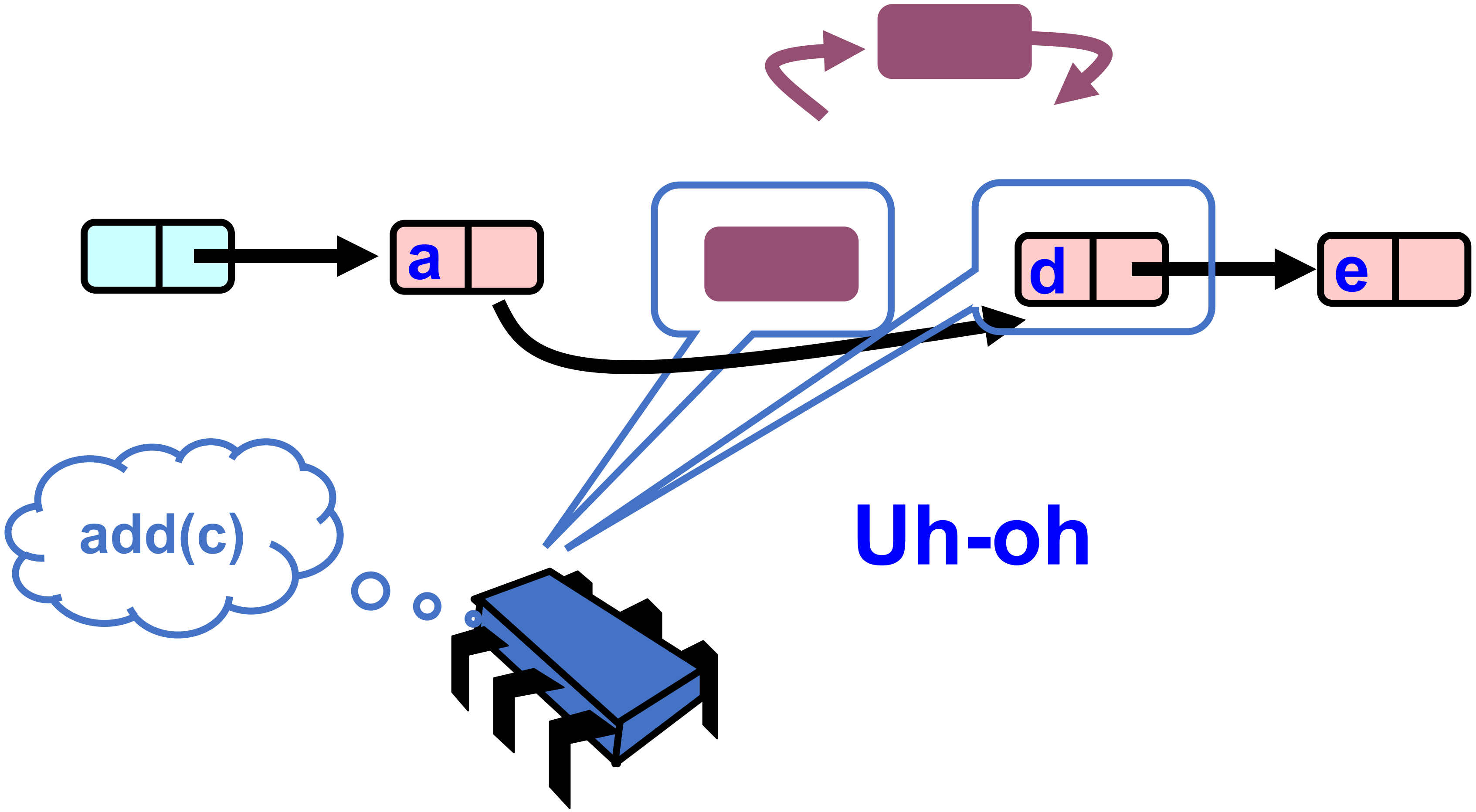
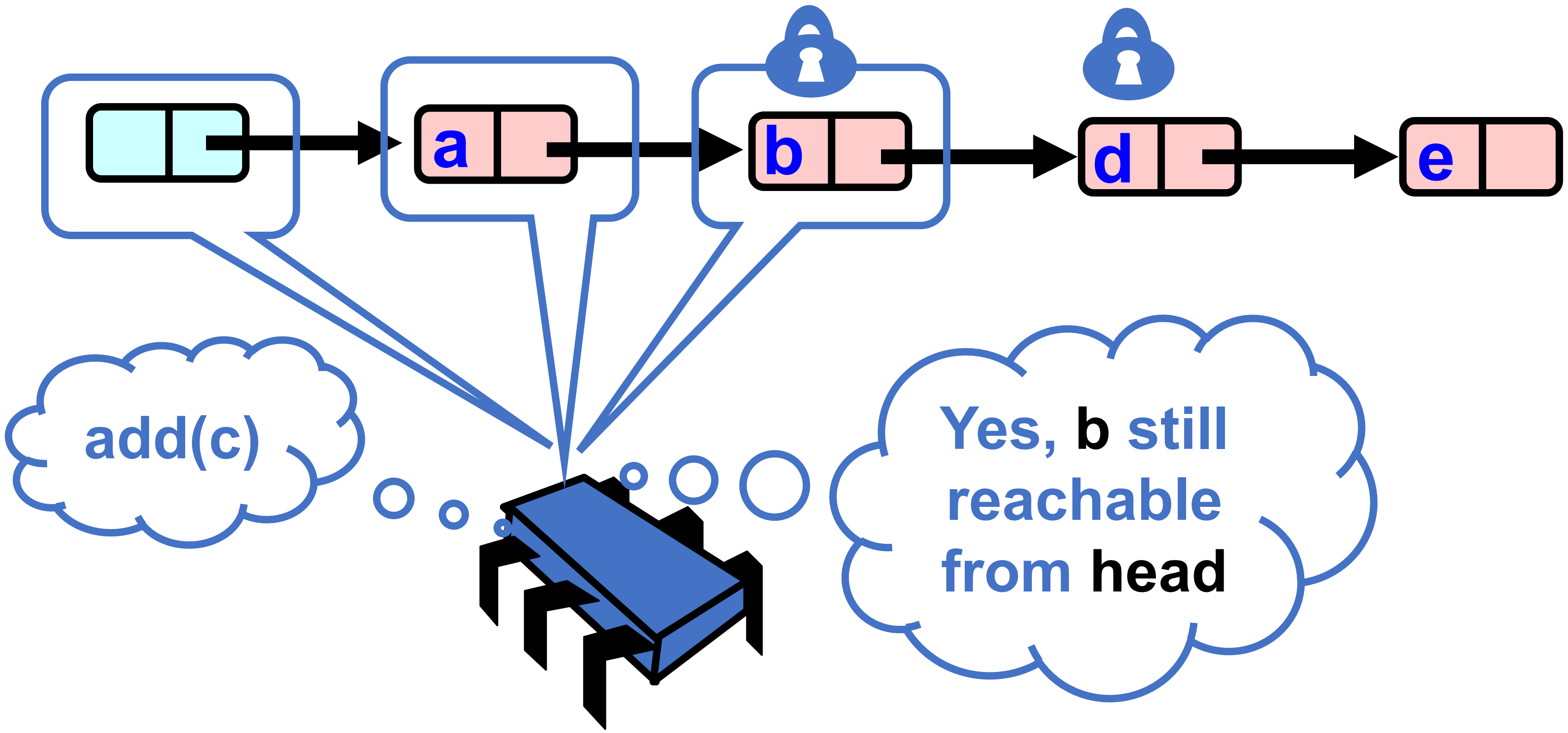


Validate – Part 1



What happens if failure?

- Ideas?

What happens if failure?

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

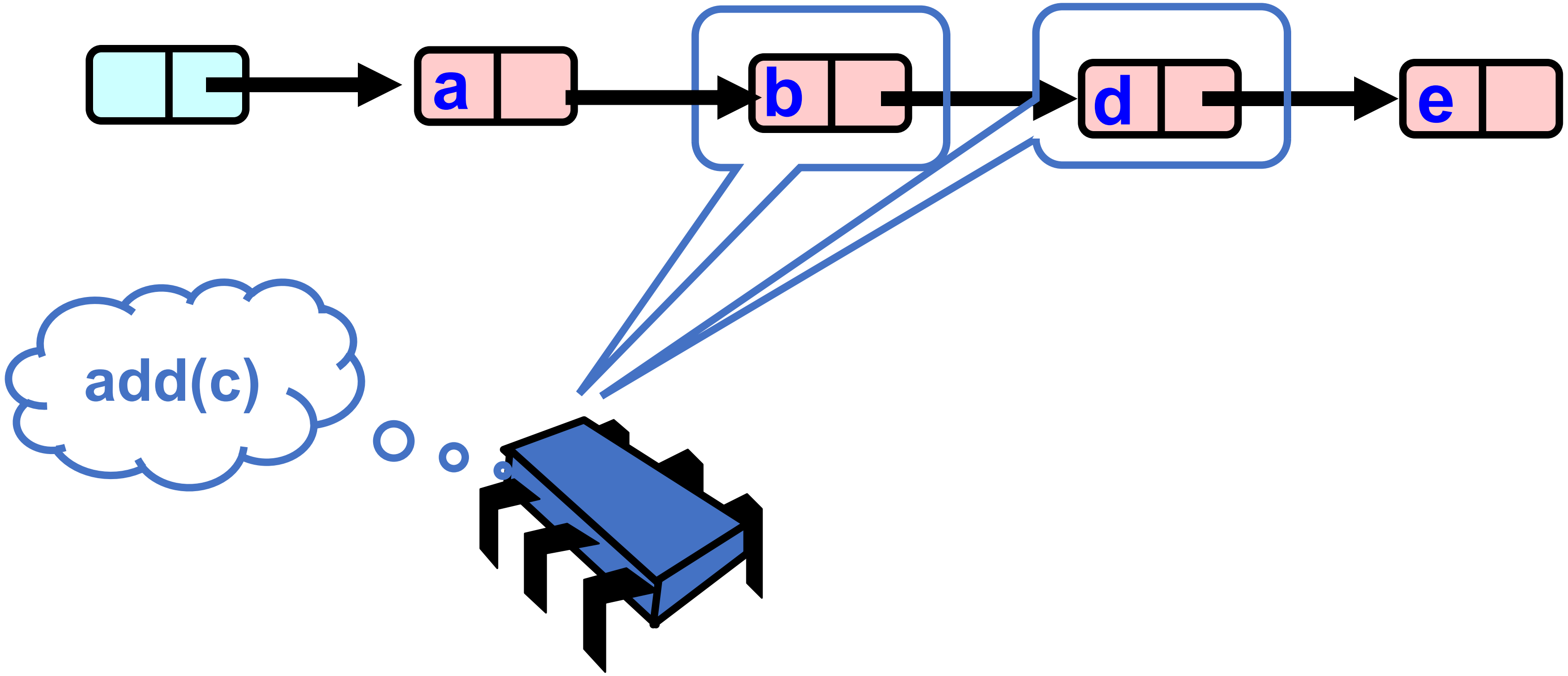
What happens if failure?

- 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?



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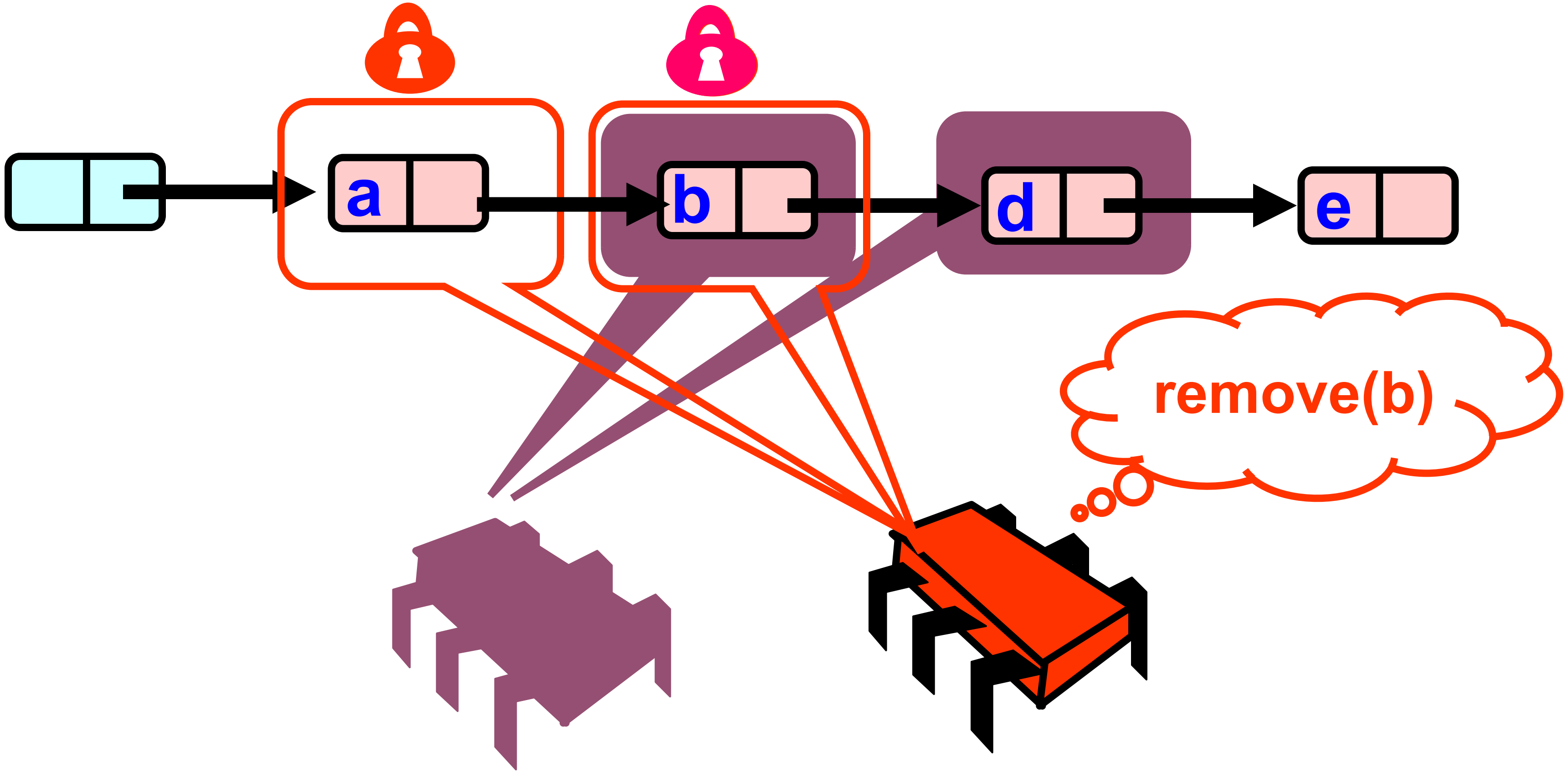

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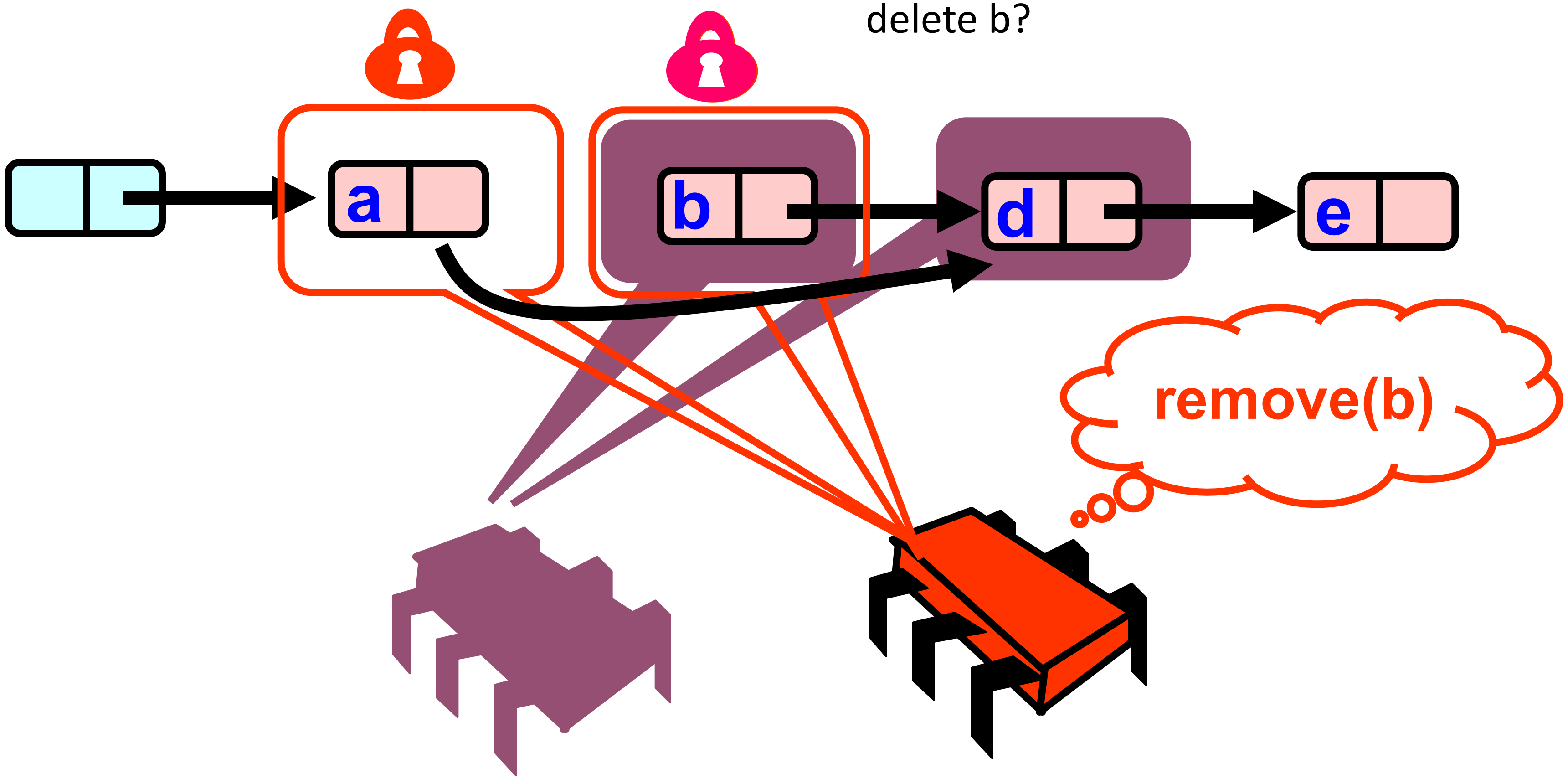

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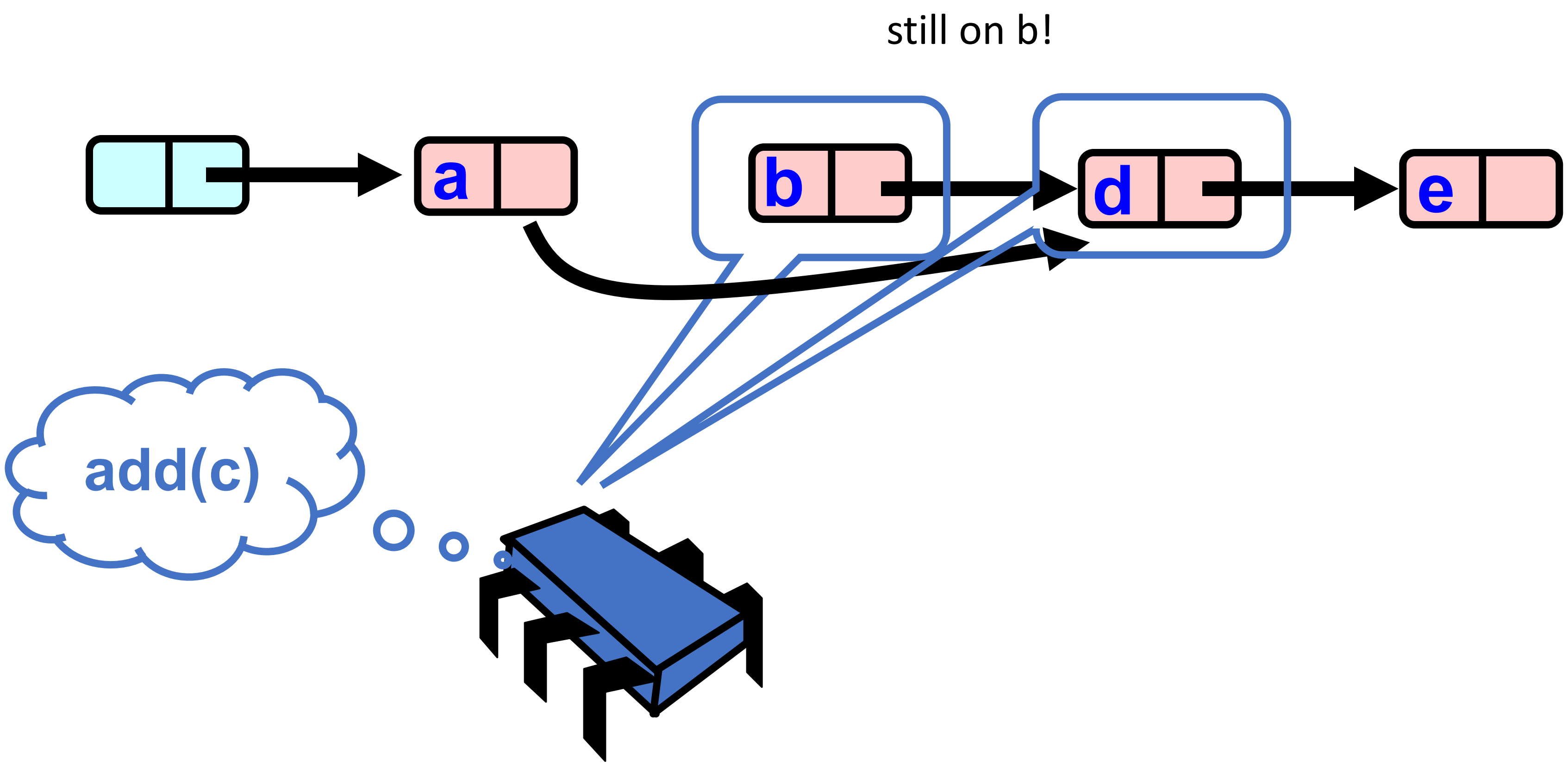
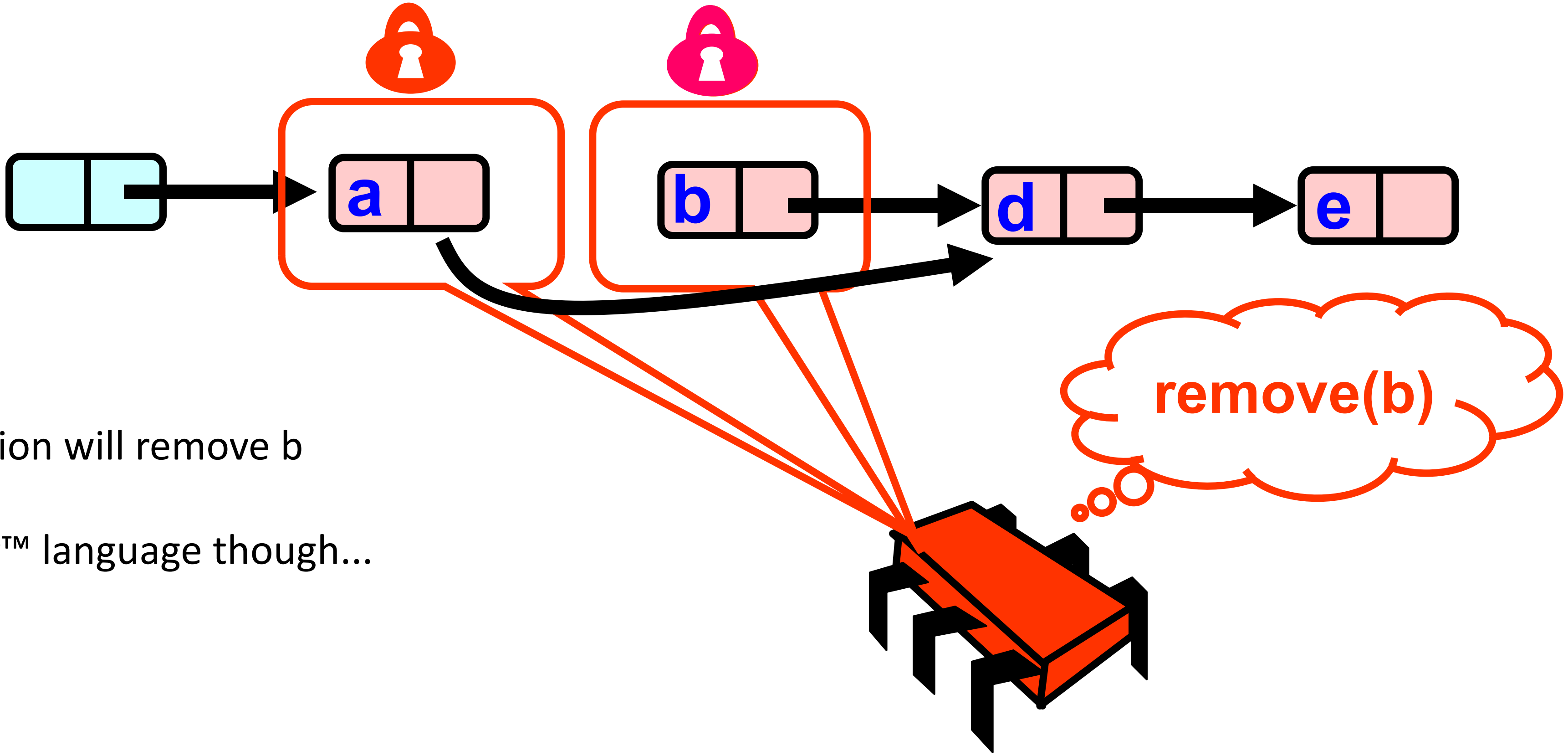


Our own garbage collector



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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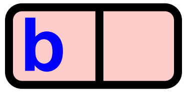

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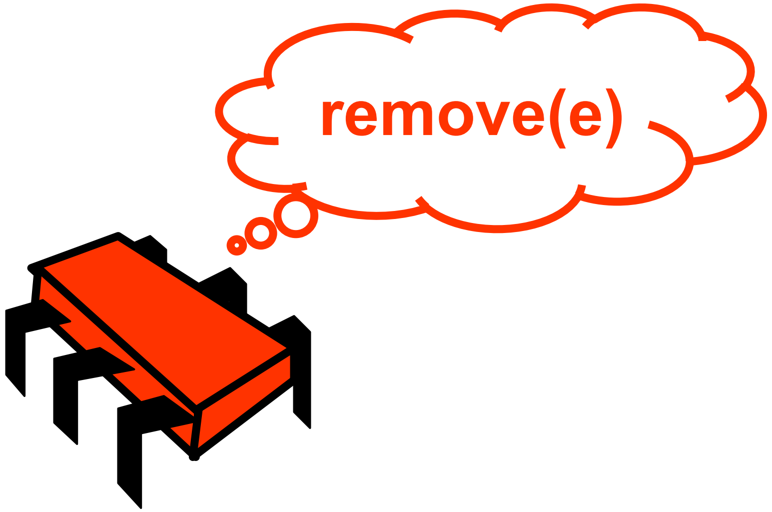

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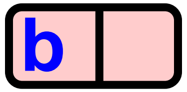

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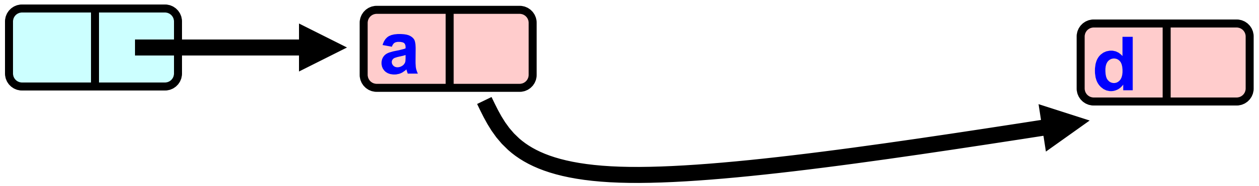

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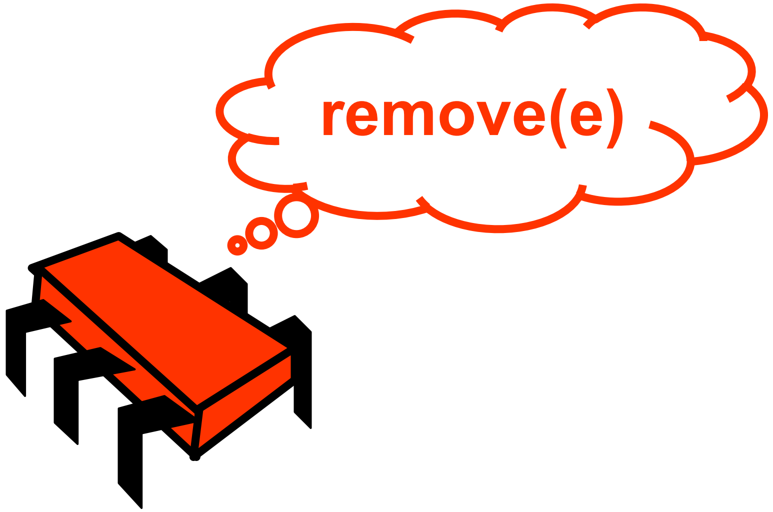

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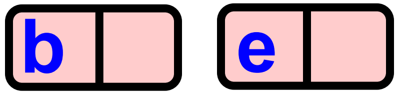
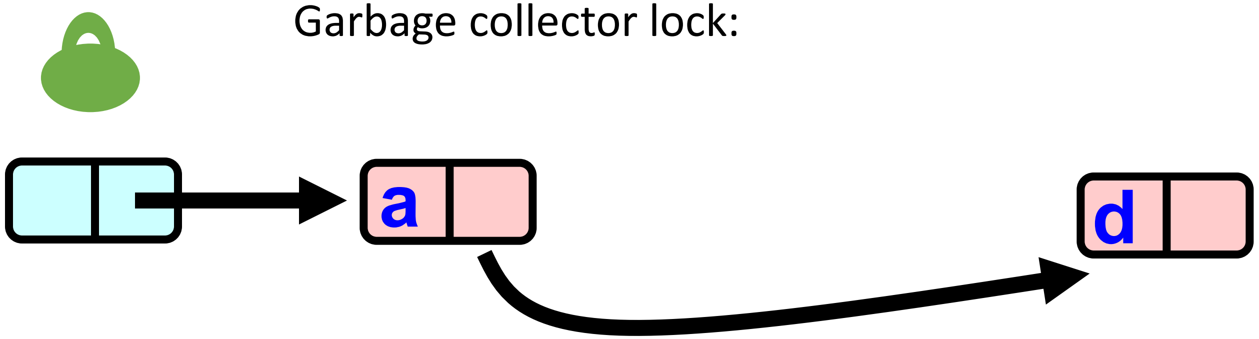
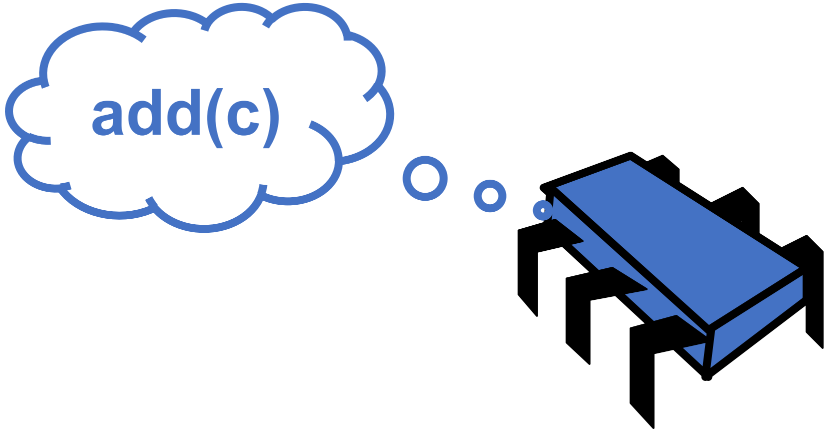


Our own garbage collector

Garbage collector lock:





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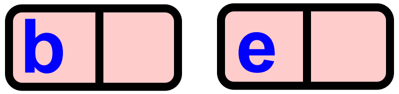

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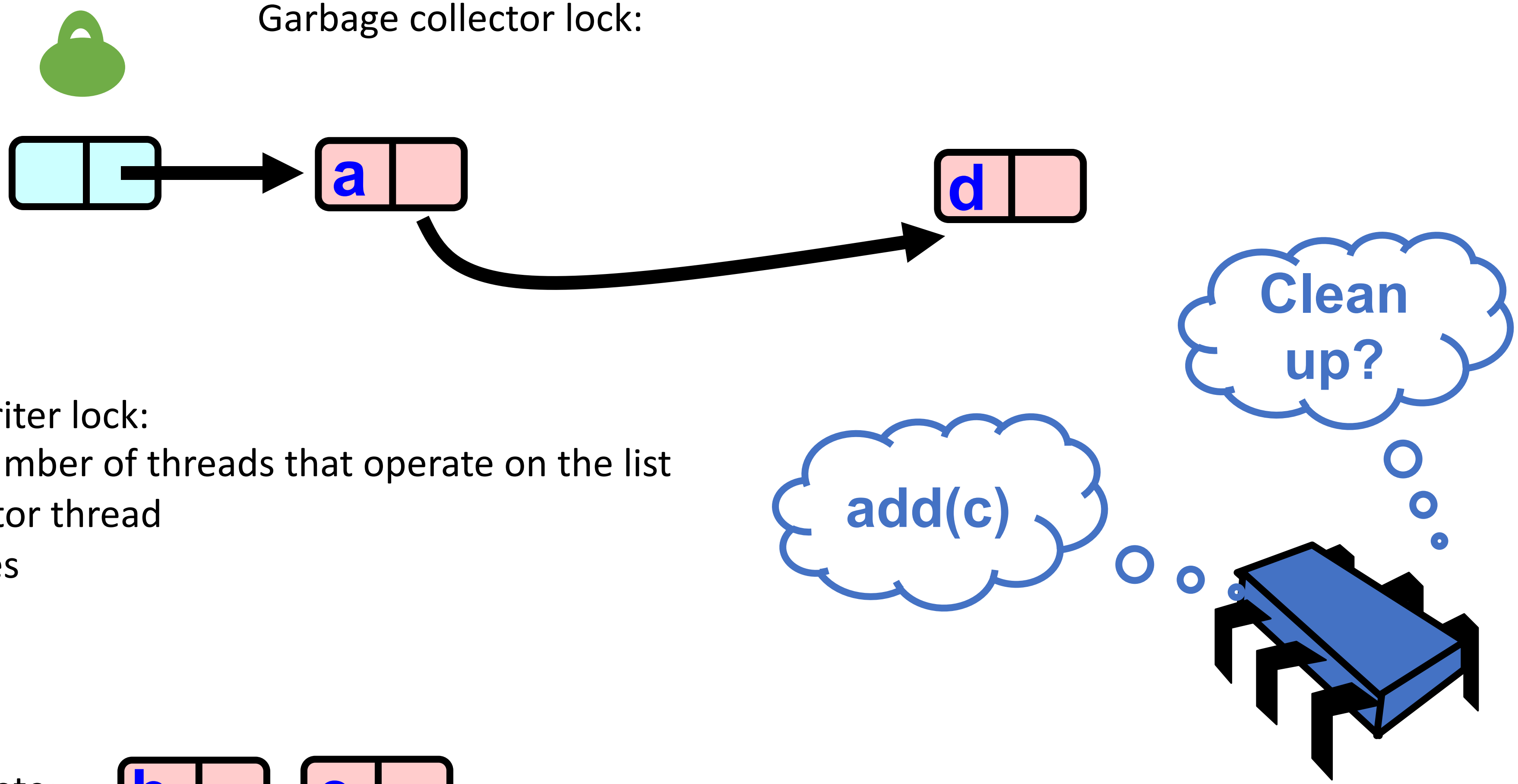
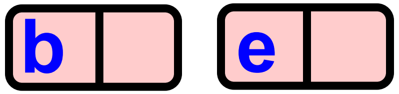

Garbage collector lock:

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

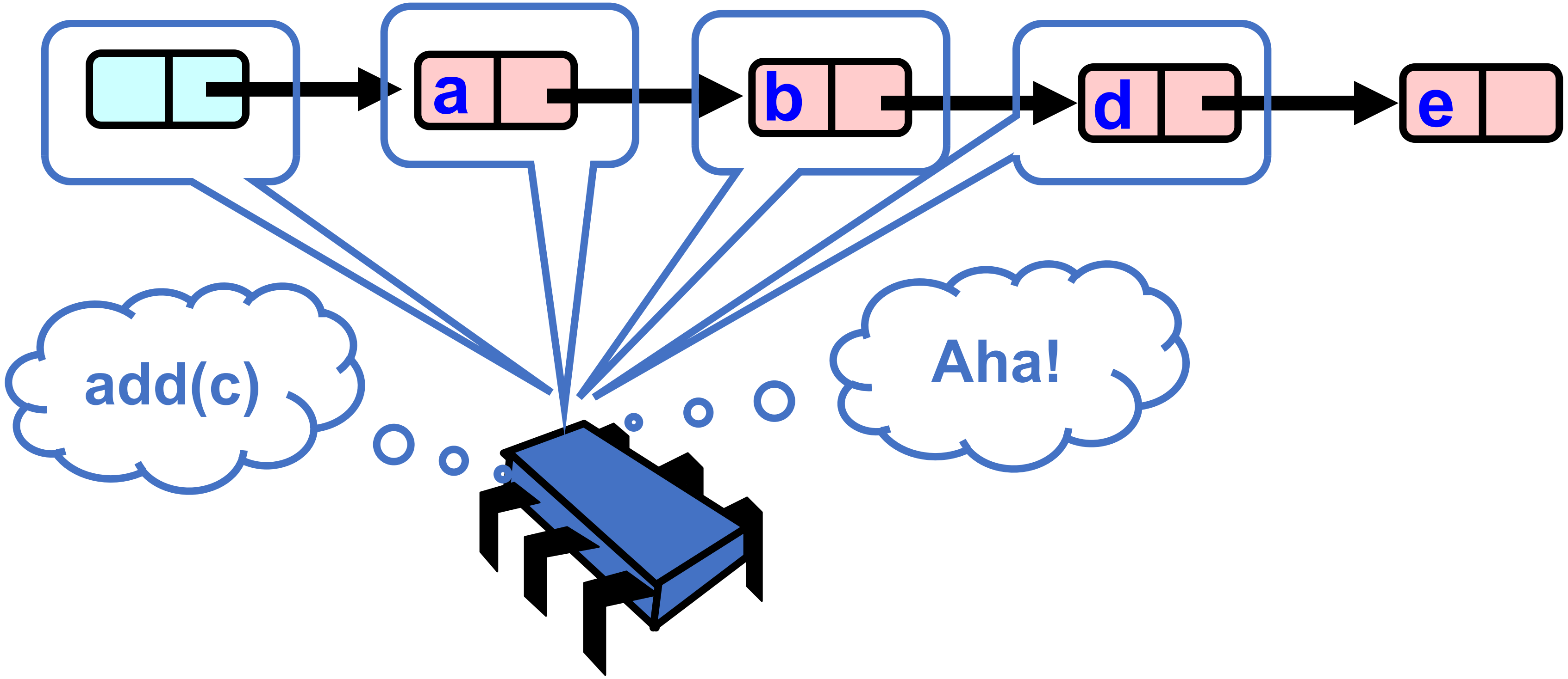
- **Strat 1:** Threads always try once to take the garbage collector lock:
  - if failed, no worries, the next operation will get a chance
  - if succeeded, then there was no contention
  - can starve garbage collection

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

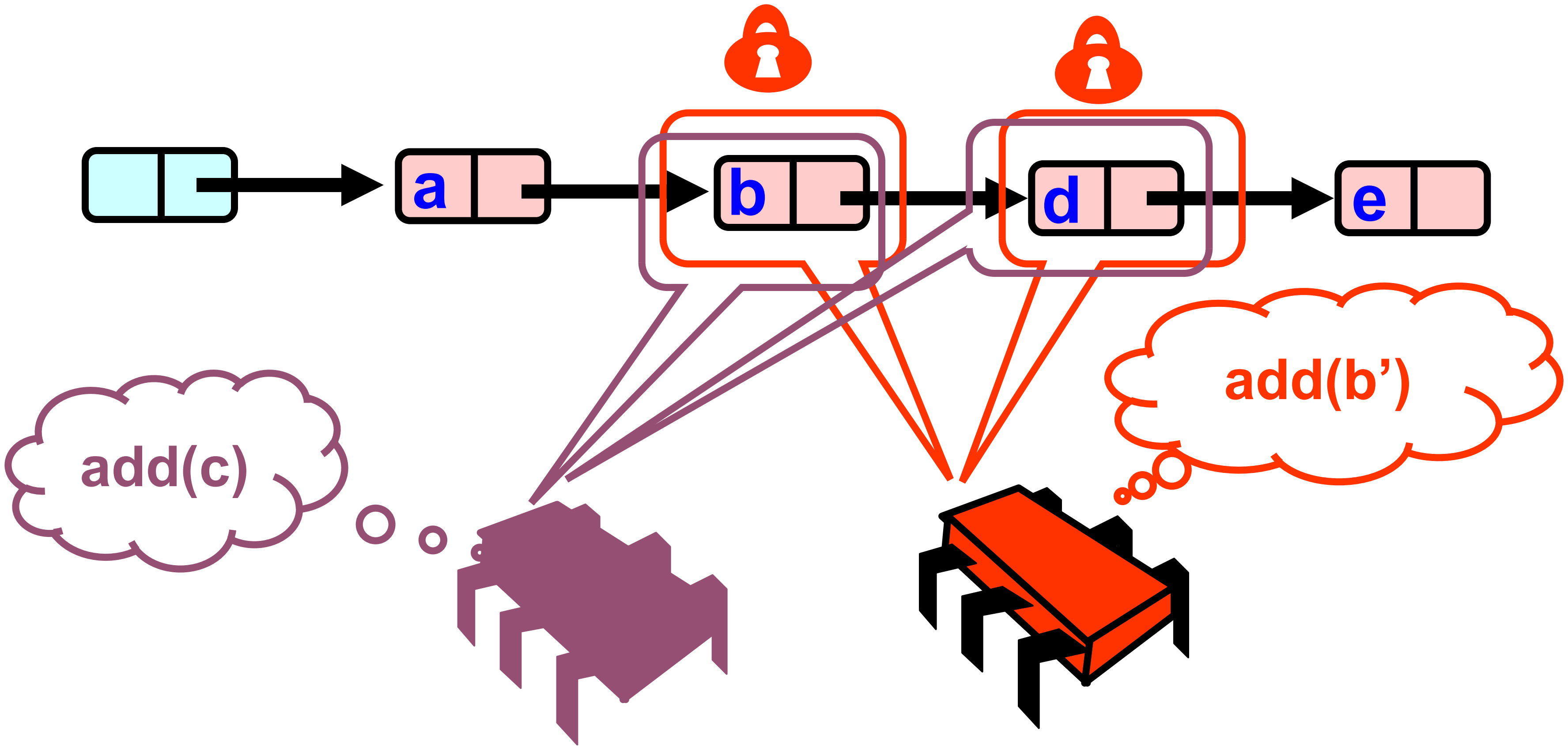
Back to the linked list

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

What Else Could Go Wrong?



What Else Coould Go Wrong?



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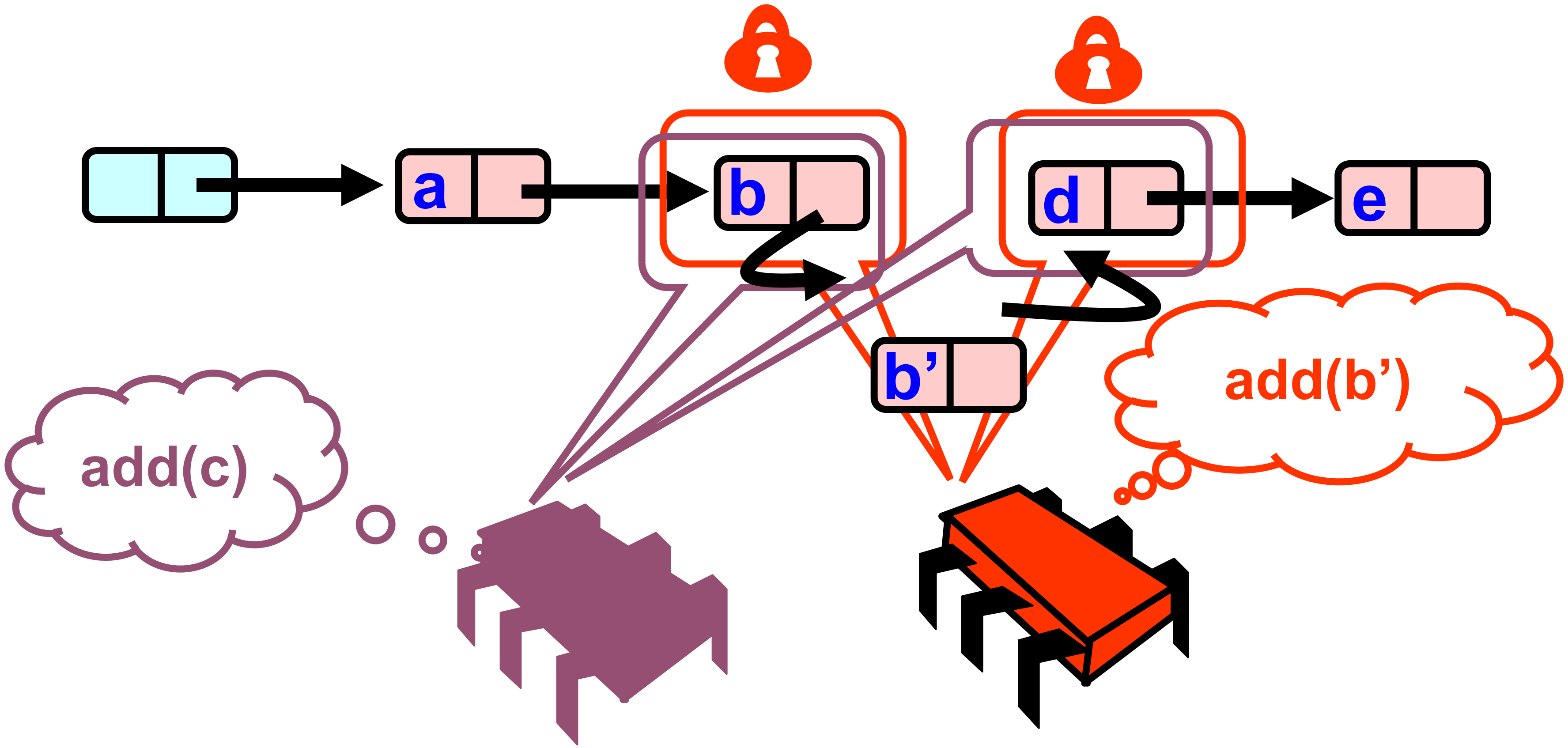

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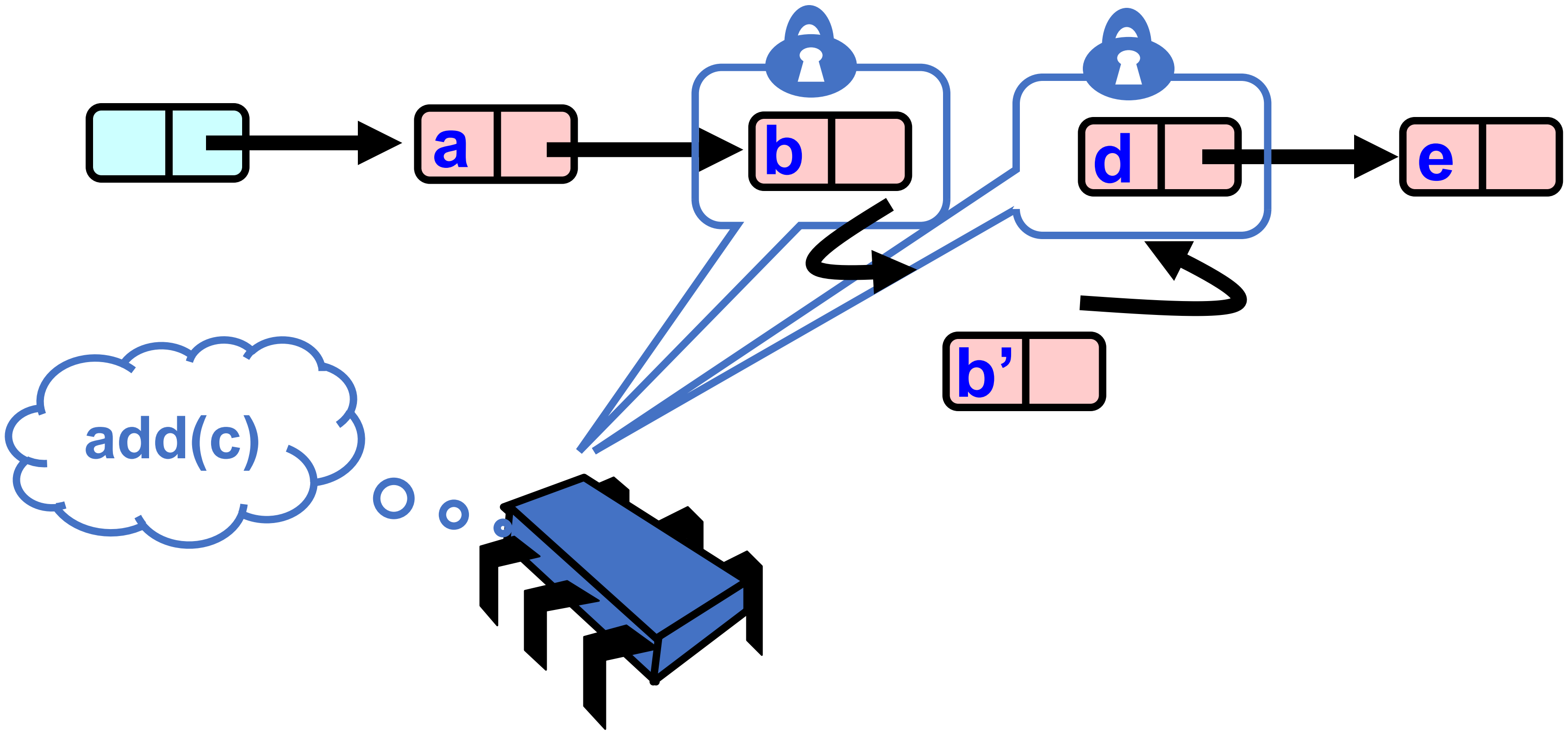
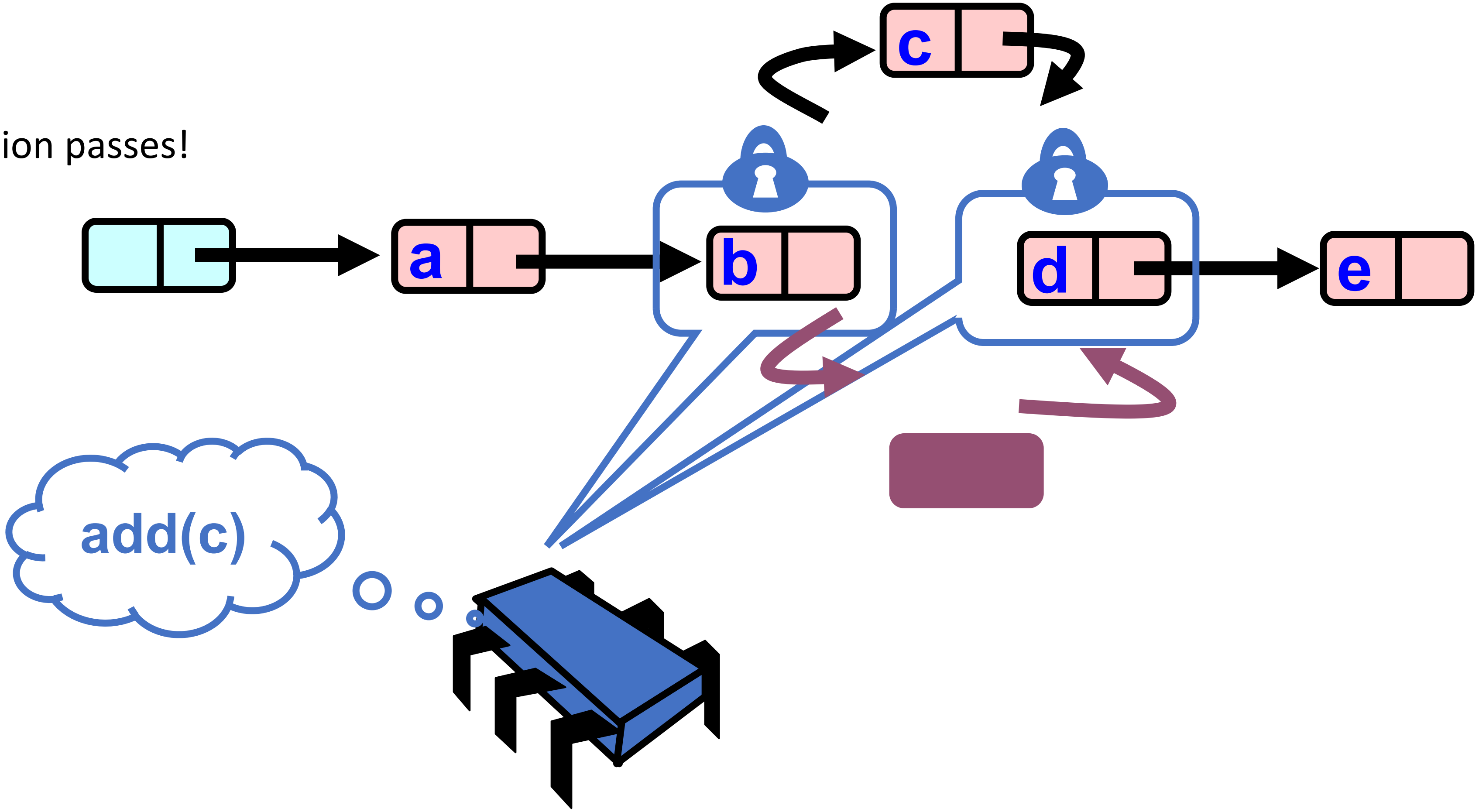
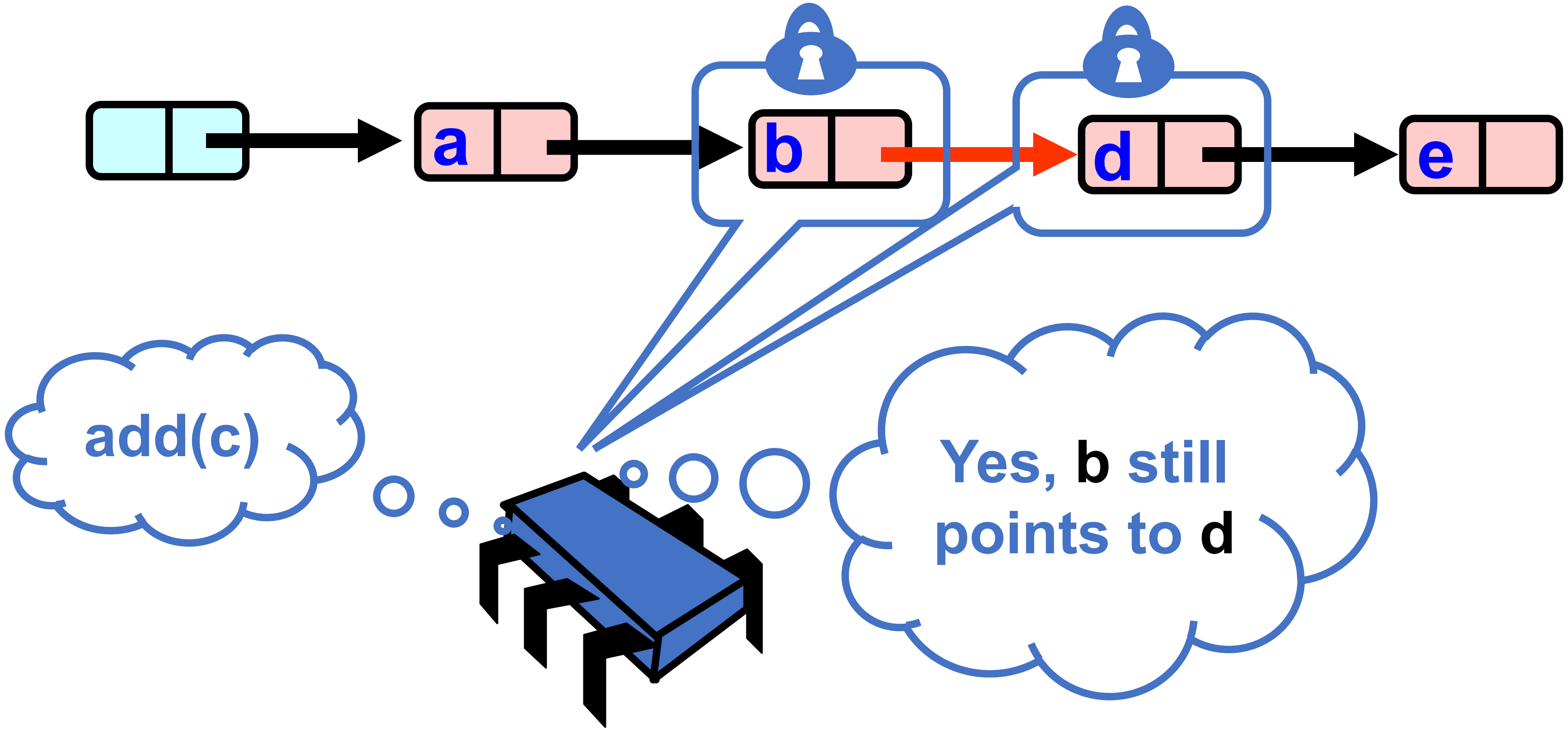


What Else Could Go Wrong?

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!
  - One extra lecture on module 3

- I really should be feeling better by Monday

- Hopefully you have started the midterm!

- Get started on HW 2