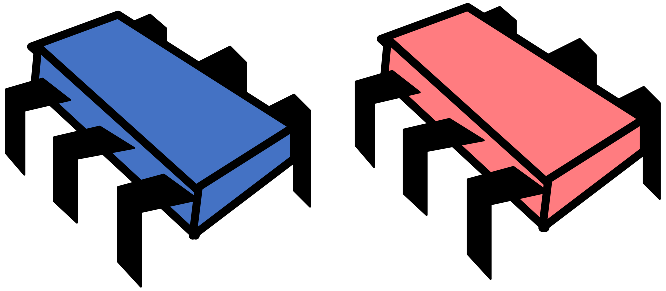
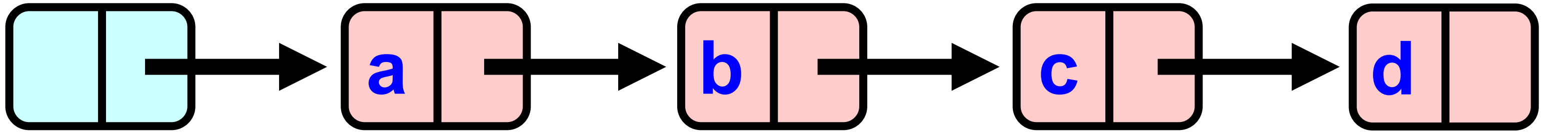
CSE113: Parallel Programming

- **Topics**:
  - Concurrent general set
  - Barriers





Announcements

- HW 4 grades will be released this week.

Announcements

- HW 5 was released last week.

Announcements

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

Quiz

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Concurrent linked lists can be implemented using locks on every node if:

◯ Locks are always acquired in the same order
◯ Two locks are acquired at a time
◯ Both of the above
◯ Neither of the above

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Lock coupling provides higher performance than a single global lock because threads can traverse the list in parallel

◯ True
◯ False

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◉ True
◯ False

Quiz

Optimistic concurrency refers to the pattern where functions optimistically assume that no other thread will interfere. In the case where another thread interferes, the program is left in an erroneous state, but since this is so rare, it does not tend to happen in practice.

◯ True
◯ False

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Optimistic concurrency refers to the pattern where functions optimistically assume that no other thread will interfere. In the case where another thread interferes, the program is left in an erroneous state, but since this is so rare, it does not tend to happen in practice.

○ True
◉ False

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After this lecture, do you think you would be able to optimize your implementation of the concurrent stack in homework 2? Write a few sentences on what you might try.

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Coarse-grained vs. Fine-grained locking?

Review

Add and remove: What could go wrong?

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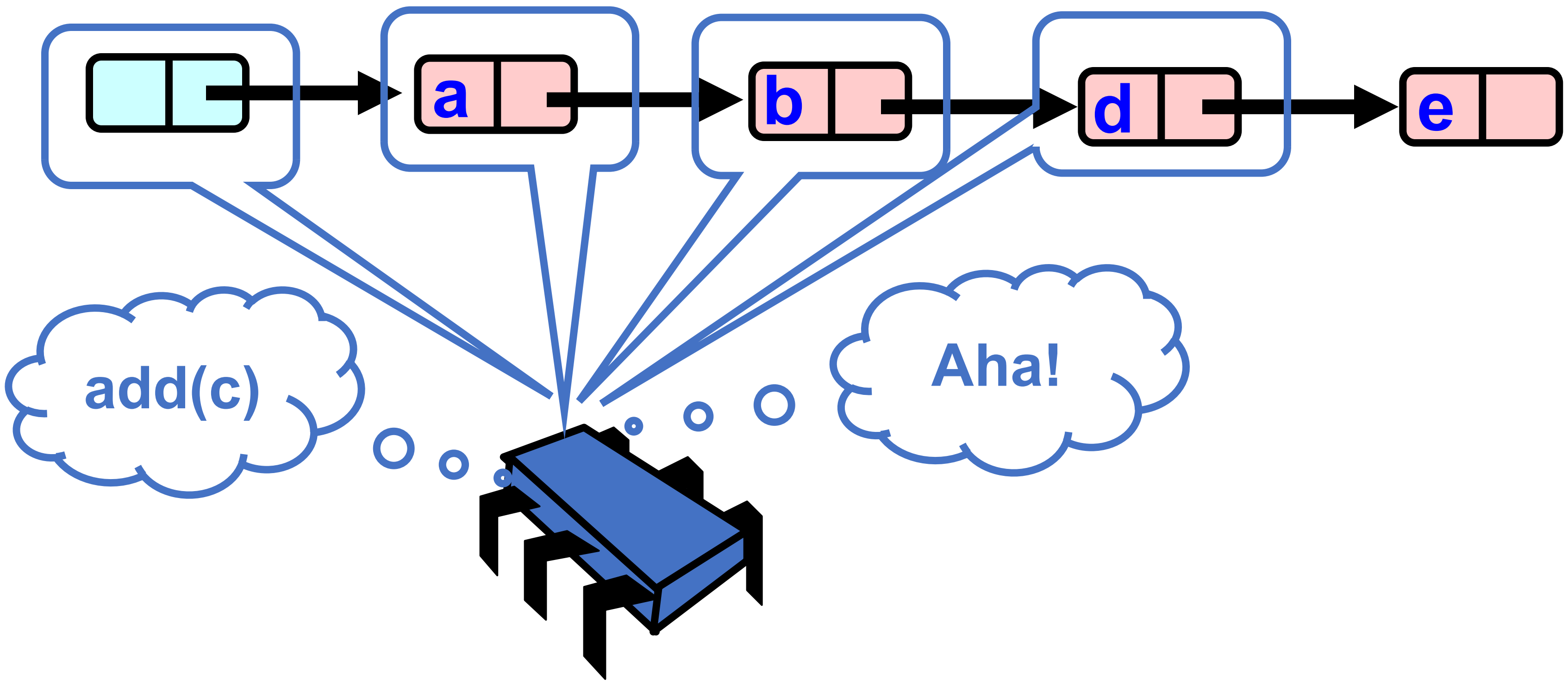

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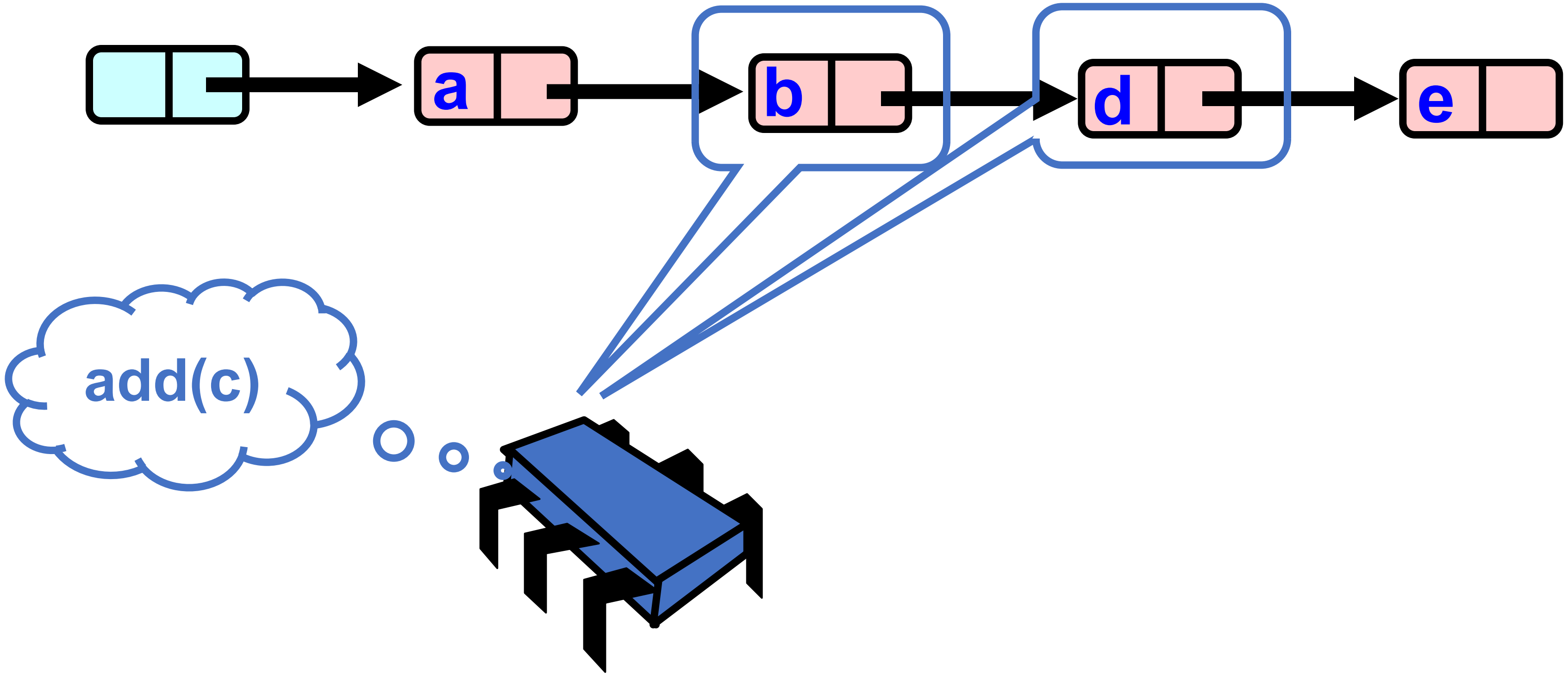

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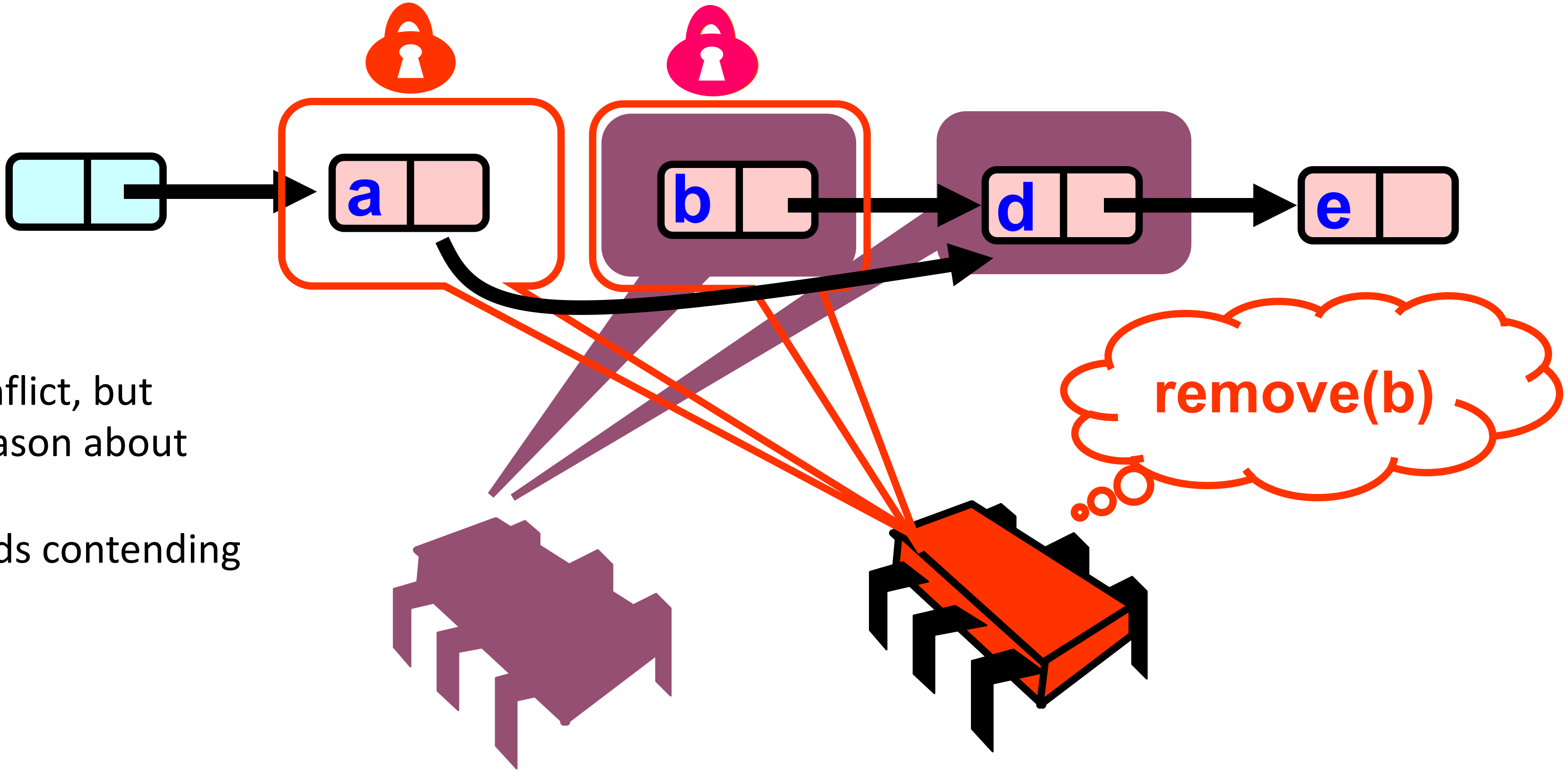
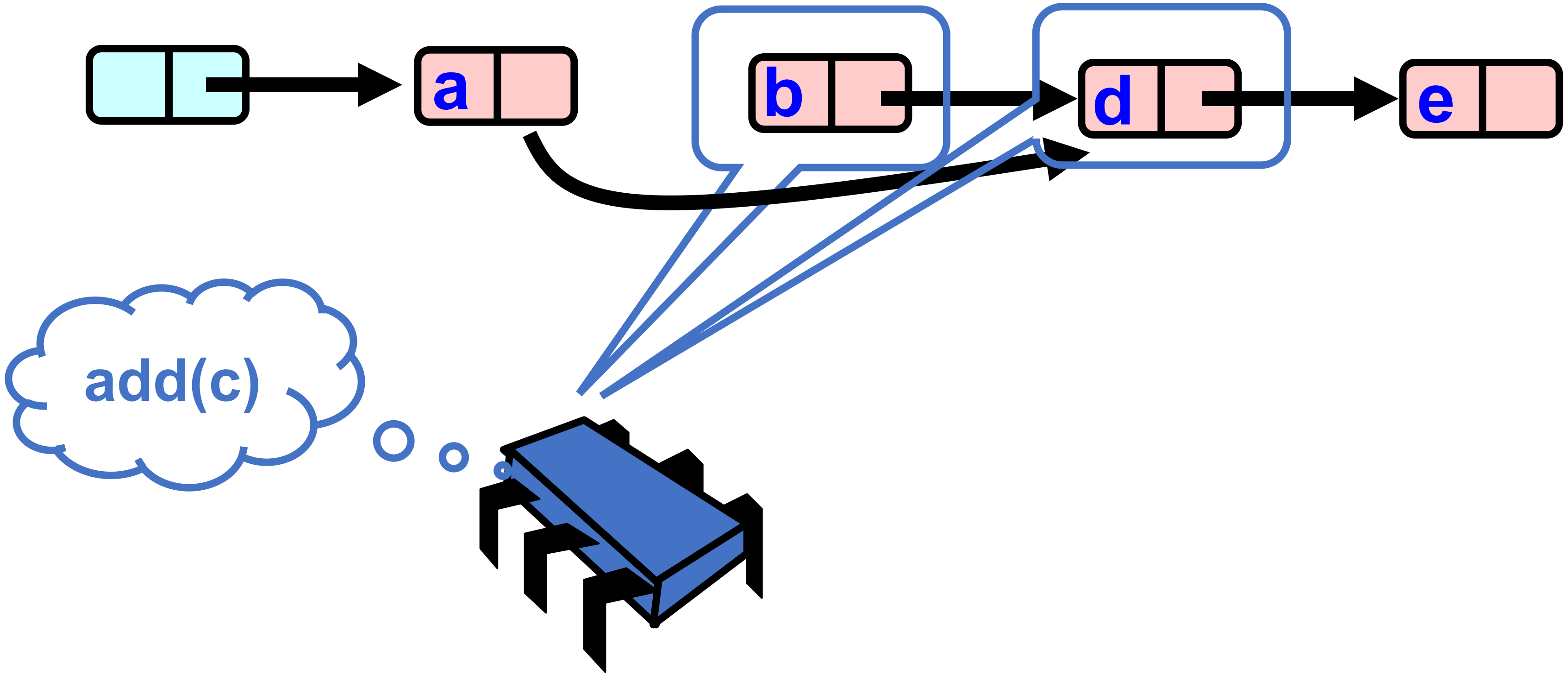


No more data conflict, but we do need to reason about interleavings.
Concurrent threads contending for values.

What could go wrong?



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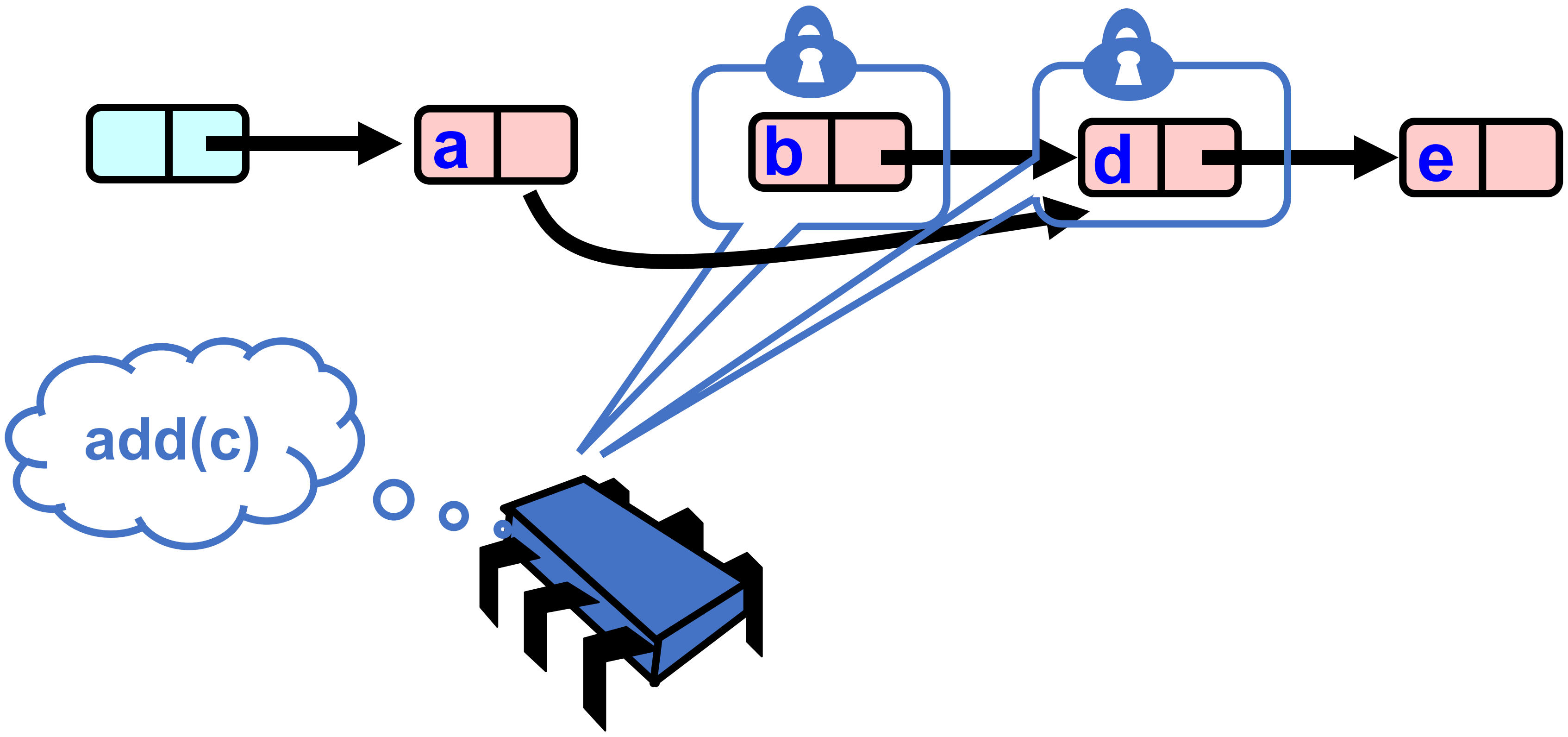

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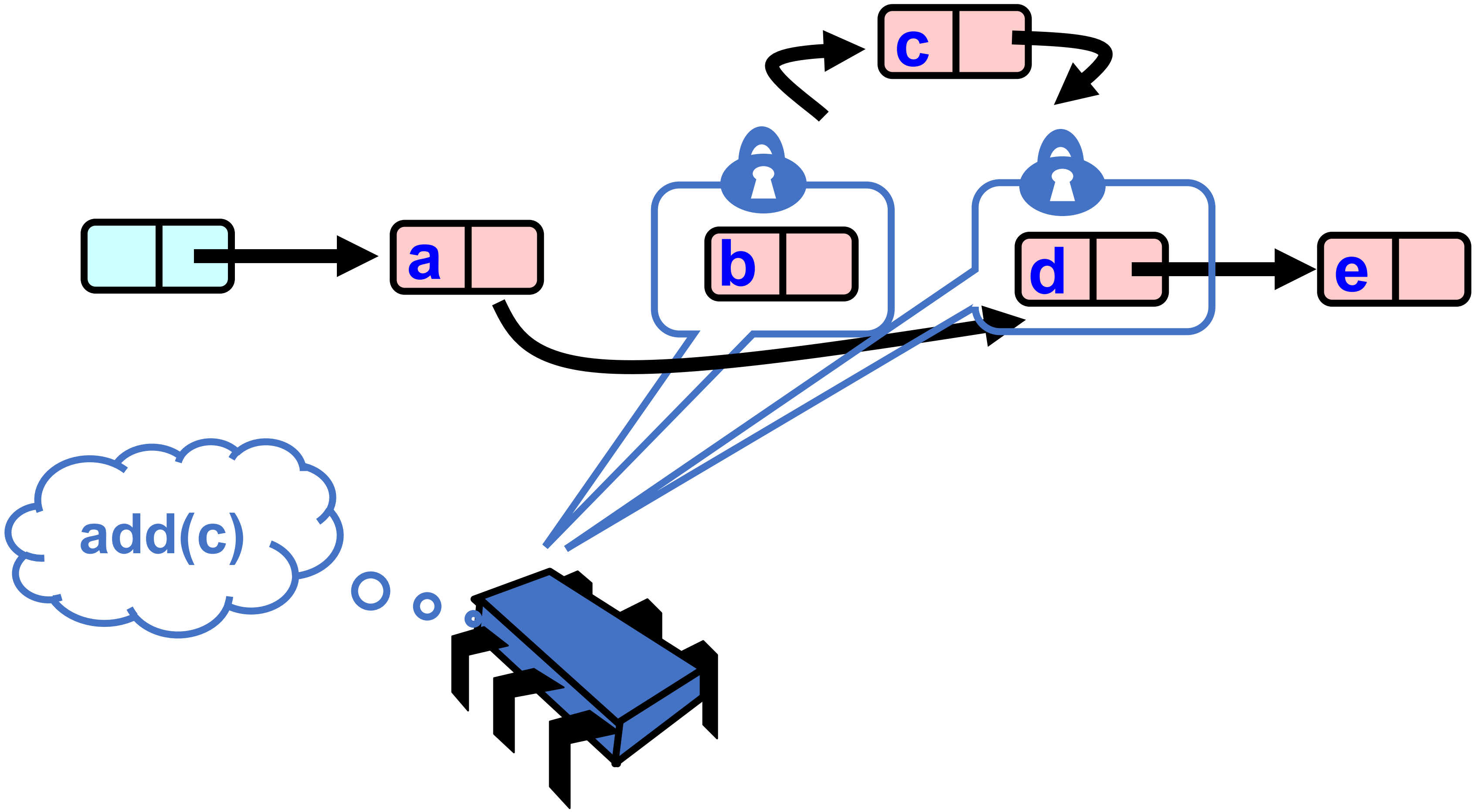

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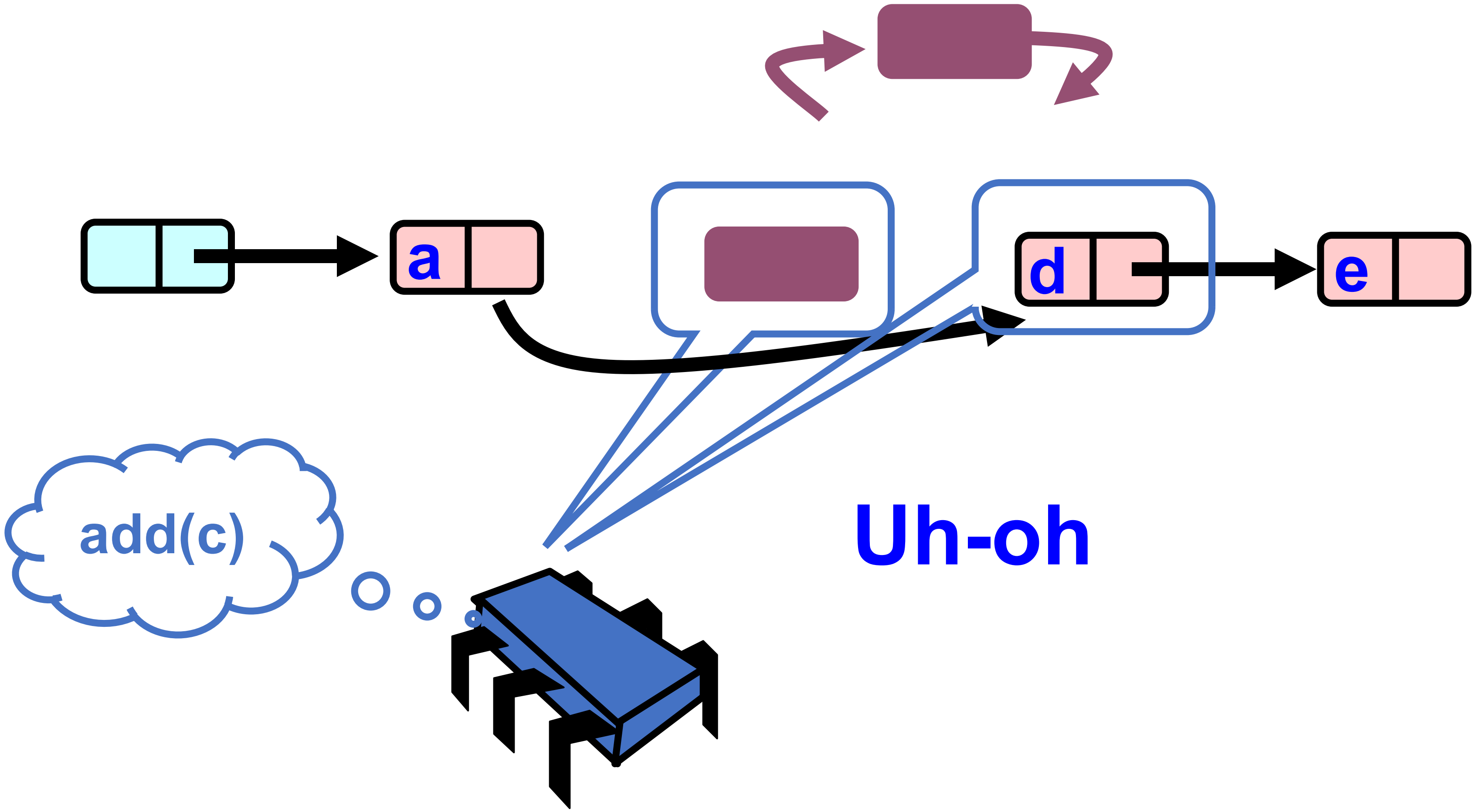
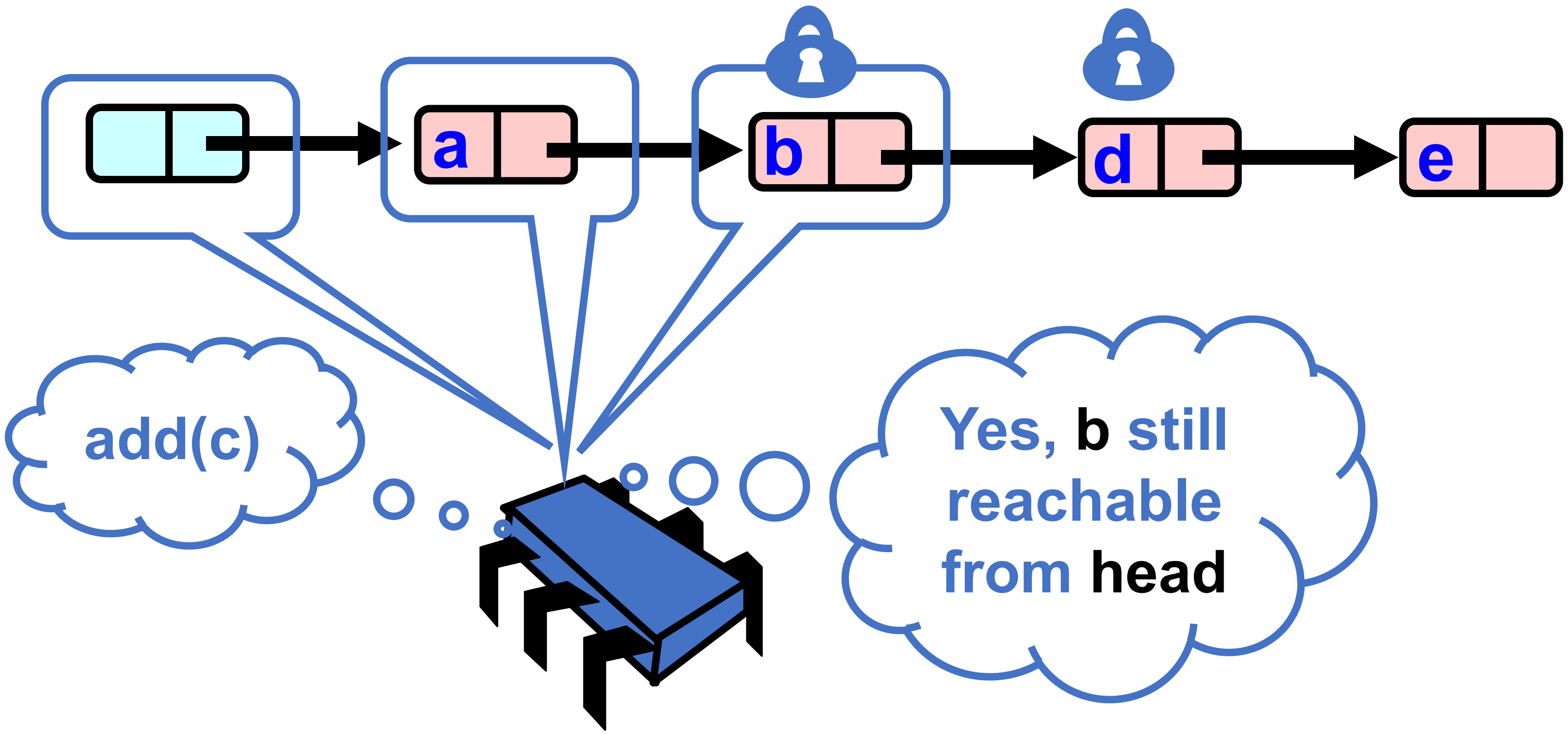
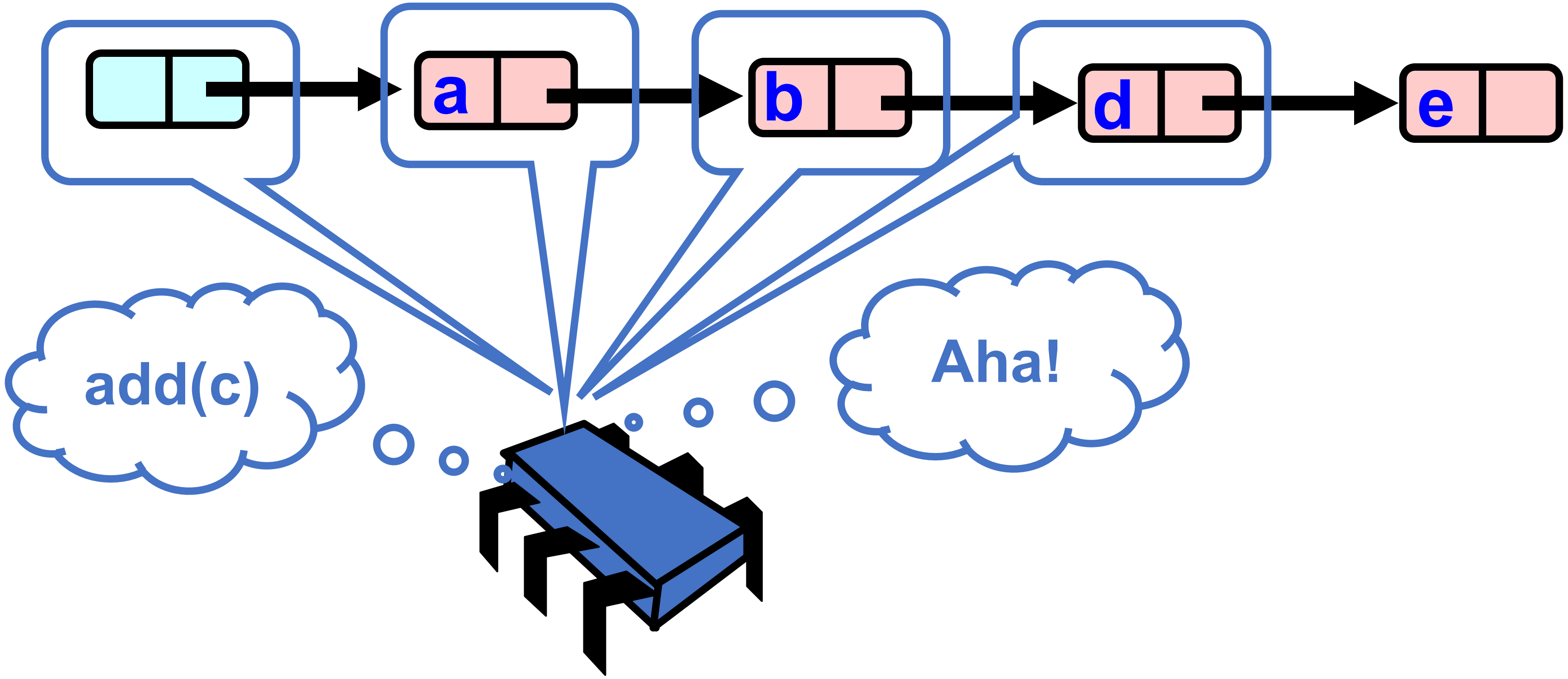


Validate – Part 1



Add and Add: What could go wrong?

What Else Could Go Wrong?



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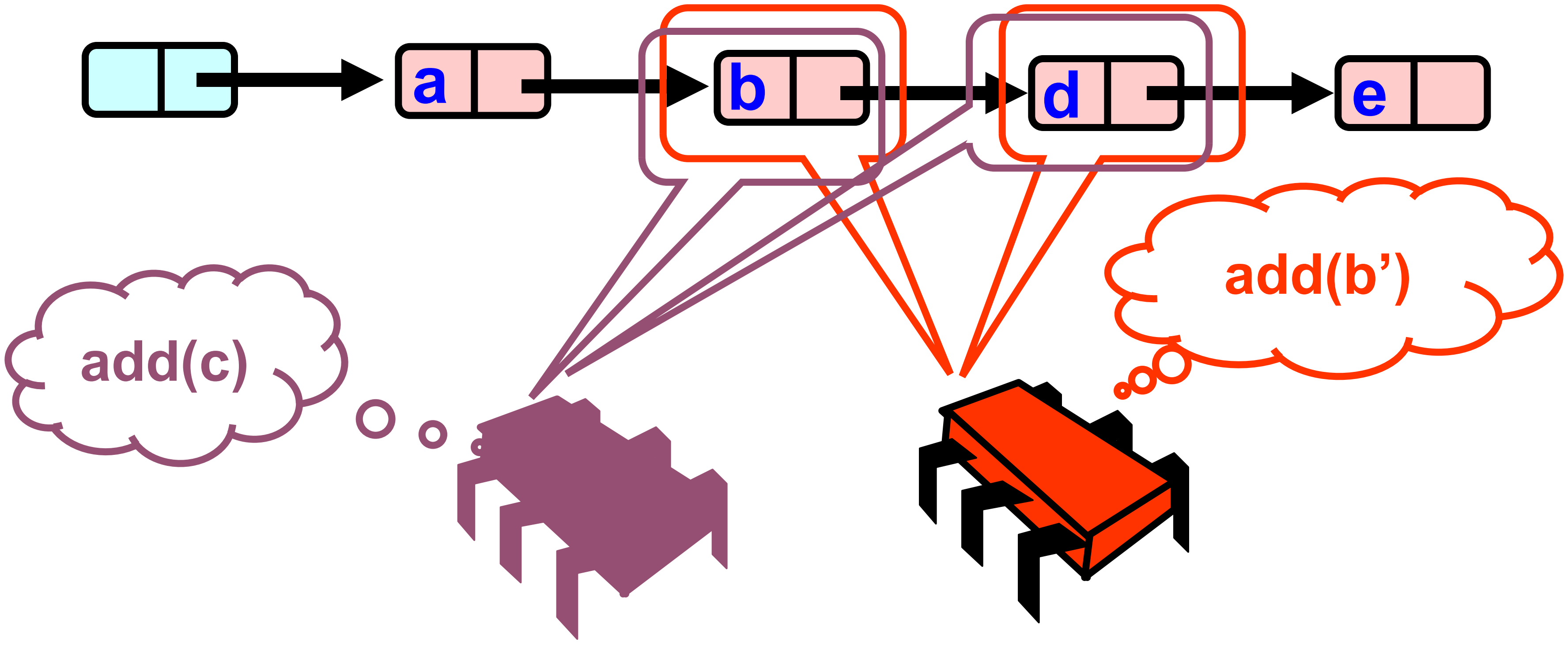

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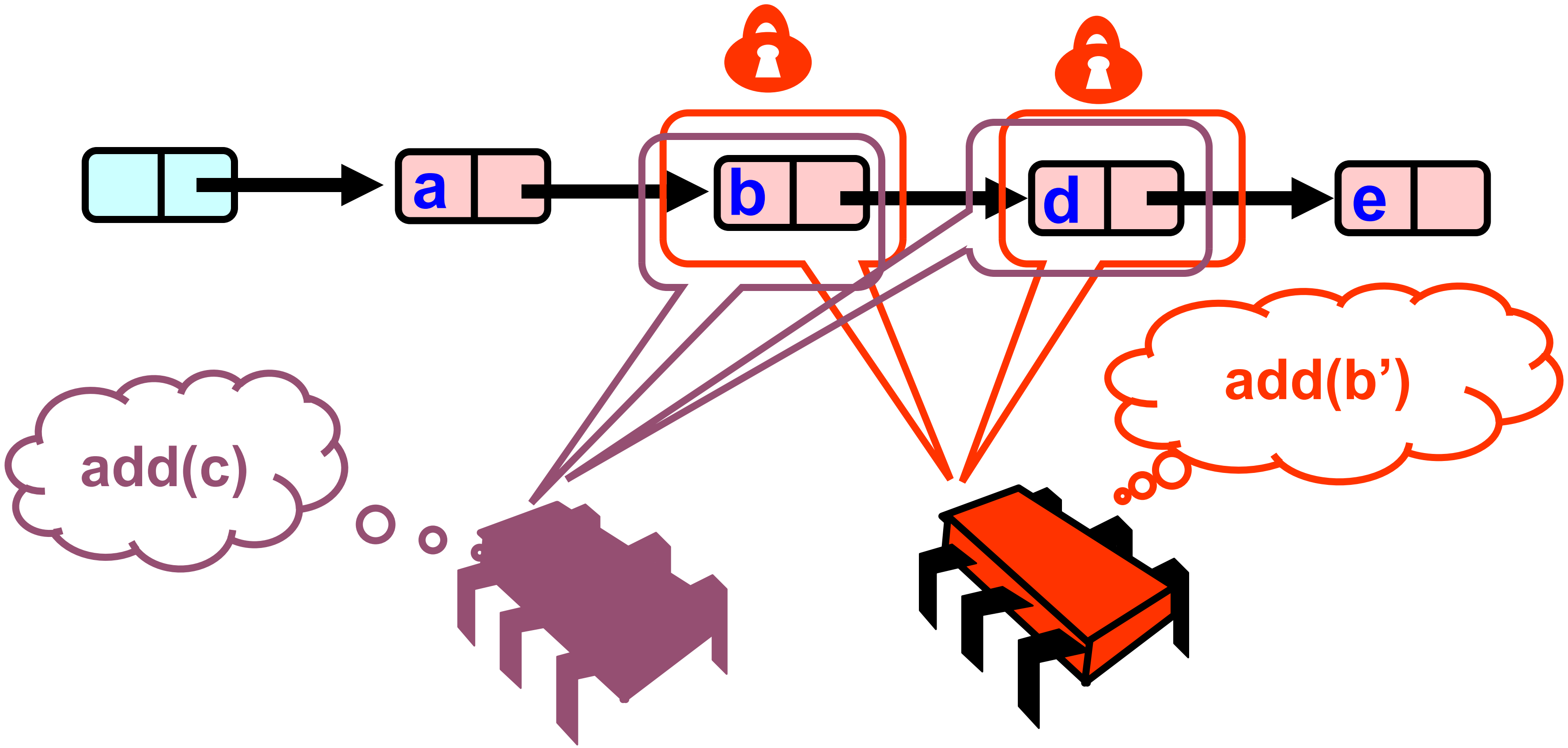

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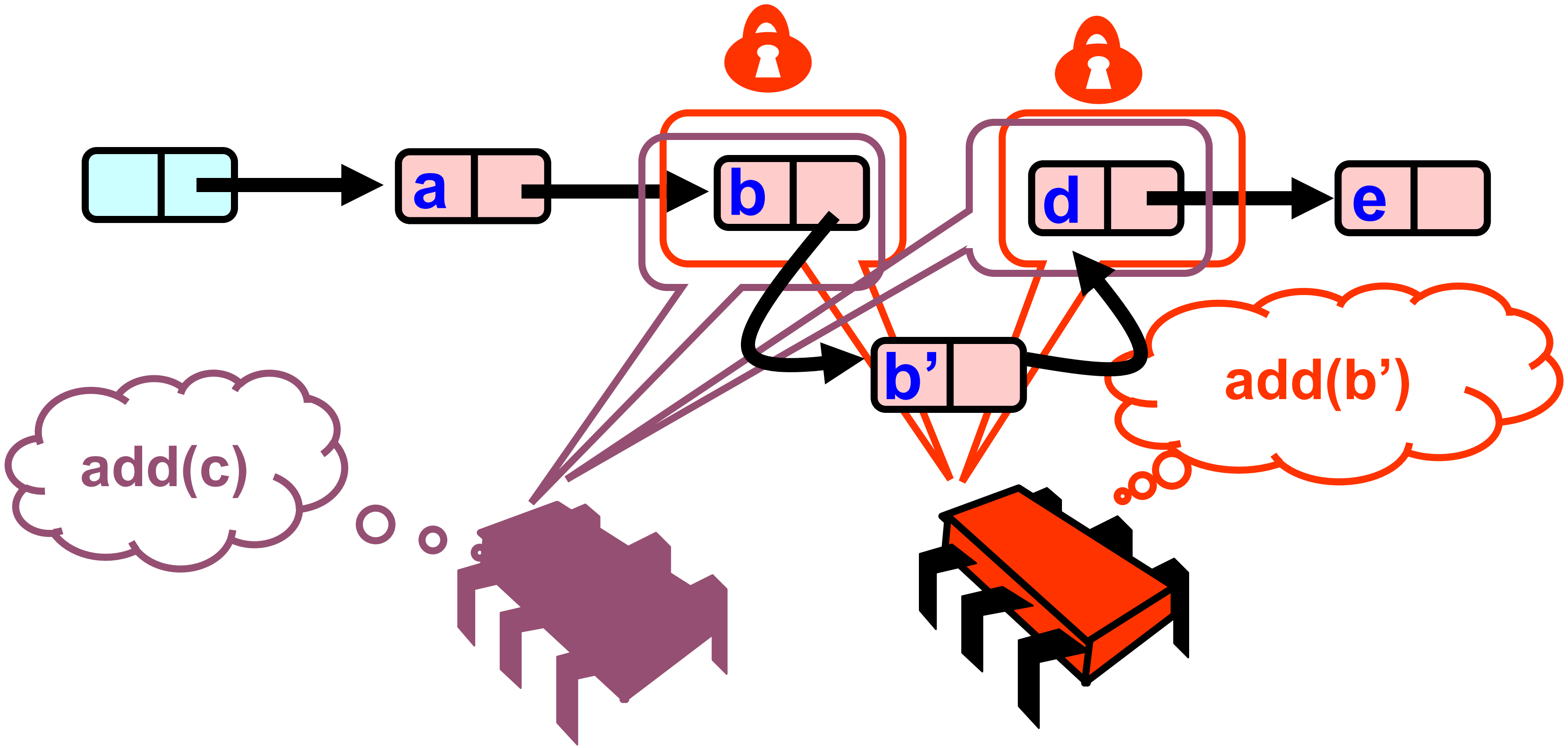

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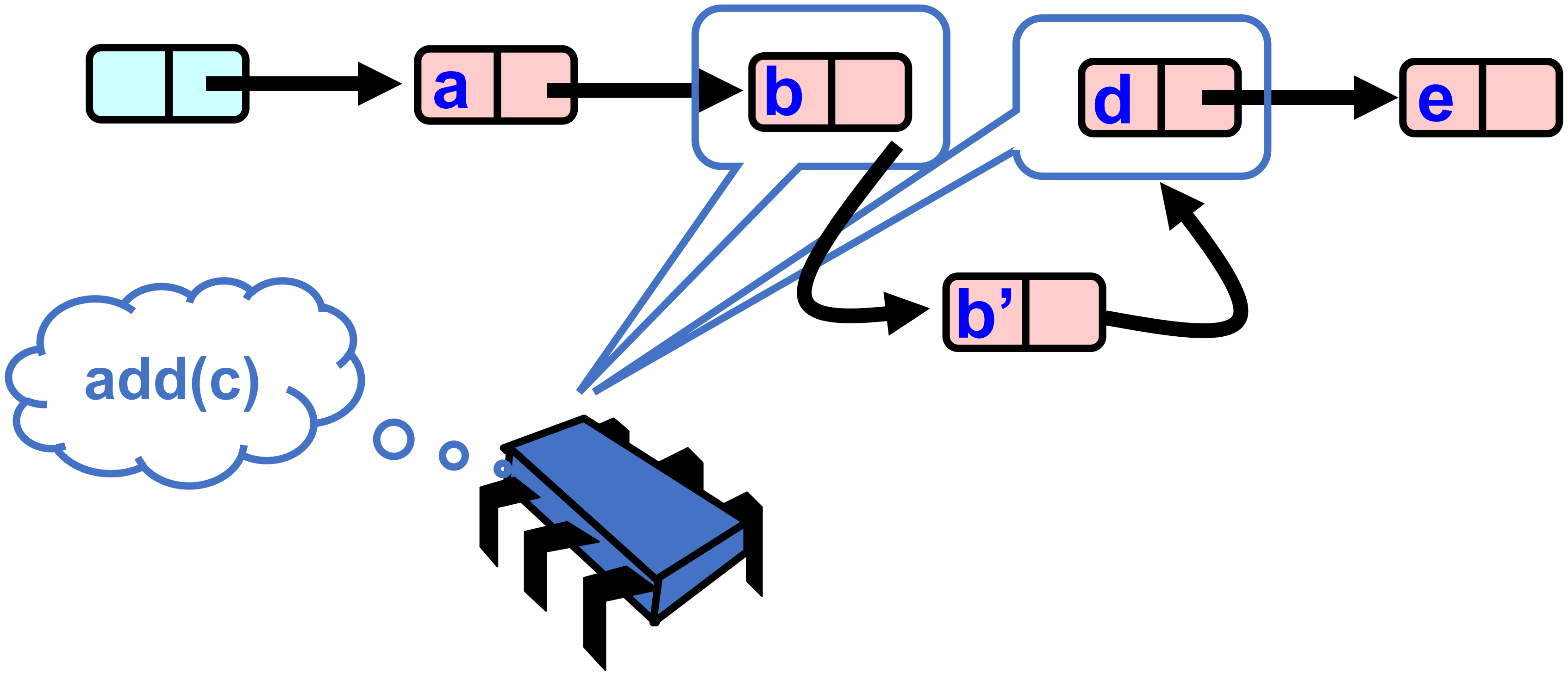

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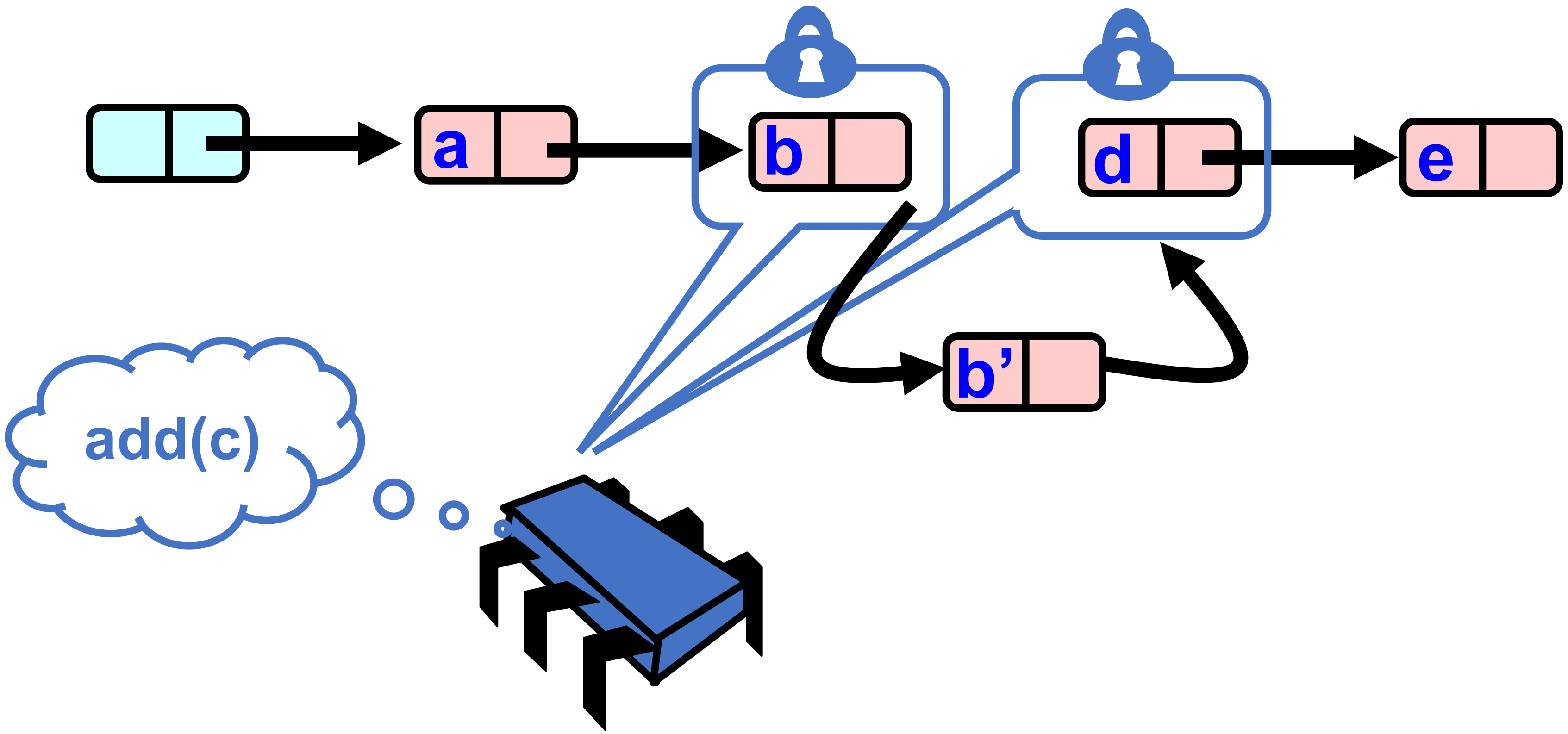
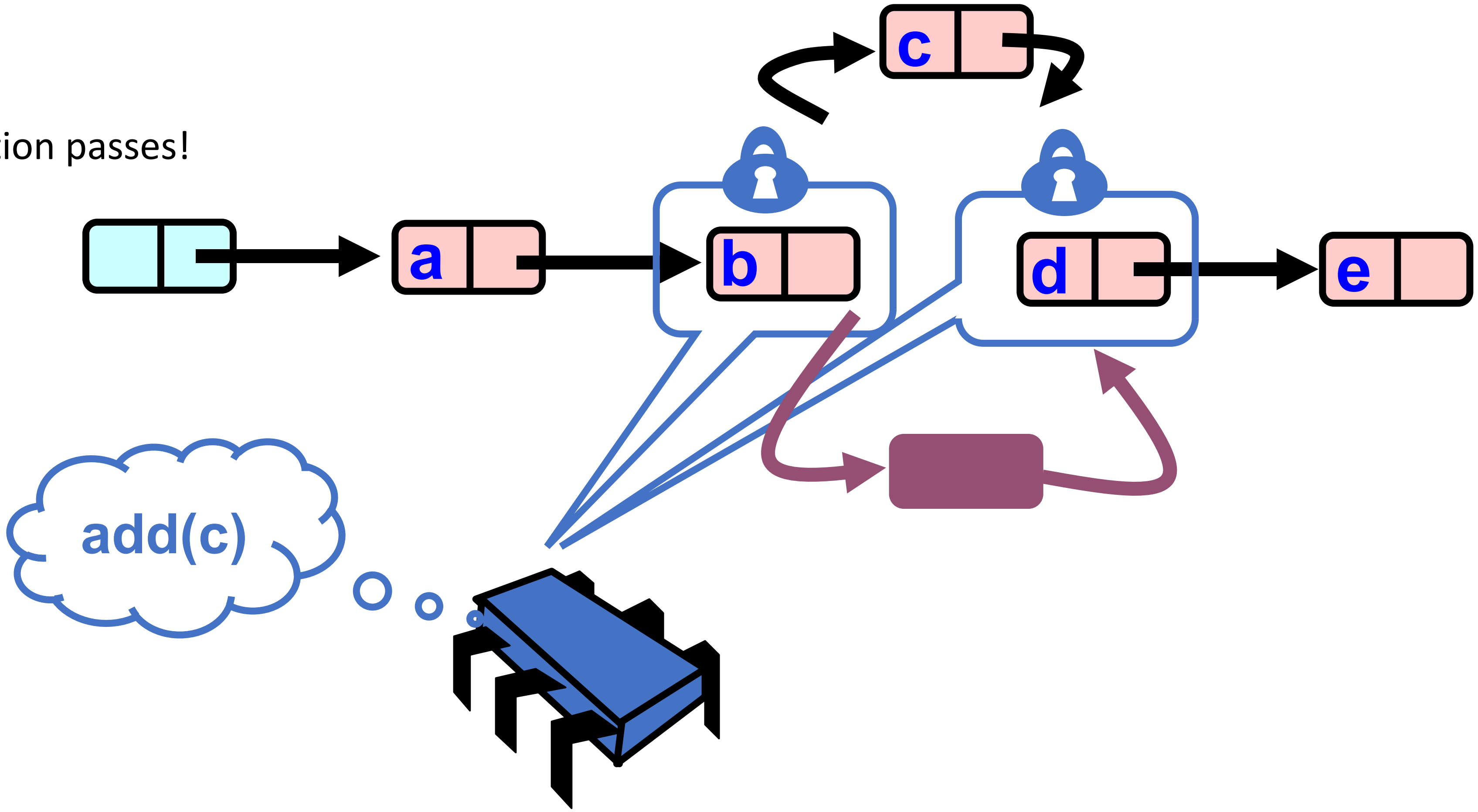
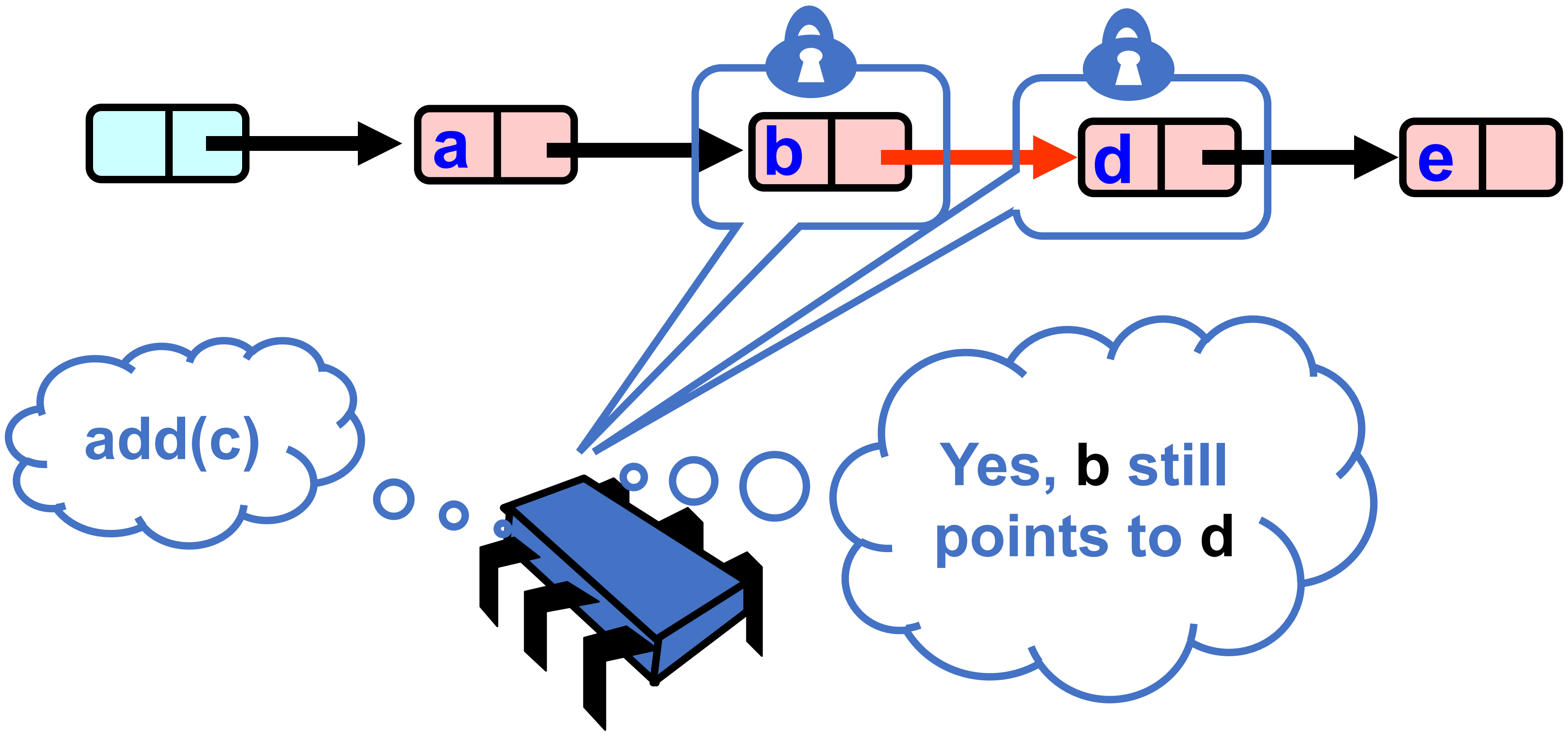


What Else Could Go Wrong?

Validation passes!



Validate Part 2
(while holding locks)



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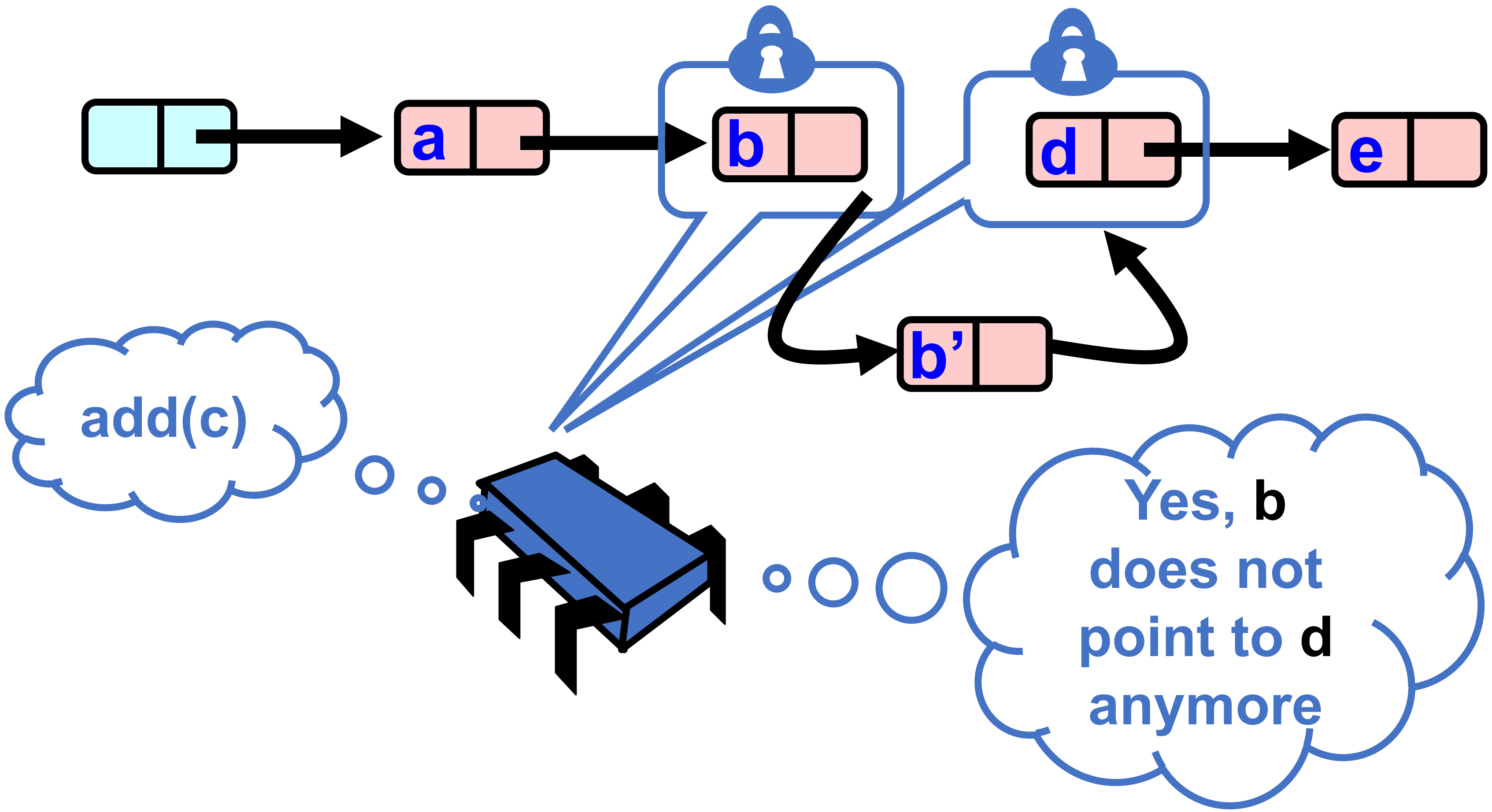


New Material

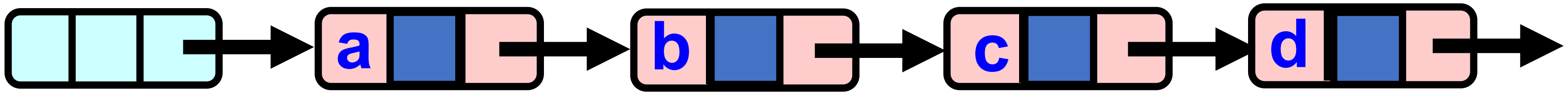
Can we optimize more?

- Scan the list once?
- We need to make sure that the node is not removed.
- Instead of scanning to check reachability, leave a mark on removed nodes.

Two step removal List

- **`remove()`**
  - Scans list (as before)
  - Locks predecessor & current (as before)
- Logical delete
  - Marks current node as removed (new!)
- Physical delete
  - Redirects predecessor’s next (as before)

Two step removal Removal



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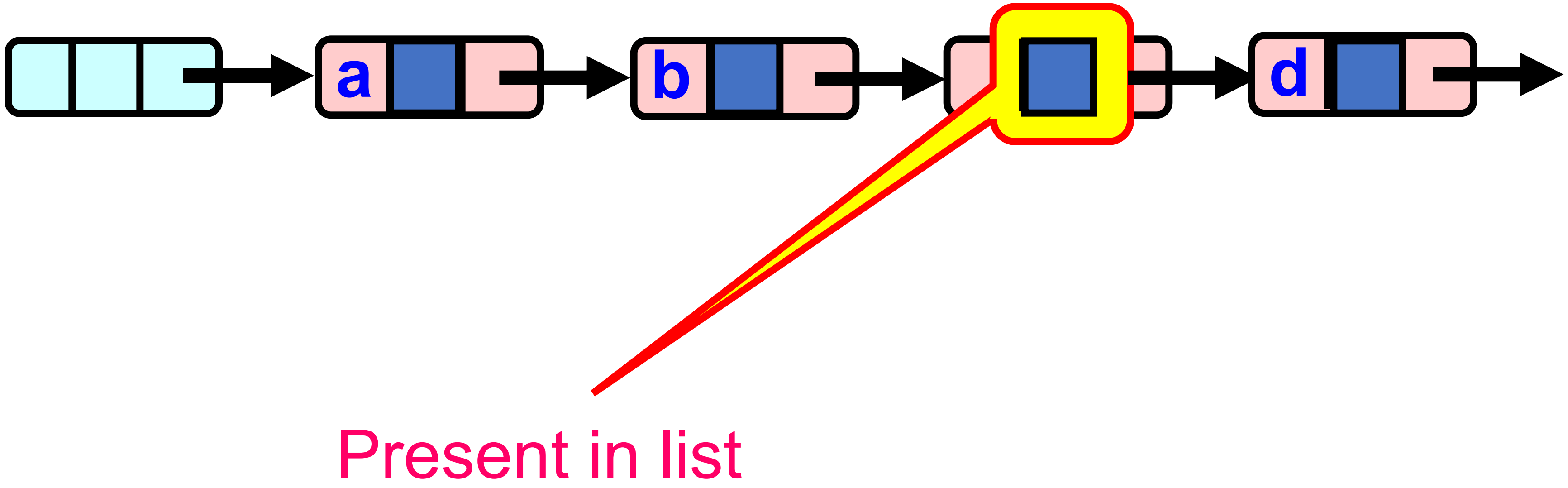

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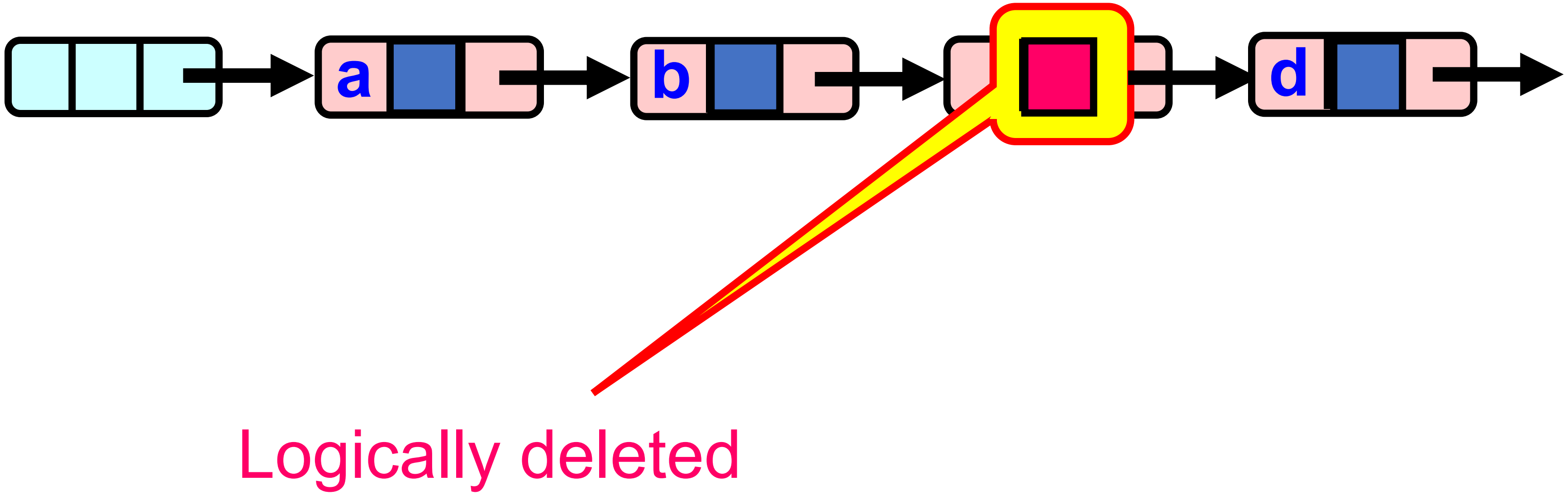

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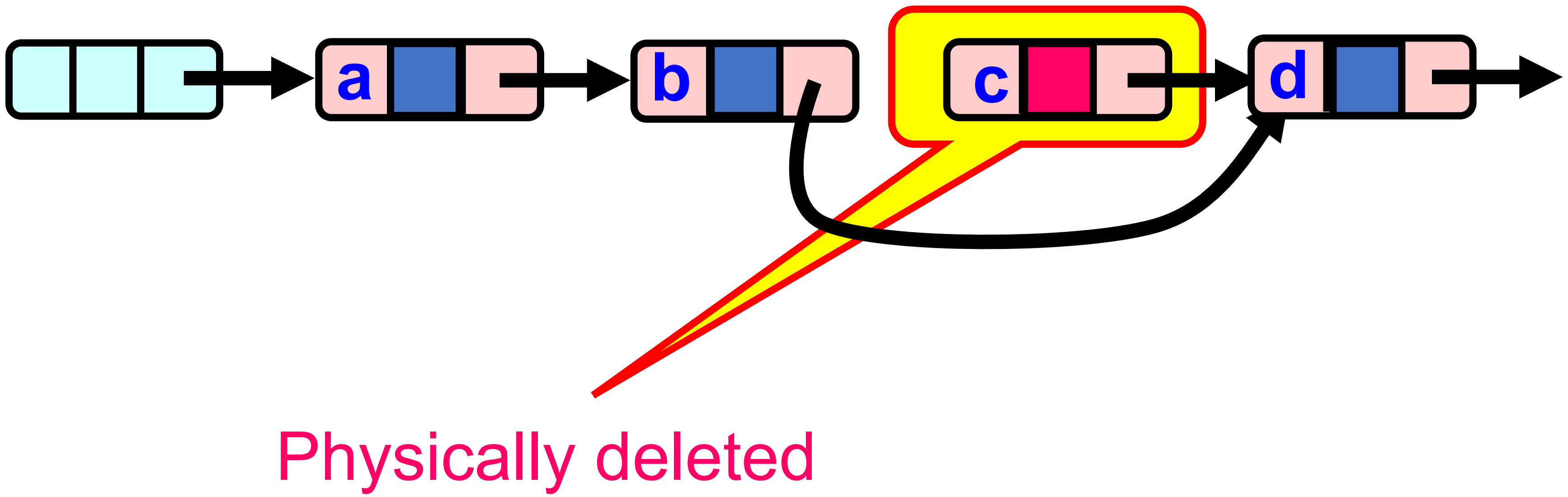

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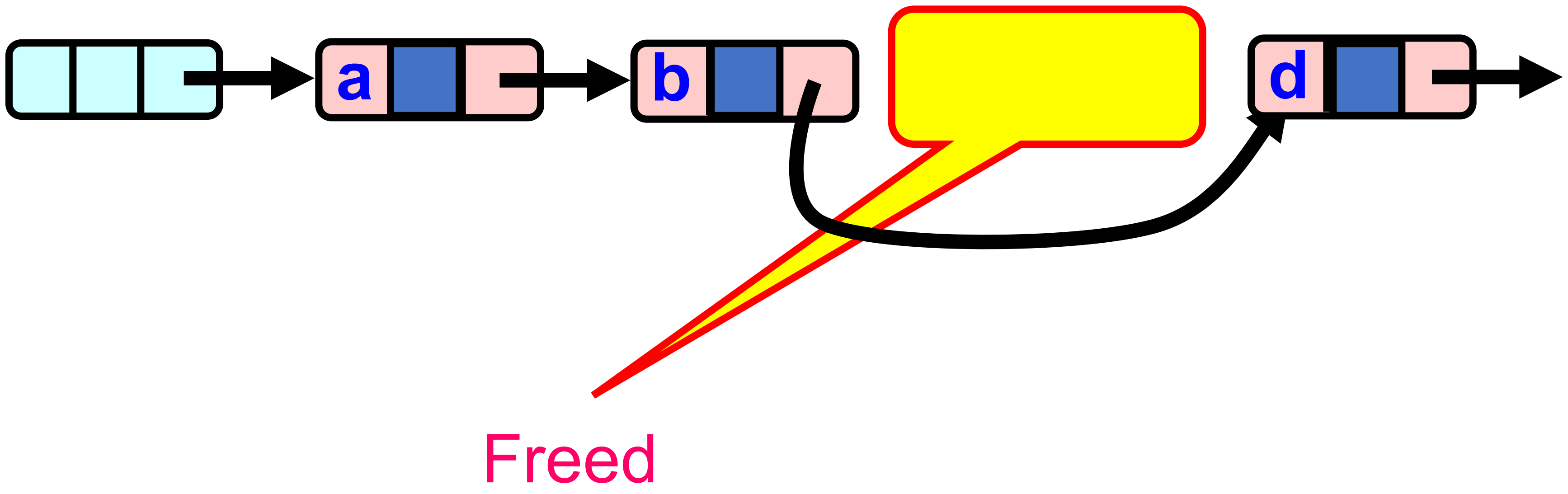


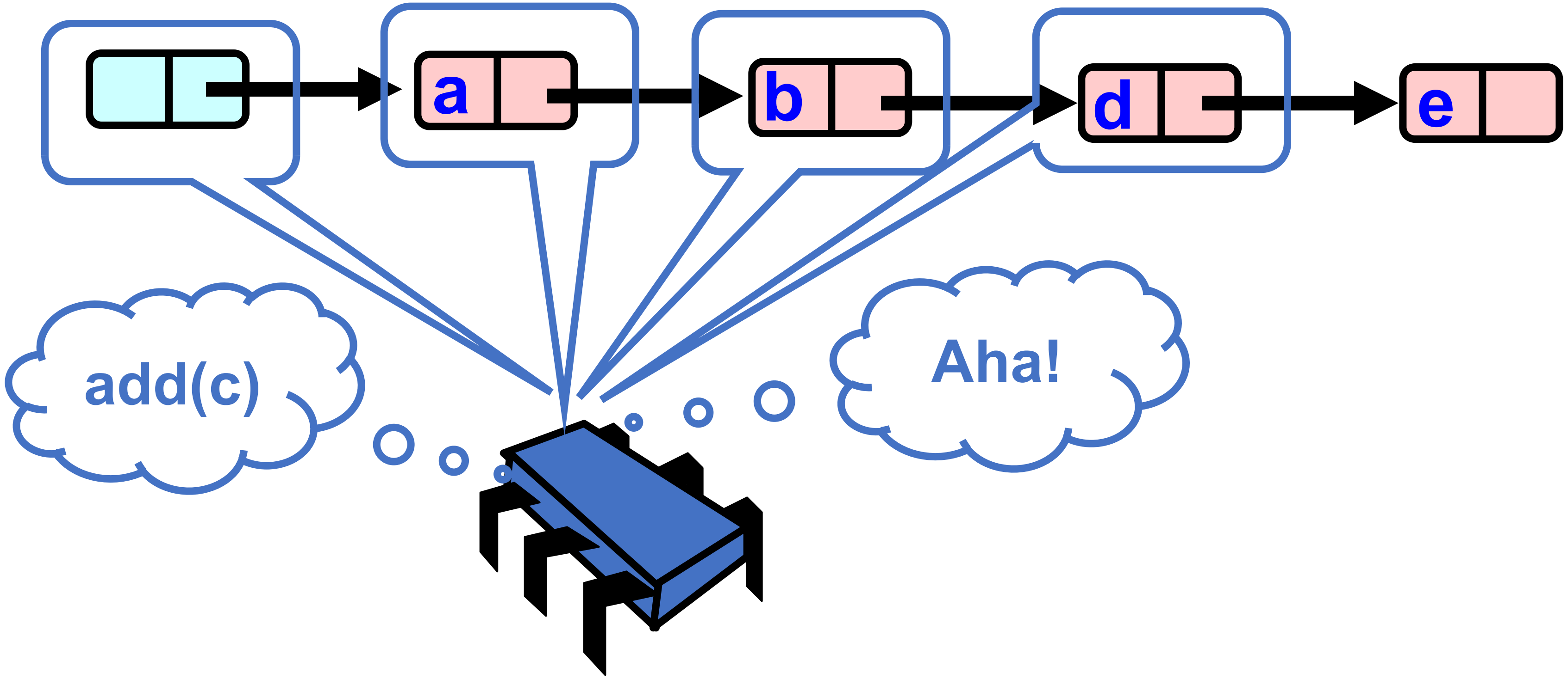
Two step remove list

- All Methods
  - Scan through locked and marked nodes
- Must still lock pred and curr nodes.

Validation

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

What could go wrong?



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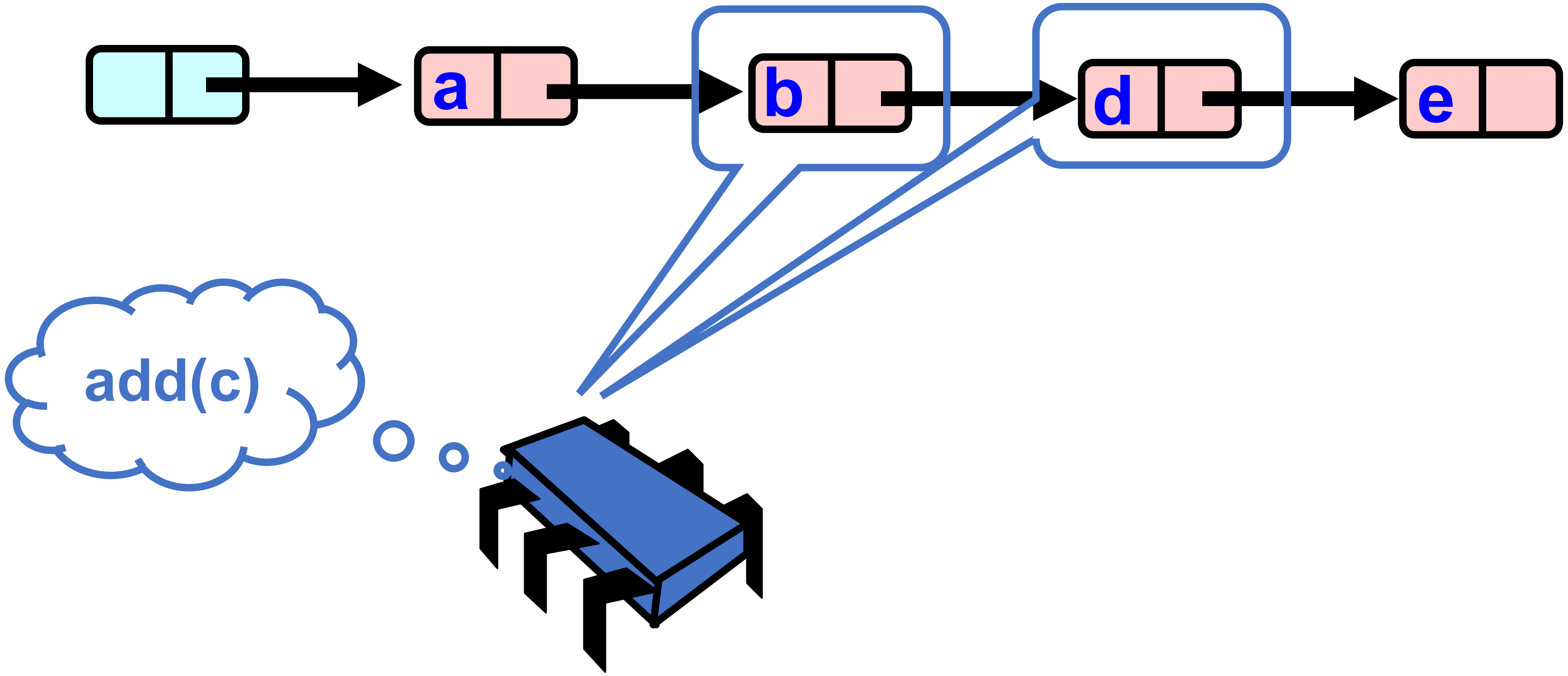

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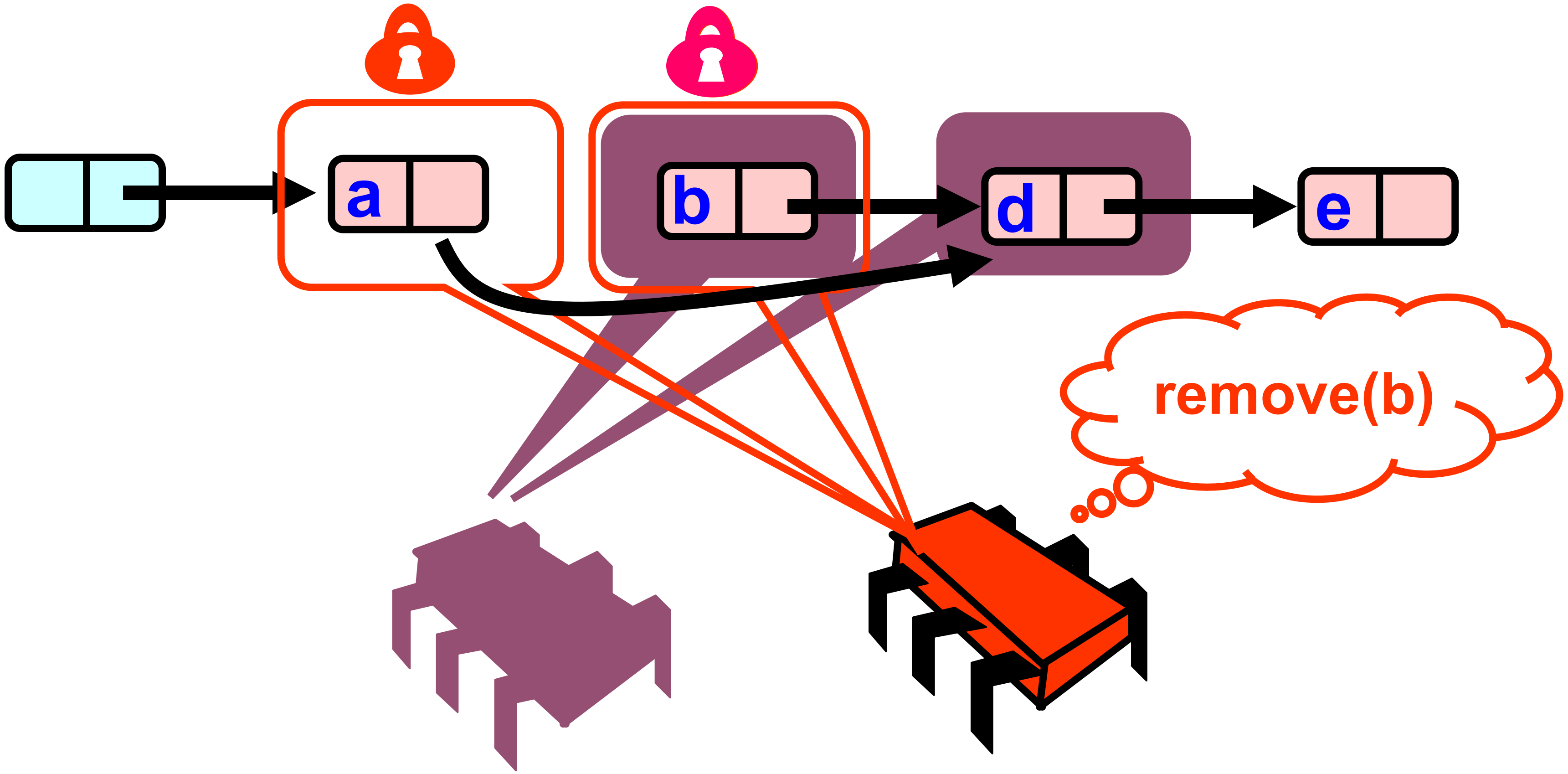

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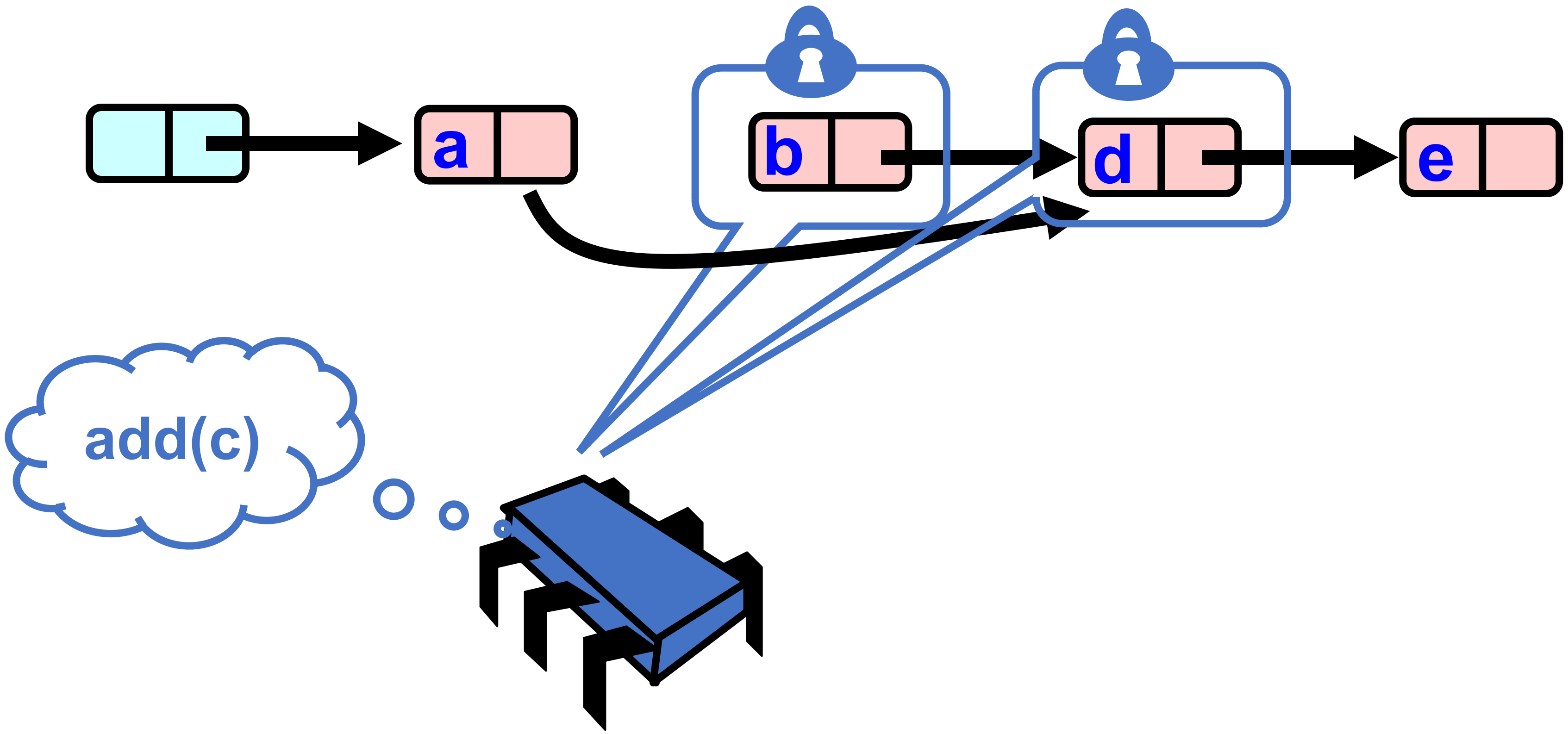

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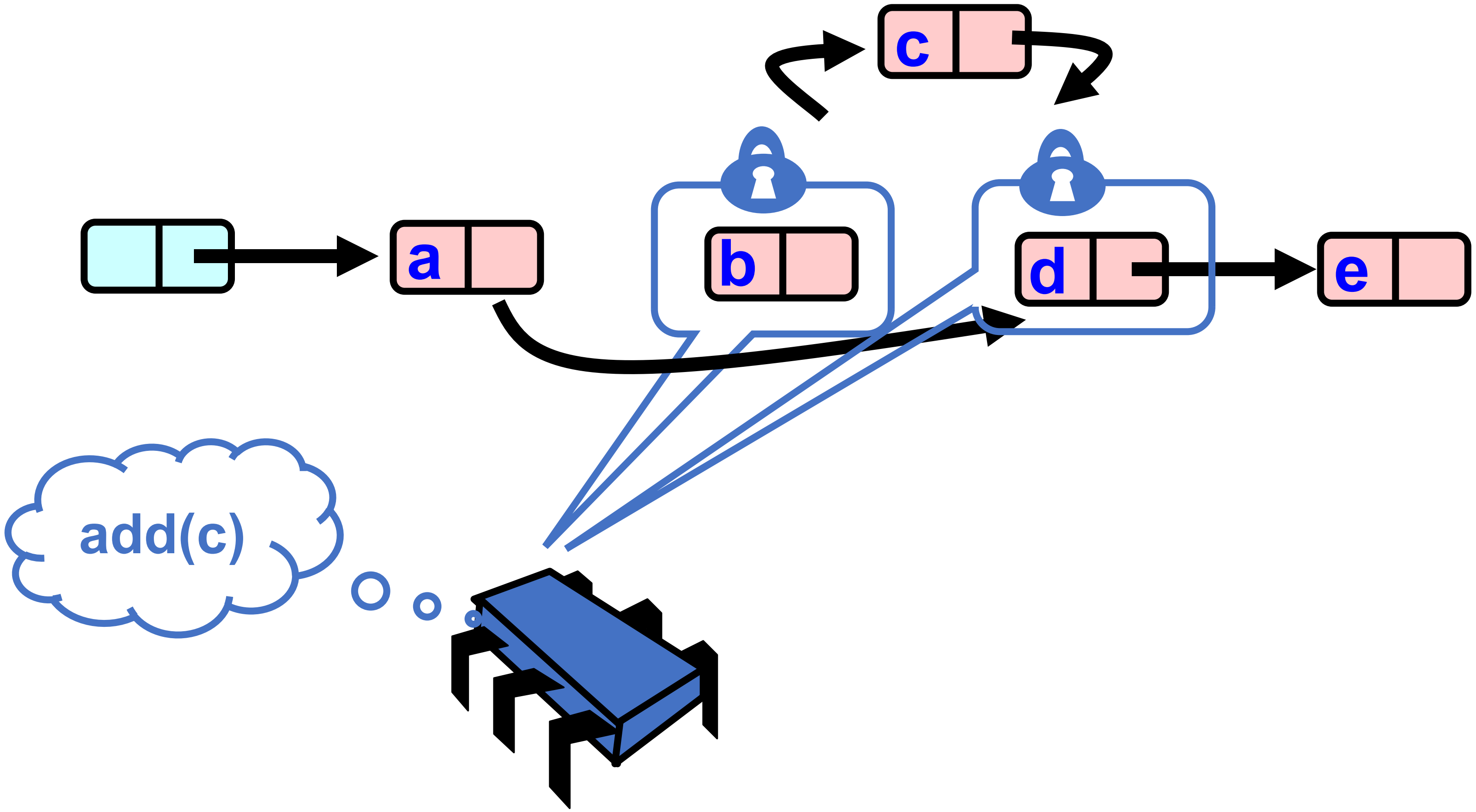

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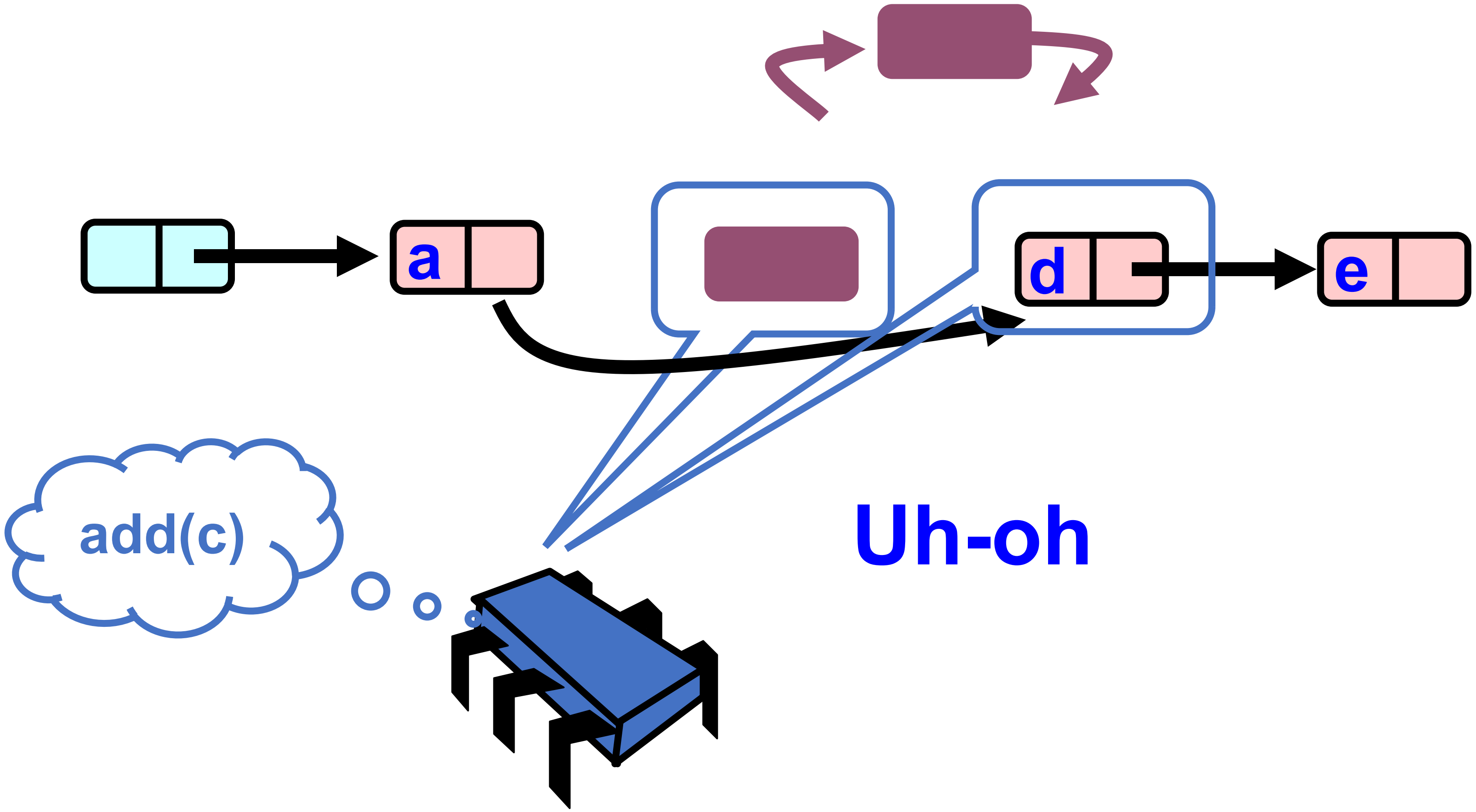
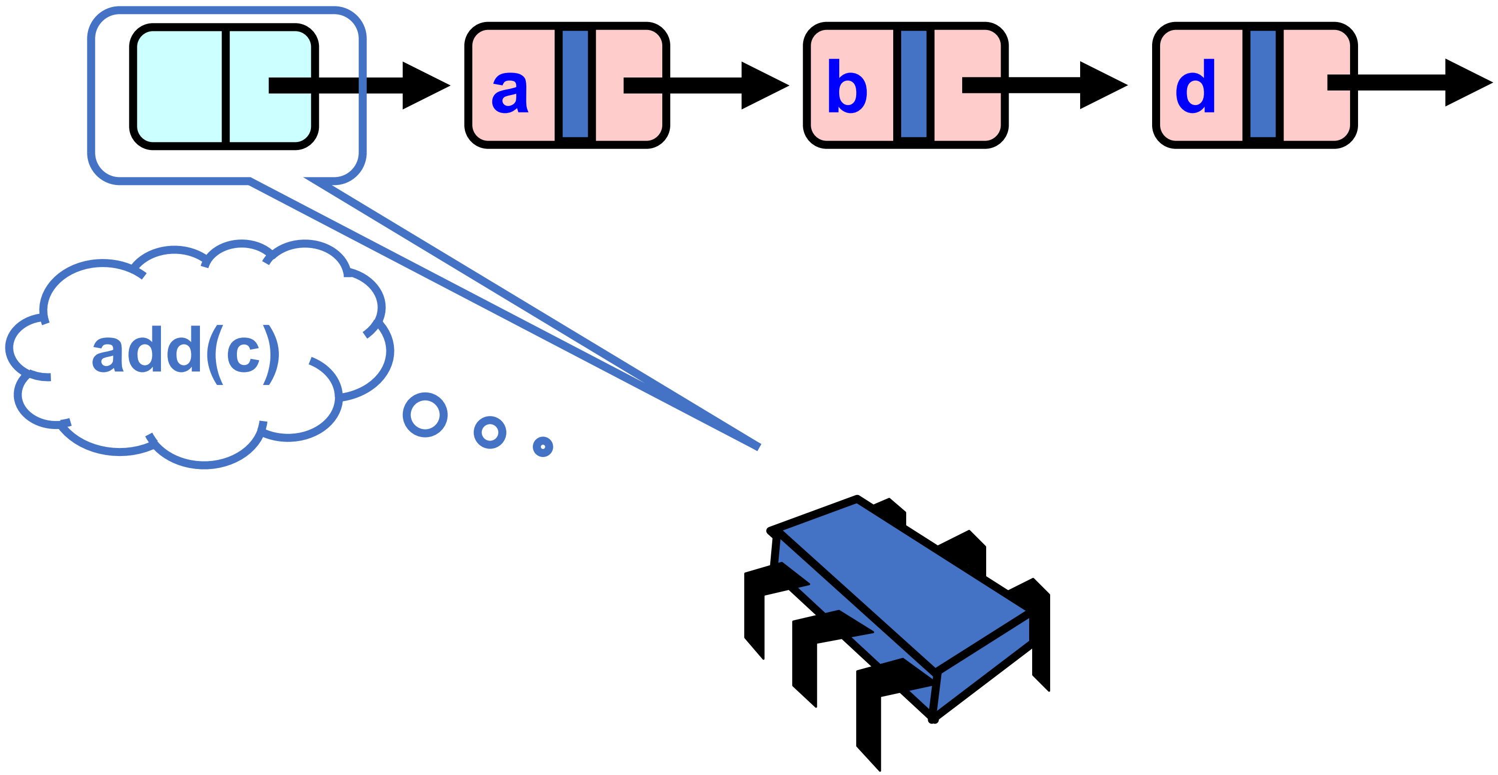


Fixed with logical flag



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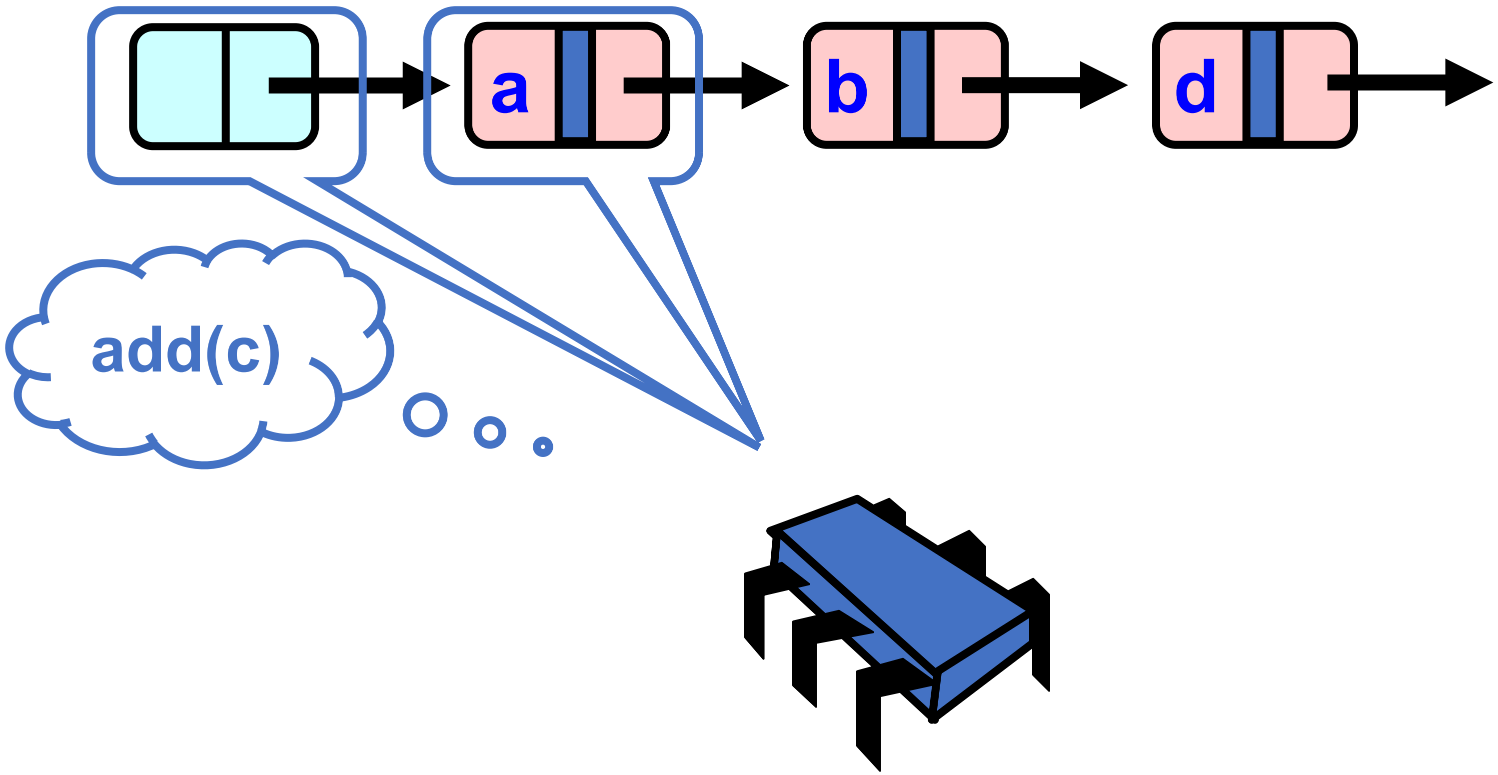

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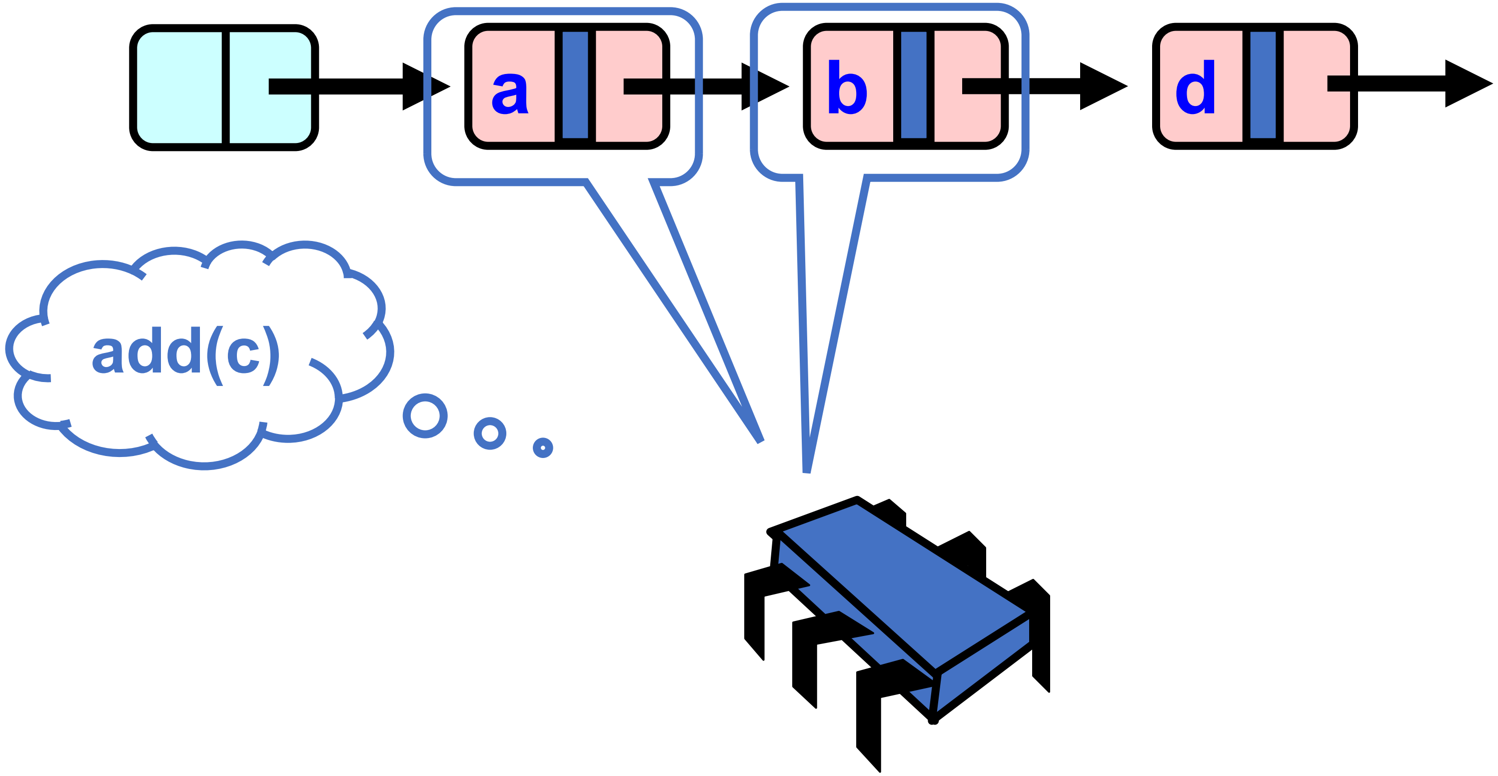

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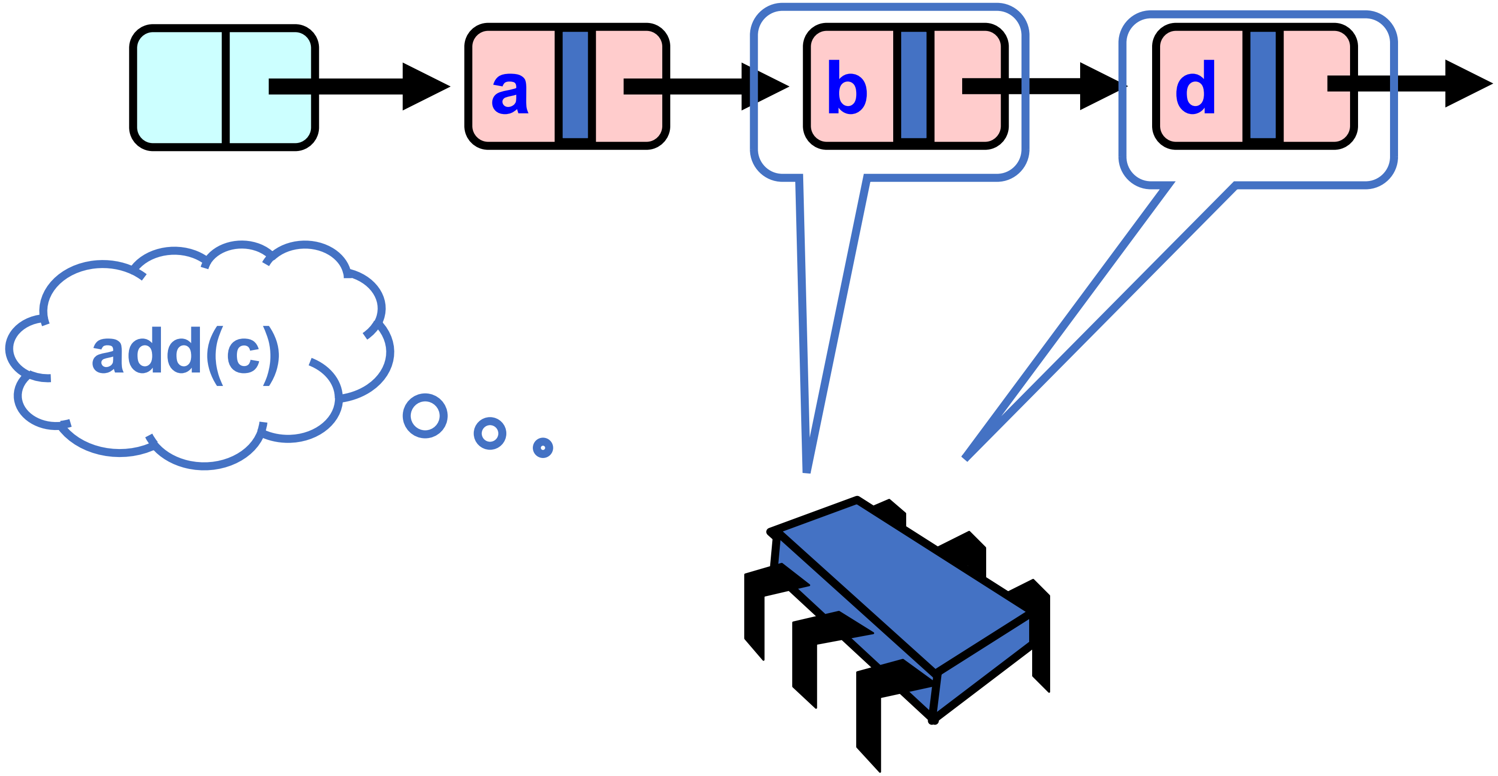

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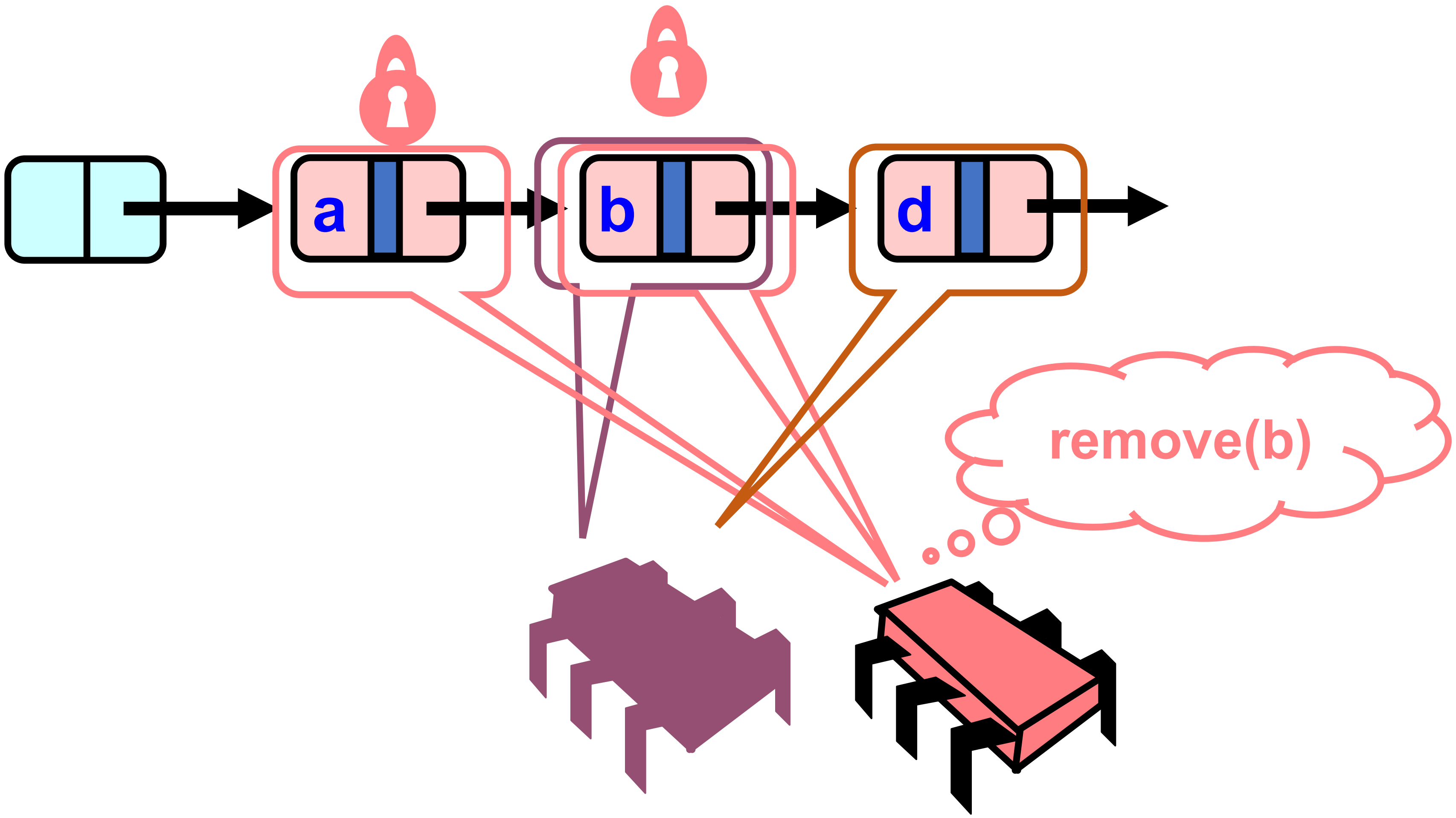

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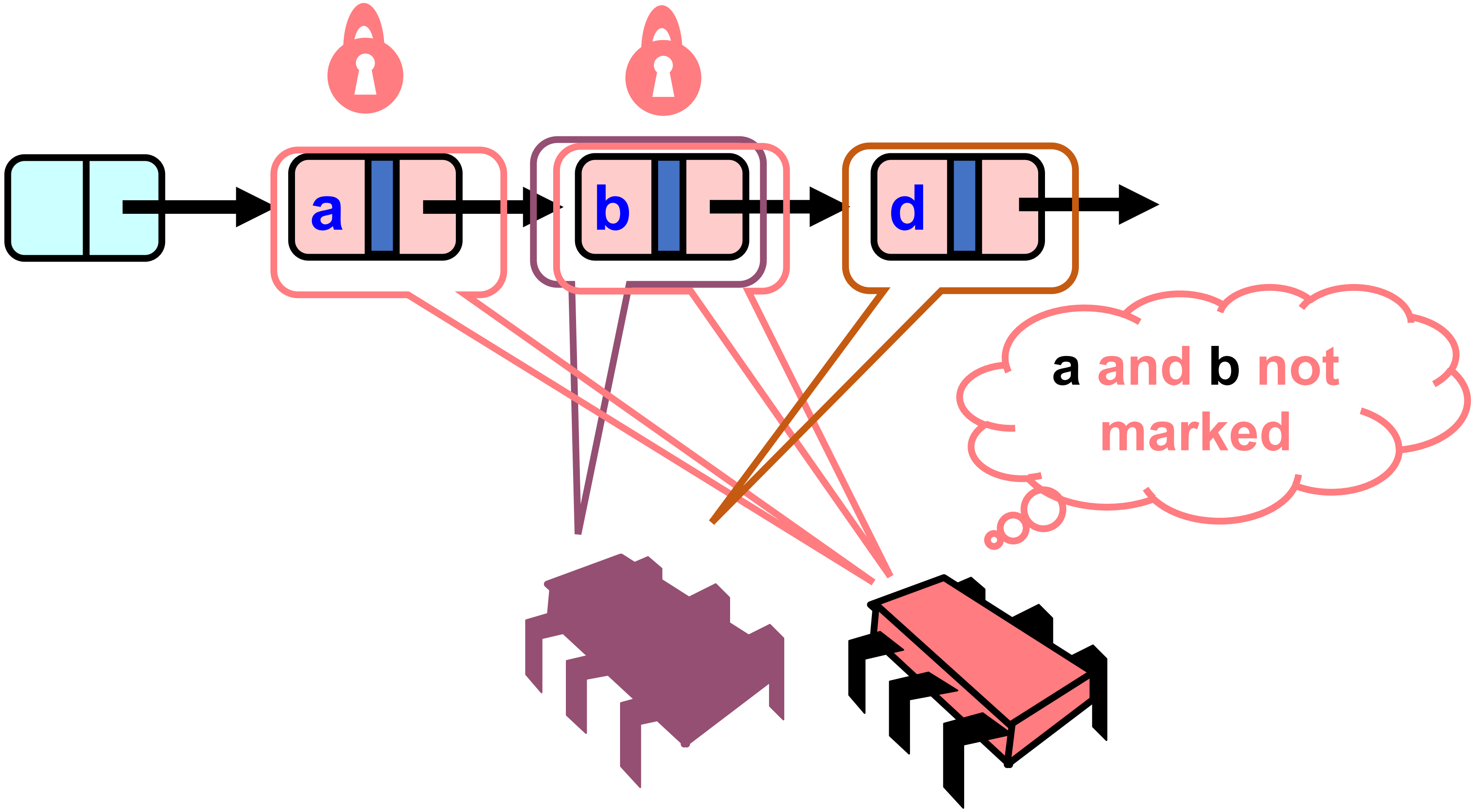

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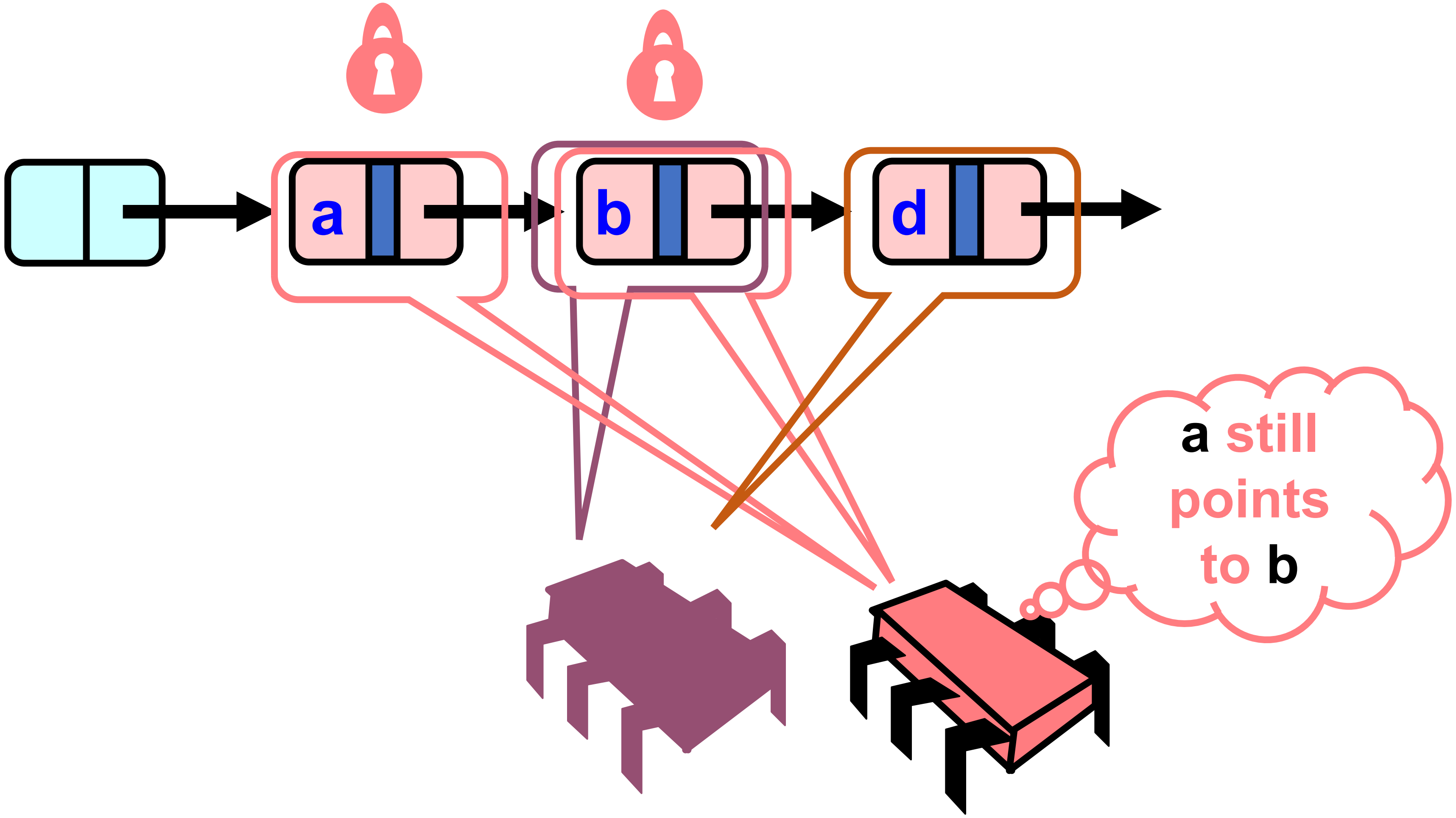

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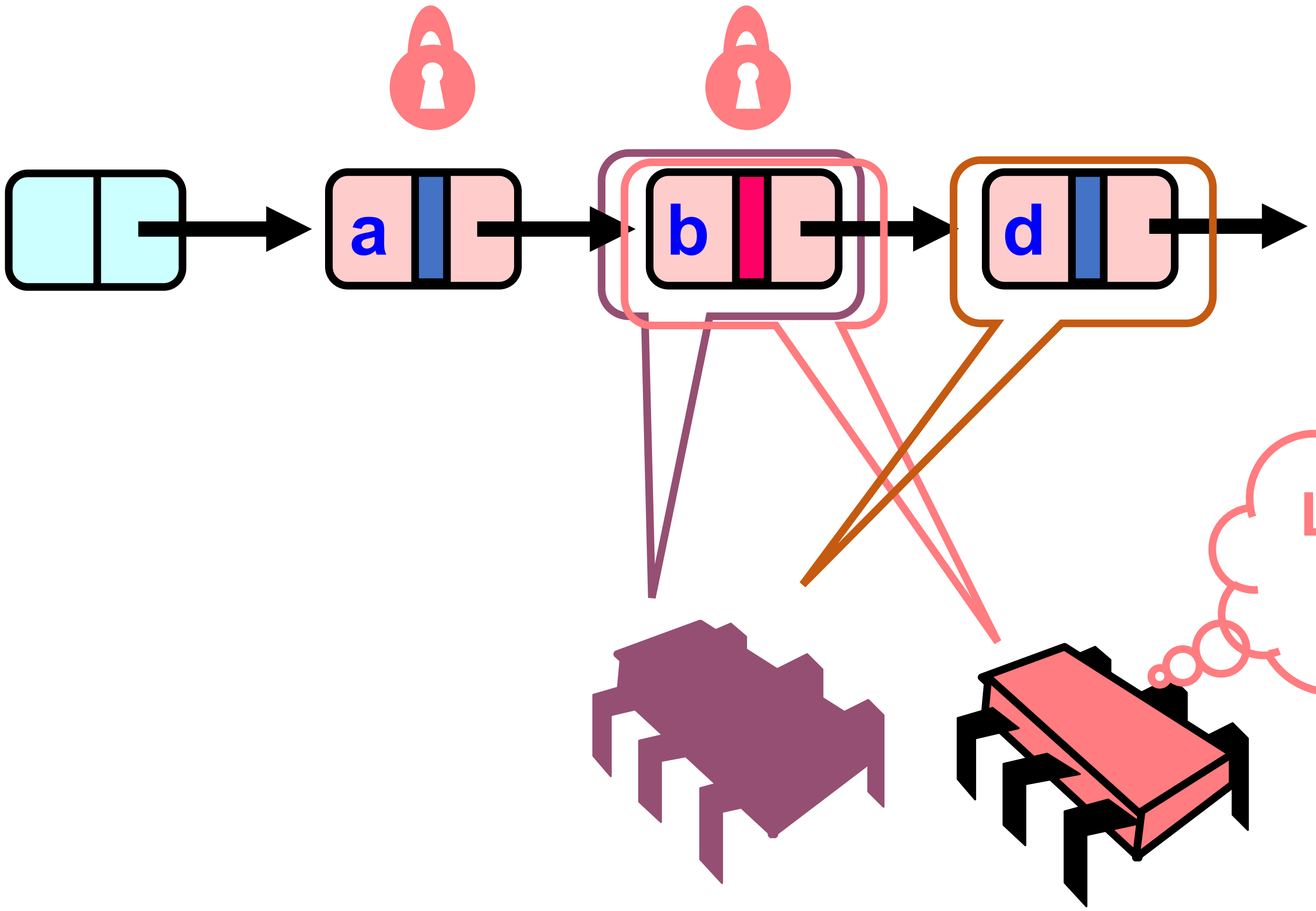

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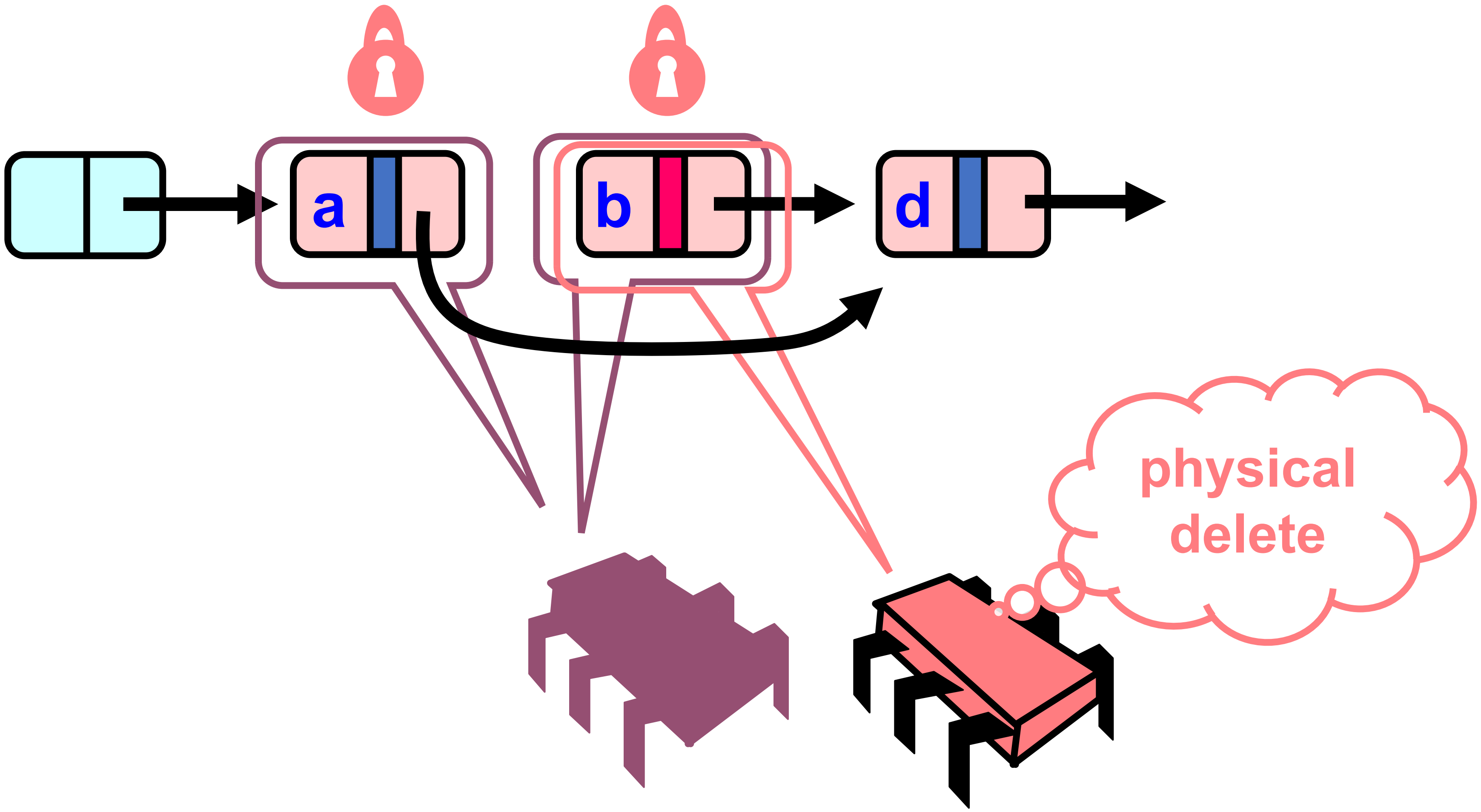

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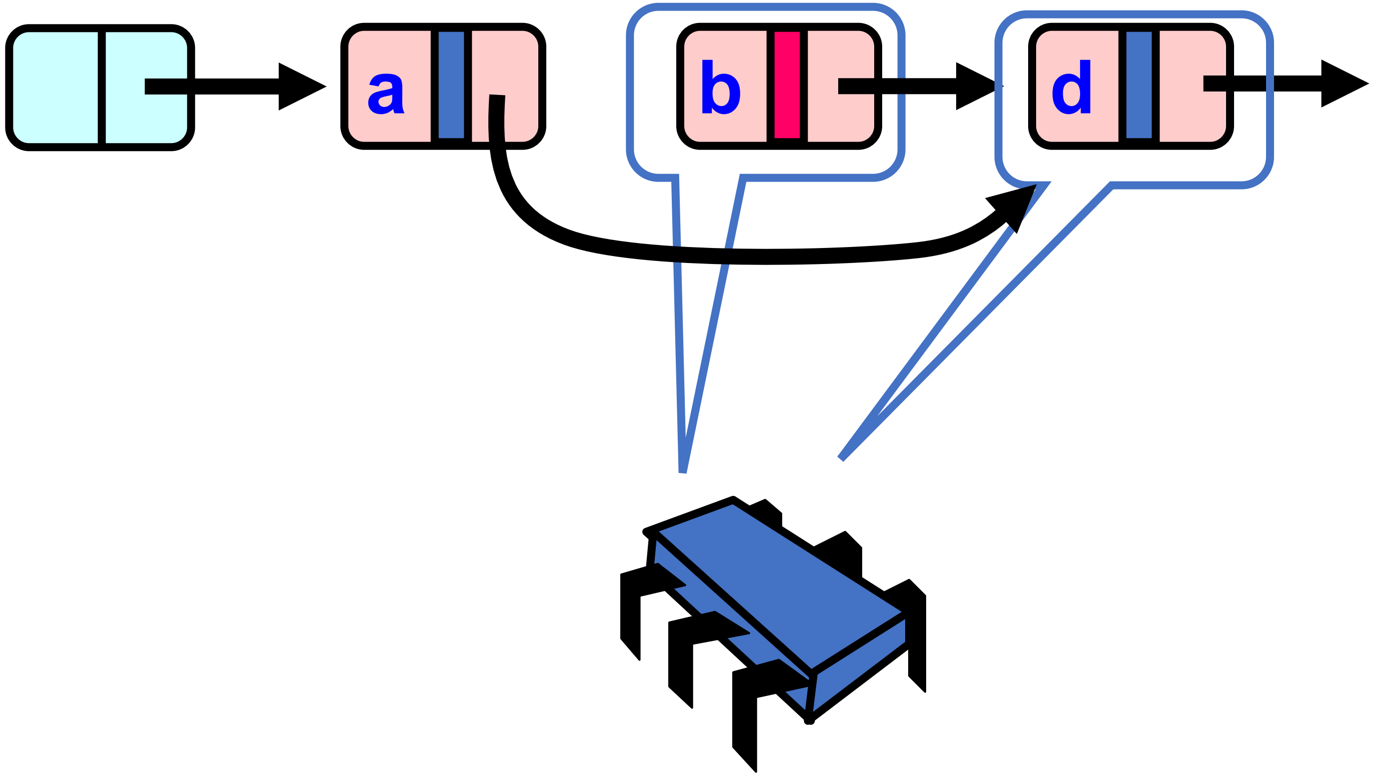

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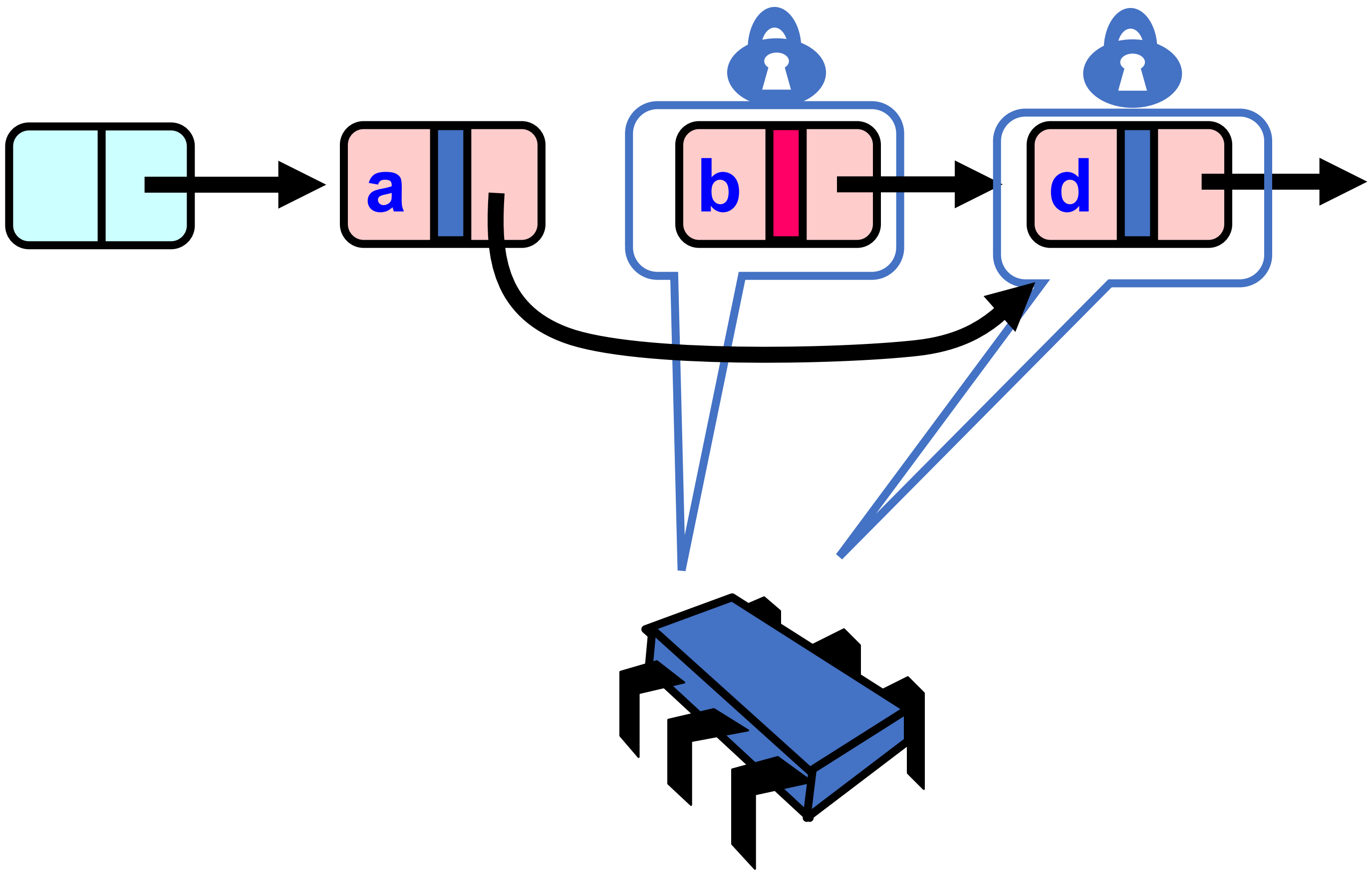

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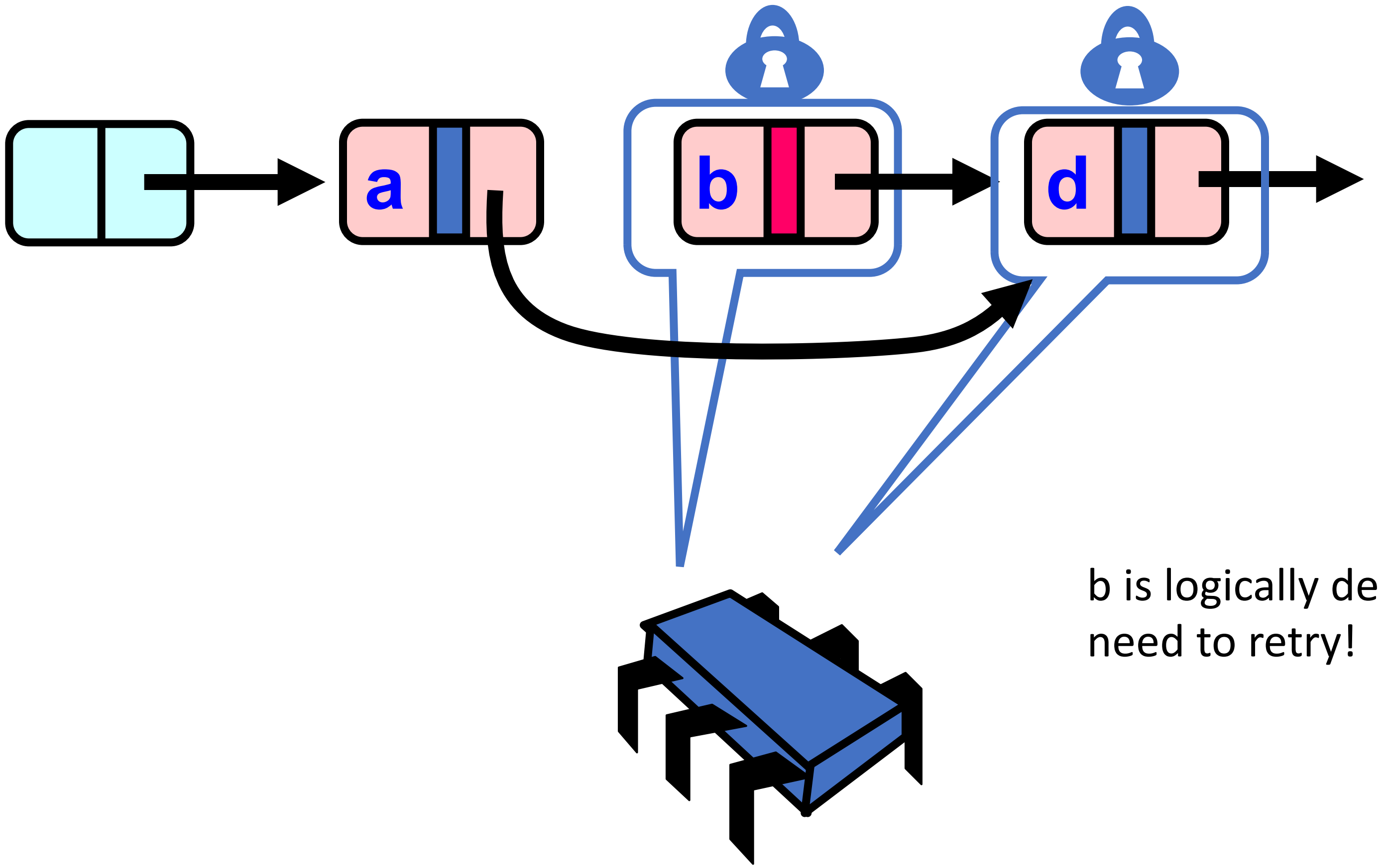


b is logically deleted so we need to retry!

To complete the picture

- Need to do similar reasoning with all combination of object methods.
- More information in the book!

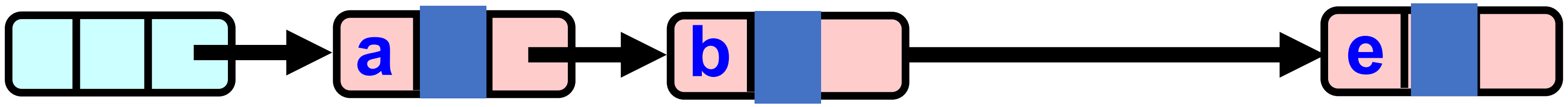
How good?

- Good:
  - Uncontended calls don’t re-traverse
- Bad
  - add() and remove() use locks

Lock-free Lists

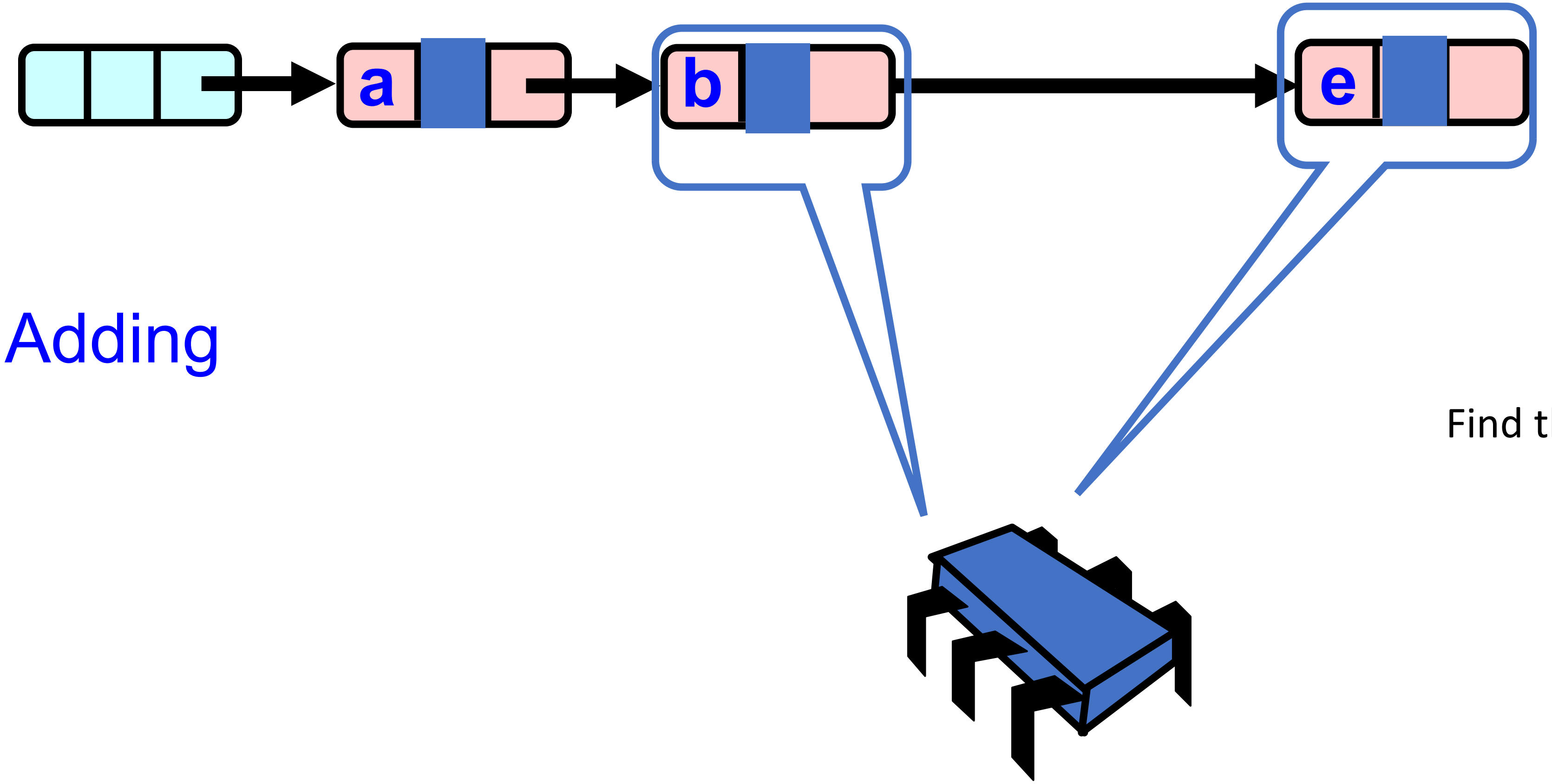
- Next logical step
  - lock-free add() and remove()
- What sort of atomics do we need?
  - Loads/stores -> RMWs?

Lock-free Lists



Adding

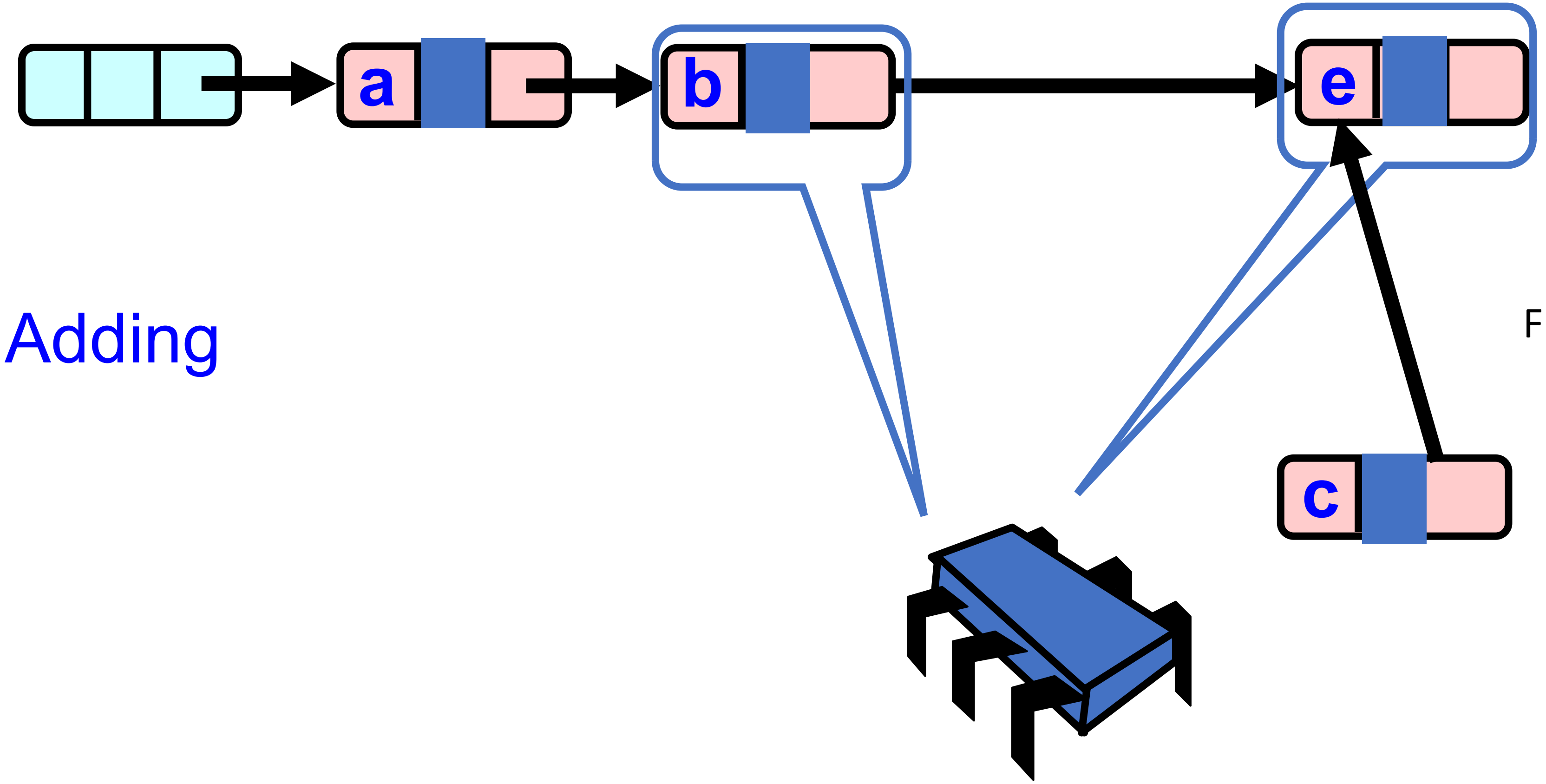
Lock-free Lists



Adding

Find the location

Lock-free Lists

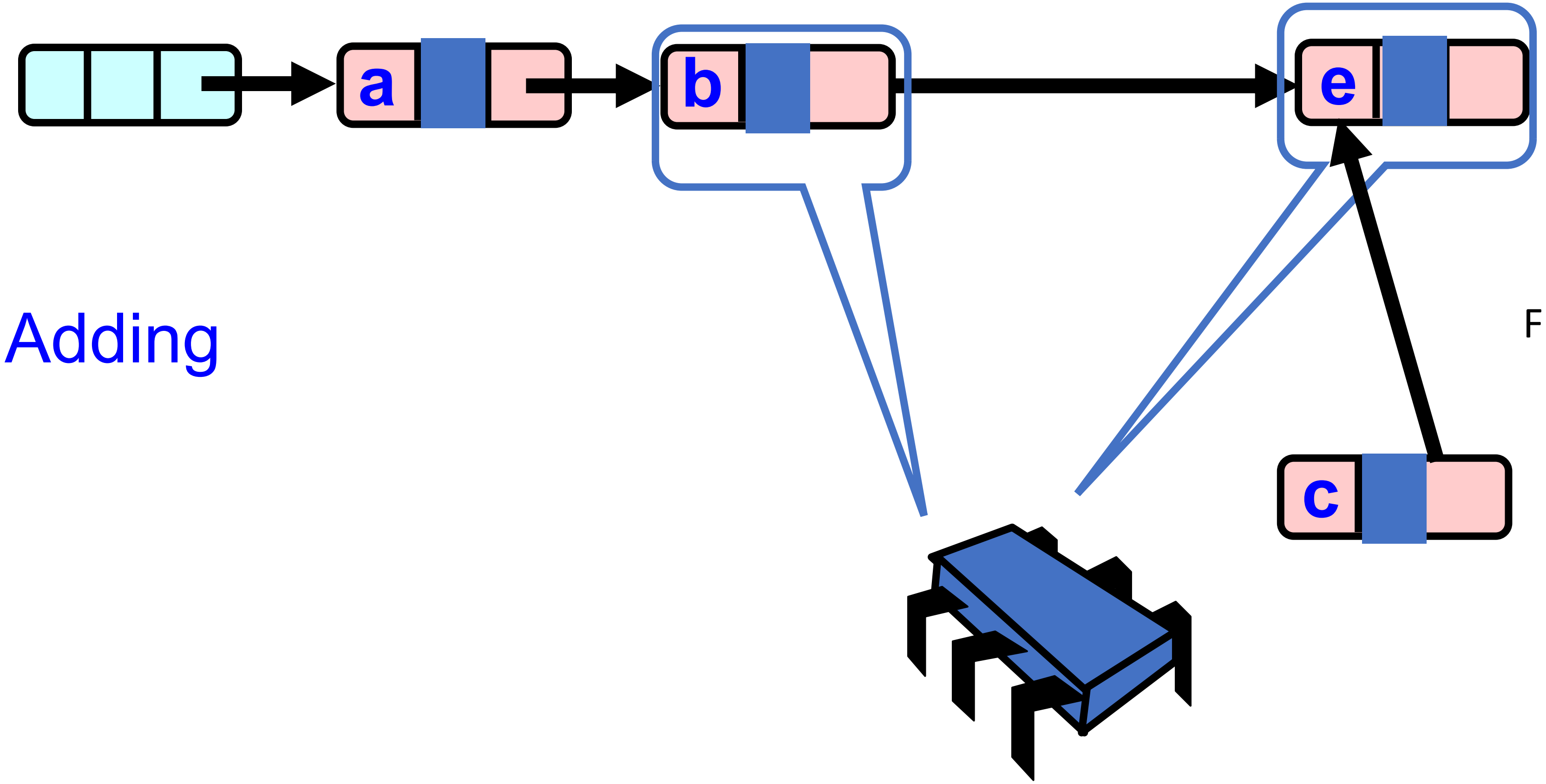


Adding

Find the location

create “c”

Lock-free Lists



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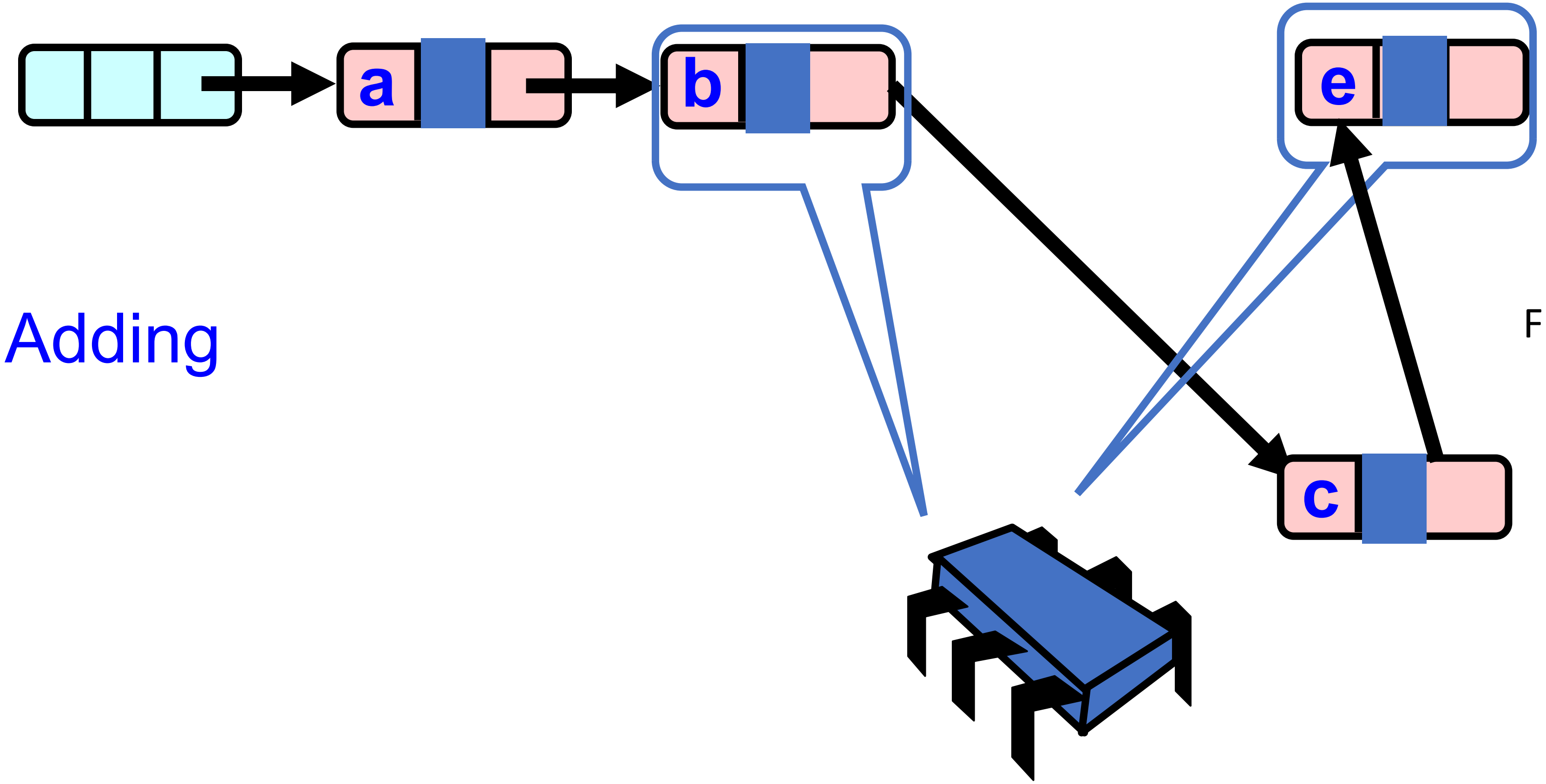
Lock-free Lists



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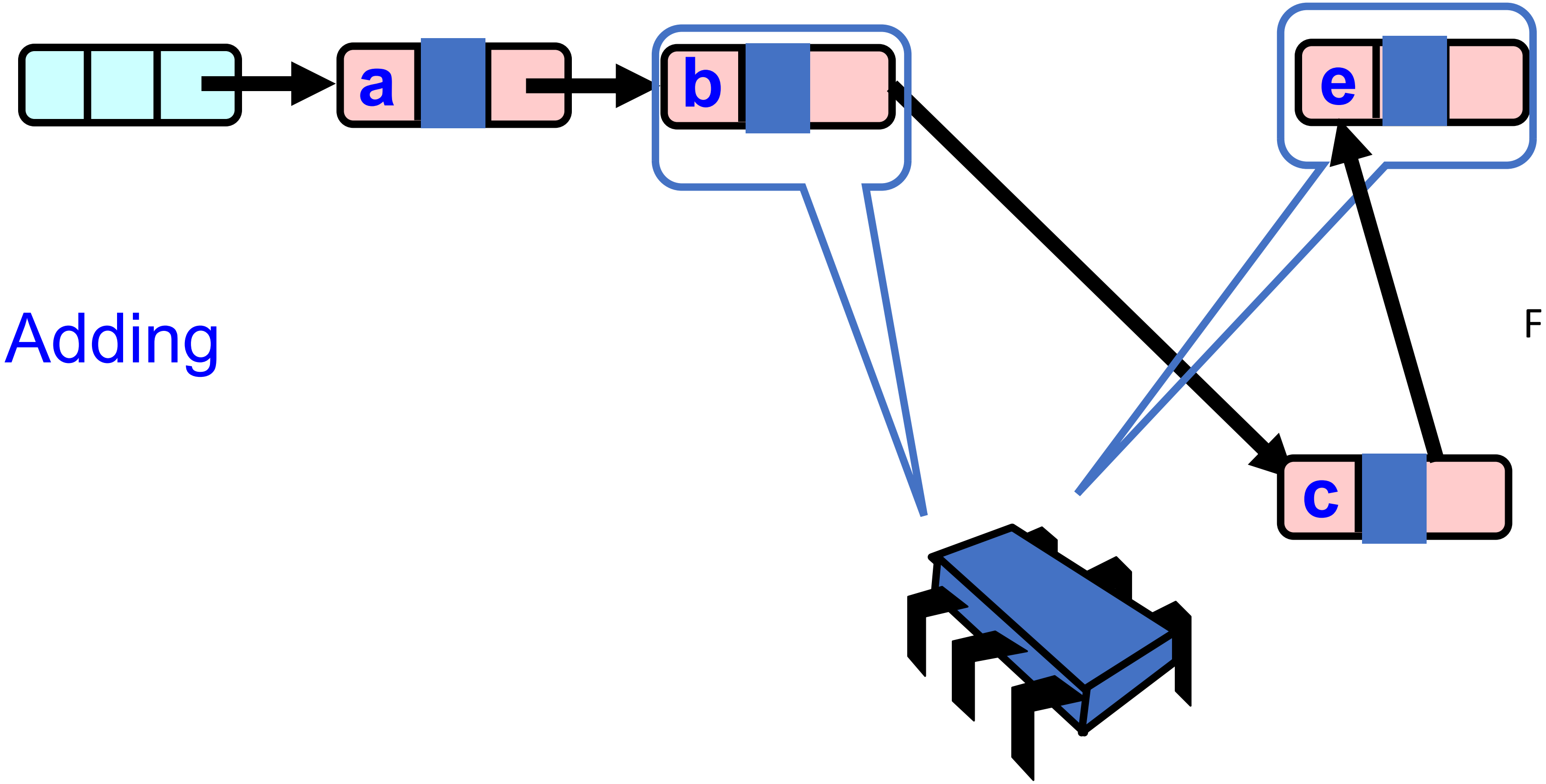


Adding

Find the location

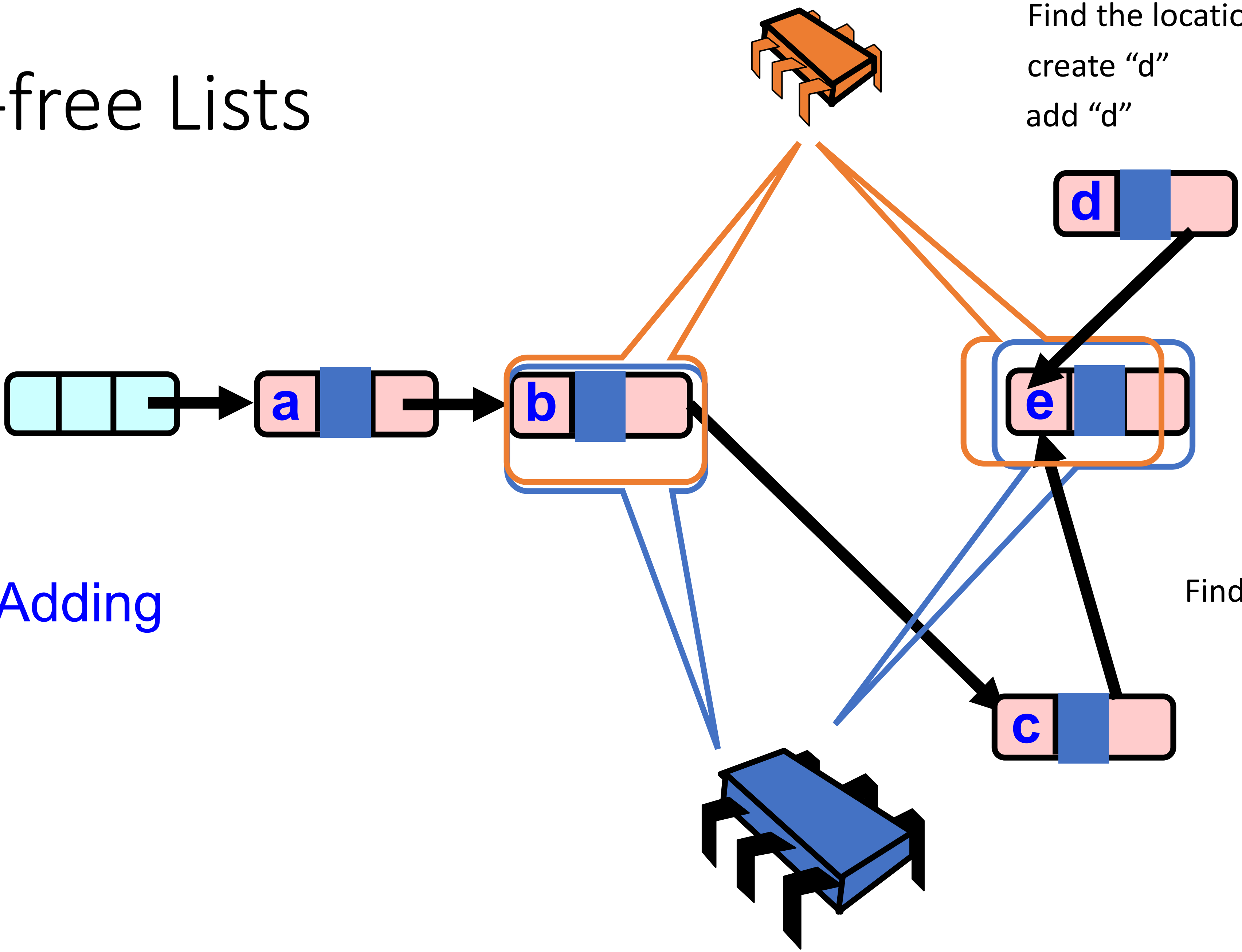
create “c”

add “c”

Can this just be a regular store?

Lock-free Lists

Adding



Find the location

create “d”

add “d”

Can this just be a regular store?

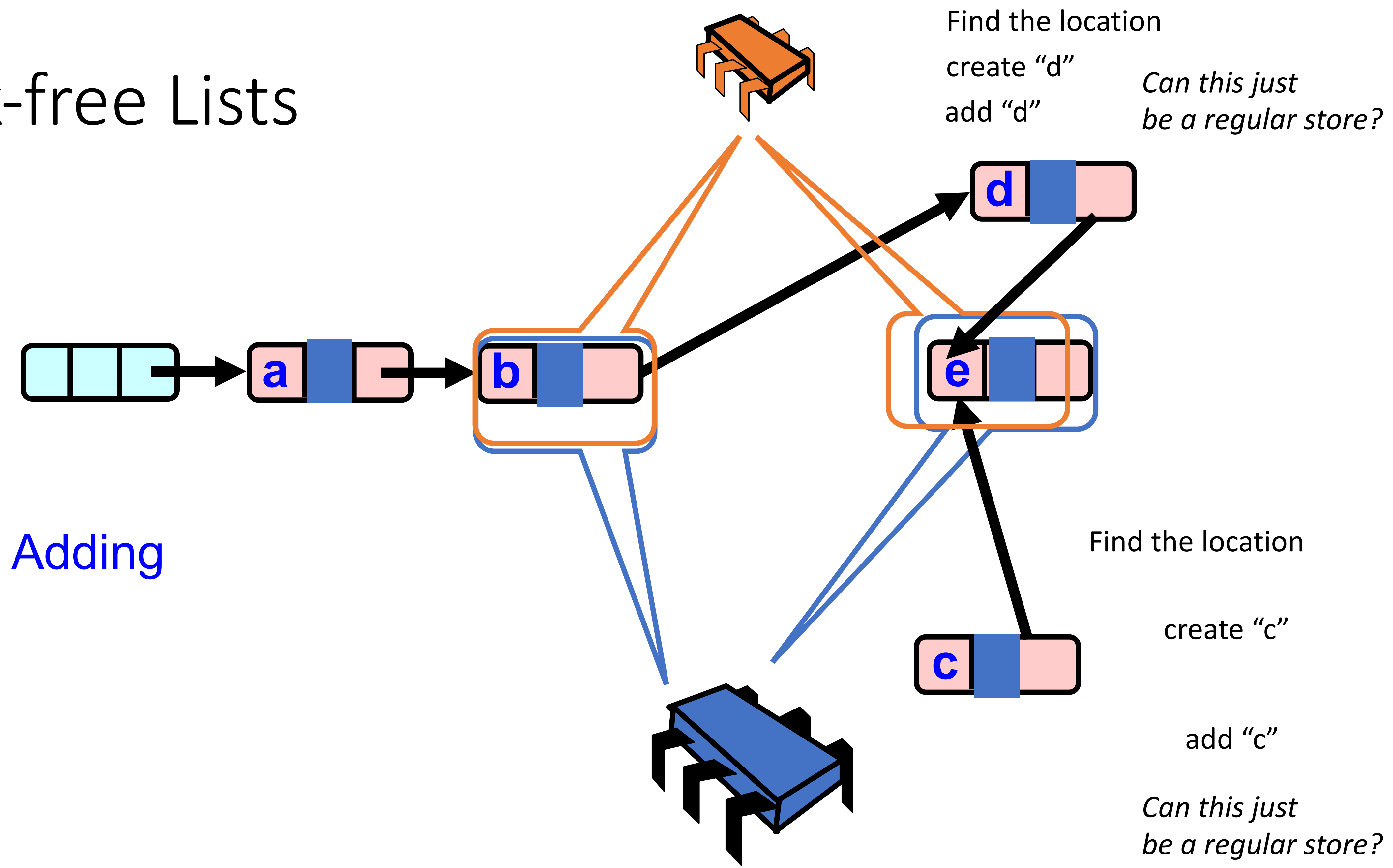
Find the location

create “c”

add “c”

Can this just be a regular store?

Lock-free Lists



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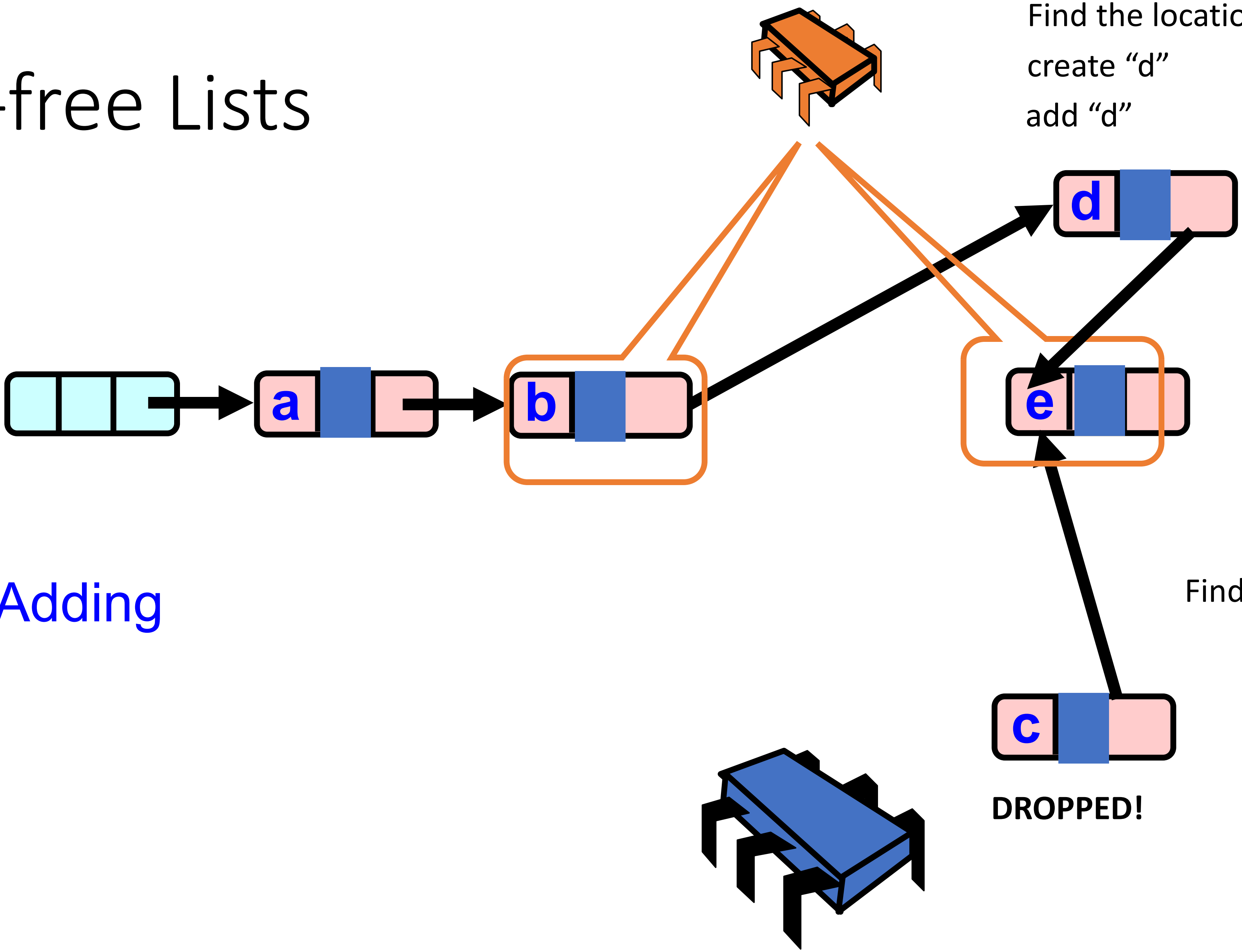

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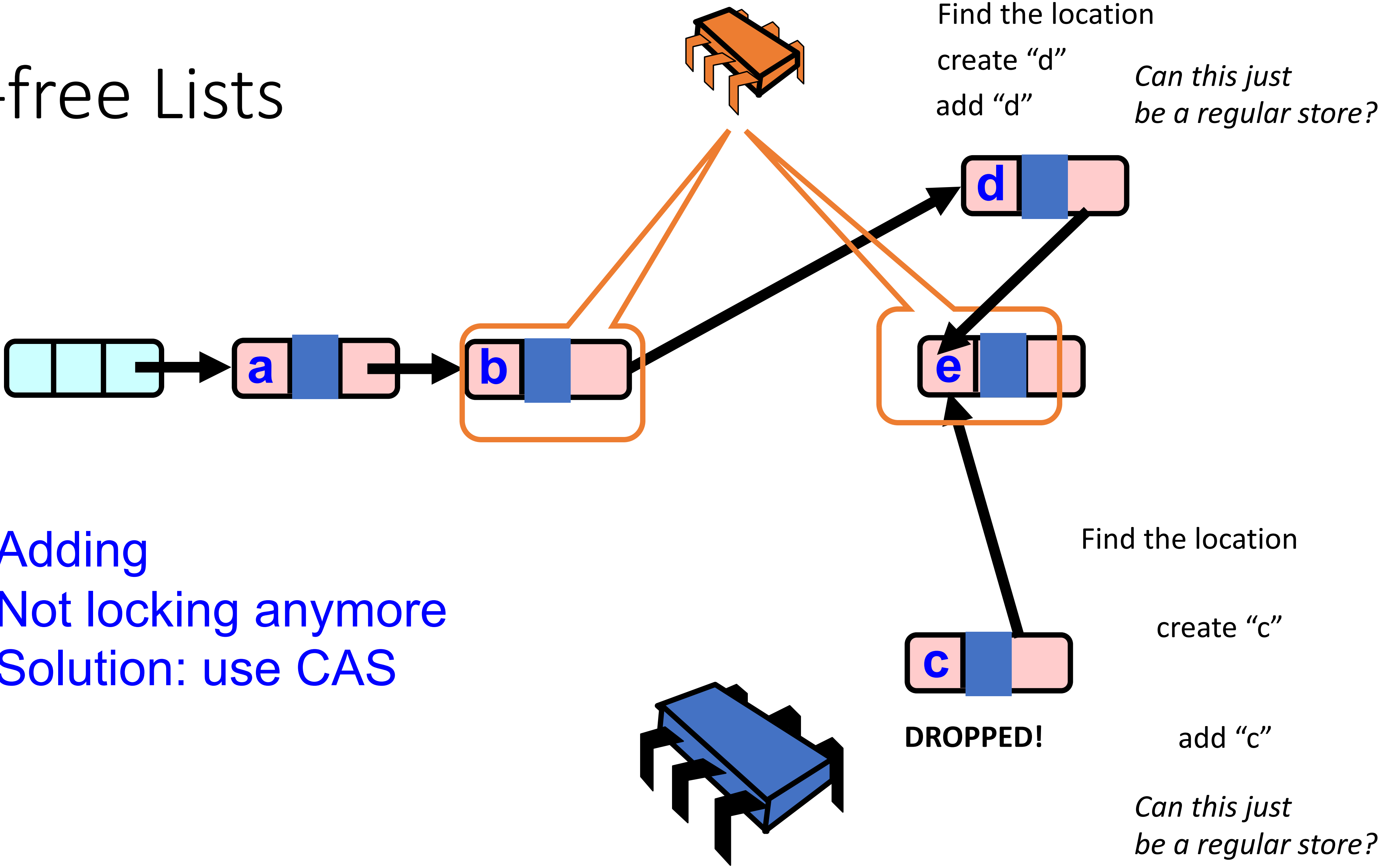


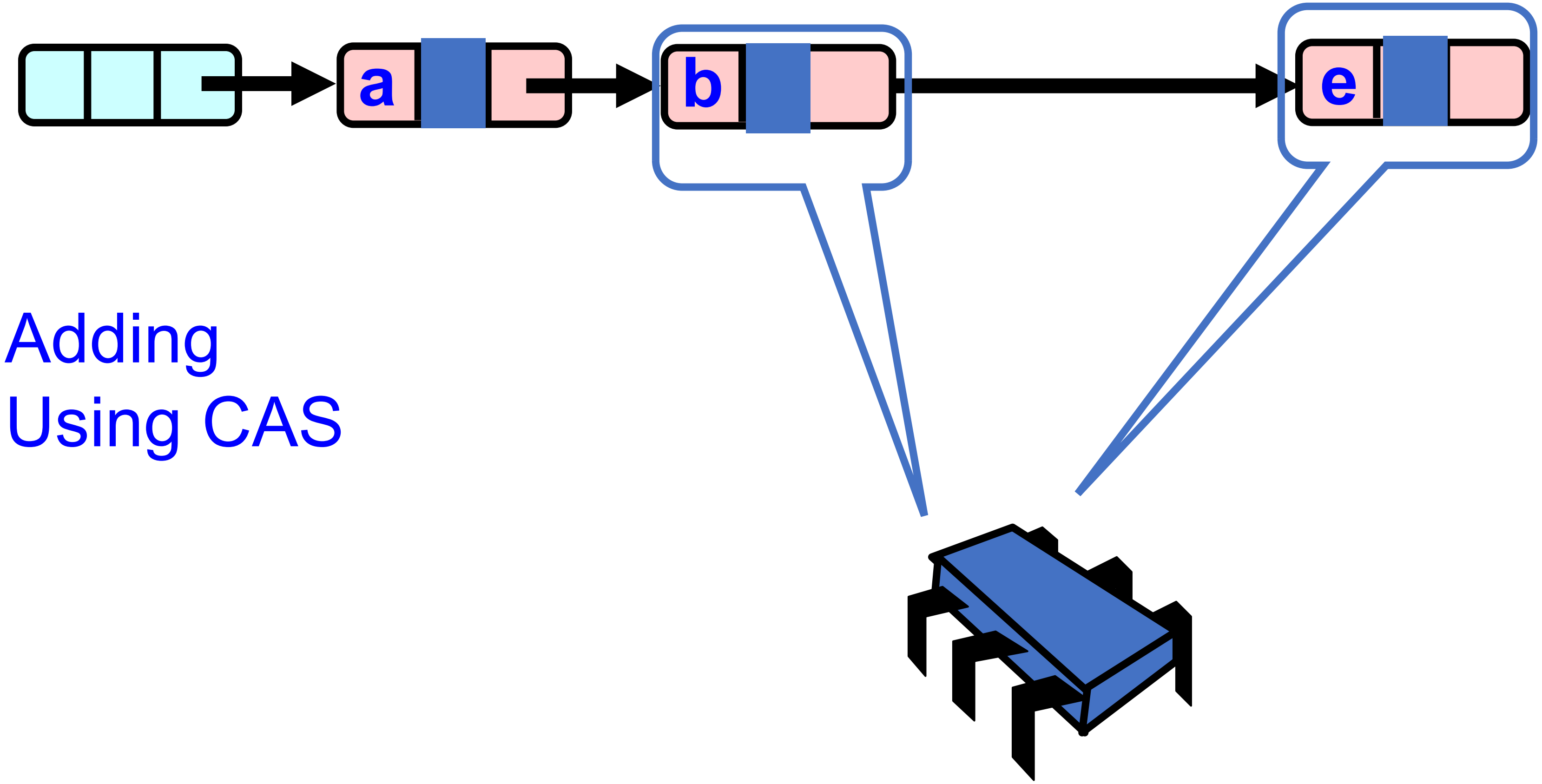
Adding
Not locking anymore
Solution: use CAS

Lock-free Lists

Find the location

Cache your insertion point!

b.next == e



Adding
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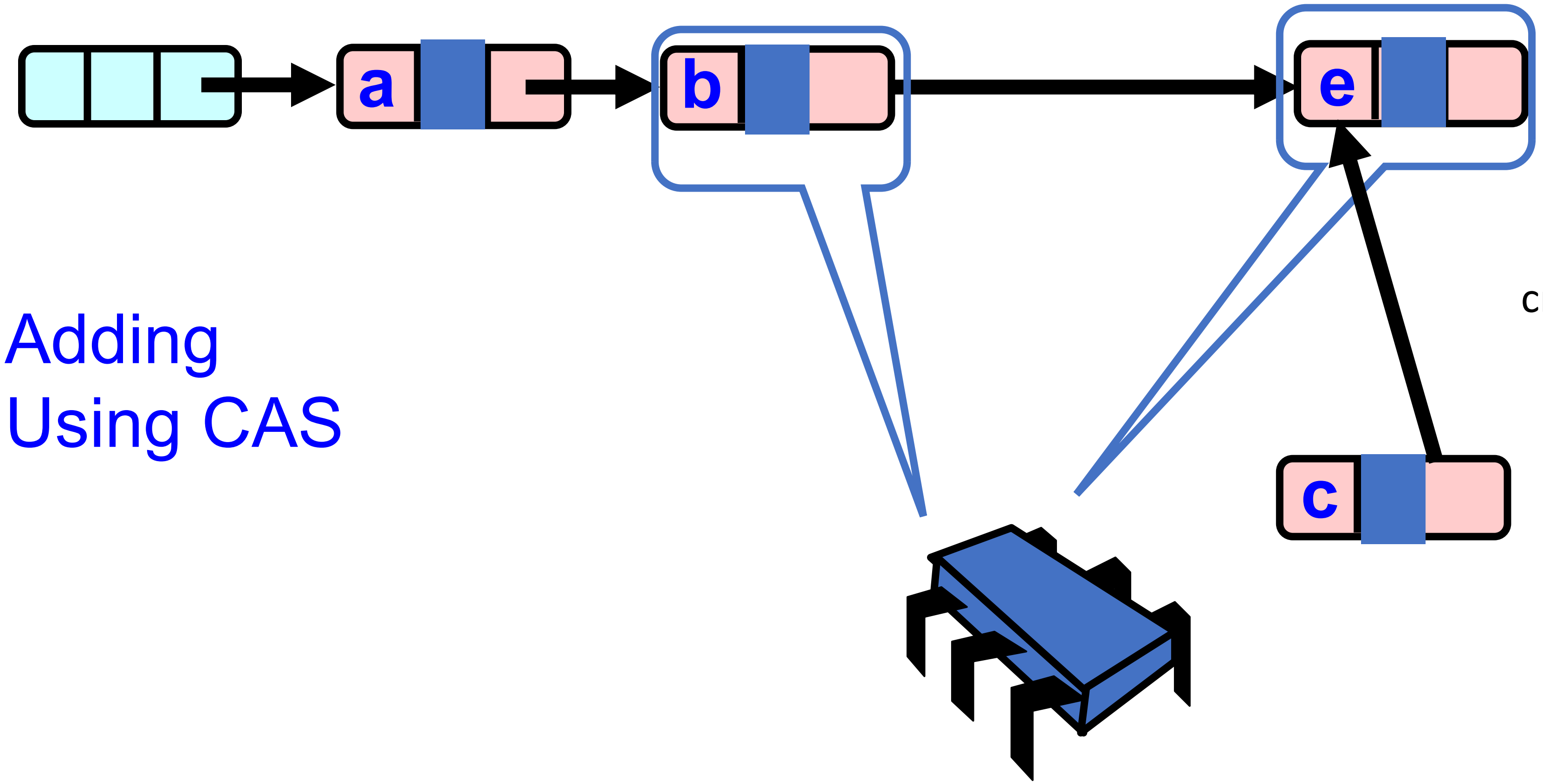


Adding
Using CAS

Lock-free Lists

Only add if your insertion point is valid!

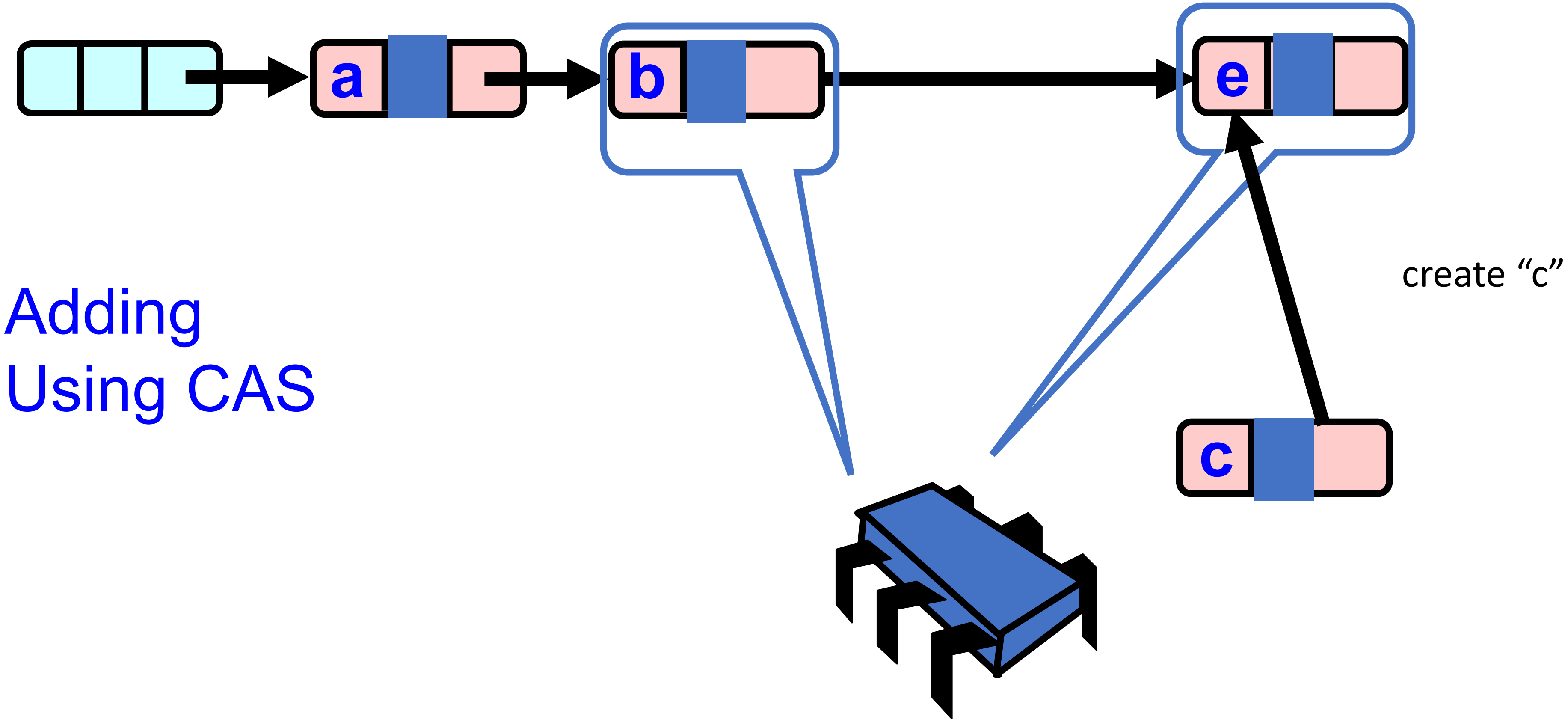
CAS(b.next, e, c);

Find the location

Cache your insertion point!

b.next == e

*notation is being abused here: e and c will be node **



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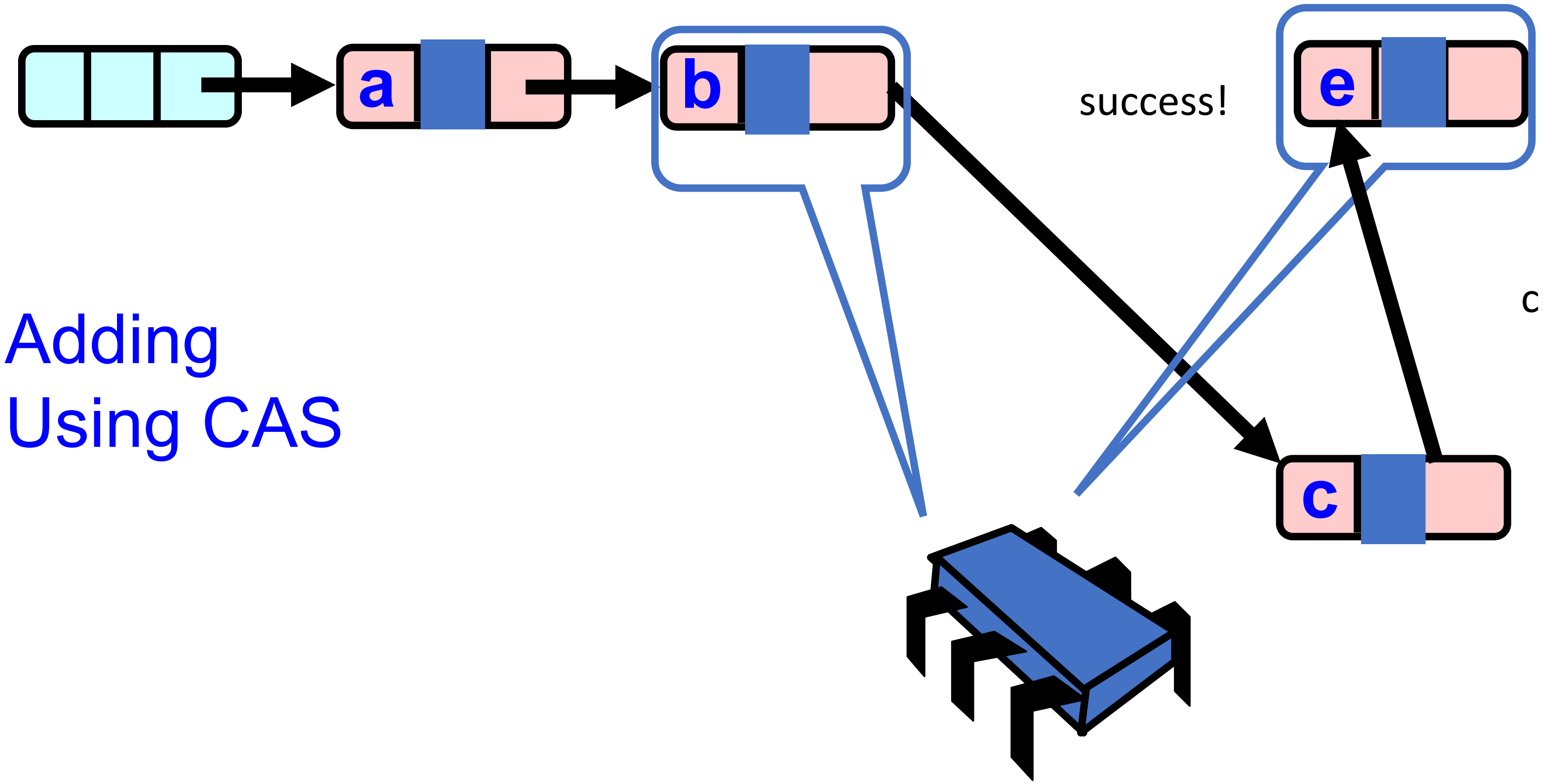

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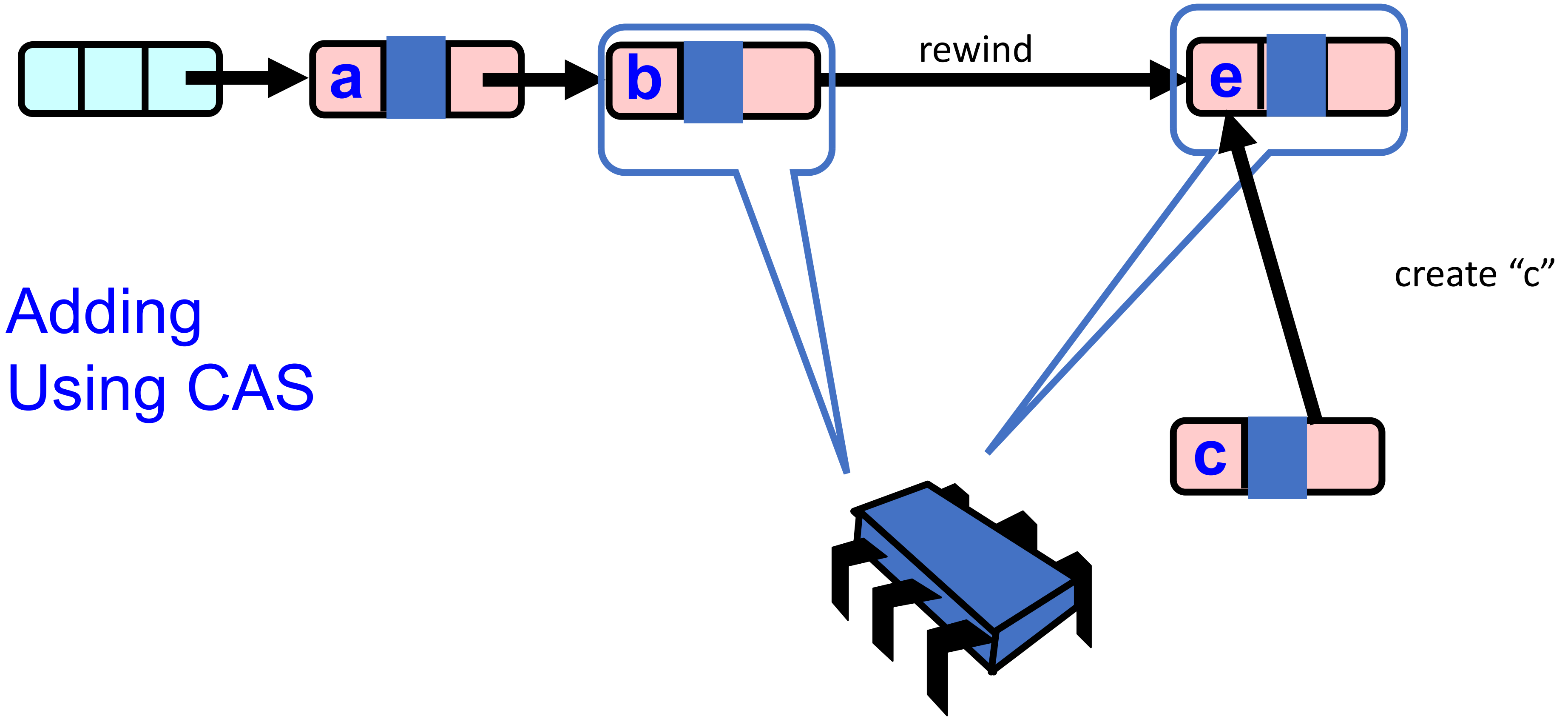

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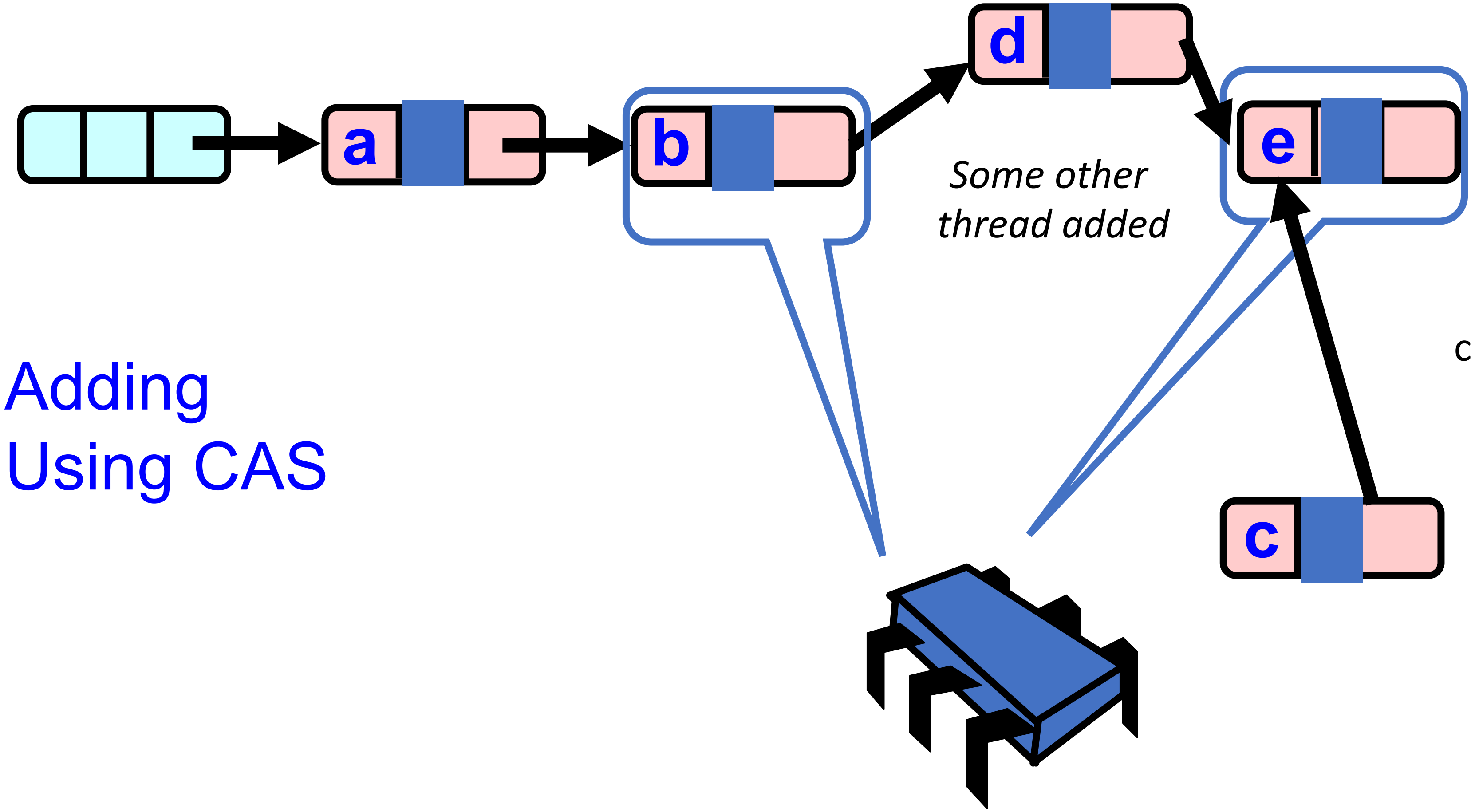

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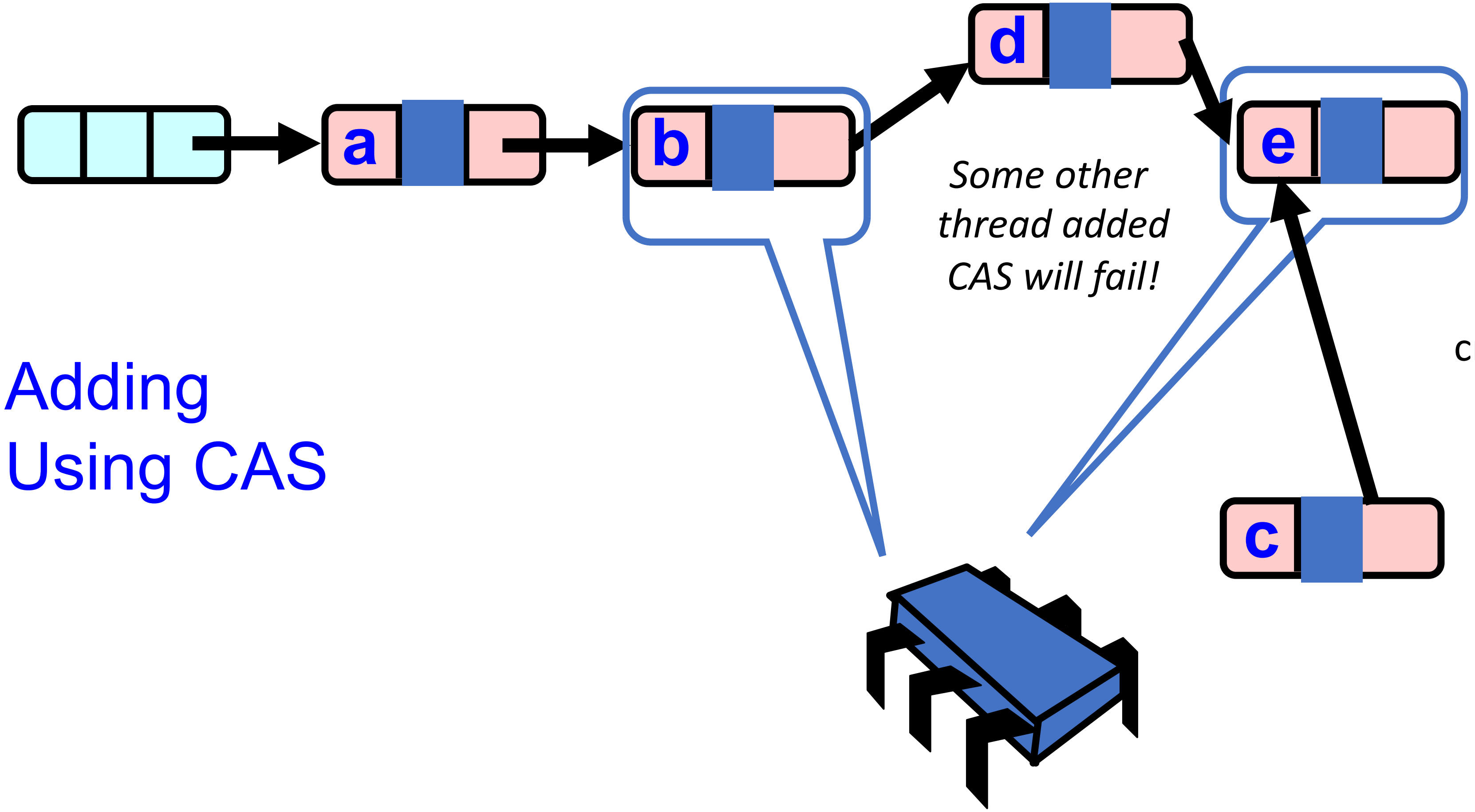

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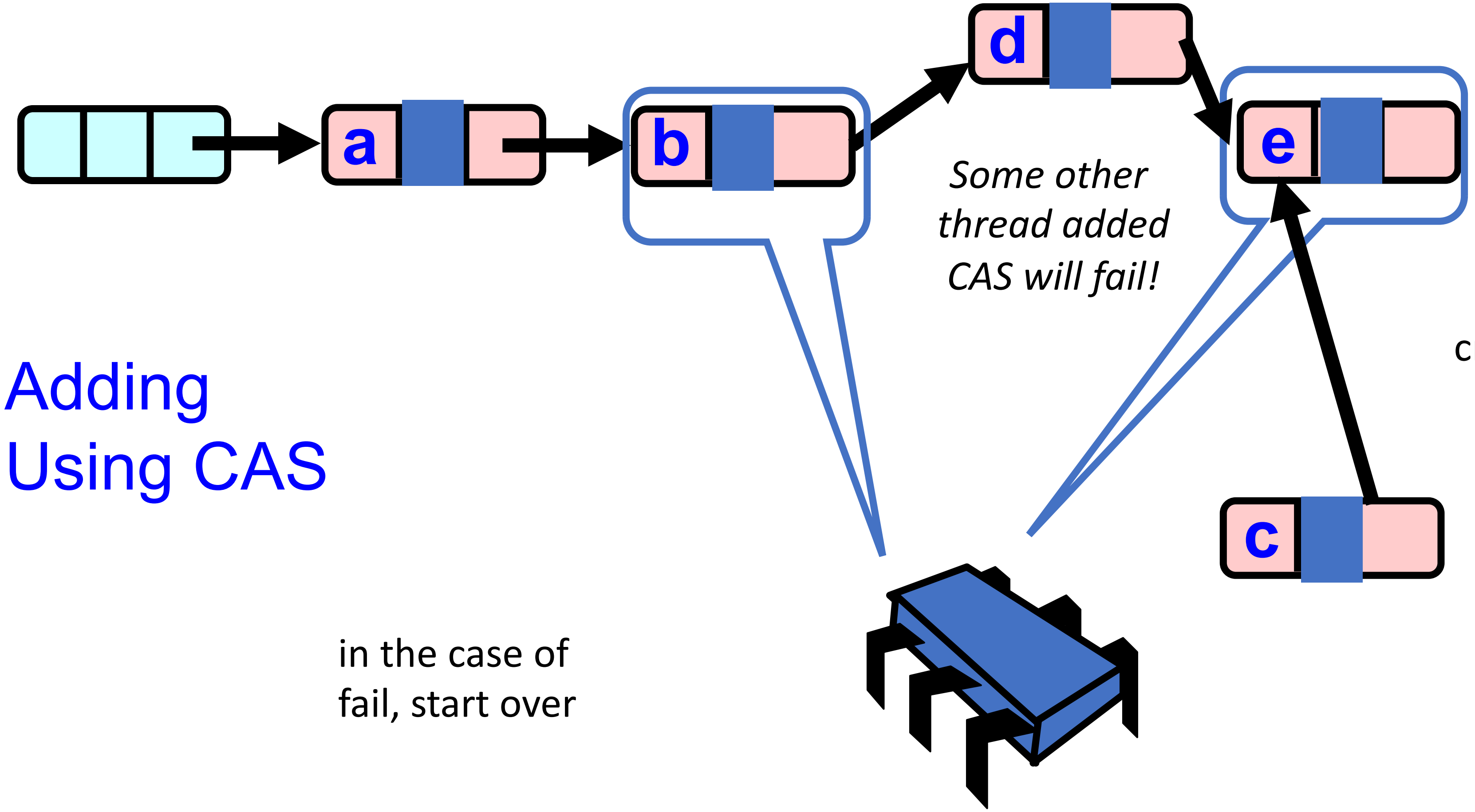
Cache your insertion point!

b.next == e

*notation is being abused here: e and c will be node **



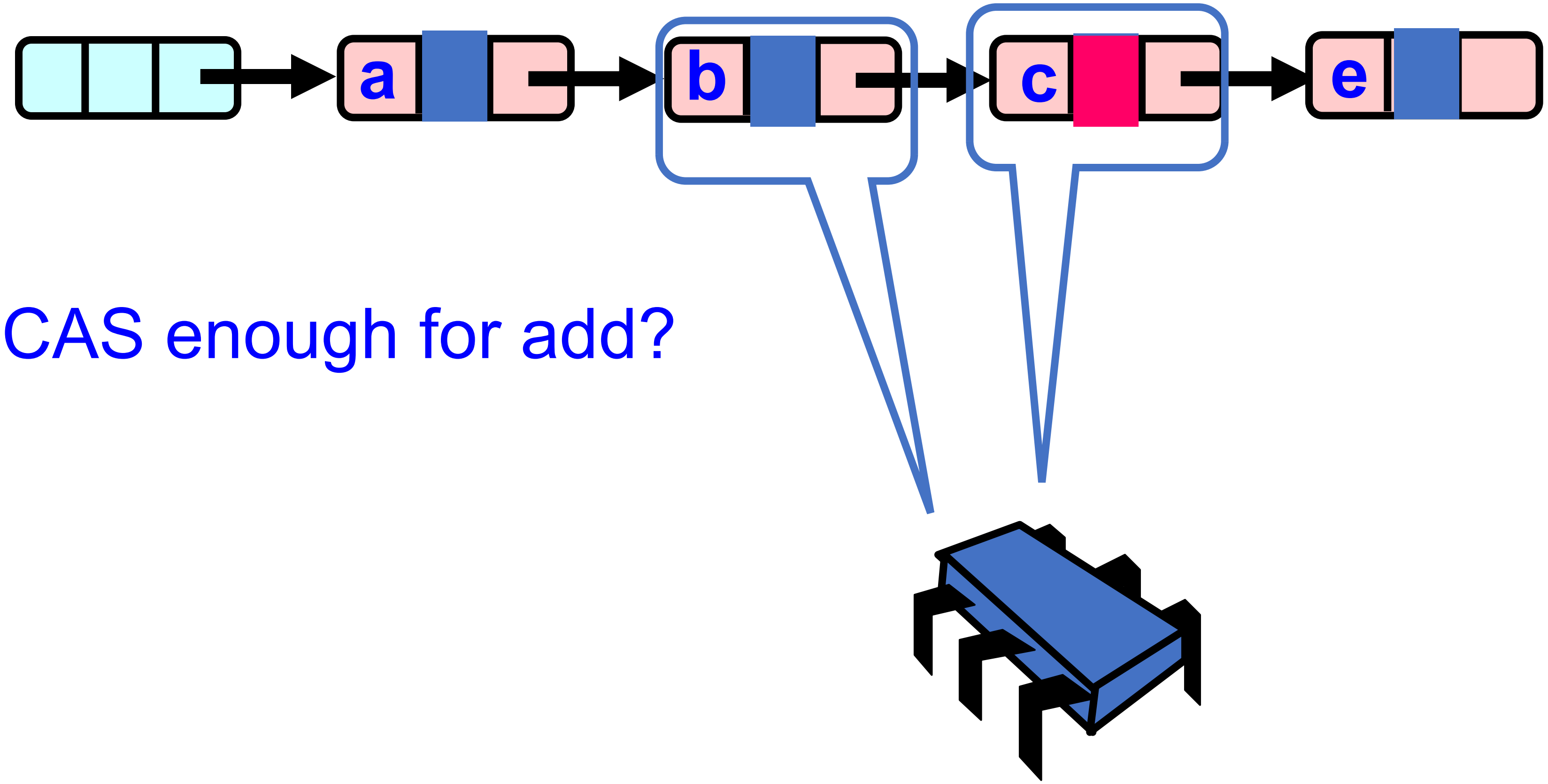
Some other thread added
CAS will fail!

create “c”

Adding Using CAS

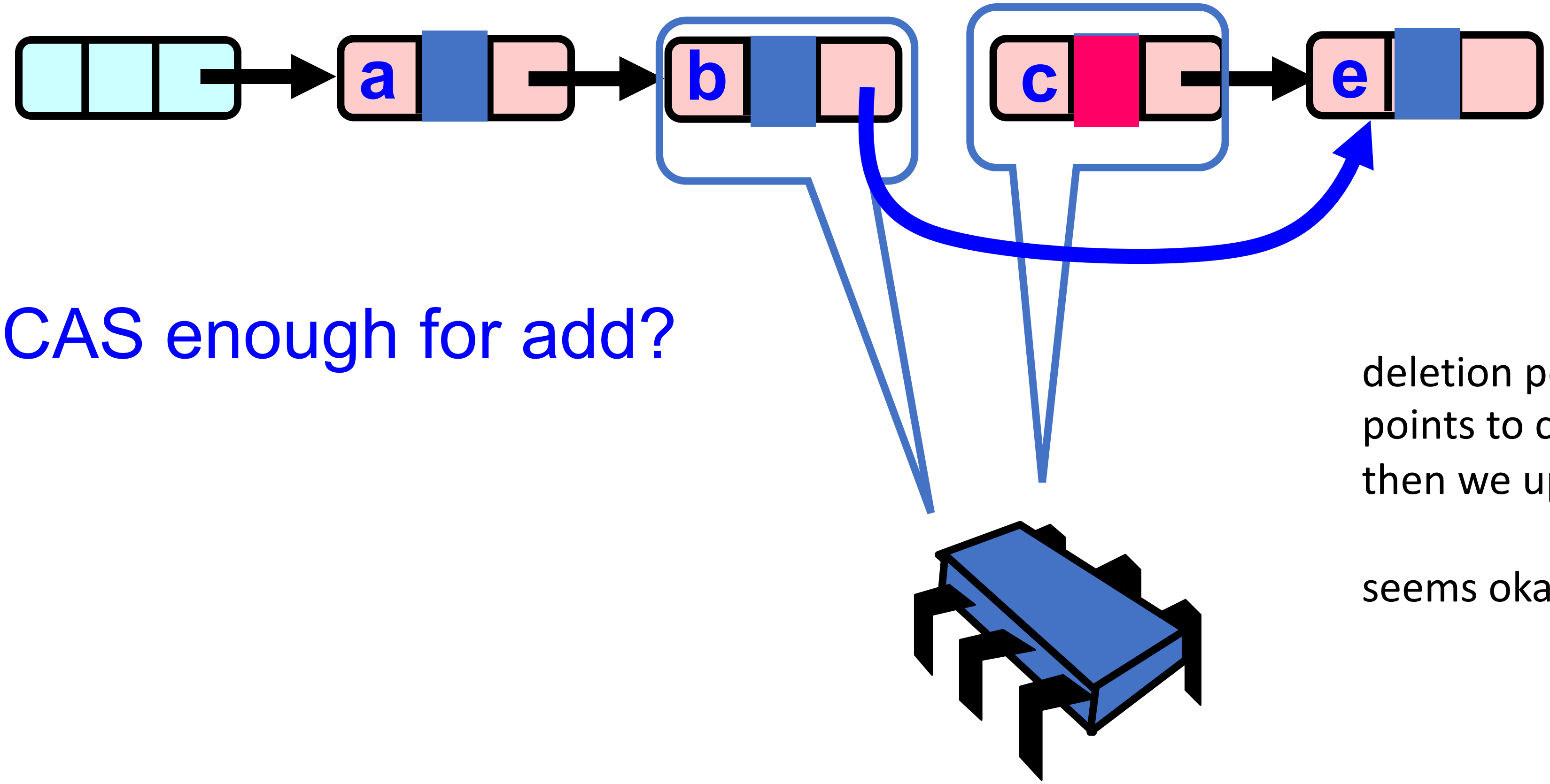
in the case of fail, start over

Lock-free Lists



CAS enough for add?

Lock-free Lists



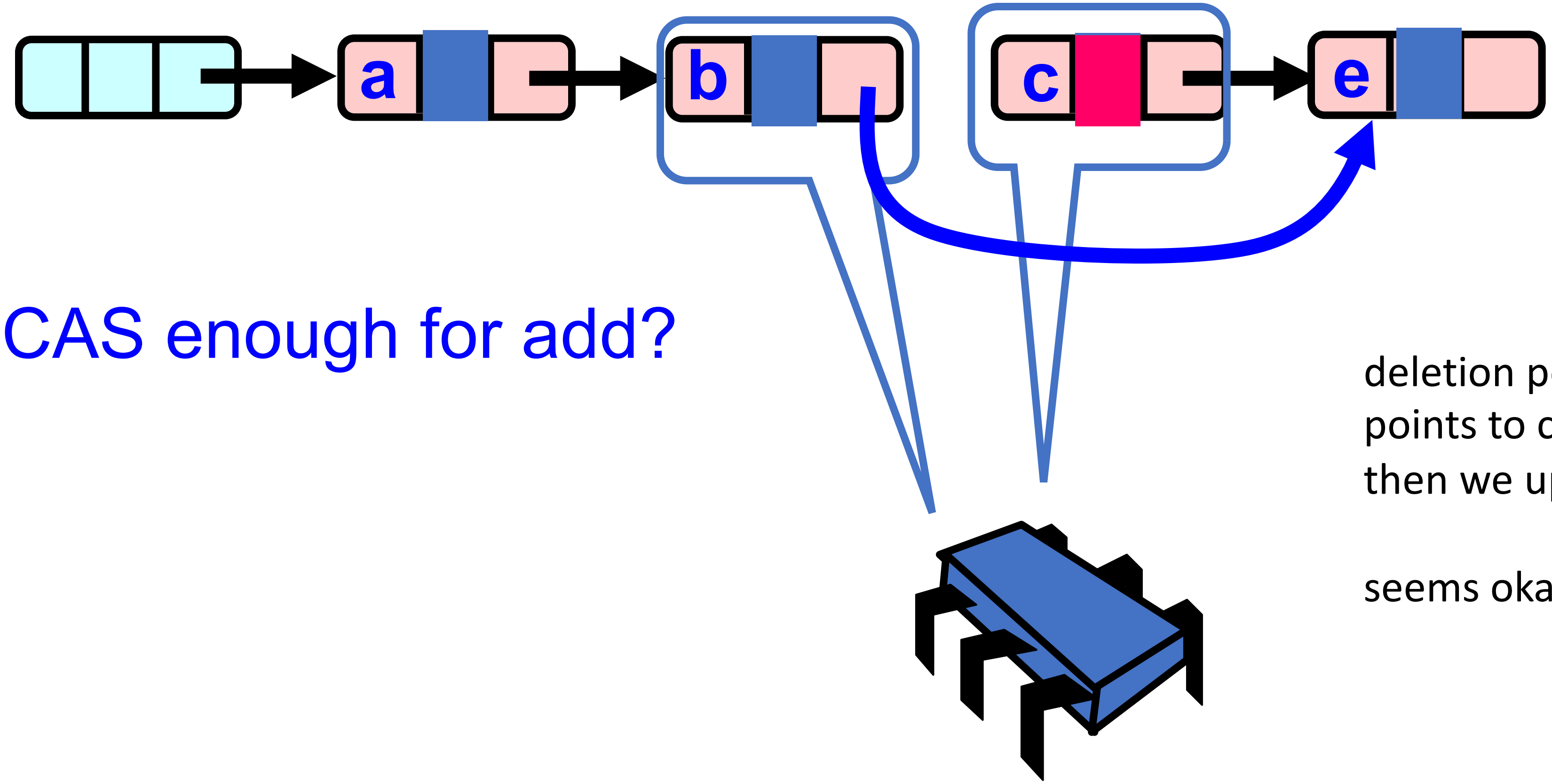
CAS enough for add?

deletion point requires b points to c. If that is valid then we update to e.

seems okay...

Lock-free Lists

ensures that nobody has added a node between b and c



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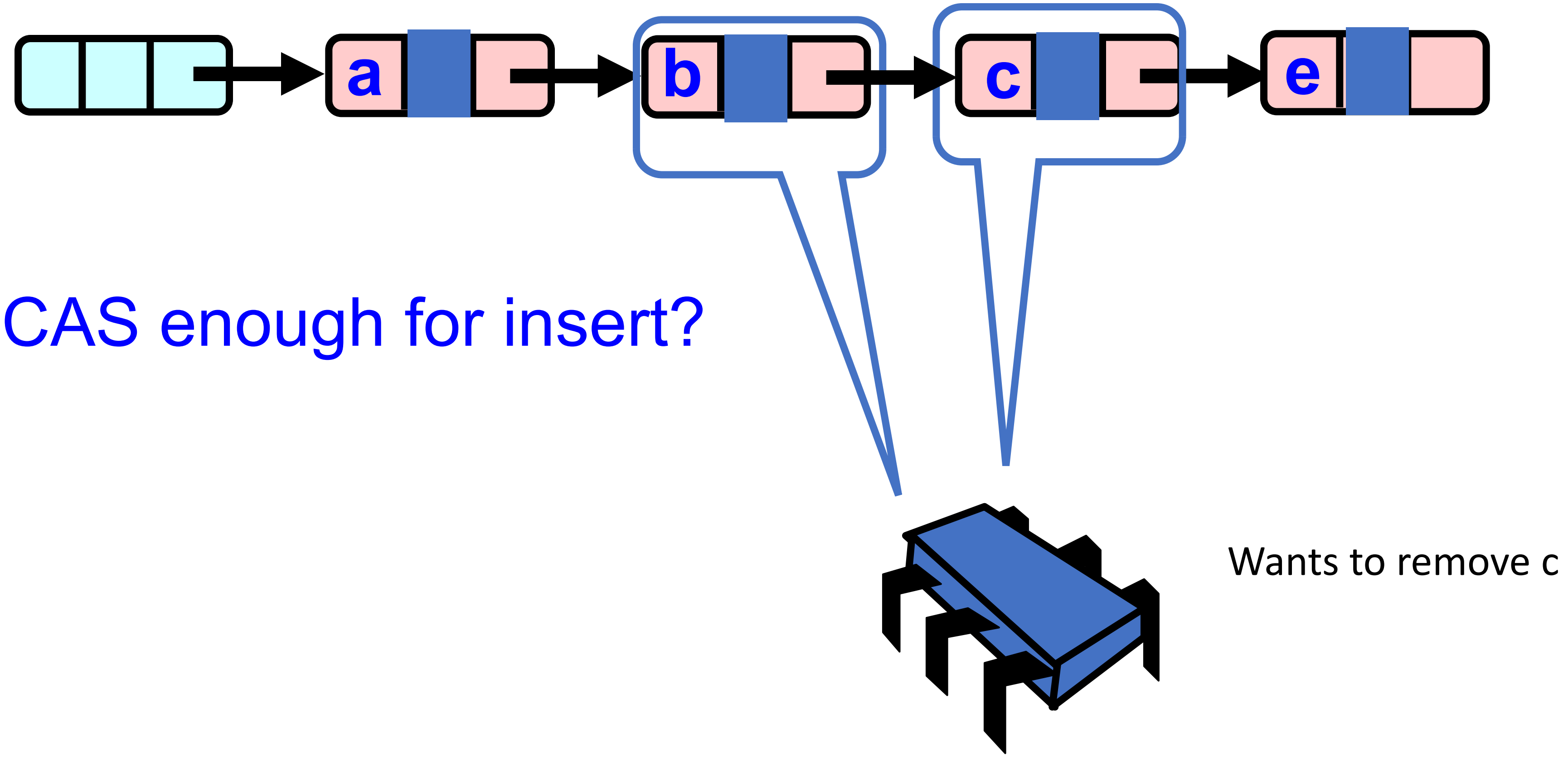
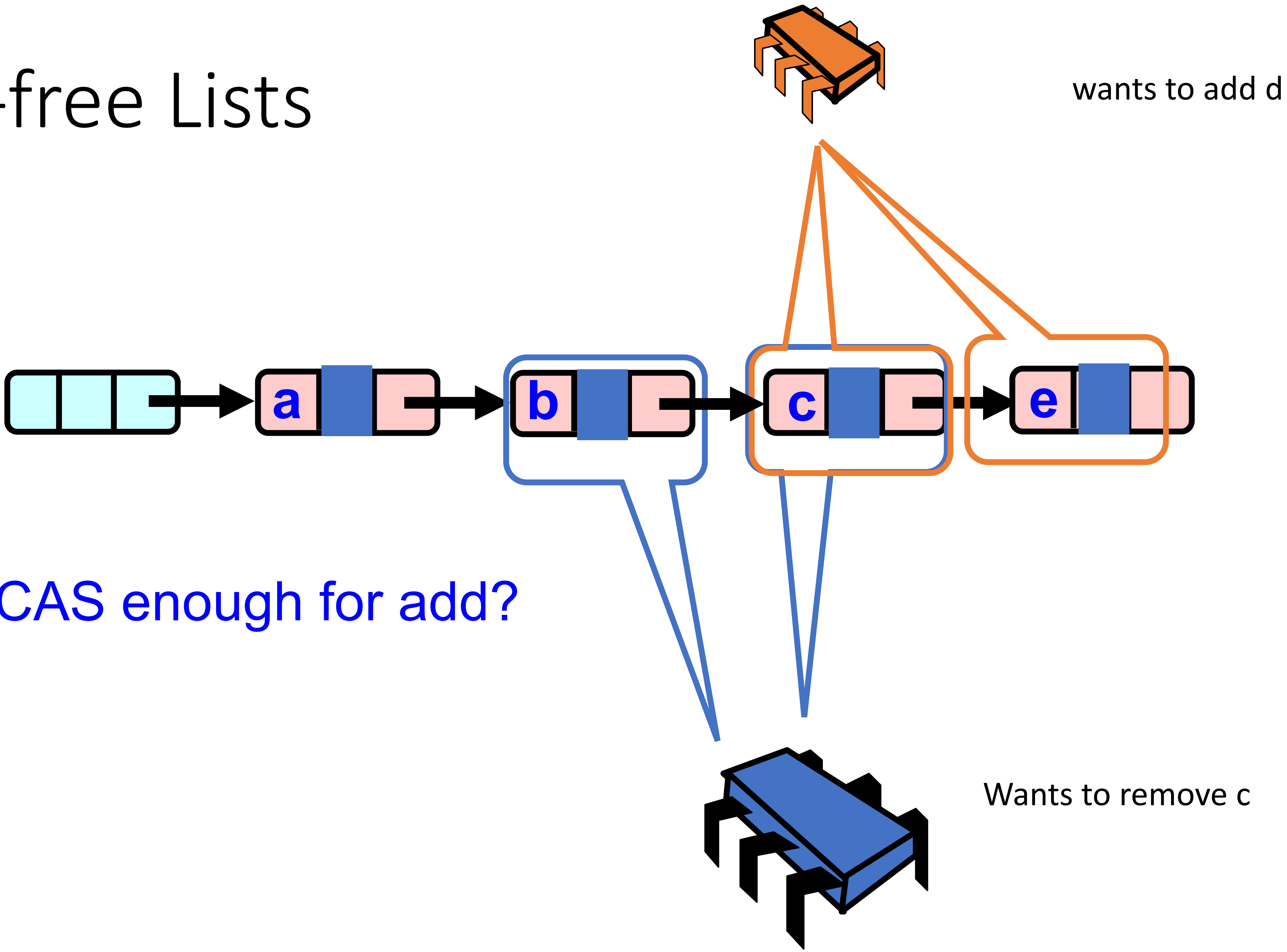
Lock-free Lists

Rewind



CAS enough for insert?

Lock-free Lists



CAS enough for add?

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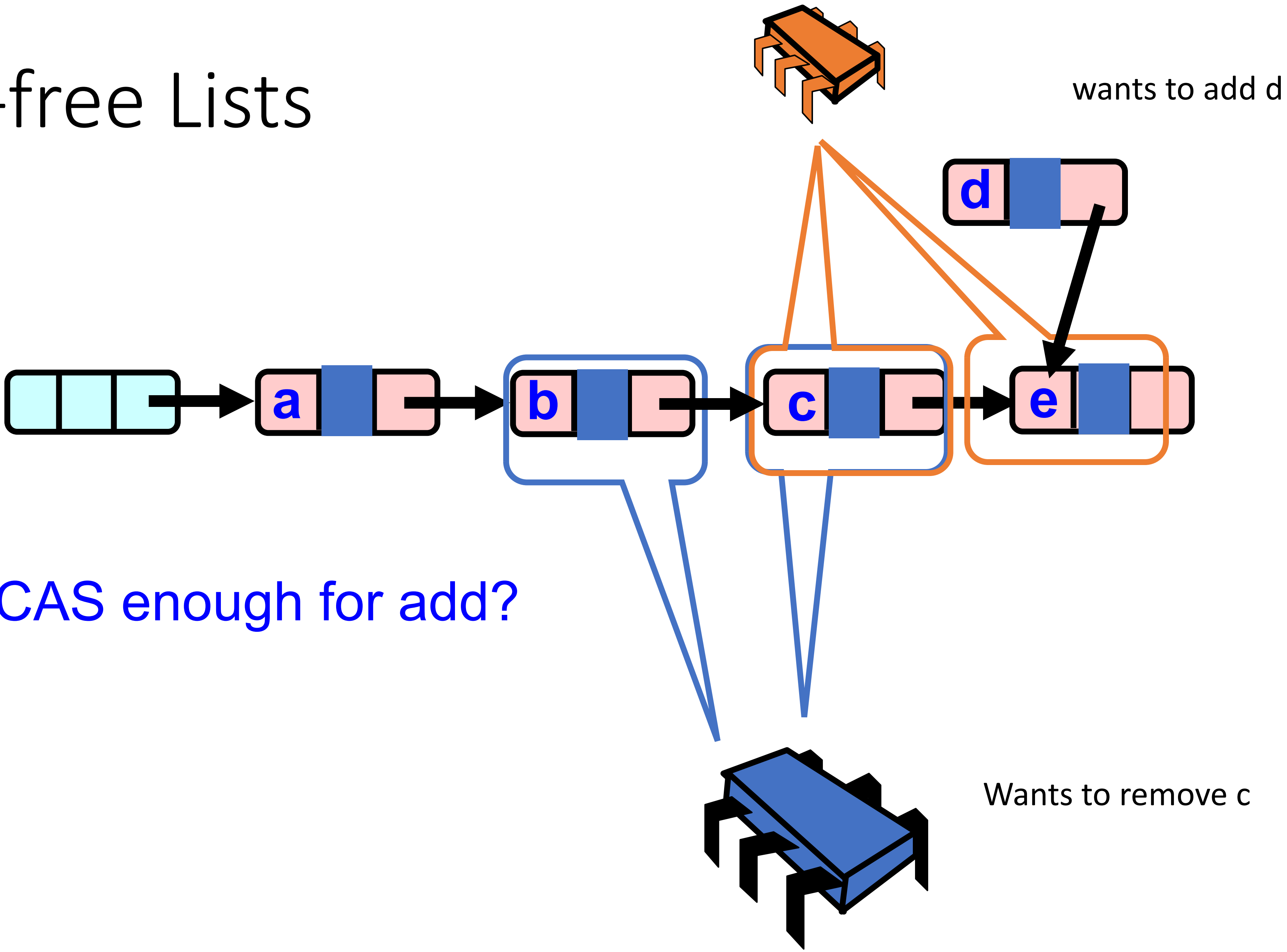

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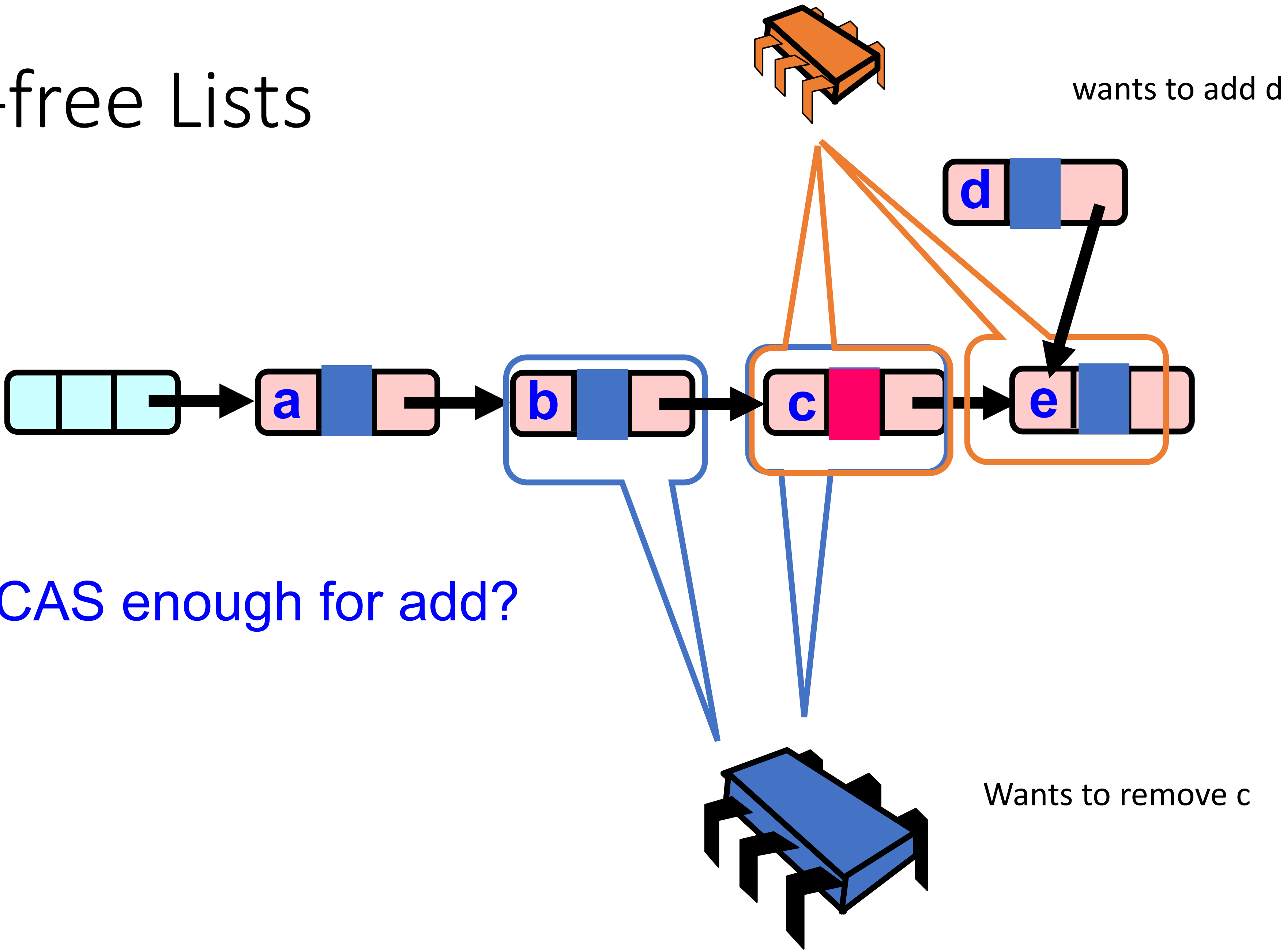
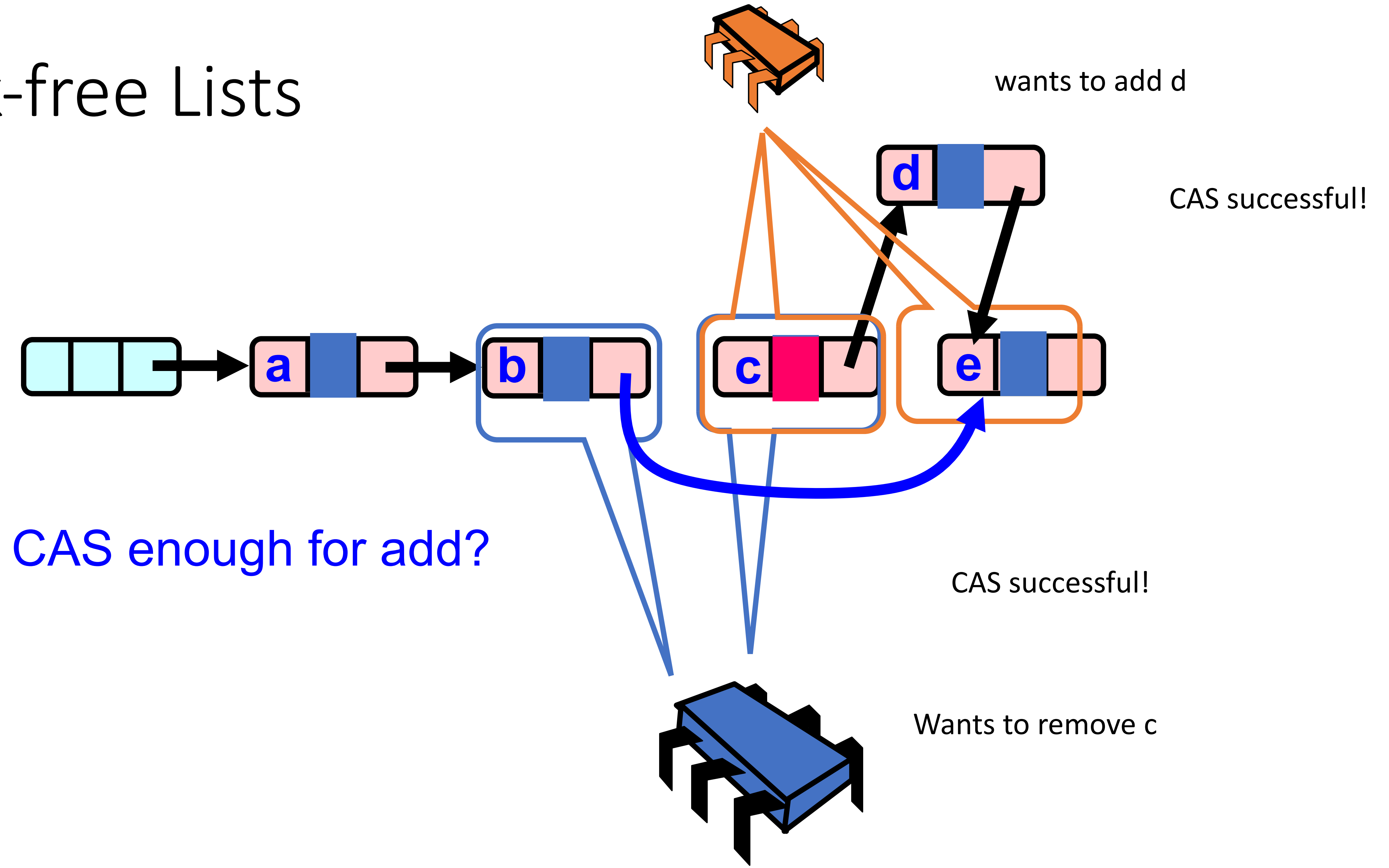


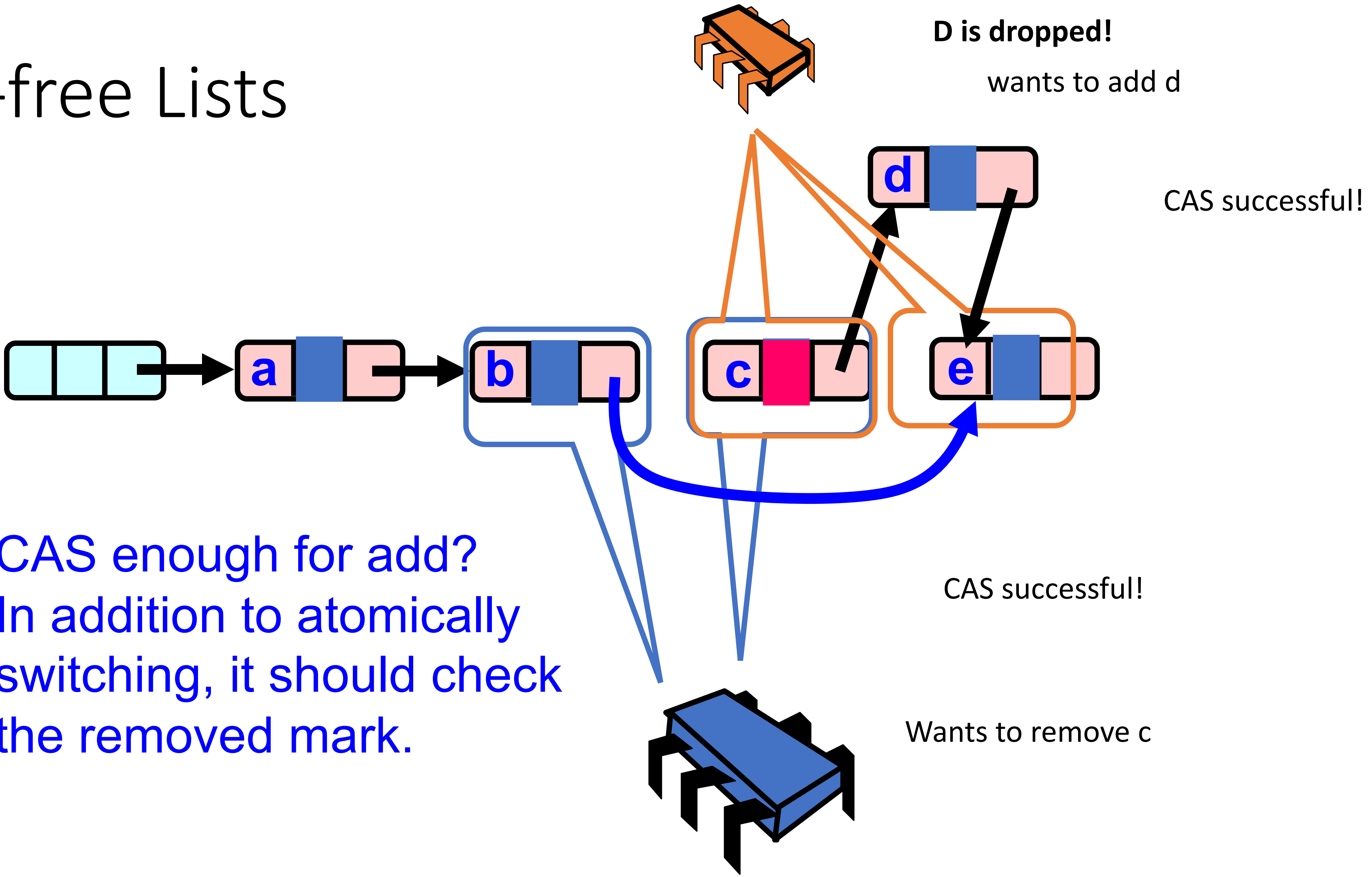
CAS enough for add?

Lock-free Lists



CAS enough for add?

Lock-free Lists

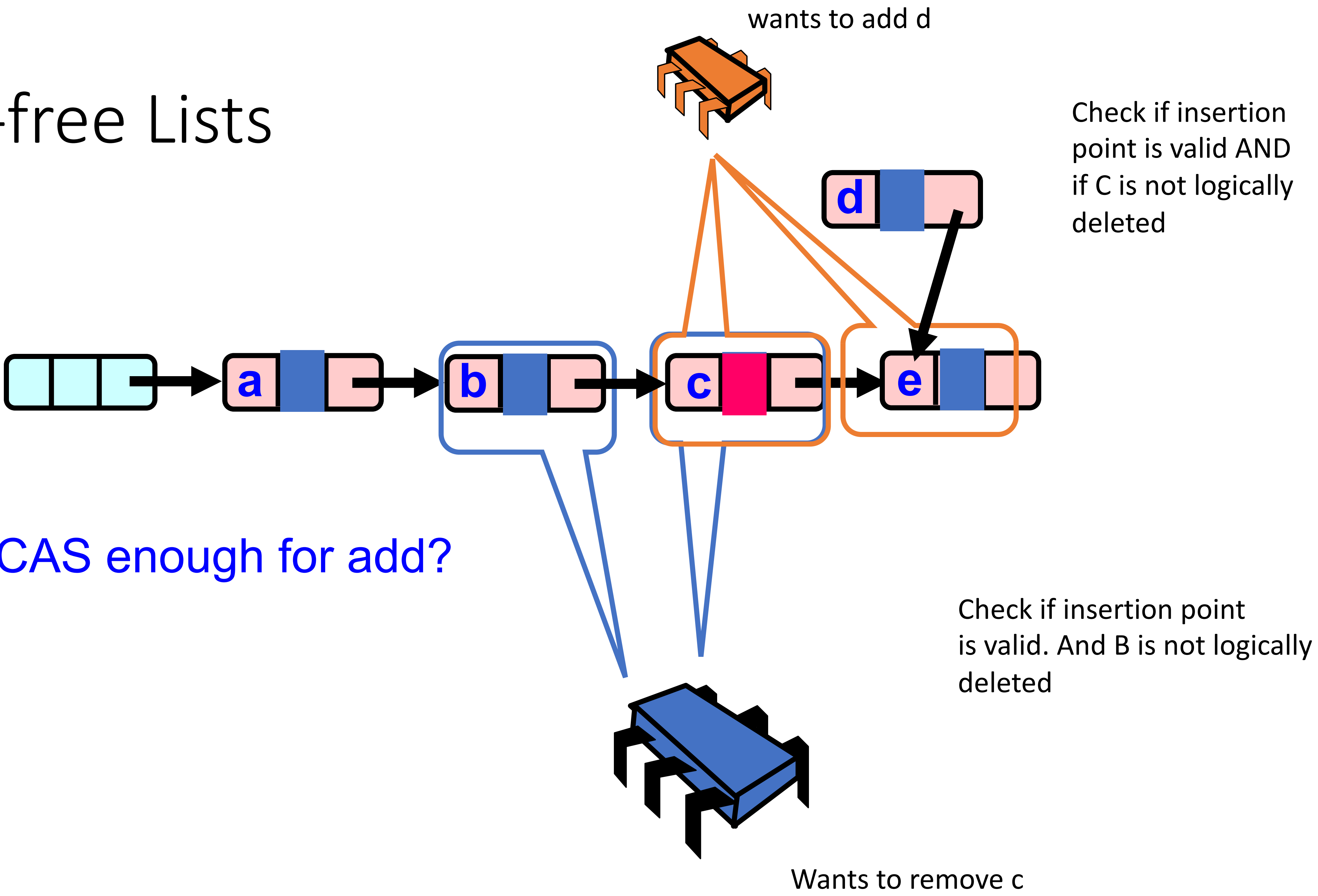


CAS enough for add?
In addition to atomically switching, it should check the removed mark.

Solution

- Use AtomicMarkableReference
- Atomic CAS that checks not only the address, but also a bit.
- We can say: update pointer if
  the insertion point is valid AND
  the node has not been logically removed.

Lock-free Lists



CAS enough for add?

Marking a Node

- **AtomicMarkableReference** class
  - Java.util.concurrent.atomic package
  - But we're using a better™ language (C++)

This stuff is tricky

- Focus on understanding the concepts:
  - Locks are easiest, but can impede performance
  - Fine-grained locks are better, but more difficult
  - Optimistic concurrency can take you far. CAS is your friend

- When reasoning about correctness:
  - You have to consider all combination of adds/removes.
  - Thread sanitizer will help, but not as much as in mutexes. Other research tools can help.

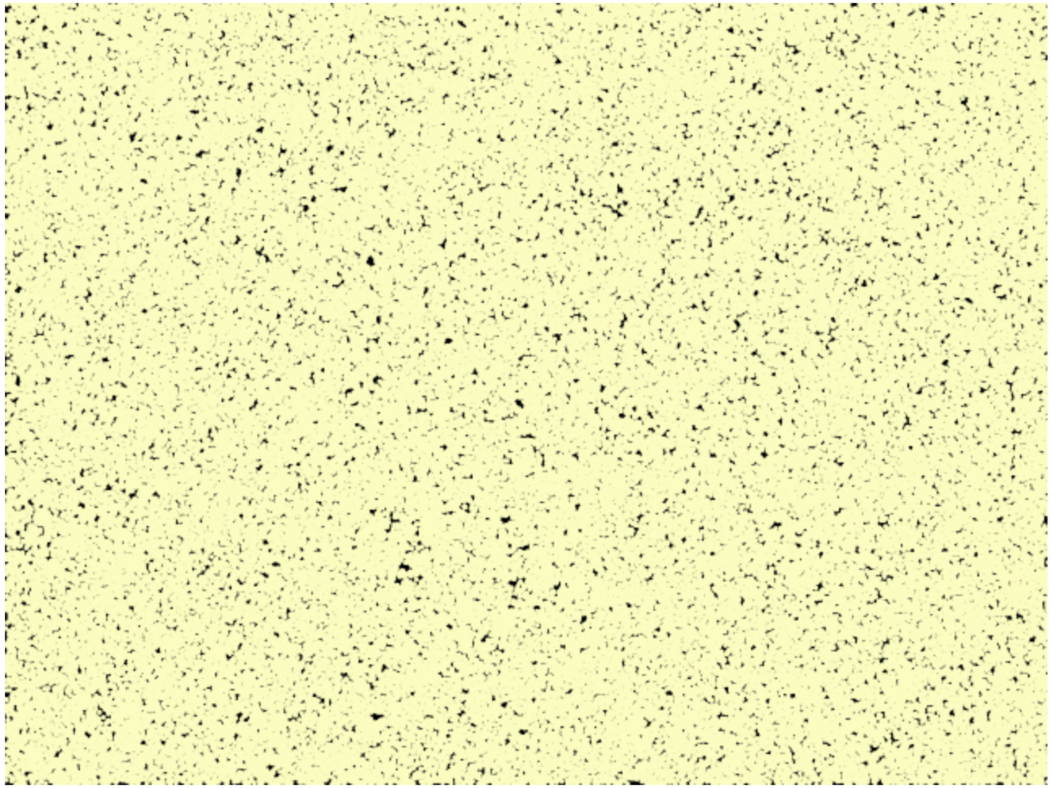
Barriers

Barriers

- A barrier is a concurrent object (like a mutex):
  - Only one method: `barrier` (called `await` in the book)
- Separates computational phases

Barrier Examples

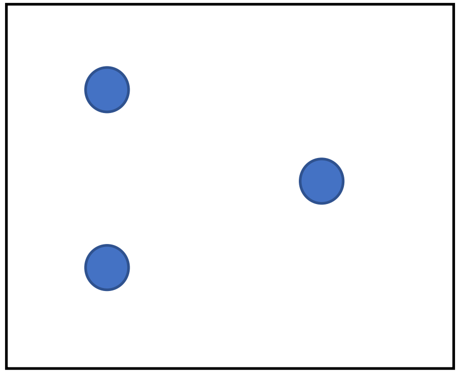
Particle simulation



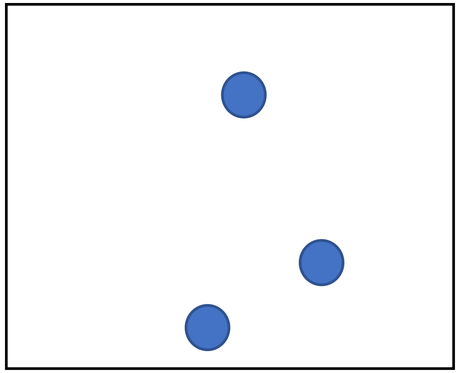
by Yanwen Xu

Barrier Examples

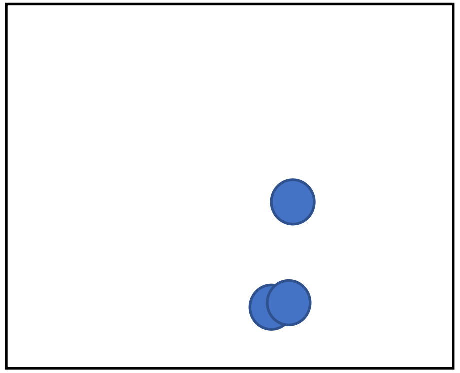
Particle simulation



time = 0



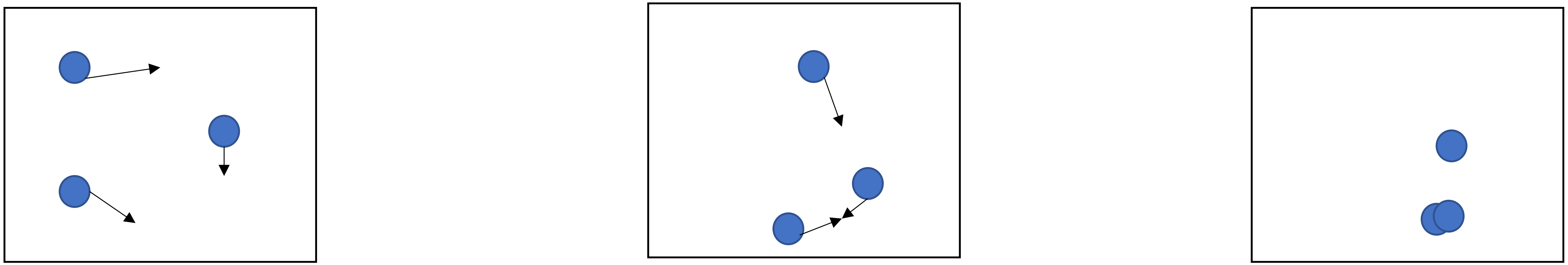
time = 1



time = 2

Barrier Examples

Particle simulation

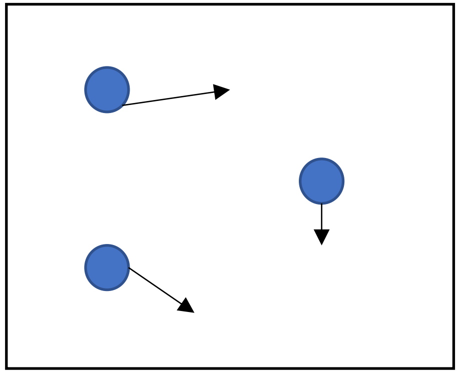


time = 0 time = 1 time = 2

At each time, compute
new positions for each particle
(in parallel)

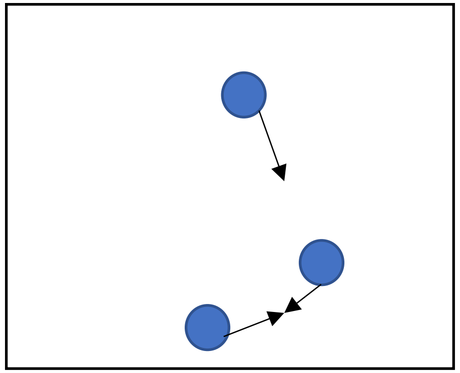
Barrier Examples

Particle simulation



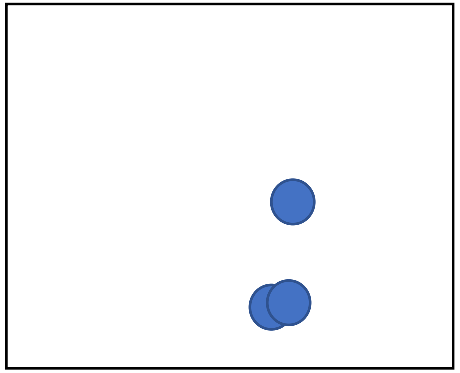
time = 0

`barrier();`



time = 1

`barrier();`



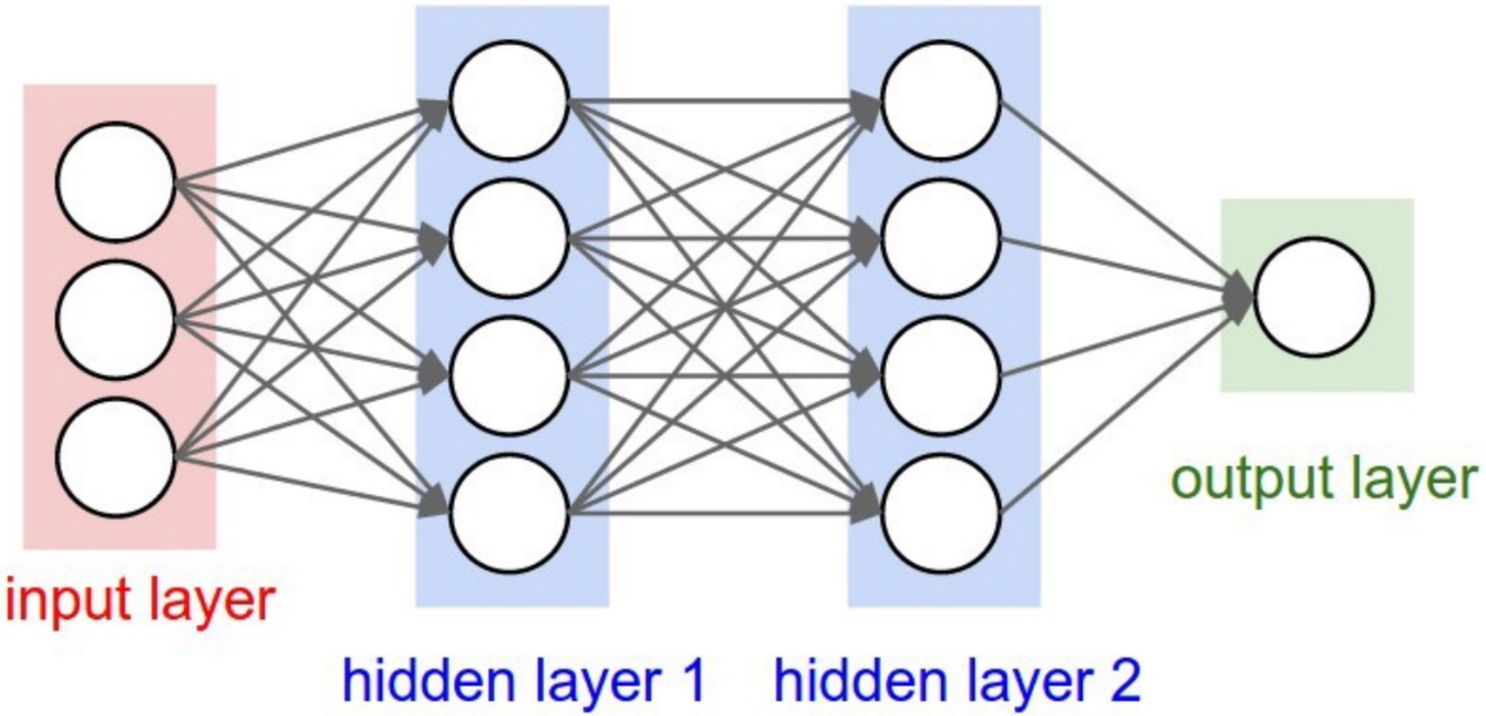
time = 2

At each time, compute
new positions for each particle
(in parallel)

But you need to wait for all particles to be
computed before starting the next time step

Barrier Examples

- Deep neural networks



from http://cs231n.stanford.edu/

Barrier Examples

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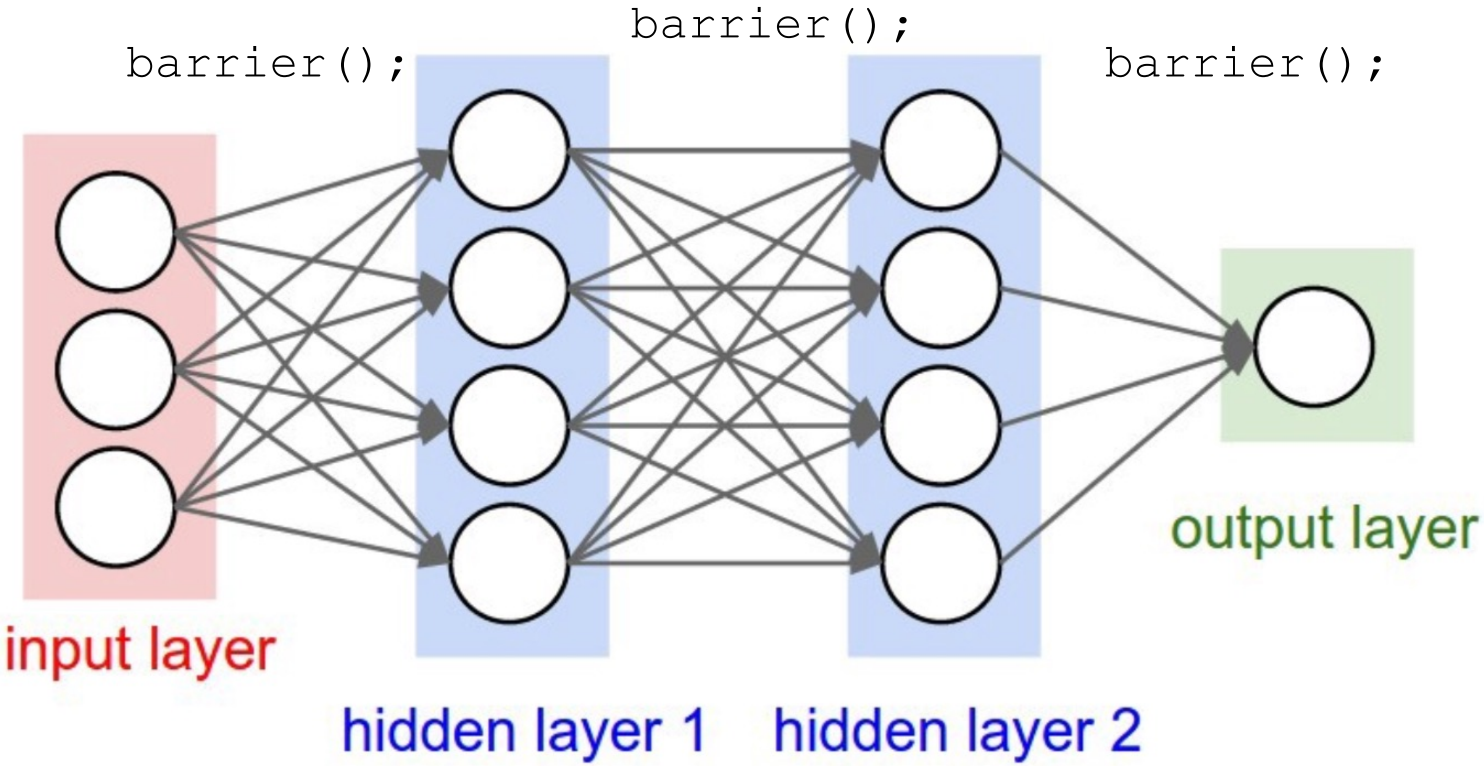

from http://cs231n.stanford.edu/

Barriers

- Intuition: threads stop and wait for each other:
  - Threads ***arrive*** at the barrier
  - Threads ***wait*** at the barrier
  - Threads ***leave*** the barrier once all other threads have arrived

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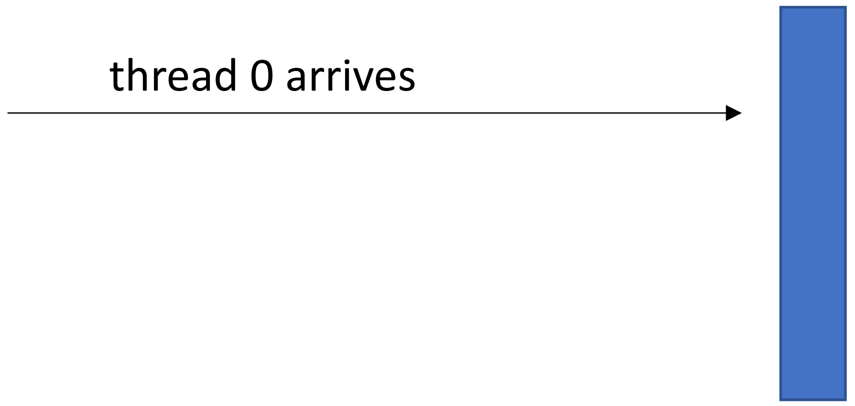

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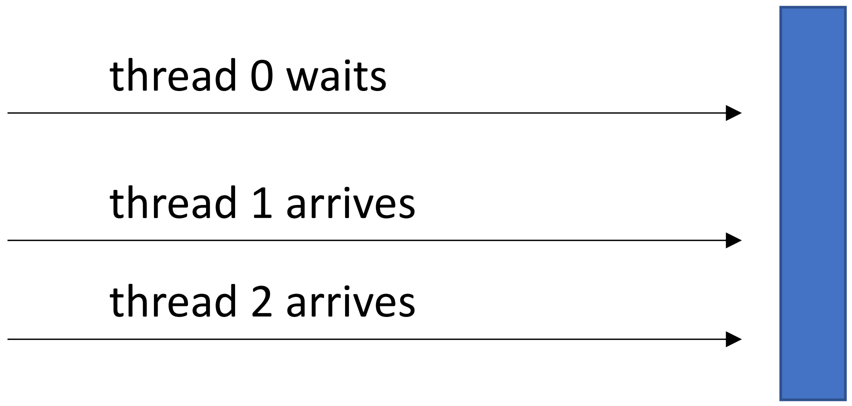

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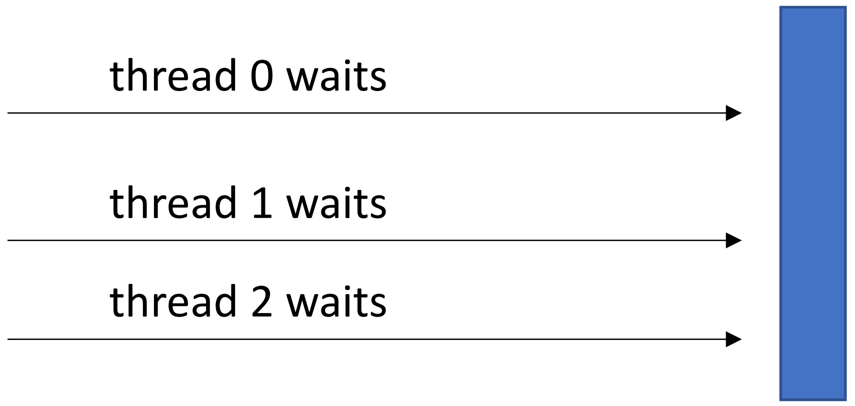

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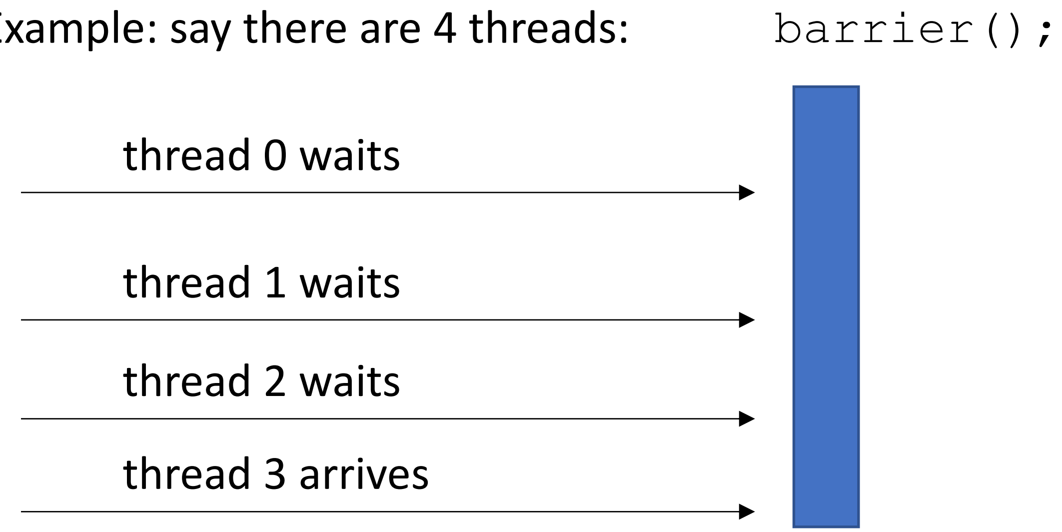

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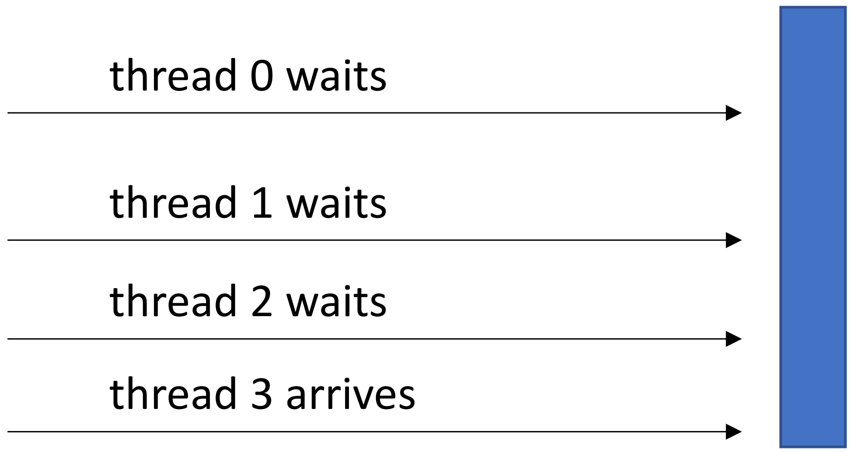

now that they have all arrived

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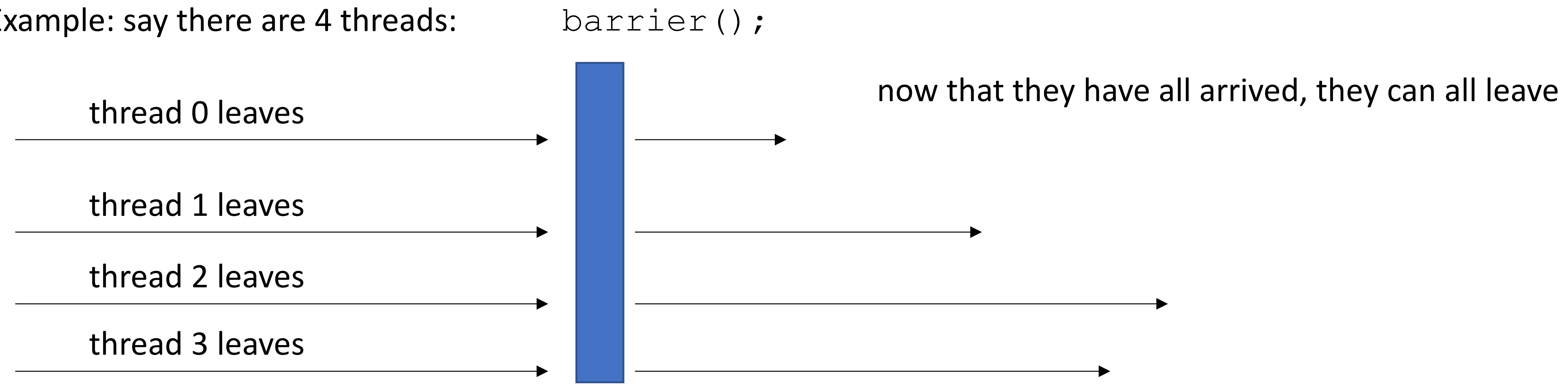

A more formal specification

Given a global barrier `B`
and a global memory location x where
initially *x = 0;

Thread 0:

```
*x = 1;
B.barrier();
```

Thread 1:

```
B.barrier();
var = *x;
```

First, what would we expect
var to be after this program?

thread 0

thread 1

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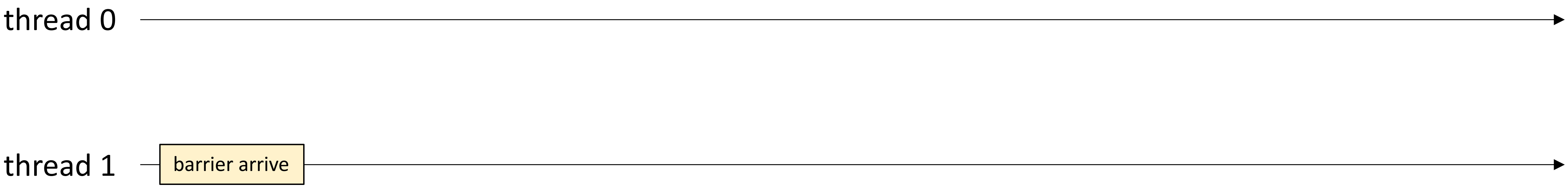
gives an event:
barrier arrive



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Given a global barrier `B`

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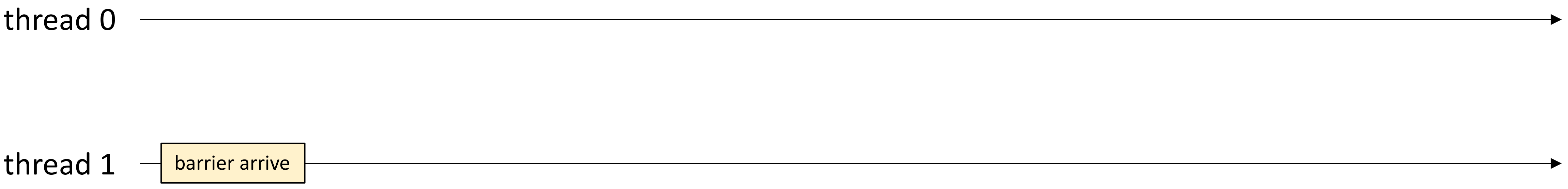
Thread 1:

```
B.barrier();
var = *x;
```

gives an event:
barrier arrive

barrier arrive needs to wait for all threads
to arrive (similar to how a mutex request must wait for
another to release)



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```
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```

now that all threads have arrived:
They can leave (1 event at the same time)

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Thread 1:

```
B.barrier();
var = *x;
```

This finishes the barrier execution

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Thread 1:
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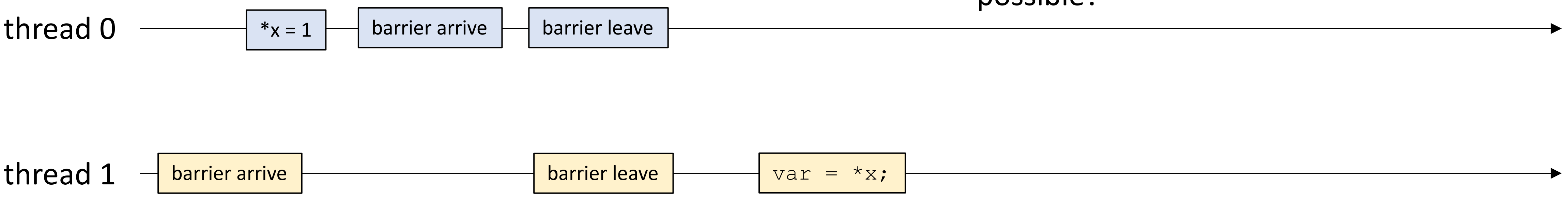
var = *x;
```

what value must this read? Any other value possible?



One more example, assume initially `*x = *y = 0`

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*x = 1;
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```

Thread 1:

```
*y = 2;
B.barrier();
```

Thread 2:

```
B.barrier();
var = *x + *y;
```

thread 0

thread 1

thread 2

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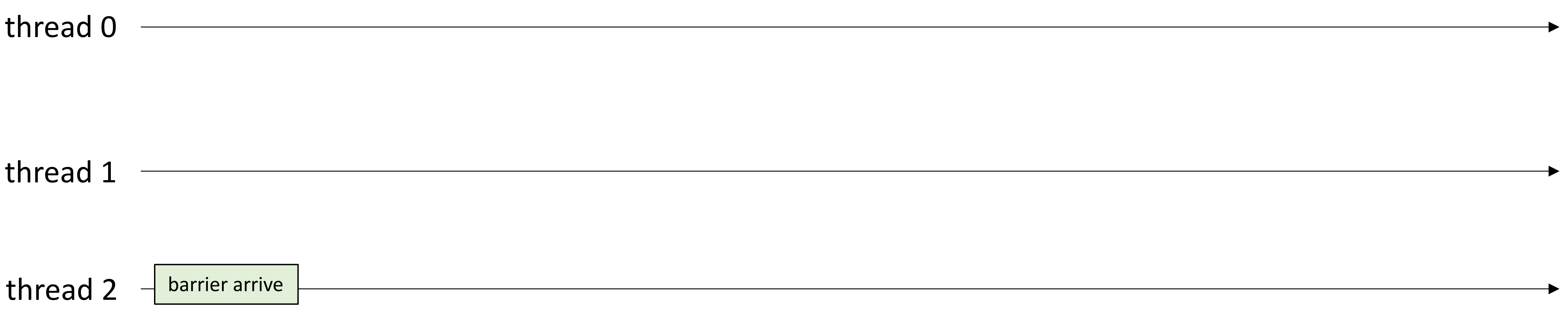

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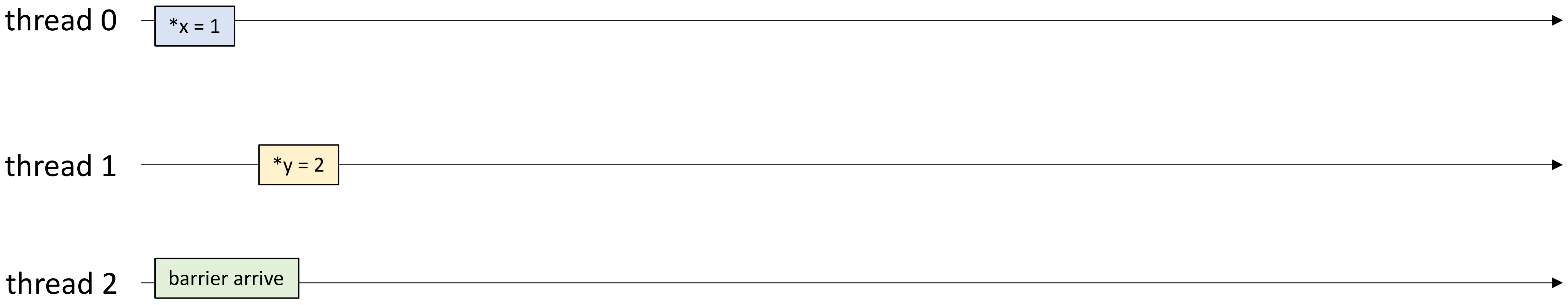

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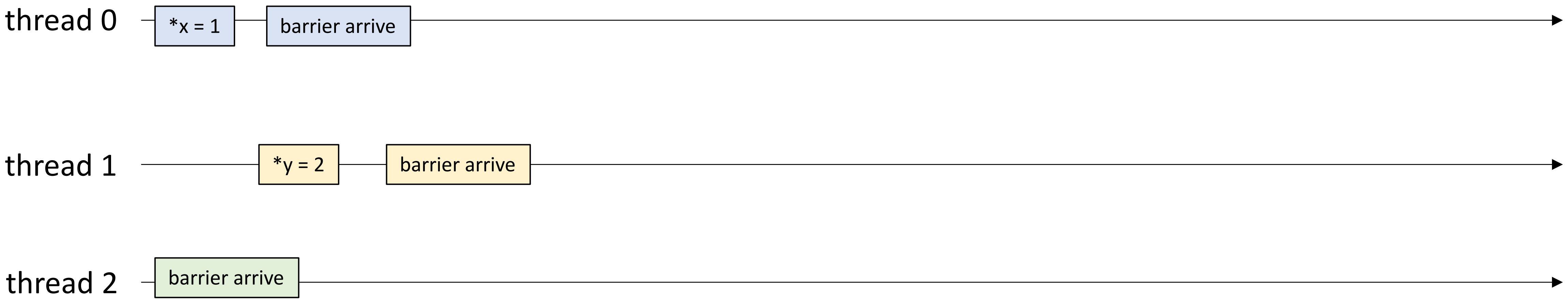

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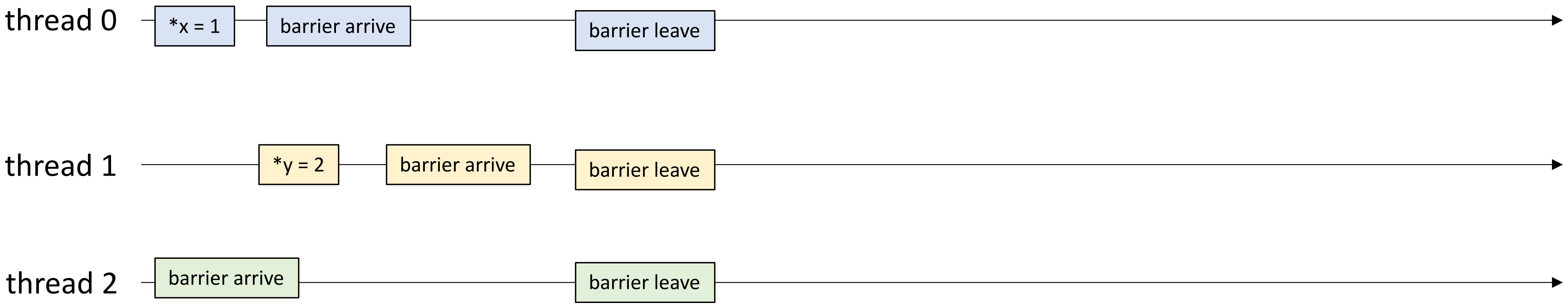
They've all arrived



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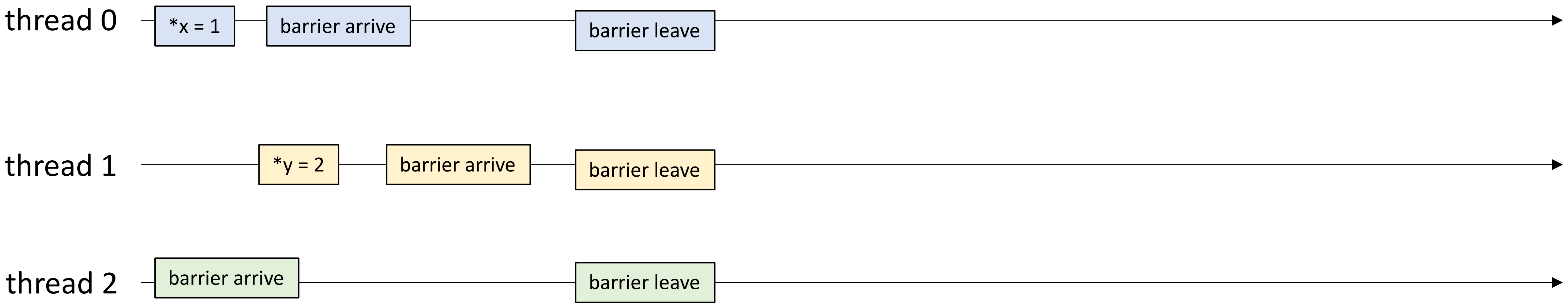

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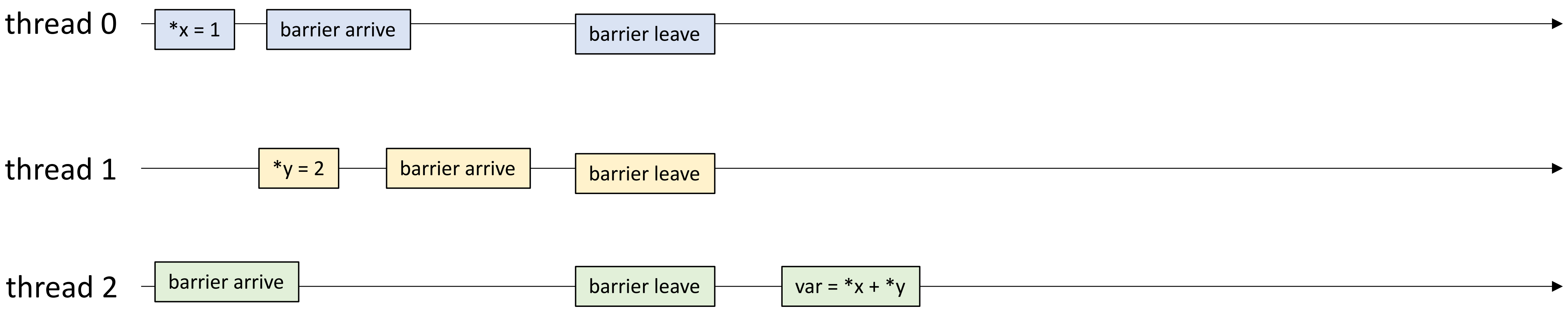

What is this guaranteed to be?

One more example, assume initially `*x = *y = 0`

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```

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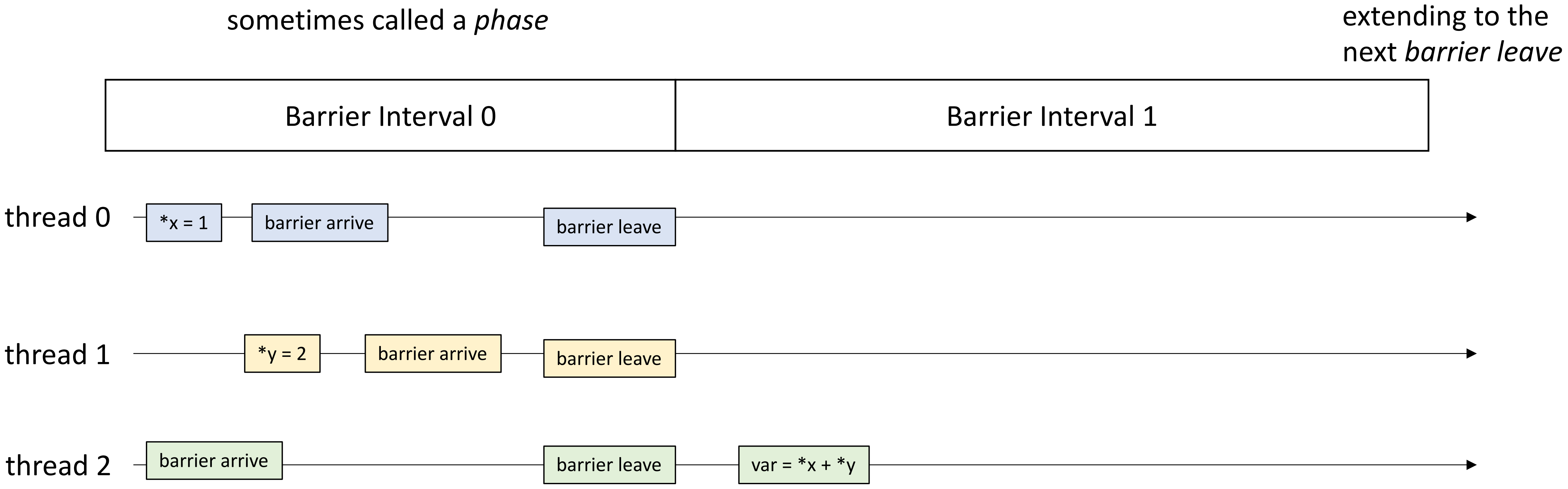


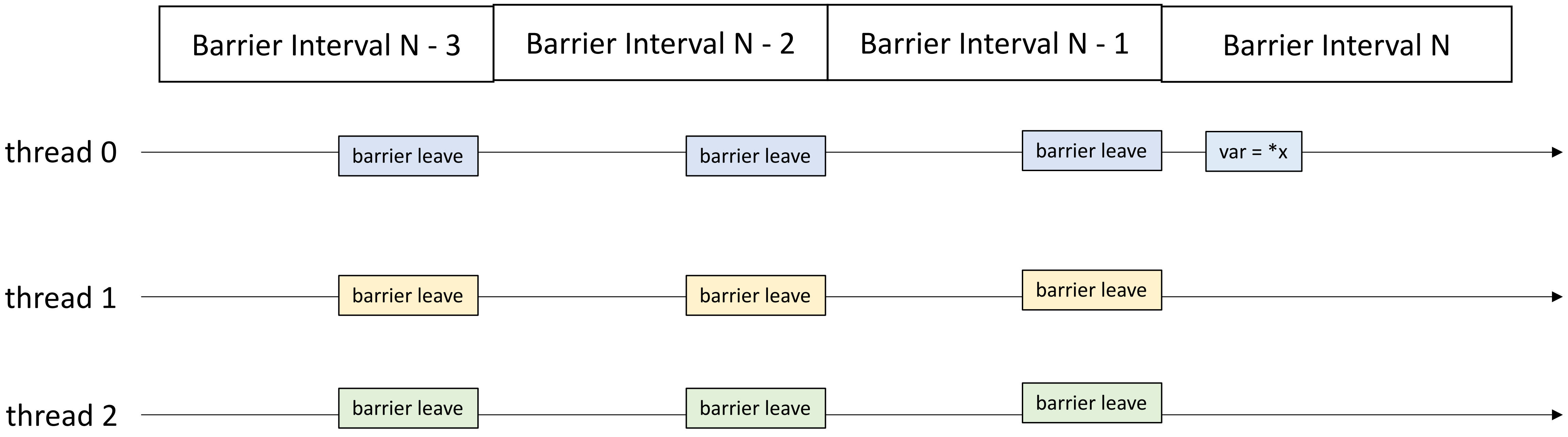
Barriers

- Barrier Property:
  - If the only concurrent object you use in your program is a barrier (no mutexes, concurrent data-structures, atomic accesses)
  - If every barrier interval contains no data conflicts, then

    your program will be deterministic (only 1 outcome allowed)
  - much easier to reason about ☺

Assume we are reading from x

We are only allowed to return one possible value



no data conflicts means that x is written to at most once per barrier interval

Assume we are reading from x

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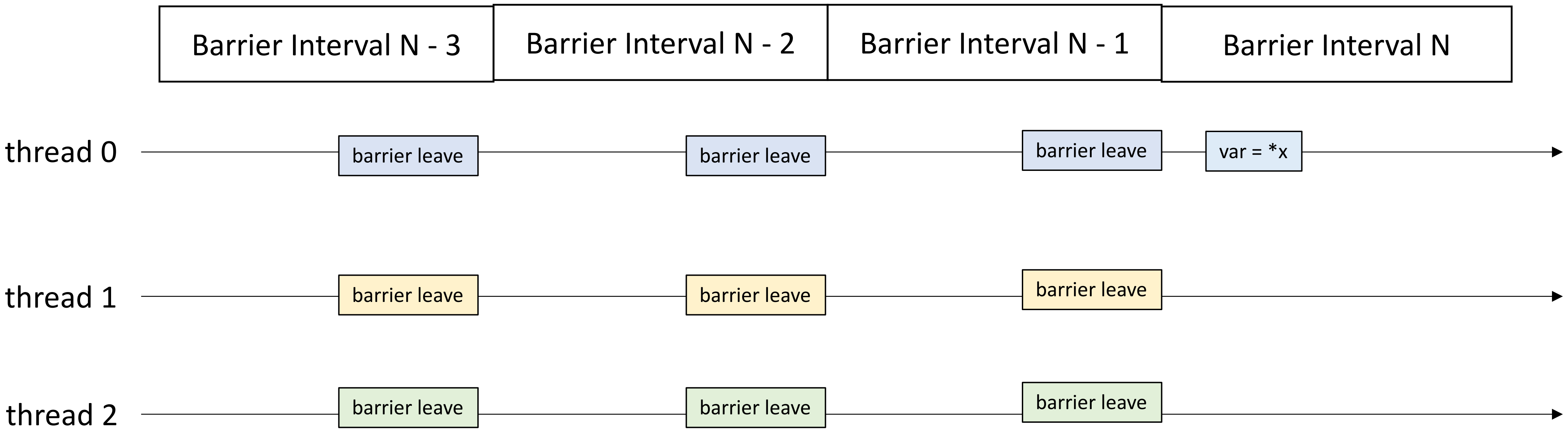
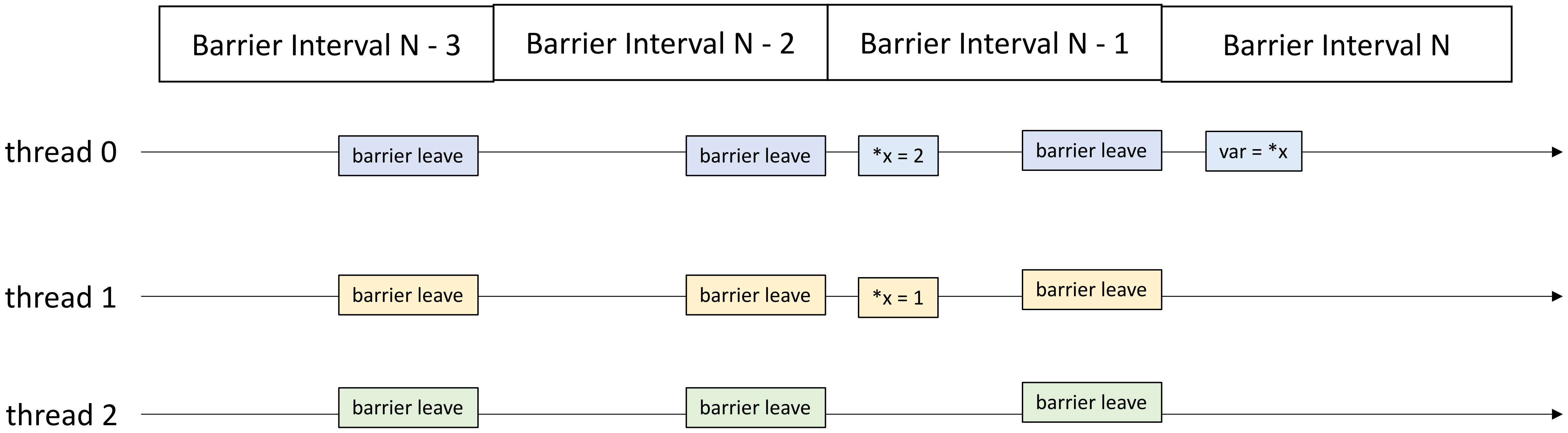


no data conflicts means that x is written to at most once per barrier interval

Assume we are reading from x

We are only allowed to return one possible value

not allowed

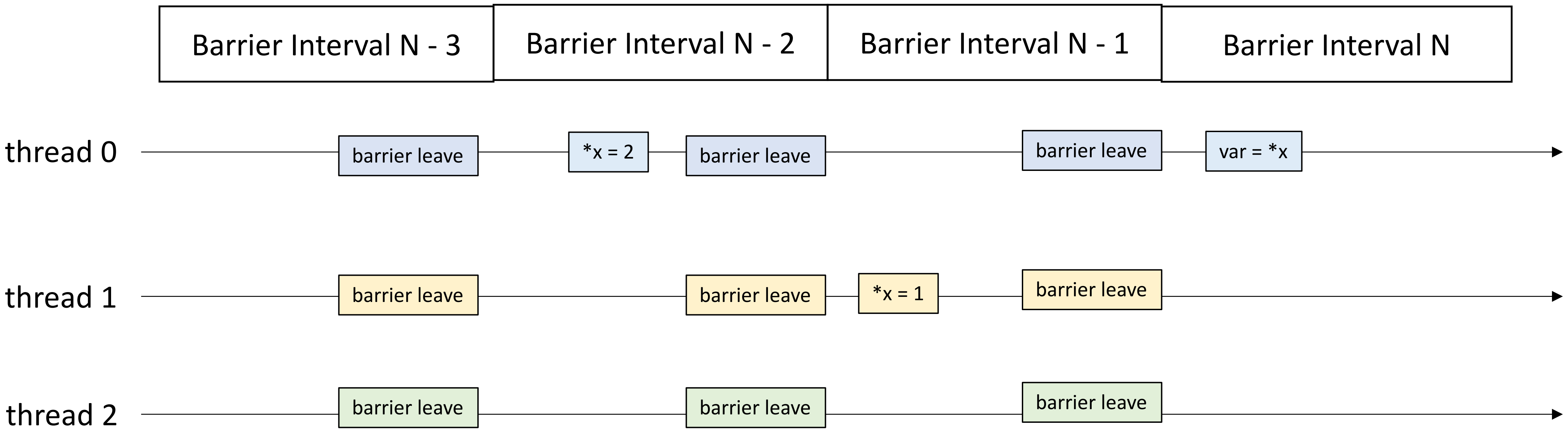


no data conflicts means that x is written to at most once per barrier interval

Assume we are reading from x

We are only allowed to return one possible value

we will read from the write from the most recent barrier interval



Schedule

- **Barriers**
  - Specification
  - **Implementation**

Barrier Implementation

- First attempt at implementation

```
class Barrier {
  private:
    atomic_int counter;
    int num_threads;
  public:
    Barrier(int num_threads) {
      counter = 0;
      this->num_threads = num_threads;
    }

     void barrier() {
        // ??
     }

}
```

Barrier Implementation

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  public:
    Barrier(int num_threads) {
      counter = 0;
      this->num_threads = num_threads;
    }

     void barrier() {
        int arrival_num = atomic_fetch_add(&counter, 1);
        // What next?
     }

}
```

Barrier Implementation

First handle the case where the thread is the last thread to arrive

```
class Barrier {
  private:
    atomic_int counter;
    int num_threads;
  public:
    Barrier(int num_threads) {
      counter = 0;
      this->num_threads = num_threads;
    }

     void barrier() {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads - 1) {
           counter.store(0);
        }
        // What next?
     }

}
```

Barrier Implementation

Spin while there is a thread waiting at the barrier

```
class Barrier {
  private:
    atomic_int counter;
    int num_threads;
  public:
    Barrier(int num_threads) {
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    }

     void barrier() {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads - 1) {
           counter.store(0);
        }
        else {
          while (counter.load() != 0);
        }
      }

}
```

Barrier Implementation

Spin while there
is a thread waiting
at the barrier

Does this work?

```
class Barrier {
  private:
    atomic_int counter;
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        }
        else {
          while (counter.load() != 0);
        }
     }

}
```

Thread 0:

```
B.barrier();
B.barrier();
```

```
void barrier() {
       int arrival_num = atomic_fetch_add(&counter, 1);
       if (arrival_num == num_threads) {
          counter.store(0);
       }
       else {
         while (counter.load() != 0);
       }
    }
```

Thread 1:

```
B.barrier();
B.barrier();
```

thread 0

thread 1

num_threads == 2

Thread 0:

```
B.barrier();
B.barrier();
```

```
void barrier() {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads - 1) {
          counter.store(0);
        }
        else {
          while (counter.load() != 0);
        }
      }
```

Thread 1:

```
B.barrier();
B.barrier();
```

arrival_num = 1

arrival_num = 0

thread 0

thread 1

```
num_threads == 2
counter == 2
```

Thread 0:

```
B.barrier();
B.barrier();
```

```
void barrier() {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads - 1) {
          counter.store(0);
        }
        else {
          while (counter.load() != 0);
        }
     }
```

Thread 1:

```
B.barrier();
B.barrier();
```

arrival_num = 1

arrival_num = 0

thread 0

thread 1

```
num_threads == 2
counter == 0
```

Thread 0:

```
B.barrier();
B.barrier();
```

```
void barrier() {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads - 1) {
           counter.store(0);
        }
        else {
          while (counter.load() != 0);
        }
     }
```

Thread 1:

```
B.barrier();
B.barrier();
```

arrival_num = 1

arrival_num = 0

thread 0

thread 1

```
num_threads == 2
counter == 0
```

Thread 0:

```
B.barrier();
B.barrier();
```

```
void barrier() {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads - 1) {
           counter.store(0);
        }
        else {
          while (counter.load() != 0);
        }
    }
```

Thread 1:

```
B.barrier();
B.barrier();
```

Leaves barrier

arrival_num = 0

in a perfect world,
thread 1 executes now and leaves the barrier

thread 0

thread 1

```
num_threads == 2
counter == 0
```

Thread 0:

```
B.barrier();
B.barrier();
```

```
void barrier() {
      int arrival_num = atomic_fetch_add(&counter, 1);
      if (arrival_num == num_threads - 1) {
         counter.store(0);
      }
      else {
        while (counter.load() != 0);
      }
   }
```

Thread 1:

```
B.barrier();
B.barrier();
```

Leaves barrier

arrival_num = 0

in a perfect world,
thread 1 executes now and leaves the barrier

but what if the OS preempted thread 1? Or it was asleep?

```
num_threads == 2
counter == 0
```

__Thread 0:__

```
B.barrier();
B.barrier();
```

```
void barrier() {
    int arrival_num = atomic_fetch_add(&counter, 1);
    if (arrival_num == num_threads - 1) {
      counter.store(0);
    }
    else {
     while (counter.load() != 0);
    }
}
```

__Thread 1:__

```
B.barrier();
B.barrier();
```

enters next barrier

arrival_num = 0

in a perfect world,
thread 1 executes now and leaves the barrier

but what if the OS preempted thread 1? Or it was asleep?

```
num_threads == 2
counter == 1
```

Thread 0:

```
B.barrier();
B.barrier();
```

```
void barrier() {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads - 1) {
           counter.store(0);
        }
        else {
          while (counter.load() != 0);
        }
    }
```

Thread 1:

```
B.barrier();
B.barrier();
```

arrival_num == 0

arrival_num = 0

in a perfect world,
thread 1 executes now and leaves the barrier

but what if the OS preempted thread 1? Or it was asleep?

```
num_threads == 2
counter == 1
```

Thread 0:

```
B.barrier();
B.barrier();
```

```
void barrier() {
      int arrival_num = atomic_fetch_add(&counter, 1);
      if (arrival_num == num_threads - 1) {
         counter.store(0);
      }
      else {
        while (counter.load() != 0);
      }
   }
```

Thread 1:

```
B.barrier();
B.barrier();
```

Thread 1 wakes up! Doesn't think its missed anything

arrival_num == 0

arrival_num = 0

in a perfect world,
thread 1 executes now and leaves the barrier

```
num_threads == 2
counter == 1
```

Thread 0:

```
B.barrier();
B.barrier();
```

```
void barrier() {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads - 1) {
            counter.store(0);
        }
        else {
          while (counter.load()  != 0);
        }
    }
```

Thread 1:

```
B.barrier();
B.barrier();
```

Thread 1 wakes up! Doesn't think its missed anything

arrival_num == 0

arrival_num = 0

in a perfect world,
thread 1 executes now and leaves the barrier

Both threads get stuck here!

Thread 0:

```
B.barrier();
B.barrier();
```

```
void barrier() {
      int arrival_num = atomic_fetch_add(&counter, 1);
      if (arrival_num == num_threads - 1) {
         counter.store(0);
      }
      else {
        while (counter.load() != 0);
      }
    }
```

Thread 1:

```
B.barrier();
B.barrier();
```

Ideas for fixing?

Thread 0:

```
B.barrier();
B.barrier();
```

```
void barrier() {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads - 1) {
           counter.store(0);
        }
        else {
          while (counter.load() != 0);
        }
    }
```

Thread 1:

```
B.barrier();
B.barrier();
```

Ideas for fixing?

Two different barriers that alternate?

Thread 0:

```
B0.barrier();
B1.barrier();
```

```
void barrier() {
      int arrival_num = atomic_fetch_add(&counter, 1);
      if (arrival_num == num_threads - 1) {
         counter.store(0);
      }
      else {
        while (counter.load() != 0);
      }
   }
```

Thread 1:

```
B0.barrier();
B1.barrier();
```

Ideas for fixing?

Two different barriers that alternate?

Pros: simple to implement

Cons: user has to alternate barriers

Thread 0:

```
B0.barrier();
B1.barrier();
```

```
void barrier() {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads - 1) {
           counter.store(0);
        }
        else {
          while (counter.load() != 0);
        }
     }
```

Thread 1:

```
B0.barrier();
B1.barrier();
```

Ideas for fixing?

Two different barriers that alternate?

Pros: simple to implement

Cons: user has to alternate barriers

```
B.barrier();
if (...) {
  B.barrier();
}
B.barrier();
```

How to alternate these calls?

Sense Reversing Barrier

- Alternating ”sense” dynamically

Thread 0:

```
B.barrier();
B.barrier();
```

sync on sense = false

Thread 1:

```
B.barrier();
B.barrier();
```

Sense Reversing Barrier

- Alternating ”sense” dynamically

<u>Thread 0:</u>

```
B.barrier();
B.barrier();
```

sync on sense = true

<u>Thread 1:</u>

```
B.barrier();
B.barrier();
```

```
class SenseBarrier {
  private:
    atomic_int counter;
    int num_threads;
    atomic_bool sense;
    bool thread_sense[num_threads];
  public:
    Barrier(int num_threads) {
      counter = 0;
      this->num_threads = num_threads;
      sense = false;
      thread_sense = {true, ...};
    }

     void barrier(int tid) {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads) {
           counter.store(0);
           sense = thread_sense[tid];
        }
        else {
          while (sense != thread_sense[tid]);
        }
        thread_sense[tid] = !thread_sense[tid];
     }
}
```

thread_sense = true

```
num_threads == 2
counter == 0
sense = false
```

thread_sense = true

Thread 0:

```
B.barrier();
B.barrier();
```

```
void barrier(int tid) {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads-1) {
           counter.store(0);
           sense = thread_sense[tid];
        }
        else {
          while (sense != thread_sense[tid]);
        }
        thread_sense[tid] = !thread_sense[tid];
     }
```

Thread 1:

```
B.barrier();
B.barrier();
```

thread_sense = true

arrival_num = 1

Thread 0:

```
B.barrier();
B.barrier();
```

```
num_threads == 2
counter == 2
sense = false
```

```
void barrier(int tid) {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads-1) {
            counter.store(0);
            sense = thread_sense[tid];
        }
        else {
          while (sense != thread_sense[tid]);
        }
        thread_sense[tid] = !thread_sense[tid];
    }
```

thread_sense = true

arrival_num = 0

Thread 1:

```
B.barrier();
B.barrier();
```

```
num_threads == 2
counter == 2
sense = false
```

thread_sense = true

arrival_num = 1

Thread 0:

```
B.barrier();
B.barrier();
```

```
void barrier(int tid) {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads-1) {
            counter.store(0);
            sense = thread_sense[tid];
        }
        else {
          while (sense != thread_sense[tid]);
        }
        thread_sense[tid] = !thread_sense[tid];
    }
```

thread_sense = true

arrival_num = 0

Thread 1:

```
B.barrier();
B.barrier();
```

thread_sense = false

arrival_num = 1

Thread 0:

`B.barrier();`

`B.barrier();`

```
num_threads == 2
counter == 0
sense = true
```

```
void barrier(int tid) {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads-1) {
           counter.store(0);
           sense = thread_sense[tid];
        }
        else {
          while (sense != thread_sense[tid]);
        }
        thread_sense[tid] = !thread_sense[tid];
     }
```

thread_sense = true

arrival_num = 0

Thread 1:

`B.barrier();`

`B.barrier();`

```
num_threads == 2
counter == 0
sense = true
```

thread_sense = false

arrival_num = ?

Thread 0:

```
B.barrier();
B.barrier();
```

```
void barrier(int tid) {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads-1) {
           counter.store(0);
           sense = thread_sense[tid];
        }
        else {
          while (sense != thread_sense[tid]);
        }
        thread_sense[tid] = !thread_sense[tid];
     }
```

thread_sense = true

arrival_num = 0

Thread 1:

```
B.barrier();
B.barrier();
```

Remember the issue! Thread 1 went to sleep around this time and thread 0 went into the barrier again!

thread_sense = false

arrival_num = 0

Thread 0:

```
B.barrier();
B.barrier();
```

```
num_threads == 2
counter == 1
sense = true
```

```
void barrier(int tid) {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads-1) {
           counter.store(0);
           sense = thread_sense[tid];
        }
        else {
          while (sense != thread_sense[tid]);
        }
        thread_sense[tid] = !thread_sense[tid];
     }
```

thread_sense = true

arrival_num = 0

Thread 1:

```
B.barrier();
B.barrier();
```

```
num_threads == 2
counter == 1
sense = true
```

thread_sense = false

arrival_num = 0

Thread 0:

```
B.barrier();
B.barrier();
```

```
void barrier(int tid) {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads-1) {
           counter.store(0);
           sense = thread_sense[tid];
        }
        else {
          while (sense != thread_sense[tid]);
        }
        thread_sense[tid] = !thread_sense[tid];
     }
```

thread_sense = true

arrival_num = 0

Thread 1:

```
B.barrier();
B.barrier();
```

both are waiting!,
but thread 1 can leave

thread_sense = false

arrival_num = 0

Thread 0:

```
B.barrier();
B.barrier();
```

```
num_threads == 2
counter == 1
sense = true
```

```
void barrier(int tid) {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads-1) {
           counter.store(0);
           sense = thread_sense[tid];
        }
        else {
          while (sense != thread_sense[tid]);
        }
        thread_sense[tid] = !thread_sense[tid];
     }
```

thread_sense = false

arrival_num = 0

Thread 1:

```
B.barrier();
B.barrier();
```

both are waiting!,
but thread 1 can leave

```
num_threads == 2
counter == 1
sense = true
```

thread_sense = false

arrival_num = 0

Thread 0:

```
B.barrier();
B.barrier();
```

```
void barrier(int tid) {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads-1) {
           counter.store(0);
           sense = thread_sense[tid];
        }
        else {
          while (sense != thread_sense[tid]);
        }
        thread_sense[tid] = !thread_sense[tid];
    }
```

thread_sense = false

arrival_num = ?

Thread 1:

```
B.barrier();
B.barrier();
```

Thread 1 finishes the barrier

thread_sense = false

arrival_num = 0

Thread 0:

B.barrier();

B.barrier();

num_threads == 2

counter == 1

sense = true

```
void barrier(int tid) {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads-1) {
           counter.store(0);
           sense = thread_sense[tid];
        }
        else {
          while (sense != thread_sense[tid]);
        }
        thread_sense[tid] = !thread_sense[tid];
     }
```

thread_sense = false

arrival_num = ?

Thread 1:

B.barrier();

B.barrier();

Goes into the second barrier

```
num_threads == 2
counter == 2
sense = true
```

thread_sense = false

arrival_num = 0

Thread 0:

```
B.barrier();
B.barrier();
```

```
void barrier(int tid) {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads-1) {
           counter.store(0);
           sense = thread_sense[tid];
        }
        else {
          while (sense != thread_sense[tid]);
        }
        thread_sense[tid] = !thread_sense[tid];
     }
```

thread_sense = false

arrival_num = 1

Thread 1:

```
B.barrier();
B.barrier();
```

Goes into the second barrier

num_threads == 2
counter == 2
sense = true

thread_sense = false
arrival_num = 0

Thread 0:

B.barrier();
B.barrier();

```
void barrier(int tid) {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads-1) {
            counter.store(0);
            sense = thread_sense[tid];
        }
        else {
          while (sense != thread_sense[tid]);
        }
        thread_sense[tid] = !thread_sense[tid];
    }
```

thread_sense = false
arrival_num = 1

Thread 1:

B.barrier();
B.barrier();

Goes into the second barrier

num_threads == 2
counter == 0
sense = false

thread_sense = false
arrival_num = 0

Thread 0:
```
B.barrier();
B.barrier();
```

```
void barrier(int tid) {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads-1) {
           counter.store(0);
           sense = thread_sense[tid];
        }
        else {
          while (sense != thread_sense[tid]);
        }
        thread_sense[tid] = !thread_sense[tid];
     }
```

thread_sense = false
arrival_num = 1

Thread 1:
```
B.barrier();
B.barrier();
```

Goes into the second barrier

```
num_threads == 2
counter == 0
sense = false
```

thread_sense = false

arrival_num = 0

Thread 0:

```
B.barrier();
B.barrier();
```

```
void barrier(int tid) {
        int arrival_num = atomic_fetch_add(&counter, 1);
        if (arrival_num == num_threads-1) {
            counter.store(0);
            sense = thread_sense[tid];
        }
        else {
          while (sense != thread_sense[tid]);
        }
        thread_sense[tid] = !thread_sense[tid];
    }
```

thread_sense = false

arrival_num = 1

Thread 1:

```
B.barrier();
B.barrier();
```

thread 0 can leave, thread 1 can leave and the barrier works as expected!