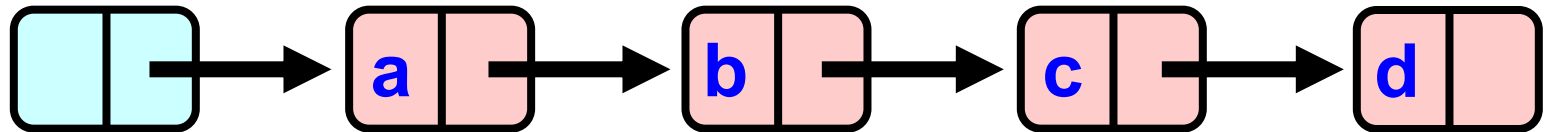
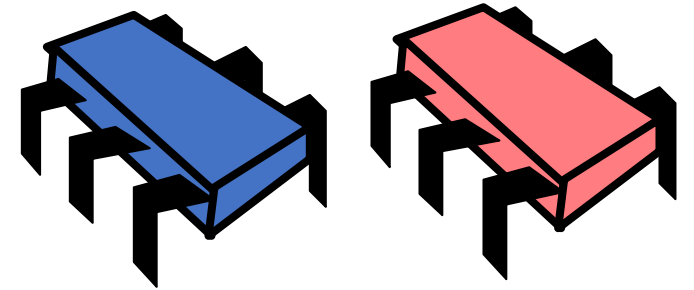


CSE113: Parallel Programming

- **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

Quiz

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

Quiz

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

- ☐ Locks are always acquired in the same order
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Quiz

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

- ☐ True
- ☐ False

Quiz

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

- ☒ 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

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

Quiz

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.

Quiz

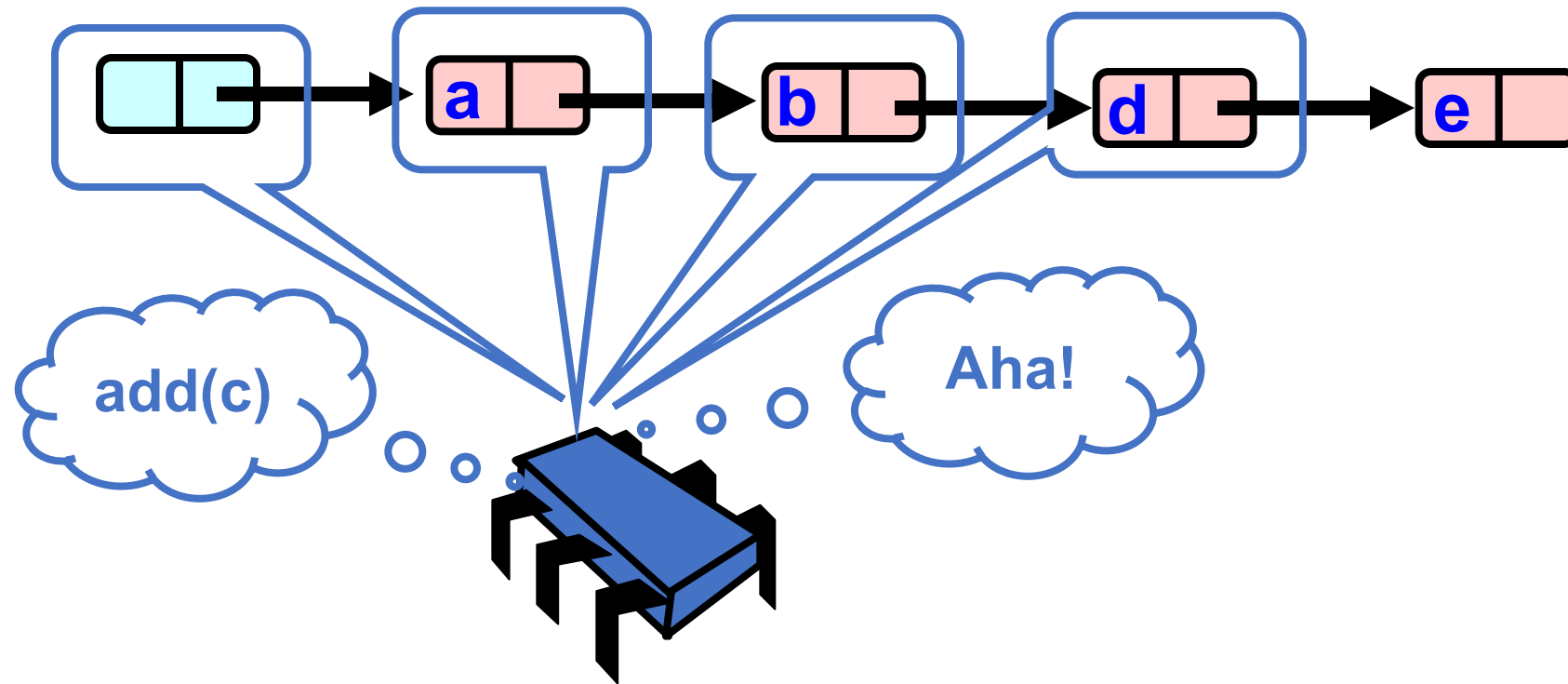
After this lecture, do you think you would be able to optimize your implementation of the concurrent stack in homework 2? Write a few sentences on what you might try.

Coarse-grained vs. Fine-grained locking?

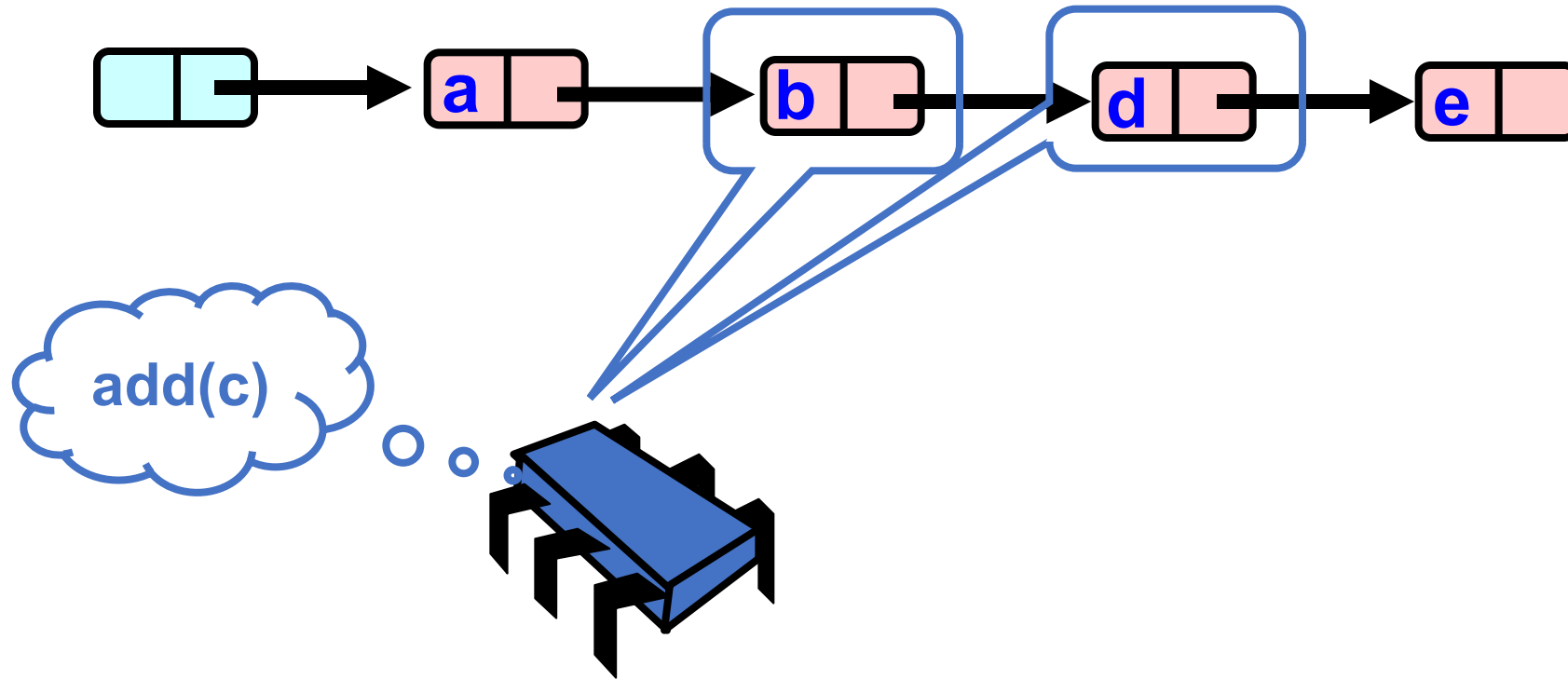
Review

Add and remove: What could go wrong?

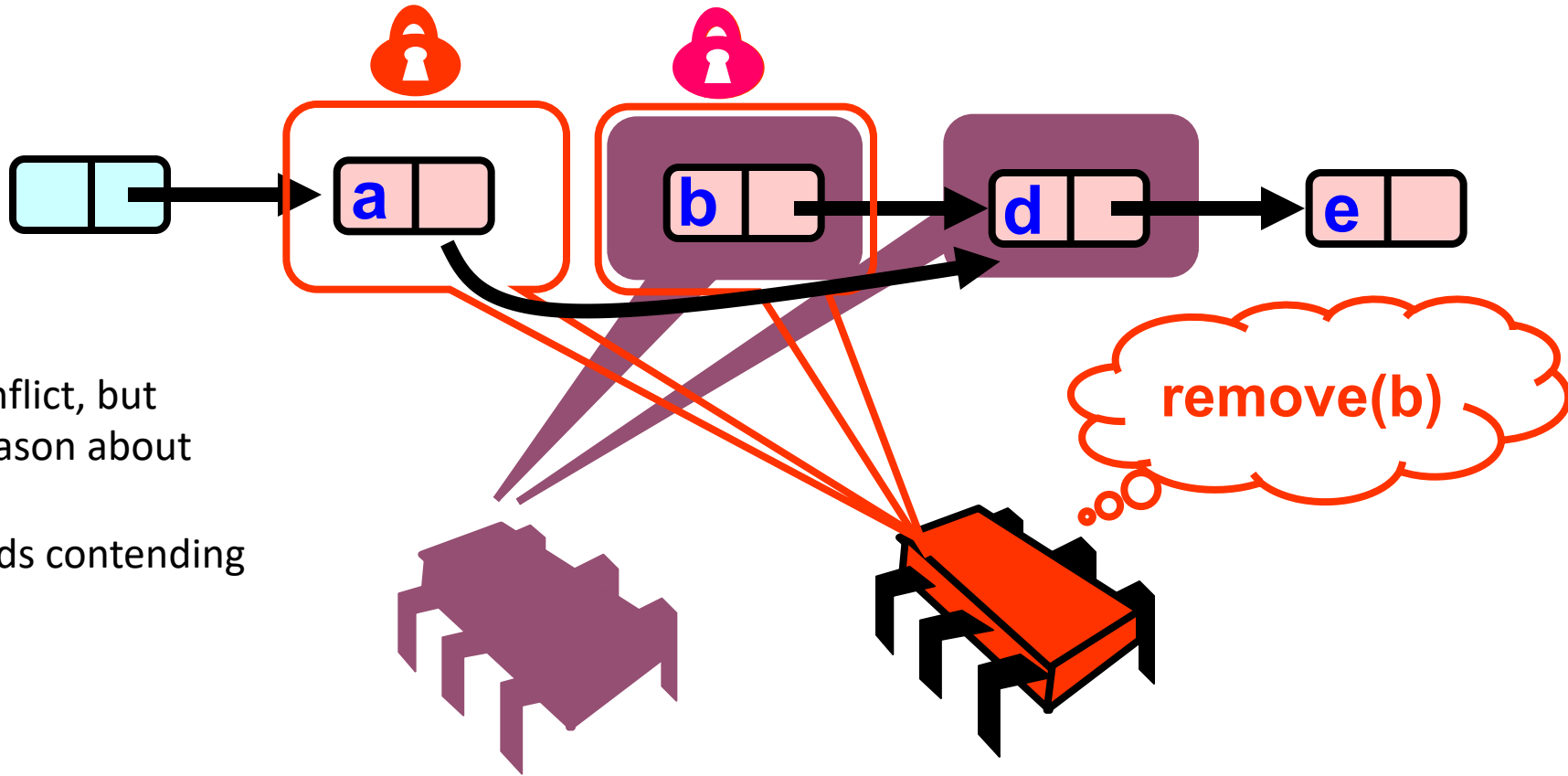
Add and remove: What could go wrong?



What could go wrong?

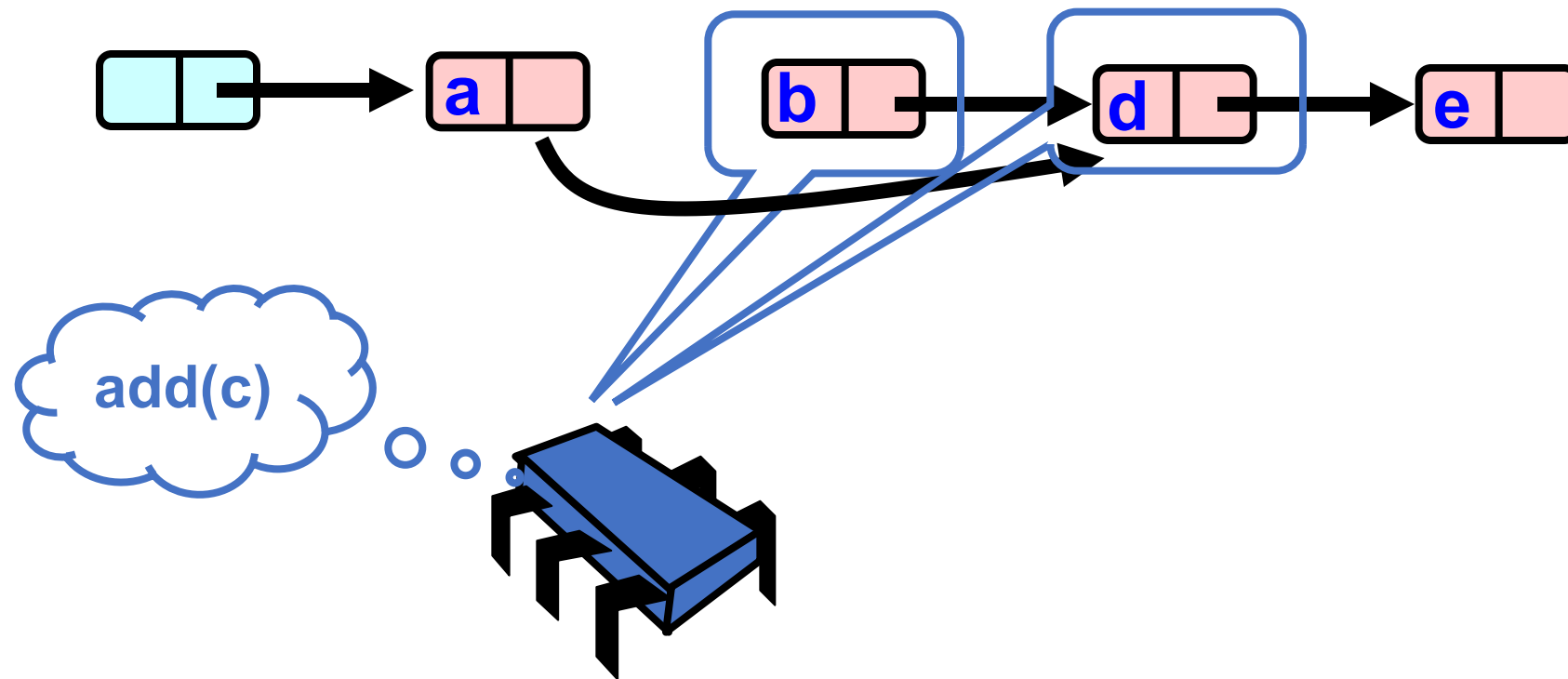


What could go wrong?

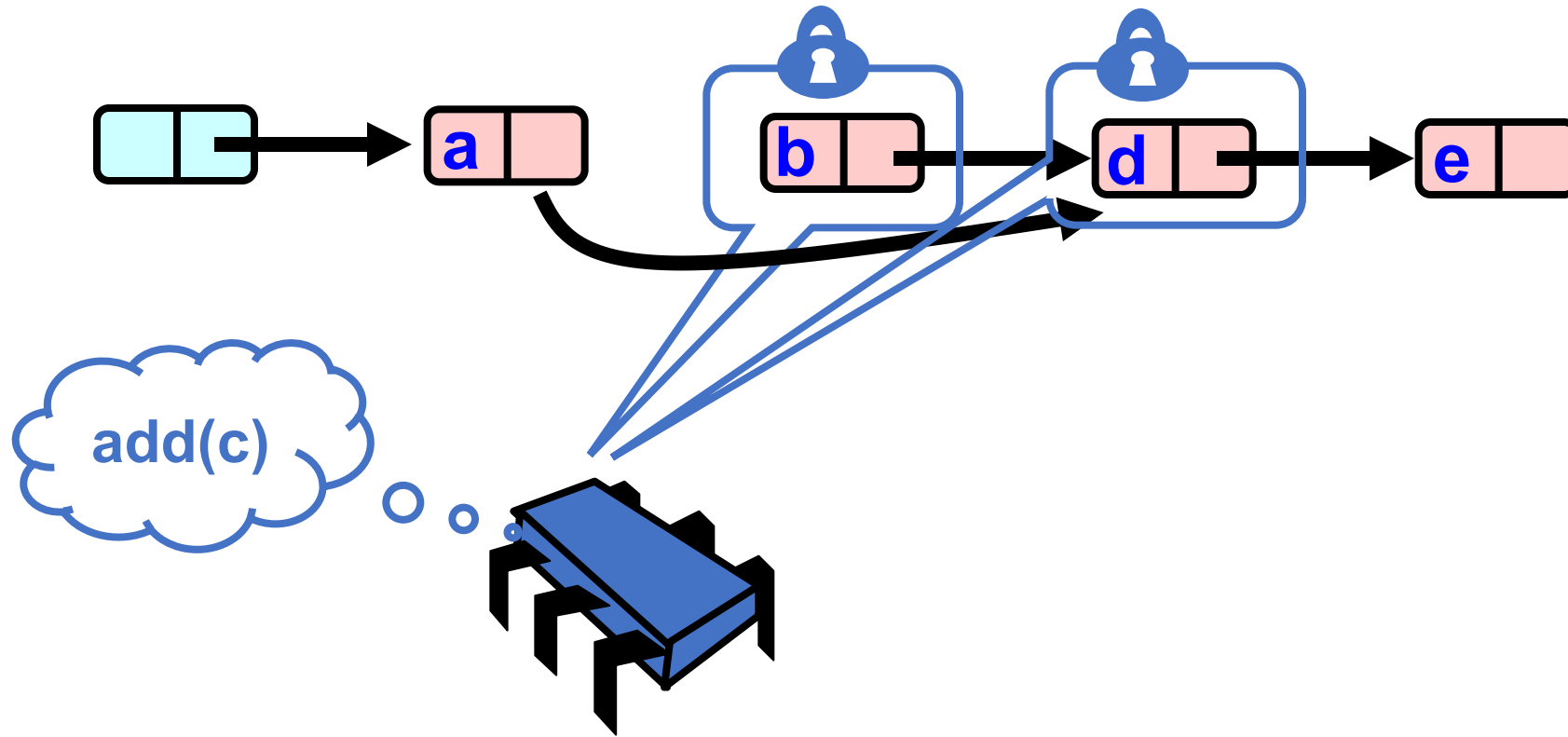


No more data conflict, but
we do need to reason about
interleavings.
Concurrent threads contending
for values.

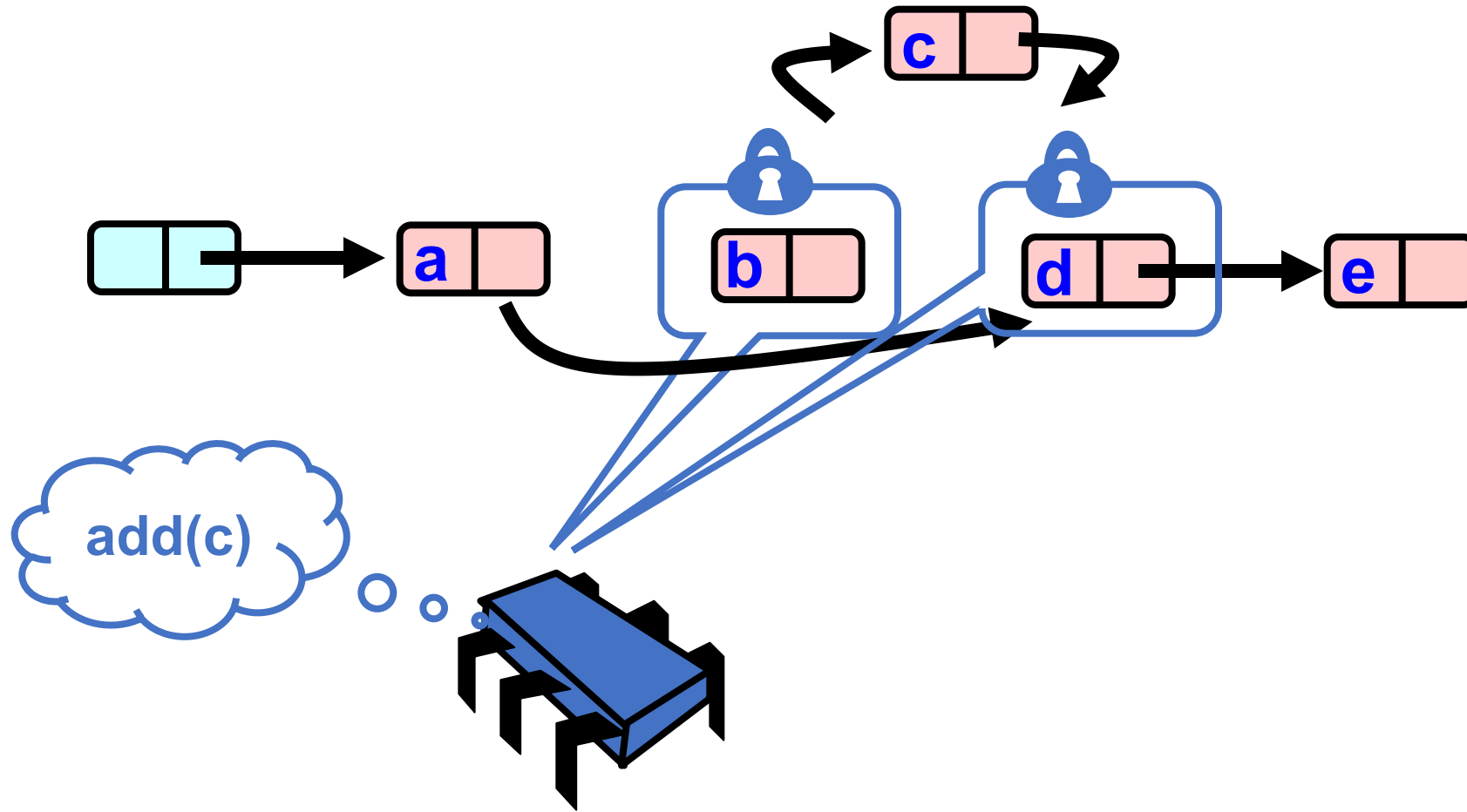
What could go wrong?



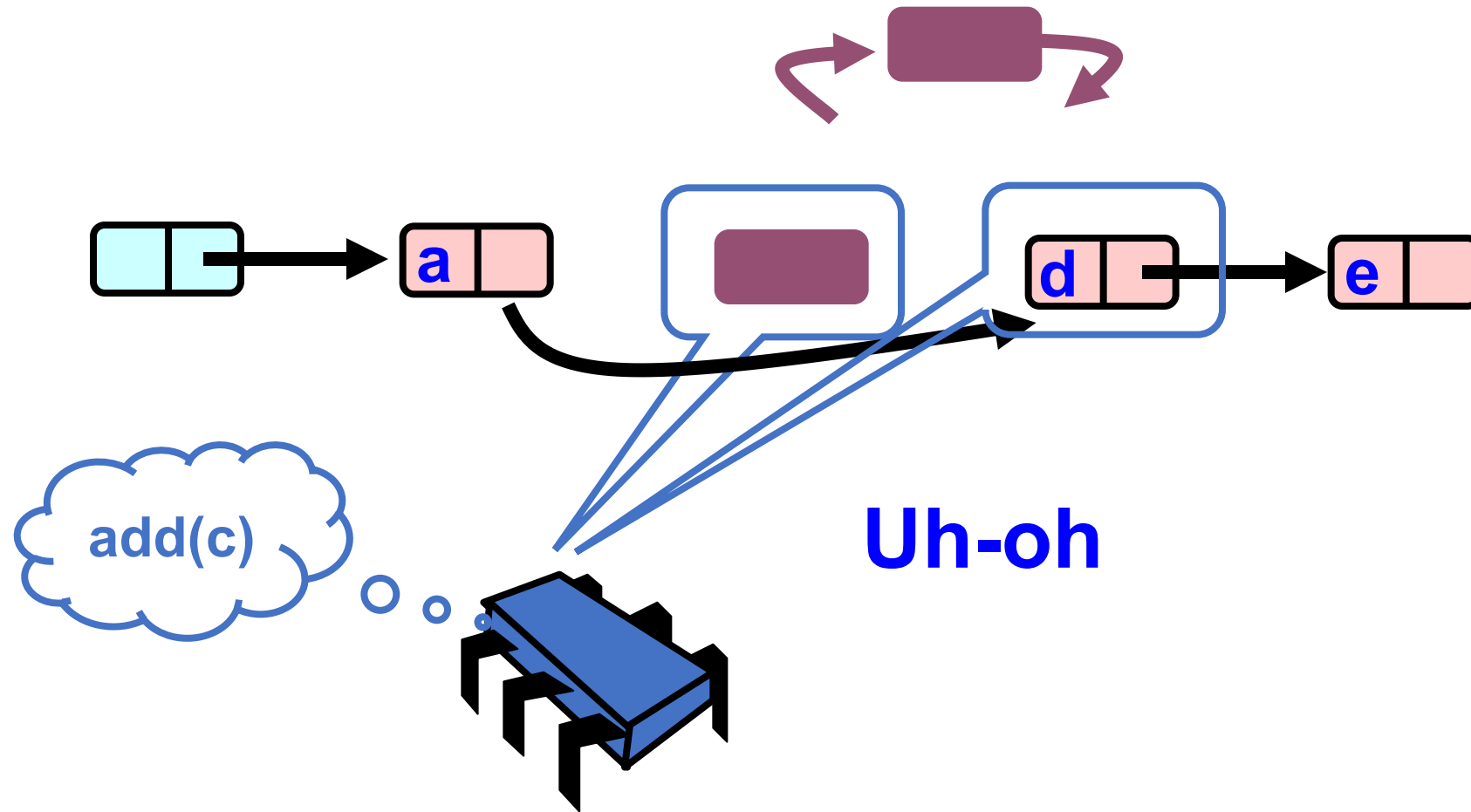
What could go wrong?



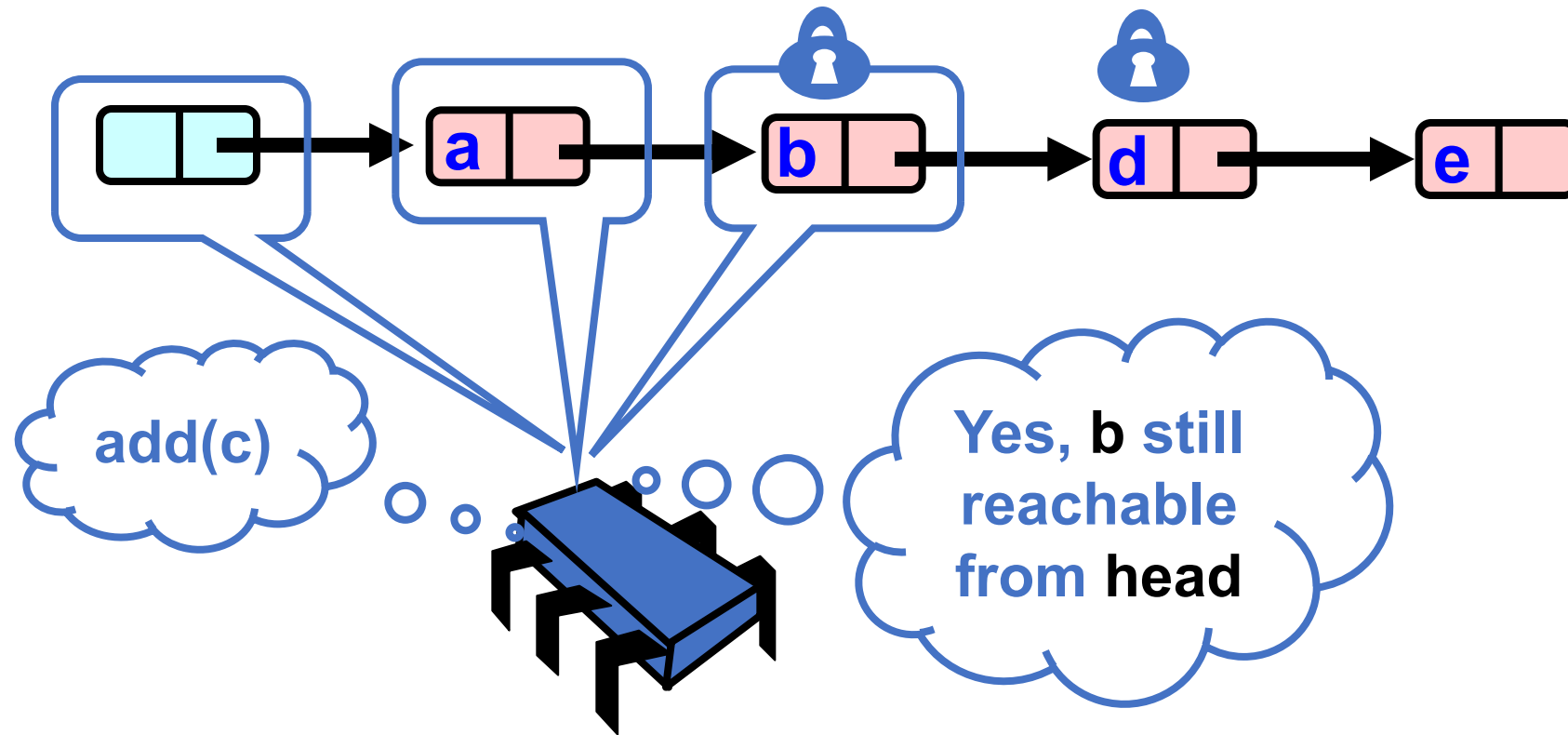
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What could go wrong?

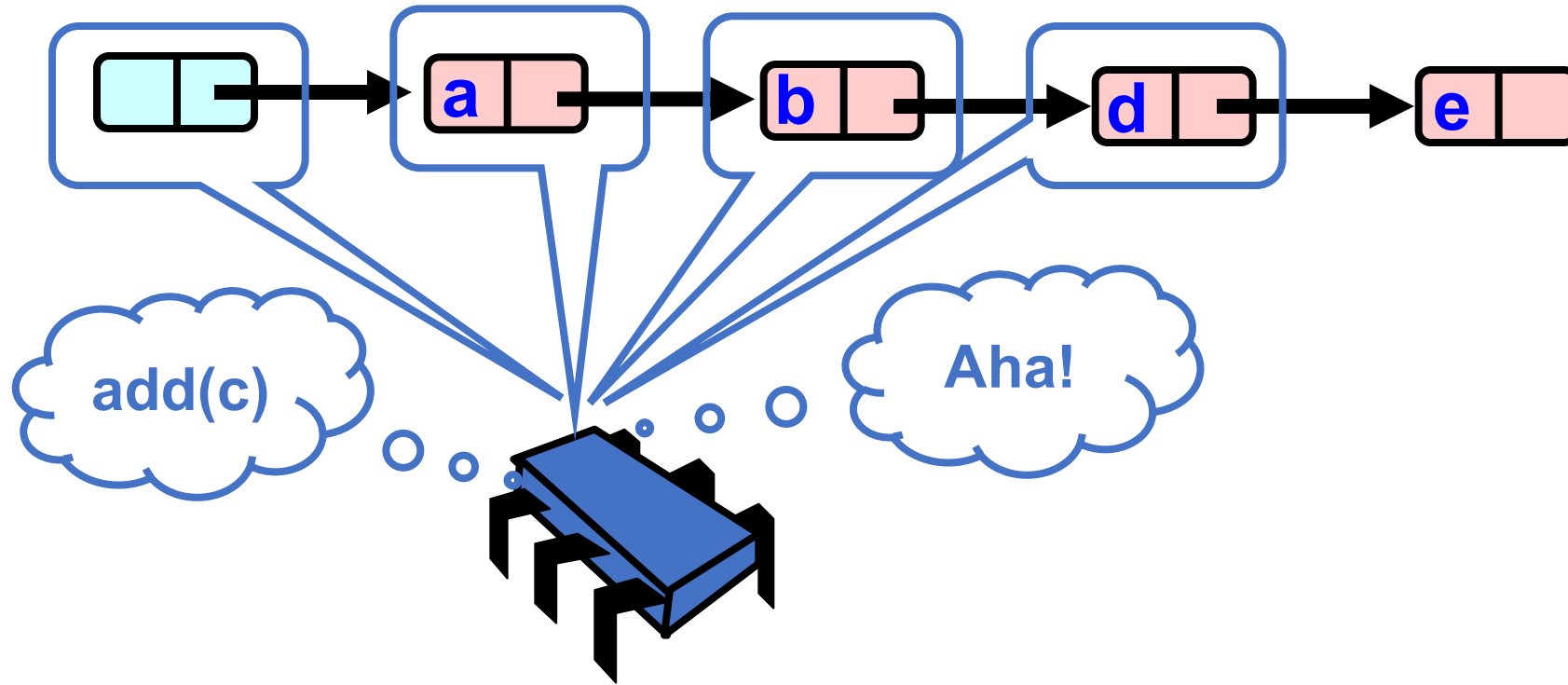


Validate – Part 1

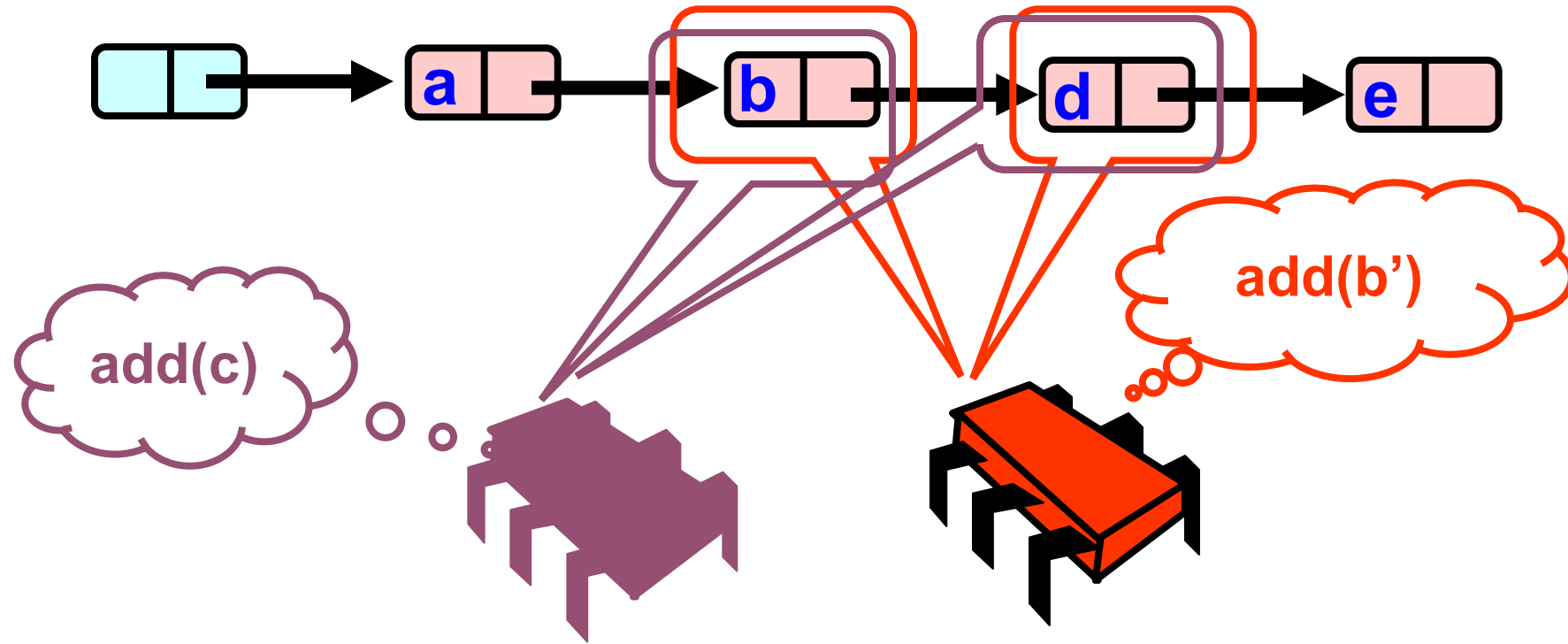


Add and Add: What could go wrong?

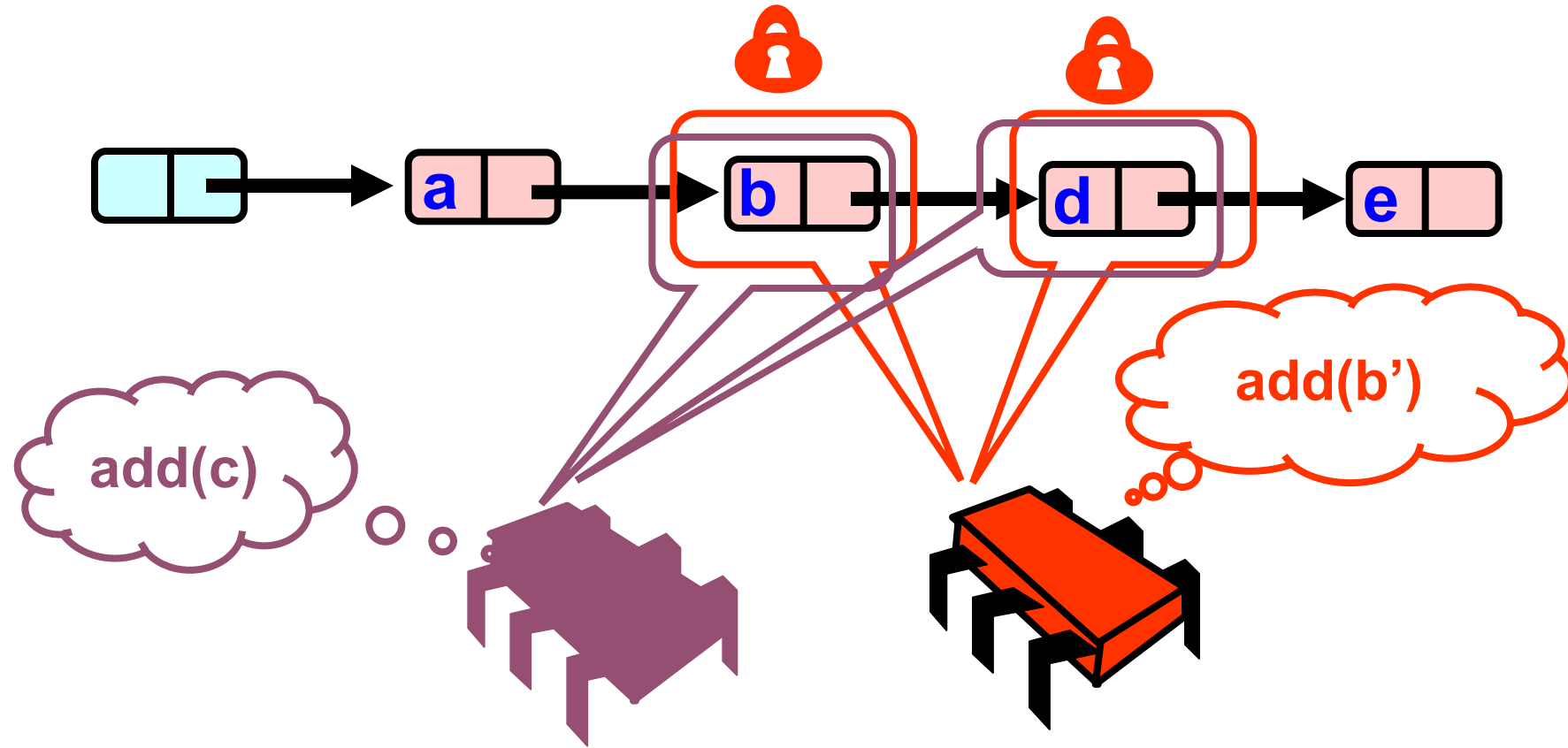
What Else Could Go Wrong?



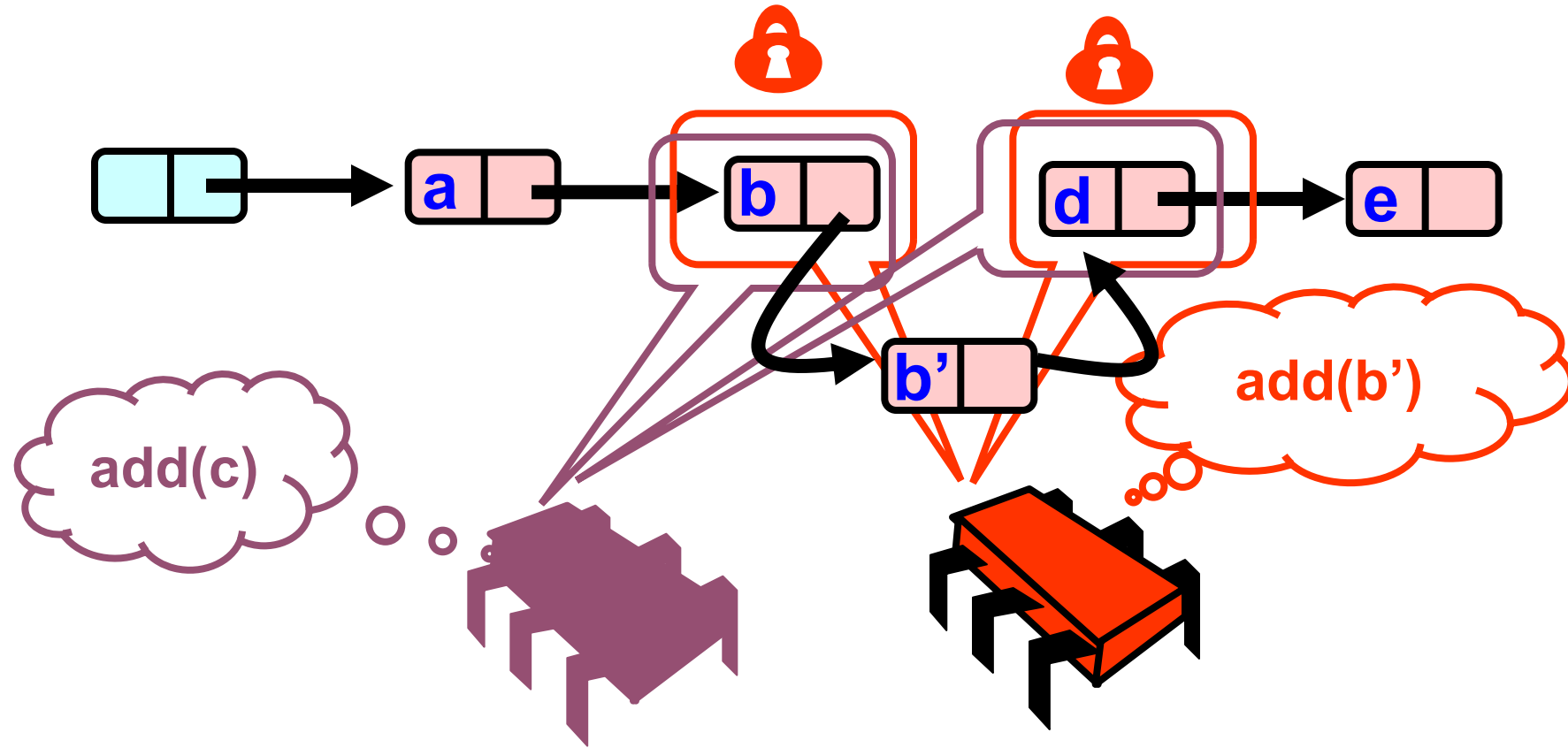
What Else Could Go Wrong?



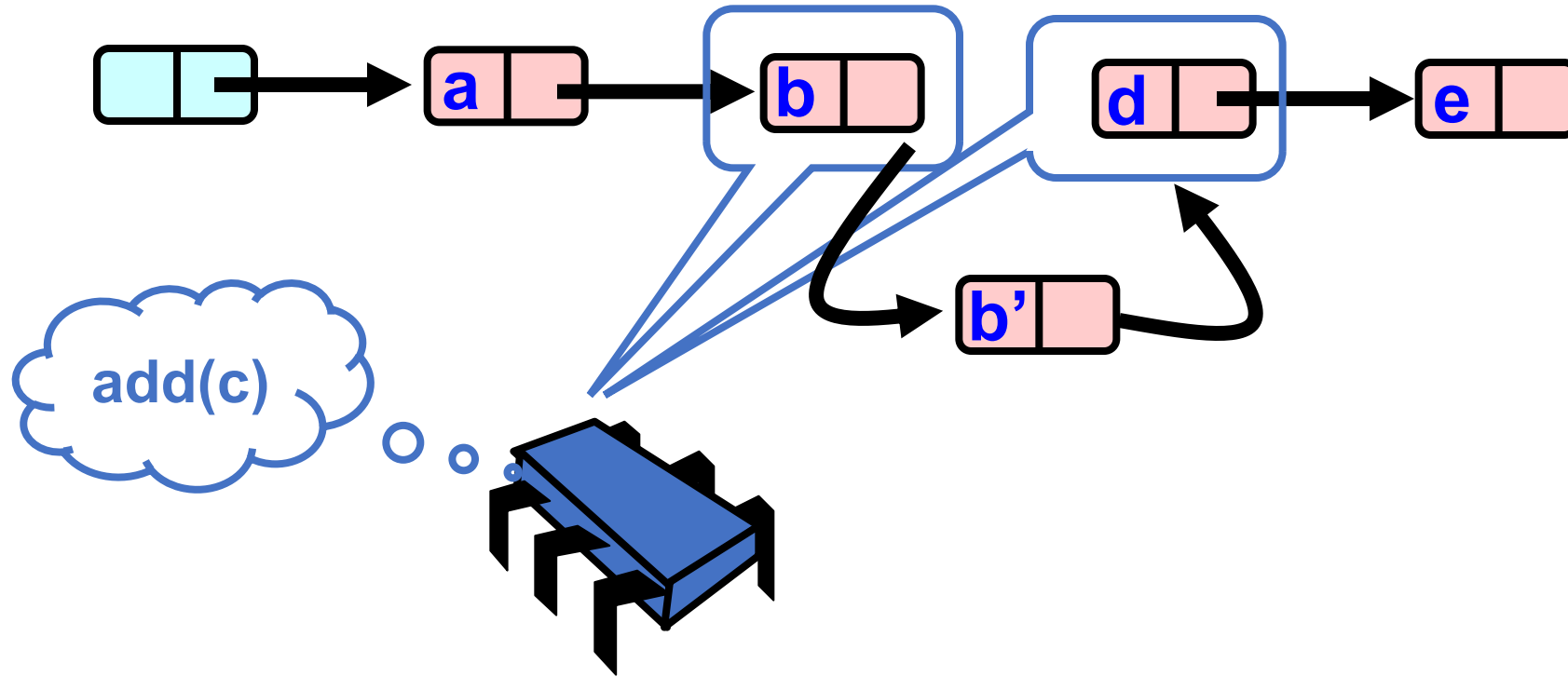
What Else Could Go Wrong?



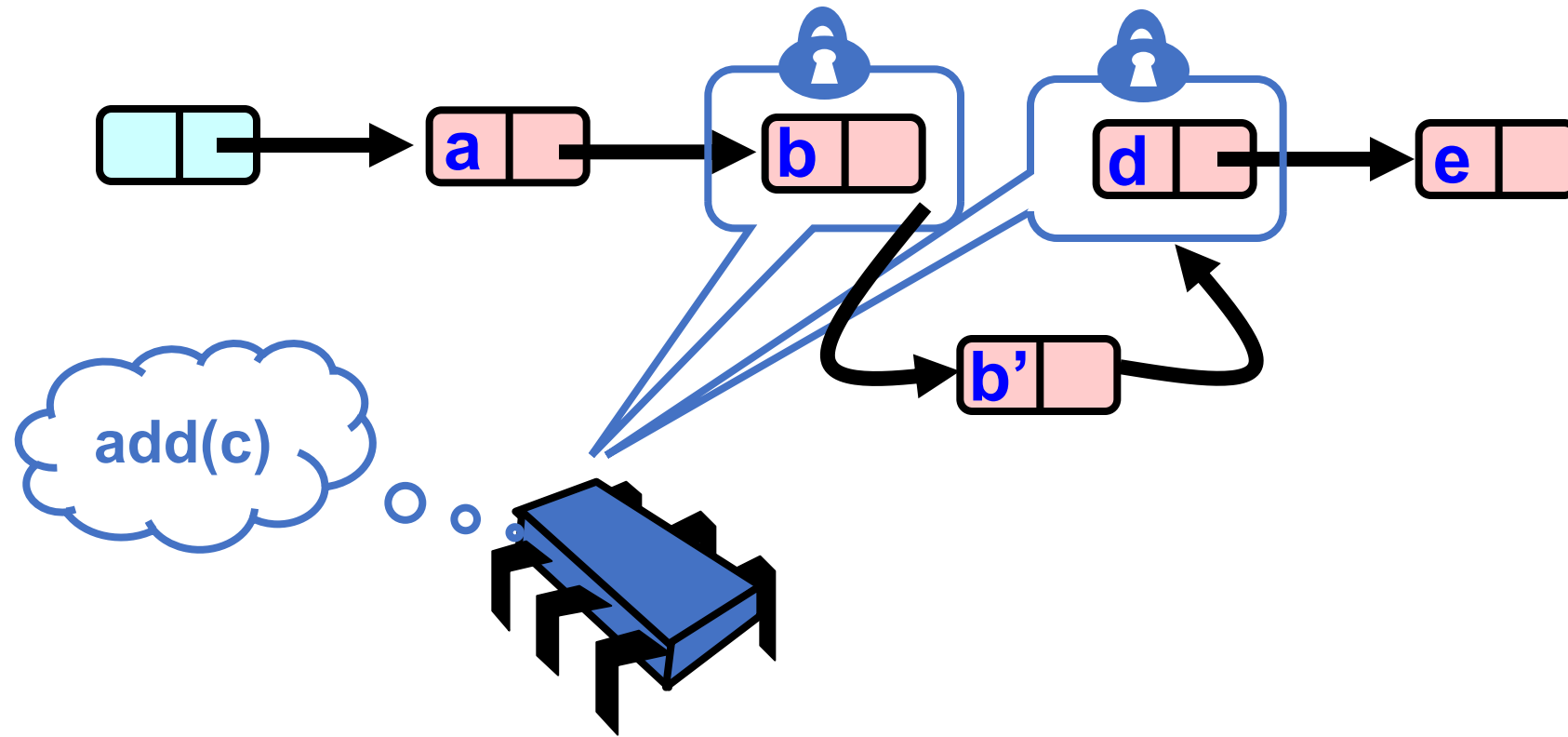
What Else Could Go Wrong?



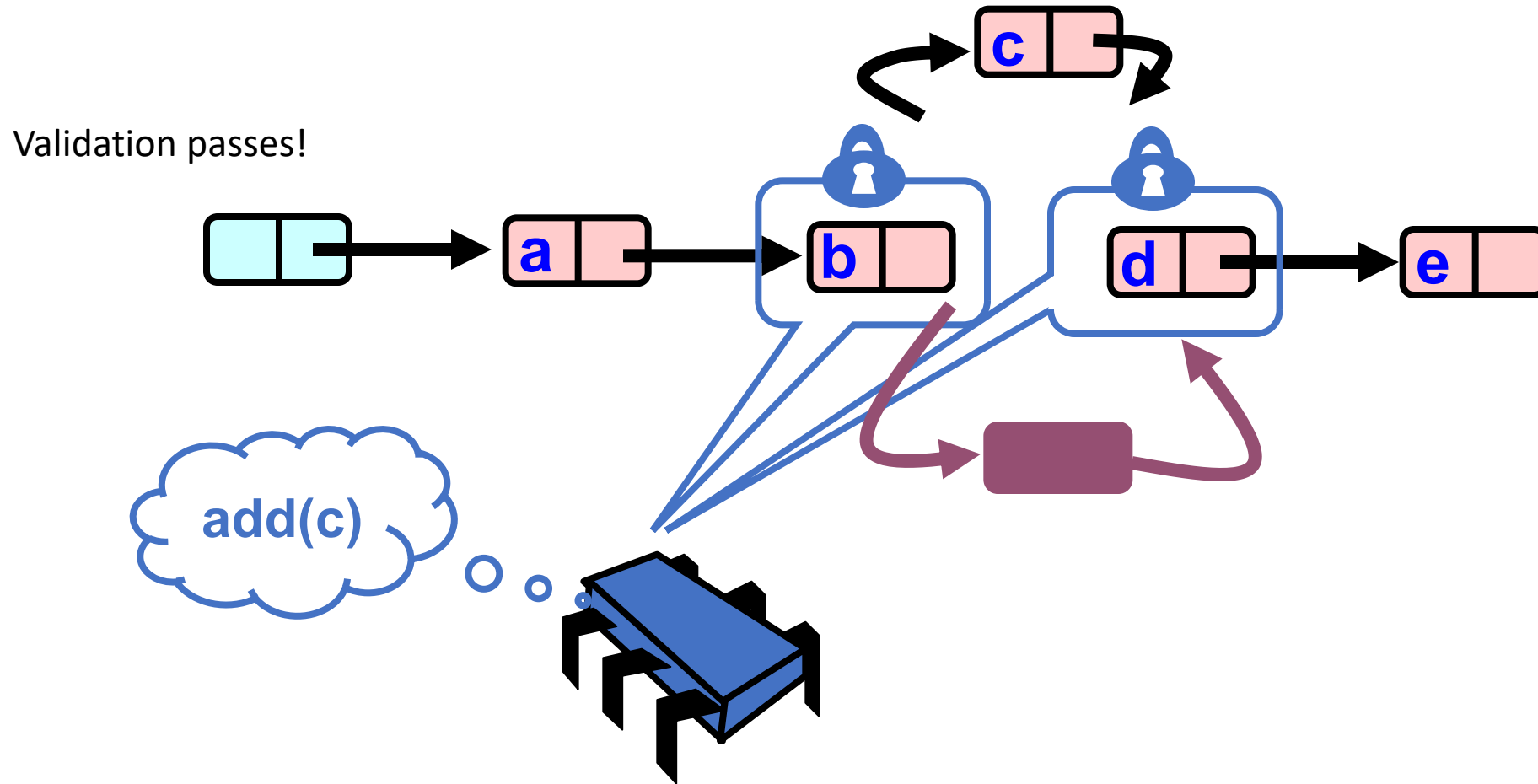
What Else Could Go Wrong?



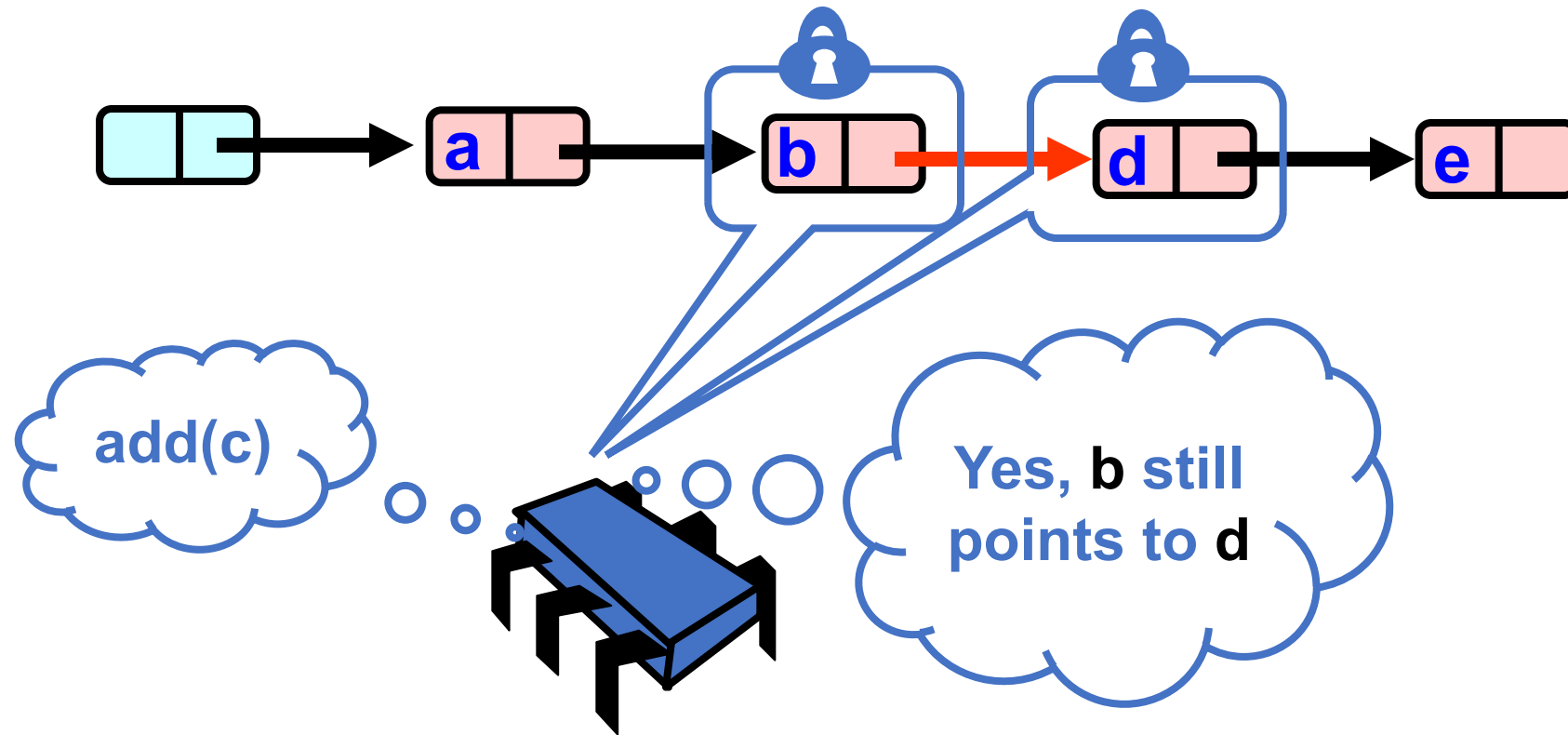
What Else Could Go Wrong?



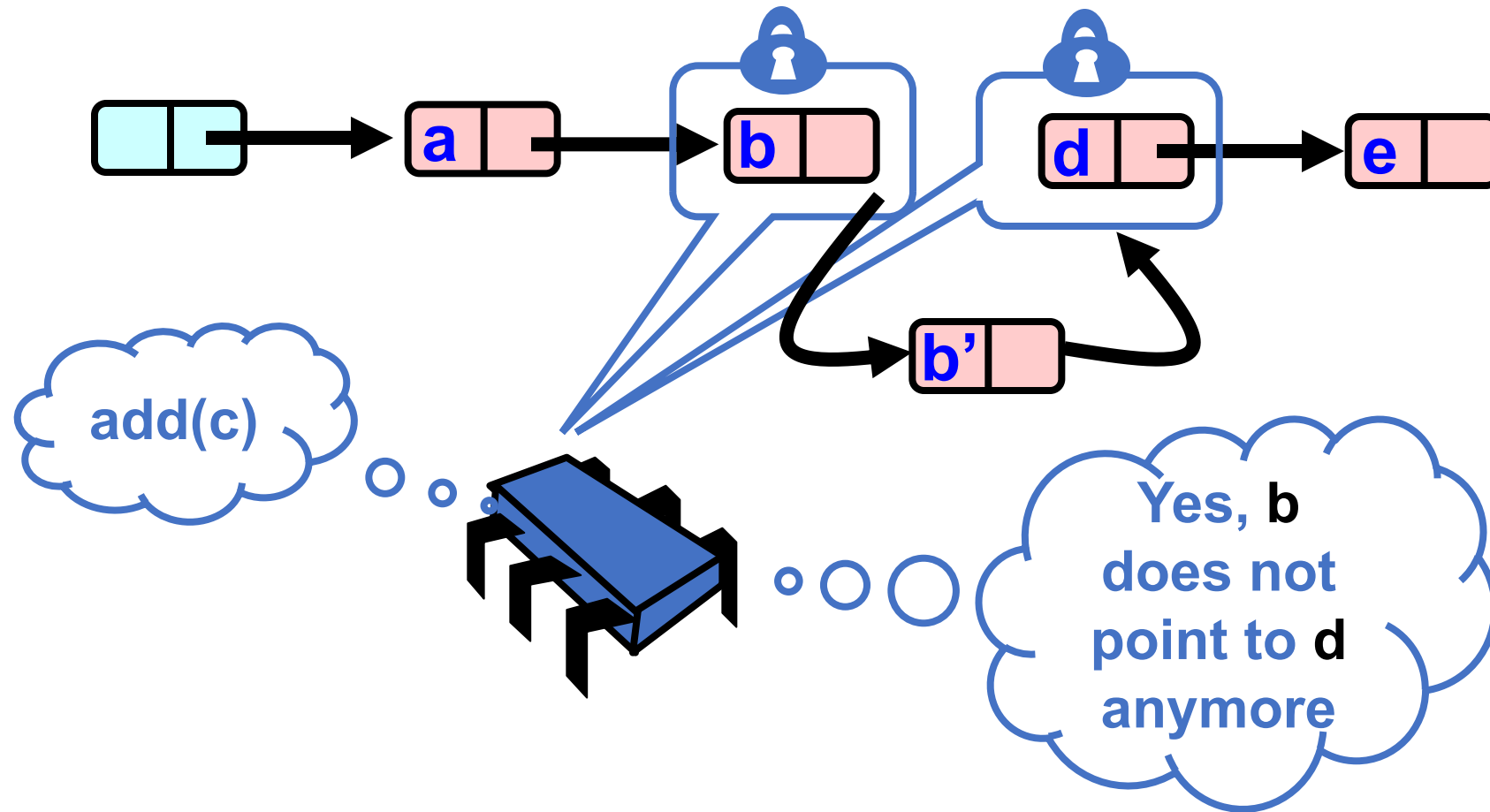
What Else Could Go Wrong?



Validate Part 2 (while holding locks)



What Else Could Go Wrong?



New Material

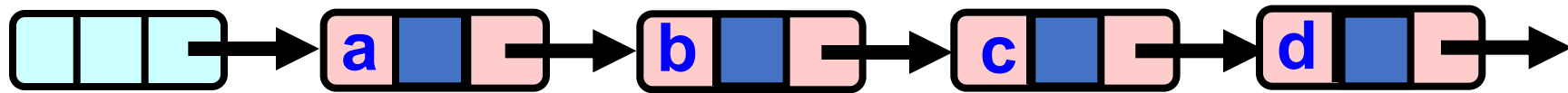
Can we optimize more?

- 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. Now the information that a node is removed is inside the node; we don't need to get it from the predecessor.

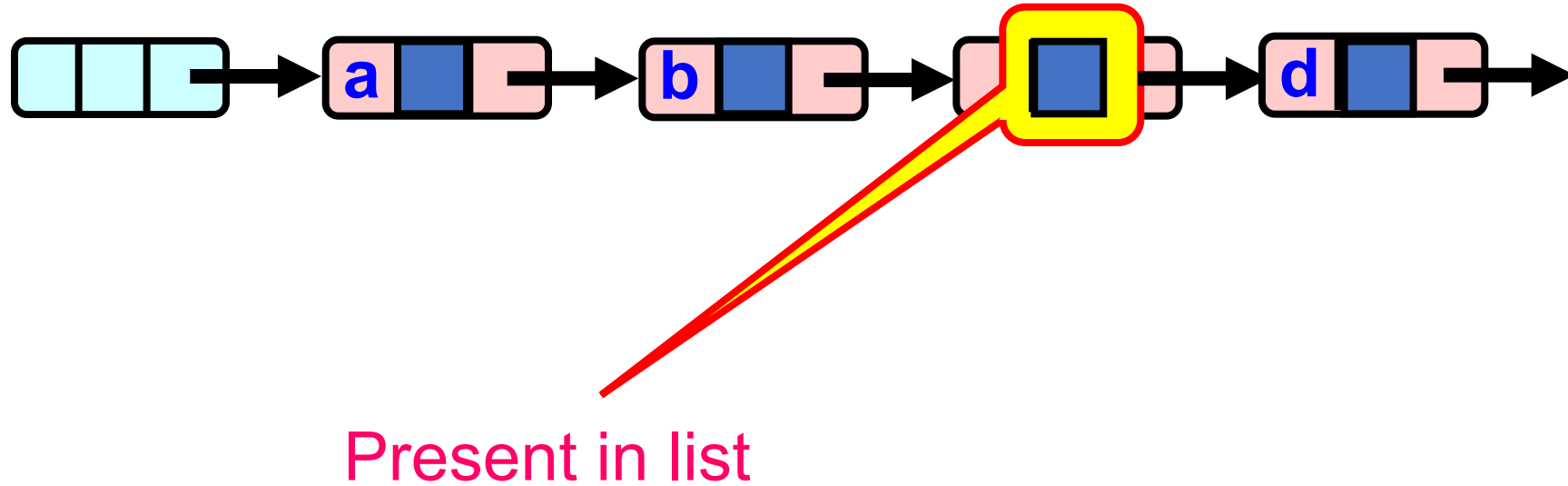
Two step removal List

- **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)

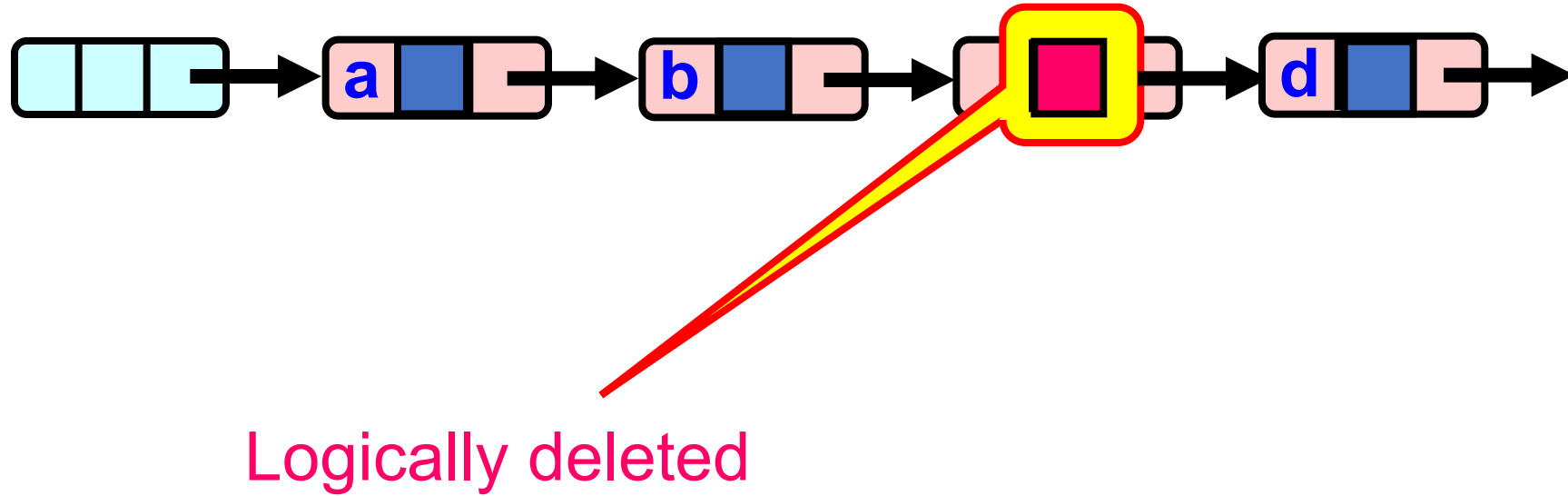
Two step removal Removal



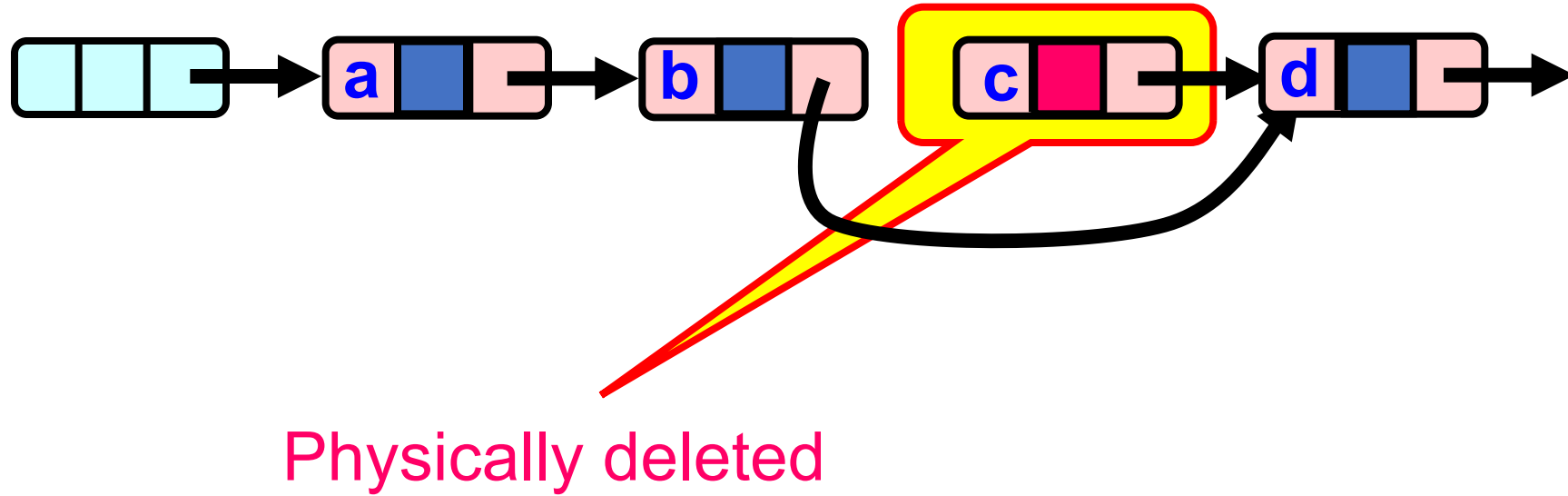
Two step removal Removal



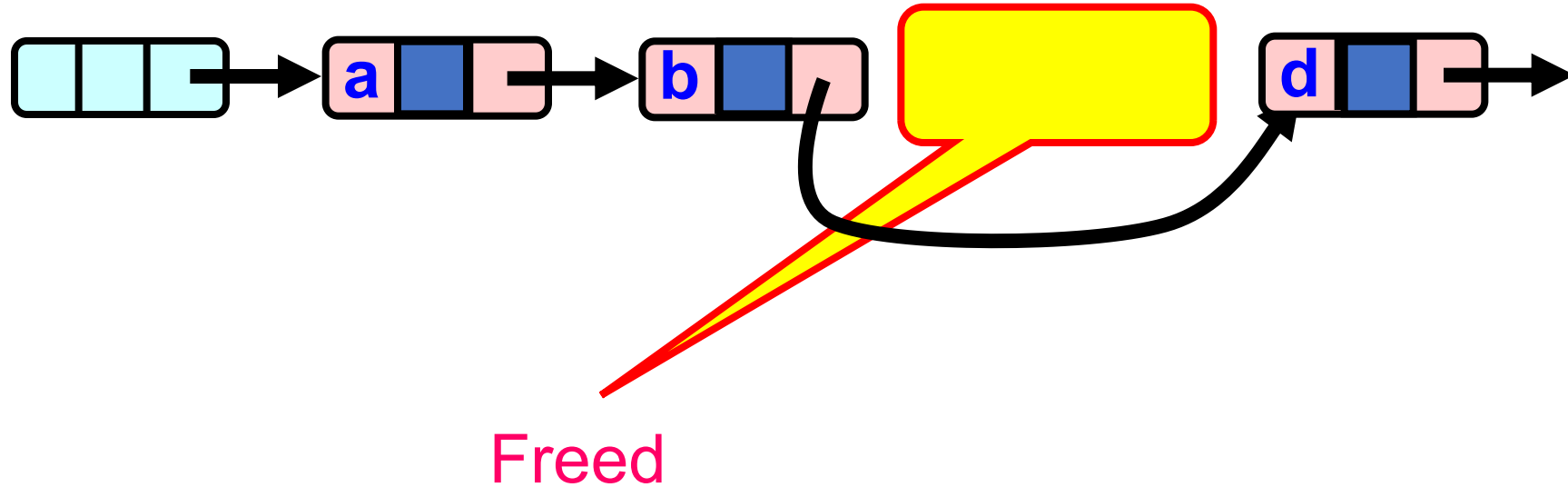
Two step removal Removal



Two step removal Removal



Two step removal Removal



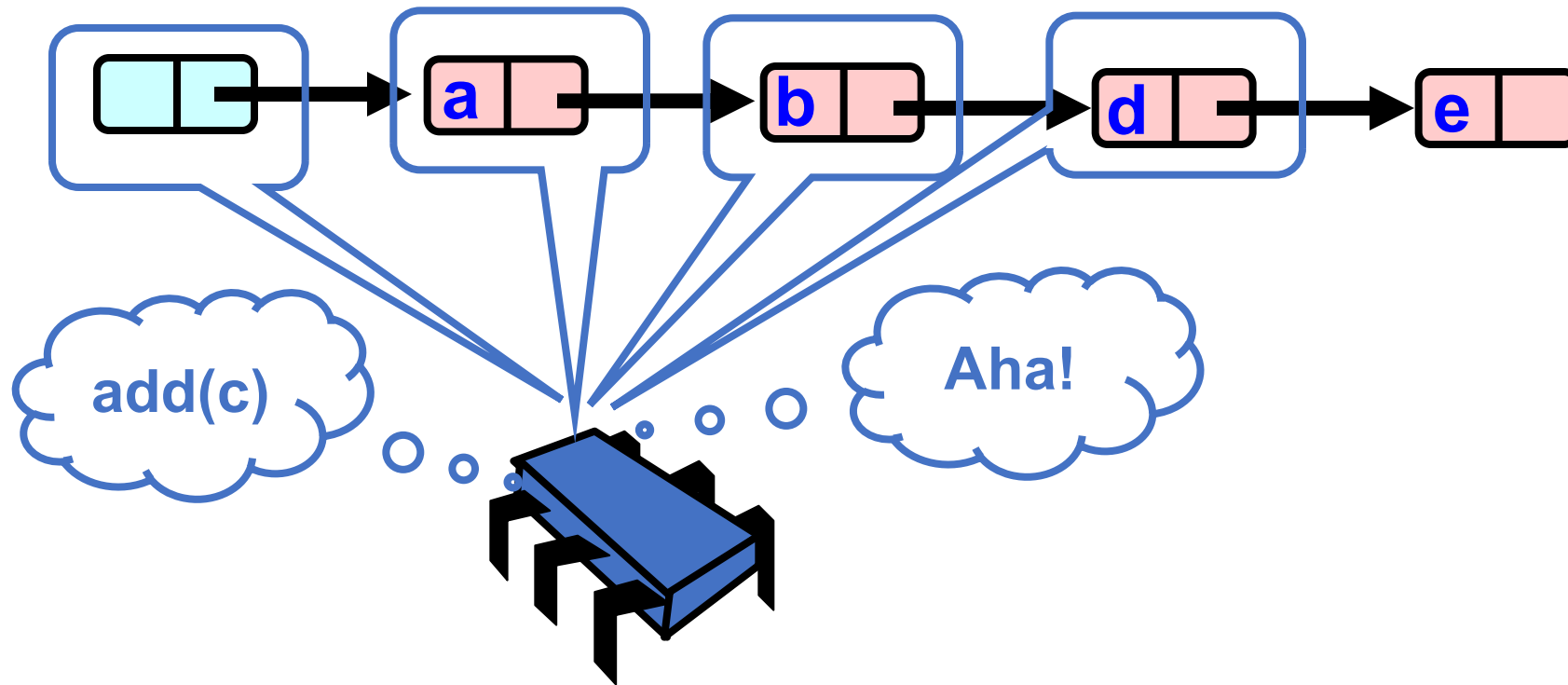
Two step remove list

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

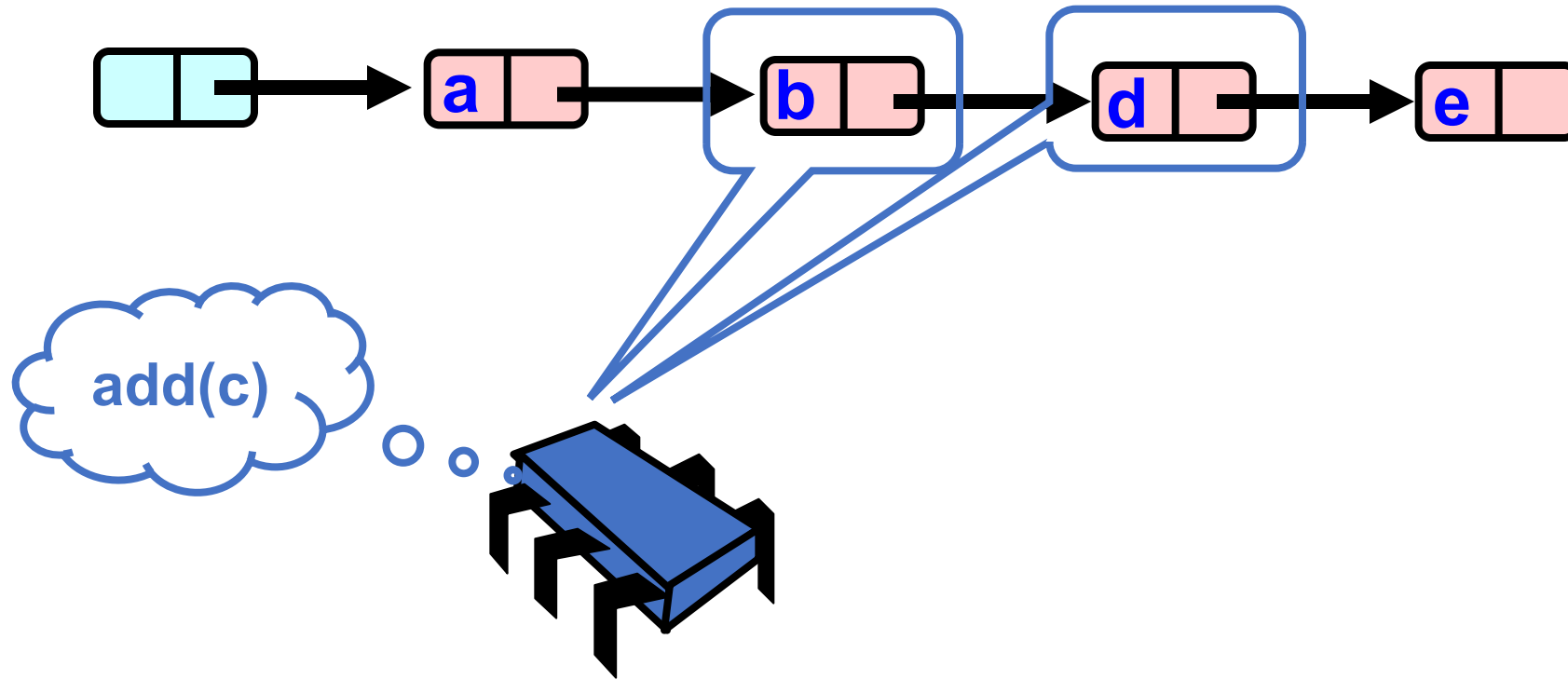
Validation

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

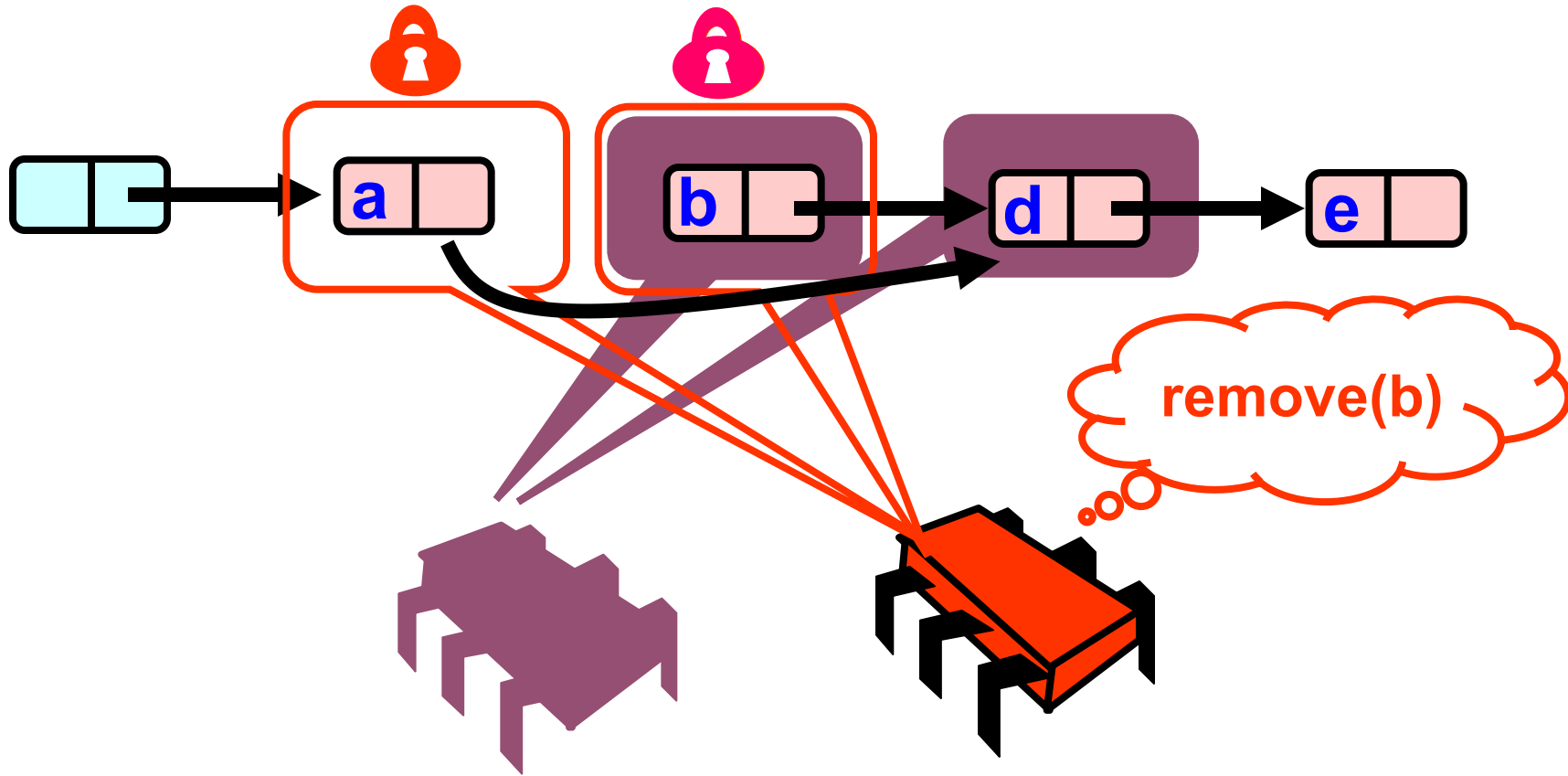
What could go wrong?



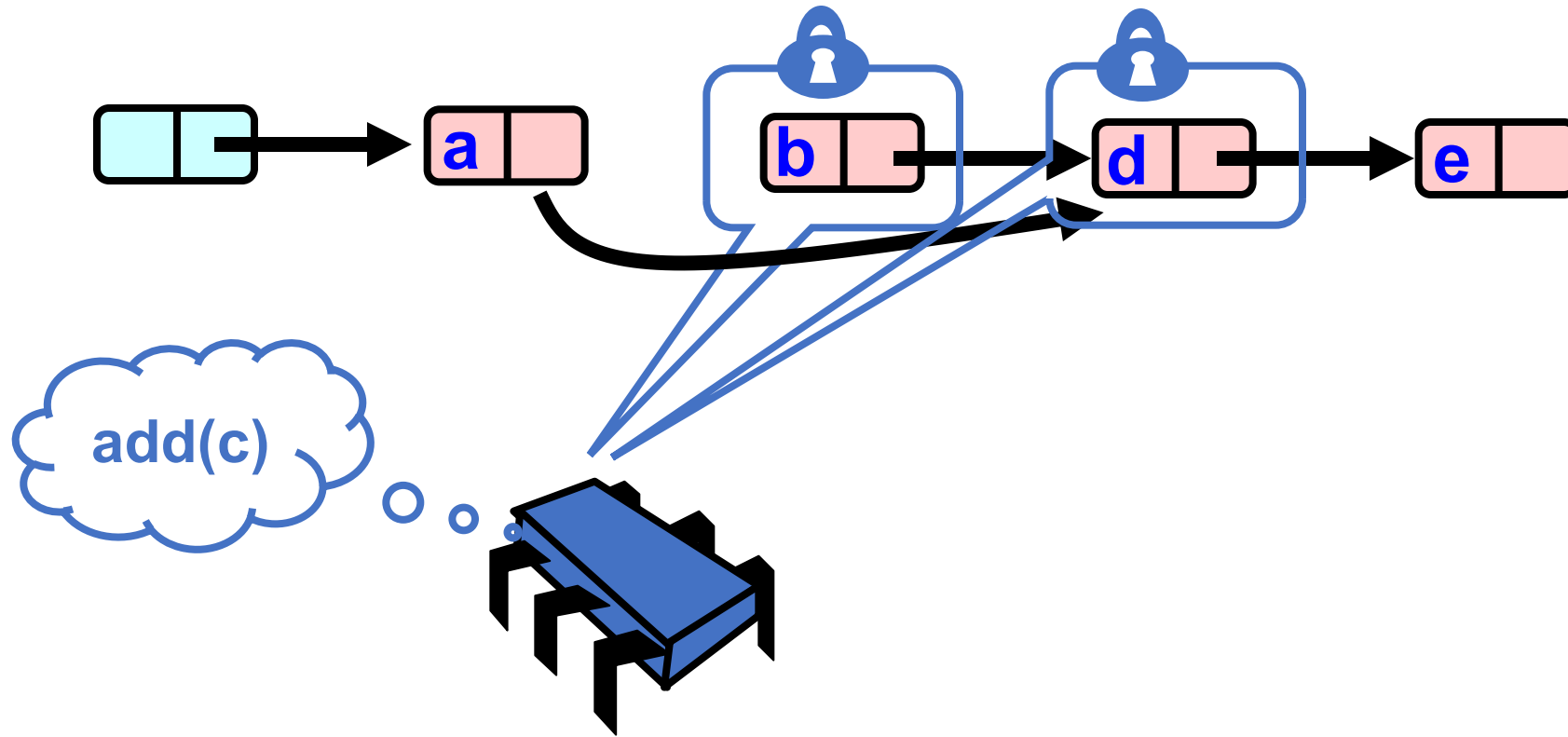
What could go wrong?



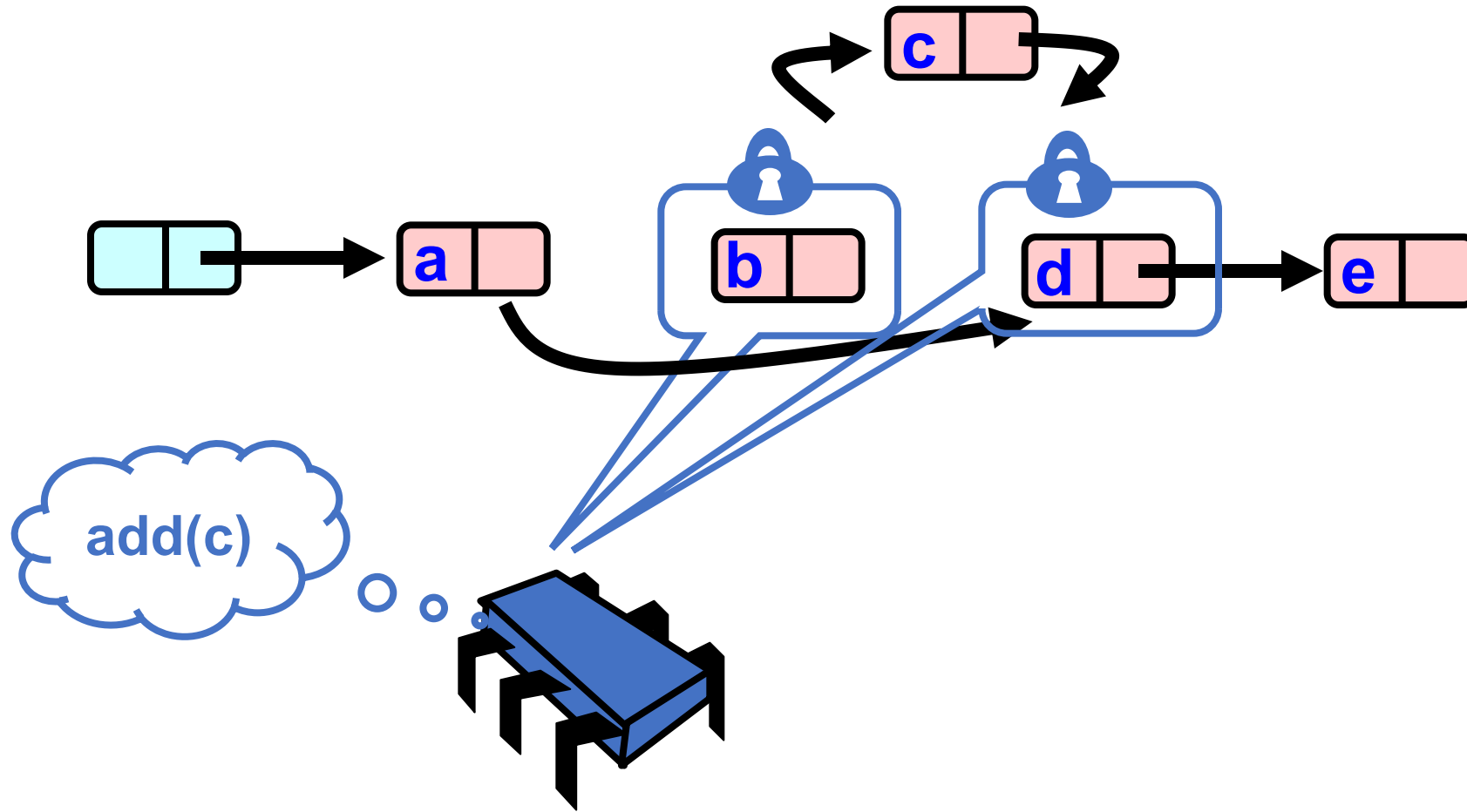
What could go wrong?



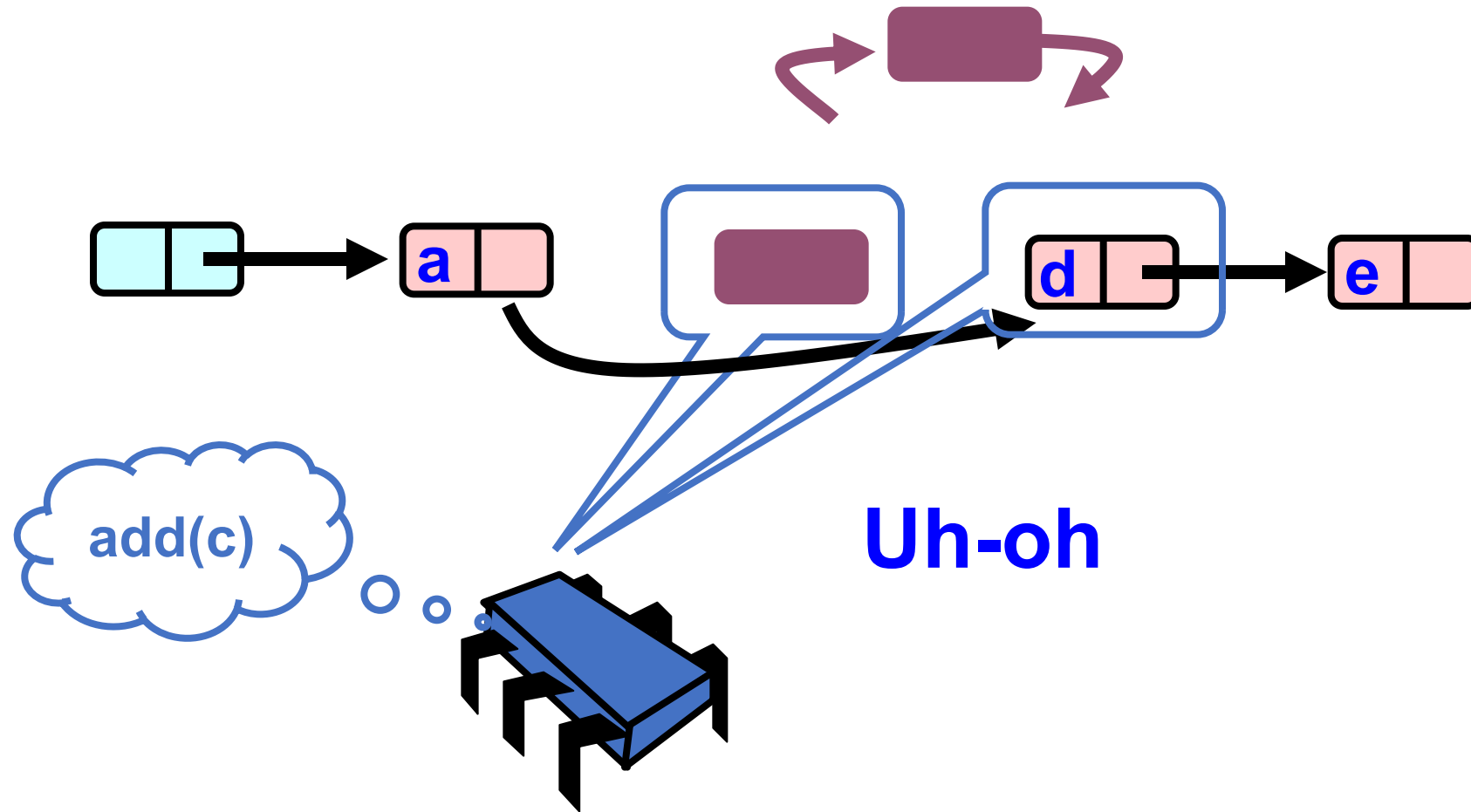
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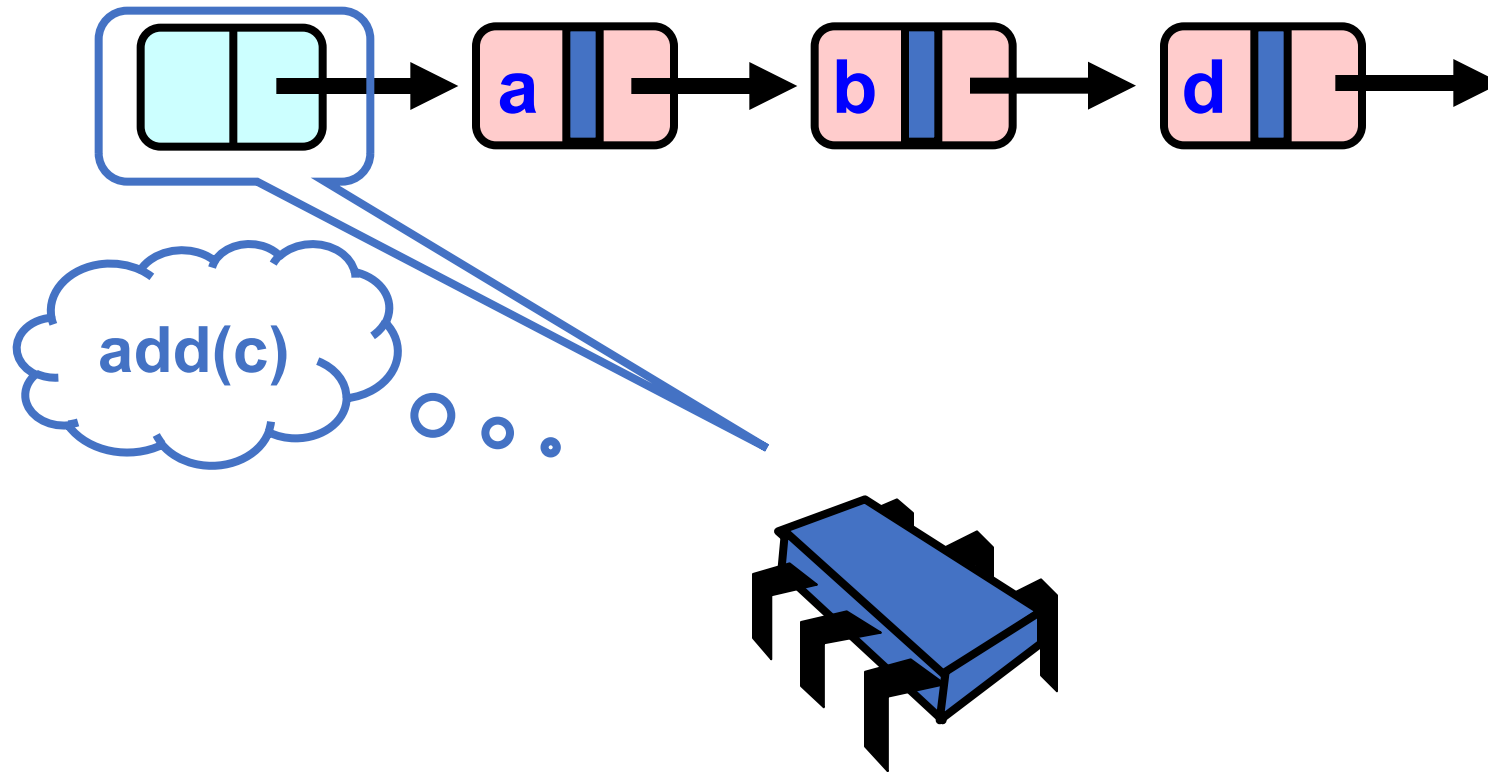
What could go wrong?



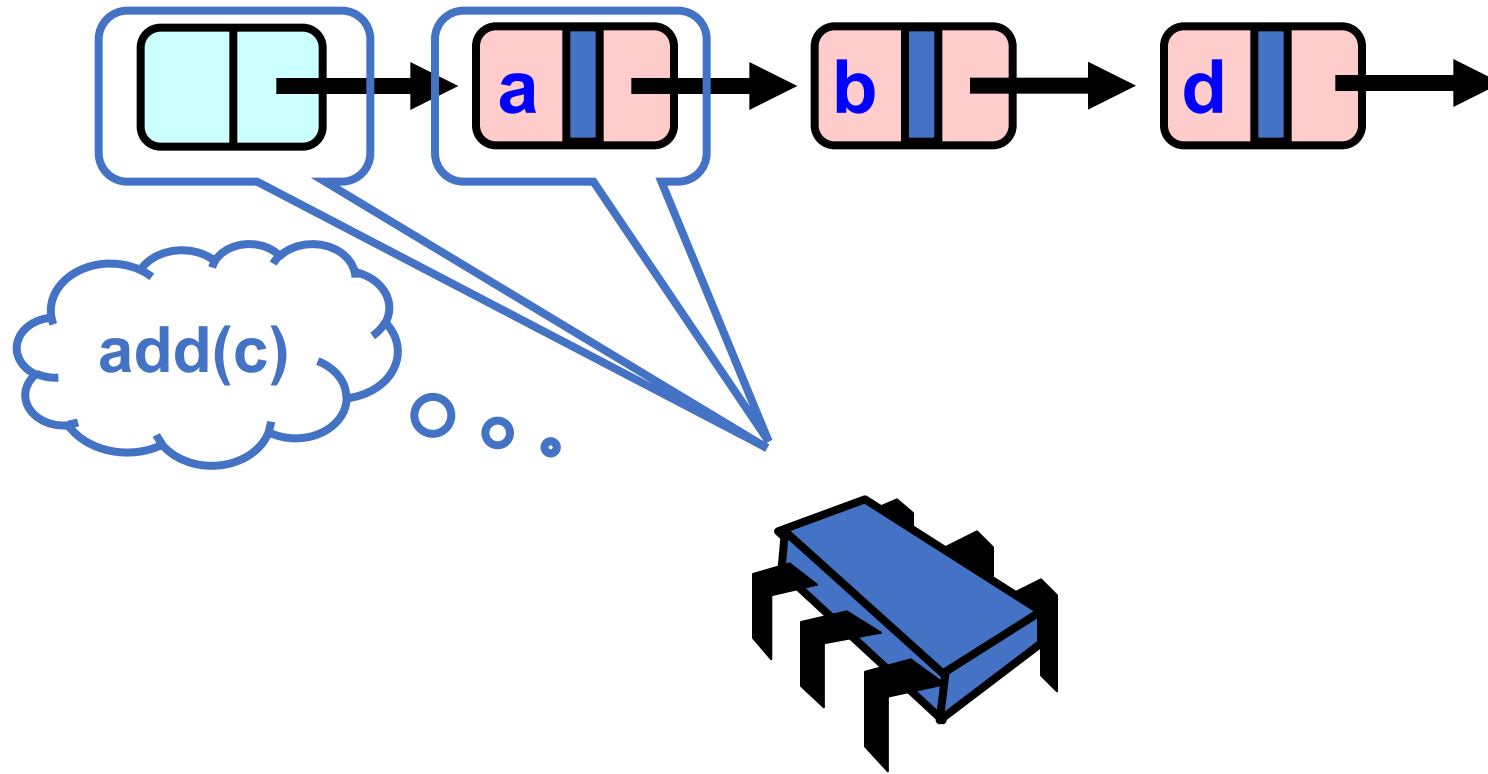
What could go wrong?



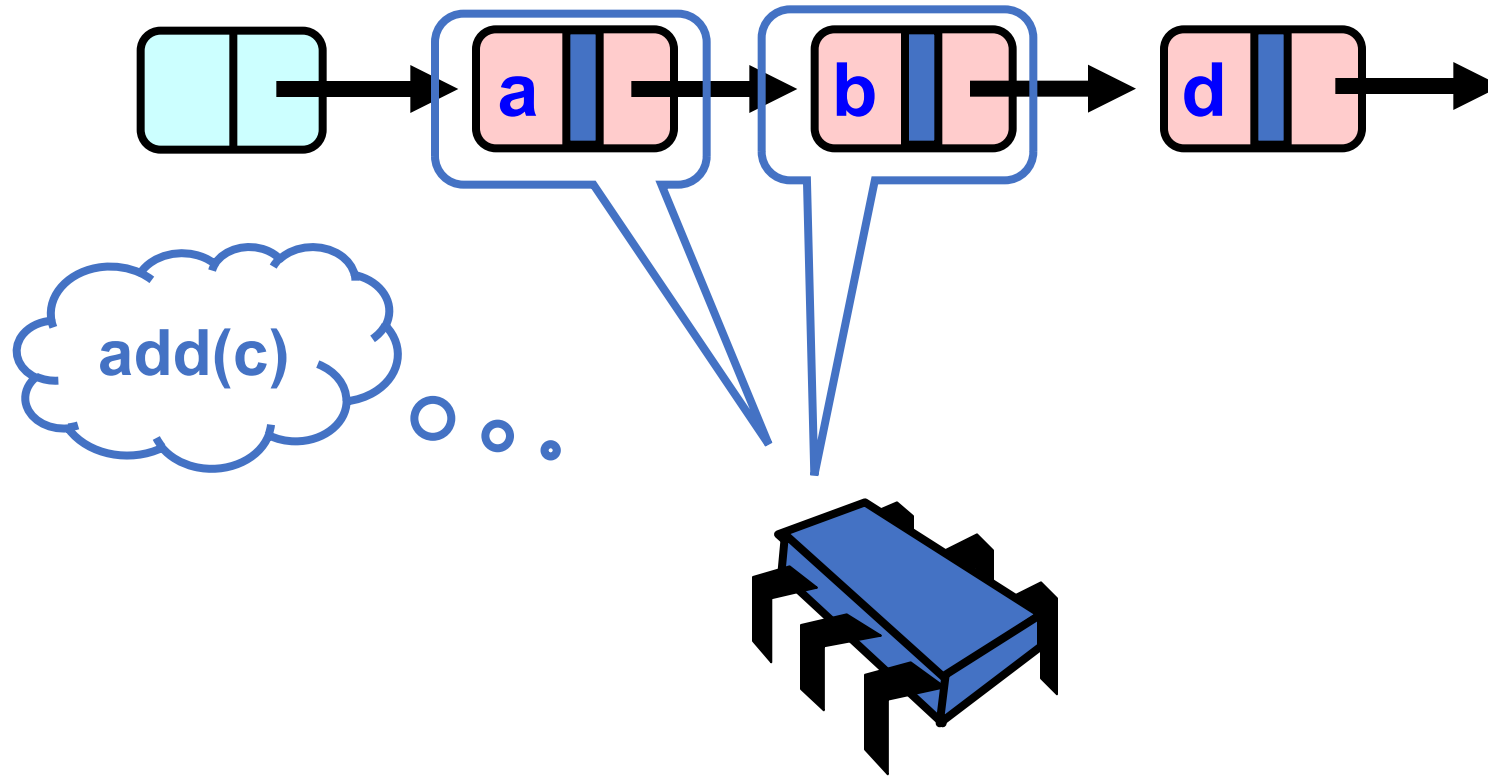
Fixed with logical flag



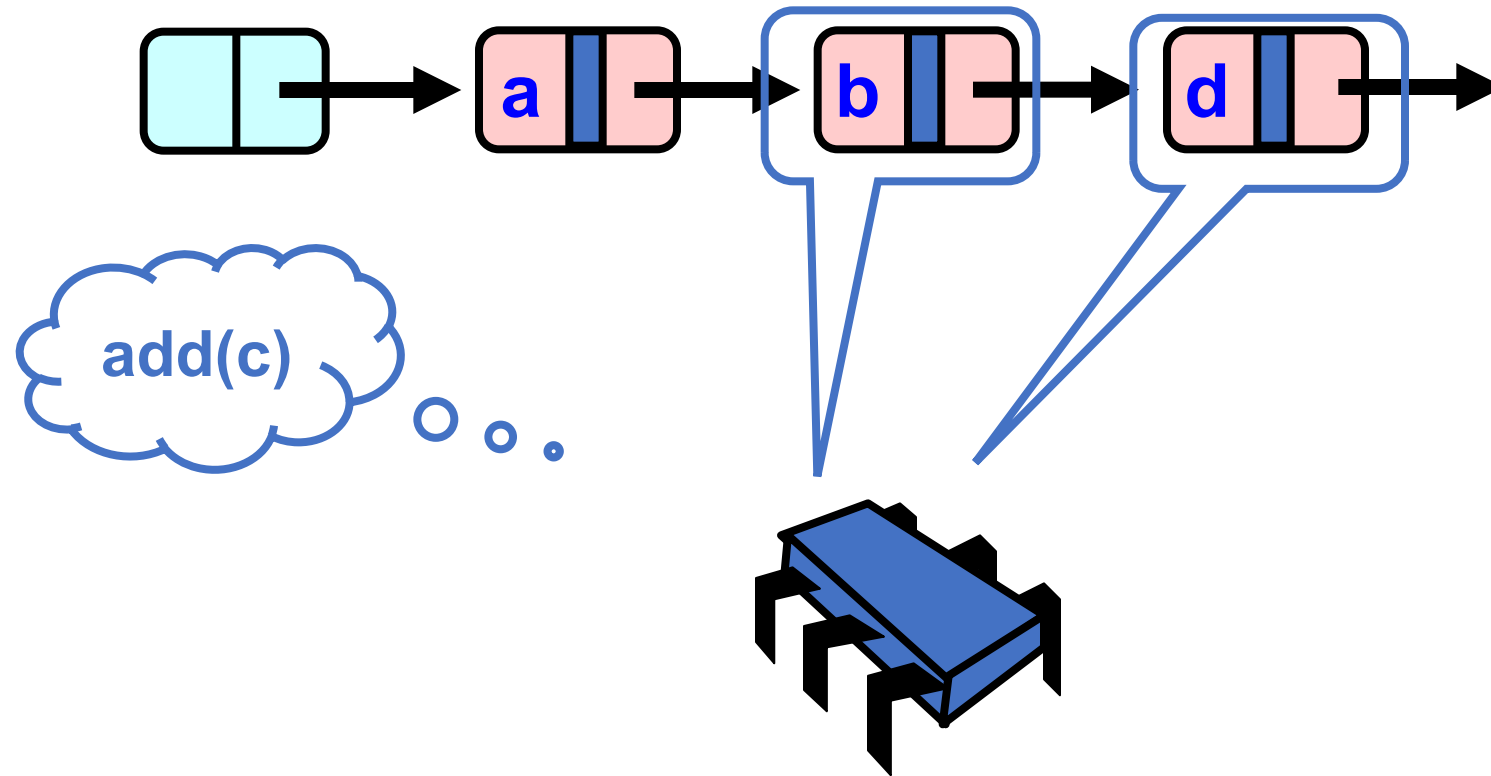
Fixed with logical flag



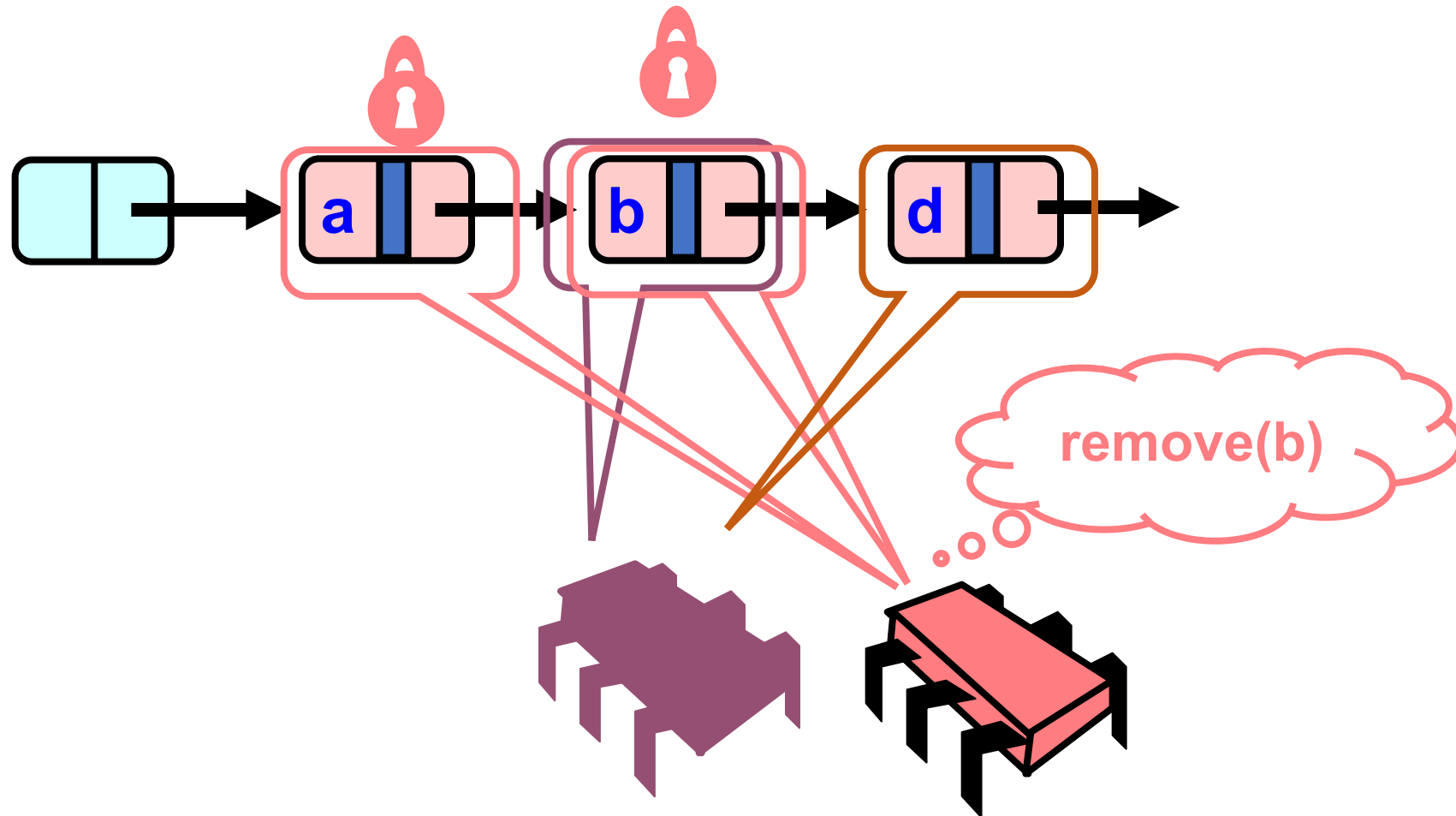
Fixed with logical flag



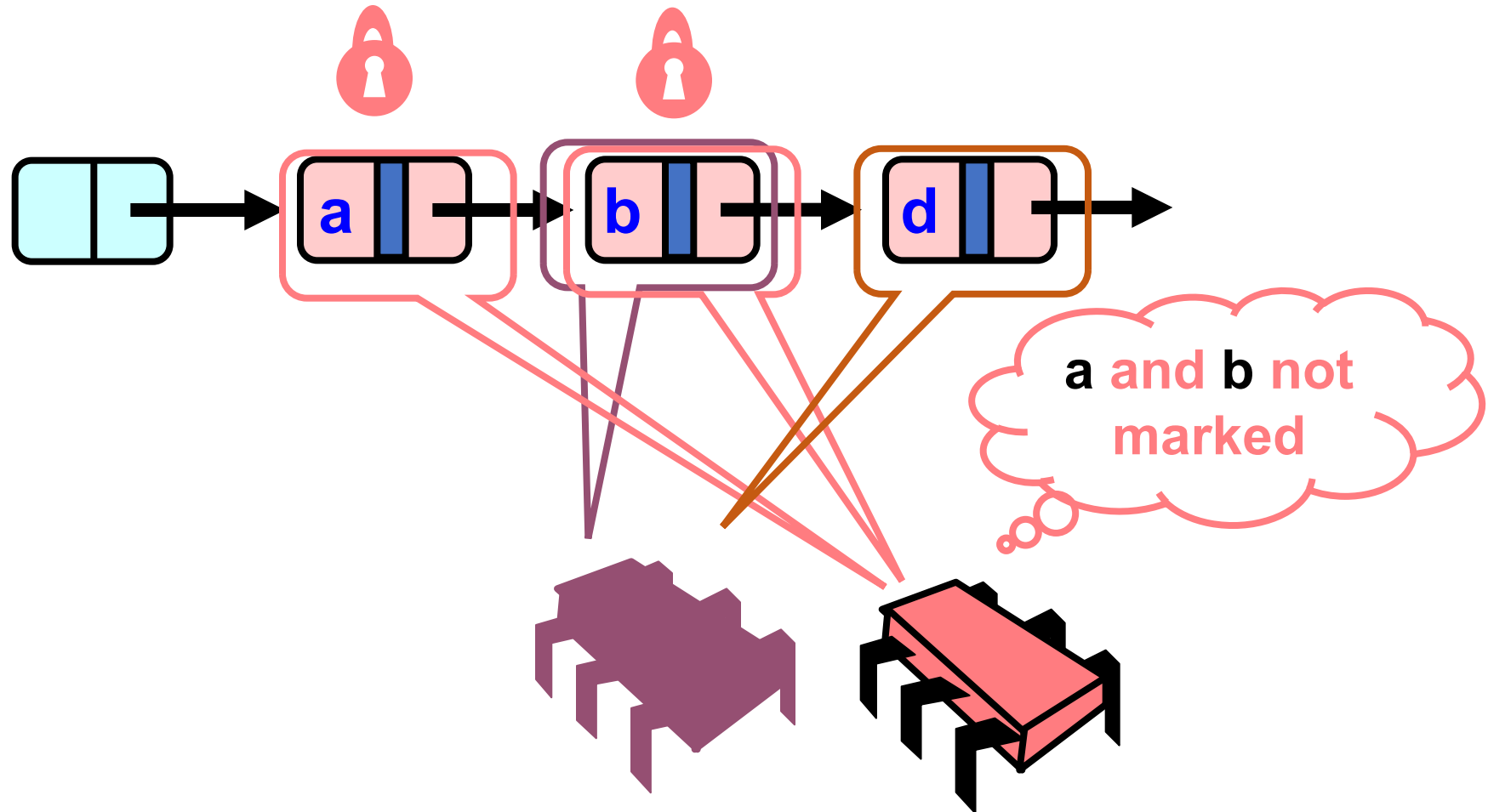
Fixed with logical flag



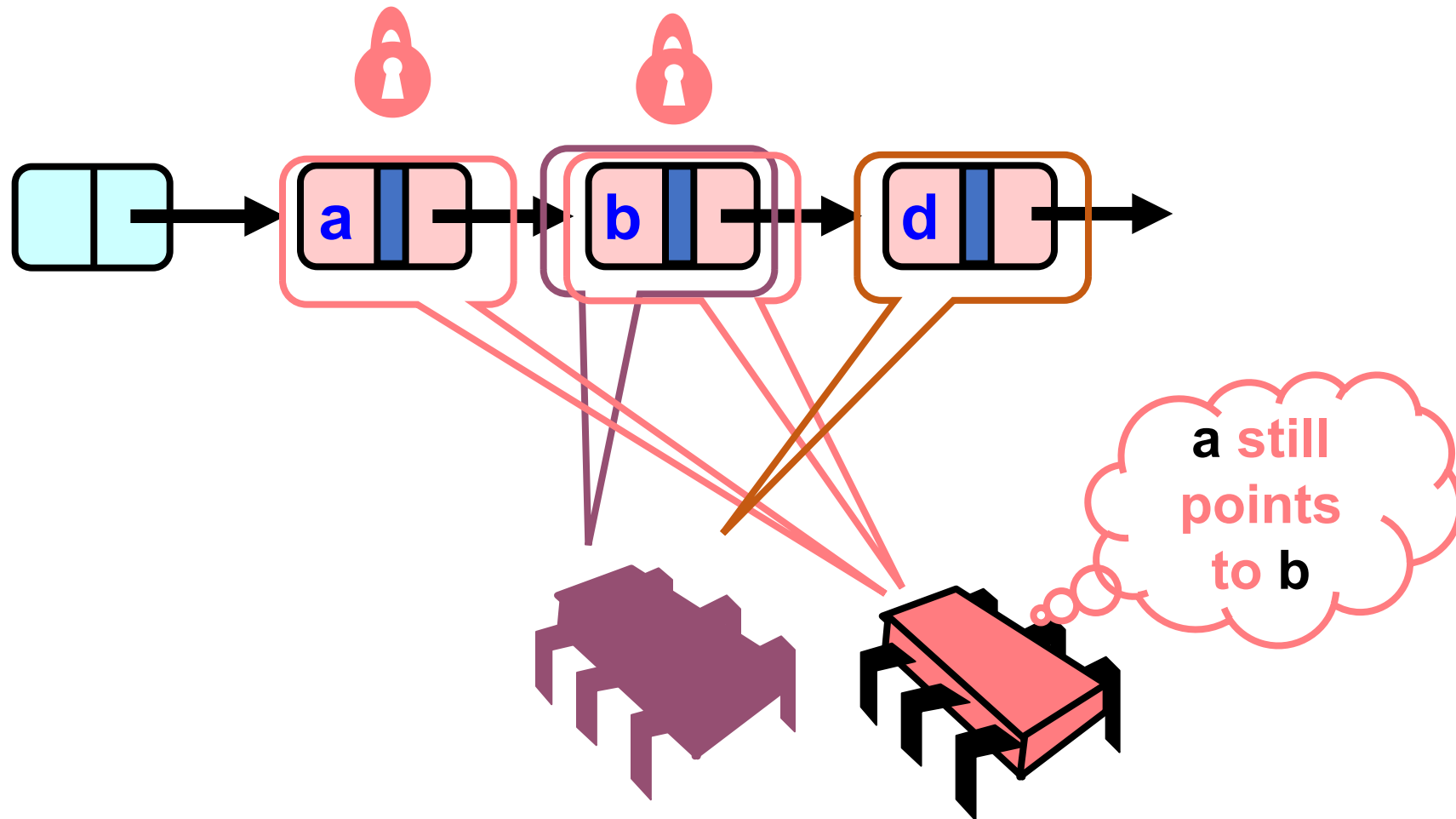
Fixed with logical flag



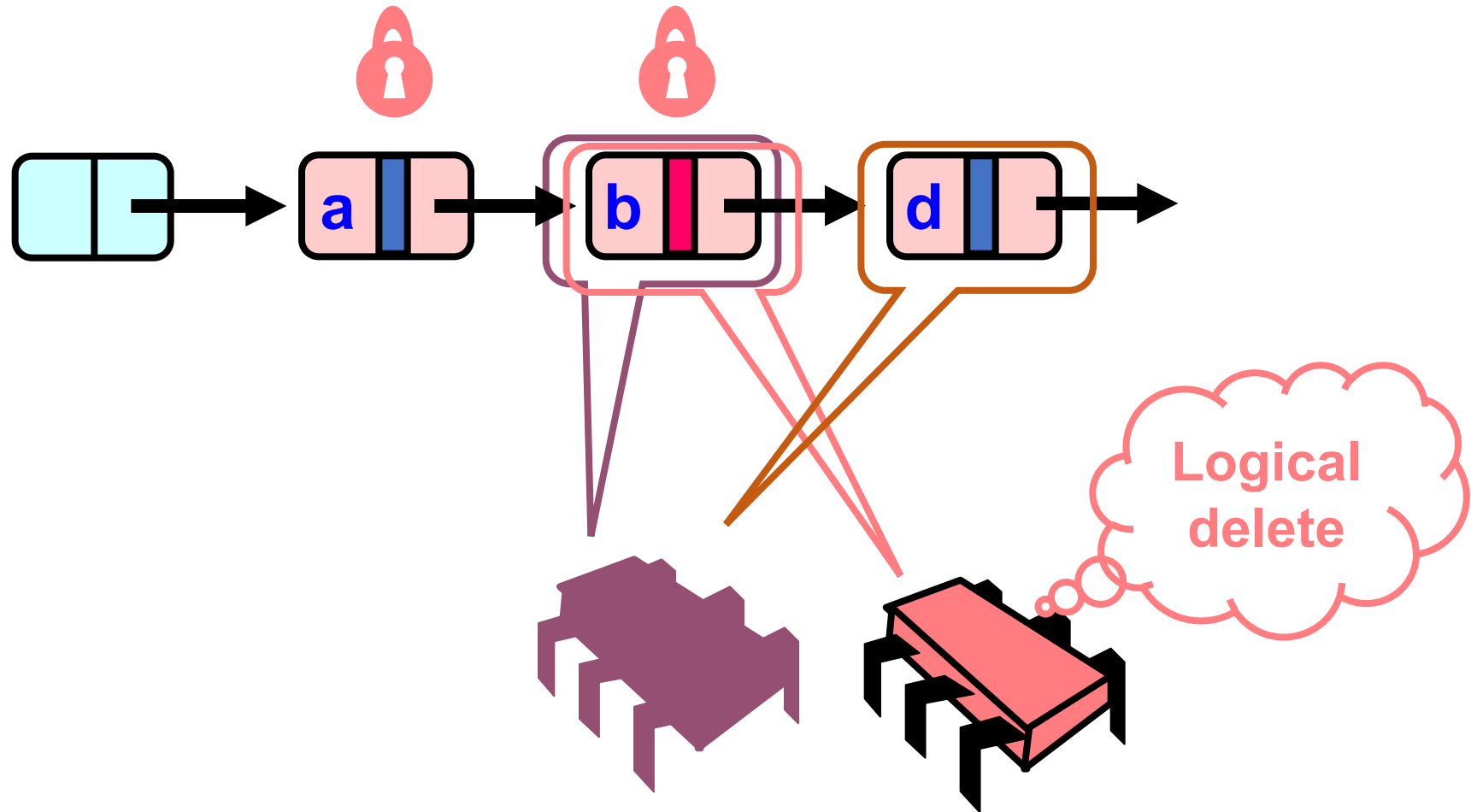
Fixed with logical flag



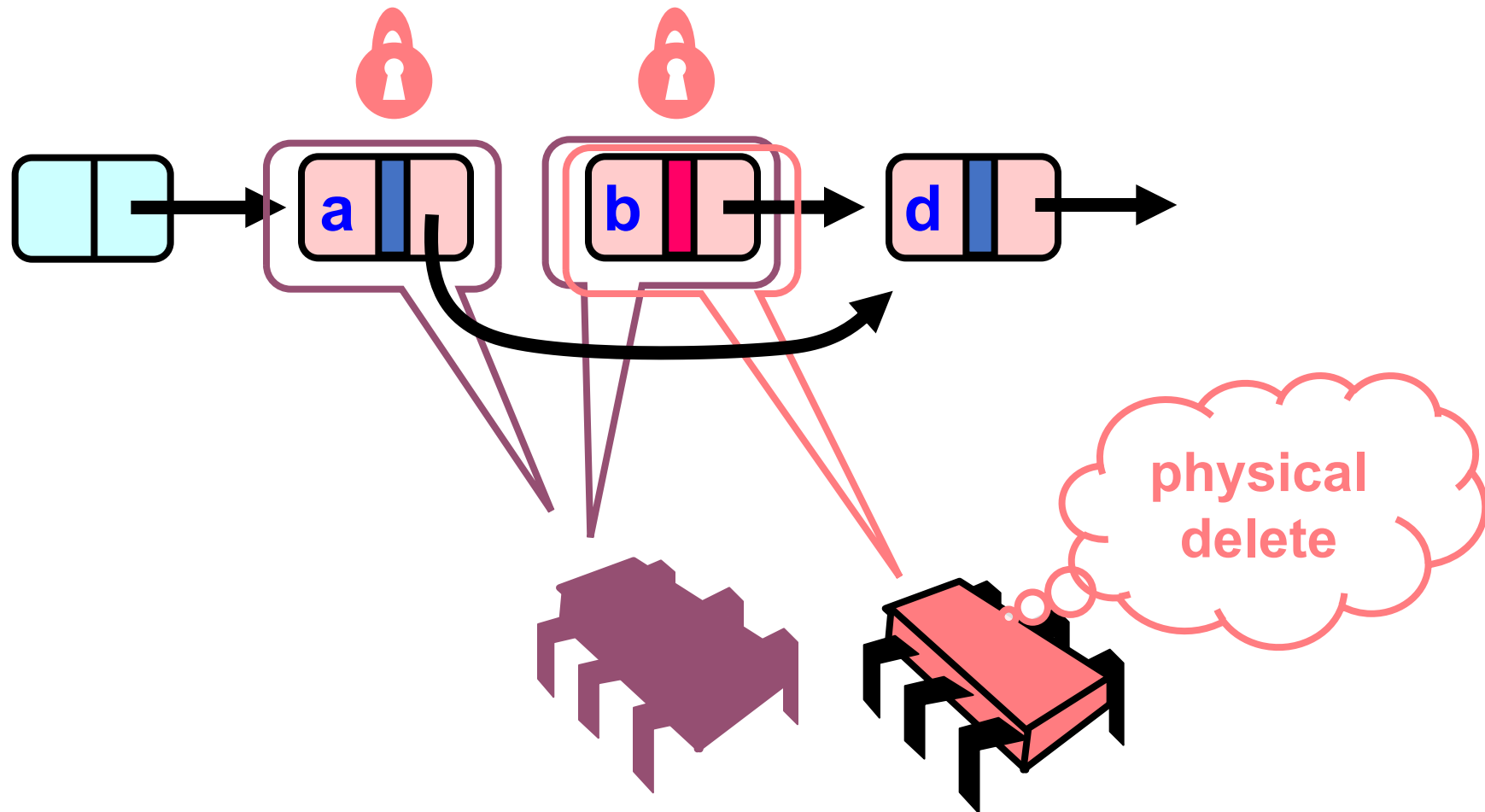
Fixed with logical flag



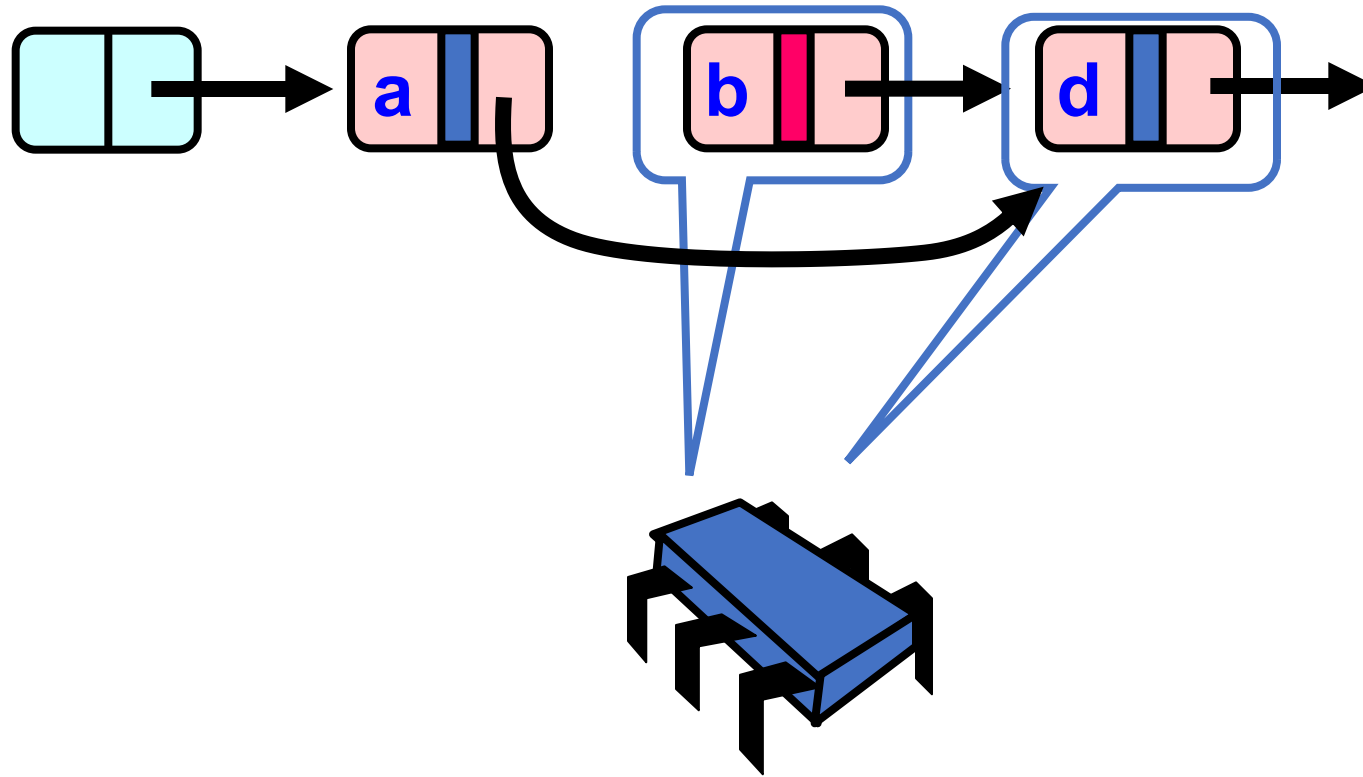
Fixed with logical flag



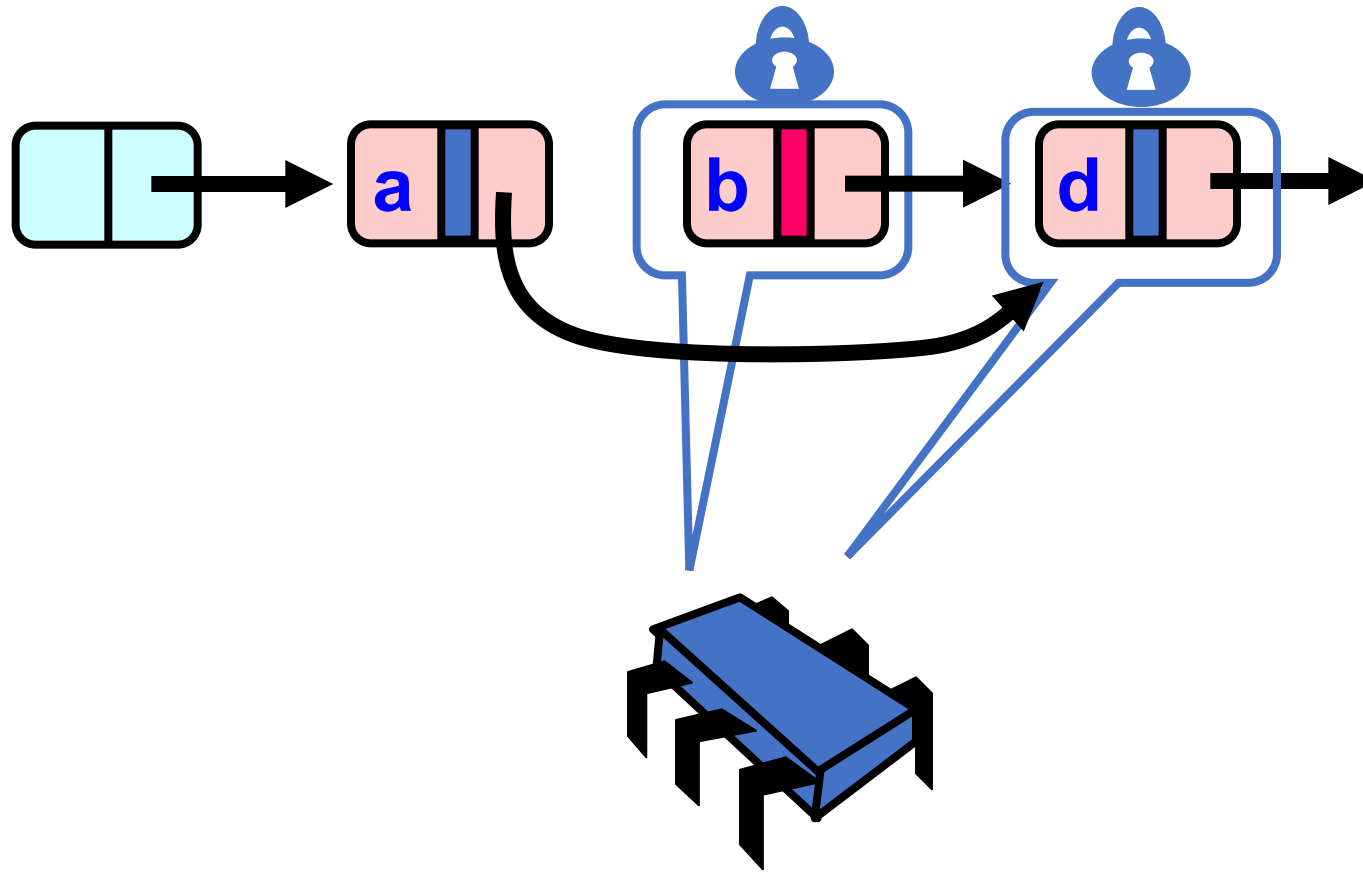
Fixed with logical flag



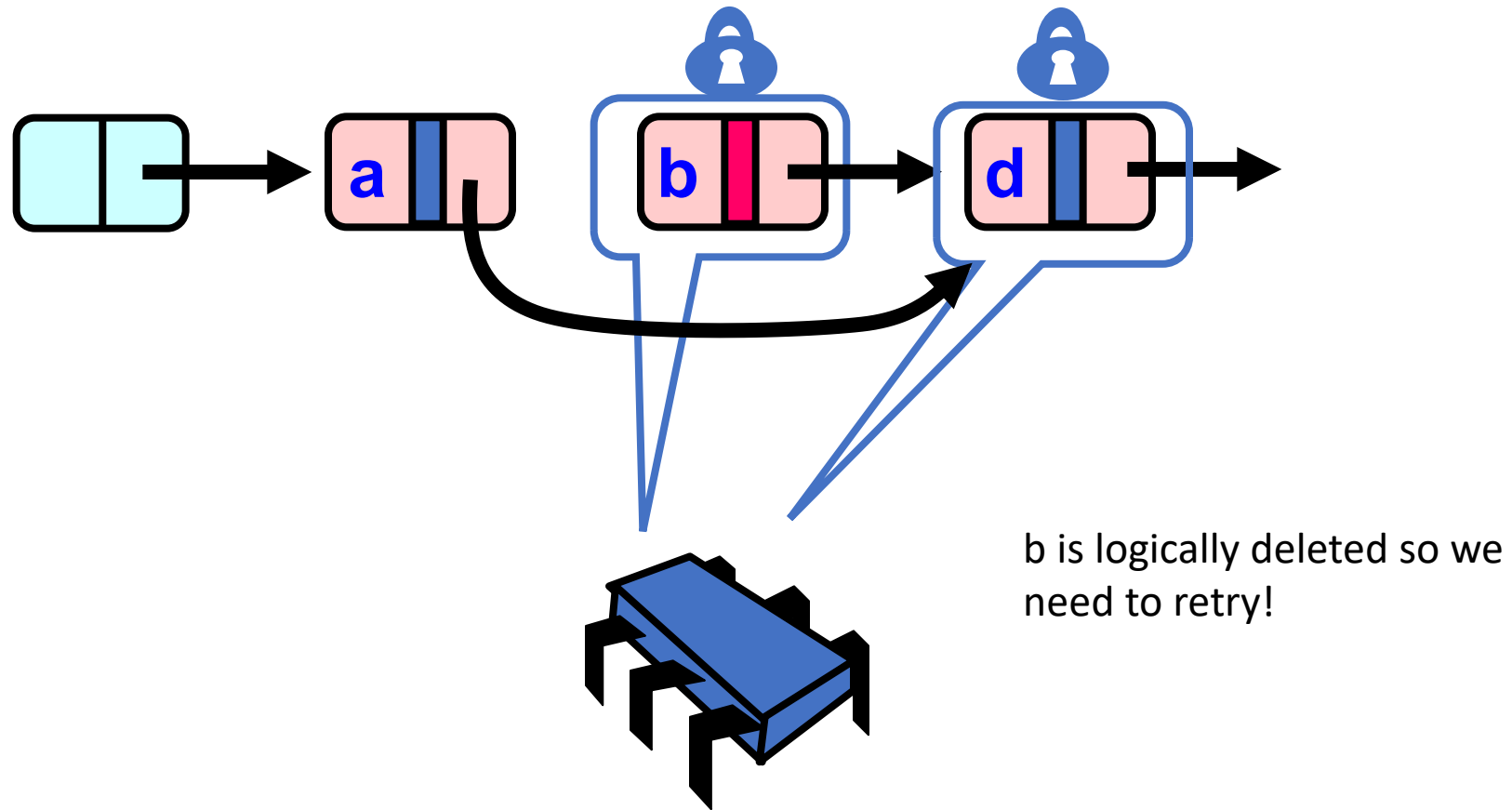
Fixed with logical flag



Fixed with logical flag



Fixed with logical flag



To complete the picture

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

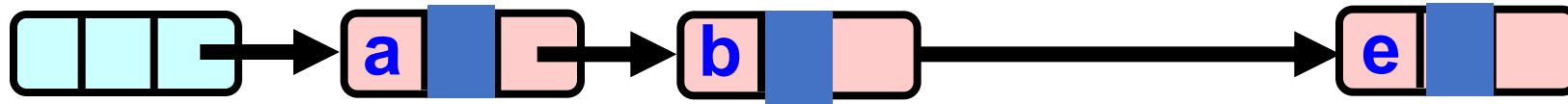
How good?

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

Lock-free Lists

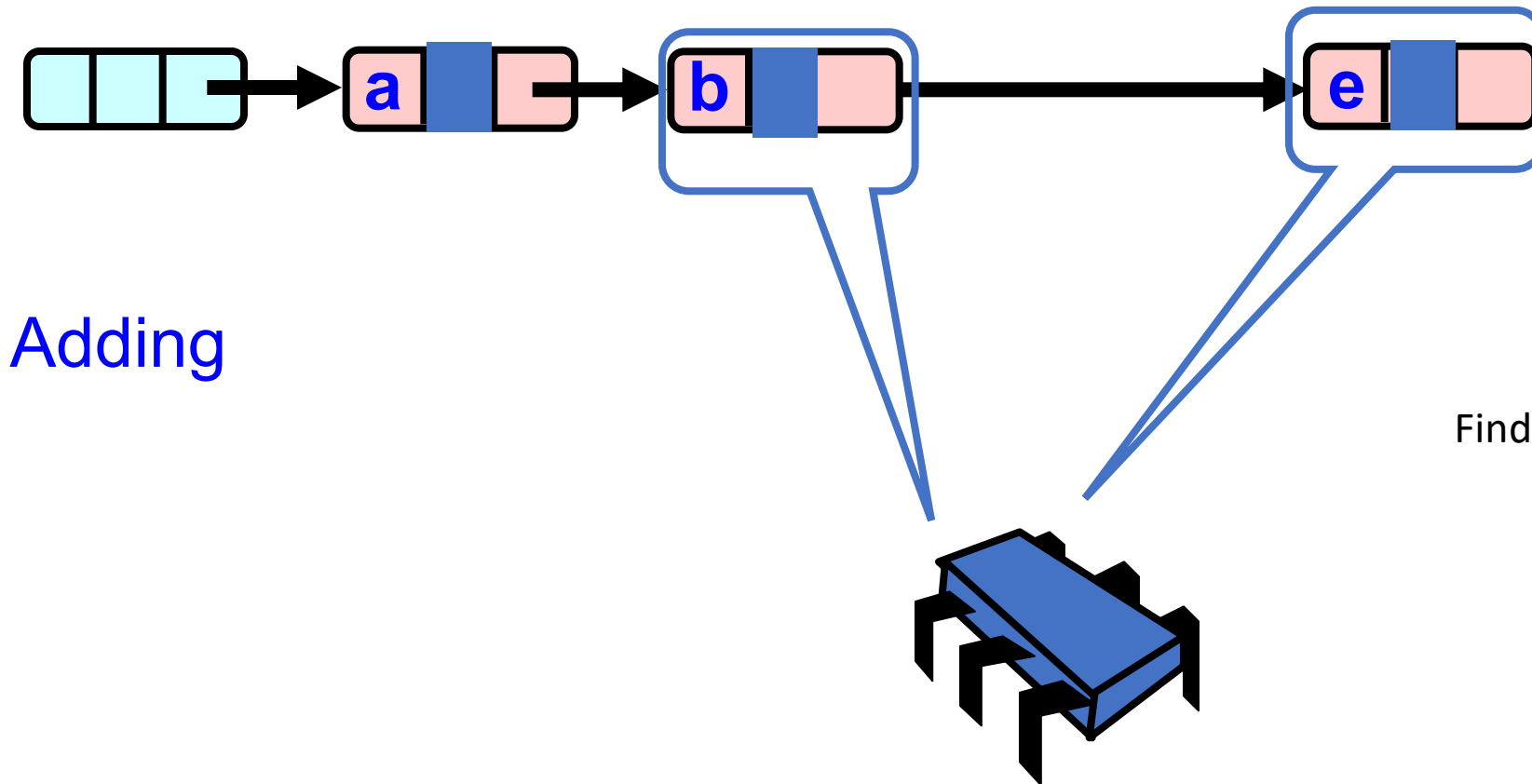
- Next logical step
 - lock-free add() and remove()
- What sort of atomics do we need?
 - Loads/stores -> RMWs?

Lock-free Lists

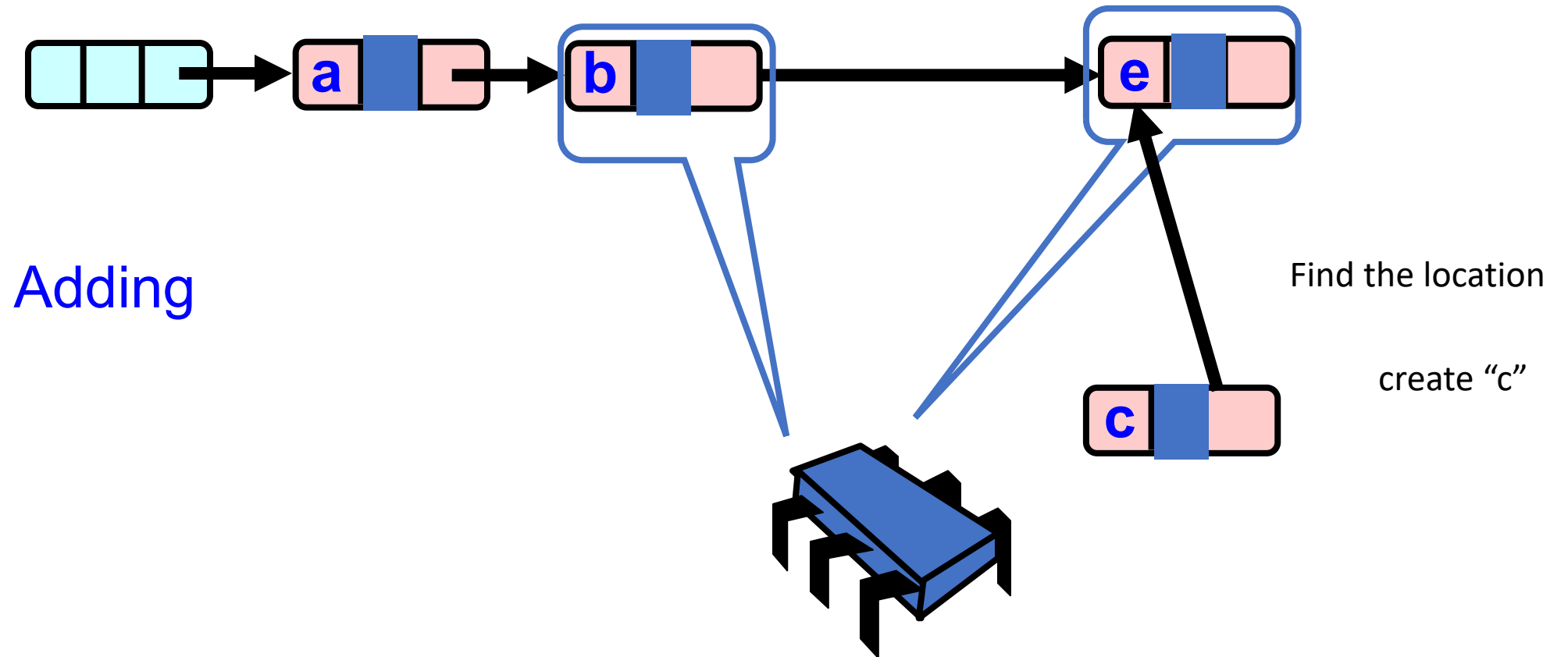


Adding

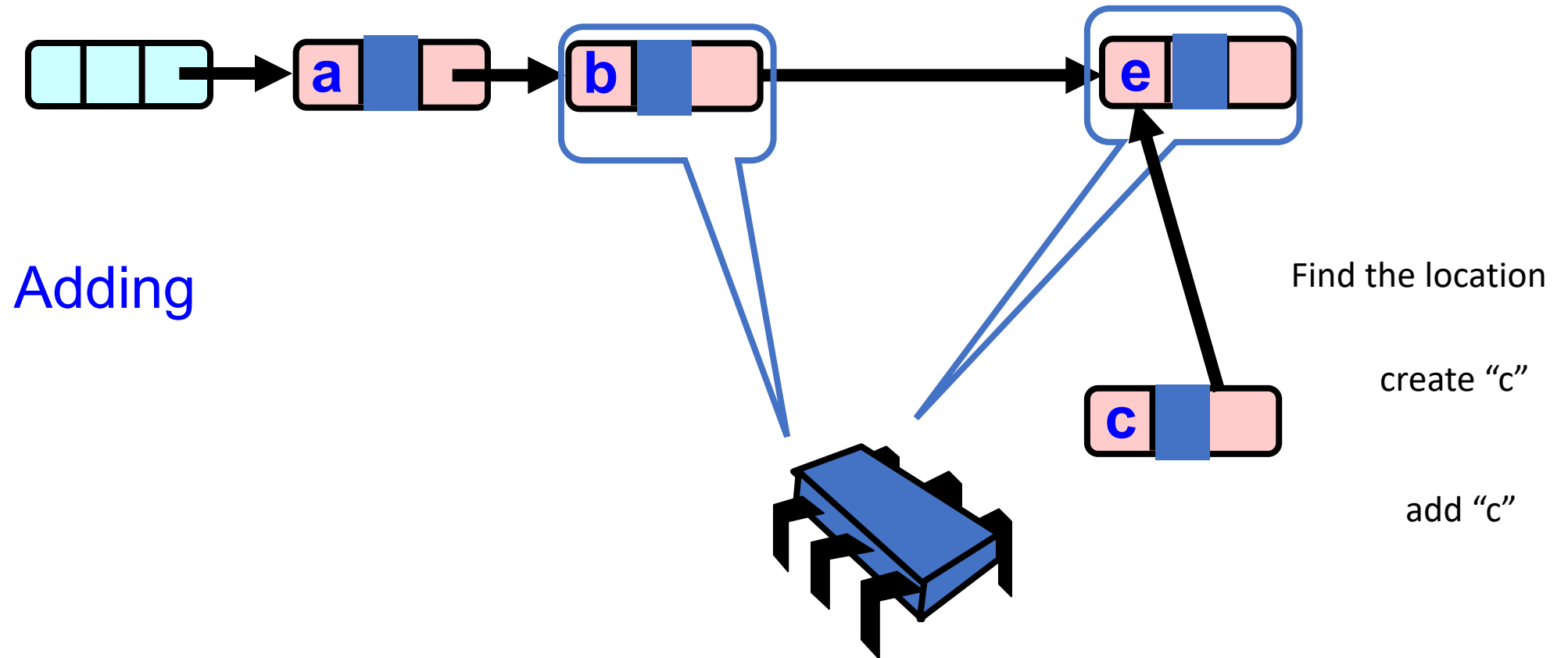
Lock-free Lists



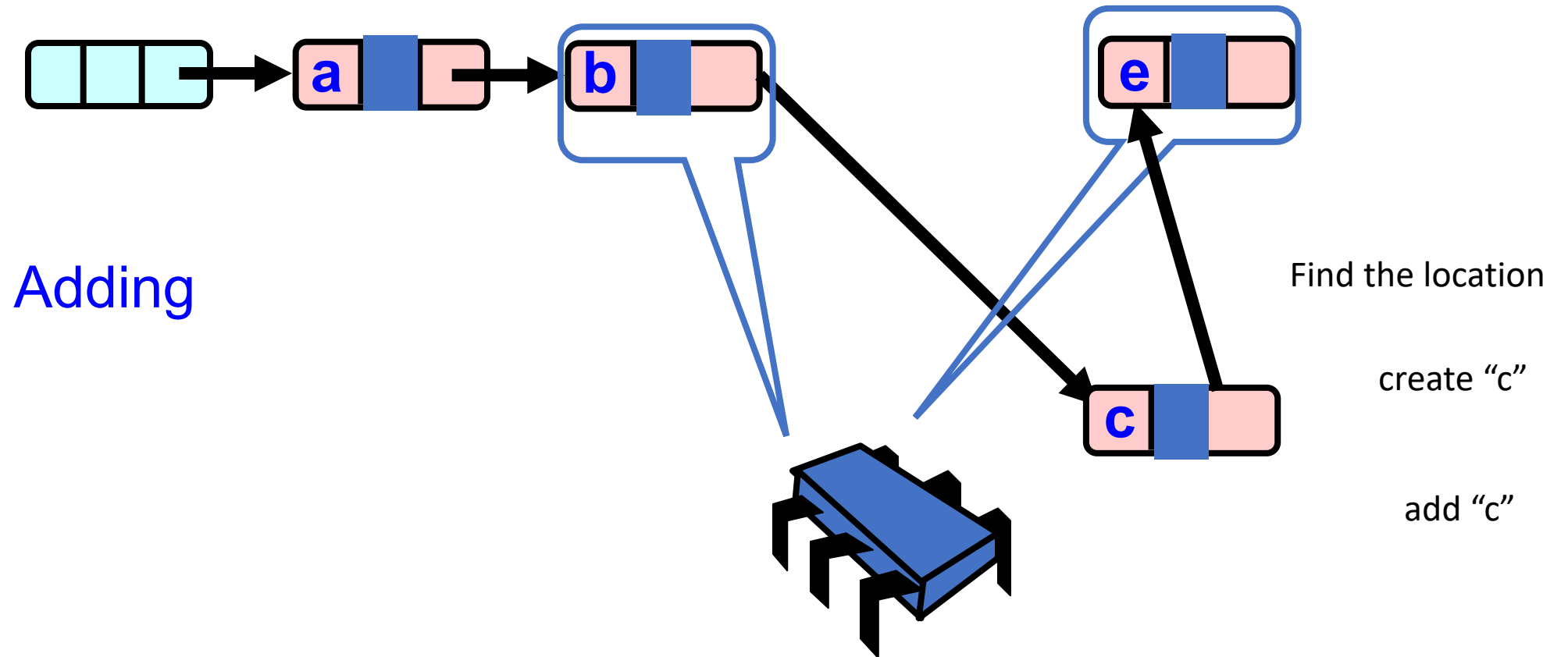
Lock-free Lists



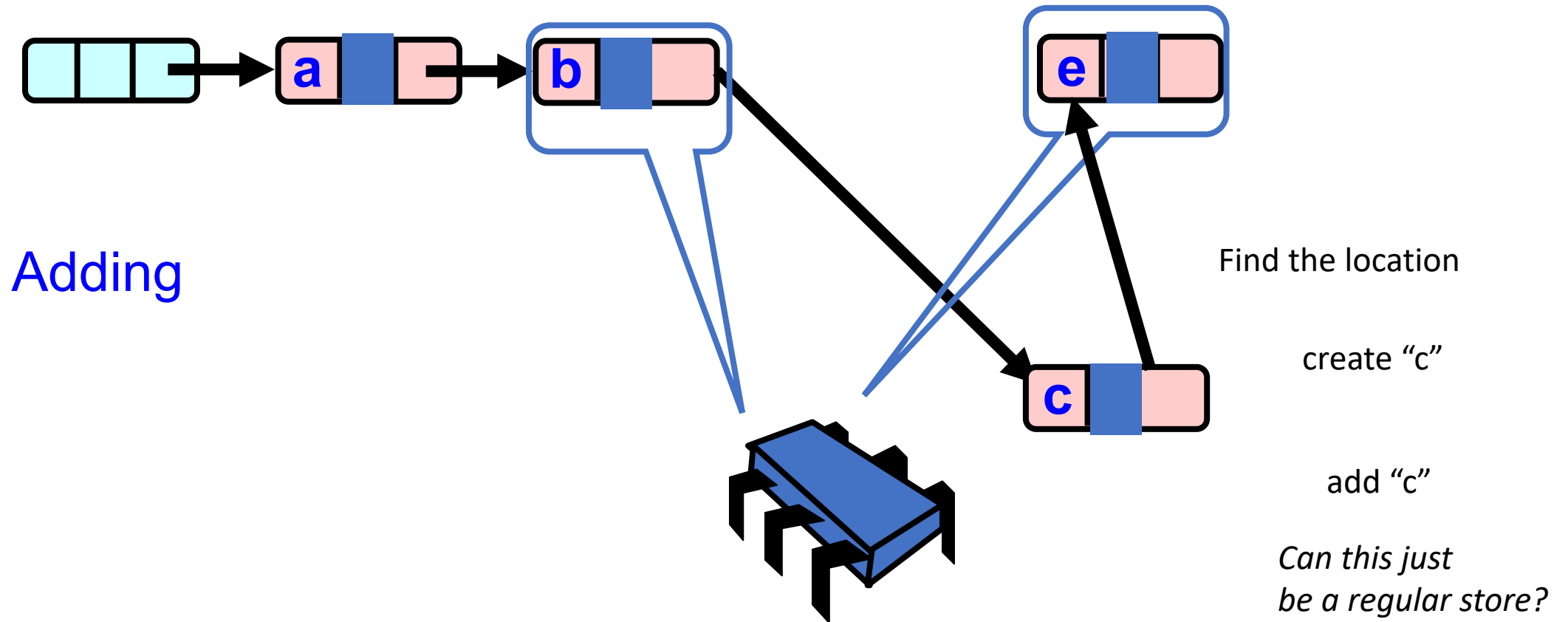
Lock-free Lists



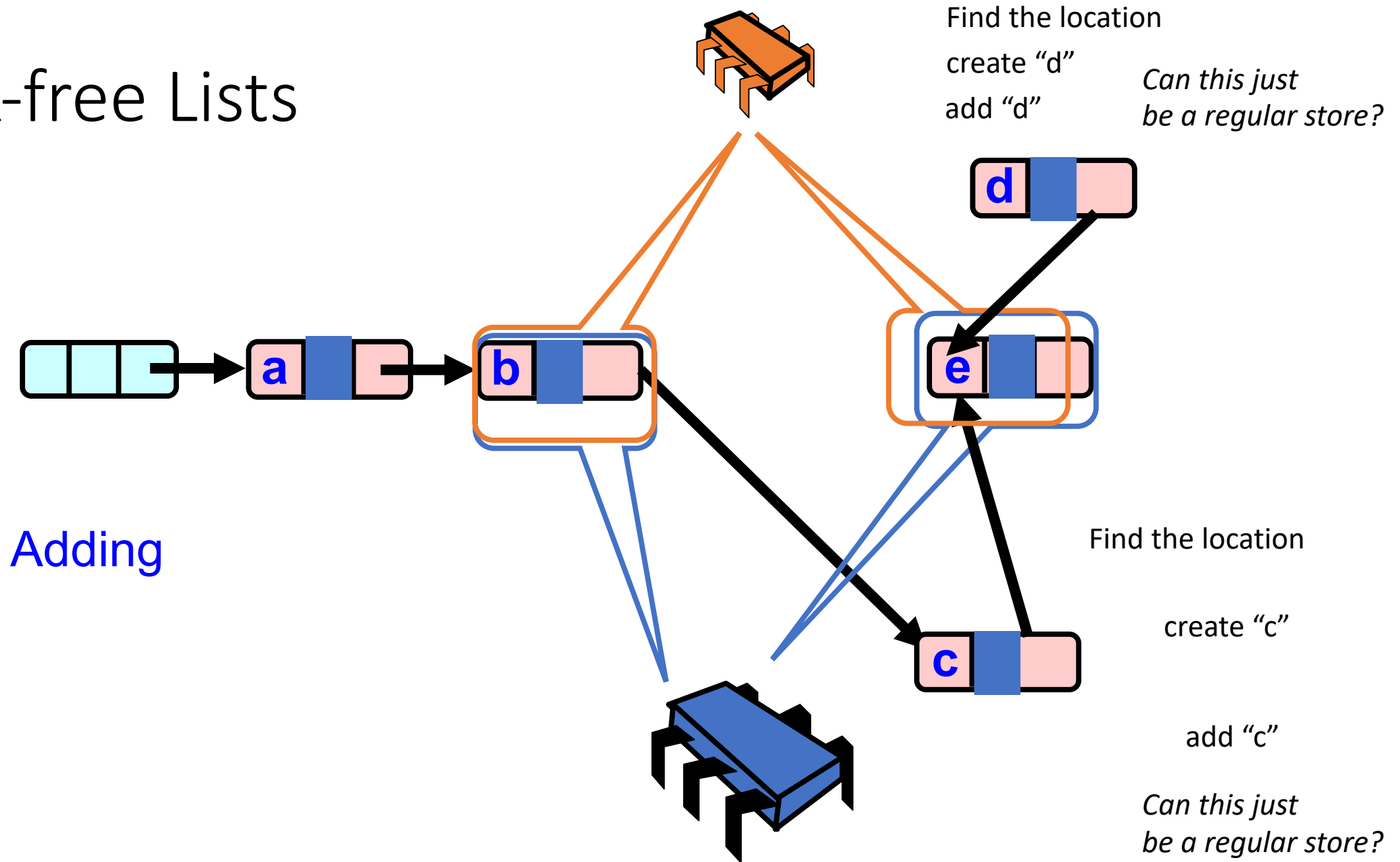
Lock-free Lists



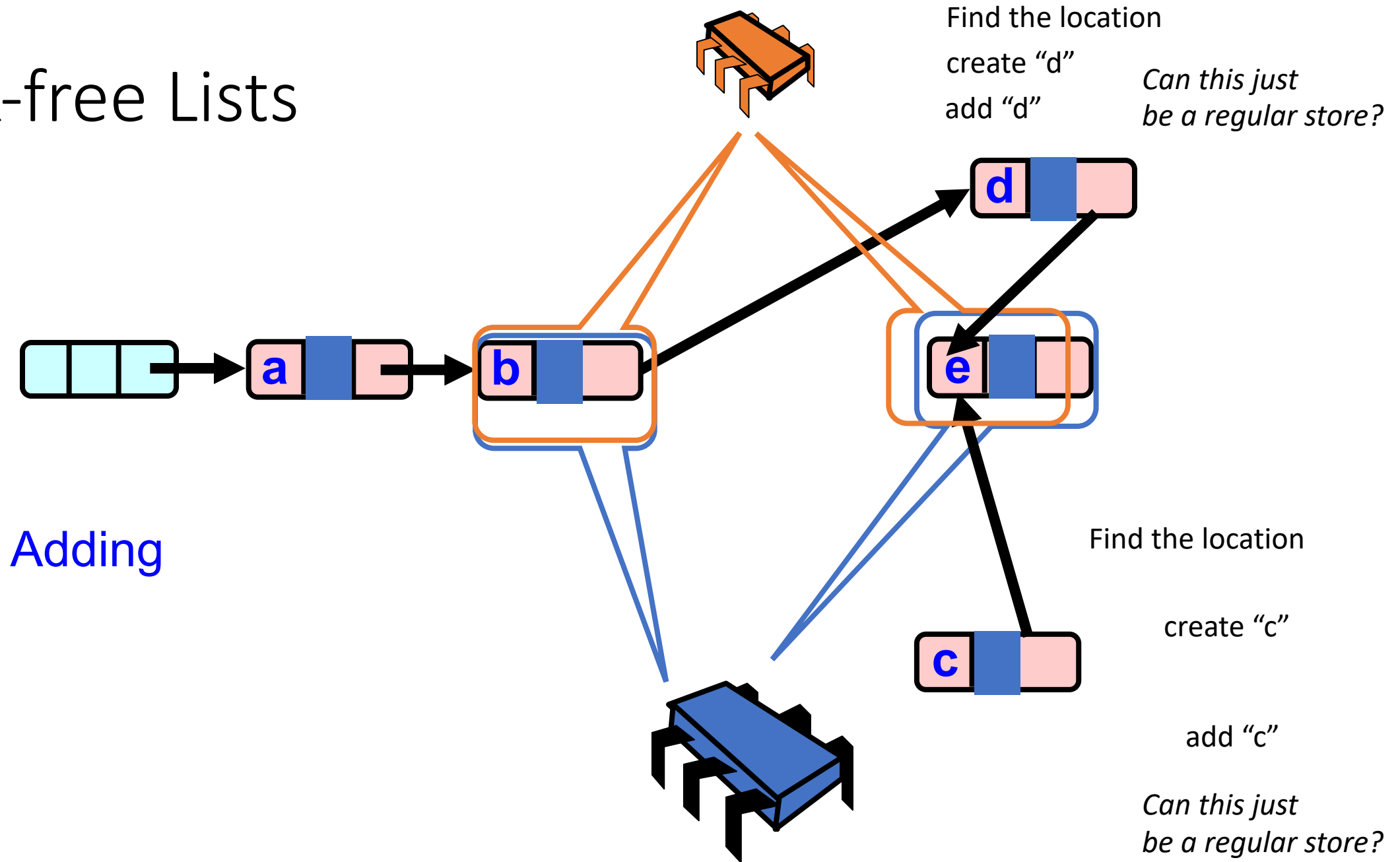
Lock-free Lists



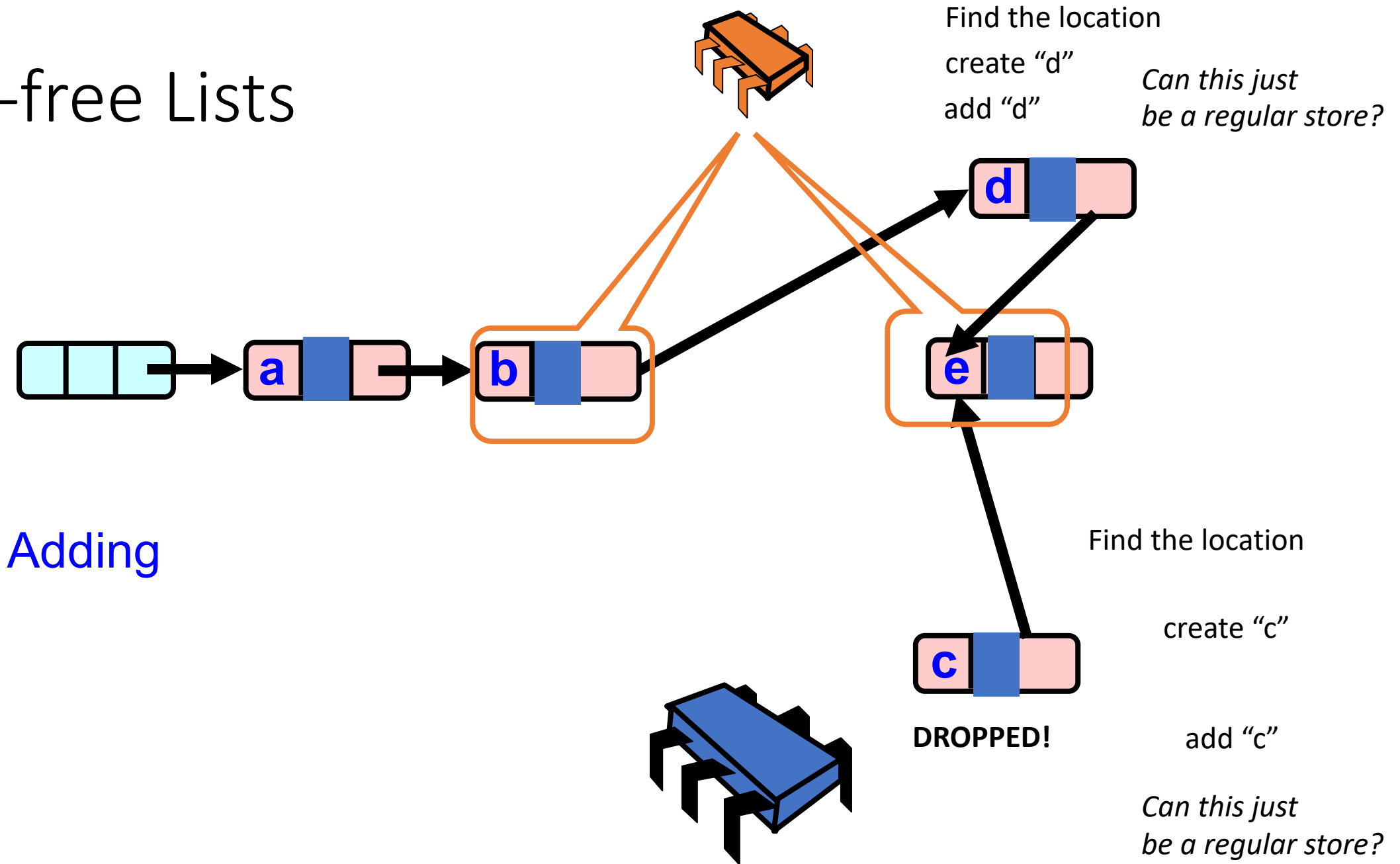
Lock-free Lists



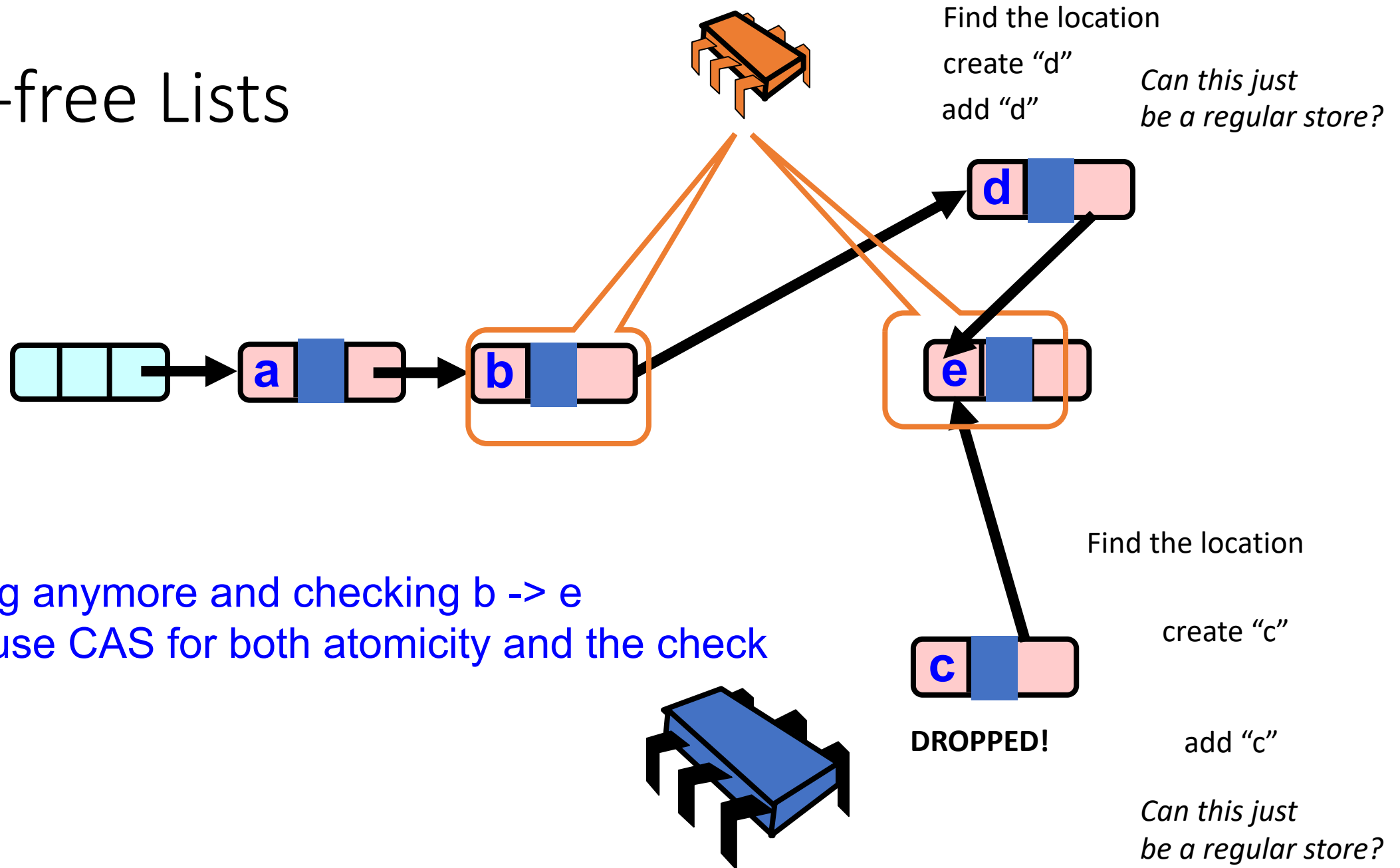
Lock-free Lists



Lock-free Lists



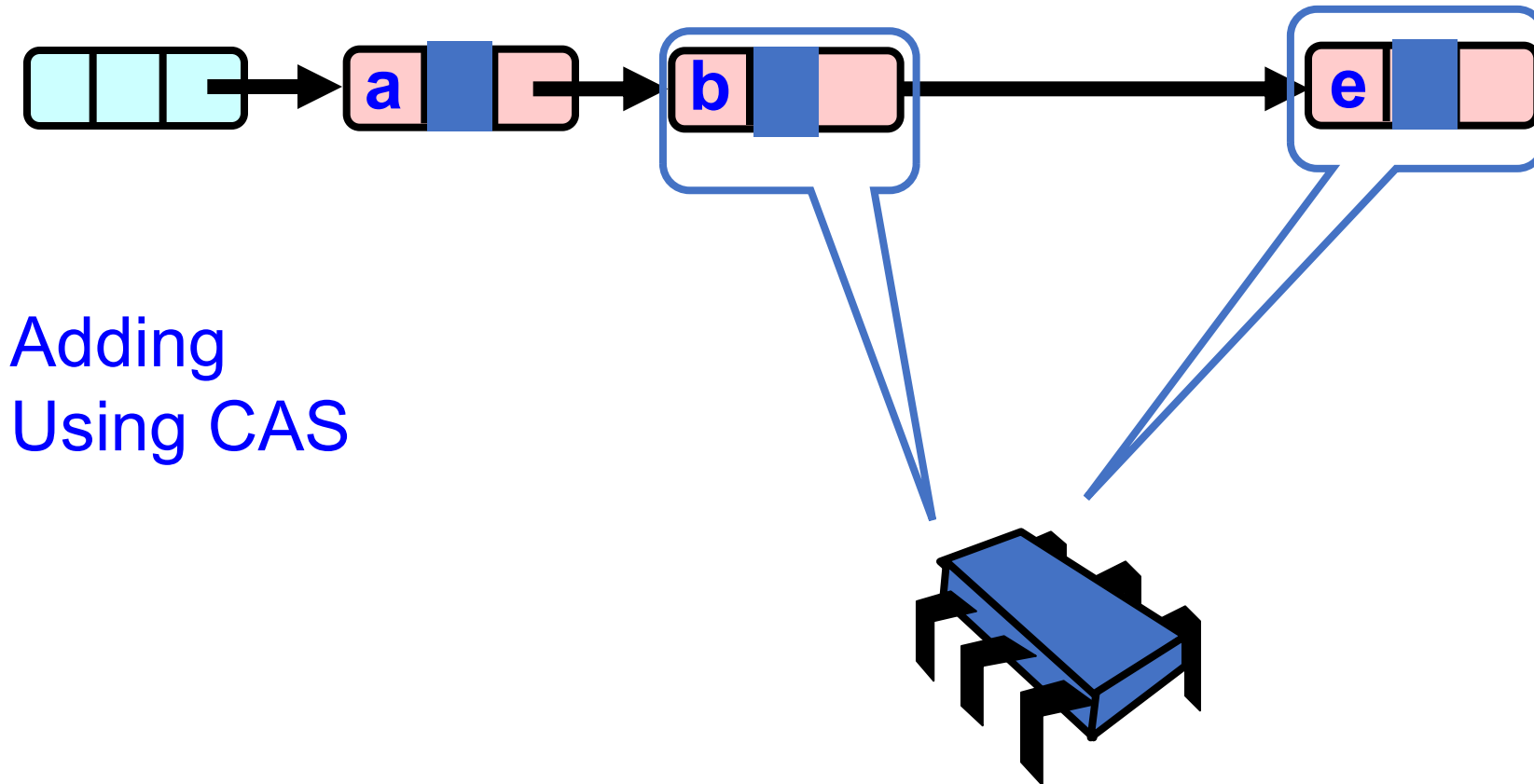
Lock-free Lists



Lock-free Lists

Find the location
Cache your insertion
point!

`b.next == e`

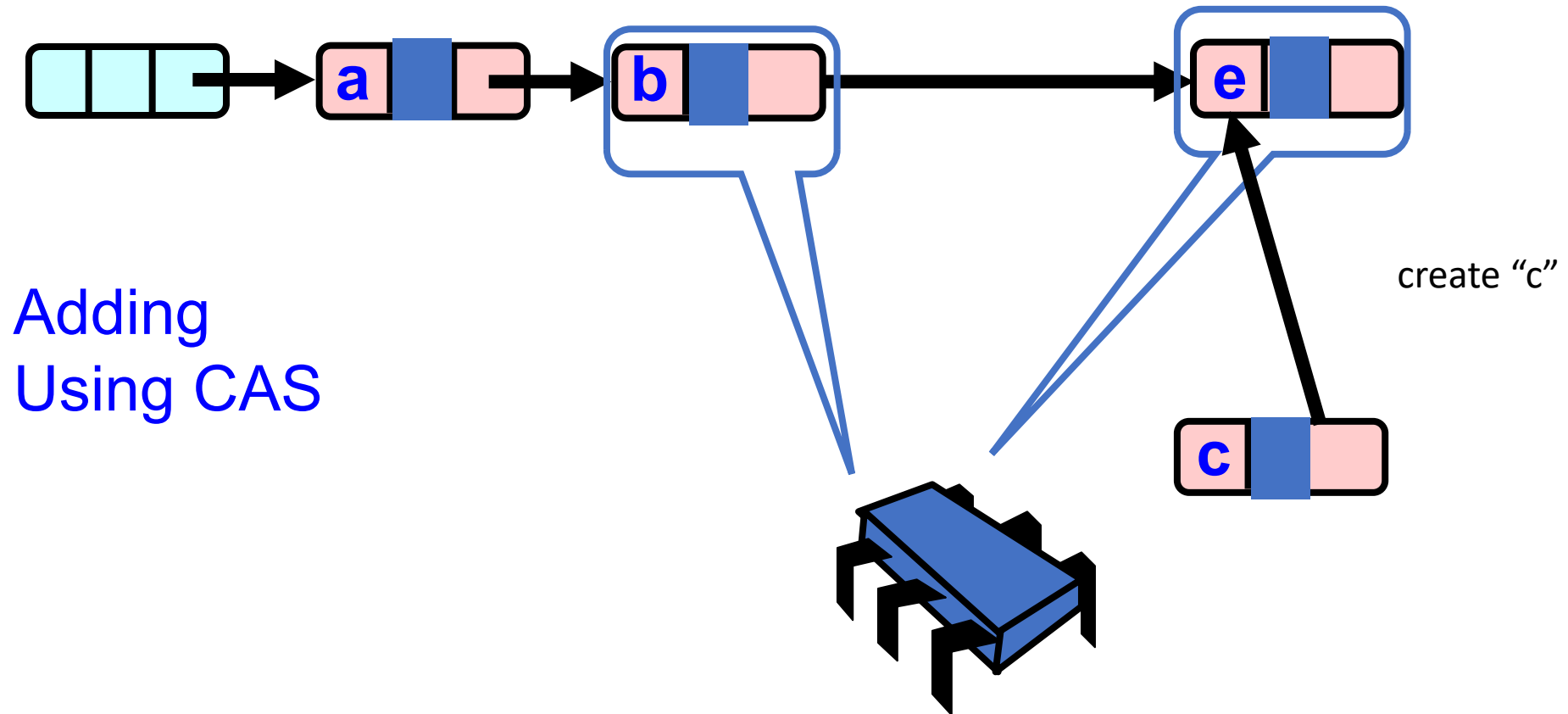


Adding
Using CAS

Lock-free Lists

Find the location
Cache your insertion
point!

`b.next == e`



Lock-free Lists

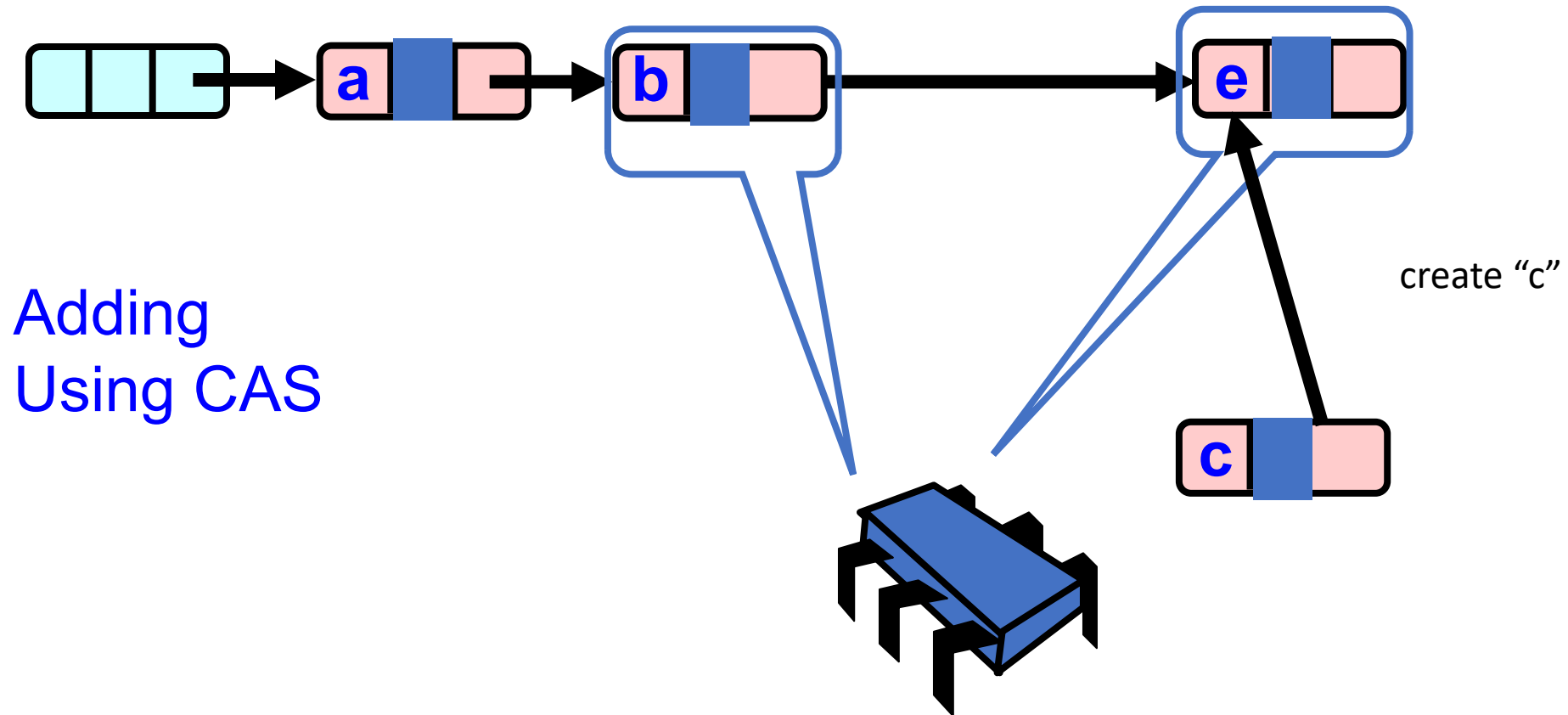
Only add if your insertion point is valid!

`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 **



Lock-free Lists

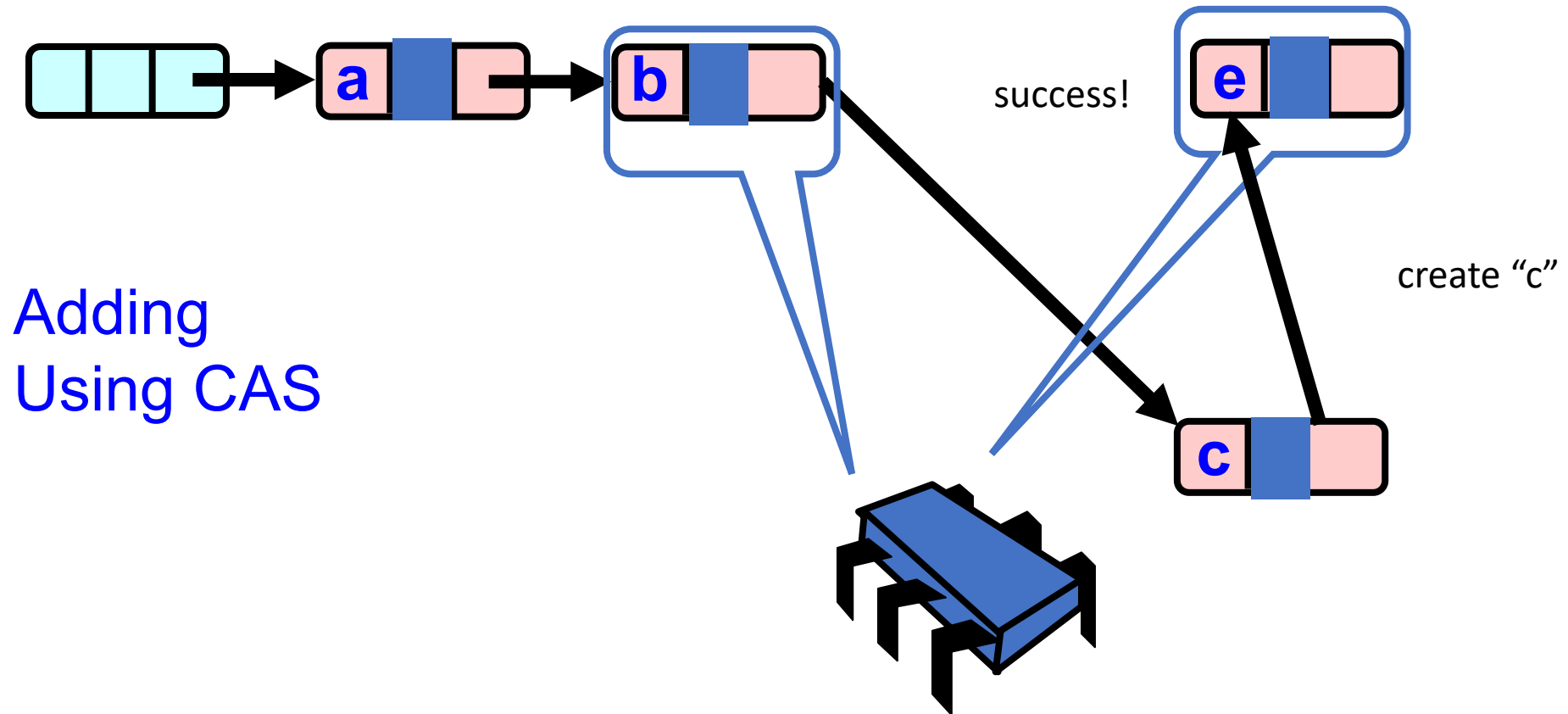
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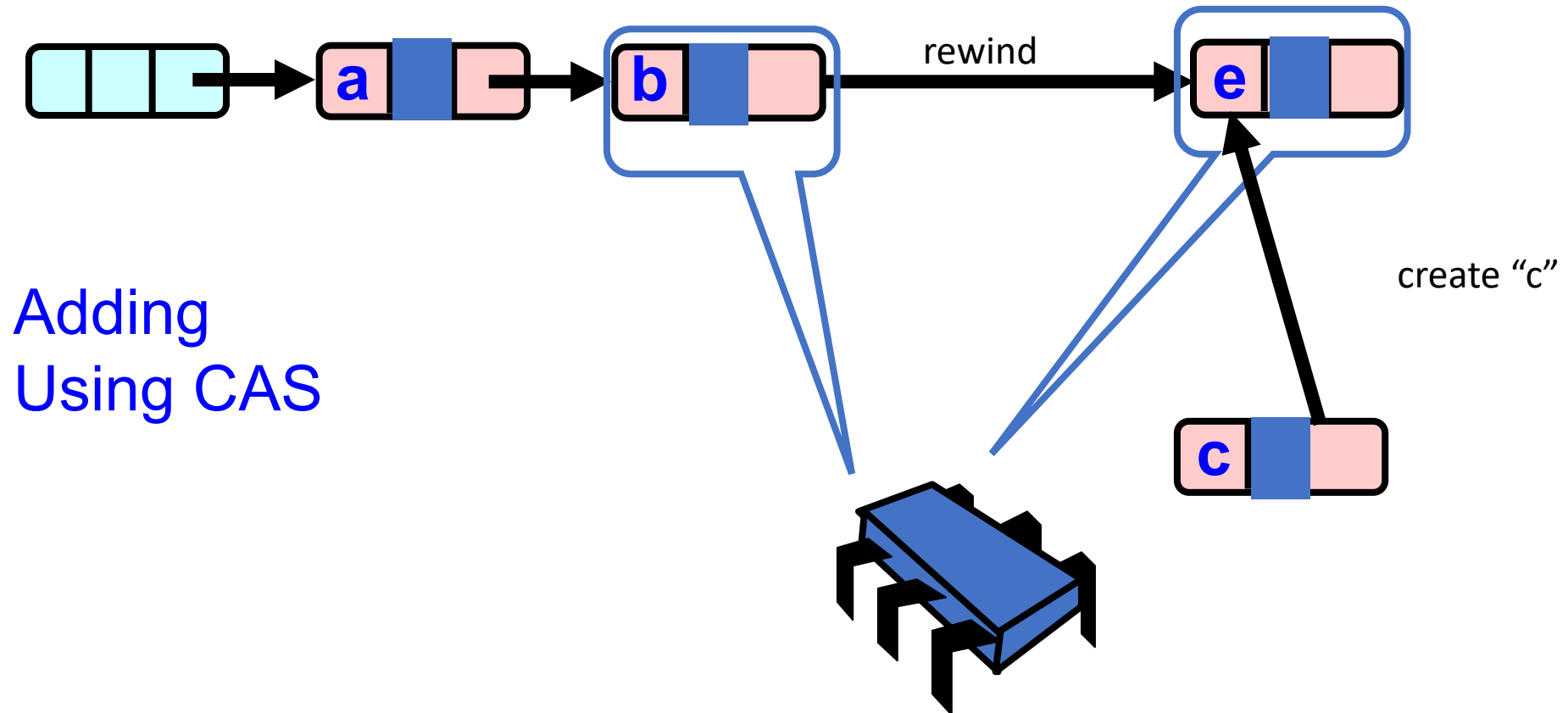
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Lock-free Lists

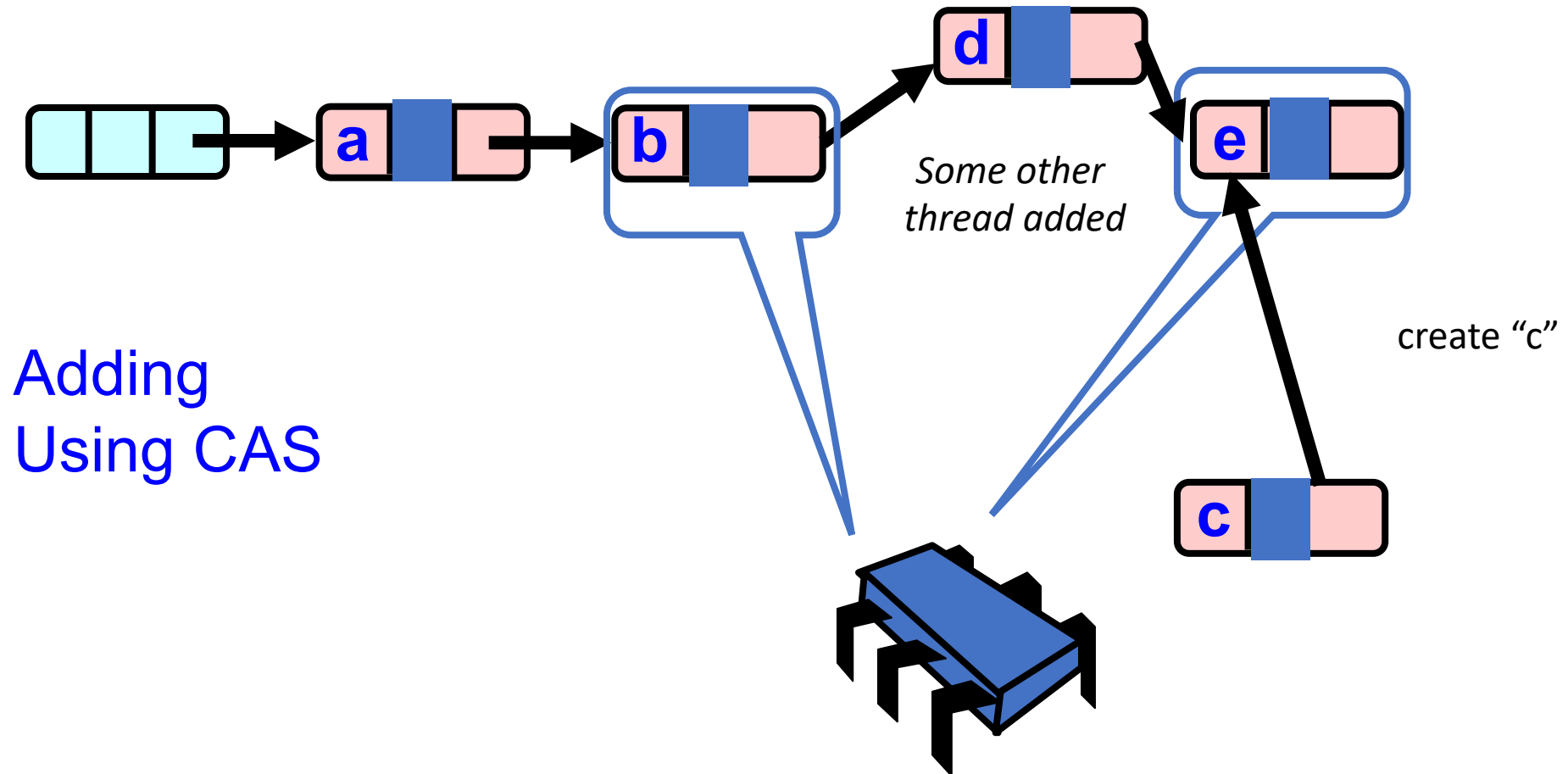
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Lock-free Lists

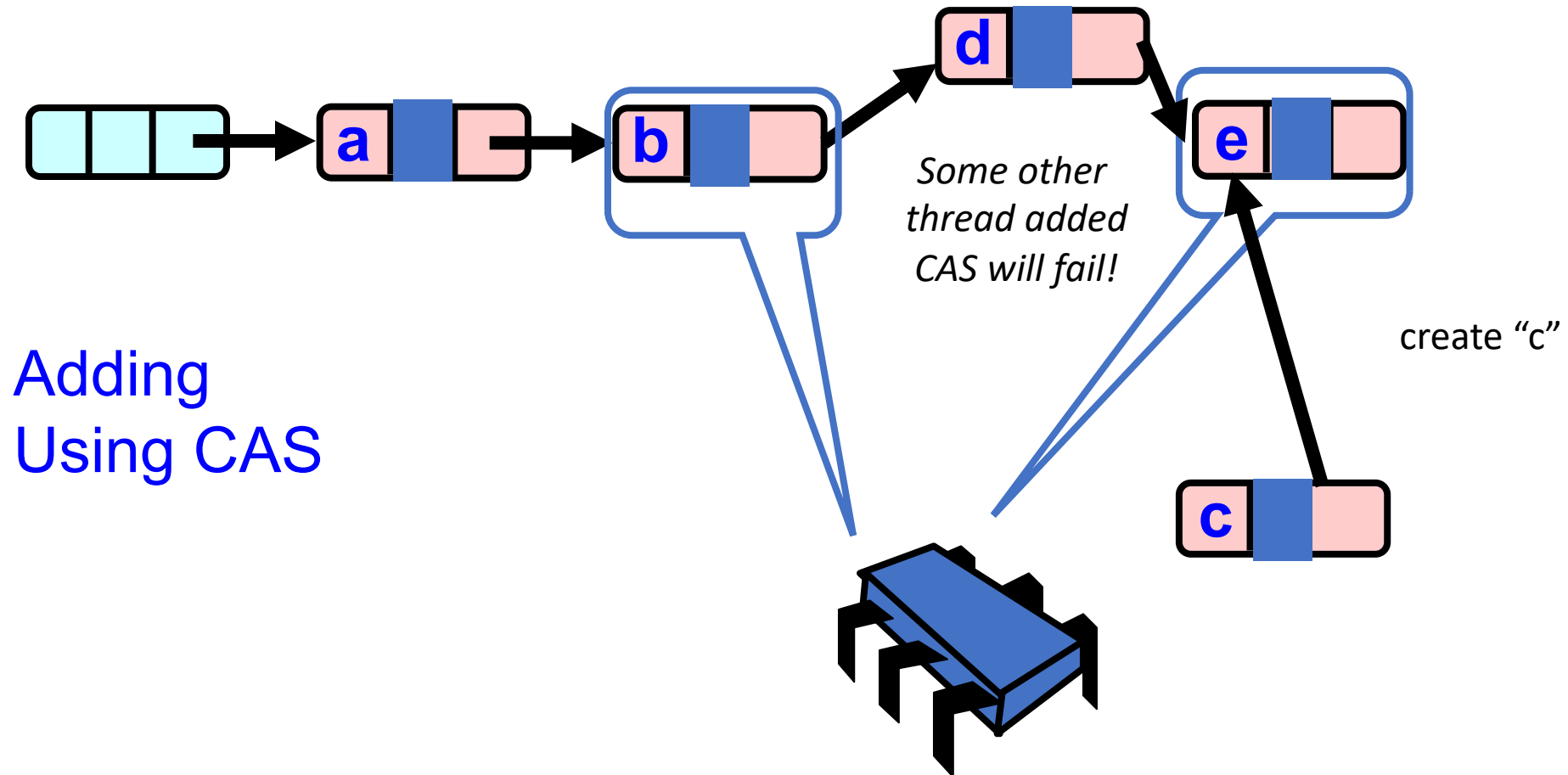
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Lock-free Lists

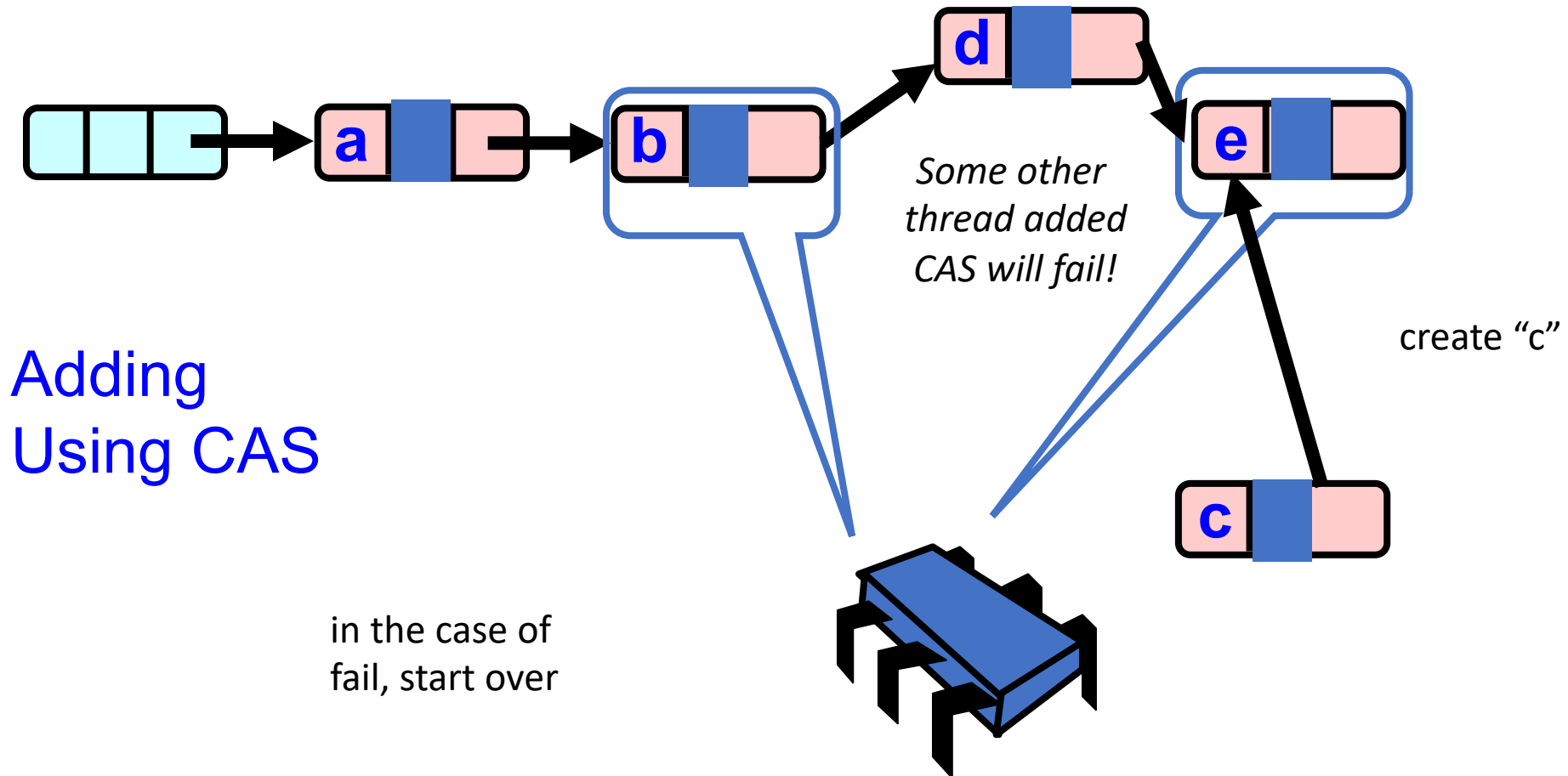
Only add if your insertion point is valid!

`CAS(b.next, e, c);`

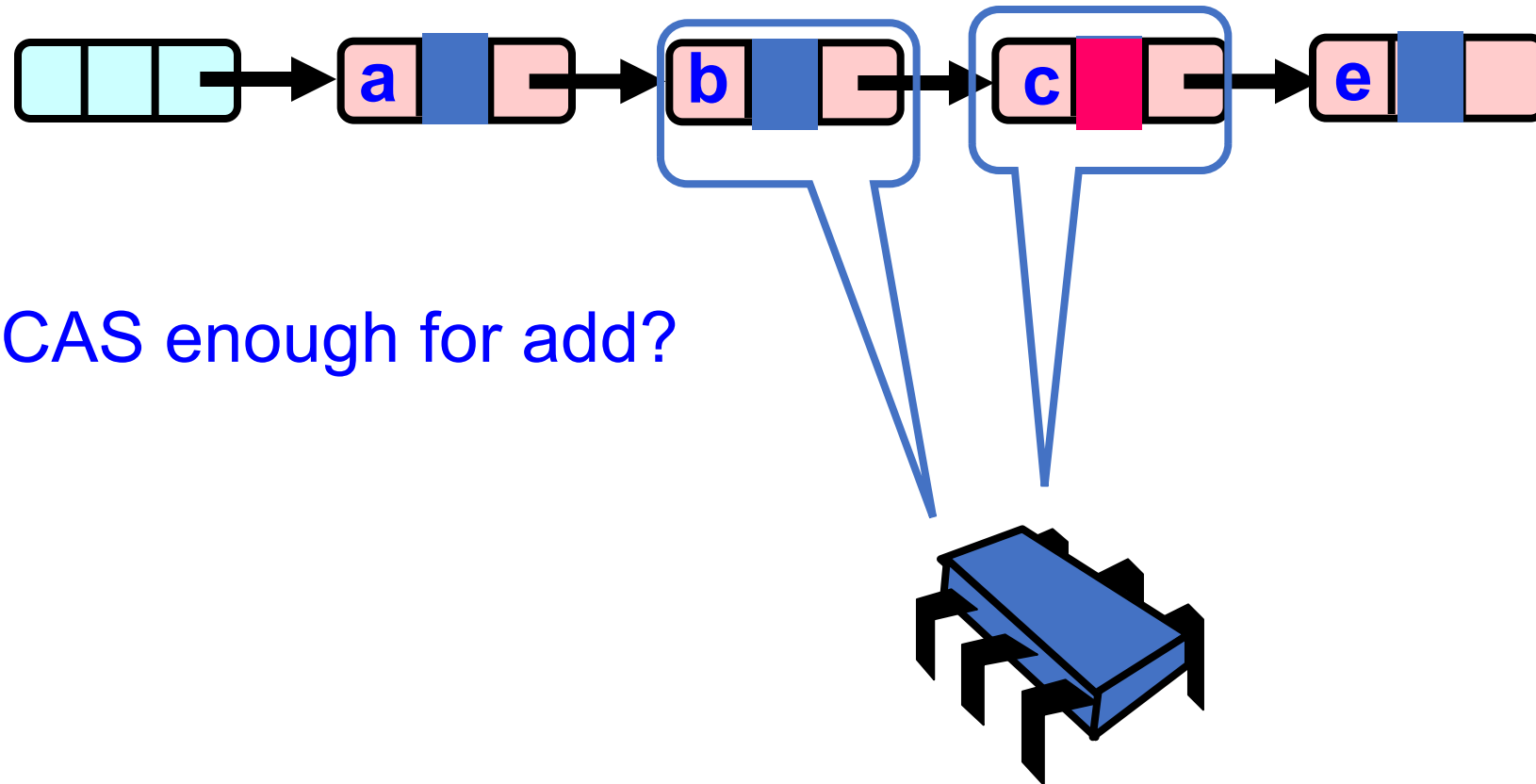
Find the location
Cache your insertion point!

`b.next == e`

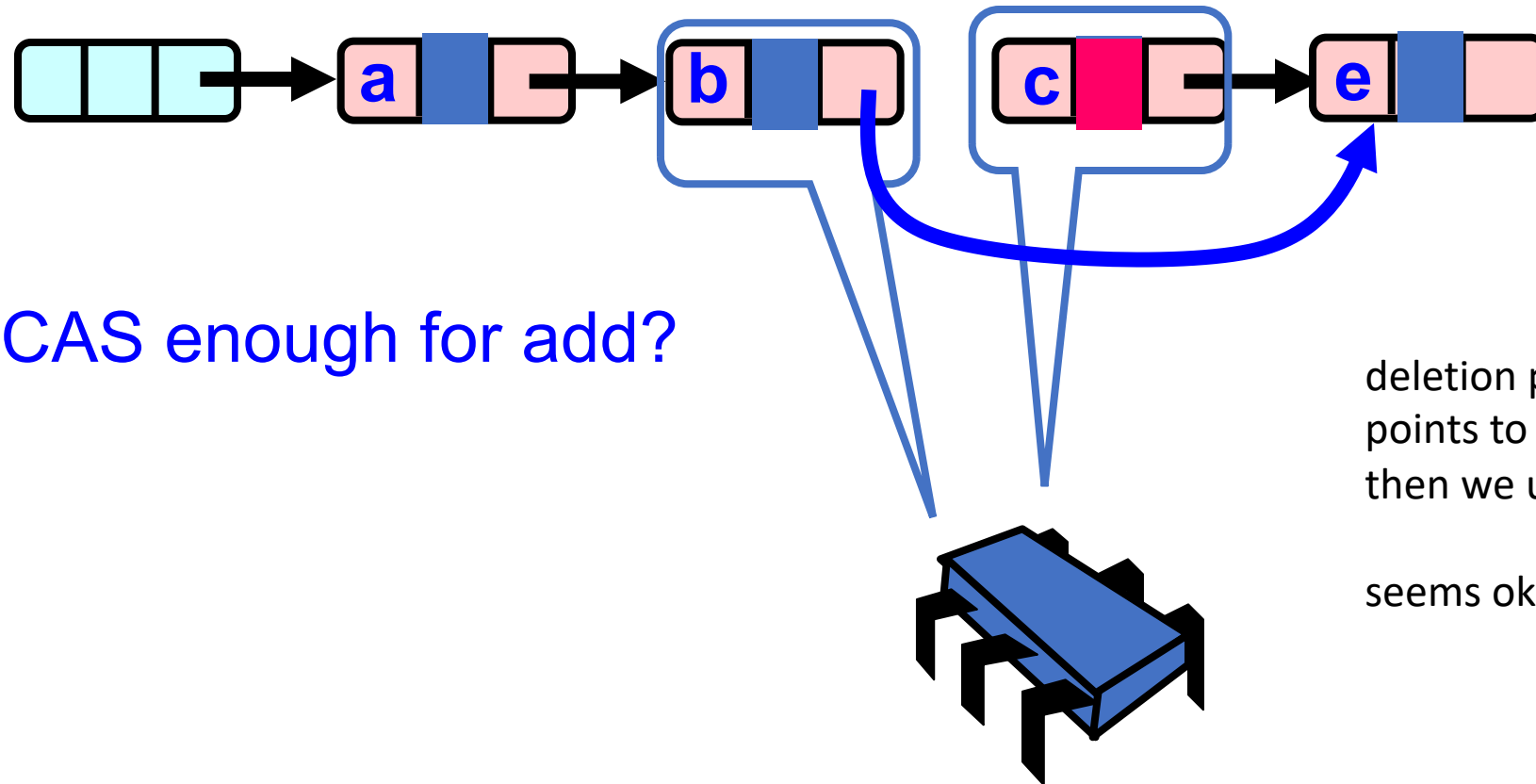
*notation is being abused here: e and c will be node **



Lock-free Lists



Lock-free Lists



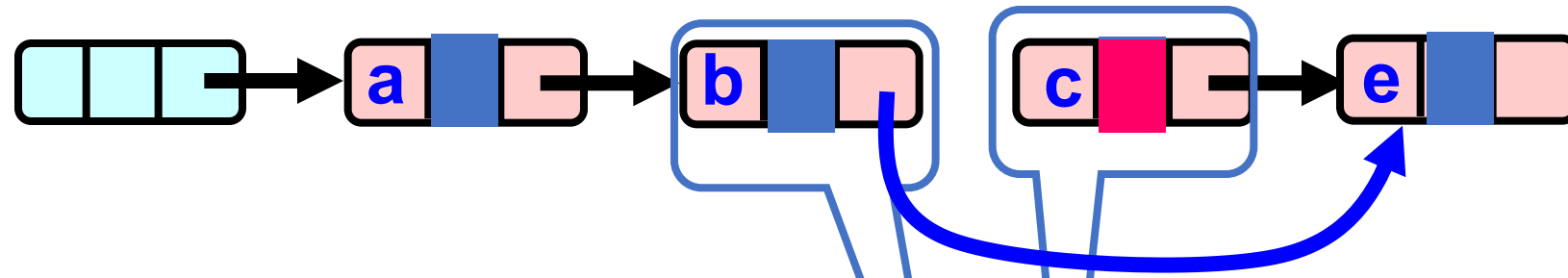
CAS enough for add?

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

seems okay...

Lock-free Lists

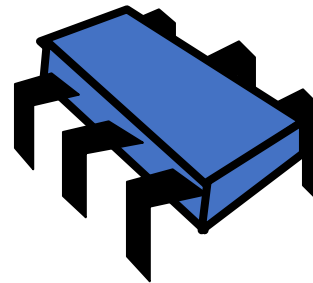
*ensures that nobody has added a node
between b and c*



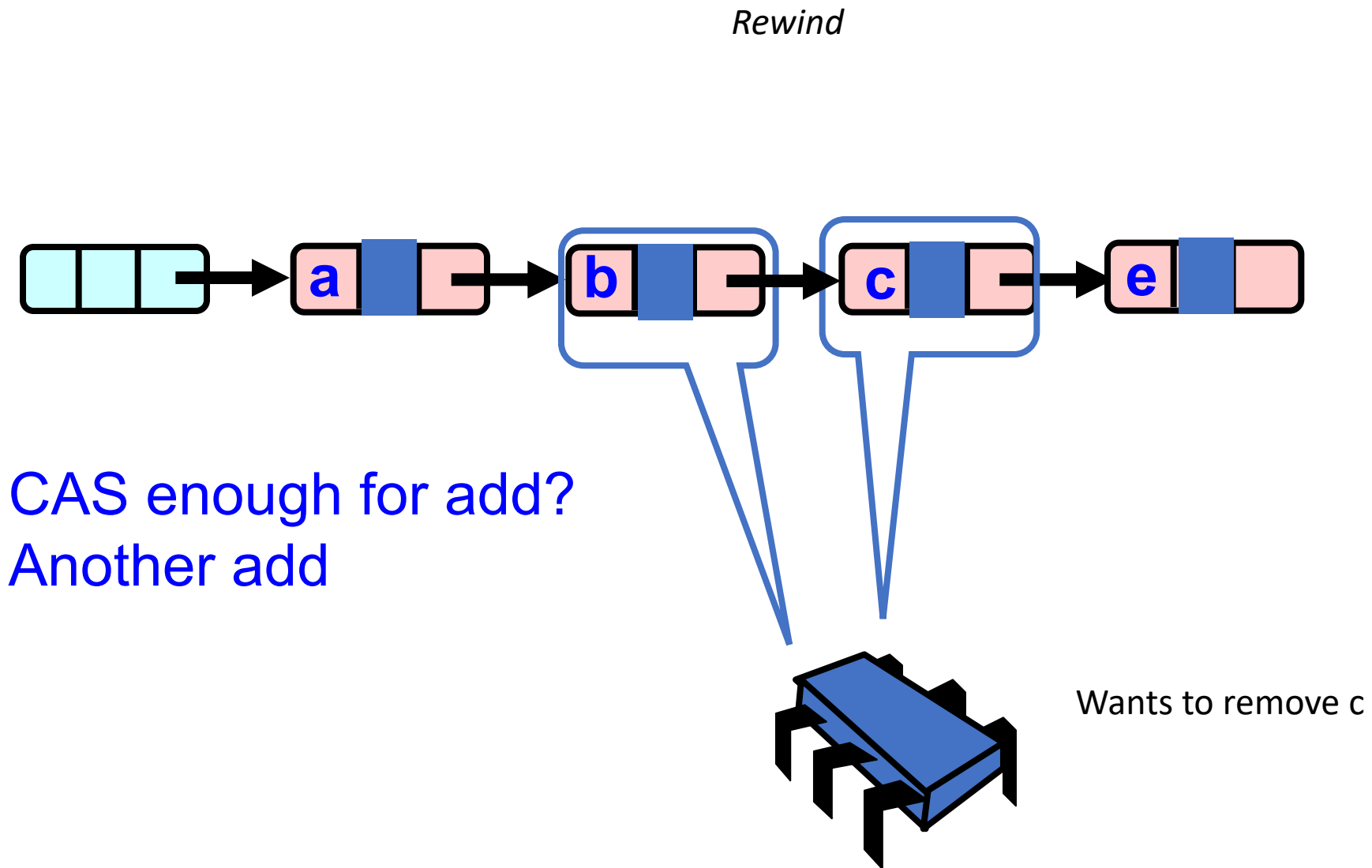
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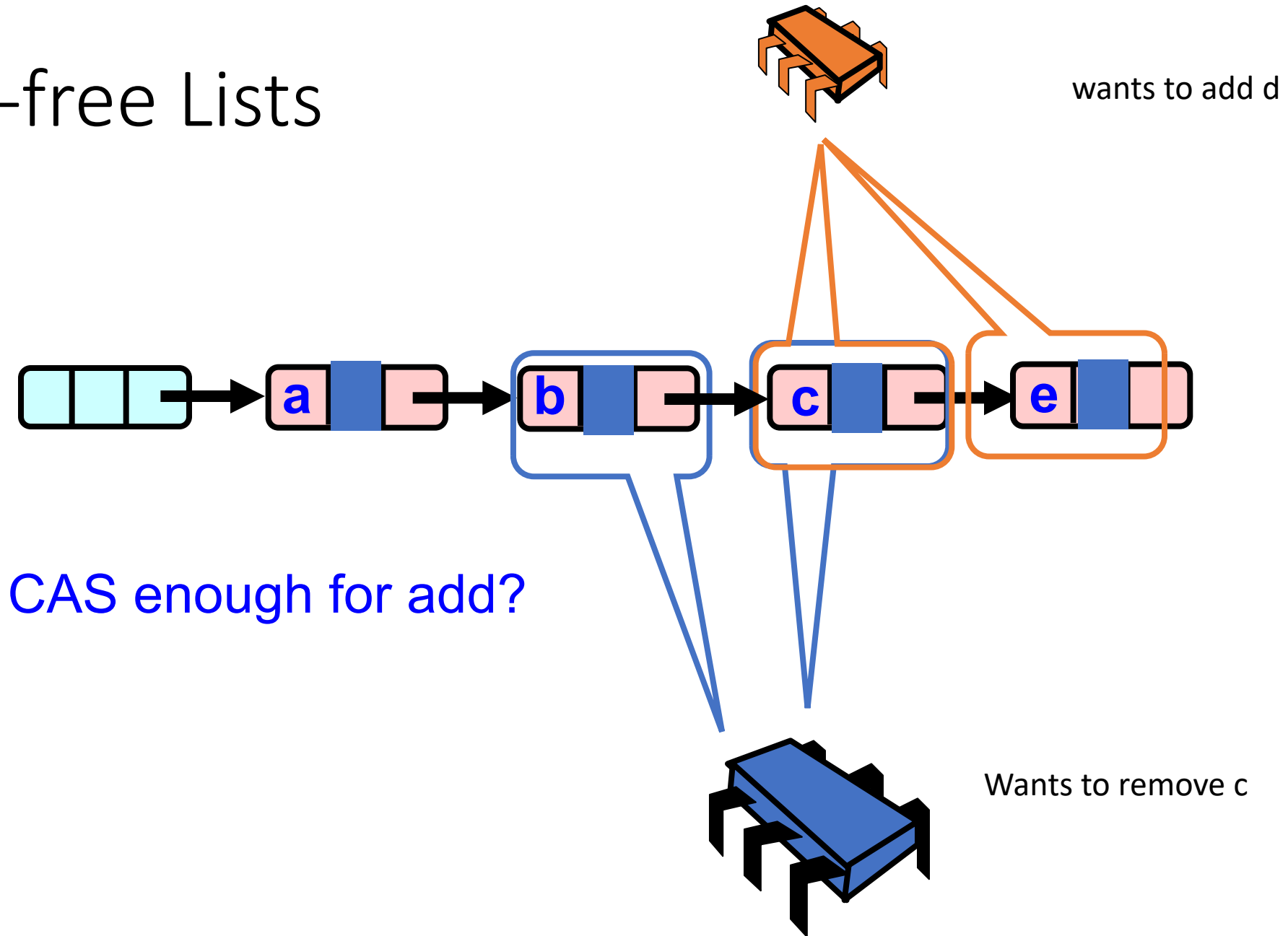
seems okay...



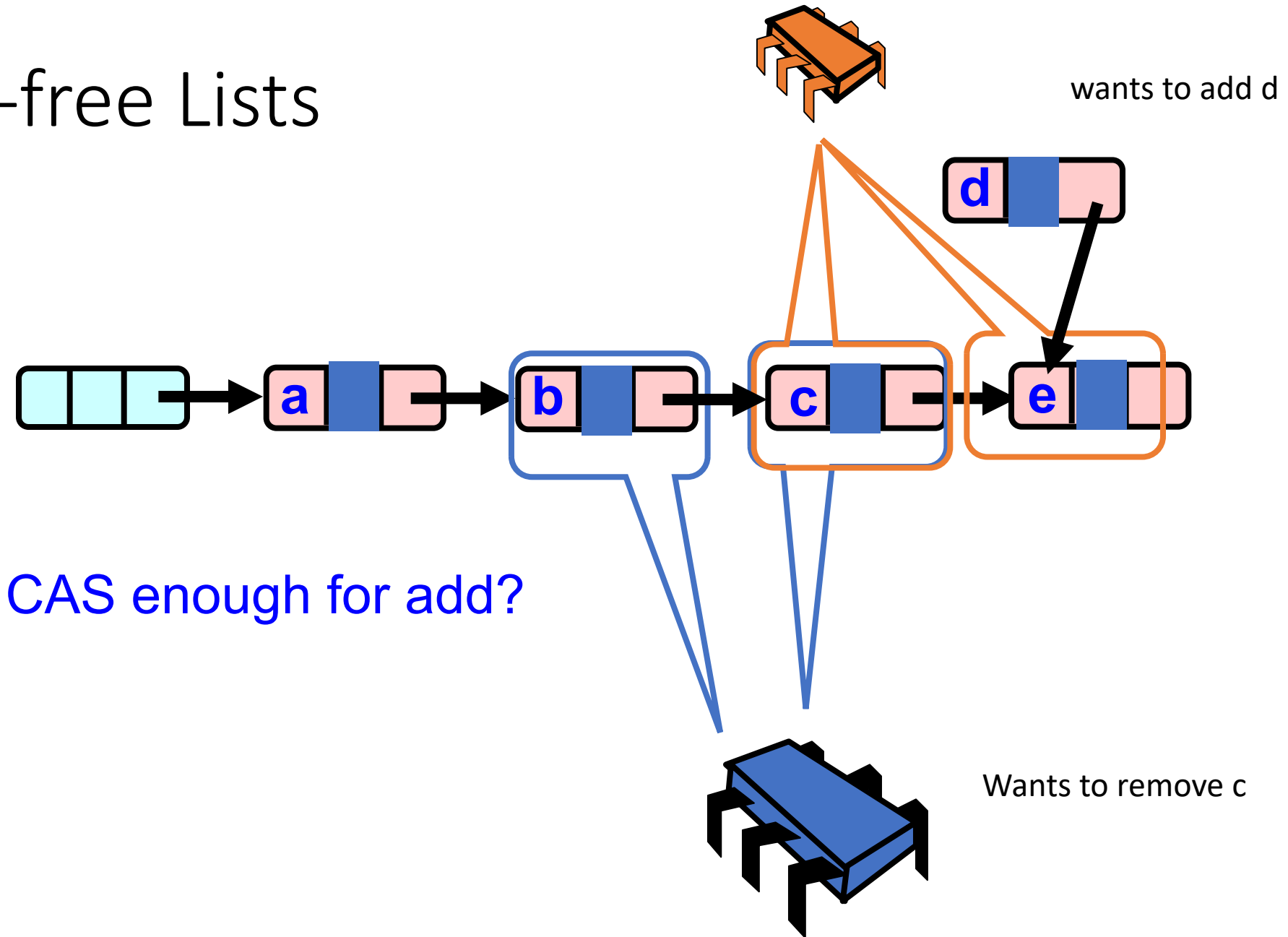
Lock-free Lists



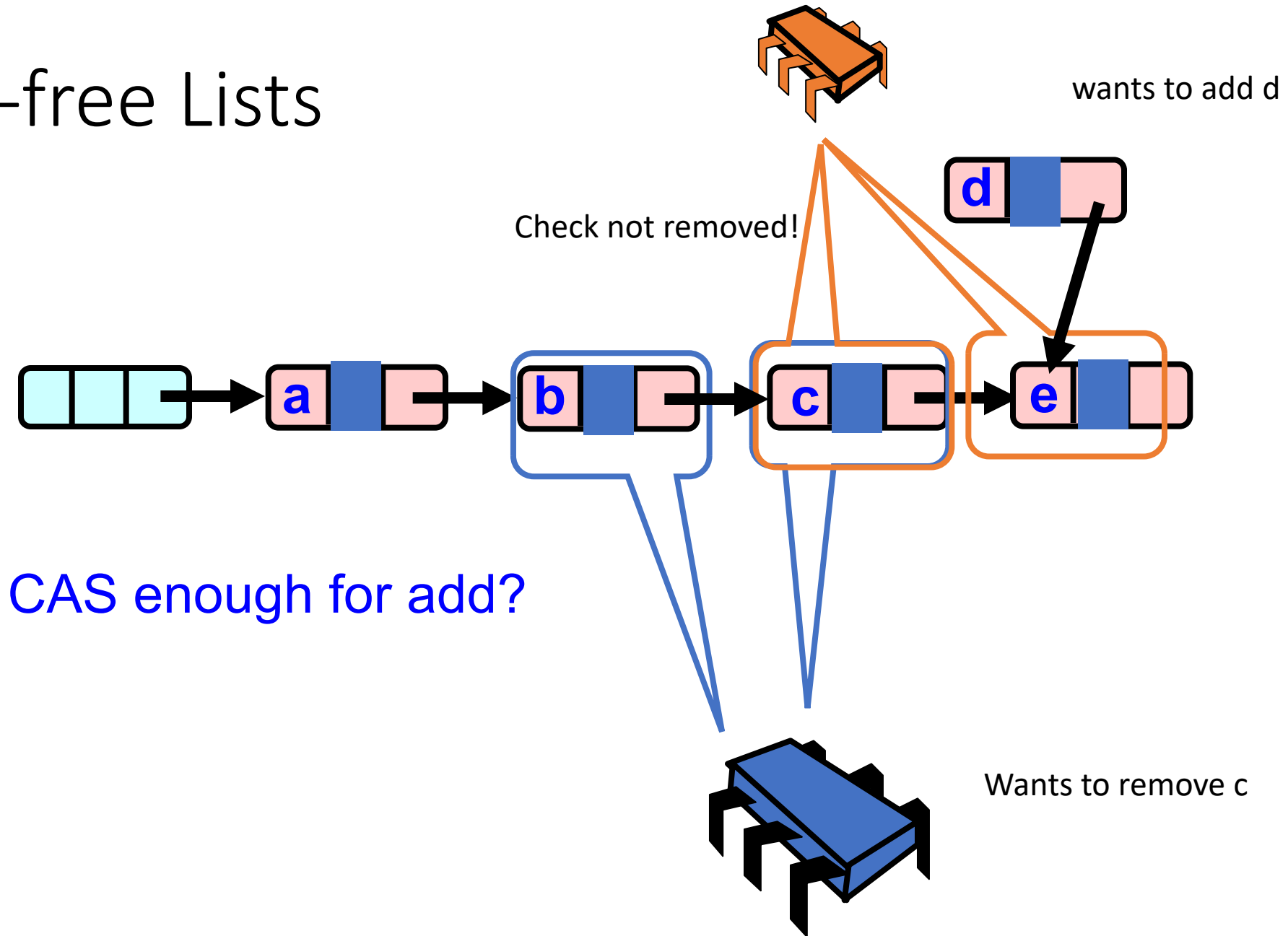
Lock-free Lists



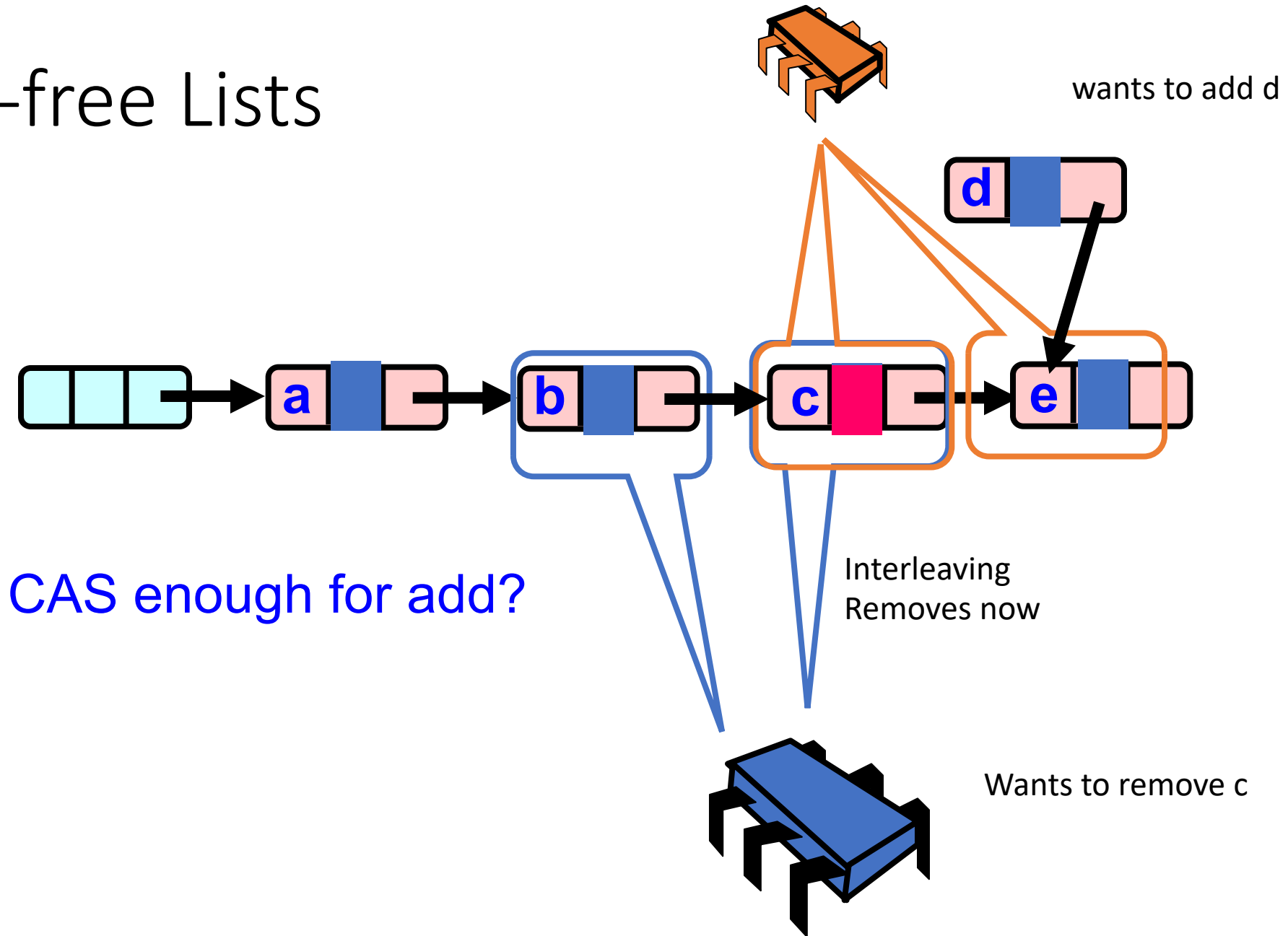
Lock-free Lists



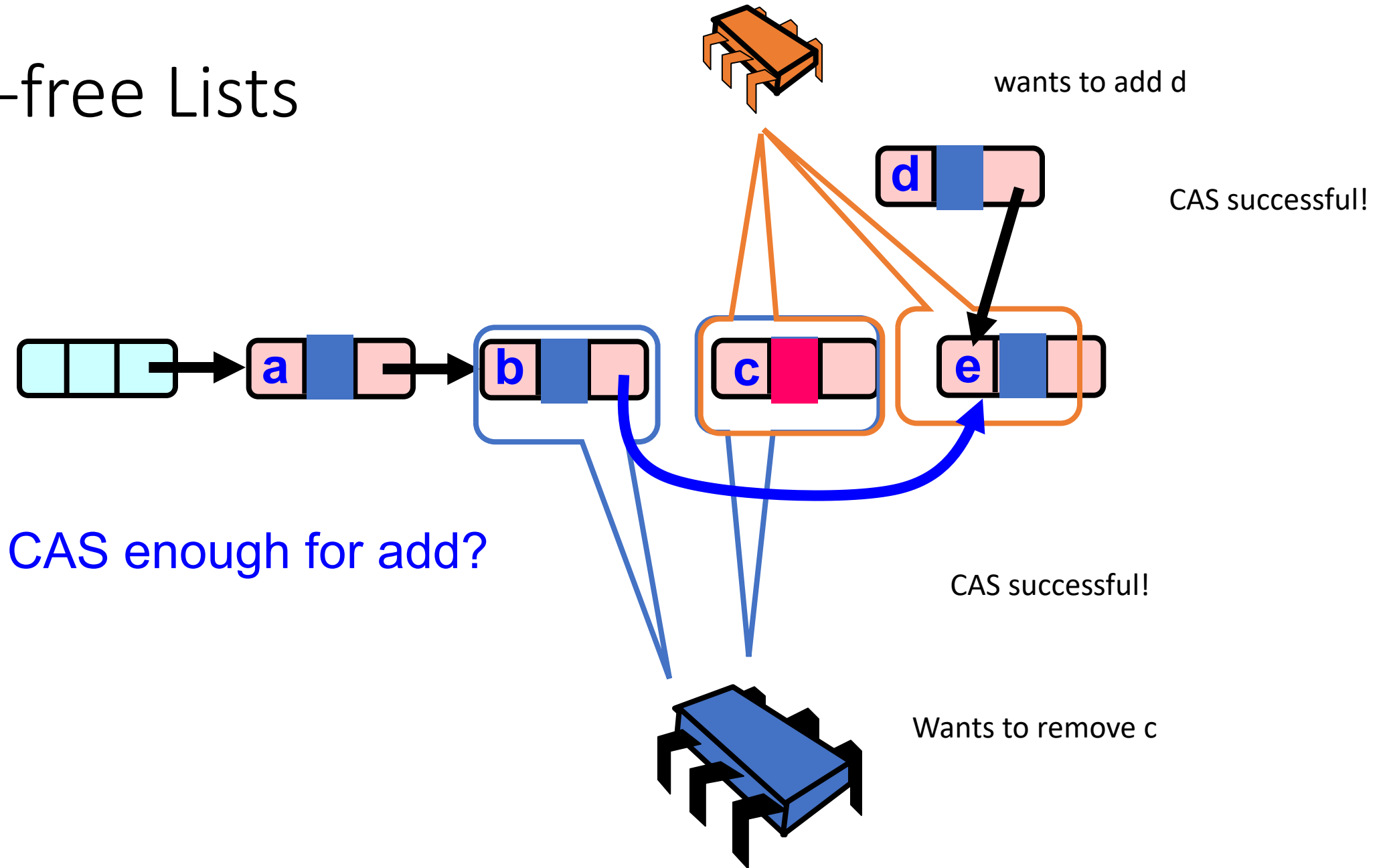
Lock-free Lists



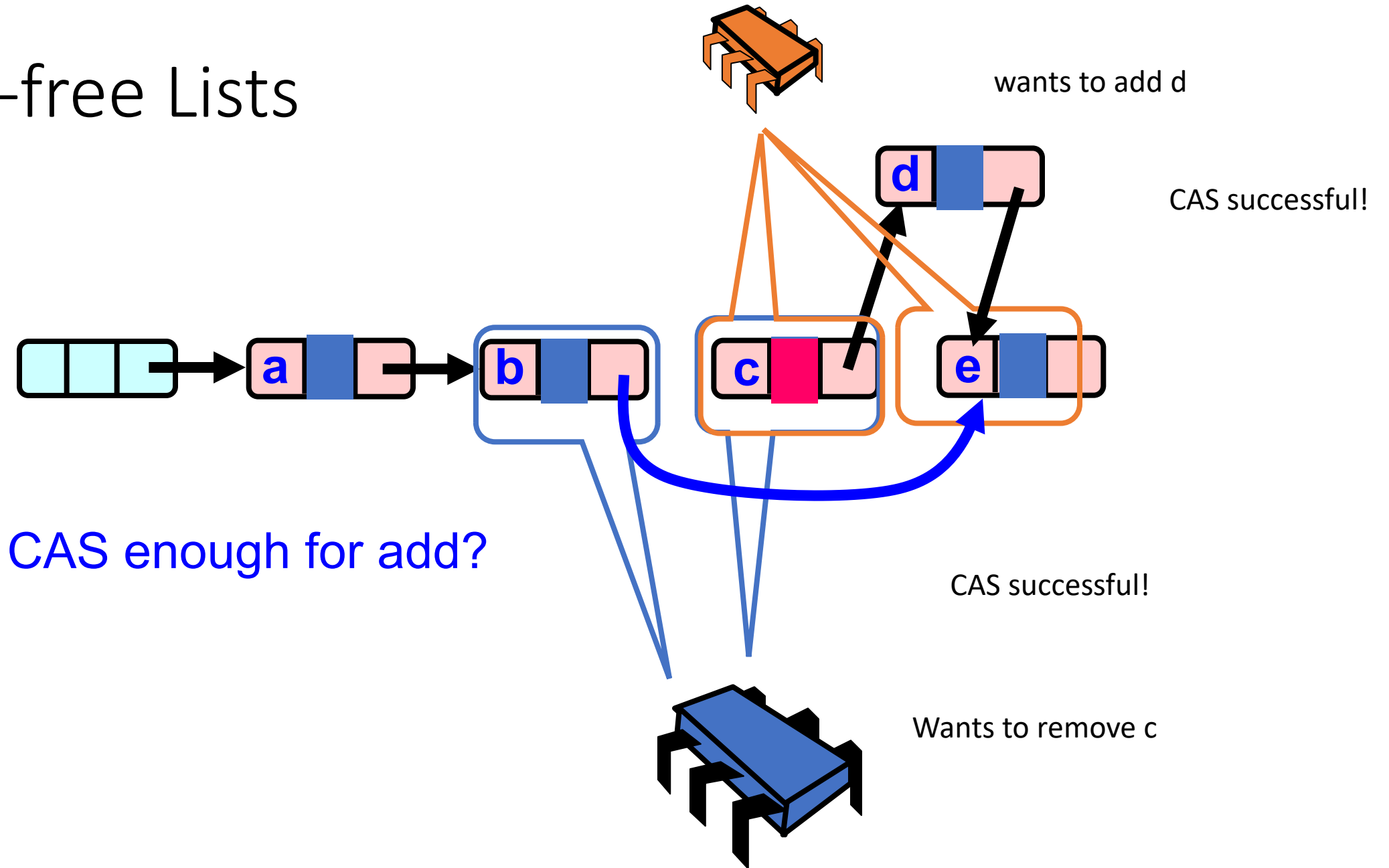
Lock-free Lists



Lock-free Lists

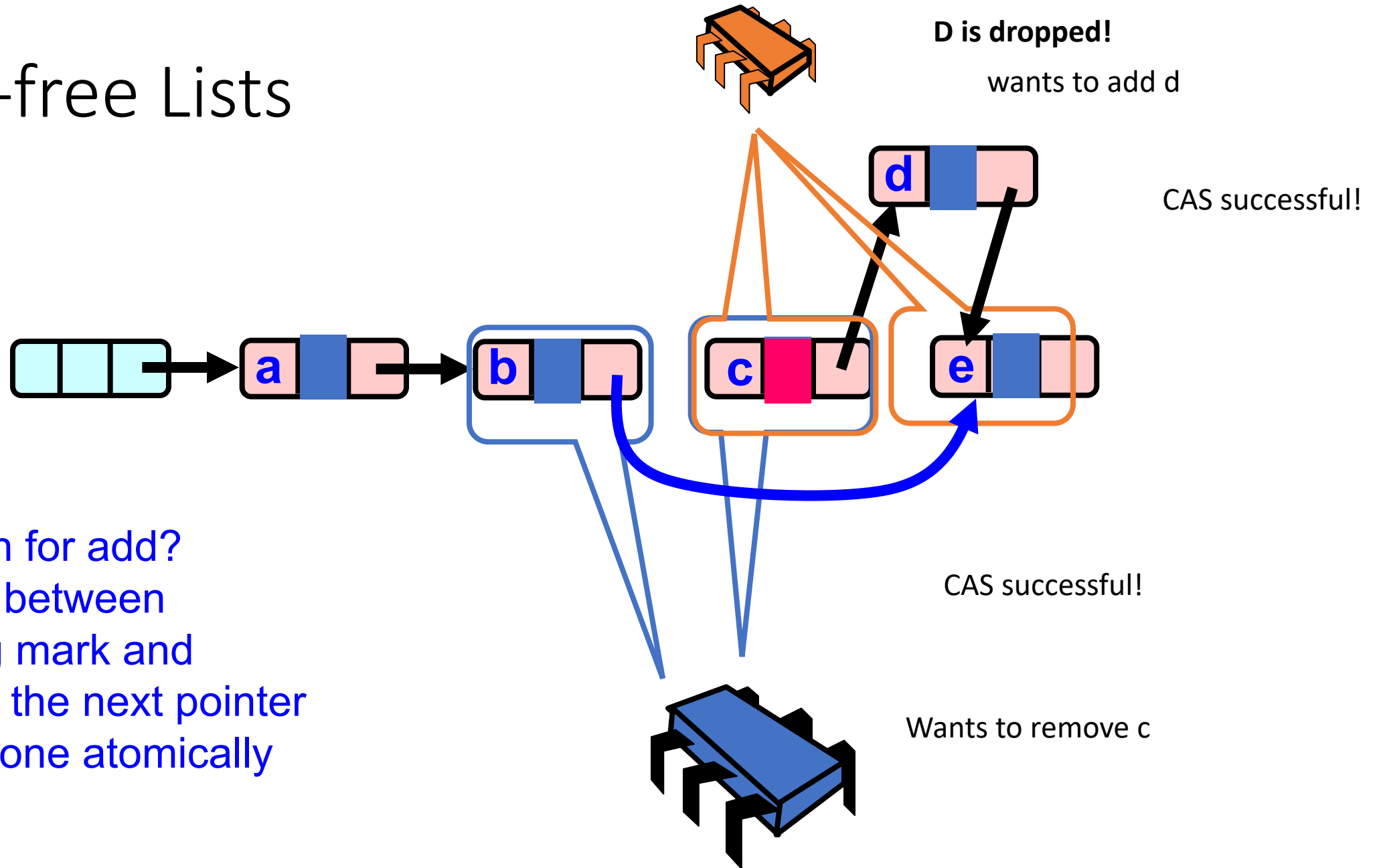


Lock-free Lists



Lock-free Lists

CAS enough for add?
Interleaving between
checking mark and
updating the next pointer
Should be done atomically



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.

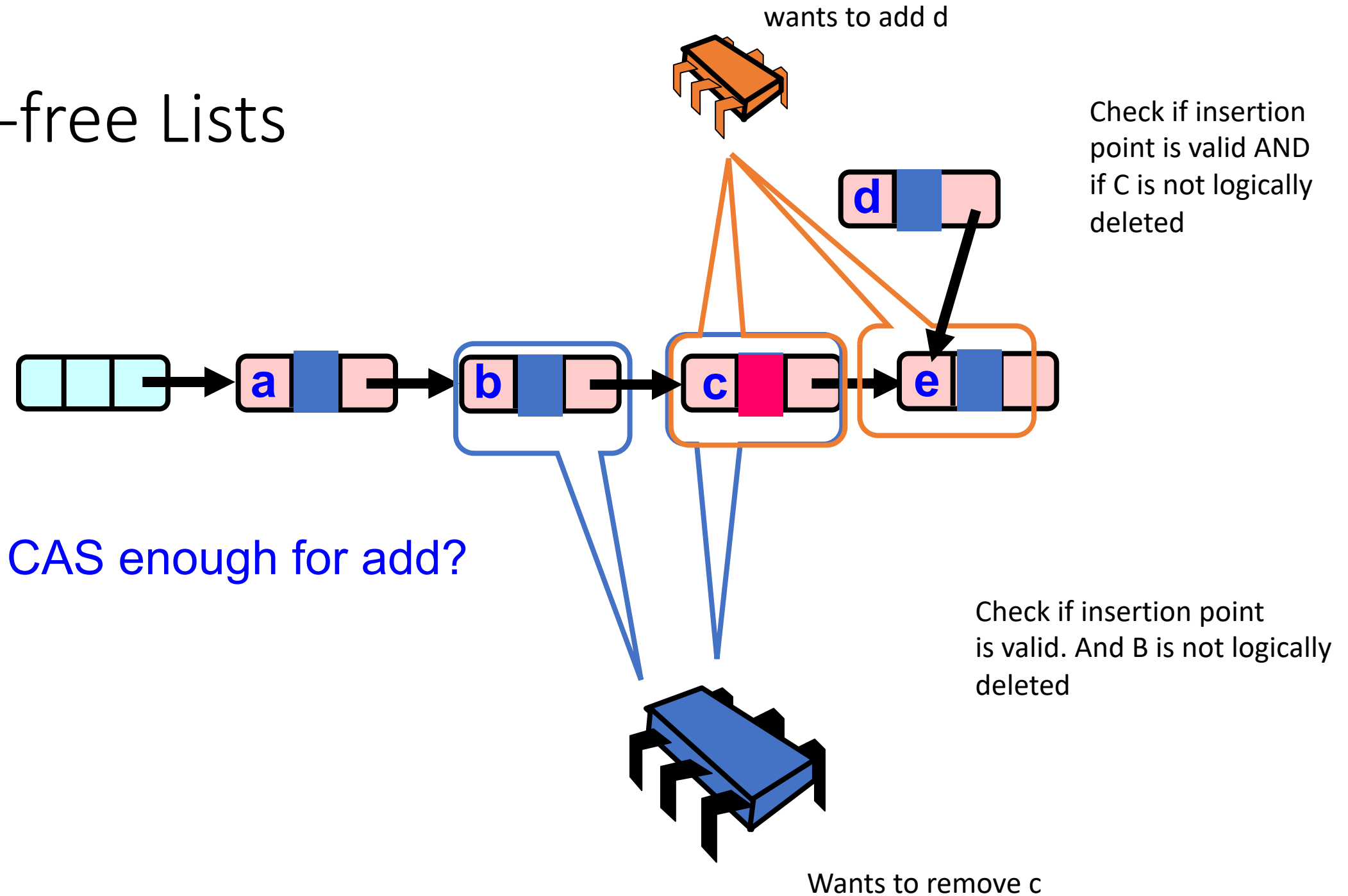
Marking a Node

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



`CAS(c.next, <0, e>, <0, d>)`

Lock-free Lists



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.

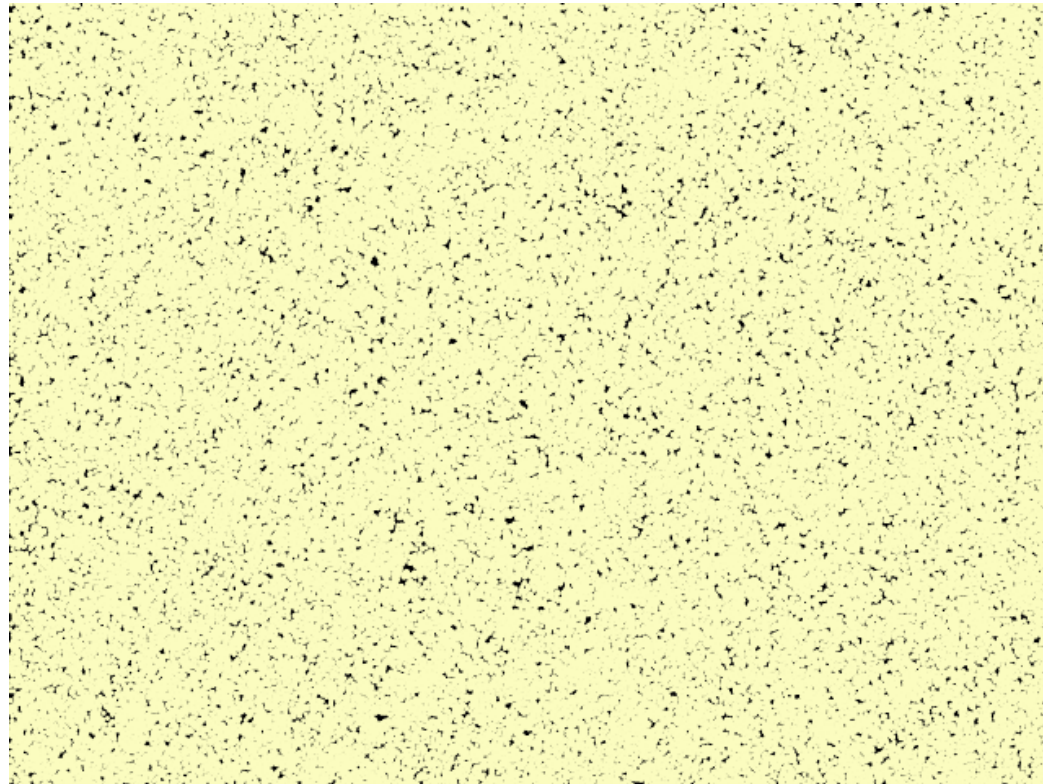
Barriers

Barriers

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

Barrier Examples

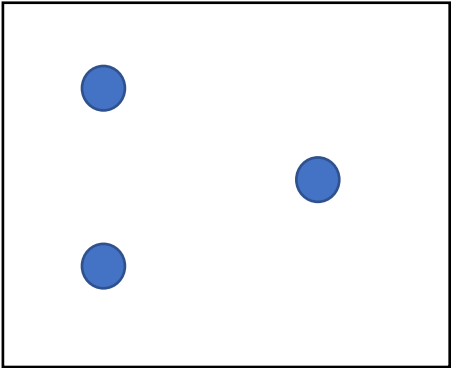
Particle simulation



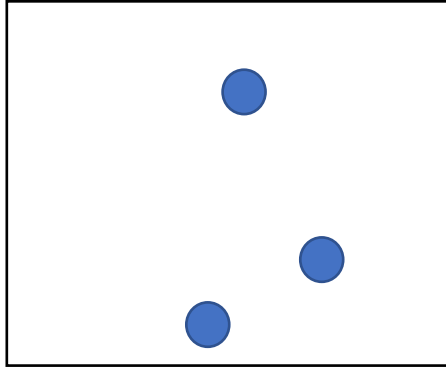
by Yanwen Xu

Barrier Examples

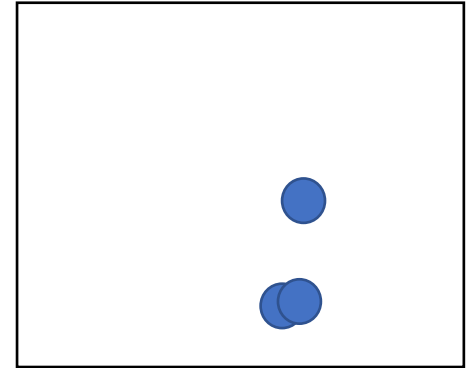
Particle simulation



time = 0



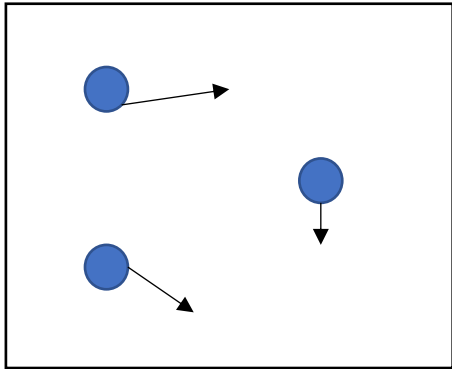
time = 1



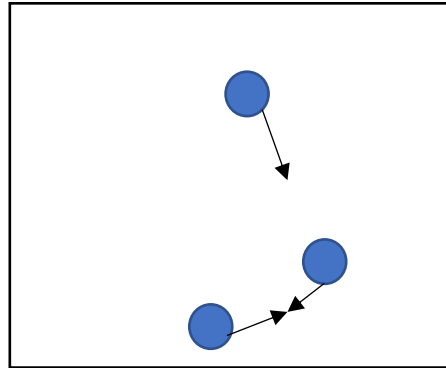
time = 2

Barrier Examples

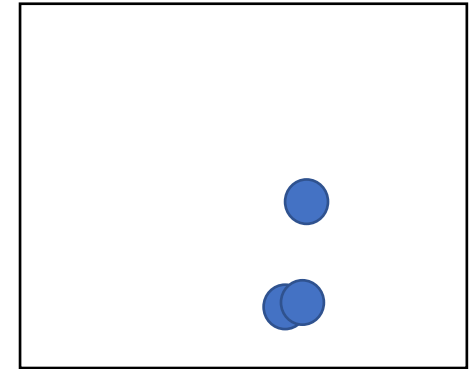
Particle simulation



time = 0



time = 1

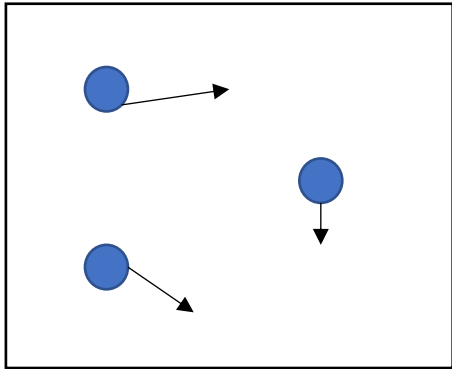


time = 2

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

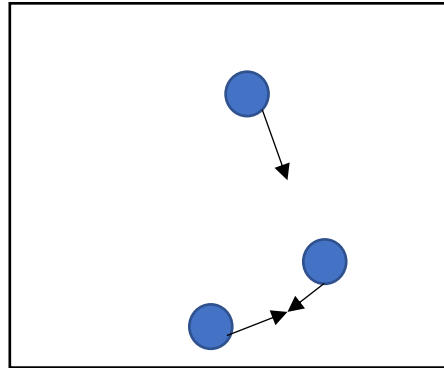
Barrier Examples

Particle simulation



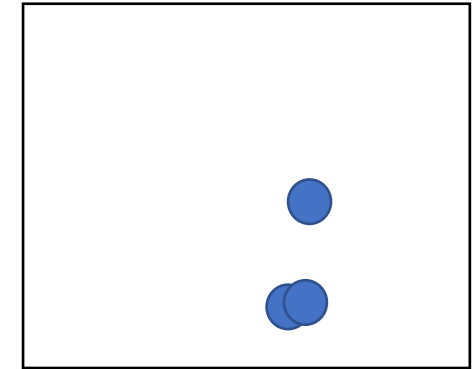
time = 0

`barrier();`



time = 1

`barrier();`



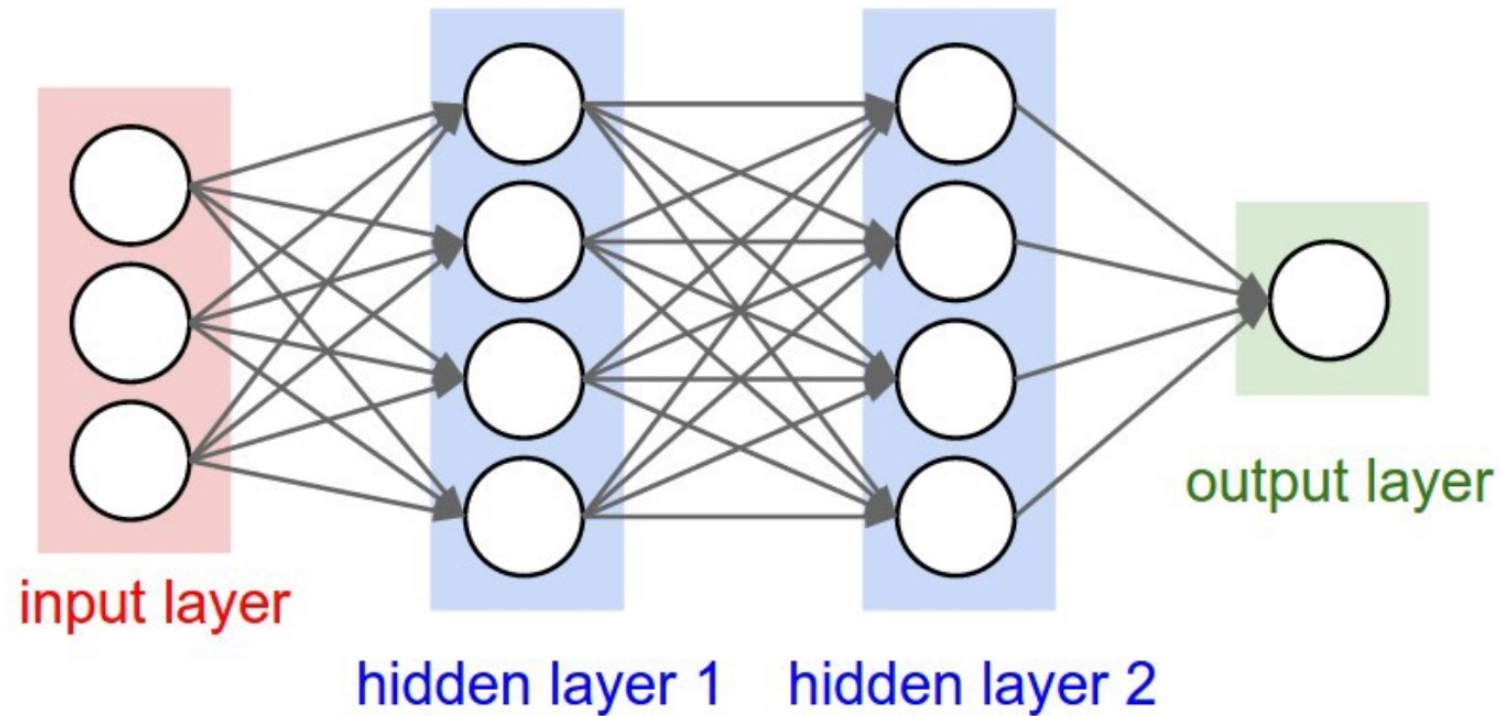
time = 2

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

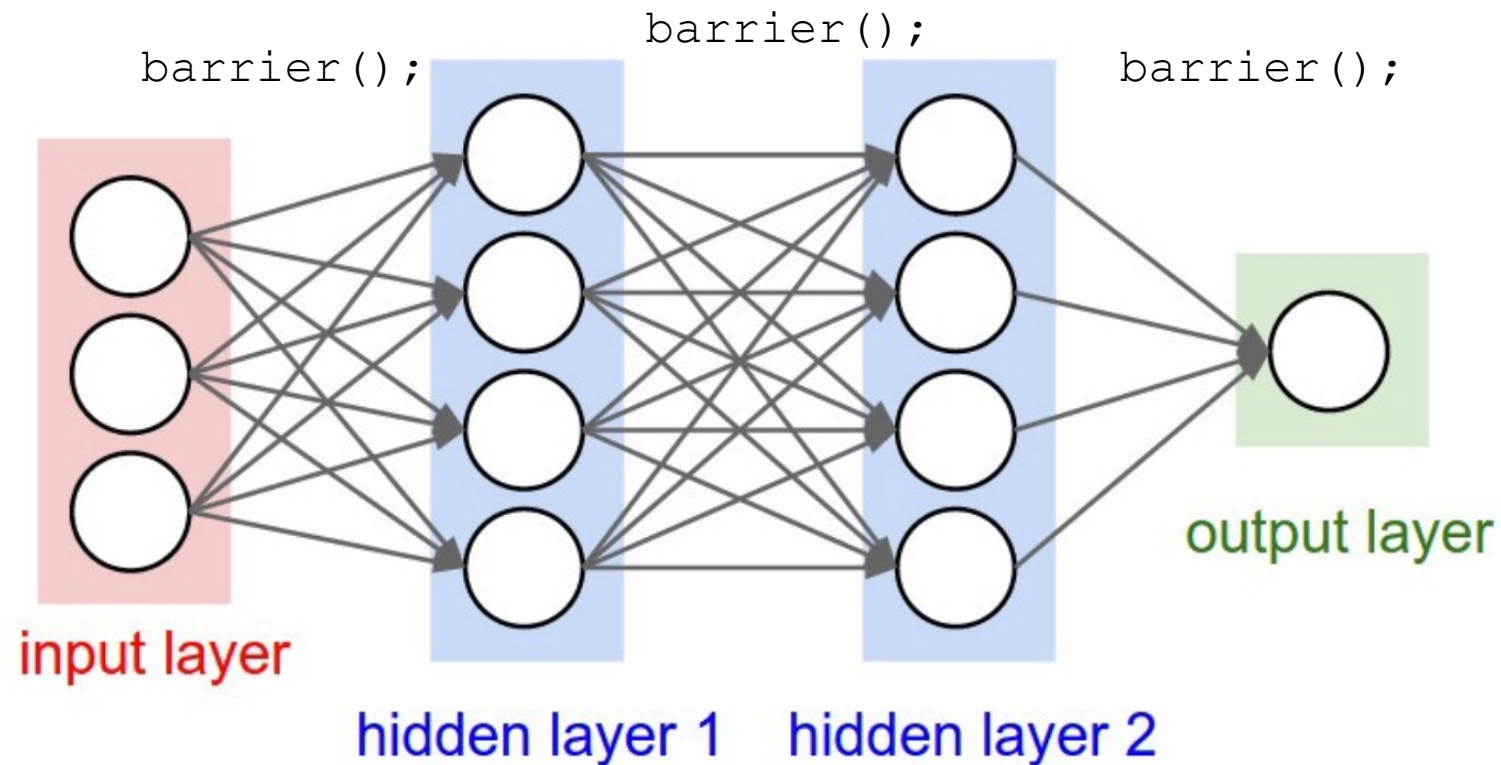
Barrier Examples

- Deep neural networks



Barrier Examples

- Deep neural networks



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

Barriers

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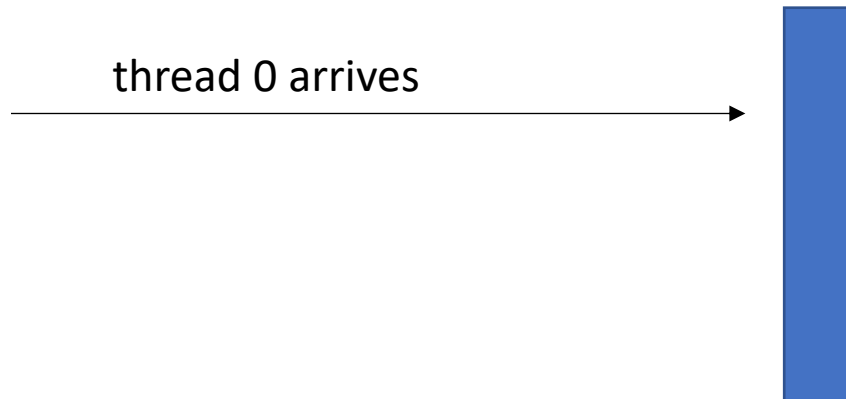
Example: say there are 4 threads: `barrier();`



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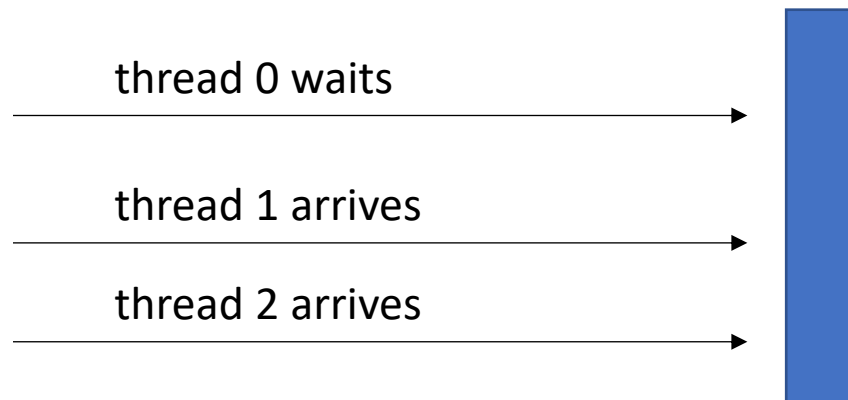
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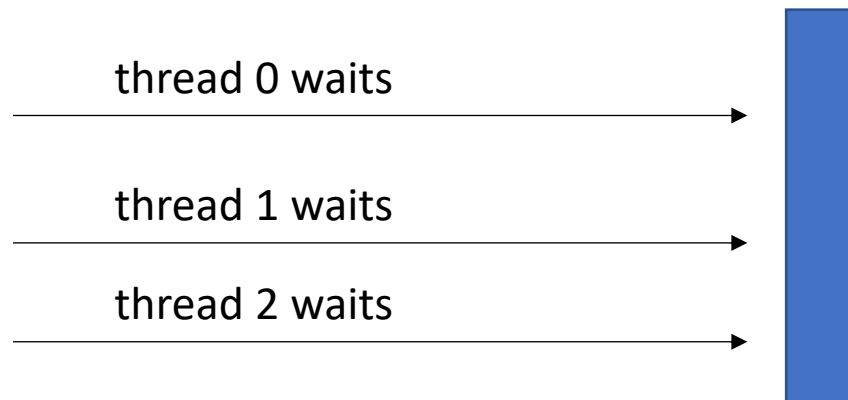
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Barriers

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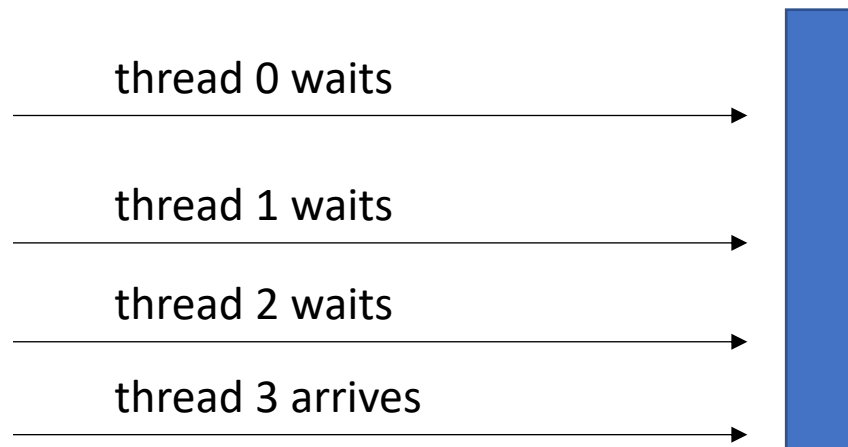
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Example: say there are 4 threads: `barrier();`

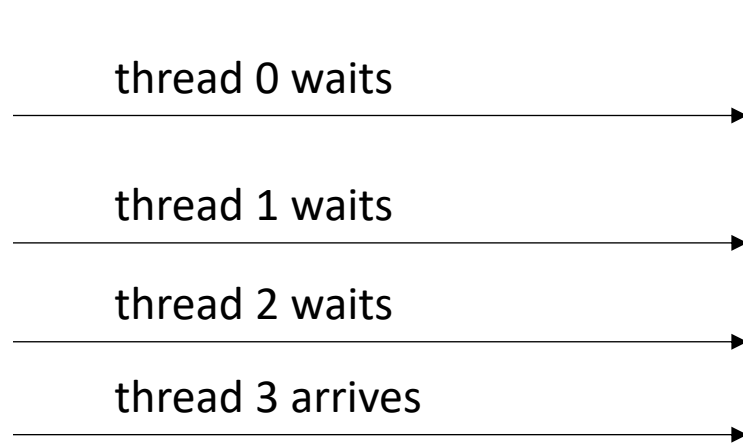


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- Intuition: threads stop and wait for each other:
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 - Threads **wait** at the barrier
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Example: say there are 4 threads:

`barrier();`



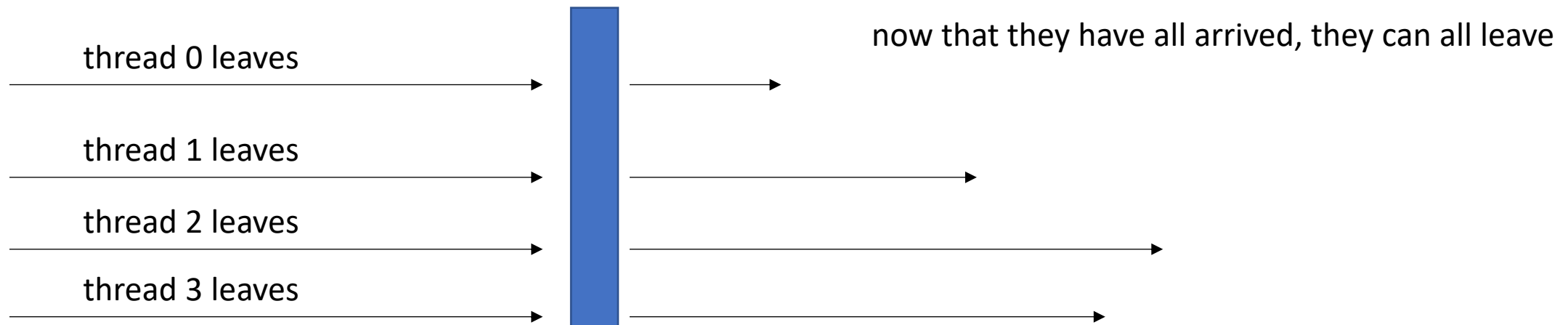
now that they have all arrived

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

Example: say there are 4 threads:

`barrier();`



A more formal specification

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

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

Thread 0:

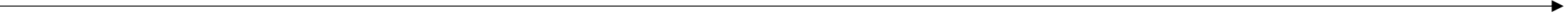
```
*x = 1;
```

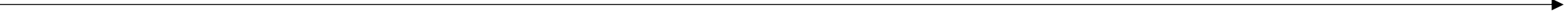
```
B.barrier();
```

Thread 1:

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

```
var = *x;
```

thread 0 

thread 1 

A more formal specification

Given a global barrier B
and a global memory location x where
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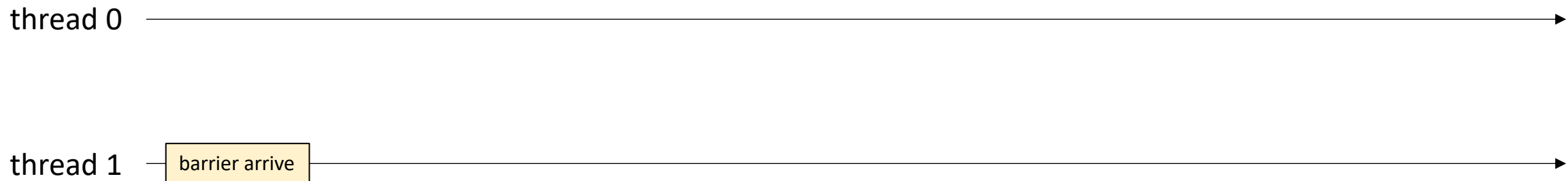
Thread 0:

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

Thread 1:

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

gives an event:
barrier arrive



A more formal specification

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Thread 0:

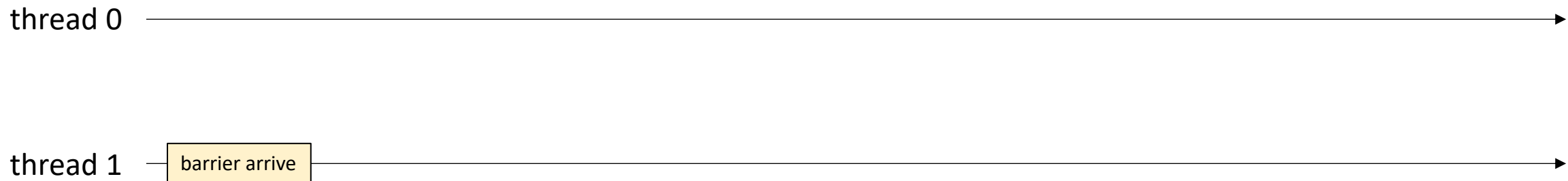
```
*x = 1;  
B.barrier();
```

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)



A more formal specification

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

Thread 0:

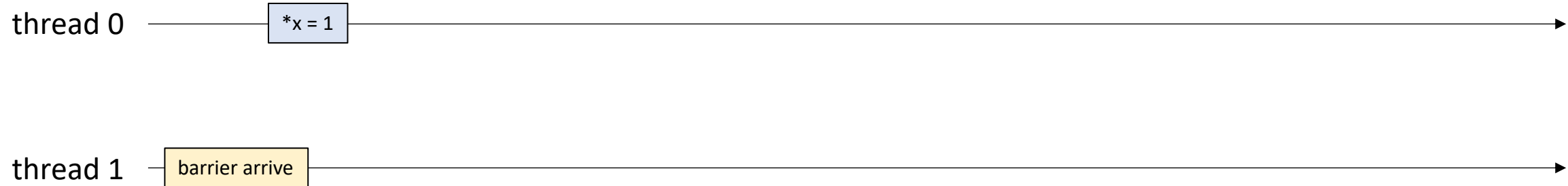
```
*x = 1;
```

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

Thread 1:

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



A more formal specification

Given a global barrier B
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Thread 0:

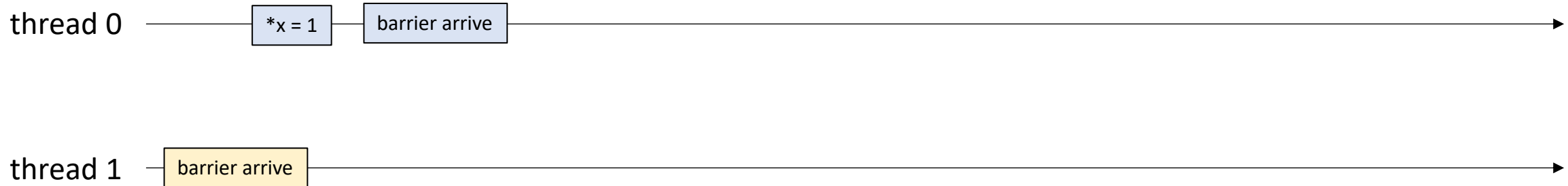
```
*x = 1;
```

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

Thread 1:

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

```
var = *x;
```



A more formal specification

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

Thread 0:

```
*x = 1;
```

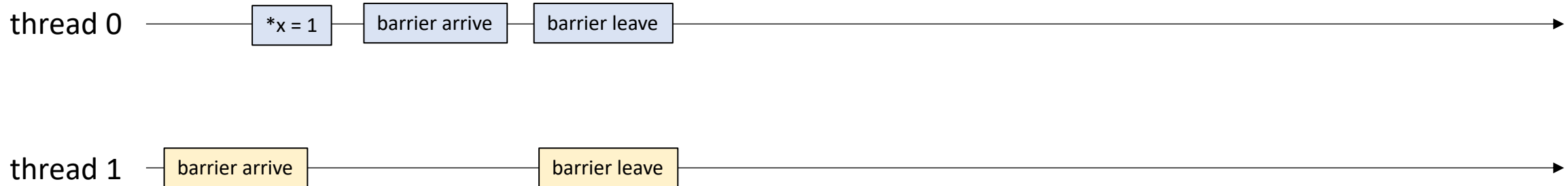
```
B.barrier();
```

Thread 1:

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

```
var = *x;
```

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



A more formal specification

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

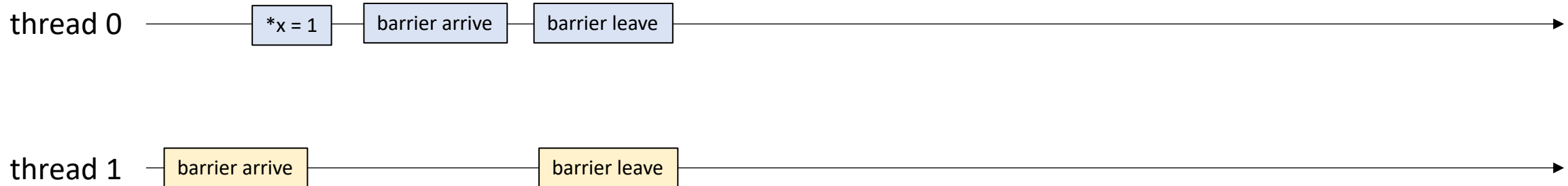
Thread 0:

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

Thread 1:

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

This finishes the barrier execution



A more formal specification

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

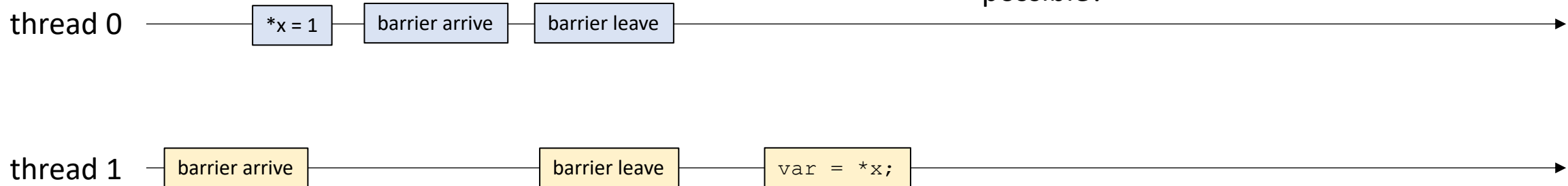
Thread 0:

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

Thread 1:

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

what value must this read? Any other value possible?



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

Thread 0:


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


Thread 1:

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

Thread 2:

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

thread 0 

thread 1 

thread 2 

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

Thread 0:

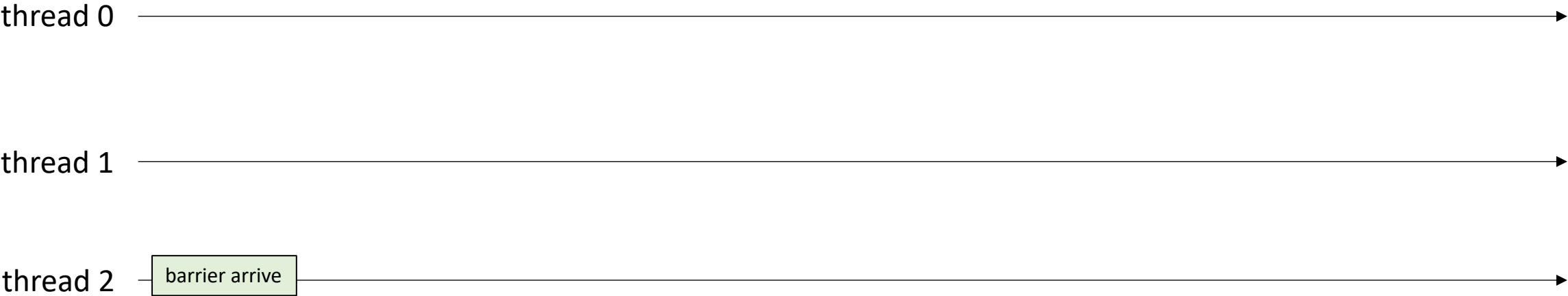
```
*x = 1;  
B.barrier();
```

Thread 1:

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B.barrier();
```

Thread 2:

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

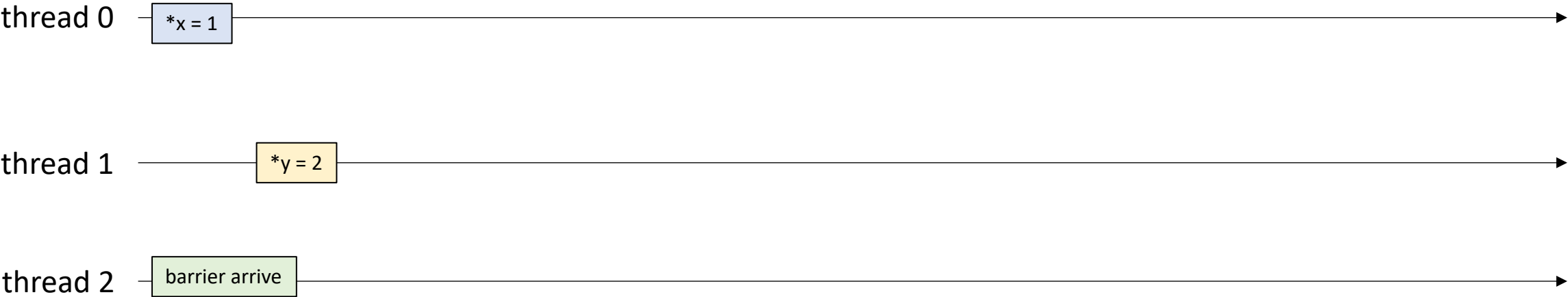


One more example, assume initially $*x = *y = 0$

Thread 0:
`*x = 1;`
`B.barrier();`

Thread 1:
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`B.barrier();`

Thread 2:
`B.barrier();`
`var = *x + *y;`

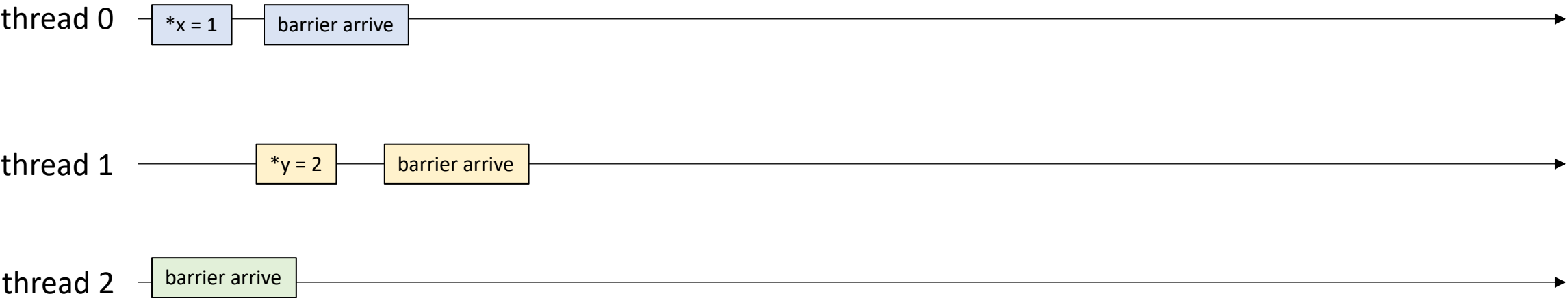


One more example, assume initially $*x = *y = 0$

Thread 0:
`*x = 1;`
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Thread 1:
`*y = 2;`
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Thread 2:
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`var = *x + *y;`



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

Thread 0:

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*x = 1;  
B.barrier();
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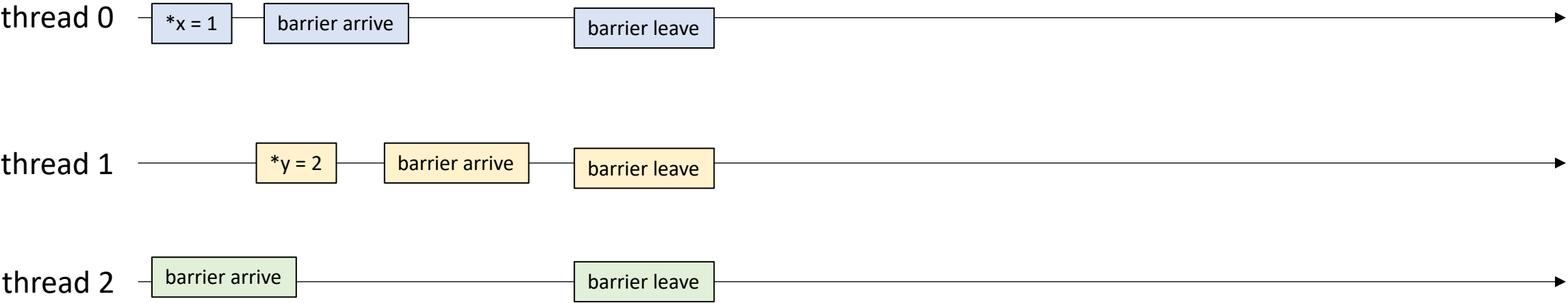
Thread 1:

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

Thread 2:

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

They've all arrived



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

Thread 0:

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

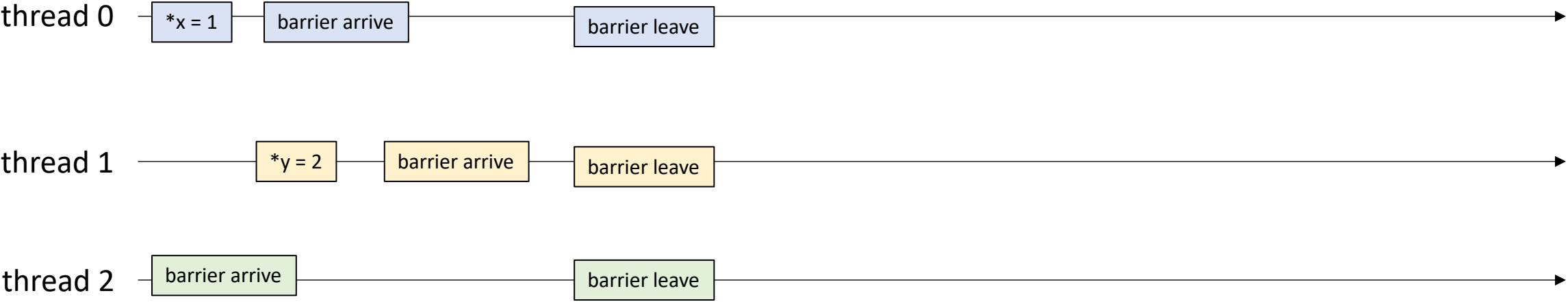
Thread 1:

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

Thread 2:

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

They've all arrived

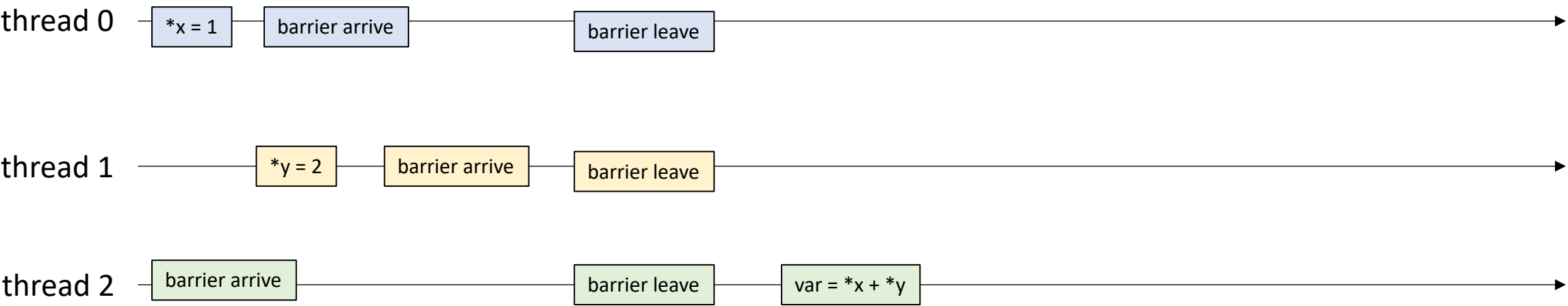


One more example, assume initially $*x = *y = 0$

Thread 0:
`*x = 1;`
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Thread 1:
`*y = 2;`
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Thread 2:
`B.barrier();`
`var = *x + *y;`



What is this guaranteed to be?

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

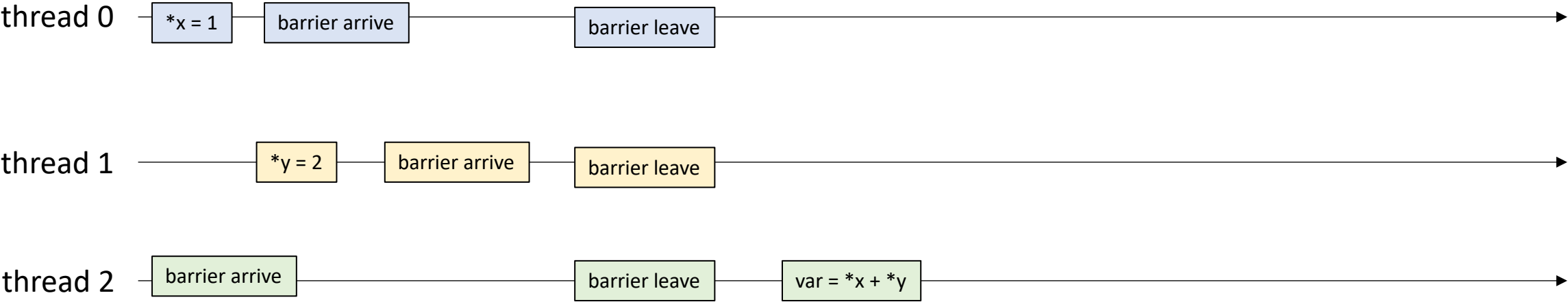
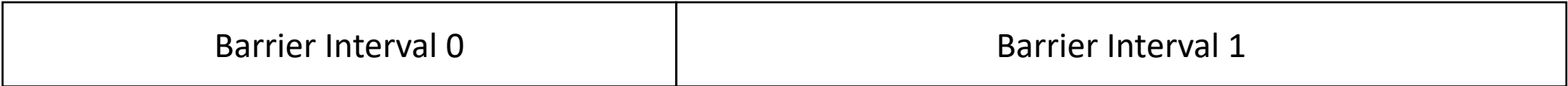
Thread 0:
`*x = 1;`
`B.barrier();`

Thread 1:
`*y = 2;`
`B.barrier();`

Thread 2:
`B.barrier();`
`var = *x + *y;`

sometimes called a *phase*

extending to the next *barrier leave*

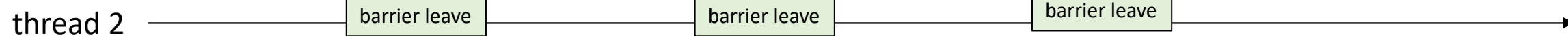
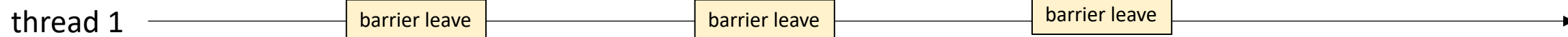
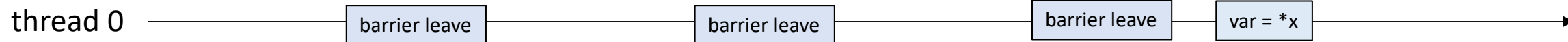
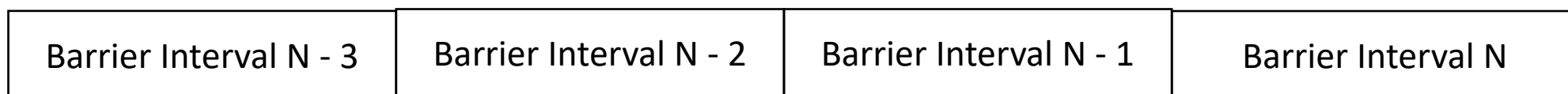


Barriers

- 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

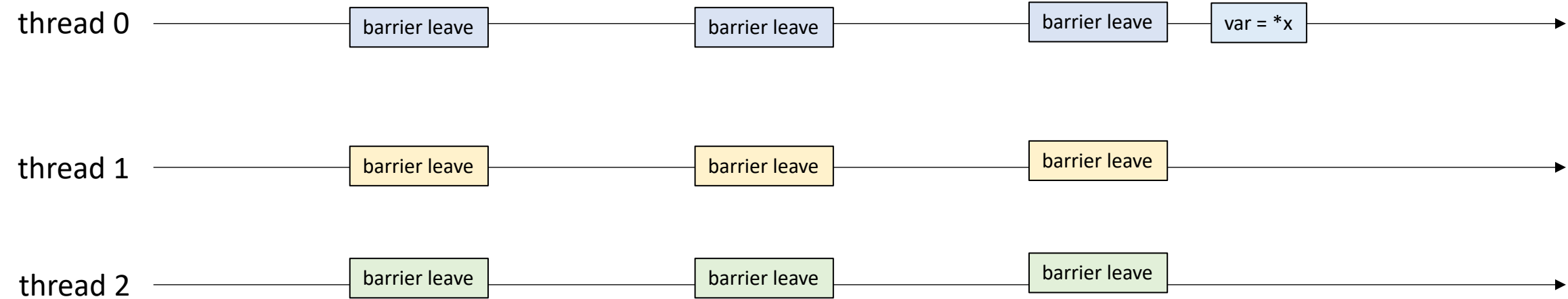
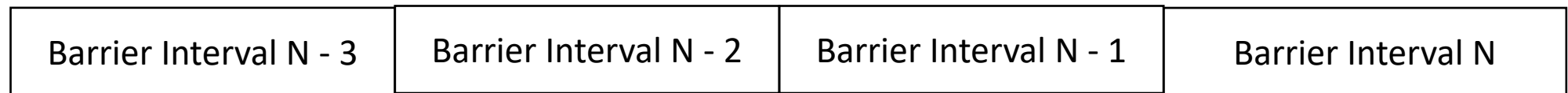
We are only allowed to
return one possible
value



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

Assume we are reading
from x

We are only allowed to
return one possible
value

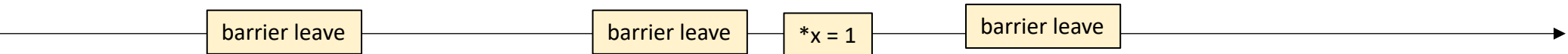
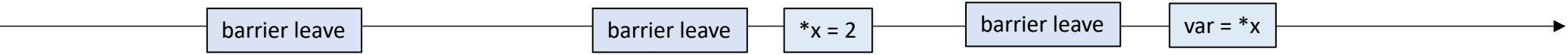
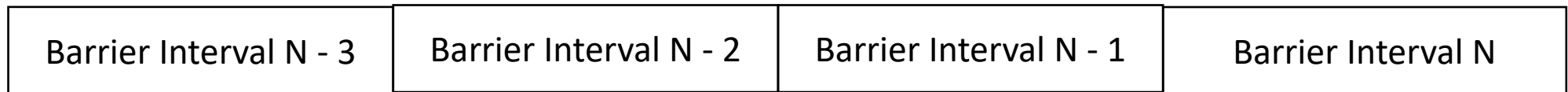


no data conflicts means that x is written to at most once
per barrier interval

Assume we are reading
from x

We are only allowed to
return one possible
value

not allowed

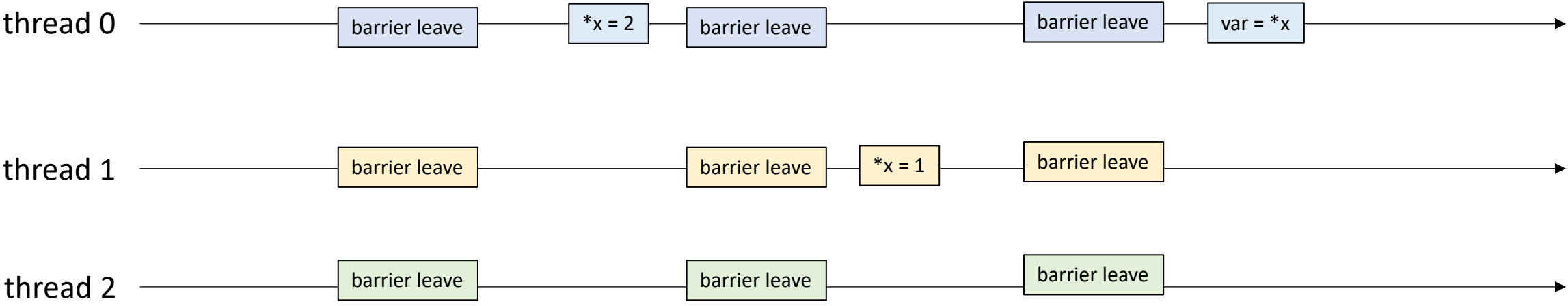
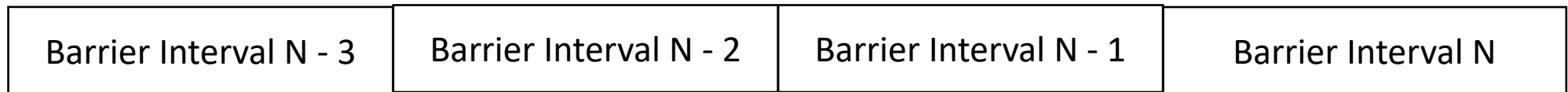


no data conflicts means that x is written to at most once
per barrier interval

Assume we are reading
from x

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

We are only allowed to
return one possible
value



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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class Barrier {  
    private:  
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        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);  
            // 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?

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class Barrier {  
    private:  
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    public:  
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            }  
            else {  
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            }  
        }  
}
```

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) {  
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    }  
    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);  
    }  
}
```



Leaves barrier

Thread 1:

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



enters next barrier

Thread 1:

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



arrival_num == 0

Thread 1:

```
B.barrier();  
B.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 wakes up! Doesn't think its missed anything

arrival_num == 0

Thread 1:

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

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

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

Thread 0:

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

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

sync on sense = true

Thread 1:

```
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();

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();

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();

thread_sense = false
arrival_num = ?

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();

*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();

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();

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

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();

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

thread_sense = false
arrival_num = 0

Thread 0:

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

num_threads == 2
counter == 2
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 = 1

Thread 1:

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

Goes into the second barrier

thread_sense = false
arrival_num = 0

Thread 0:

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

num_threads == 2
counter == 2
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 = 1

Thread 1:

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

Goes into the second barrier

thread_sense = false
arrival_num = 0

Thread 0:

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

num_threads == 2
counter == 0
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 = false
arrival_num = 1

Thread 1:

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

Goes into the second barrier

thread_sense = false
arrival_num = 0

Thread 0:

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

```
num_threads == 2  
counter == 0  
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 = false
arrival_num = 1

Thread 1:

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

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