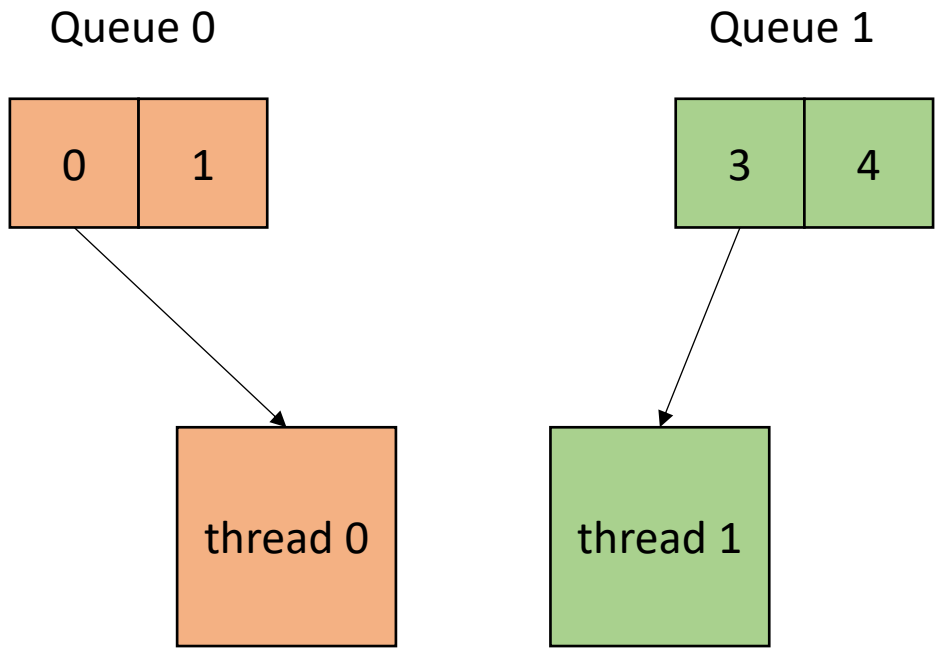
# CSE113: Parallel Programming

Feb, 21, 2024

- **Topics**:
  - Workstealing



# Announcements

- HW 1 is completely graded
  - Let us know by the end of today if there are any issues!
- Starting on grading HW 2
  - Give us a week or so
- Grading midterm on Friday

# Announcements

- HW 3 is out
  - Last day to turn it in is Tuesday Feb. 27
  - Plenty of time to get help
    - Office hours
    - Piazza
    - Etc.

- You should be able to do part 2 after today's lecture

# Announcements

- Planned ~2 more lectures on concurrent data structures
  - Today:
    - Workstealing
  - Monday:
    - General Concurrent Sets

# Announcements

- Green computing faculty talks!
  - Wednesdays at 11
  - Room E2 180
  - Good chance to see the academic job experience, feel free to join!

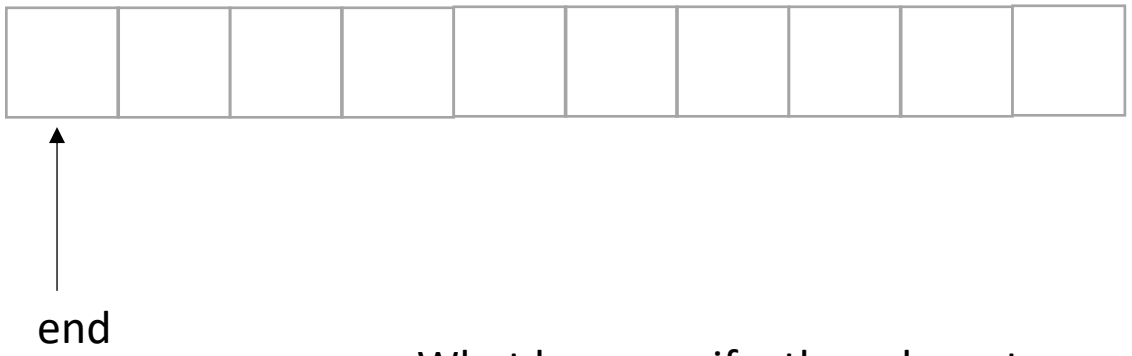
# Previous quiz + Review

# Previous quiz + Review

Input/output queues use atomic increments and decrements to protect against threads that are trying to concurrently enqueue and dequeue

- ◯ True
- ◯ False

# Implementation




Thread 0:
*enq(6);*

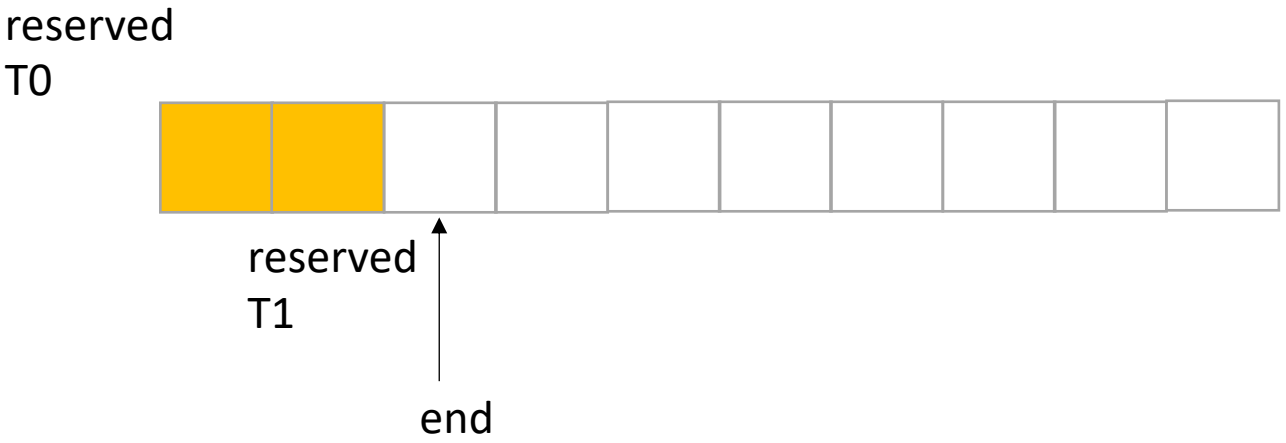
Thread 1:
*enq(7);*

What happens if a thread wants to add an element?

Think concurrently:

```
reserved_index = atomic_fetch_add(&end, 1);
```

# Implementation

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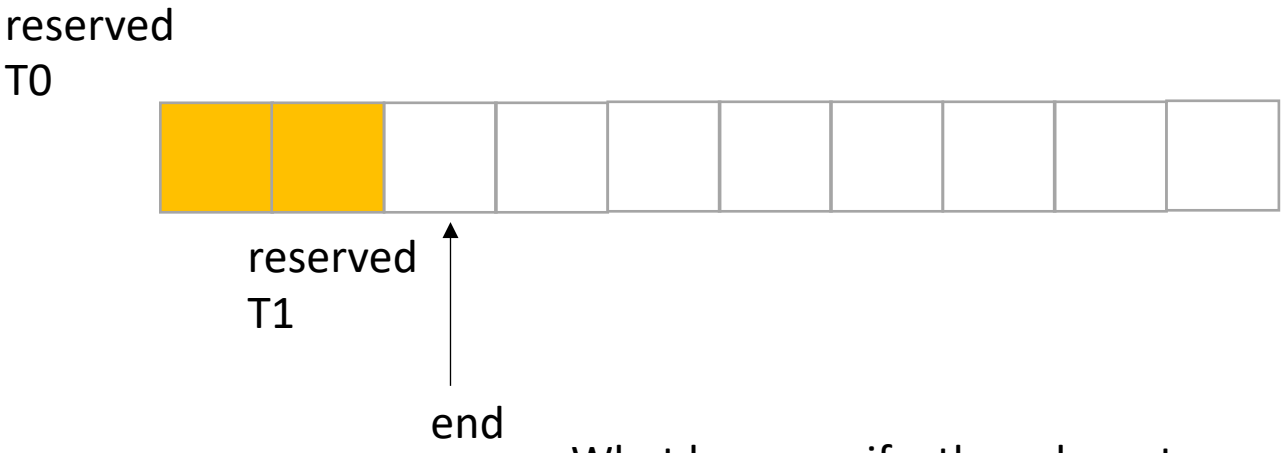
*does it matter which order threads add their data?*

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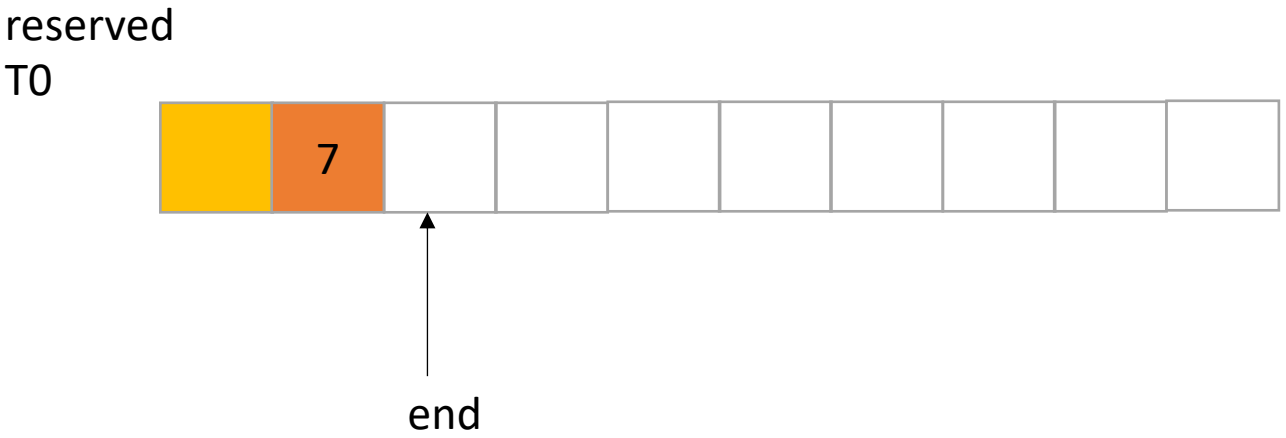


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Thread 1:
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What happens if a thread wants to add an element?

Think concurrently:

```
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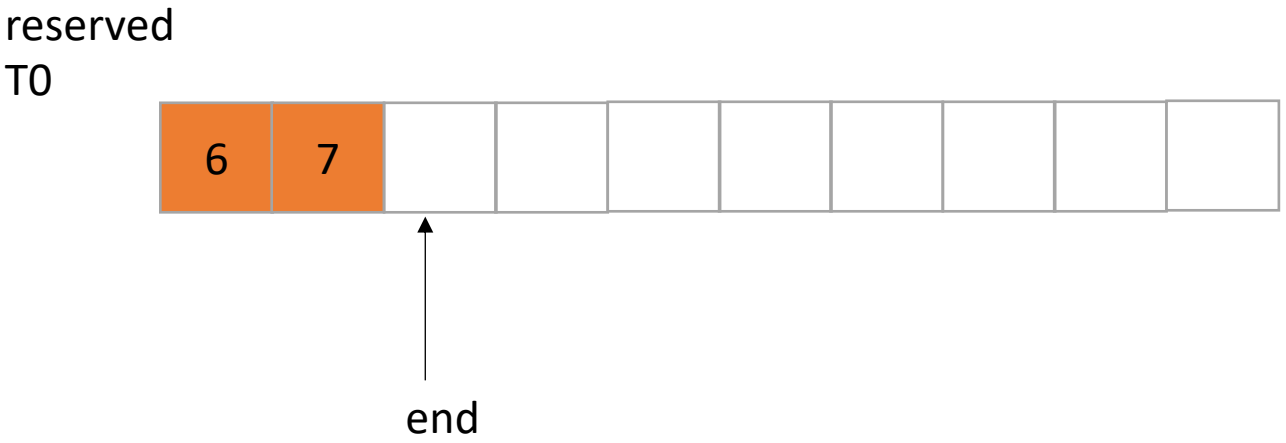
```

# Implementation

*does it matter which order threads add their data? No! Because there are no deqs!*

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*enq(6);*

Thread 1:
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What happens if a thread wants to add an element?

Think concurrently:

```
reserved_index = atomic_fetch_add(&end, 1);
```

# Previous quiz + Review

Write a few questions about the pros and cons of using a specialized concurrent queue (e.g. an IO queue) and a fully general concurrent queue.

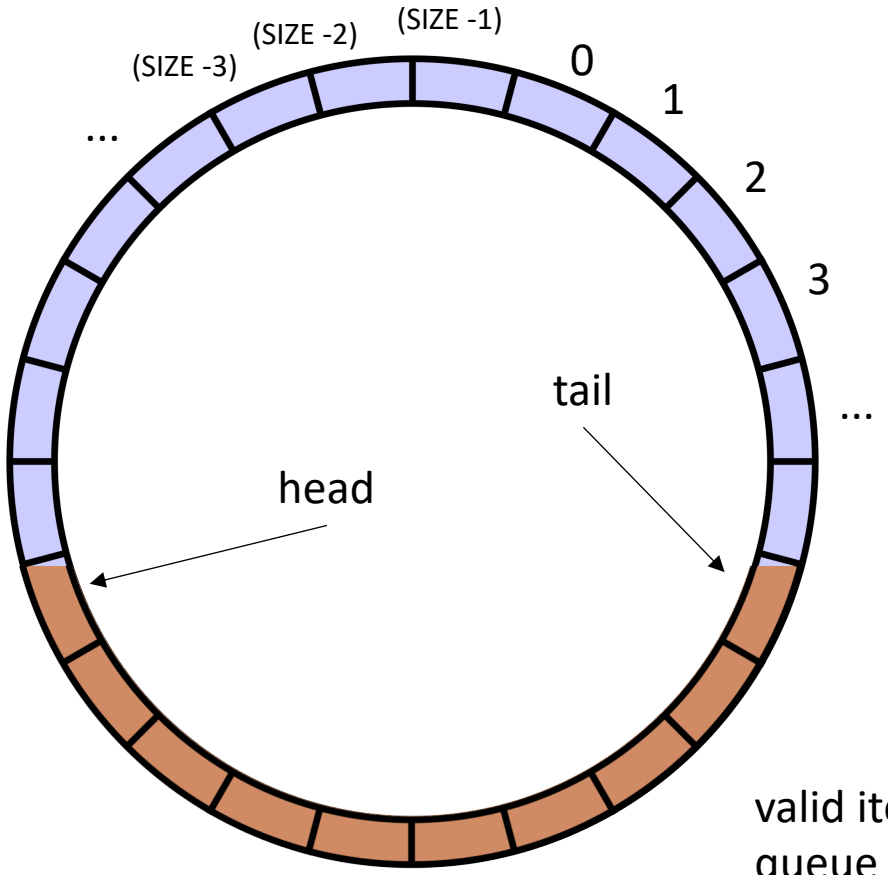
```
class InputOutputQueue {
  private:
    atomic_int front;
    atomic_int end;
    int list[SIZE];

  public:
    InputOutputQueue() {
        front = end = 0;
     }

     void enq(int x) {
        int reserved_index = atomic_fetch_add(&end, 1);
        list[reserved_index] = x;
     }

     void deq() {
       int reserved_index = atomic_fetch_add(&front, 1);
       return list[reserved_index];
     }

     int size() {
        return end.load() - front.load();
     }
 }
```




valid items in the queue

```
class ProdConsQueue {
  private:
    atomic_int head;
    atomic_int tail;
    int buffer[SIZE];

  public:
    void enq(int x) {
      // wait for there to be room
      // store value at head
      // increment head
    }
    int deq() {
      // wait while queue is empty
      // get value at tail
      // increment tail
    }
}
```

# Previous quiz + Review

The performance of an application using a producer-consumer queue depends most on:

- ◯ If the queue is implemented using mutex or not
- ◯ The rate at which the consumer enqueues elements
- ◯ The rate at which the producer enqueues elements

# Previous quiz + Review

A circular buffer is:

- ◯ A useful data representation for fixed-length queues
- ◯ Part of the C++ standard library
- ◯ A special type of memory that is organized in circular pattersTrue

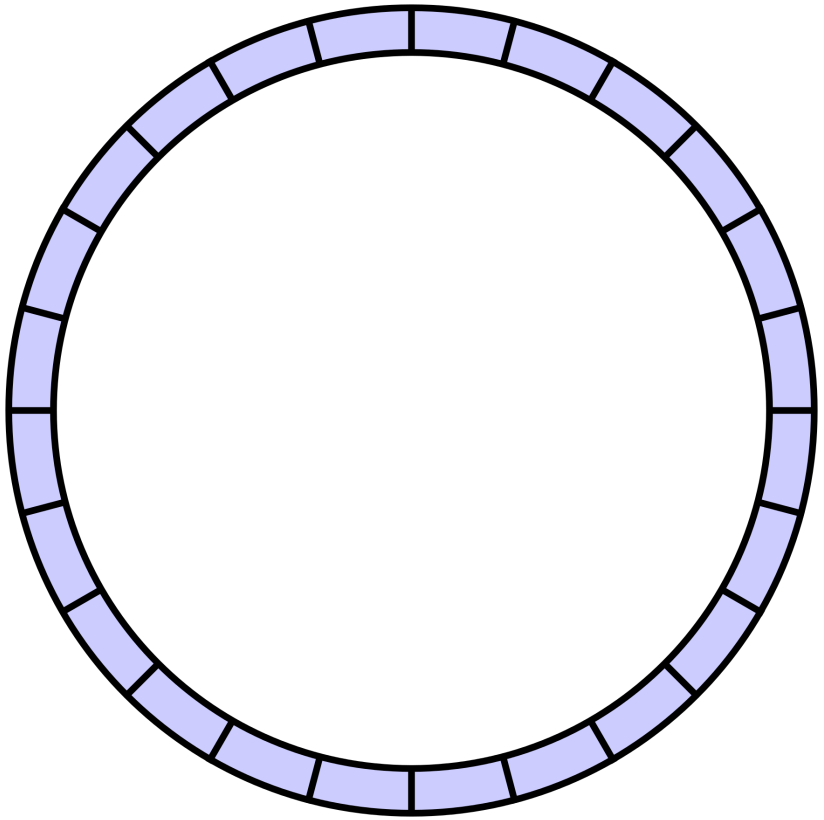
# Producer Consumer Queues

- Start with a fixed size array

We will use what is called a *circular buffer method*

# Producer Consumer Queues

- Start with a fixed size array



conceptually it is a circle

# Producer Consumer Queues

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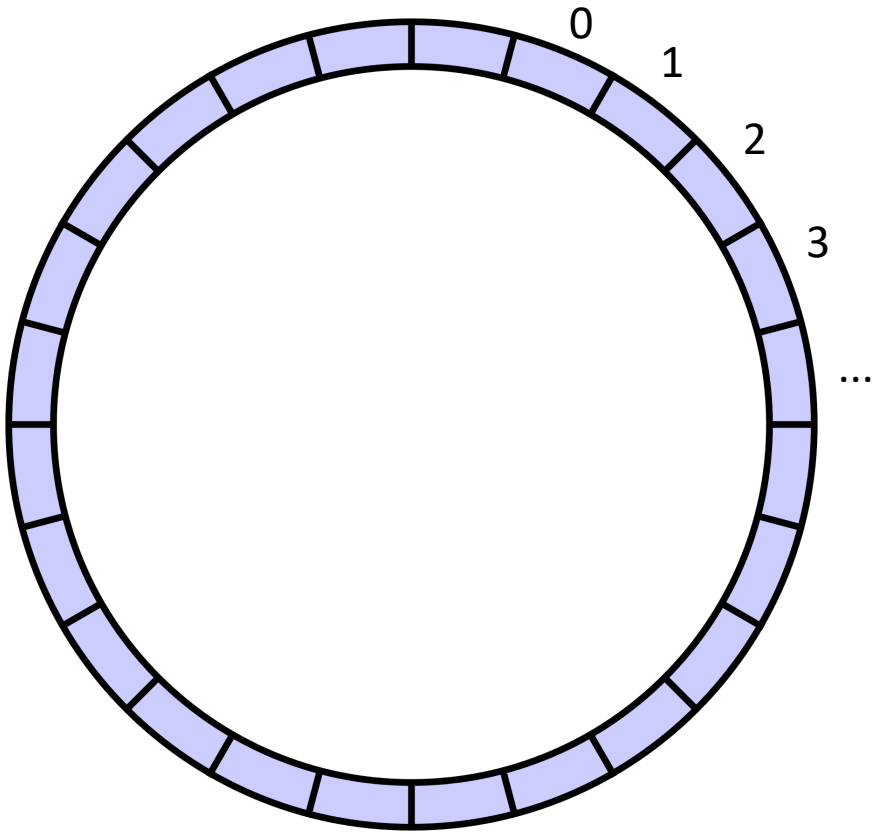


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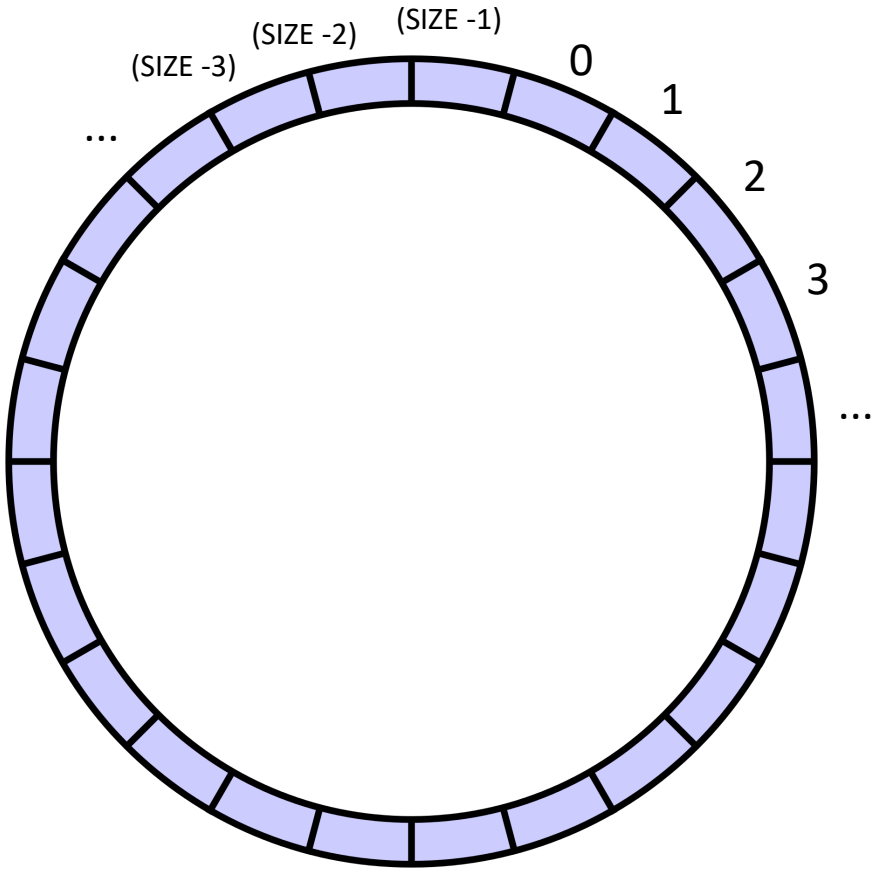


indexes will circulate in order and wrap around

conceptually it is a circle

# Producer Consumer Queues

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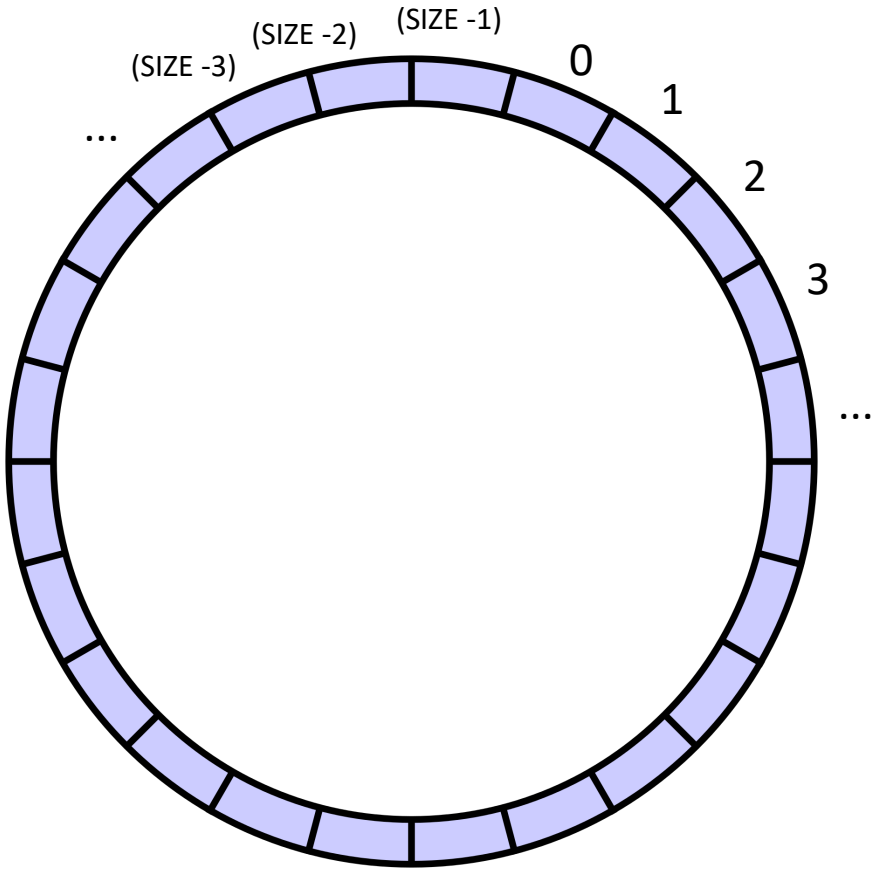


indexes will circulate in order and wrap around

we will assume modular arithmetic:

if x = (SIZE - 1) then
x + 1 == 0;

conceptually it is a circle

# Producer Consumer Queues

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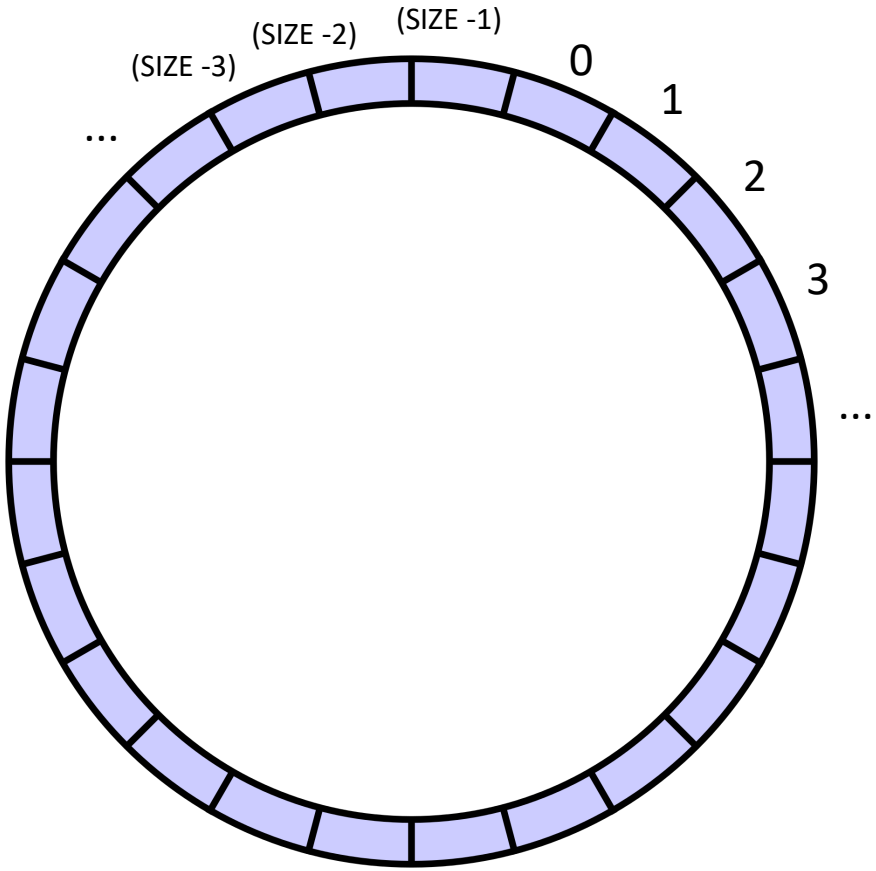


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Two variables to keep track of where to deq and enq:

head and tail

conceptually it is a circle

# Producer Consumer Queues

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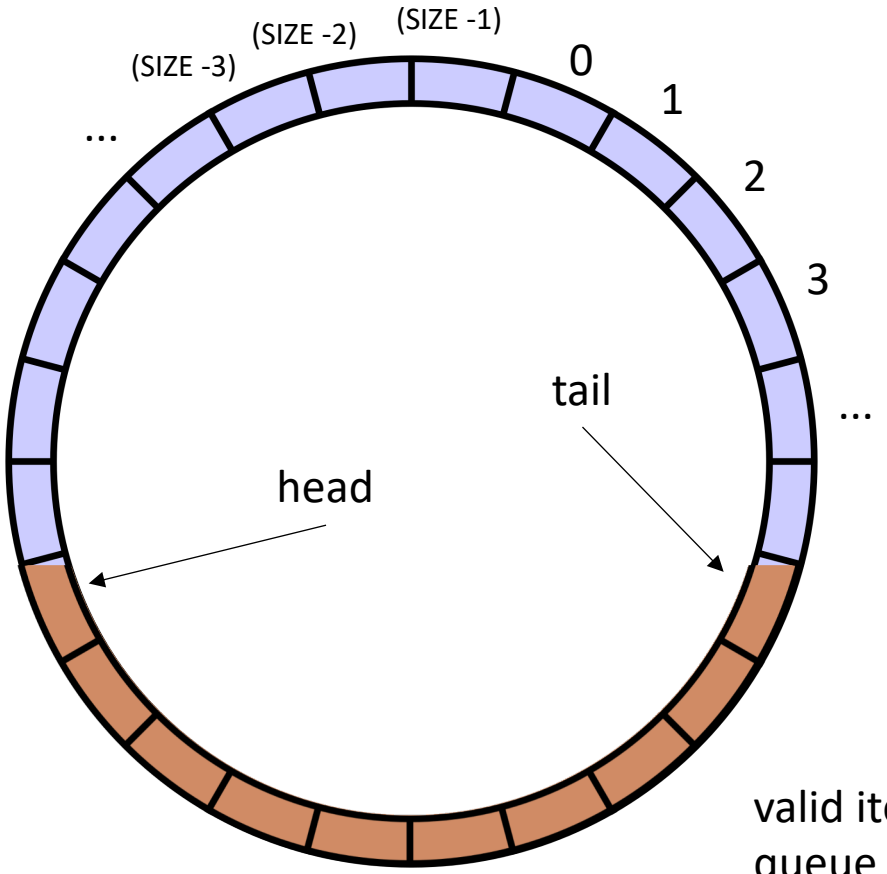


indexes will circulate in order and wrap around

Two variables to keep track of where to deq and enq:

head and tail:

enq to the head,  deq from the tail

valid items in the queue

conceptually it is a circle

# Producer Consumer Queues

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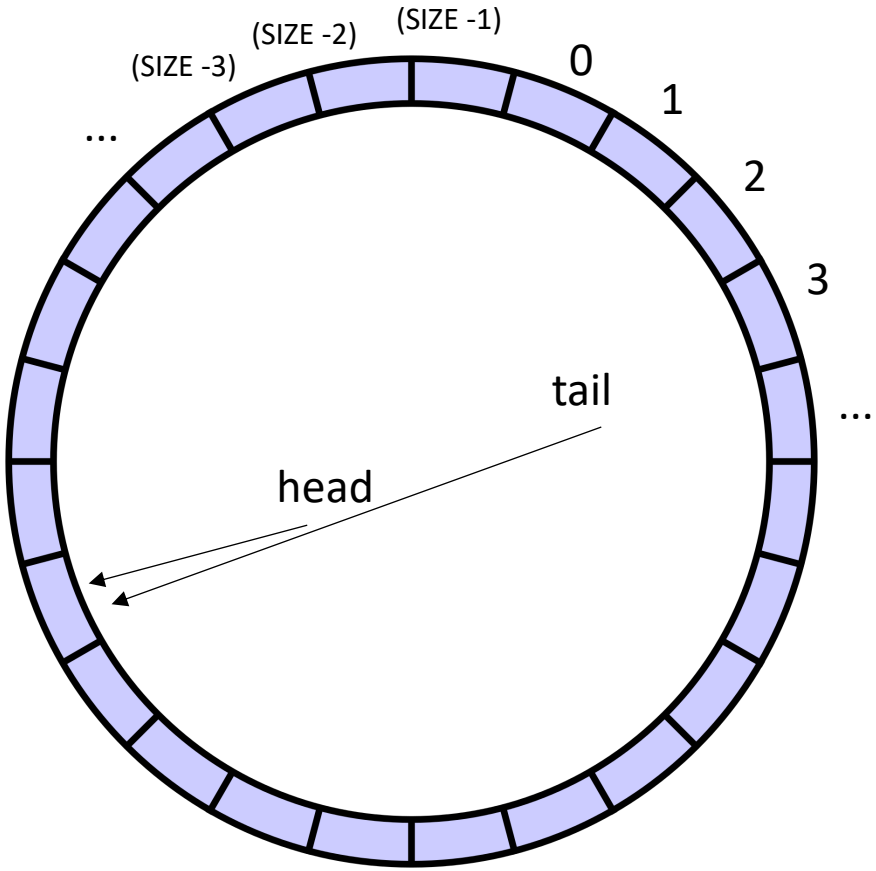


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Empty queue is when head == tail

conceptually it is a circle

# Producer Consumer Queues

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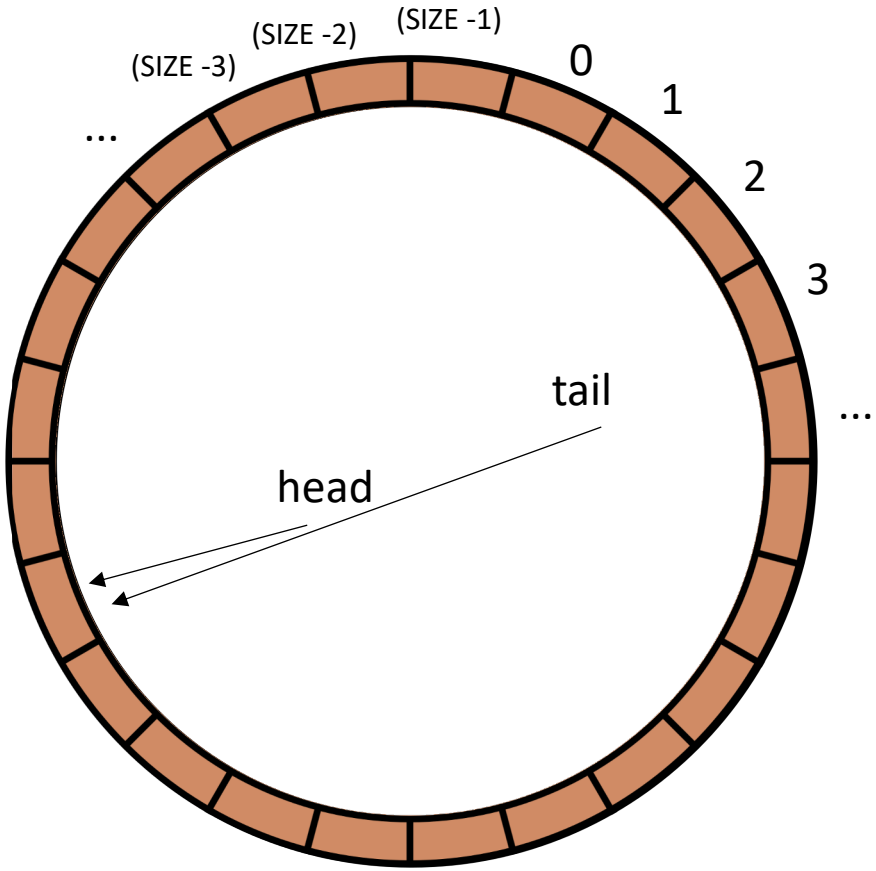


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Two variables to keep track of where to deq and enq:

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Empty queue is when
head == tail

Full queue is when
head == tail?

conceptually it is a circle

# Producer Consumer Queues

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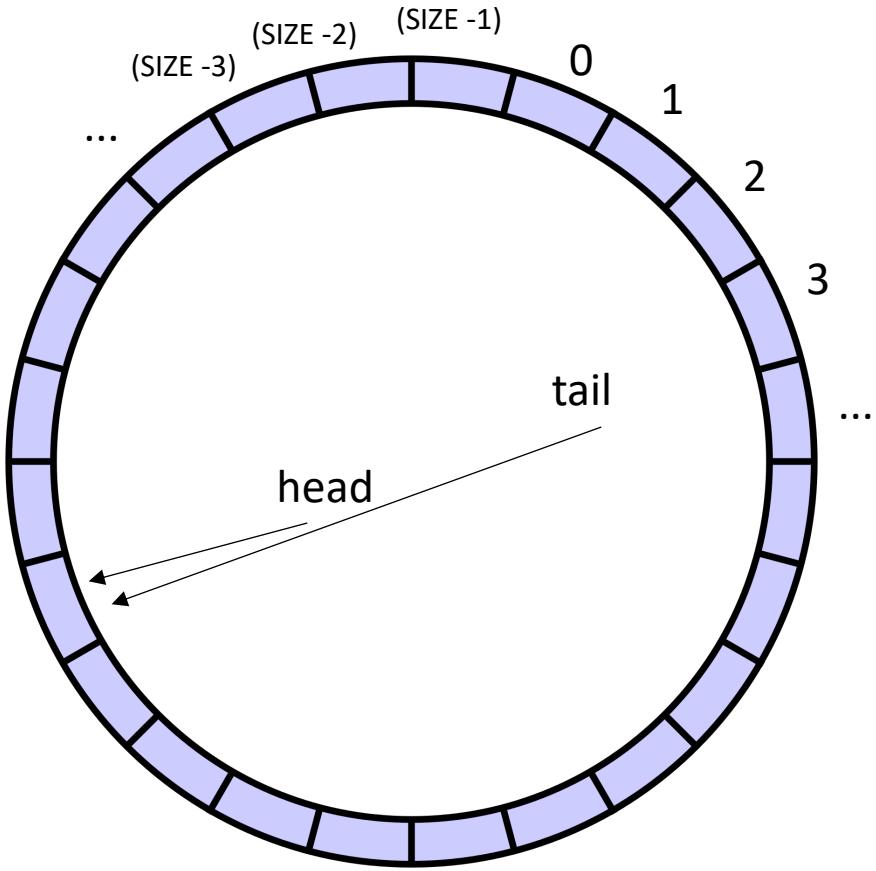


indexes will circulate in order and wrap around

Two variables to keep track of where to deq and enq:

head and tail

Empty queue is when
head == tail

Full queue is when
head == tail?

but then
how to tell
full queue from
empty?

conceptually it is a circle

# Producer Consumer Queues

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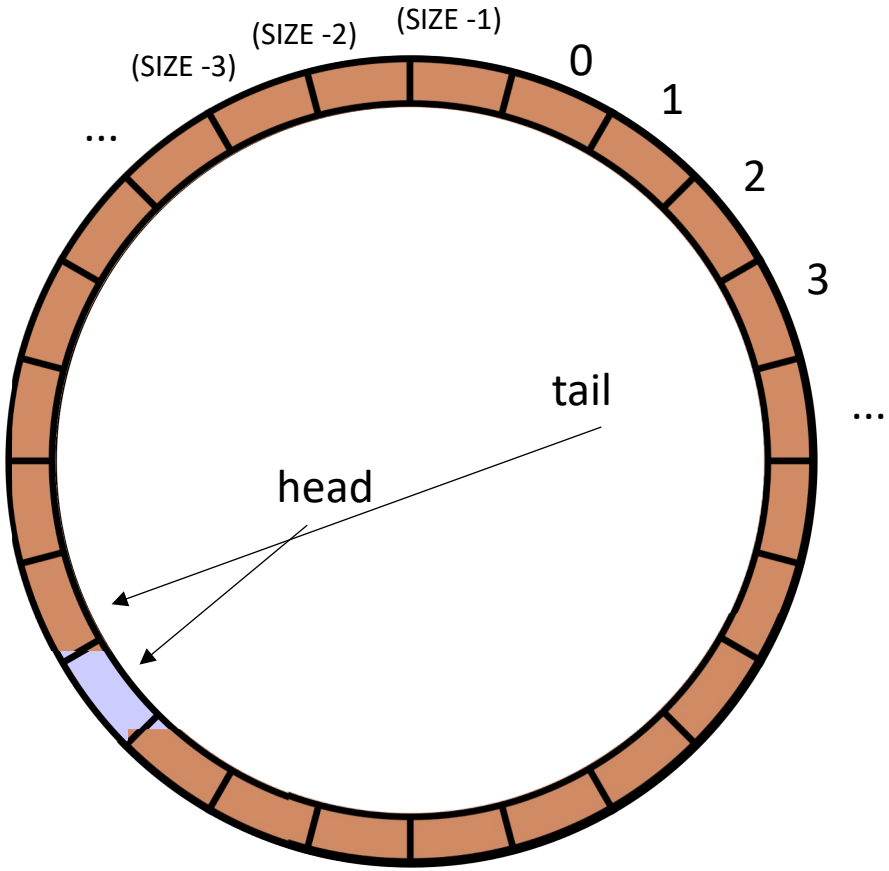



indexes will circulate in order and wrap around

Two variables to keep track of where to deq and enq:

head and tail

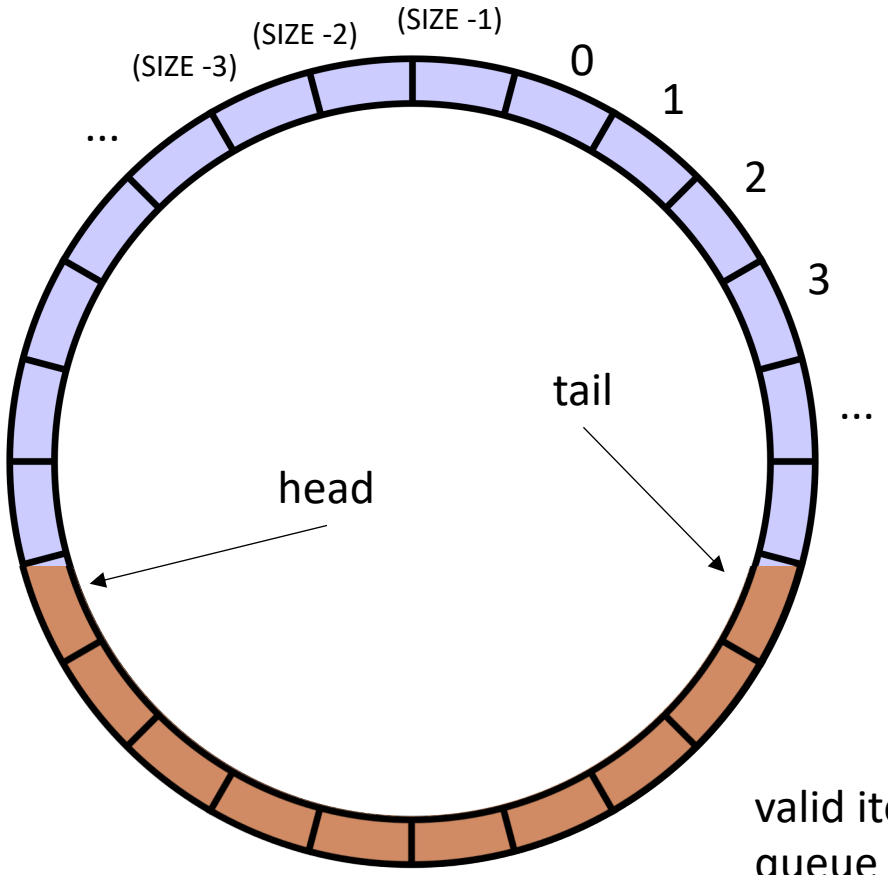
Empty queue is when
head == tail

Full queue is when
head + 1 == tail

wasting one location, but its okay...

conceptually it is a circle

# review




valid items in the queue

```
class ProdConsQueue {
  private:
    atomic_int head;
    atomic_int tail;
    int buffer[SIZE];

  public:
    void enq(int x) {
      // wait for there to be room
      // store value at head
      // increment head
    }
    int deq() {
      // wait while queue is empty
      // get value at tail
      // increment tail
    }
}
```

# On to new stuff!

- Work stealing

adds two arrays

```
for (int i = 0; i < SIZE; i++) {
  a[i] = b[i] + c[i];
}
```

adds elements with neighbors

```
for (int i = 0; i < SIZE; i++) {
  a[i] += a[i+1]
}
```

are they the same if you traverse them backwards?

adds two arrays

```
for (int i = 0; i < SIZE; i++) {
  a[i] = b[i] + c[i];
}
```

```
for (int i = SIZE-1; i >= 0; i--) {
  a[i] = b[i] + c[i];
}
```

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}
```

No!

adds two arrays

```
for (int i = 0; i < SIZE; i++) {
  a[i] = b[i] + c[i];
}
```

what about a random order?

```
for (pick i randomly) {
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No!

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for (int i = 0; i < SIZE; i++) {
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These are **DOALL** loops:

- Loop iterations are independent
- You can do them in ANY order and get the same results

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These are **DOALL** loops:

- Loop iterations are independent
- You can do them in ANY order and get the same results

- Most importantly: you can do the iterations in parallel!
- Assign each thread a set of indices to compute

# DOALL Loops

- Given a nest of For loops, can we make the outer-most loop parallel?
  - Safely
  - Efficiently

# DOALL Loops

- We will consider a special type of for loop, common in scientific applications:
  - Operates on N dimensional arrays (only side-effects are array writes)
  - Array bases are disjoint and constant
  - Bounds, indexes are a function of loop variables, input variables and constants
  - Loops Increment by 1

```
for (int i = 0; i < dim1; i++) {
  for (int j = 0; j < dim3; j++) {
    for (int k = 0; k < dim2; k++) {
      a[i][j] += b[i][k] * c[k][j];
    }
  }
}
```

matrix multiplication example

# DOALL Loops

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# DOALL Loops

- Given a nest of ***candidate*** *For* loops, determine if we can we make the outer-most loop parallel?
  - Safely
  - efficiently

- Criteria: every iteration of the outer-most loop must be *independent*
  - The loop can execute in any order, and produce the same result

# Safety Criteria

- How do we check this?
  - If the property doesn't hold then there exists 2 iterations, such that if they are re-ordered, it causes different outcomes for the loop.
  - **Write-Write conflicts**: two distinct iterations write different values to the same location
  - **Read-Write conflicts**: two distinct iterations where one iteration reads from the location written to by another iteration.

# Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*
- the loop must produce the same result for any order of the iterations

```
for (i = 0; i < size; i++) {
   a[index(i)] = loop(i);
}
```

# Safety Criteria

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index calculation based on the loop variable

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```

index calculation based on the loop variable
Computation to store in the memory location

# Safety Criteria

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}
```

**Write-write conflicts:**

for two distinct iteration variables:

$i_x$ != $i_y$

Check:

index($i_x$) != index($i_y$)

# Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*
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for (i = 0; i < size; i++) {
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}
```

**Write-write conflicts:**

for two distinct iteration variables:
$i_x$ != $i_y$
Check:
index($i_x$) != index($i_y$)

**Why?**
Because if
index($i_x$) == index($i_y$)
then:
a[index($i_x$)] will equal
either loop($i_x$) or loop($i_y$)
depending on the order

# Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*

```
for (i = 0; i < size; i++) {
    a[write_index(i)] = a[read_index(i)] + loop(i);
}
```

**Read-write conflicts:**

for two distinct iteration variables:

$i_x$ != $i_y$

Check:

write_index($i_x$) != read_index($i_y$)

# Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*

```
for (i = 0; i < size; i++) {
    a[write_index(i)] = a[read_index(i)] + loop(i);
}
```

**Read-write conflicts:**

for two distinct iteration variables:
$i_x$ != $i_y$
Check:
write_index($i_x$) != read_index($i_y$)

**Why?**

if $i_x$ iteration happens first, then iteration $i_y$ reads an updated value.

if $i_y$ happens first, then it reads the original value

# Examples:

```
for (i = 0; i < 128; i++) {
   a[i]= a[i]*2;
}
```

# Examples:

```
for (i = 0; i < 128; i++) {
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}
```

```
for (i = 0; i < 128; i++) {
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}
```

# Examples:

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for (i = 0; i < 128; i++) {
   a[i]= a[i]*2;
}
```

```
for (i = 0; i < 128; i++) {
   a[i]= a[0]*2;
}
```

```
for (i = 1; i < 128; i++) {
   a[i]= a[0]*2;
}
```

# Examples:

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for (i = 0; i < 128; i++) {
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}
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for (i = 0; i < 128; i++) {
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```
for (i = 1; i < 128; i++) {
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}
```

```
for (i = 0; i < 128; i++) {
   a[i%64]= a[i]*2;
}
```

# Examples:

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for (i = 0; i < 128; i++) {
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}
```

```
for (i = 0; i < 128; i++) {
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```

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}
```

```
for (i = 0; i < 128; i++) {
   a[i%64]= a[i]*2;
}
```

```
for (i = 0; i < 128; i++) {
   a[i%64]= a[i+64]*2;
}
```

# Parallel Schedules

- Consider the following program:

There are 3 arrays: `a, b, c.`

We want to compute

```
for (int i = 0; i < SIZE; i++) {
  c[i] = a[i] + b[i];
}
```

Is this a DOALL loop?

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There are 3 arrays: `a, b, c.`

We want to compute

```
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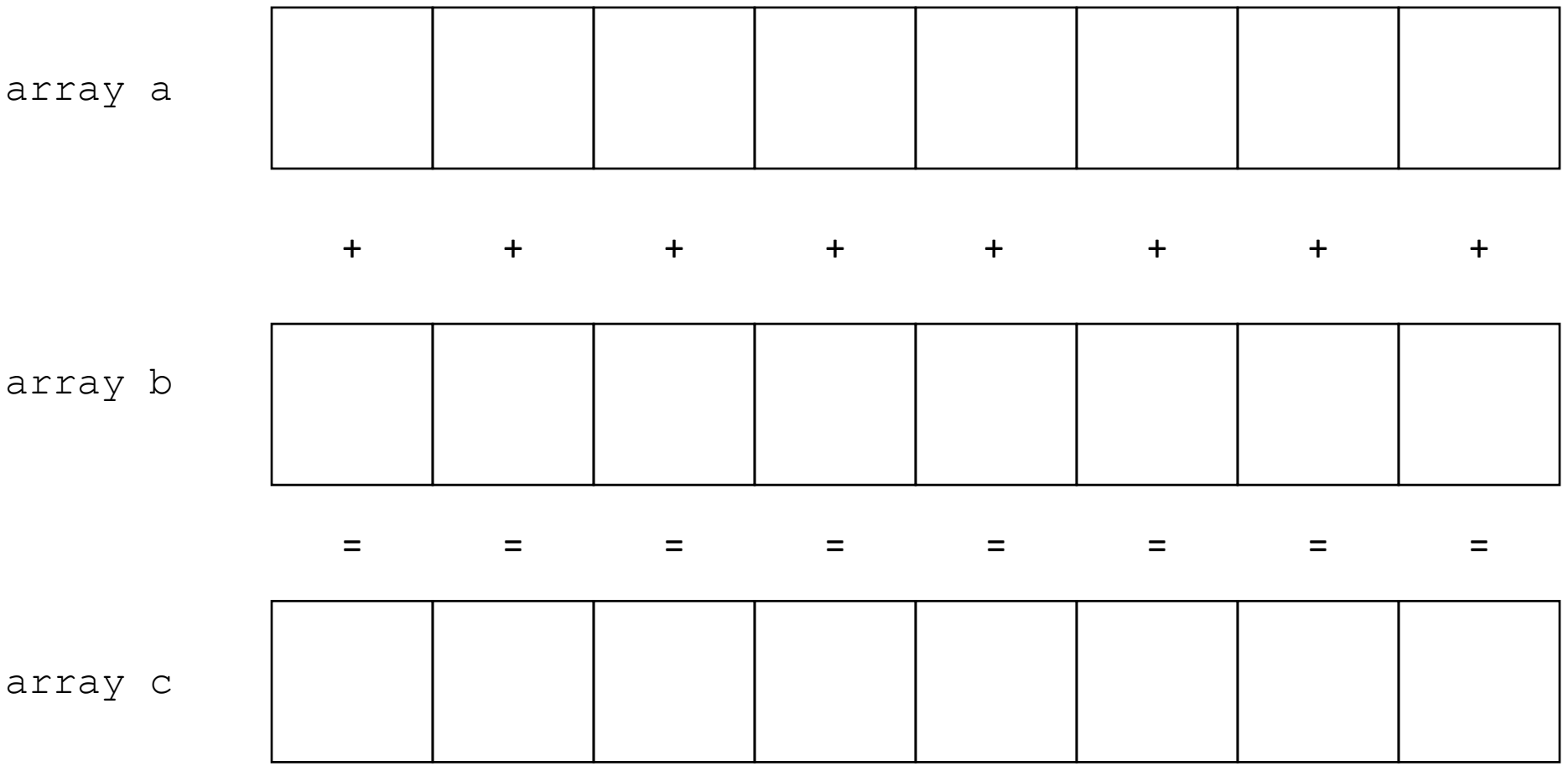
```

Is this a DOALL loop?

How should we parallelize it?

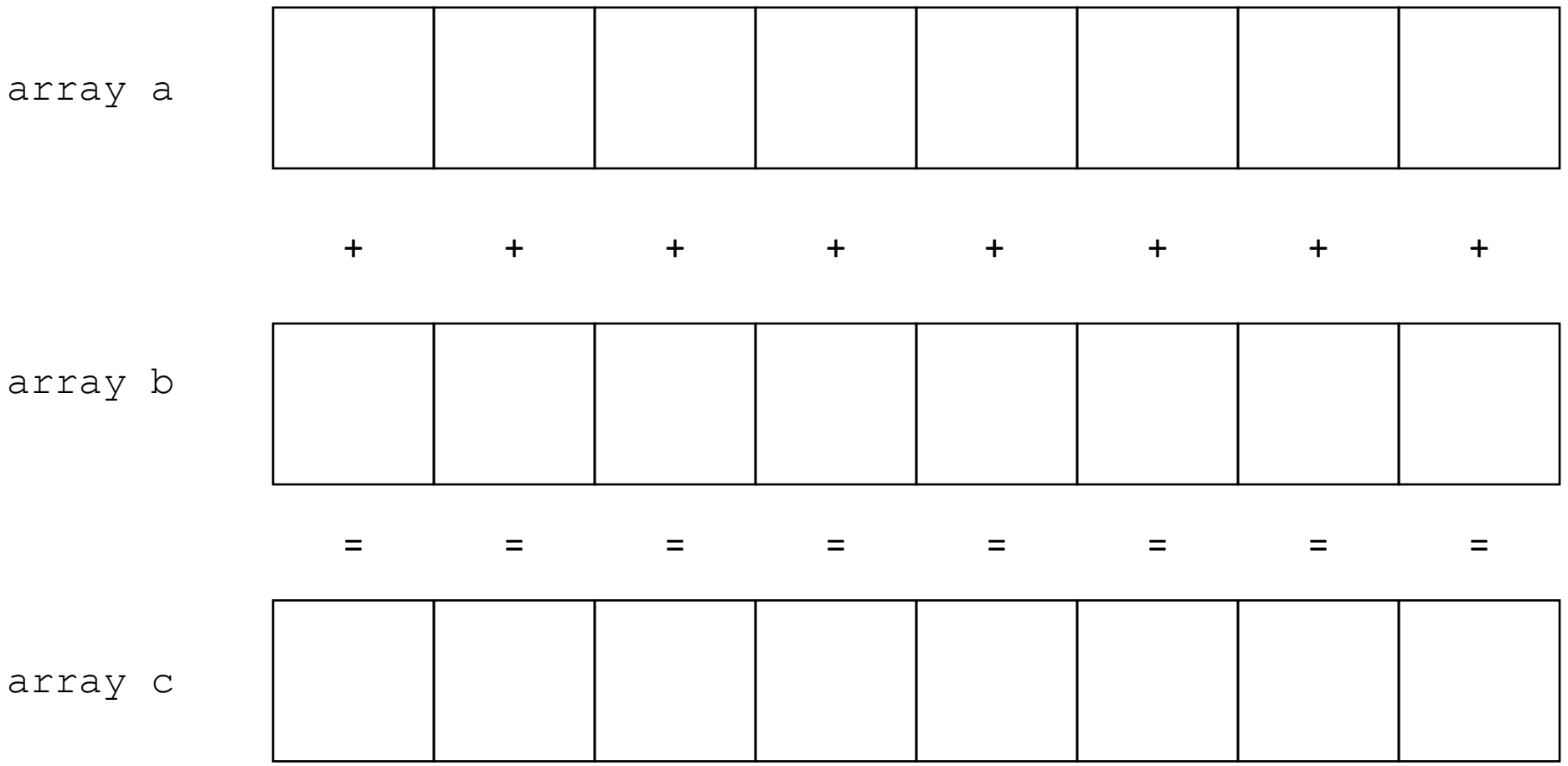
# Parallel Schedules



# Parallel Schedules

Computation can easily be divided into threads

Thread 0 - Blue
Thread 1 - Yellow
Thread 2 - Green
Thread 3 - Orange



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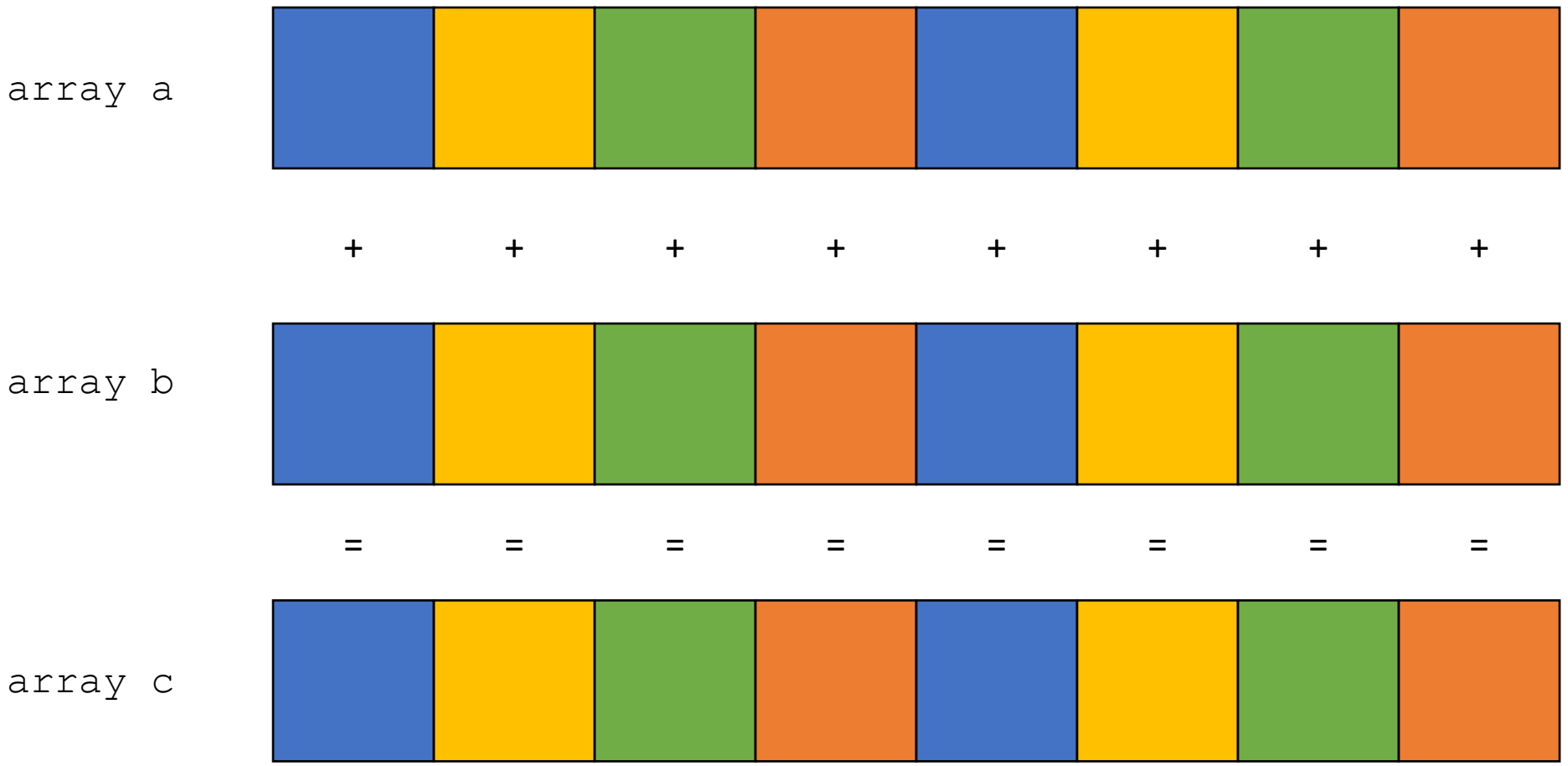

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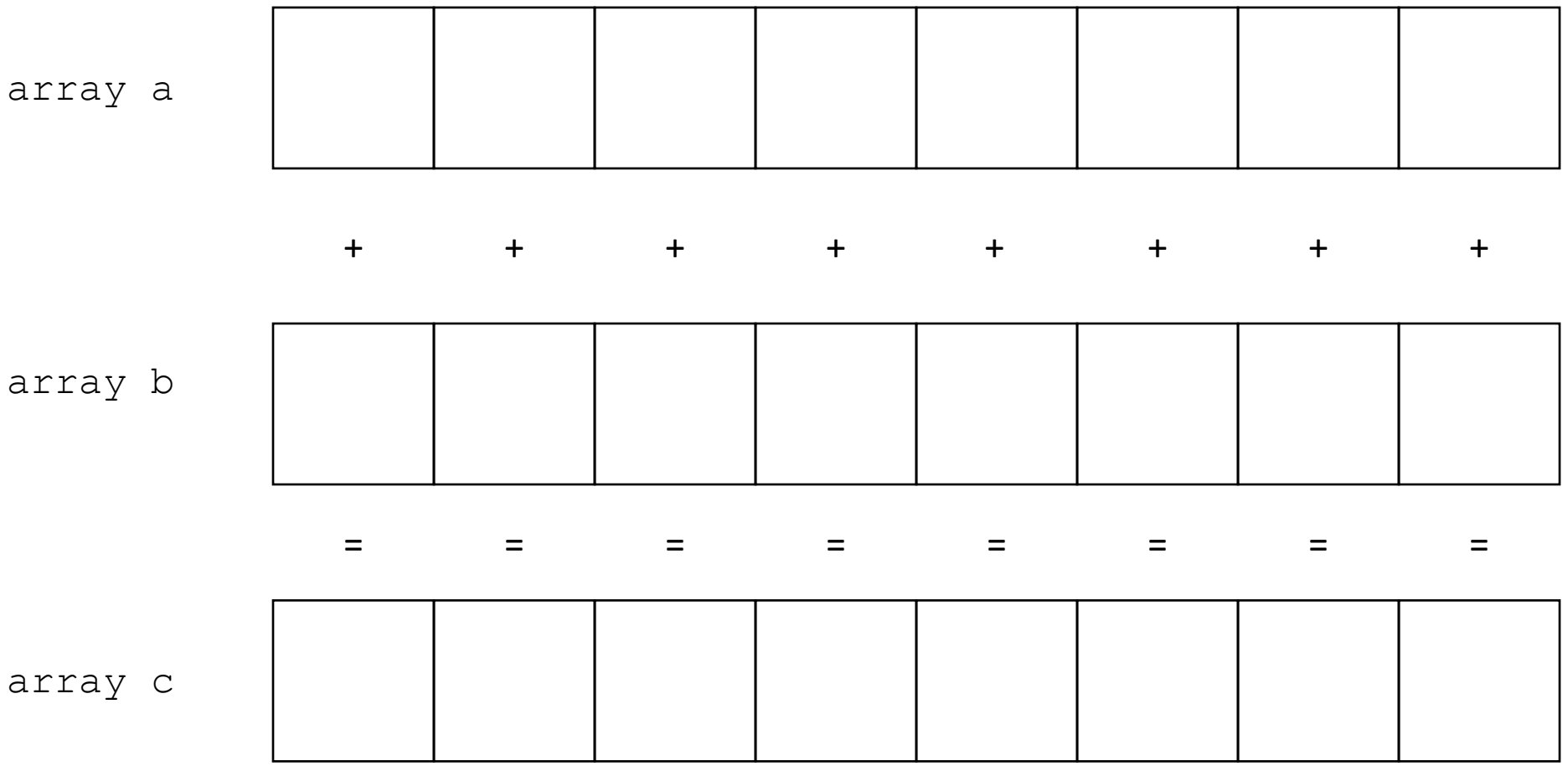

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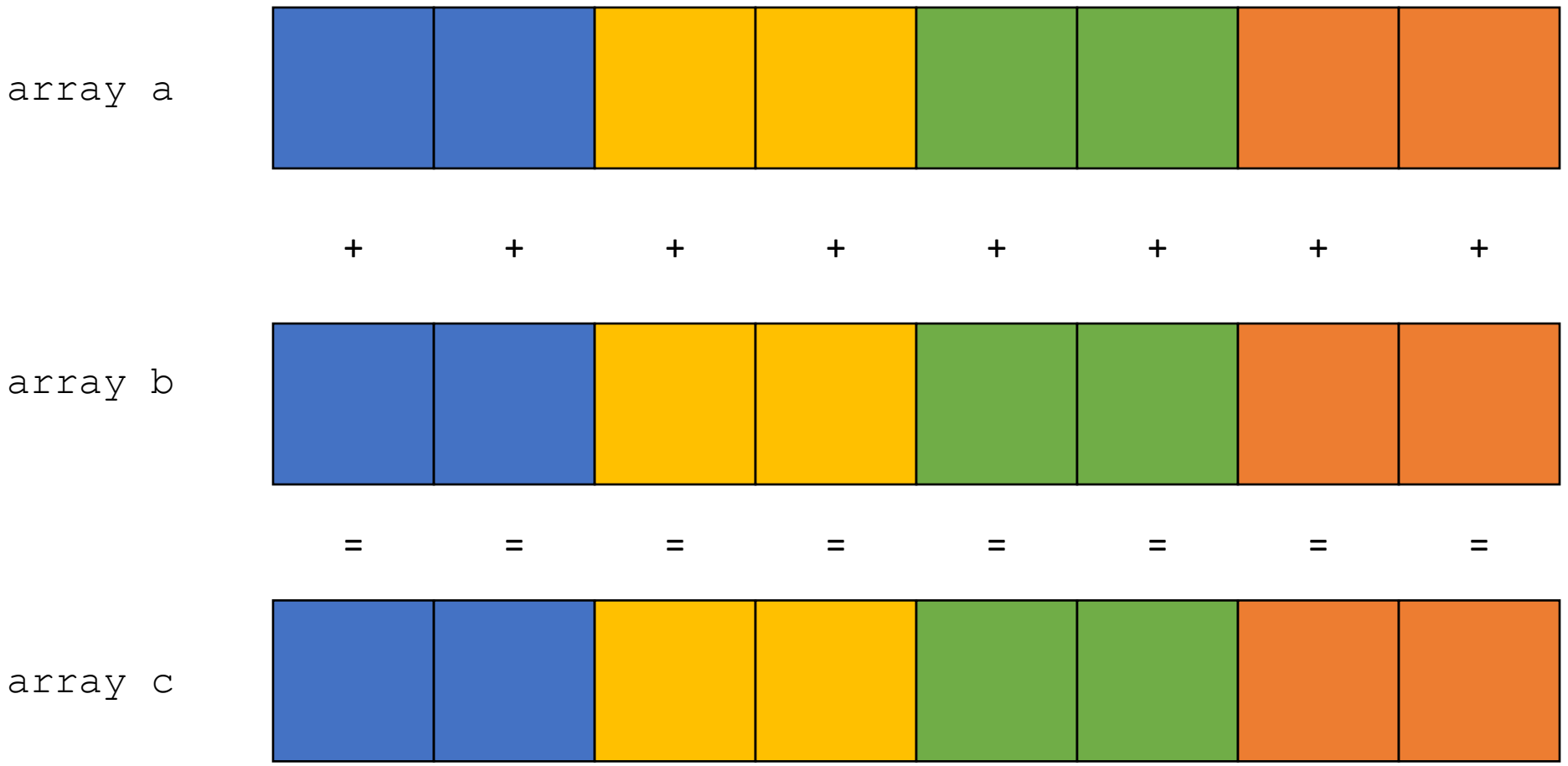
Thread 2 - Green
Thread 3 - Orange



# Parallel Schedules

- Which one is more efficient?

# Parallel Schedules

- Which one is more efficient?

- These are called Parallel Schedules for DOALL Loops
- We will discuss several of them.

# Schedule

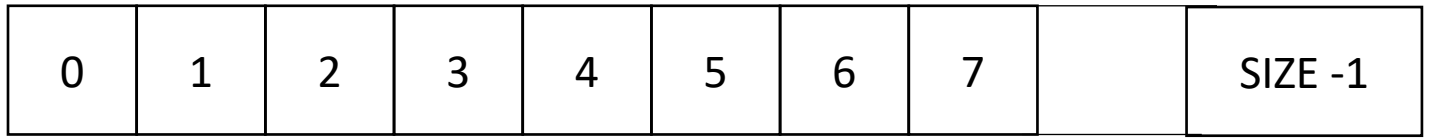
- DOALL Loops

- **Parallel Schedules:**
  - **Static**
  - Global Worklists
  - Local Worklists

# Static schedule

- Works well when loop iterations take similar amounts of time

```
void foo() {
...
  for (int x = 0; x < SIZE; x++) {
  // Each iteration takes roughly
  // equal time
  }
...
}
```



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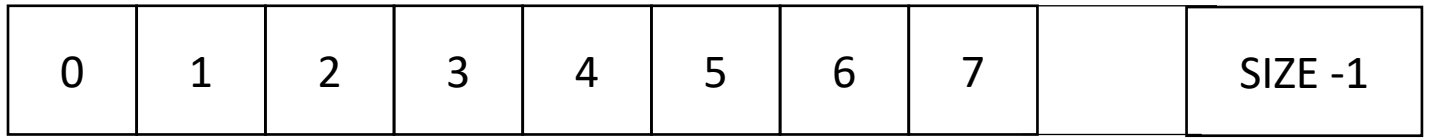
*say SIZE / NUM_THREADS = 4*



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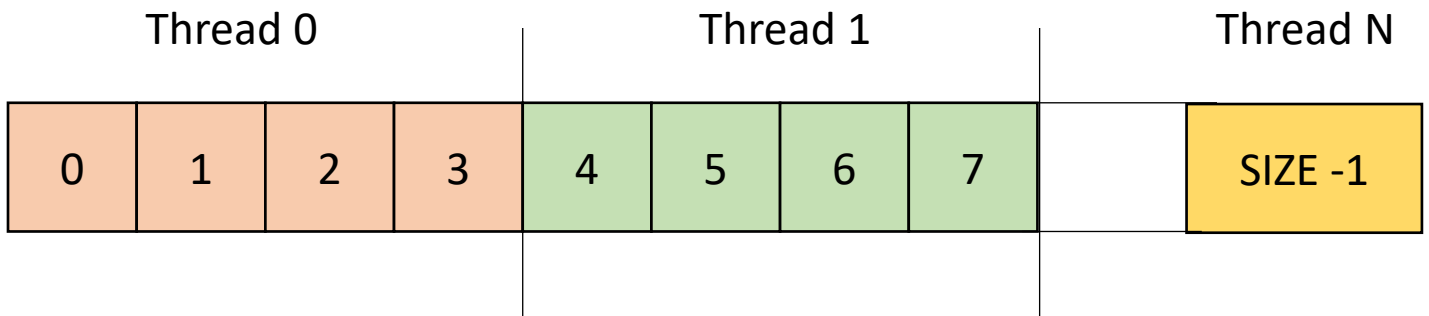

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make a new function with the for loop inside. Pass all needed variables as arguments. Take an extra argument for a thread id

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void parallel_loop(..., int tid, int num_threads)
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```

make a new function with the for loop inside. Pass all needed variables as arguments. Take an extra argument for a thread id

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  }
...
}
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```
void parallel_loop(..., int tid, int num_threads)
{

  int chunk_size = SIZE / NUM_THREADS;
  for (int x = 0; x < SIZE; x++) {
    // work based on x
  }
}
```

determine chunk size in new function

# Static schedule

- Works well when loop iterations take similar amounts of time

```
void foo() {
...
  for (int x = 0; x < SIZE; x++) {
  // Each iteration takes roughly
  // equal time
  }
...
}
```

```
void parallel_loop(..., int tid, int num_threads)
{

  int chunk_size = SIZE / NUM_THREADS;
  int start = chunk_size * tid;
  int end = start + chunk_size;
  for (int x = start; x < end; x++) {
    // work based on x
  }
}
```

Set new loop bounds

# Static schedule

- Works well when loop iterations take similar amounts of time

```
void foo() {
...
  for (int t = 0; t < NUM_THREADS; t++) {
    spawn(parallel_loop(..., t, NUM_THREADS))
  }
  join();
...
}
```

```
void parallel_loop(..., int tid, int num_threads)
{

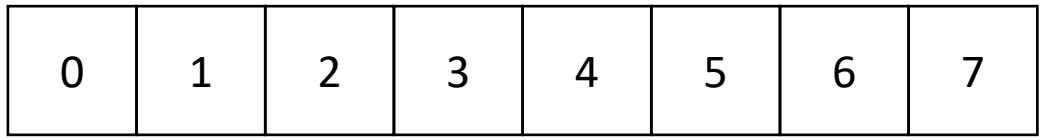
  int chunk_size = SIZE / NUM_THREADS;
  int start = chunk_size * tid;
  int end = start + chunk_size;
  for (int x = start; x < end; x++) {
    // work based on x
  }
}
```

You will need to adapt the thread spawn, join to C++

Spawn threads

# Static schedule

- Example, 2 threads/cores, array of size 8




```
chunk_size = ?

0: start = ?    1: start = ?
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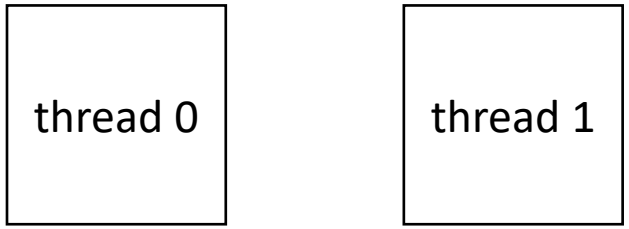
```

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# Static schedule

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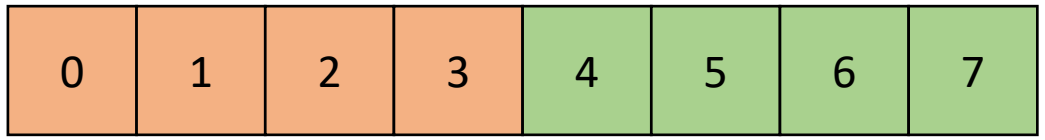


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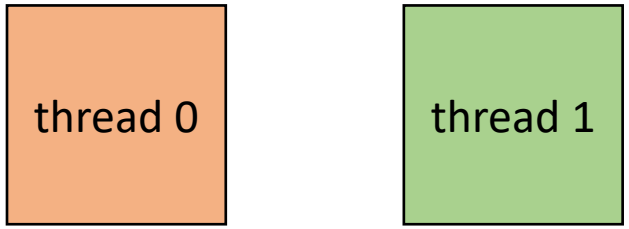


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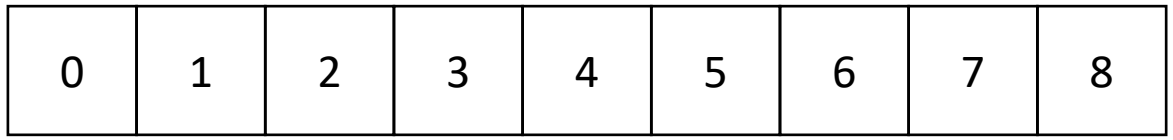
}
```

# Static schedule

- Example, 2 threads/cores, array of size 9

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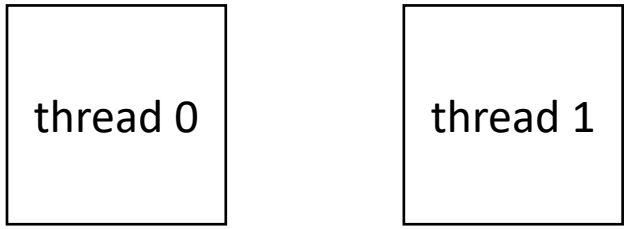





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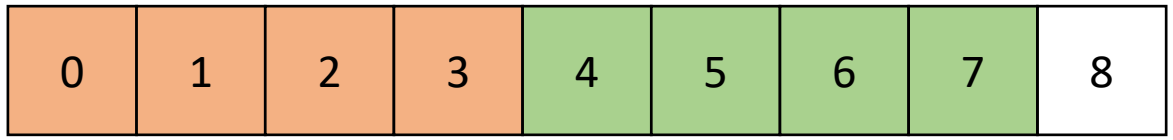
```

# Static schedule

- Example, 2 threads/cores, array of size 9

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```

```
0: start = 0
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```

```
1: start = 4
1: end = 8
```

thread 0

thread 1

```
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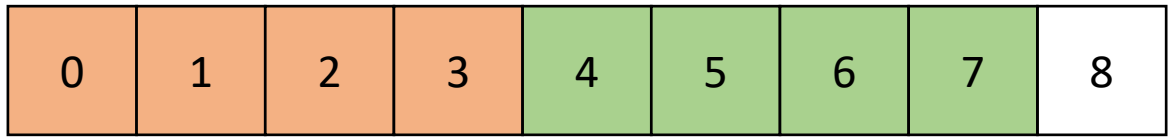


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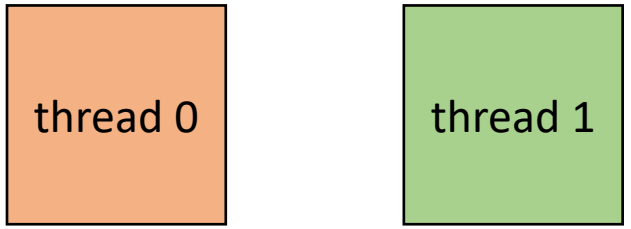


```
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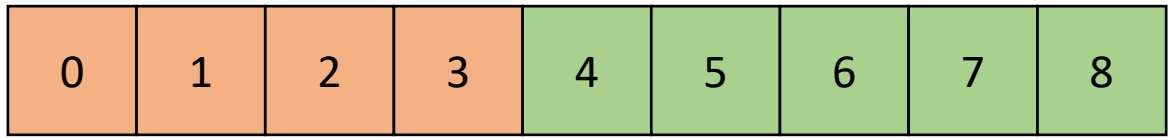
  int chunk_size = SIZE / NUM_THREADS;
  int start = chunk_size * tid;
  int end = start + chunk_size;
  if (tid == num_threads - 1) {
    end = SIZE;
  }
  for (int x = start; x < end; x++) {
    // work based on x
  }
}
```

# Static schedule

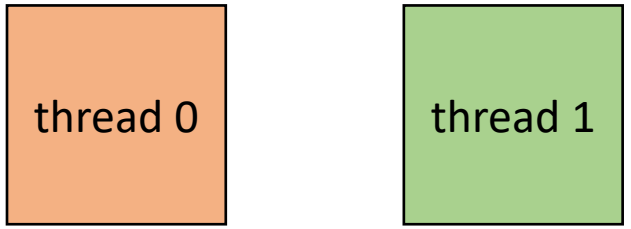
last thread gets more work

- Example, 2 threads/cores, array of size 9




```
chunk_size = 4
```

```
0: start = 0    1: start = 4
0: end = 4      1: end = ?
```

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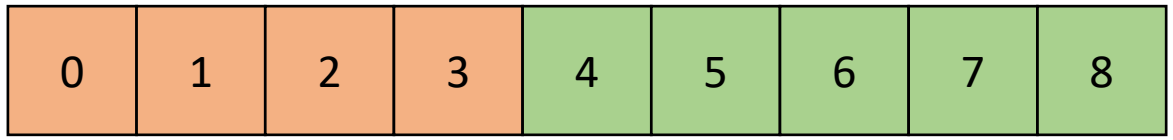
  }
}
```

# Static schedule

- Example, 2 threads/cores, array of size 9

last thread gets more work

What is the worst case?




```
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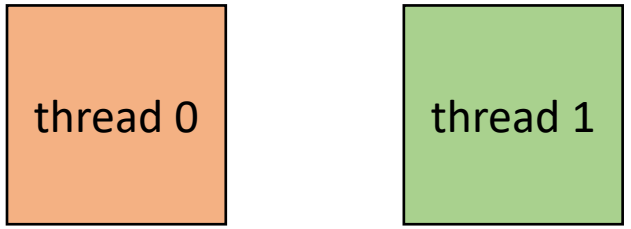





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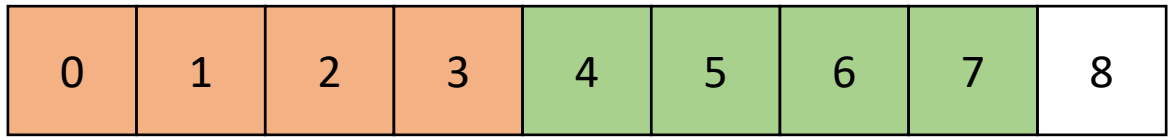
}
```

# End example

# Static schedule

- Example, 2 threads/cores, array of size 9




```
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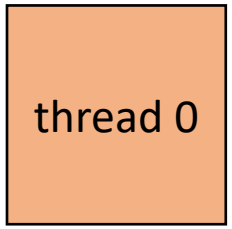



ceiling division, this will distribute uneven work in the last thread to all other threads

```
void parallel_loop(..., int tid, int num_threads)
{
  int chunk_size =
   (SIZE+(NUM_THREADS-1))/NUM_THREADS;
  int start = chunk_size * tid;
  int end = start + chunk_size;
  for (int x = start; x < end; x++) {
    // work based on x
  }
}
```

# Static schedule

- Example, 2 threads/cores, array of size 9


*out of bounds*

```
chunk_size = 5
```

```
0: start = 0
0: end = 5
```

```
1: start = 5
1: end = 10
```

thread 0

thread 1

```
void parallel_loop(..., int tid, int num_threads)
{
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# Static schedule

- Example, 2 threads/cores, array of size 9


*out of bounds*

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```

```
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```

```
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```

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void parallel_loop(..., int tid, int num_threads)
{
  int chunk_size =
   (SIZE+(NUM_THREADS-1))/NUM_THREADS;
  int start = chunk_size * tid;
  int end =
   min(start+chunk_size, SIZE)
for (int x = start; x < end; x++) {
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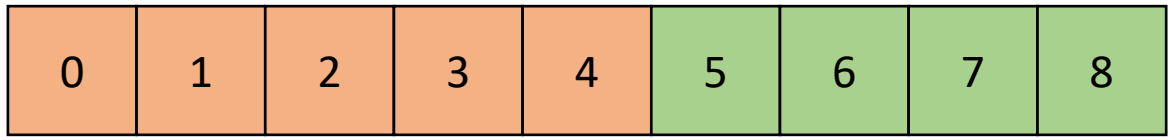
# Static schedule

- Example, 2 threads/cores, array of size 9




```
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```

```
0: start = 0
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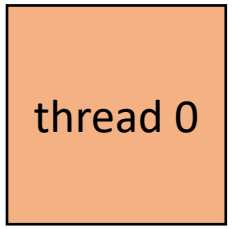
```

```
1: start = 5
1: end = 9
```





most threads do equal amounts of work, last thread may do less.

Which one is better/worse?
Max slowdown for last thread does all the extra work?

Max slowdown for ceiling?

```
void parallel_loop(..., int tid, int num_threads)
{
  int chunk_size =
   (SIZE+(NUM_THREADS-1))/NUM_THREADS;
  int start = chunk_size * tid;
  int end =
   min(start+chunk_size, SIZE)
for (int x = start; x < end; x++) {
    // work based on x
  }
}
```

# End example

# Schedule

- DOALL Loops

- **Parallel Schedules:**
  - Static
  - **Global Worklists**
  - Local Worklists

# Irregular parallelism in loops

- Tasks are not balanced
- Appears in lots of emerging workloads

# Irregular parallelism in loops

- Tasks are not balanced
- Appears in lots of emerging workloads

social network analytics where threads are parallel across users


# Irregular parallelism in loops

- Independent iterations have different amount of work to compute
- Threads with longer tasks take longer to compute.
- Threads with shorter tasks are under utilized.

```
for (x = 0; x < SIZE; x++) {
  for (y = x; y < SIZE; y++) {
    a[x,y] = b[x,y] + c[x,y];
  }
}
```

irregular (or unbalanced) parallelism: each x iteration performs different amount of work.

# Irregular parallelism in loops

- Calculate imbalance cost if x is chunked:
  - Thread 1 takes iterations 0 - SIZE/2
  - Thread 2 takes iterations SIZE/2 - SIZE

```
for (x = 0; x < SIZE; x++) {
  for (y = x; y < SIZE; y++) {
    a[x,y] = b[x,y] + c[x,y];
  }
}
```

# Irregular parallelism in loops

- Calculate imbalance cost if x is chunked:
  - Thread 1 takes iterations 0 - SIZE/2
  - Thread 2 takes iterations SIZE/2 - SIZE

Calculate how much total work:

$$\text{total\_work} = \sum_{n=0}^{SIZE} n$$

```
for (x = 0; x < SIZE; x++) {
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# Irregular parallelism in loops

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$$\text{t1\_work} = \sum_{n=0}^{SIZE/2} n$$

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Calculate how much total work:

$$\text{total\_work} = \sum_{n=0}^{SIZE} n$$

Calculate work done by first thread:

$$\text{t1\_work} = \sum_{n=0}^{SIZE/2} n$$

Calculate work work done by second thread:

t2_work = total_work − t1_work

# Irregular parallelism in loops

Example: SIZE = 64

total_work = 2016
t2_work = 496
t1_work = 1520

t1 does ~3x more work than t2

Only provides ~1.3x speedup

*Potential solution:*
Have T1 do only ¼ of the iterations
Gives a better speedup of 1.77x

*Not a feasible solution because often times load imbalance is not given by a static equation on loop bounds!*

Calculate how much total work:

$$\text{total\_work} = \sum_{n=0}^{SIZE} n$$

Calculate work done by first thread:

$$\text{t1\_work} = \sum_{n=0}^{SIZE/2} n$$

Calculate work work done by second thread:

t2_work = total_work − t1_work

# Work stealing

- Tasks are dynamically assigned to threads.

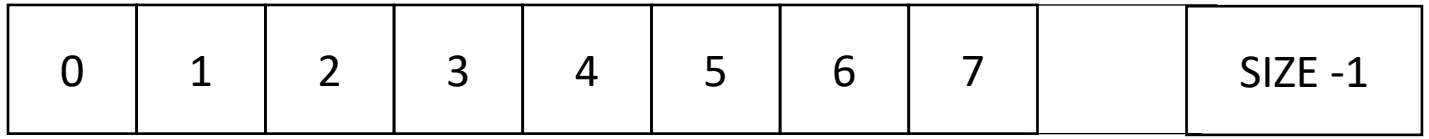
# Work stealing - global implicit worklist

- Pros
  - Simple to implement

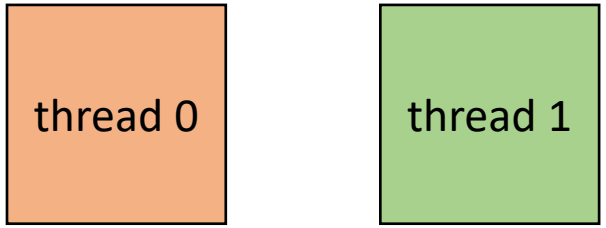
- Cons:
  - High contention on global counter
  - Potentially bad memory locality.

# Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically




*cannot color initially!*



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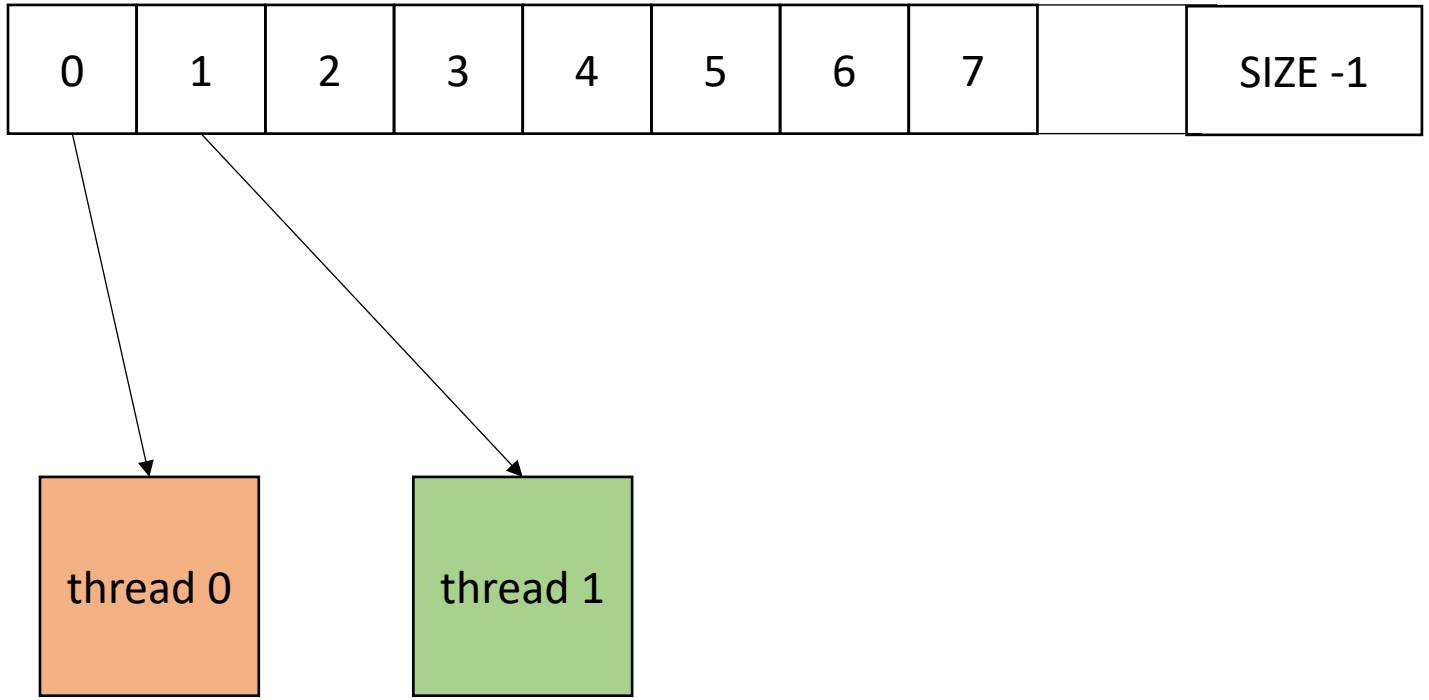

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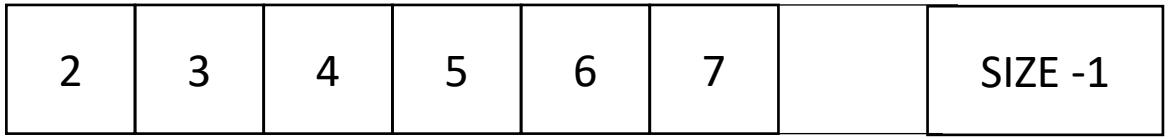


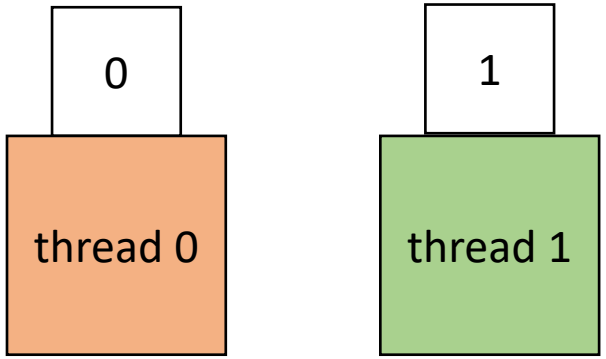

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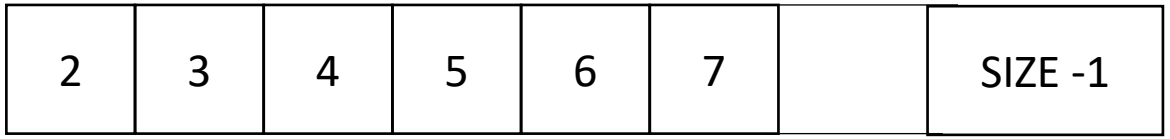
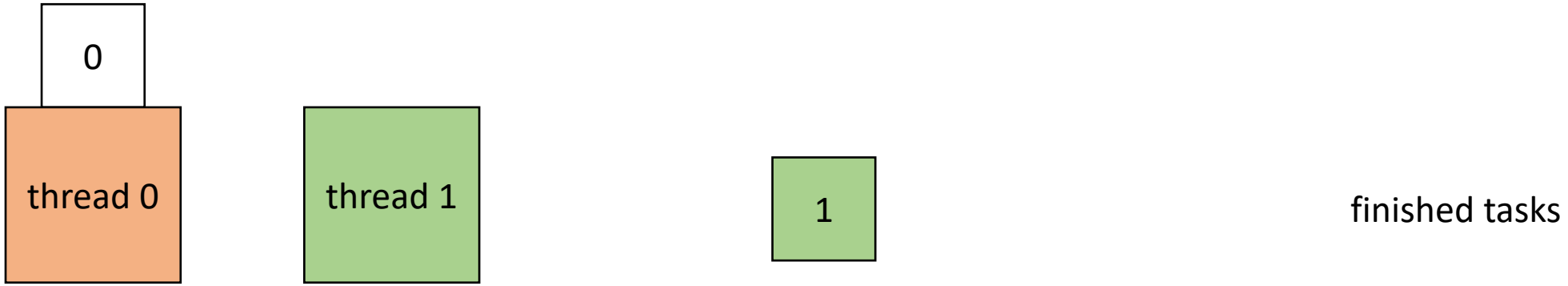
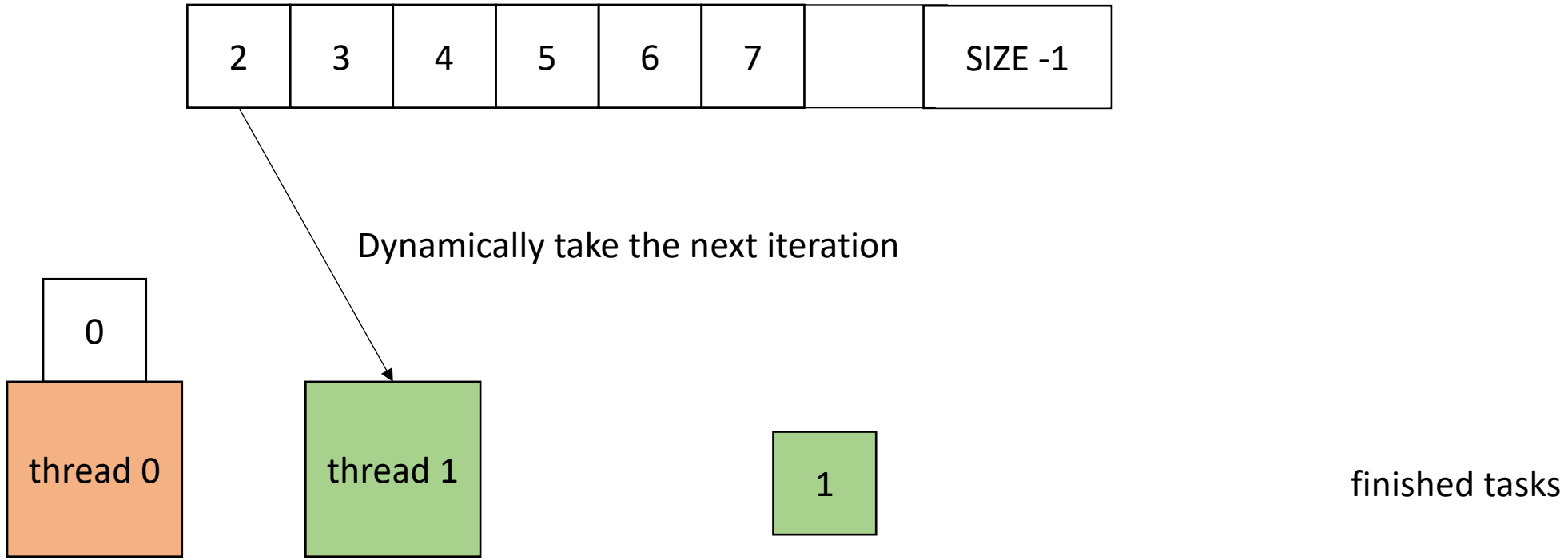


# Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



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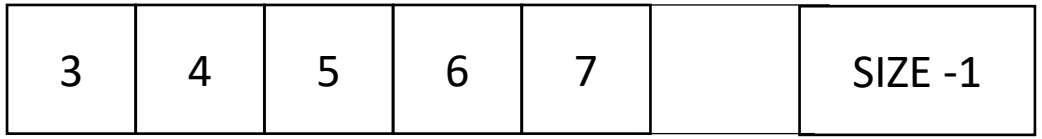


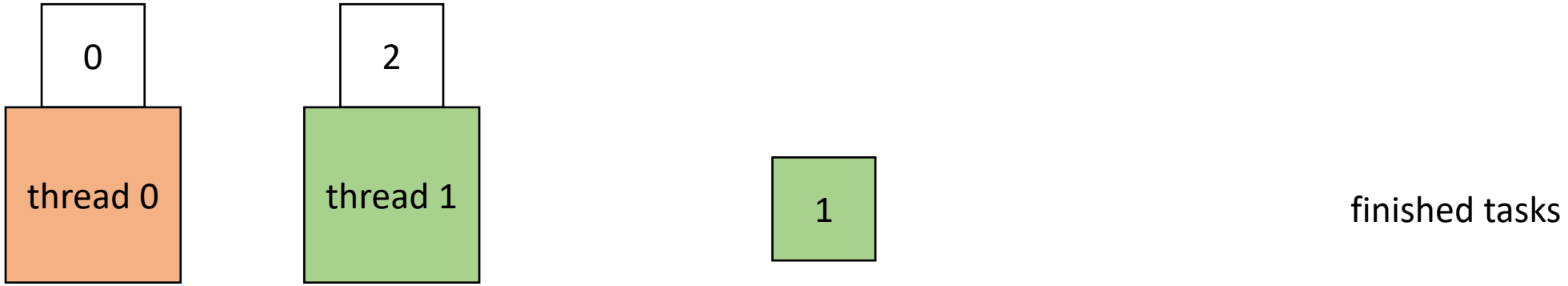

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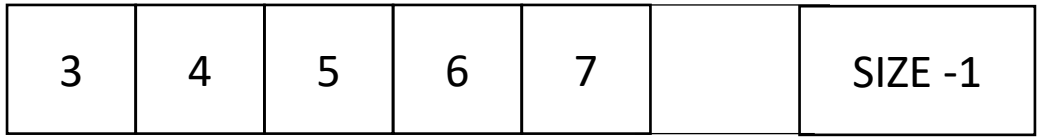


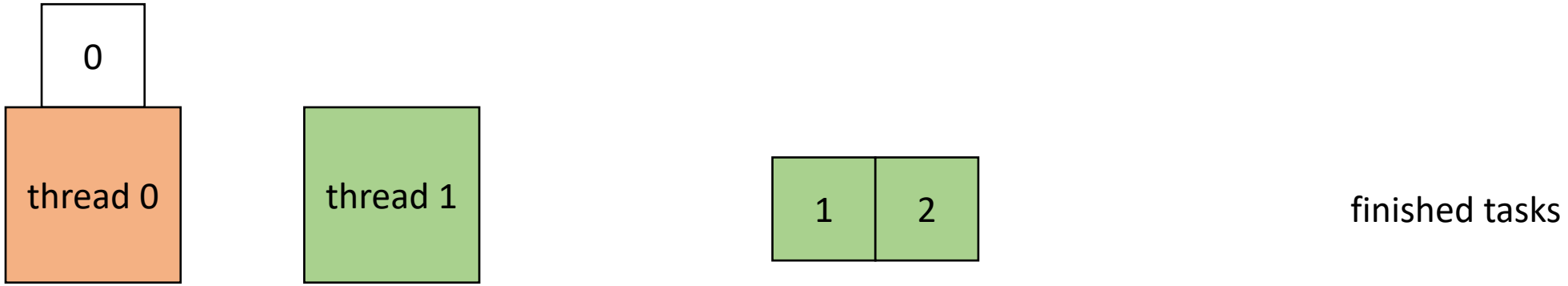

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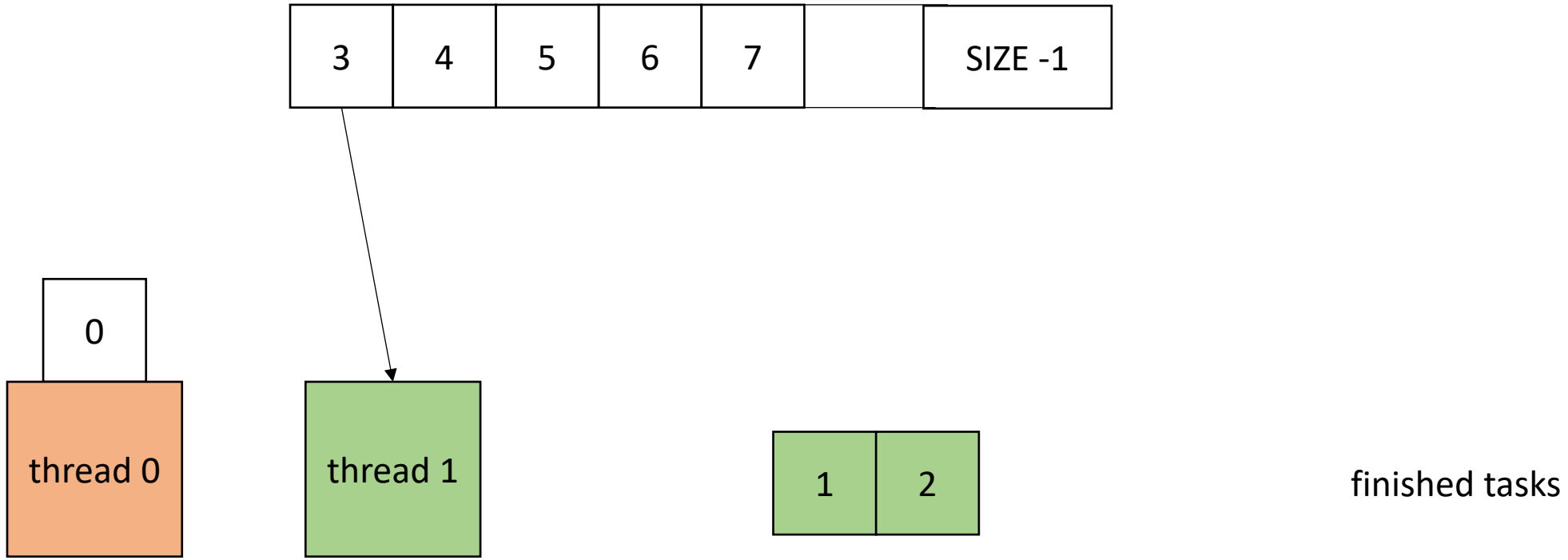
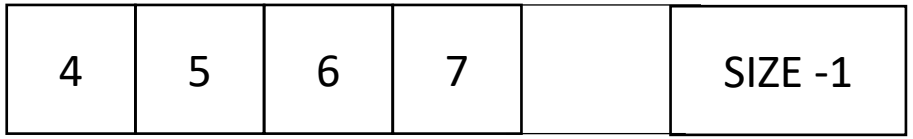
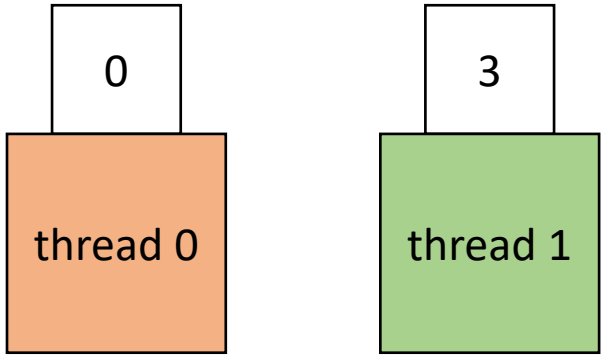


# Work stealing - global implicit worklist

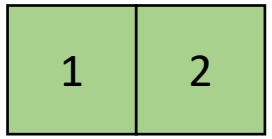
- Global worklist: threads take tasks (iterations) dynamically





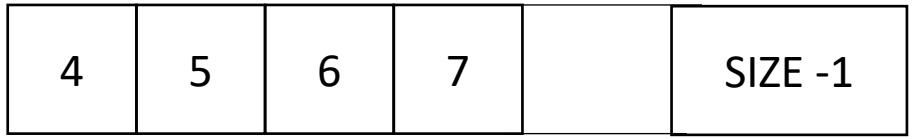


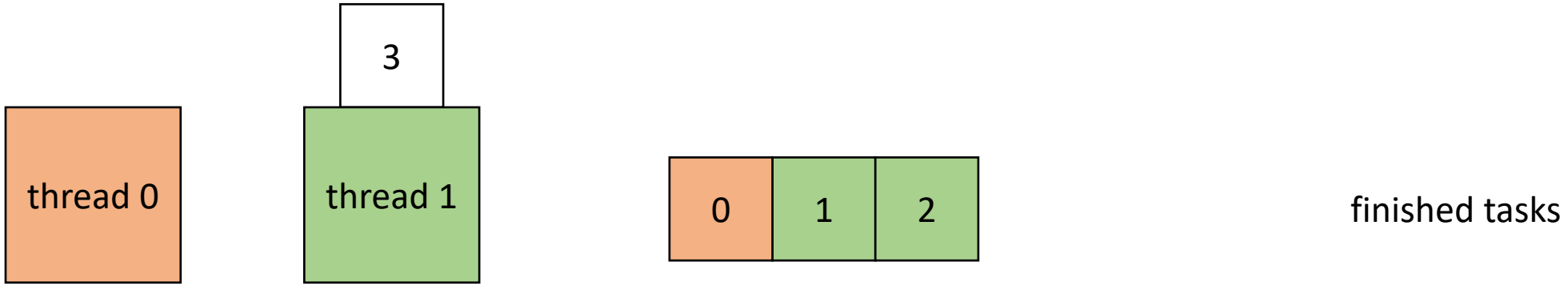



finished tasks

# Work stealing - global implicit worklist

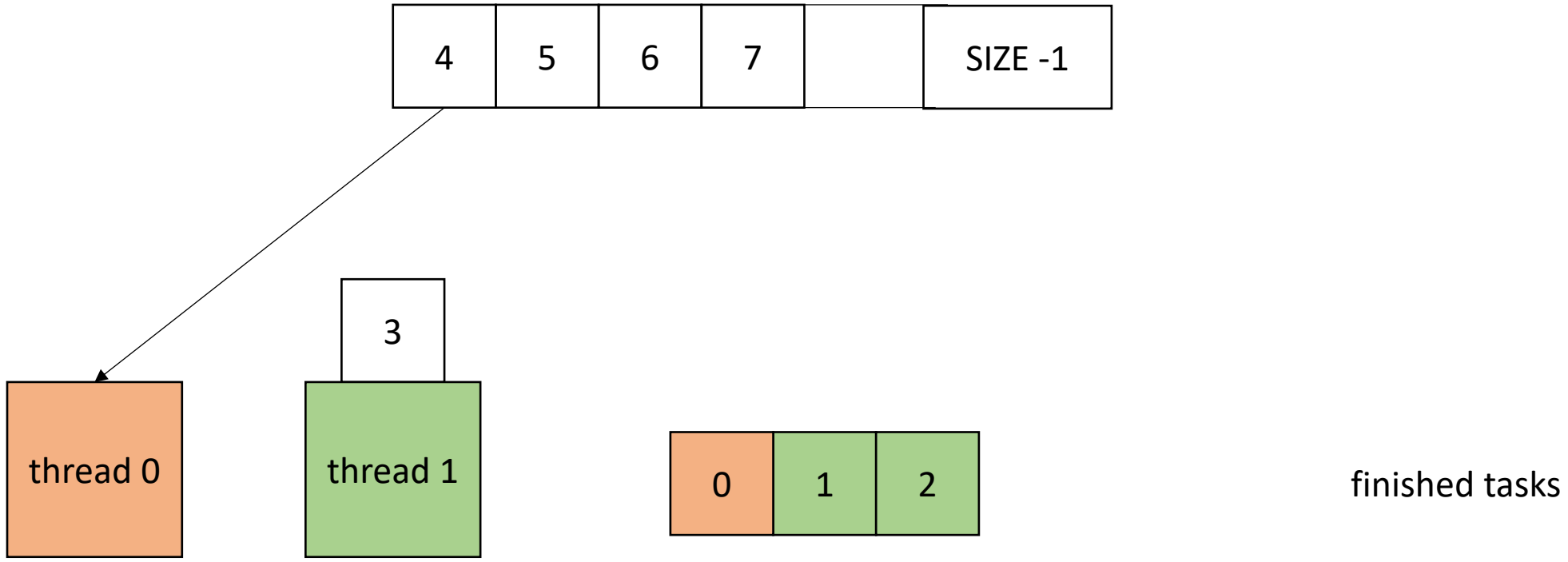
- Global worklist: threads take tasks (iterations) dynamically



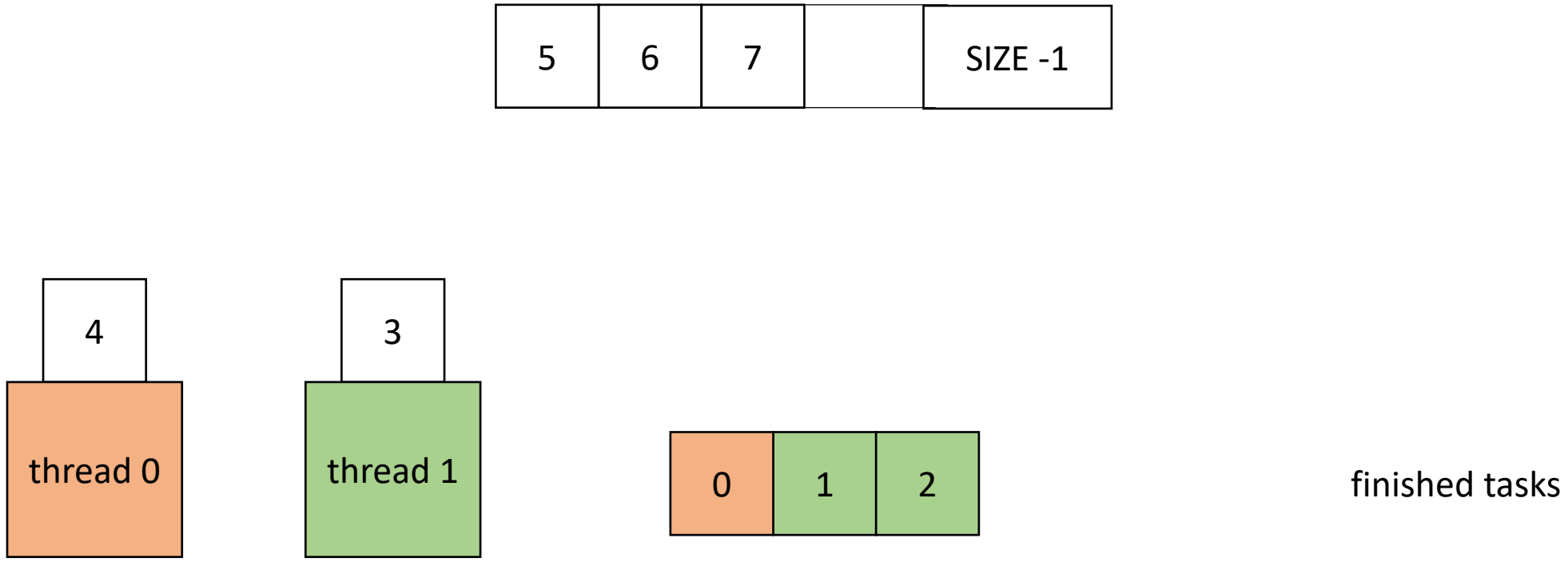
# Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



# Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



# End example

# Work stealing - global implicit worklist

- How to implement

```
void foo() {
  ...
  for (x = 0; x < SIZE; x++) {
    // dynamic work based on x
  }
  ...
}
```

# Work stealing - global implicit worklist

- How to implement

```
void foo() {
   ...
   for (x = 0; x < SIZE; x++) {
     // dynamic work based on x
   }
   ...
}
```

```
void parallel_loop(...) {

  for (x = 0; x < SIZE; x++) {
    // dynamic work based on x
  }
}
```

Replicate code in a new function. Pass all needed variables as arguments.

# Work stealing - global implicit worklist

- How to implement

```
void foo() {
   ...
   for (x = 0; x < SIZE; x++) {
     // dynamic work based on x
   }
   ...
}
```

```
atomic_int x(0);
void parallel_loop(...) {

  for (x = 0; x < SIZE; x++) {
    // dynamic work based on x
  }
}
```

move loop variable to be a global atomic variable

# Work stealing - global implicit worklist

- How to implement

```
void foo() {
   ...
   for (x = 0; x < SIZE; x++) {
      // dynamic work based on x
   }
   ...
}
```

```
atomic_int x(0);
void parallel_loop(...) {

  for (int local_x = ??
            local_x < SIZE;
            local_x = ??) {

     // dynamic work based on x
  }
}
```

change loop bounds in new function to use a local variable using global variable.

# Work stealing - global implicit worklist

- How to implement

*These must be atomic updates!*

```
void foo() {
   ...
   for (x = 0; x < SIZE; x++) {
      // dynamic work based on x
   }
   ...
}
```

```
atomic_int x(0);
void parallel_loop(...) {

   for (int local_x = atomic_fetch_add(&x,1);
            local_x < SIZE;
            local_x = atomic_fetch_add(&x,1)) {

      // dynamic work based on x
   }
}
```

change loop bounds in new function to use a local variable using global variable.

# Work stealing - global implicit worklist

- How to implement

```
void foo() {
  ...
  for (t = 0; x < THREADS; t++) {
    spawn(parallel_loop);
  }
  join();
  ...
}
```

```
atomic_int x(0);
void parallel_loop(...) {

  for (int local_x = atomic_fetch_add(&x,1);
           local_x < SIZE;
           local_x = atomic_fetch_add(&x,1)) {

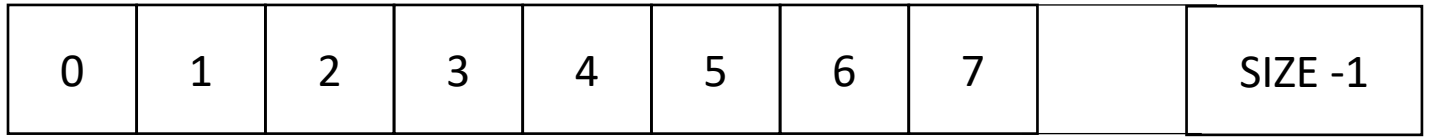
     // dynamic work based on x
  }
}
```

Spawn threads in original function and join them afterwards

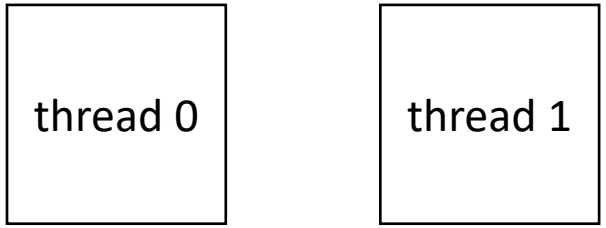
You will have to change to C++ syntax for the homework!

# Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically




```
x: 0
0 - local_x - UNDEF
1 - local_x - UNDEF
```







```
atomic_int x(0);
void parallel_loop(...) {

  for (int local_x = atomic_fetch_add(&x,1);
            local_x < SIZE;
            local_x = atomic_fetch_add(&x,1)) {

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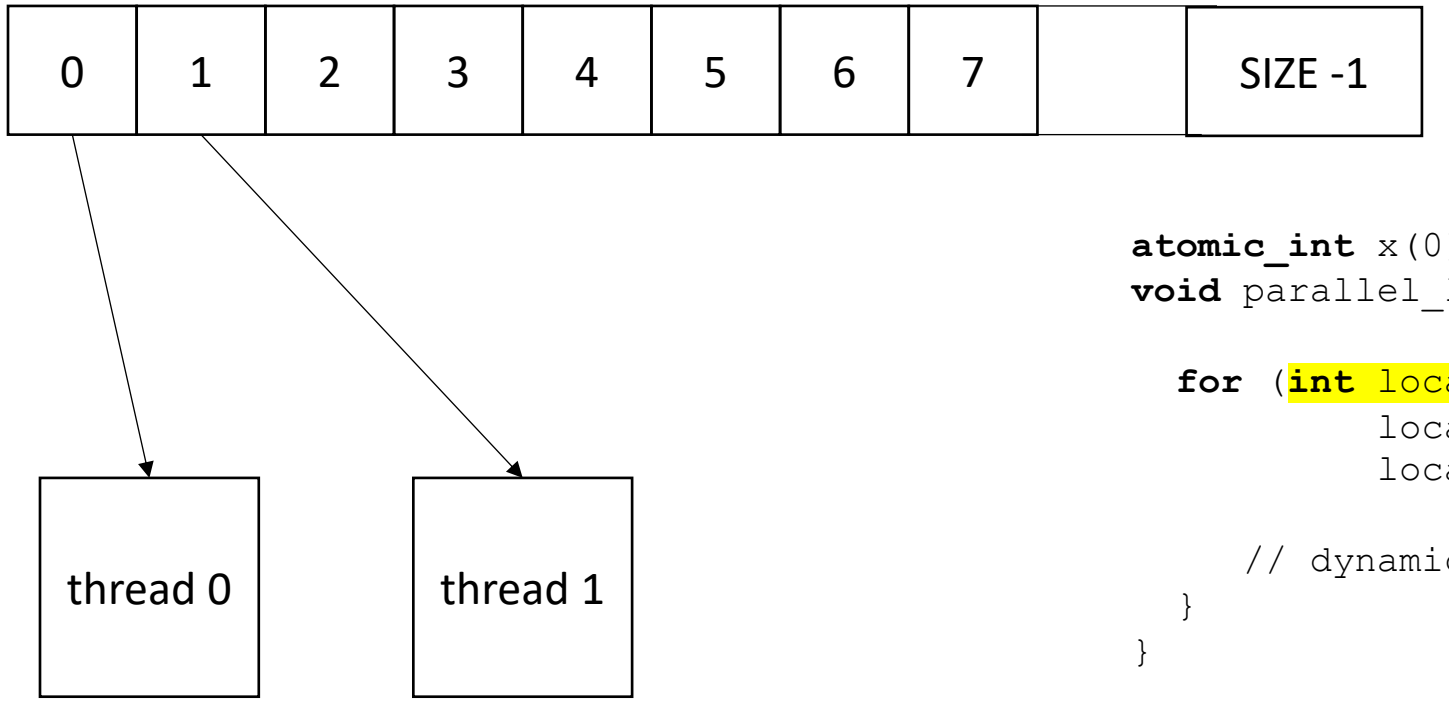
}
```

# Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically




```
x: 2
0 - local_x - 0
1 - local_x - 1
```

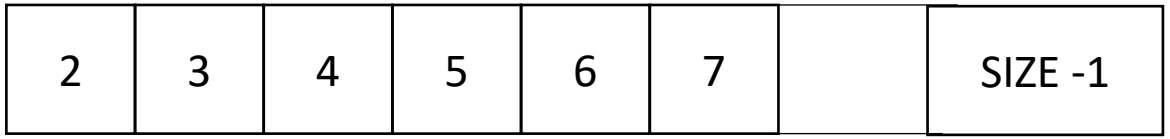
```
atomic_int x(0);
void parallel_loop(...) {

  for (int local_x = atomic_fetch_add(&x,1);
            local_x < SIZE;
            local_x = atomic_fetch_add(&x,1)) {

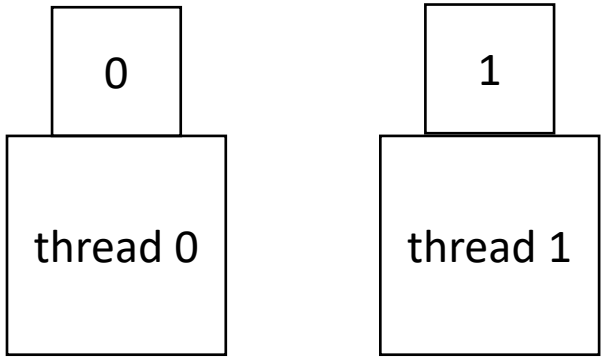
     // dynamic work based on x
  }
}
```

# Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically




```
x: 2
0 - local_x - 0
1 - local_x - 1
```







```
atomic_int x(0);
void parallel_loop(...) {

  for (int local_x = atomic_fetch_add(&x,1);
            local_x < SIZE;
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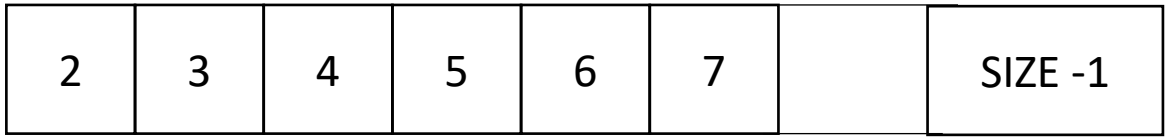
     // dynamic work based on x
  }
}
```

# Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically

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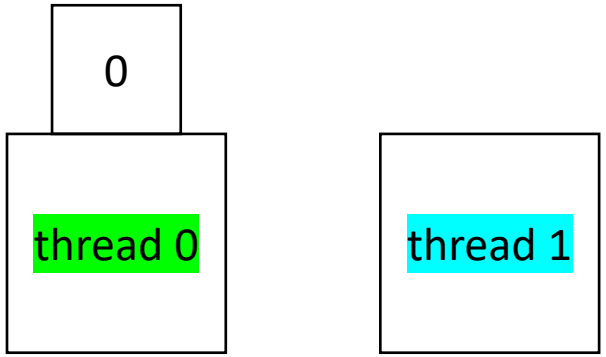


```
atomic_int x(0);
void parallel_loop(...) {

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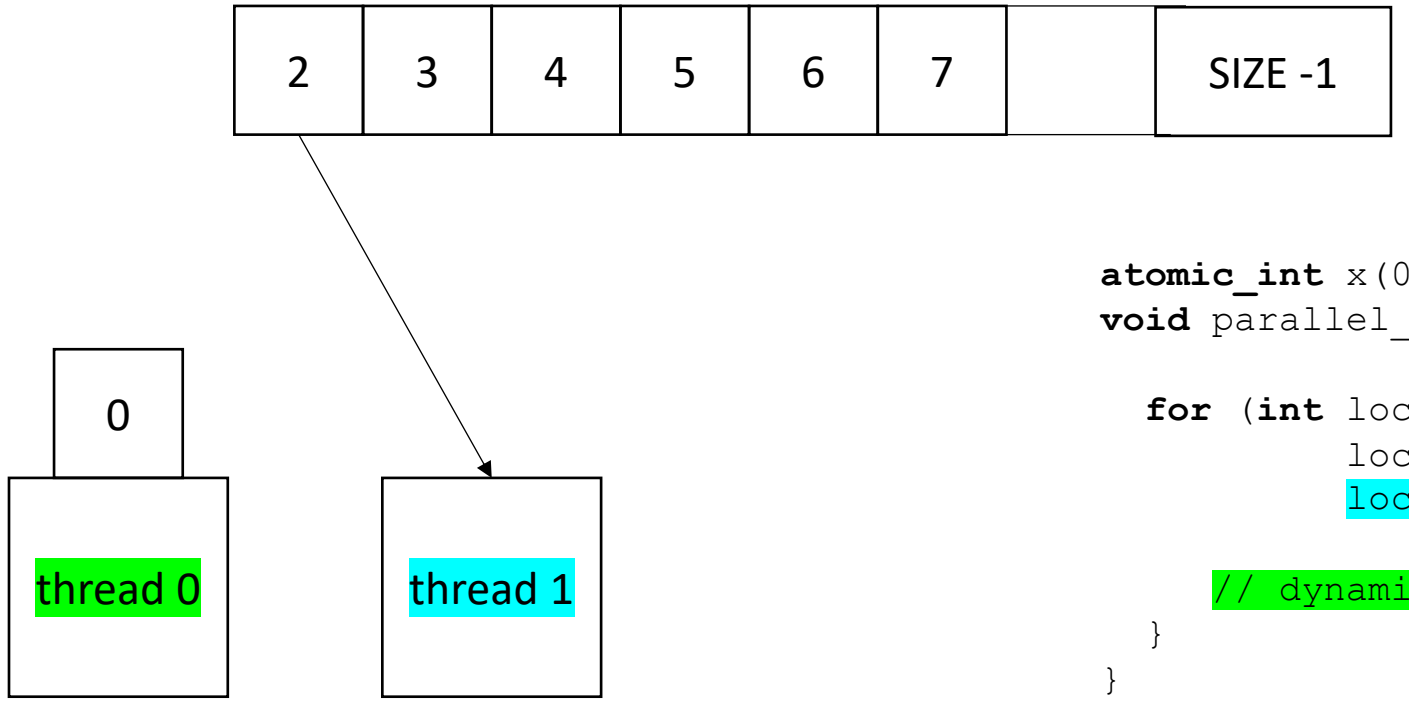
# Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically




```
x: 3
0 - local_x - 0
1 - local_x - 2
```

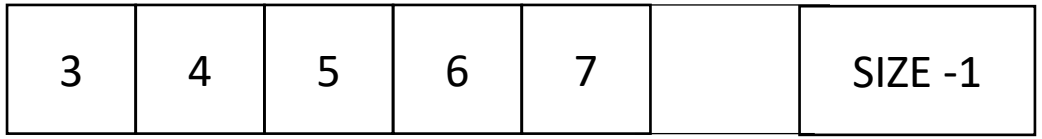
```
atomic_int x(0);
void parallel_loop(...) {

  for (int local_x = atomic_fetch_add(&x,1);
            local_x < SIZE;
            local_x = atomic_fetch_add(&x,1)) {

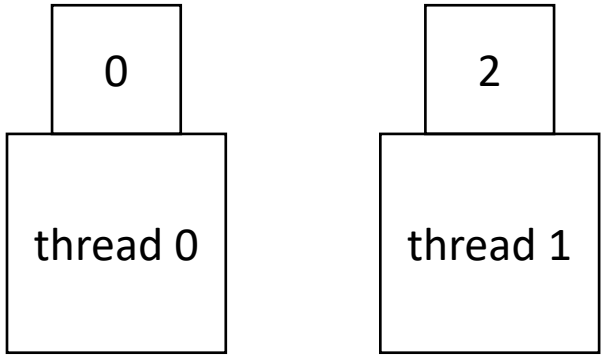
      // dynamic work based on x
  }
}
```

# Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically




```
x: 3
0 - local_x - 0
1 - local_x - 2
```




```
atomic_int x(0);
void parallel_loop(...) {

  for (int local_x = atomic_fetch_add(&x,1);
            local_x < SIZE;
            local_x = atomic_fetch_add(&x,1)) {

     // dynamic work based on x
  }
}
```

# Work stealing - global implicit worklist

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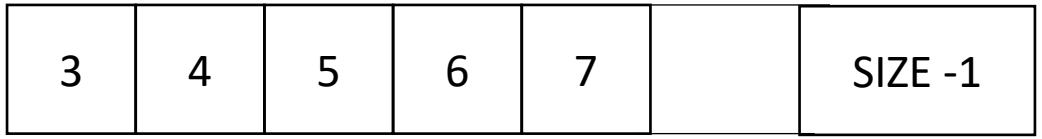


```
x: 3
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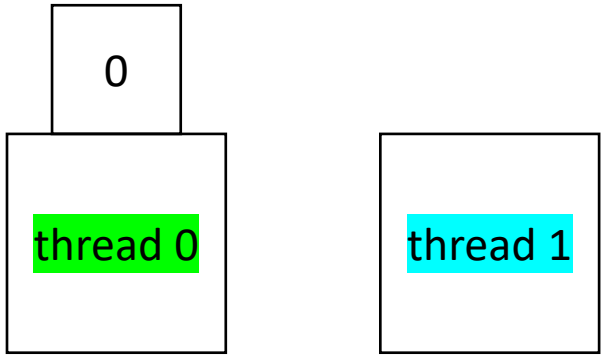
1 - local_x - 2
```




```
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void parallel_loop(...) {

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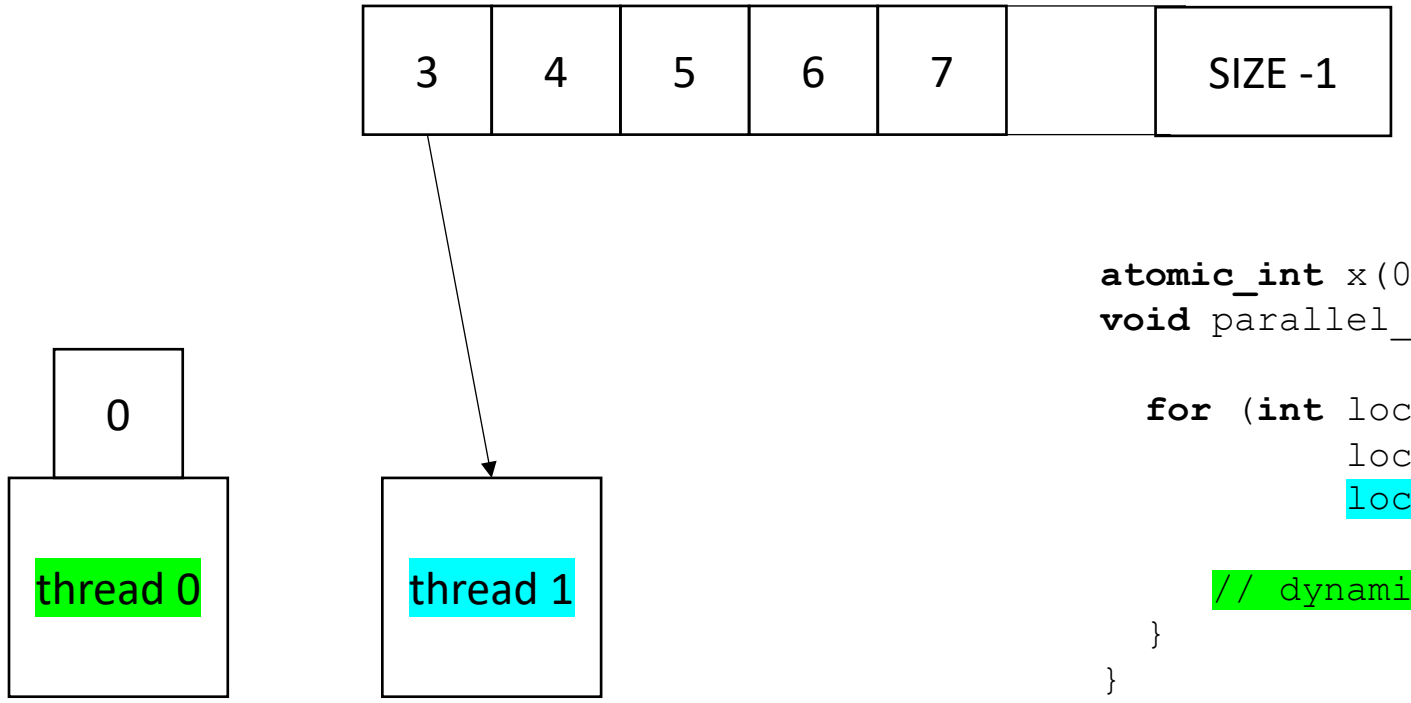



```
x: 4
0 - local_x - 0
1 - local_x - 3
```

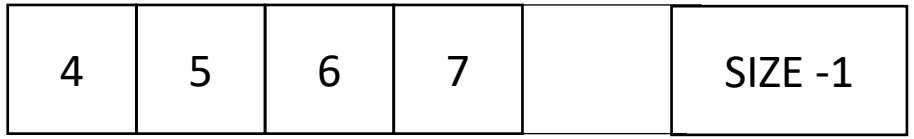
```
atomic_int x(0);
void parallel_loop(...) {

  for (int local_x = atomic_fetch_add(&x,1);
            local_x < SIZE;
            local_x = atomic_fetch_add(&x,1)) {

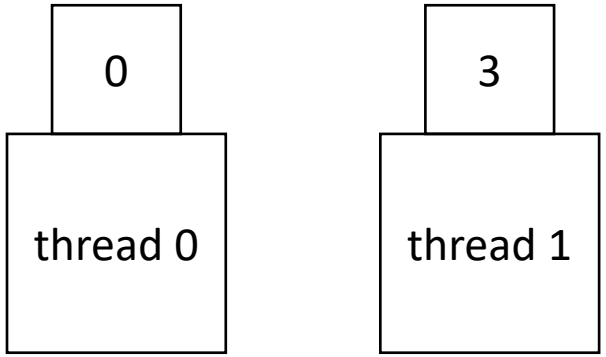
      // dynamic work based on x
  }
}
```

# Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically




```
x: 4
0 - local_x - 0
1 - local_x - 3
```




```
atomic_int x(0);
void parallel_loop(...) {

  for (int local_x = atomic_fetch_add(&x,1);
            local_x < SIZE;
            local_x = atomic_fetch_add(&x,1)) {

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  }
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```

# Work stealing - global implicit worklist

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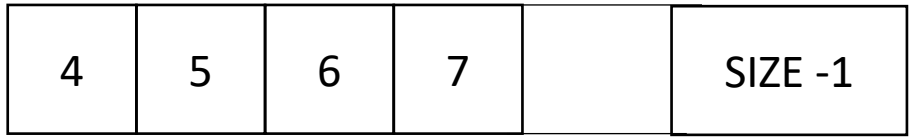
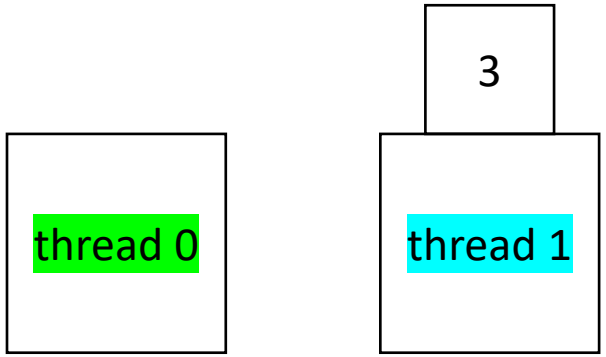



```
x: 4
0 - local_x - 0
1 - local_x - 3
```




```
atomic_int x(0);
void parallel_loop(...) {

  for (int local_x = atomic_fetch_add(&x,1);
            local_x < SIZE;
            local_x = atomic_fetch_add(&x,1)) {

     // dynamic work based on x
  }
}
```

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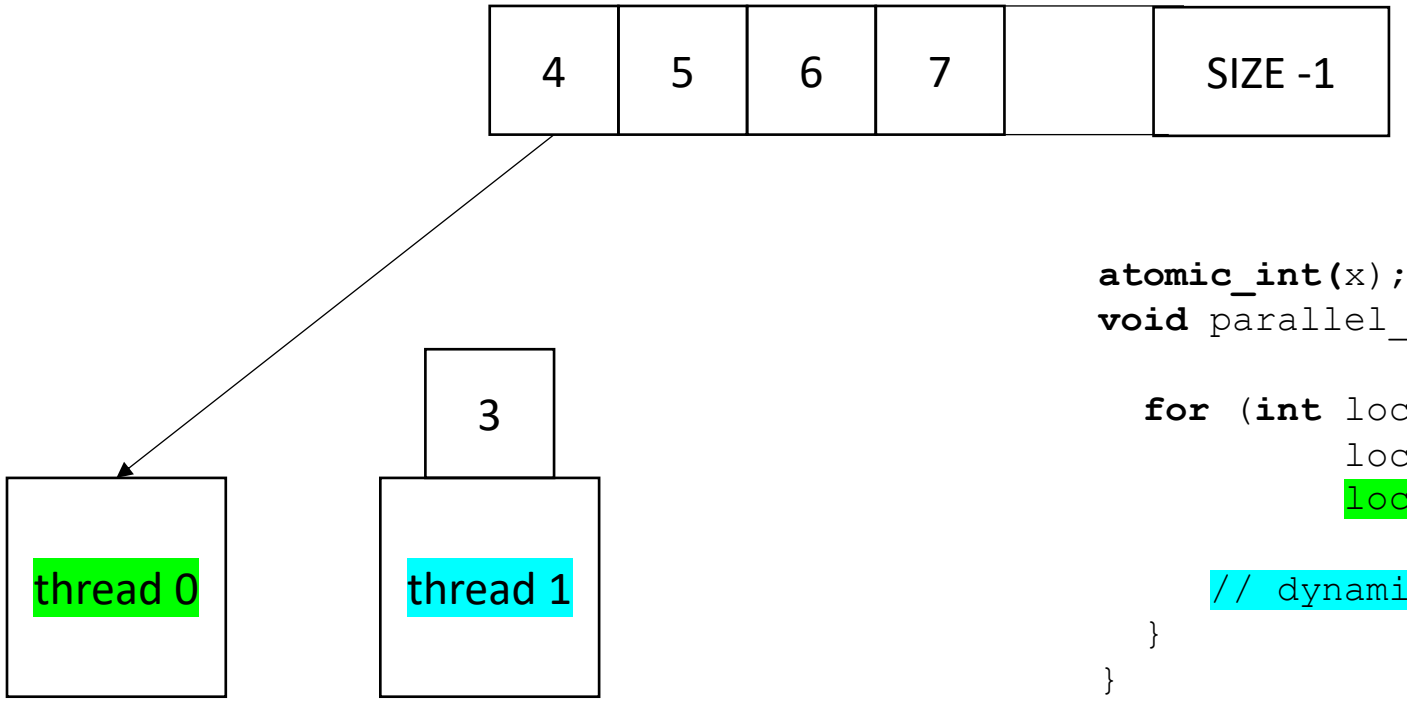
- Global worklist: threads take tasks (iterations) dynamically




```
x: 5
0 - local_x - 4
1 - local_x - 3
```

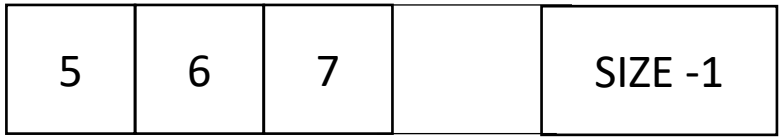
```
atomic_int(x);
void parallel_loop(...) {

  for (int local_x = atomic_fetch_add(&x,1);
            local_x < SIZE;
            local_x = atomic_fetch_add(&x,1)) {

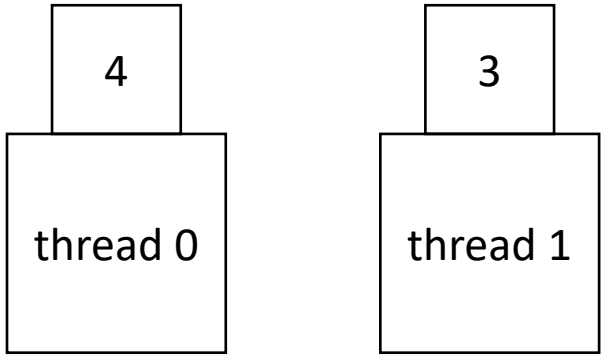
     // dynamic work based on x
  }
}
```

# Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically




```
x: 5
0 - local_x - 4
1 - local_x - 3
```




```
atomic_int x(0);
void parallel_loop(...) {

  for (int local_x = atomic_fetch_add(&x,1);
            local_x < SIZE;
            local_x = atomic_fetch_add(&x,1)) {

     // dynamic work based on x
  }
}
```

# Schedule

- DOALL Loops

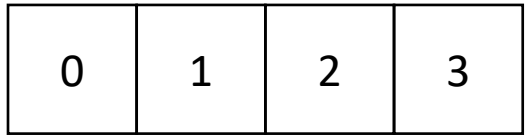
- **Parallel Schedules:**
  - Static
  - Global Worklists
  - **Local Worklists**

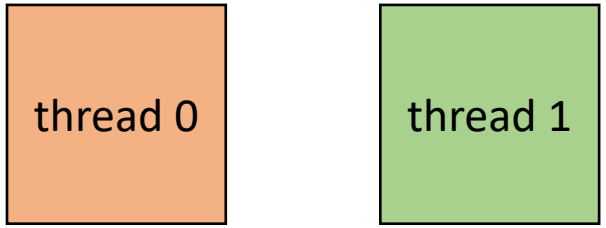
# Work stealing - local worklists

- More difficult to implement
- low contention on local data-structures
- potentially better cache locality

# Work stealing - local worklists

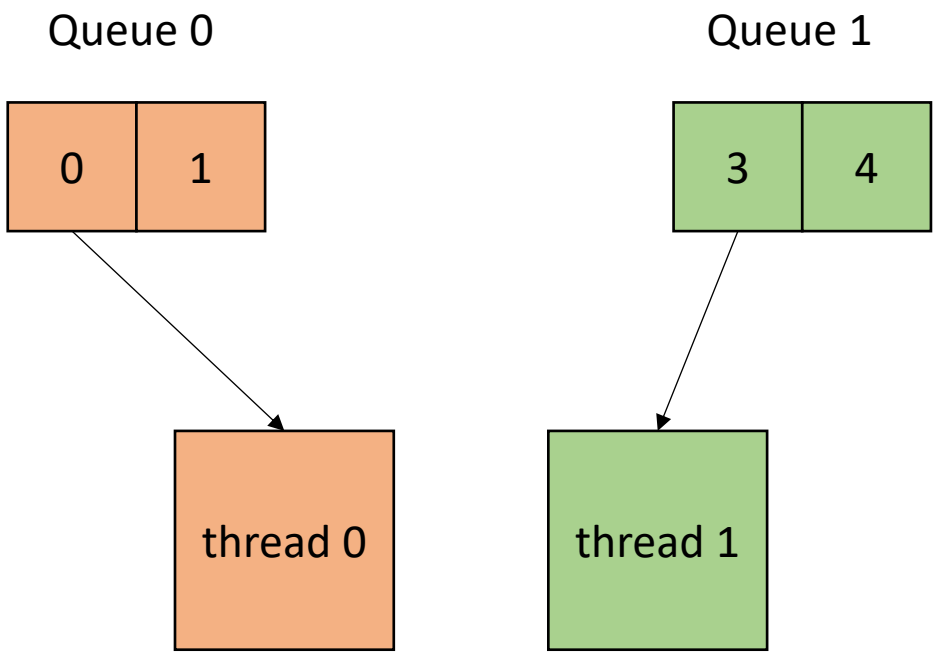
- local worklists: divide tasks into different worklists for each thread



# Work stealing - local worklists

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



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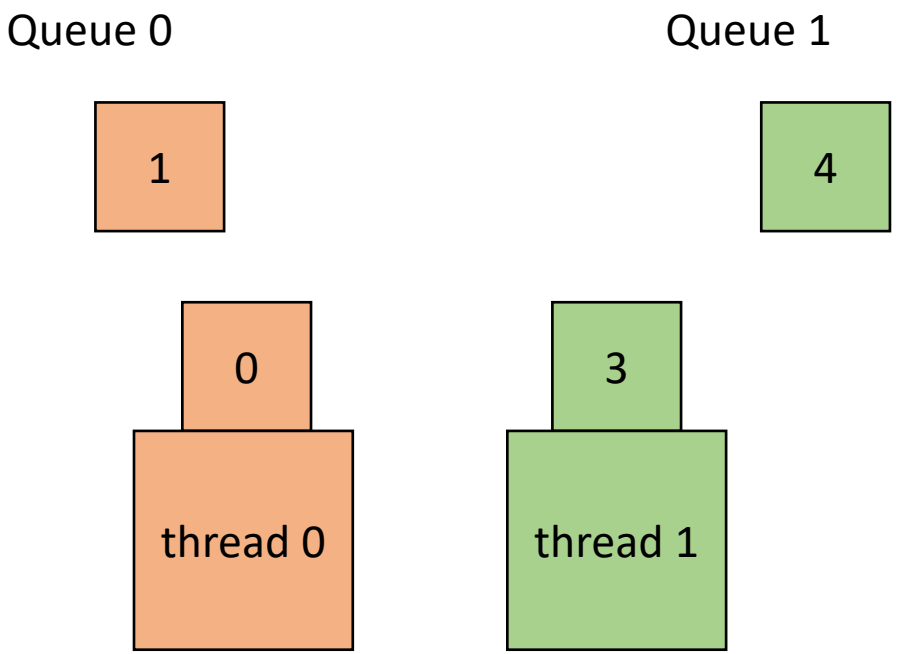

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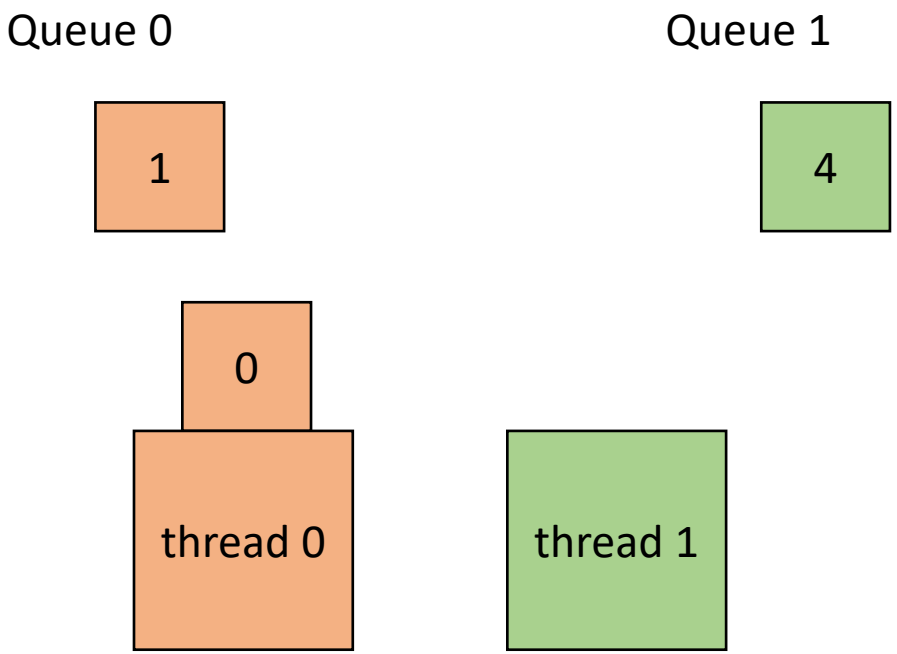

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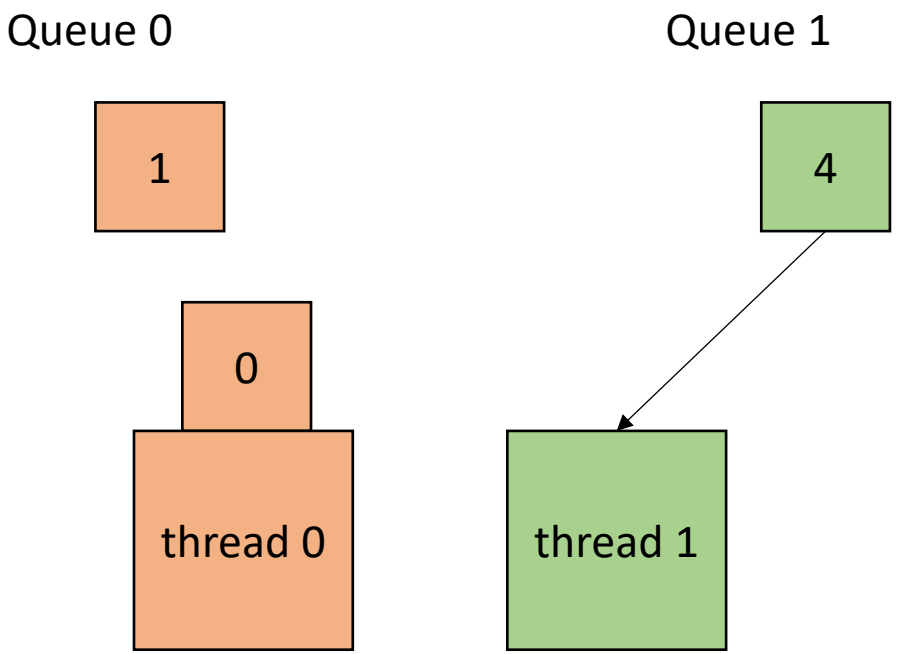

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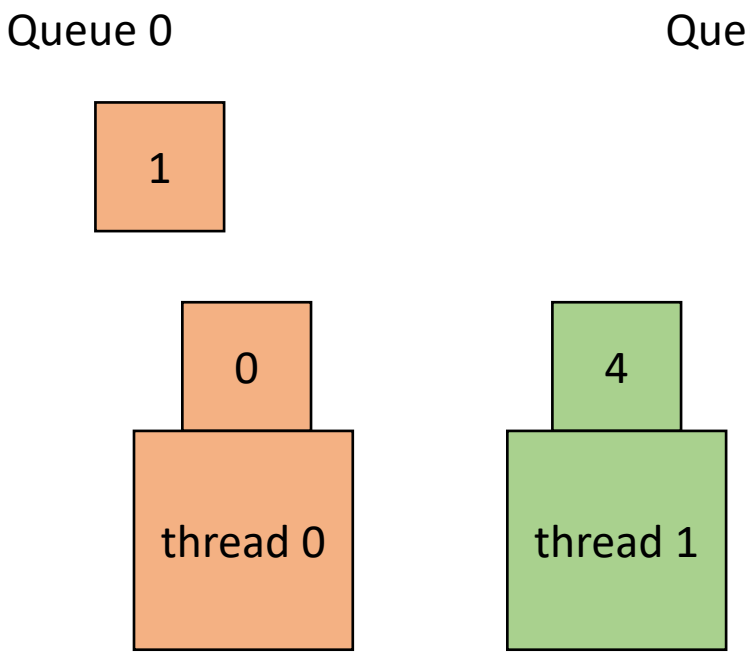
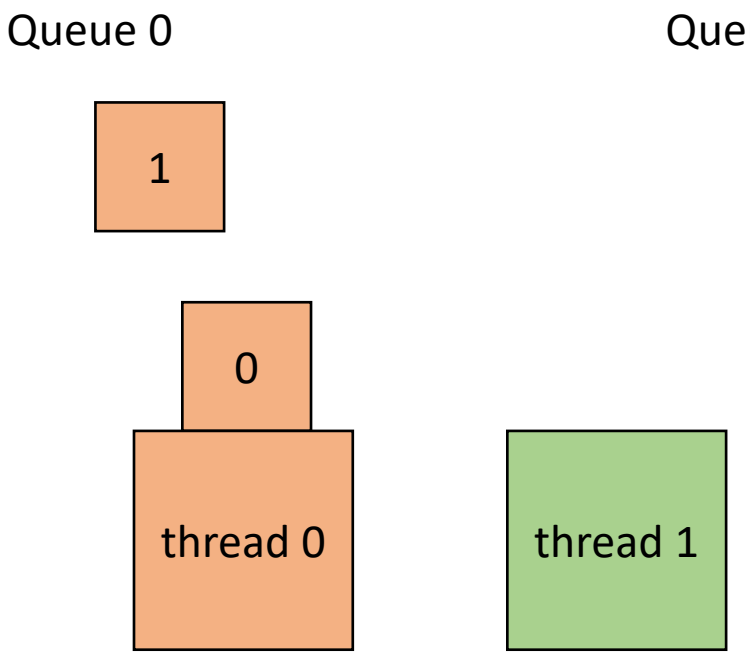


# Work stealing - local worklists

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



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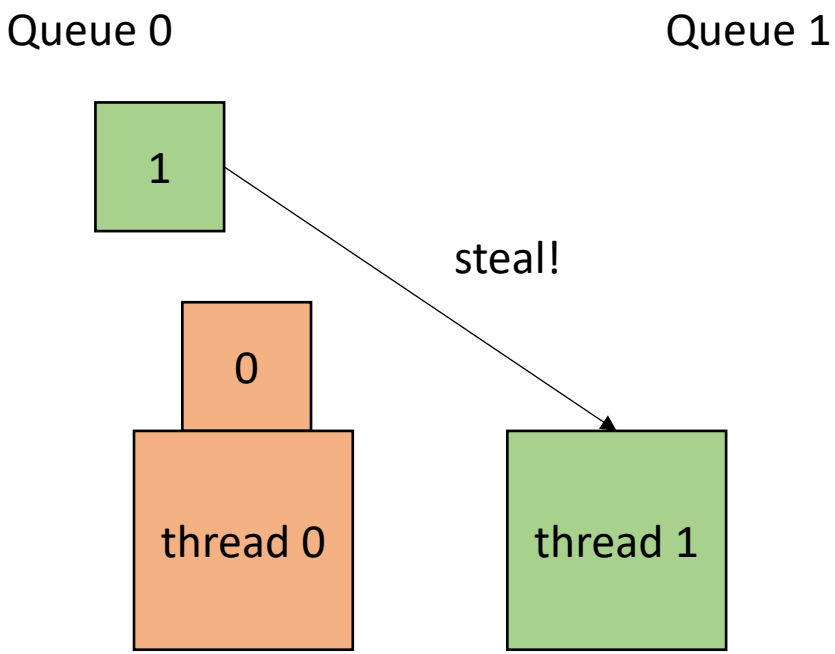

# Work stealing - local worklists

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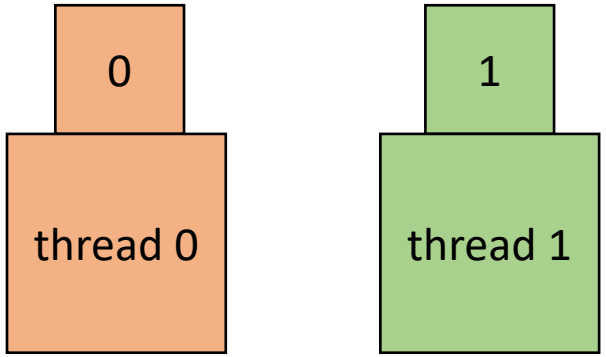
Queue 0

Queue 1



# Work stealing - local worklists

- How to implement:

```
void foo() {
  ...
  for (x = 0; x < SIZE; x++) {
    // dynamic work based on x
  }
  ...
}
```

# Work stealing - local worklists

- How to implement:

```
void foo() {
   ...
   for (x = 0; x < SIZE; x++) {
     // dynamic work based on x
   }
   ...
}
```

```
void parallel_loop(..., int tid) {

   for (x = 0; x < SIZE; x++) {
     // dynamic work based on x
   }
}
```

Make a new function, taking any variables used in loop body as args. Additionally take in a thread id

# Work stealing - local worklists

- How to implement:

```
concurrent_queues cq[NUM_THREADS];
void foo() {
  ...
  for (x = 0; x < SIZE; x++) {
    // dynamic work based on x
  }
  ...
}
```

```
void parallel_loop(..., int tid) {

  for (x = 0; x < SIZE; x++) {
    // dynamic work based on x
  }
}
```

Make a global array of concurrent queues

# Work stealing - local worklists

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}
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void parallel_loop(..., int tid) {

  for (x = 0; x < SIZE; x++) {
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  }
}
```

What type of queues?

Make a global array of concurrent queues

# Work stealing - local worklists

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void parallel_loop(..., int tid) {

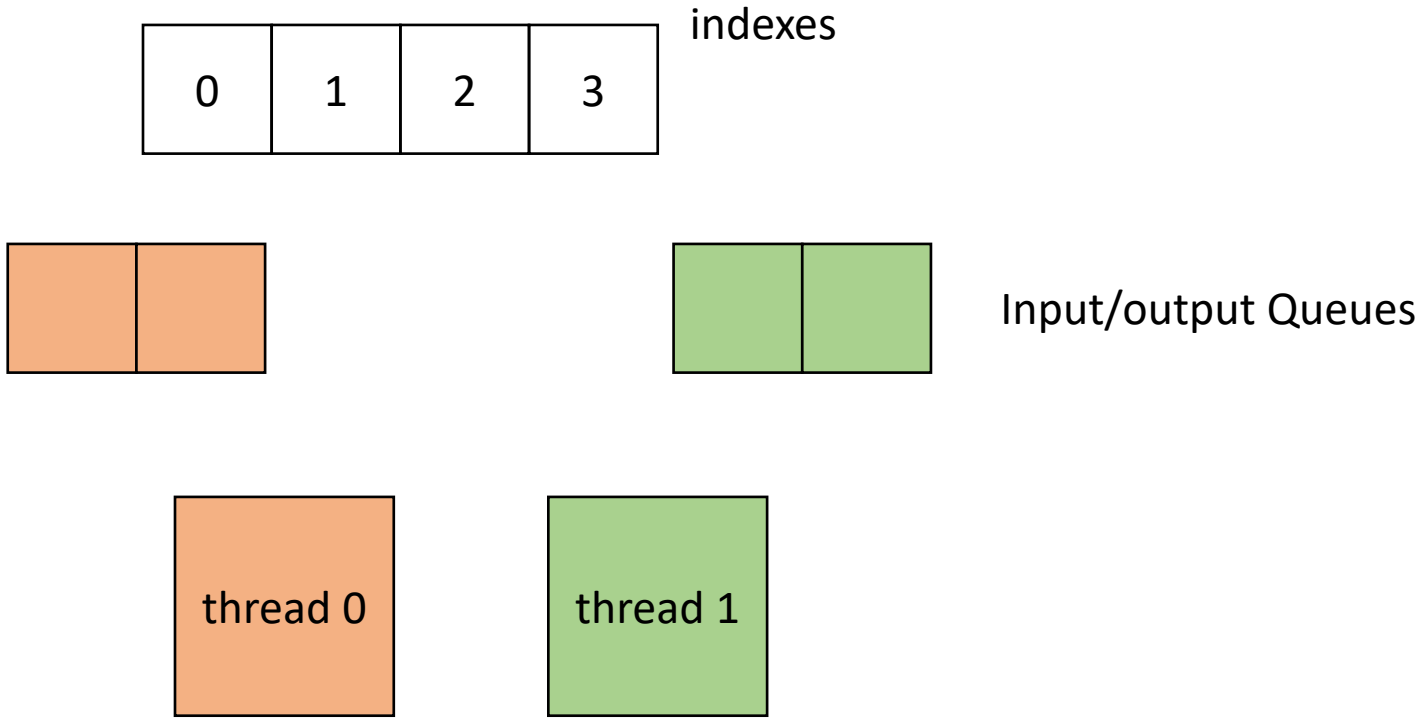
  for (x = 0; x < SIZE; x++) {
    // dynamic work based on x
  }
}
```

Make a global array of concurrent queues

What type of queues?
We're going to use InputOutput Queues!

# Work stealing - local worklists

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



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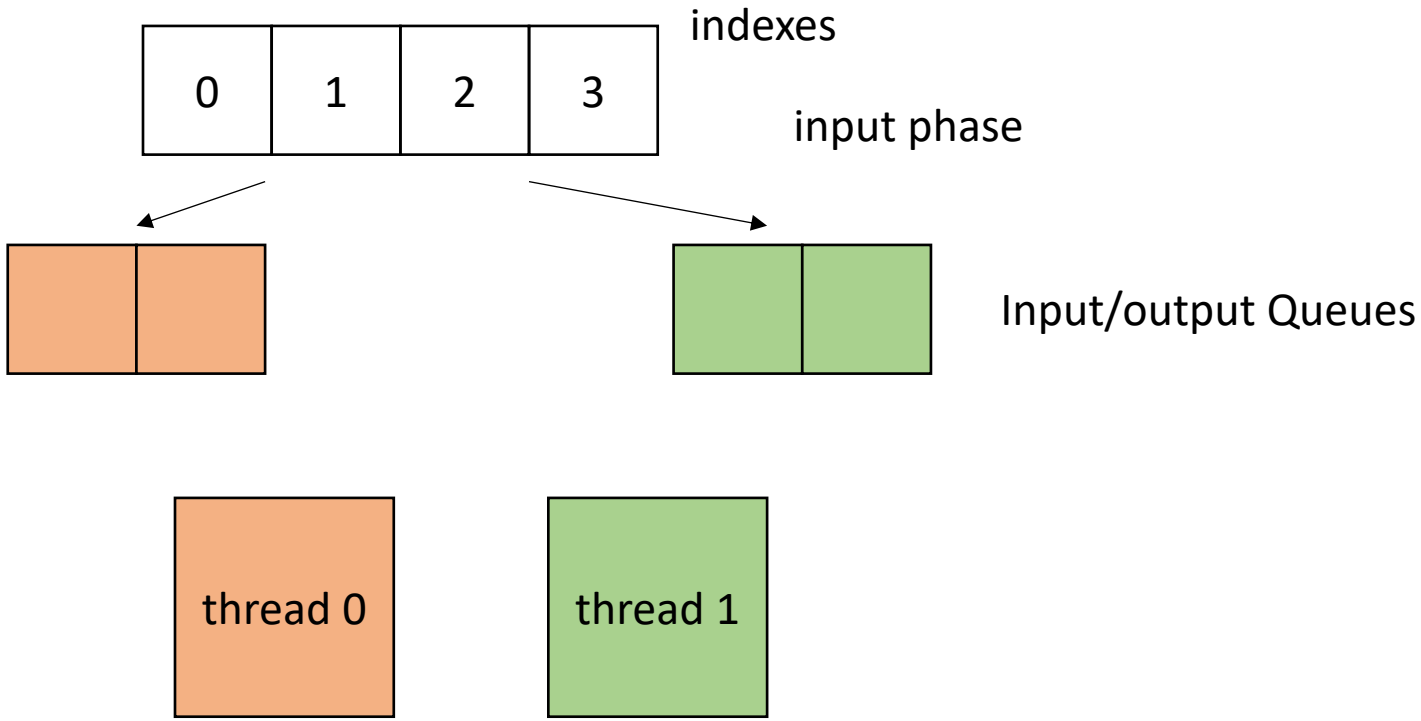

# Work stealing - local worklists

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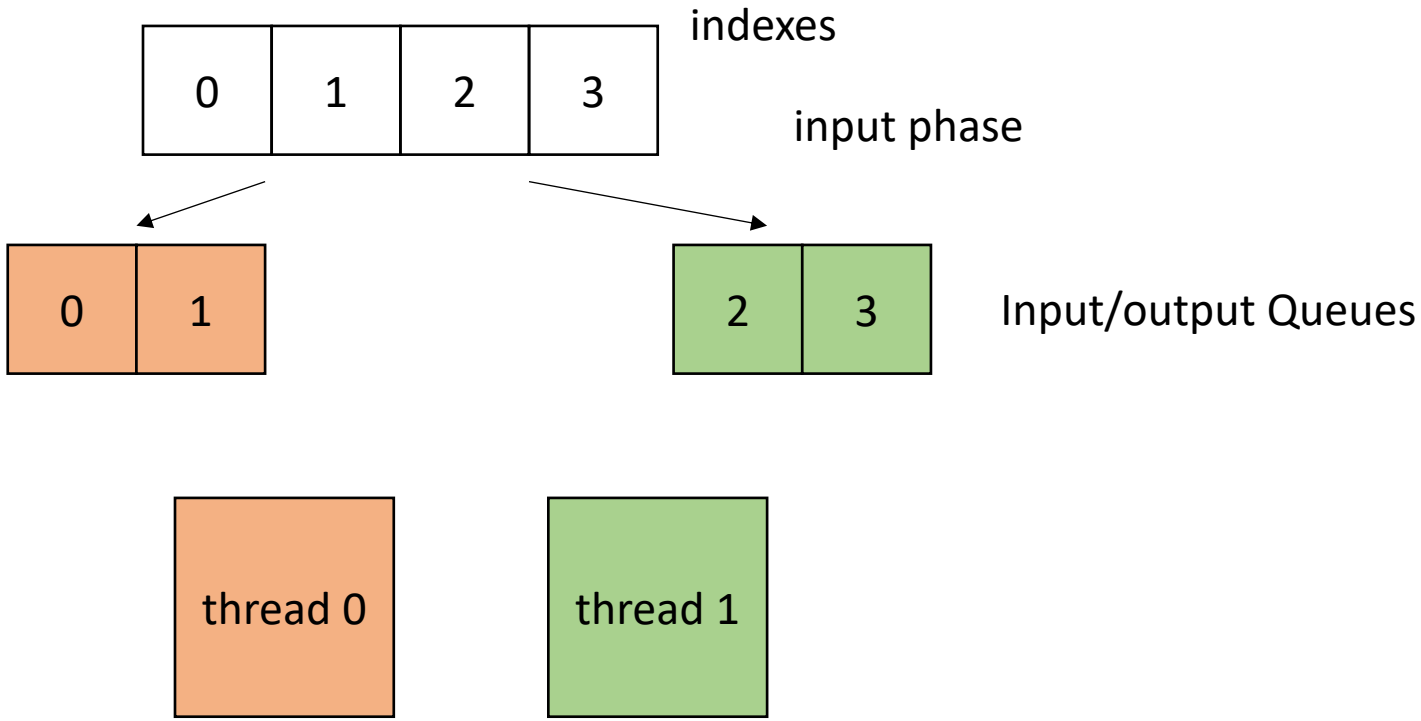
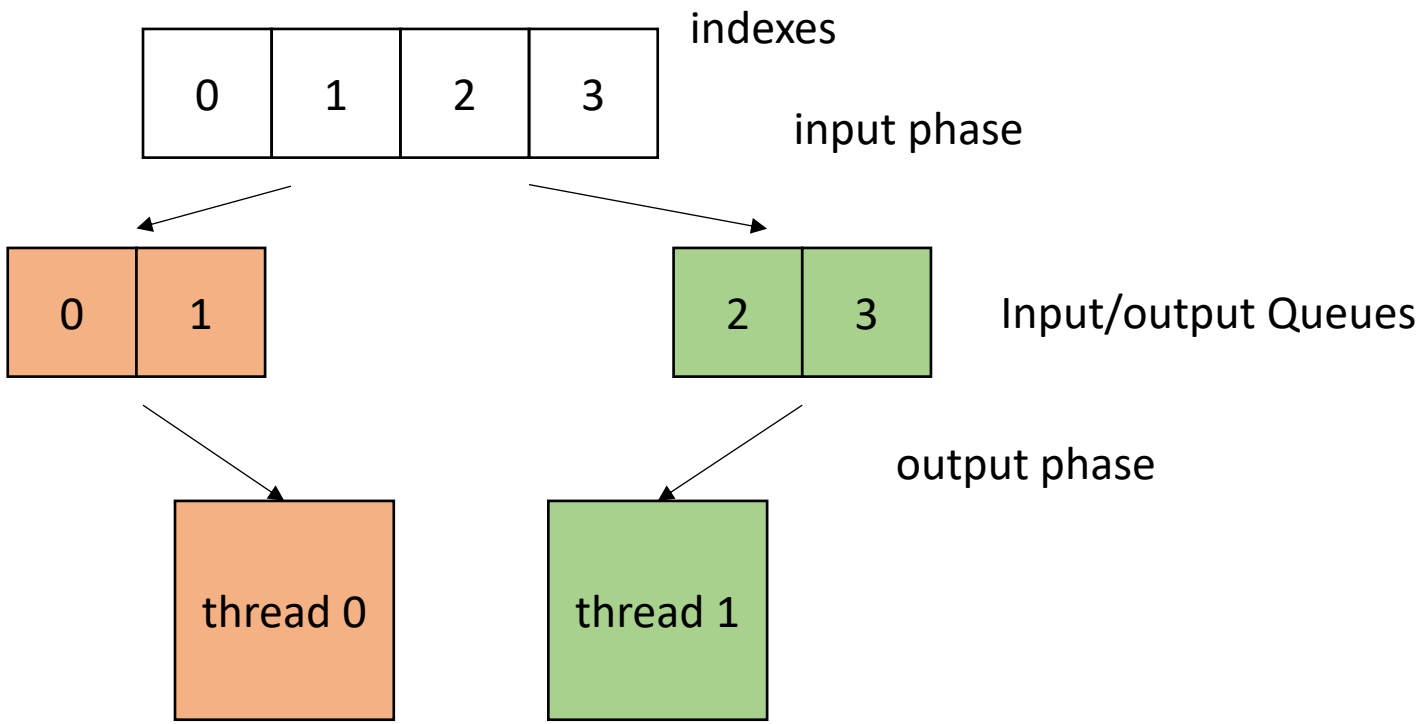


# Work stealing - local worklists

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



# Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];
void foo() {
   ...


   ...
}
```

First we need to initialize the queues

# Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];
void foo() {
   ...
   // Spawn threads to initialize
   // join initializing threads

   ...
}
```

```
void parallel_enq(..., int tid, int num_threads)
{

  int chunk_size = SIZE / NUM_THREADS;
  int start = chunk_size * tid;
  int end = start + chunk_size;
  for (int x = start; x < end; x++) {
    cq[tid].enq(x);
  }
}
```

Just like the static schedule, except we are enqueuing

# Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];
void foo() {
   ...
   // Spawn threads to initialize
   // join initializing threads

   ...
}
```

Make sure to account for boundary conditions!

```
void parallel_enq(..., int tid, int num_threads)
{

  int chunk_size = SIZE / NUM_THREADS;
  int start = chunk_size * tid;
  int end = start + chunk_size;
  for (int x = start; x < end; x++) {
    cq[tid].enq(x);
  }
}
```

Just like the static schedule, except we are enqueuing

# Work stealing - local worklists

- How to implement in a compiler:

```
NUM_THREADS = 2;
SIZE = 4;
CHUNK = 2;
```

| x | 0 | 1 | 2 | 3 |
|---|---|---|---|---|

| tid | 0 | 0 | 1 | 1 |
|---|---|---|---|---|

Make sure to account for boundary conditions!

```
void parallel_enq(..., int tid, int num_threads)
{

  int chunk_size = SIZE / NUM_THREADS;
  int start = chunk_size * tid;
  int end = start + chunk_size;
  for (int x = start; x < end; x++) {
    cq[tid].enq(x);
  }
}
```

Just like the static schedule, except we are enqueuing

# Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];
void foo() {
  ...
  // initialize queues
  // join threads

  // launch loop function
  ...
}
```

```
void parallel_loop(..., int tid, int num_threads) {

  for (x = 0; x < SIZE; x++) {
    // dynamic work based on x
  }
}
```

How do we modify the parallel loop?

# Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];
void foo() {
  ...
  // initialize queues
  // join threads

  // launch loop function
  ...
}
```

```
void parallel_loop(..., int tid, int num_threads) {

  int task = 0;
  for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
  {
    // dynamic work based on task
  }
}
```

loop until the queue is empty

# Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];
void foo() {
  ...
  // initialize queues
  // join threads

  // launch loop function
  ...
}
```

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void parallel_loop(..., int tid, int num_threads) {

  int task = 0;
  for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
  {
    // dynamic work based on task
  }
}
```

loop until the queue is empty
Are we finished?

# Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];
void foo() {
  ...
  // initialize queues
  // join threads

  // launch loop function
  ...
}
```

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

  int task = 0;
  for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
  {
    // dynamic work based on task
  }
  atomic_fetch_add(&finished_threads,1);
}
```

Track how many threads are finished

# Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];
void foo() {
   ...
   // initialize queues
   // join threads

   // launch loop function
   ...
}
```

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

   int task = 0;
   for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
   {
      // dynamic work based on task
   }
   atomic_fetch_add(&finished_threads,1);
   while (finished_threads.load() != num_threads) {

   }
}
```

While there are threads that are still working

# Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];
void foo() {
   ...
   // initialize queues
   // join threads

   // launch loop function
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   {
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   }
   atomic_fetch_add(&finished_threads,1);
   while (finished_threads.load() != num_threads) {
      int target = // pick a thread to steal from
      int task = cq[target].deq();
   }
}
```

pick a random target and steal a task

# Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];
void foo() {
  ...
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    int task = cq[target].deq();
    if (task != -1) {
      // perform task
    }
  }
}
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# Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];
void foo() {
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}
```

join the threads

```
atomic_int finished_threads(0);
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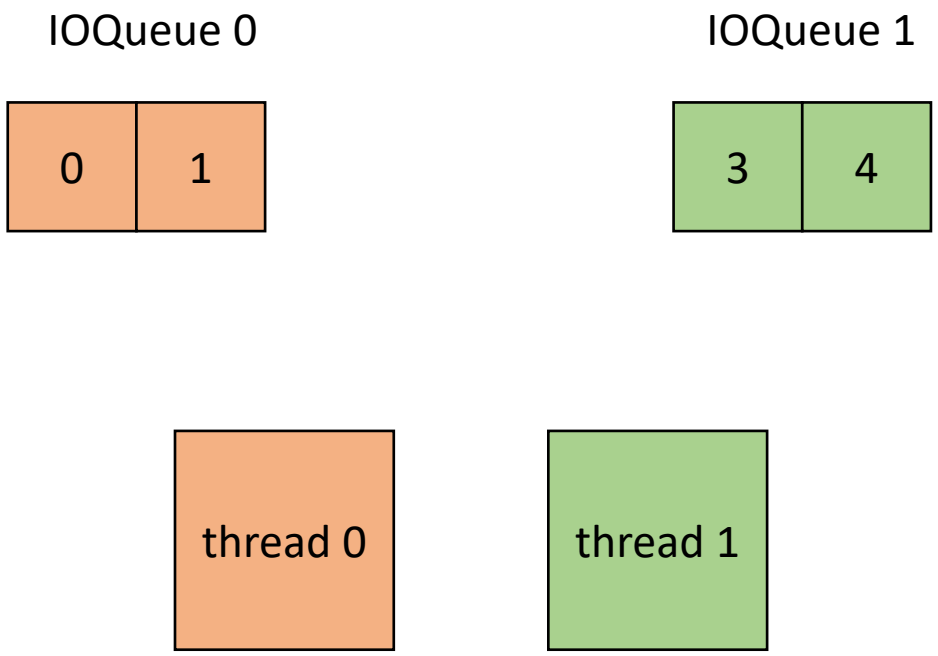


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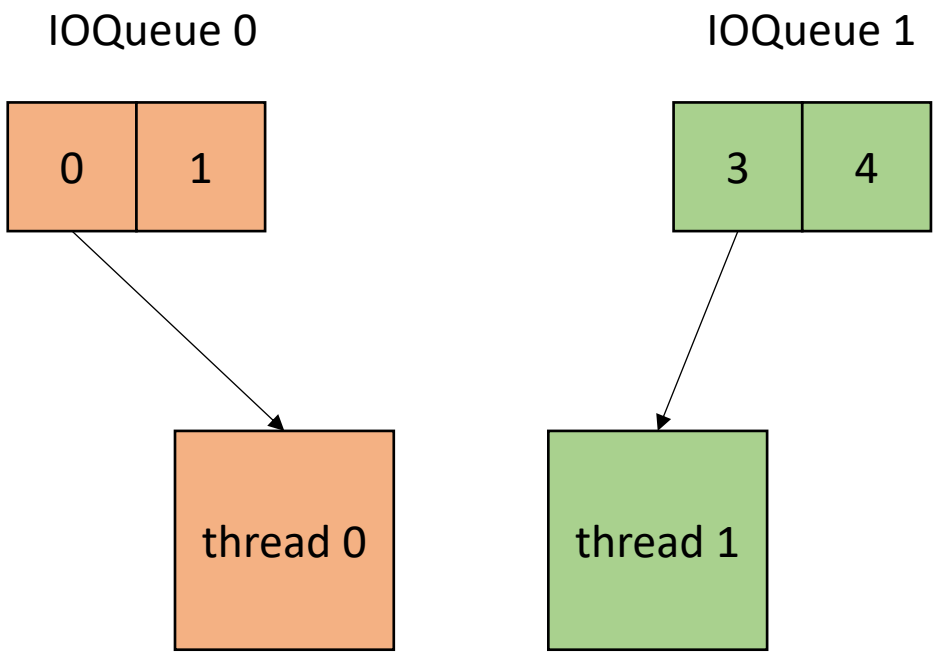


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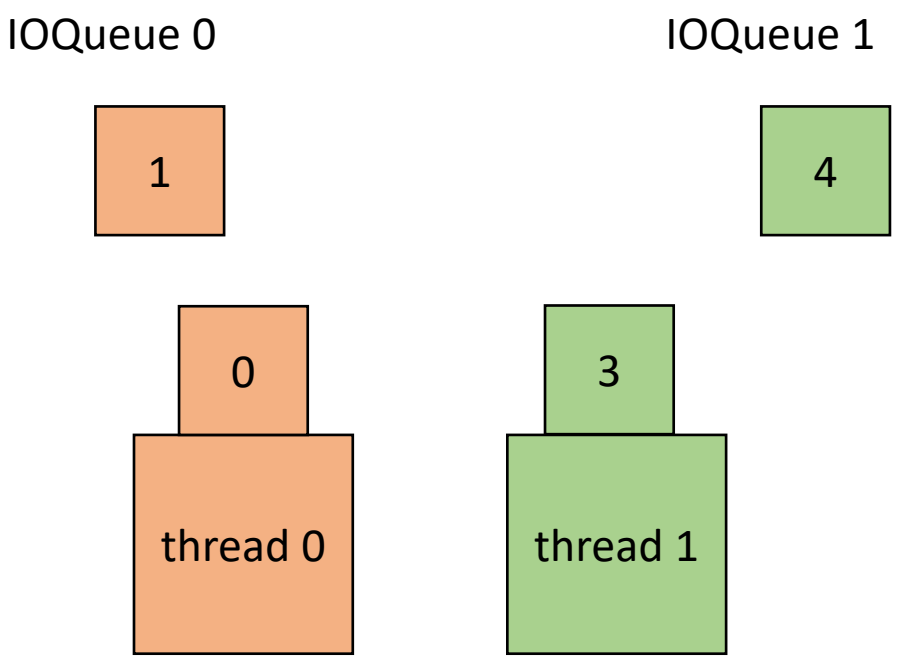


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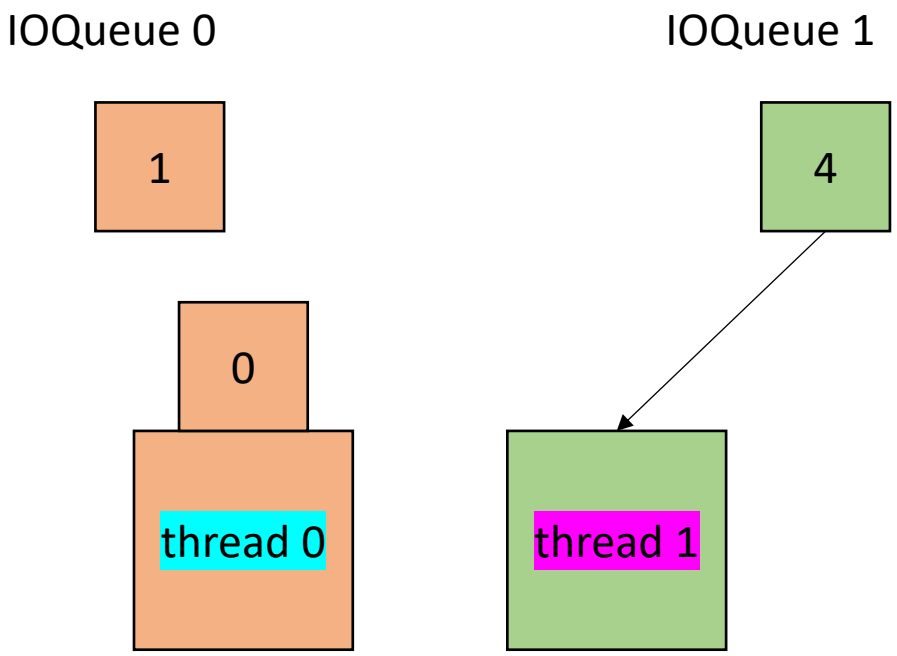


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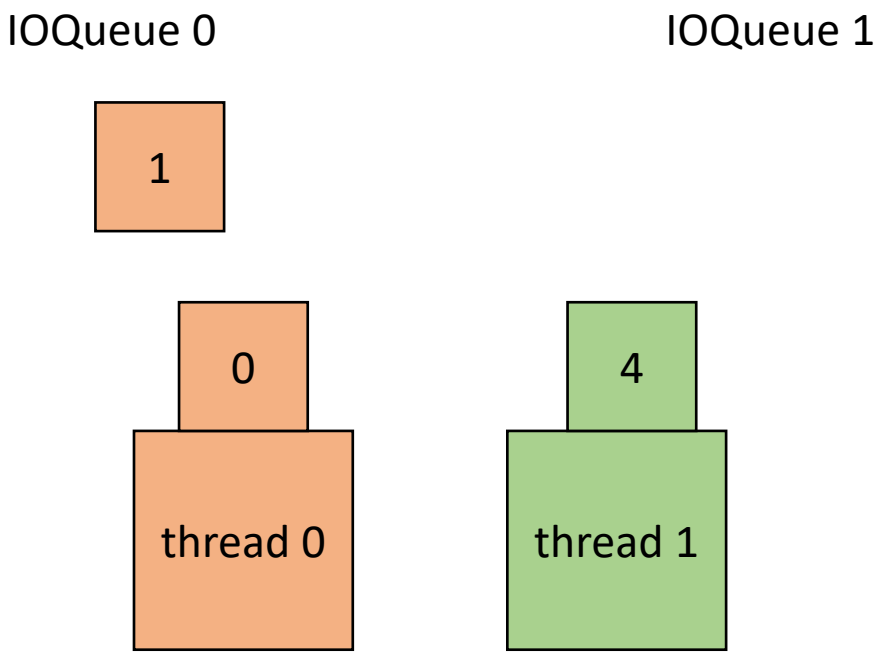


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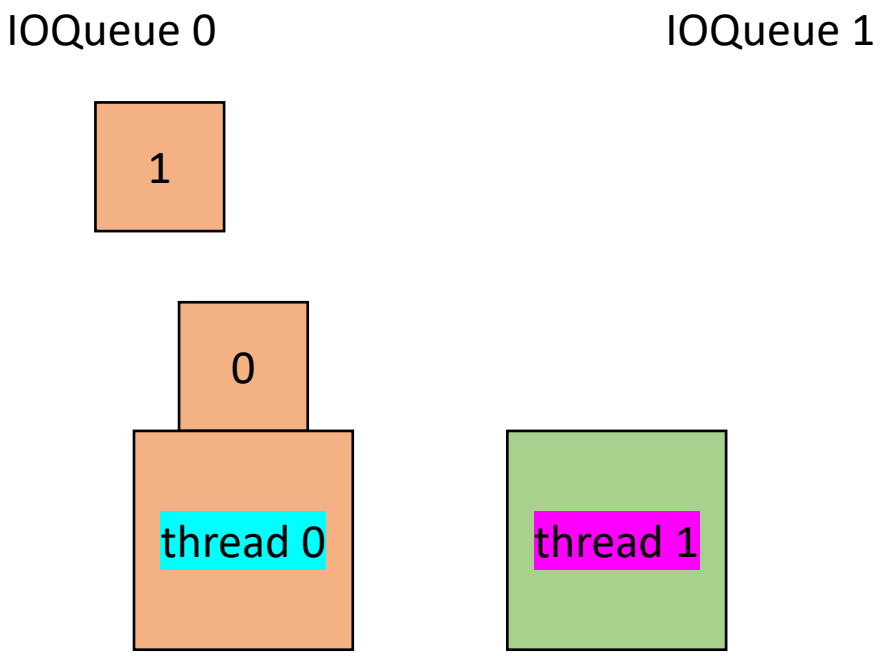


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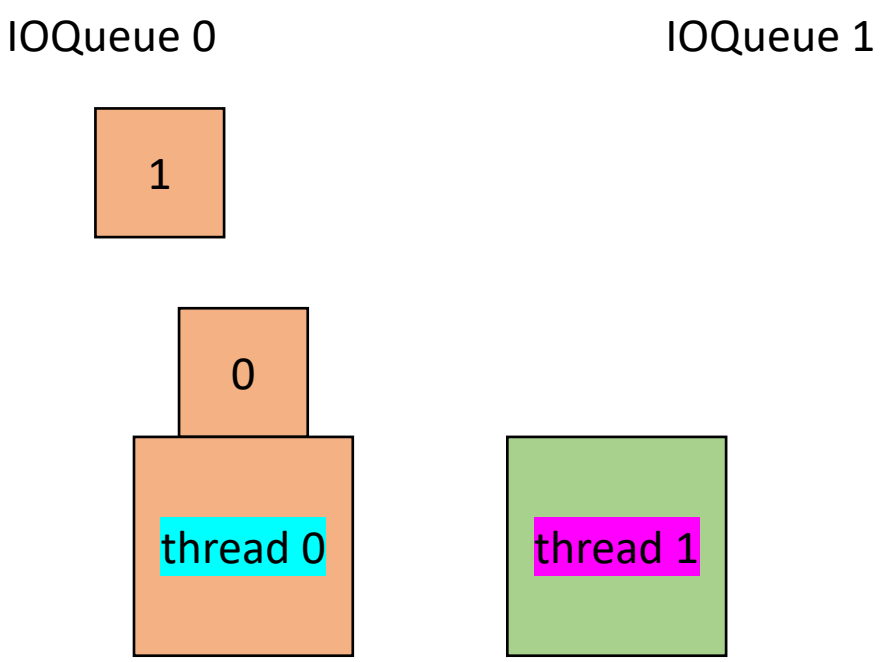
```

# Work stealing - local worklists

finished_threads: 1

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# Work stealing - local worklists

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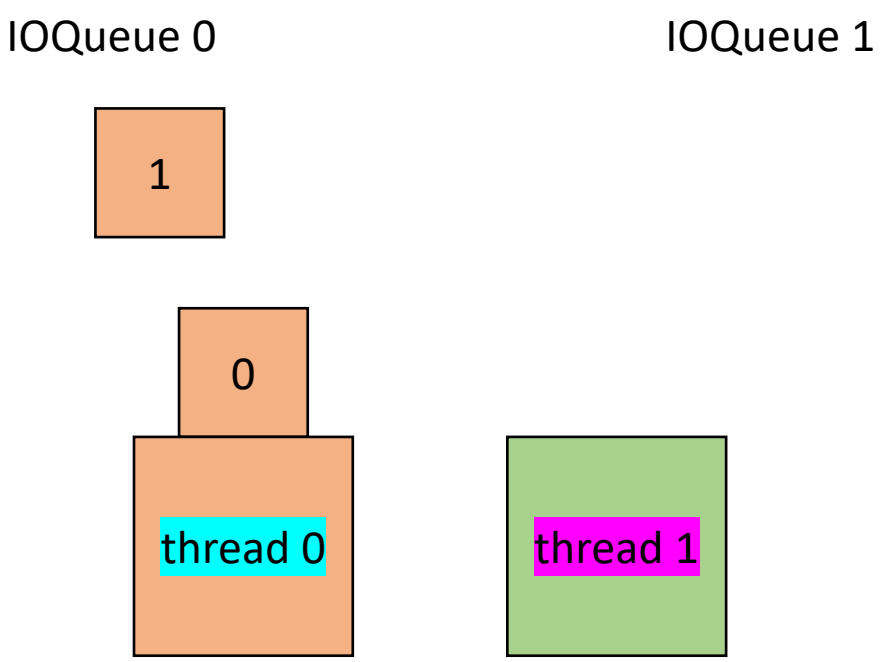


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# Work stealing - local worklists

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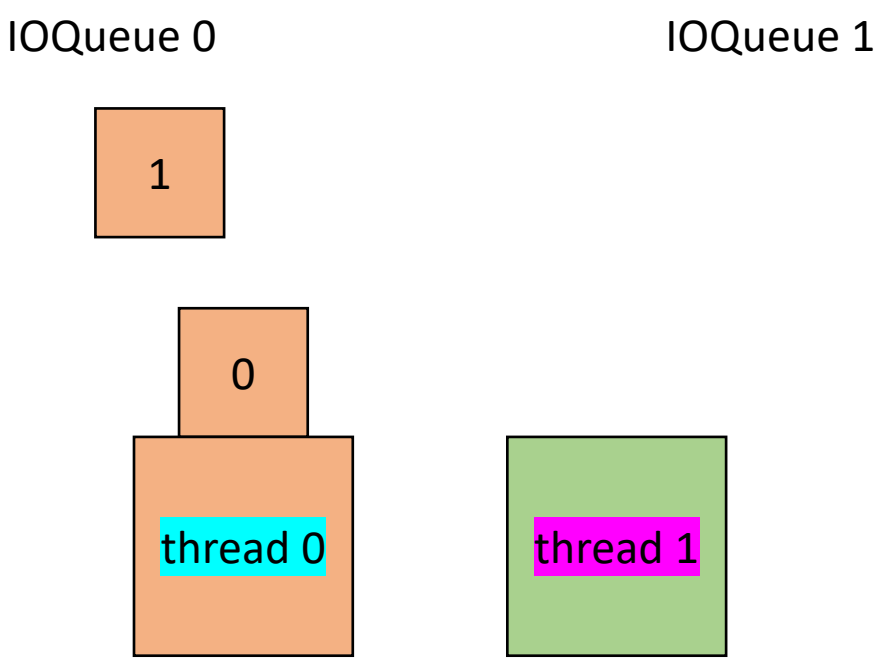


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# Work stealing - local worklists

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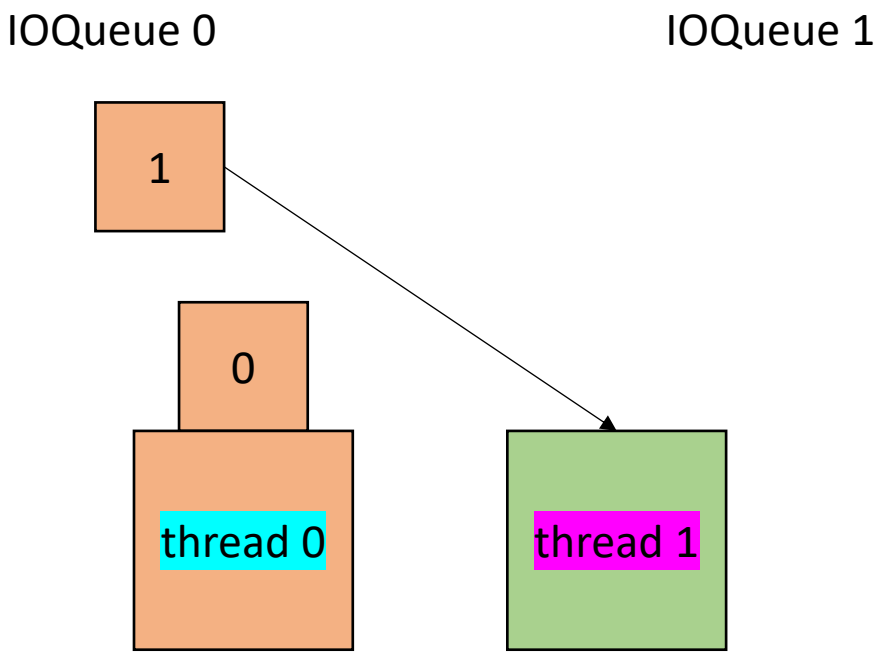


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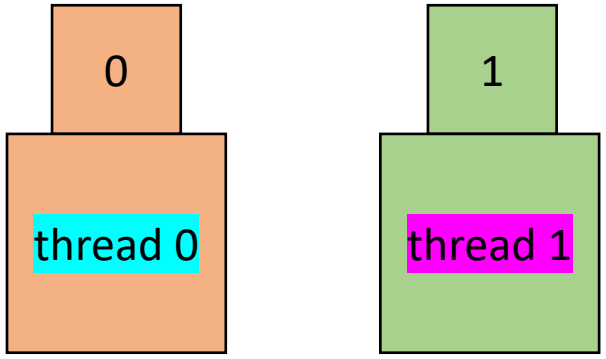
       // perform task
    }
  }
}
```

# Work stealing - local worklists

finished_threads: 1

IOQueue 0

IOQueue 1

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void parallel_loop(..., int tid, int num_threads) {

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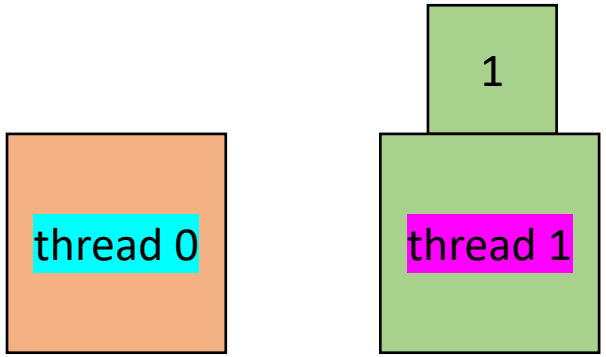
}
```

# Work stealing - local worklists

finished_threads: 1

IOQueue 0

IOQueue 1

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  int task = 0;
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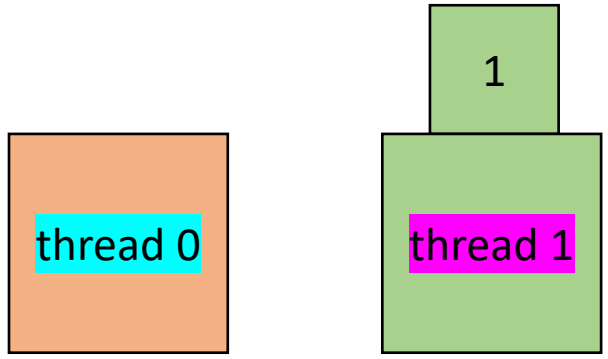
    int target = // pick a thread to steal from
    int task = cq[target].deq();
    if (task != -1) {
       // perform task
    }
  }
}
```

# Work stealing - local worklists

finished_threads: 2

IOQueue 0

IOQueue 1

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    int target = // pick a thread to steal from
    int task = cq[target].deq();
    if (task != -1) {
       // perform task
    }
  }
}
```

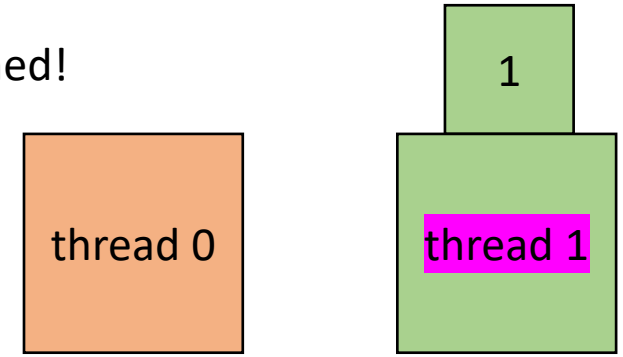
# Work stealing - local worklists

finished_threads: 2

IOQueue 0

IOQueue 1

finished!




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

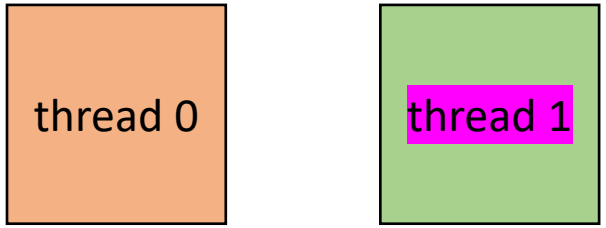
  int task = 0;
  for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
  {
    // dynamic work based on task
  }
  atomic_fetch_add(&finished_threads,1);
  while (finished_threads.load() != num_threads) {
    int target = // pick a thread to steal from
    int task = cq[target].deq();
    if (task != -1) {
       // perform task
    }
  }
}
```

# Work stealing - local worklists

finished_threads: 2

IOQueue 0

IOQueue 1

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# Work stealing - local worklists

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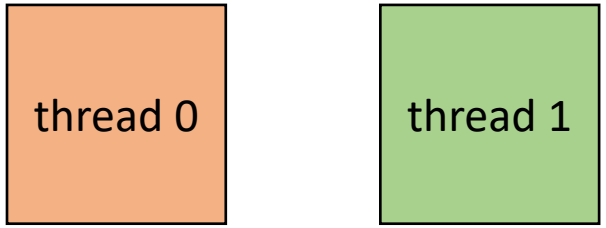


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       // perform task
    }
  }
}
```

# Next topic

- General concurrent set

# Schedule

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

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

# Set Interface

- Unordered collection of items
- No duplicates

- We will implement this as a sorted linked list

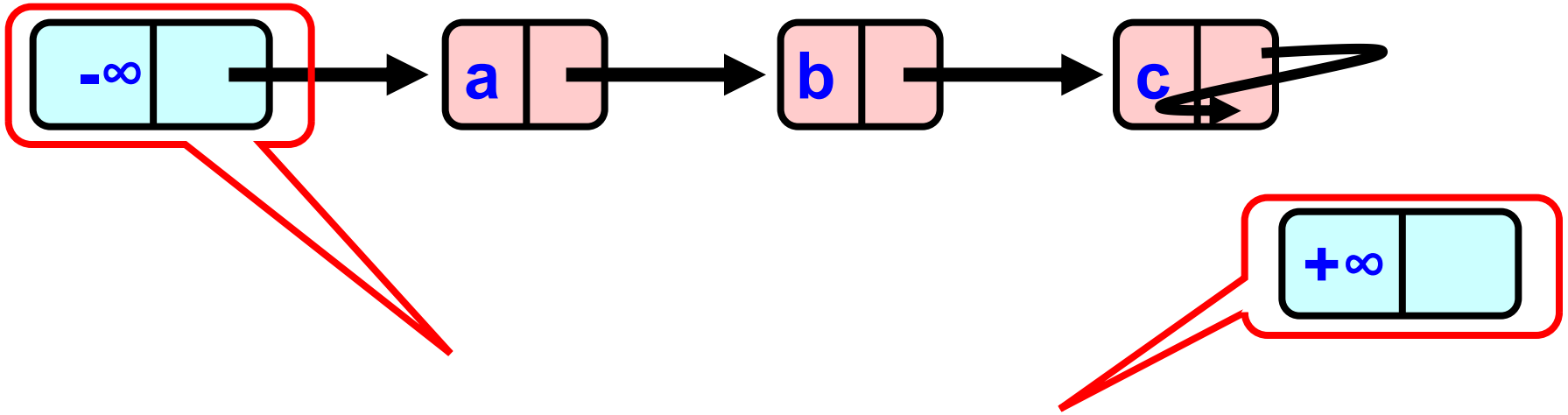
# Set Interface

- Unordered collection of items
- No duplicates
- Methods
  - **`add(x)`** put **`x`** in set
  - **`remove(x)`** take **`x`** out of set
  - **`contains(x)`** tests if **`x`** in set

# List Node

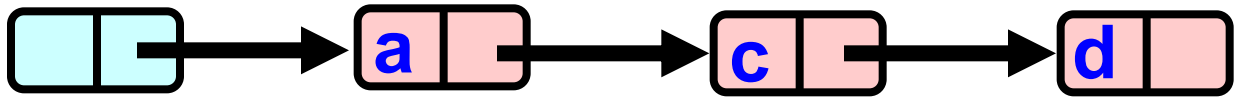
```
class Node {
 public:
    Value v;
    int key;
    Node *next;
}
```

# The List-Based Set

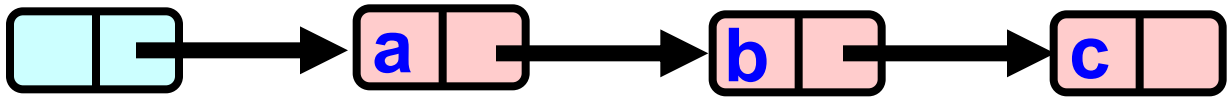


# Sequential List Based Set

**add(b)**

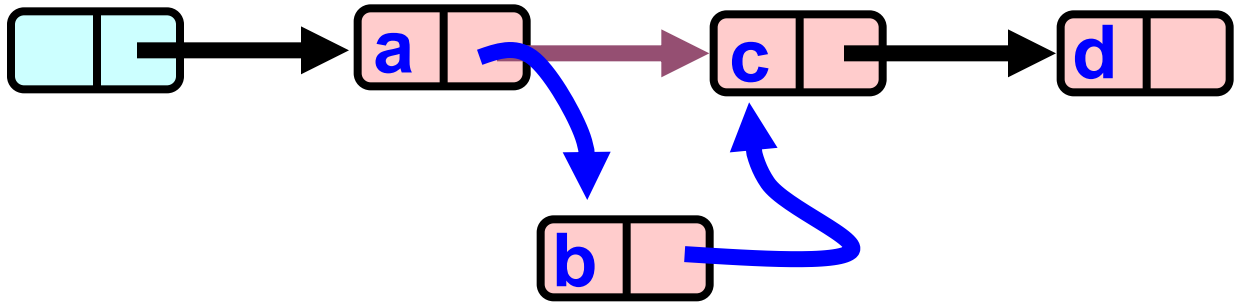



**remove(b)**

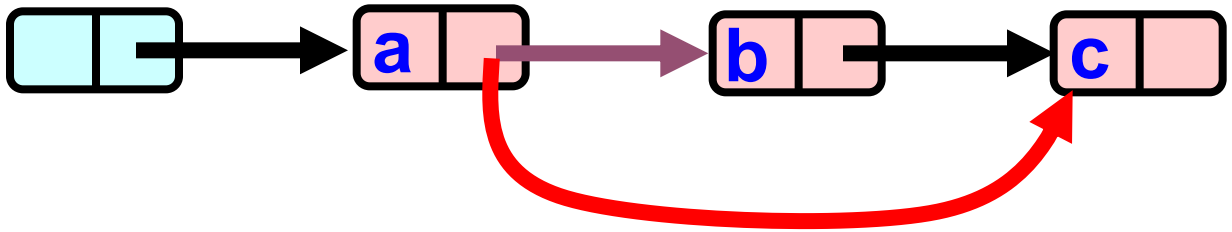


# Sequential List Based Set

**add(b)**



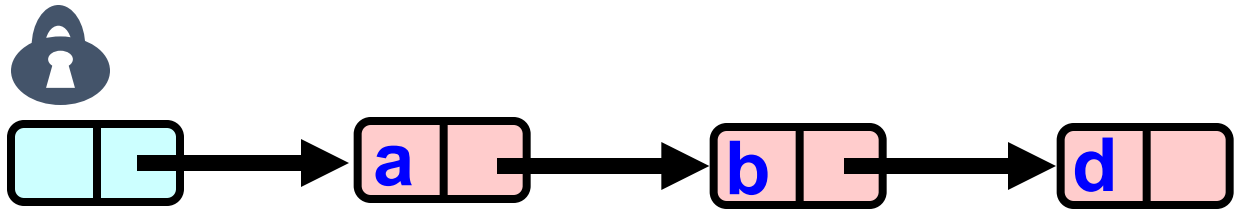

**remove(b)**



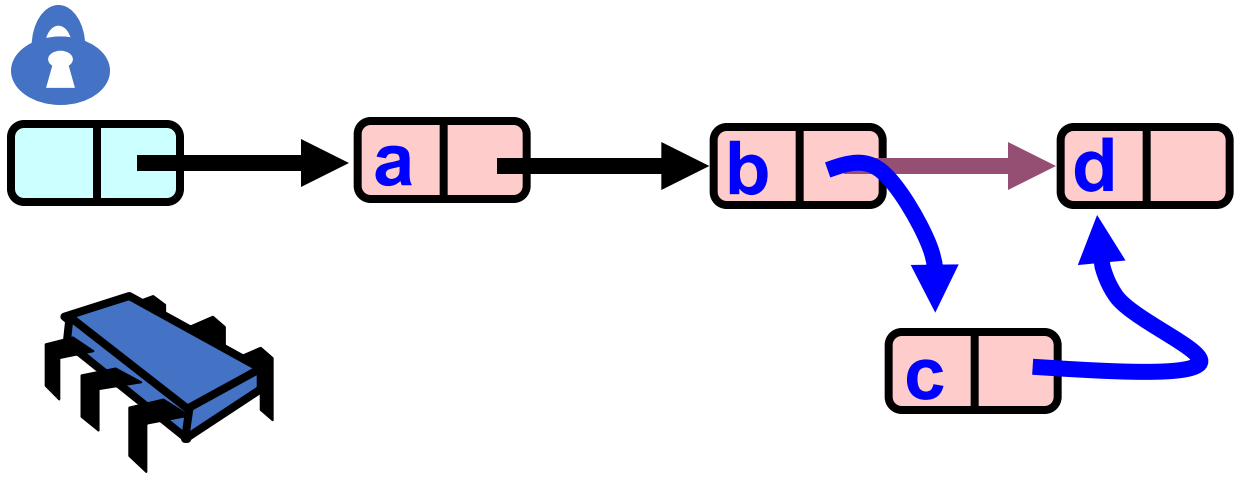
# Schedule

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

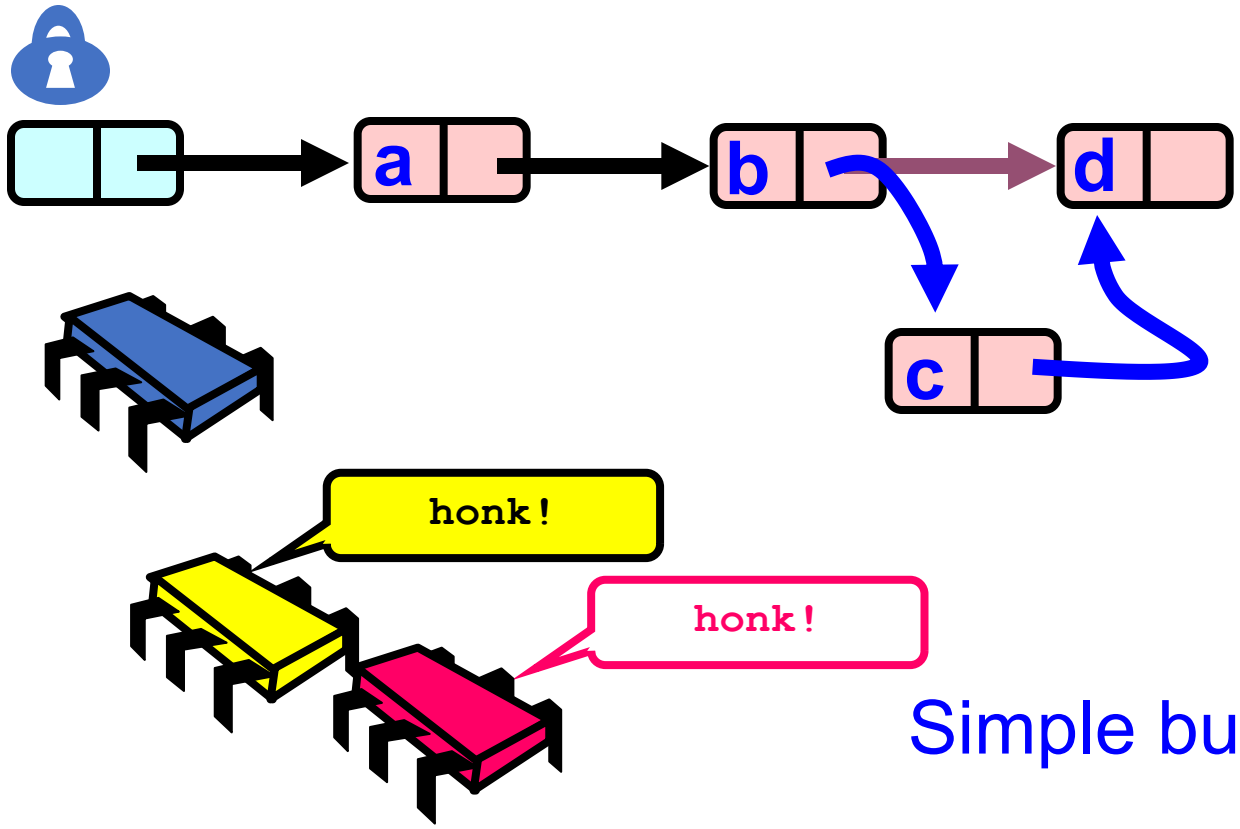
# Coarse-Grained Locking



# Coarse-Grained Locking



# Coarse-Grained Locking




Simple but inefficient!

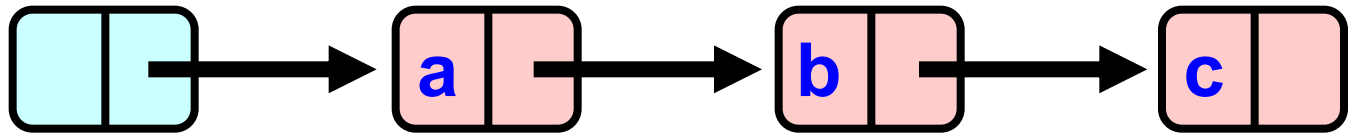
# Schedule

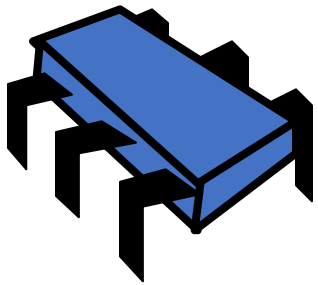
- Concurrent set
  - Coarse-grained lock
  - **fine-grained lock**
  - optimistic locking

# Fine-grained Locking

- Requires **careful** thought
- Split object into pieces
  - Each piece has own lock
  - Methods that work on disjoint pieces need not exclude each other

# Hand-over-Hand locking



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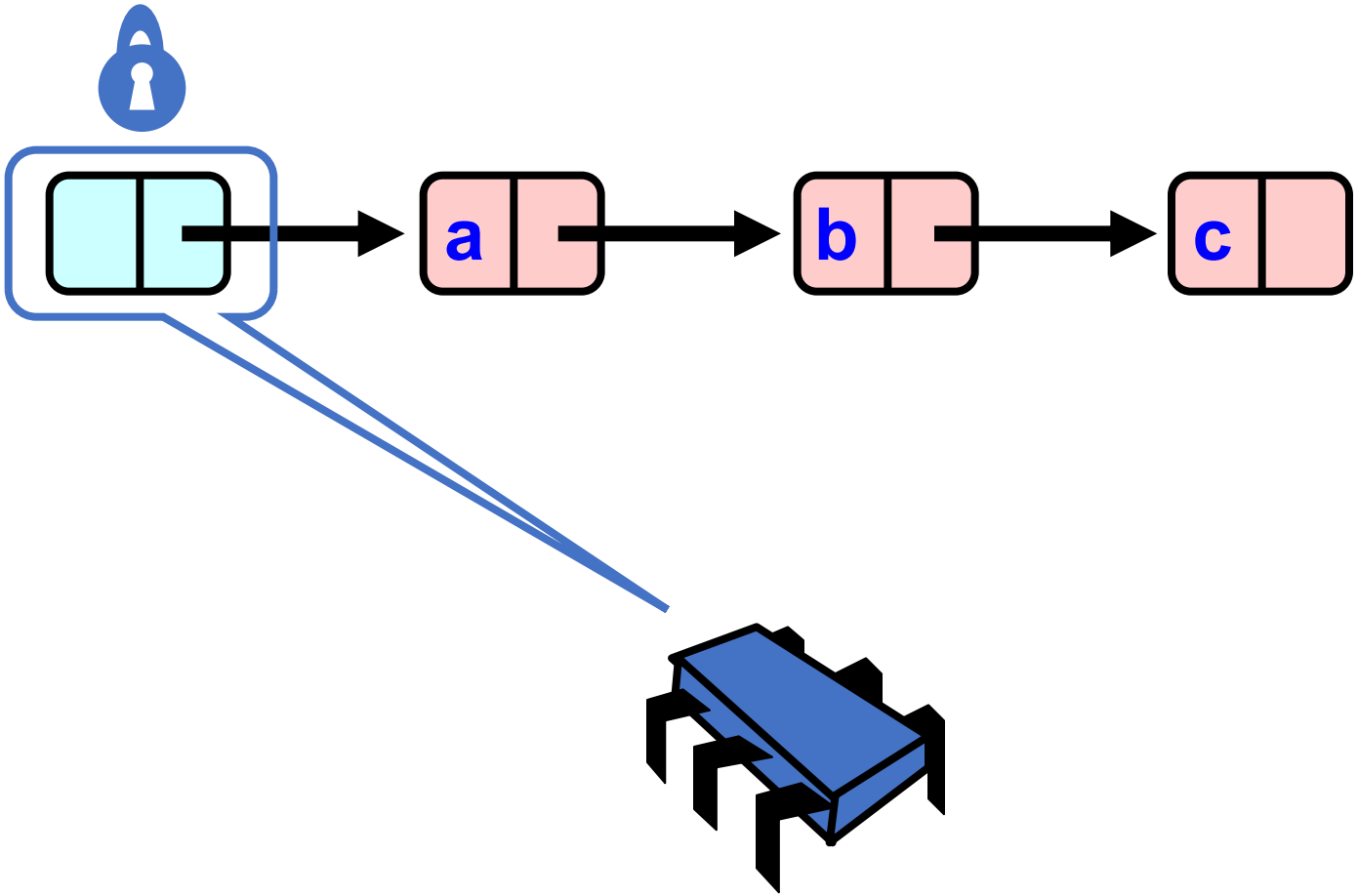

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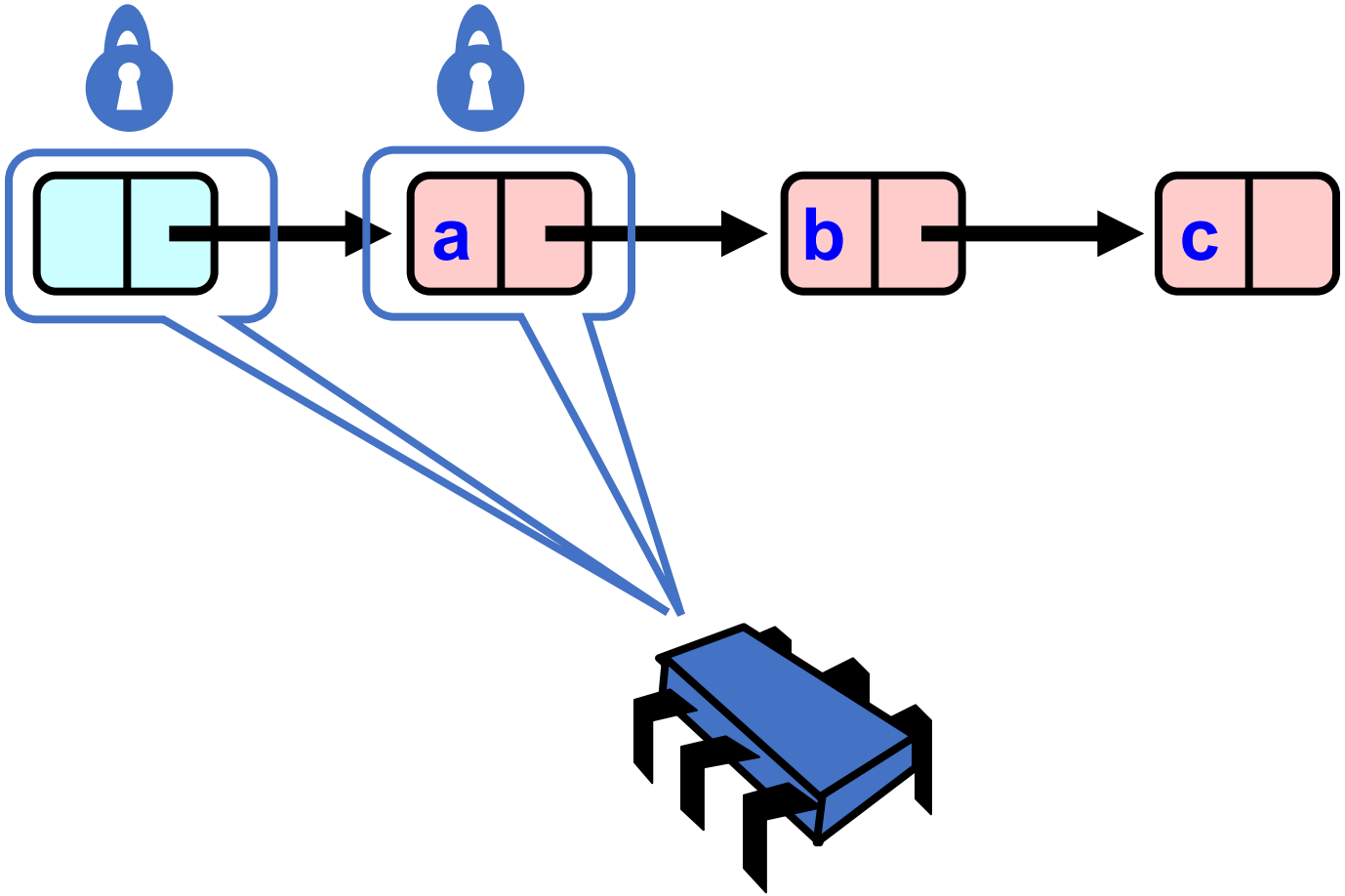

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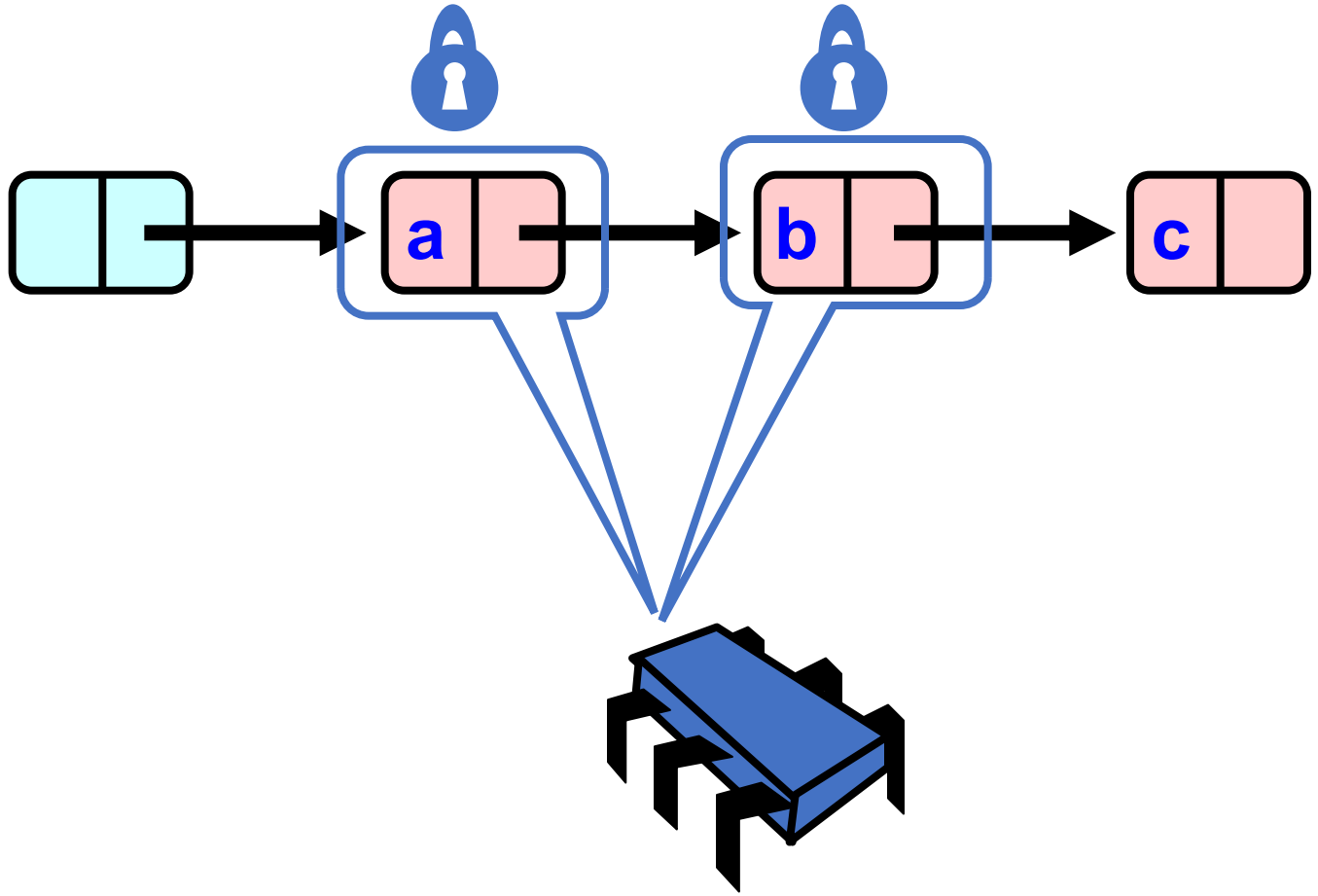

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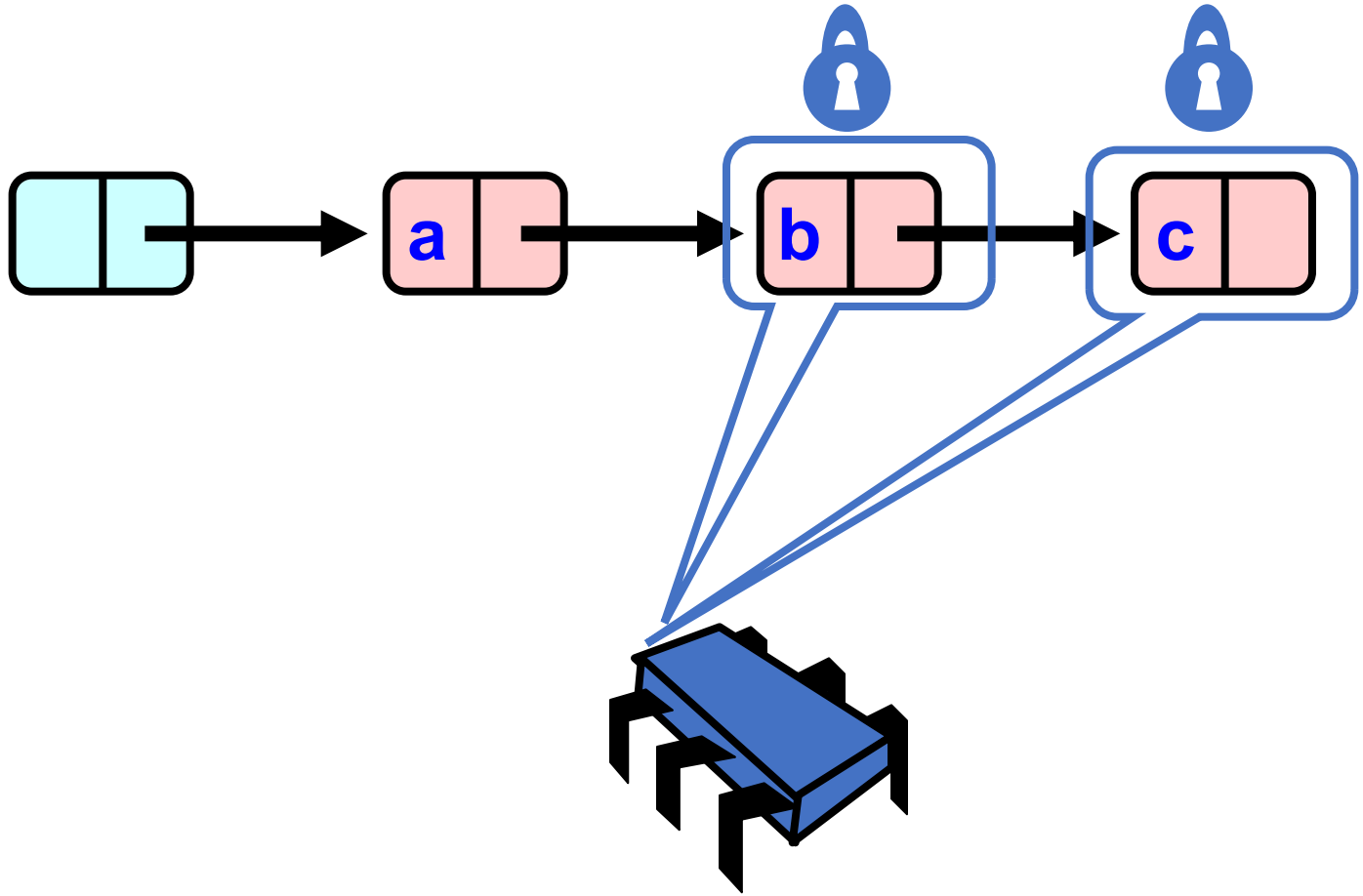
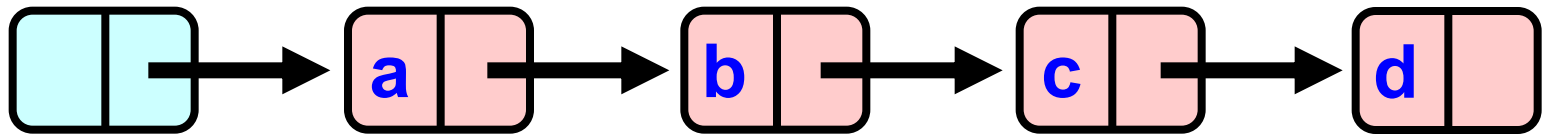
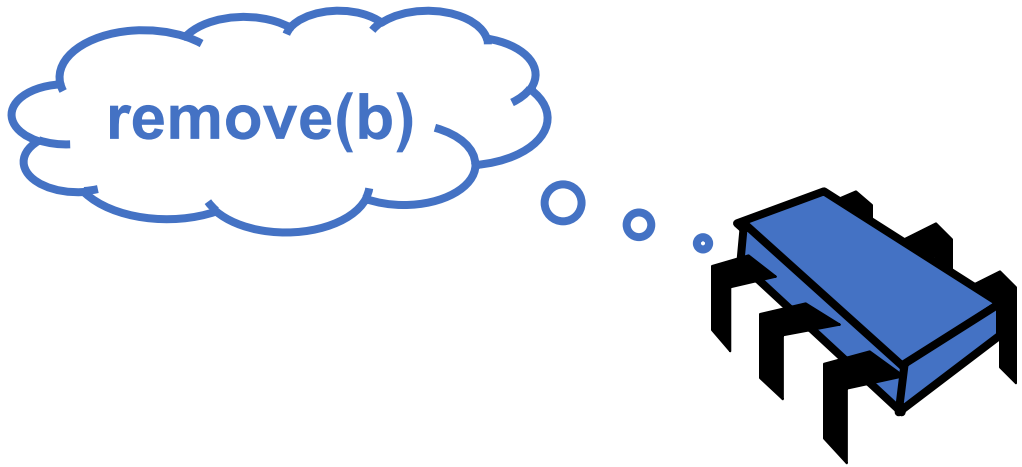


# Removing a Node



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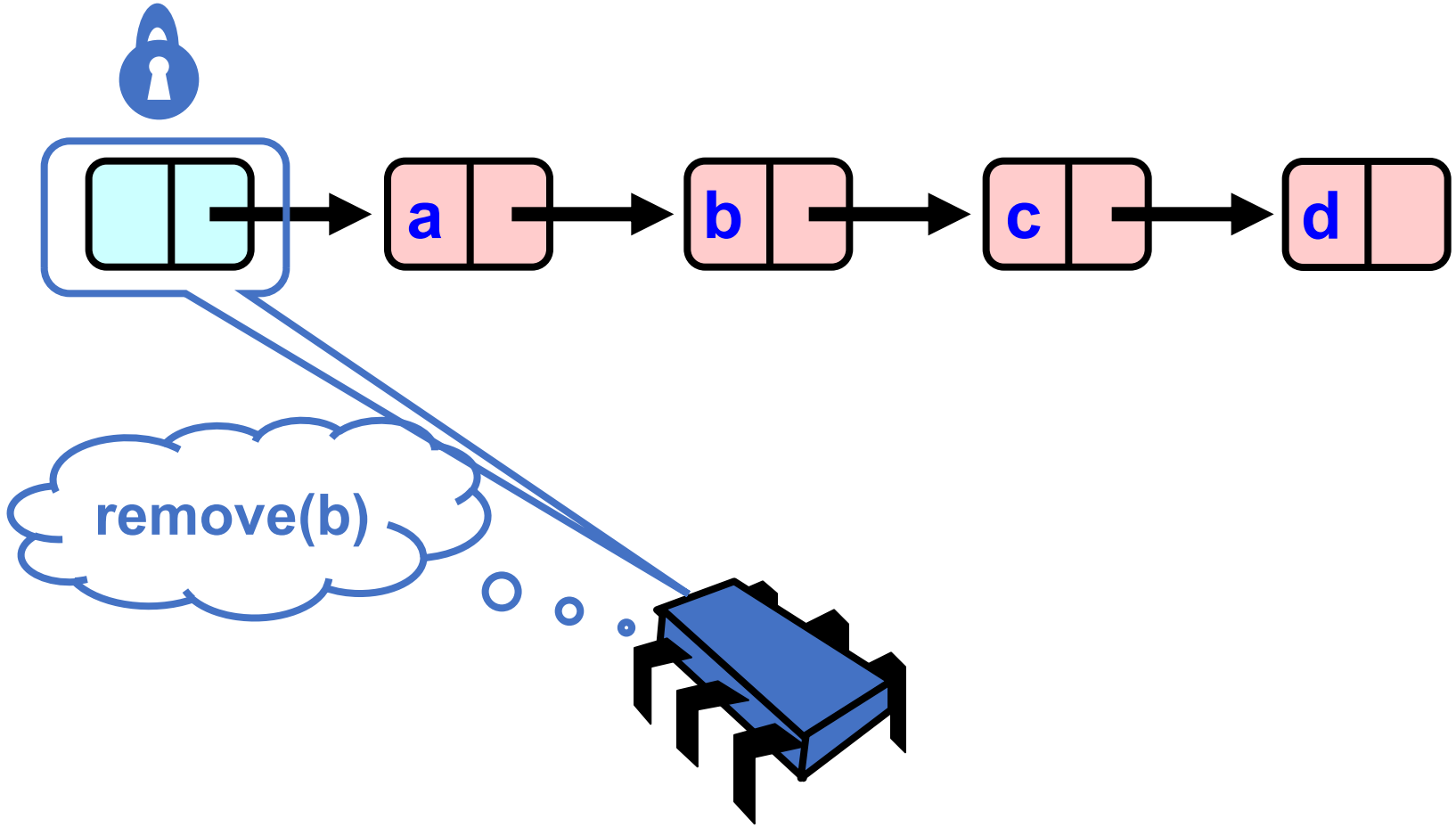

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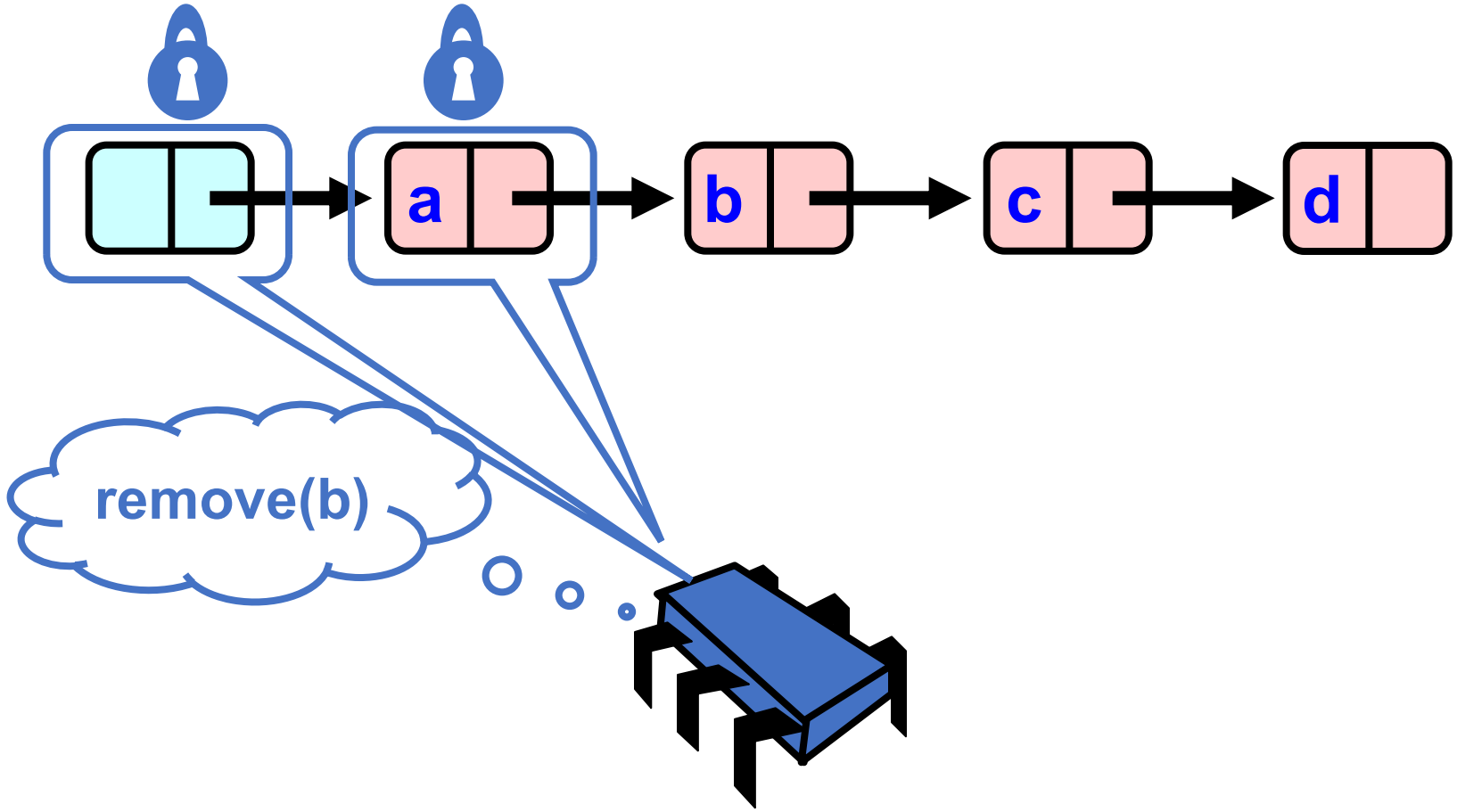

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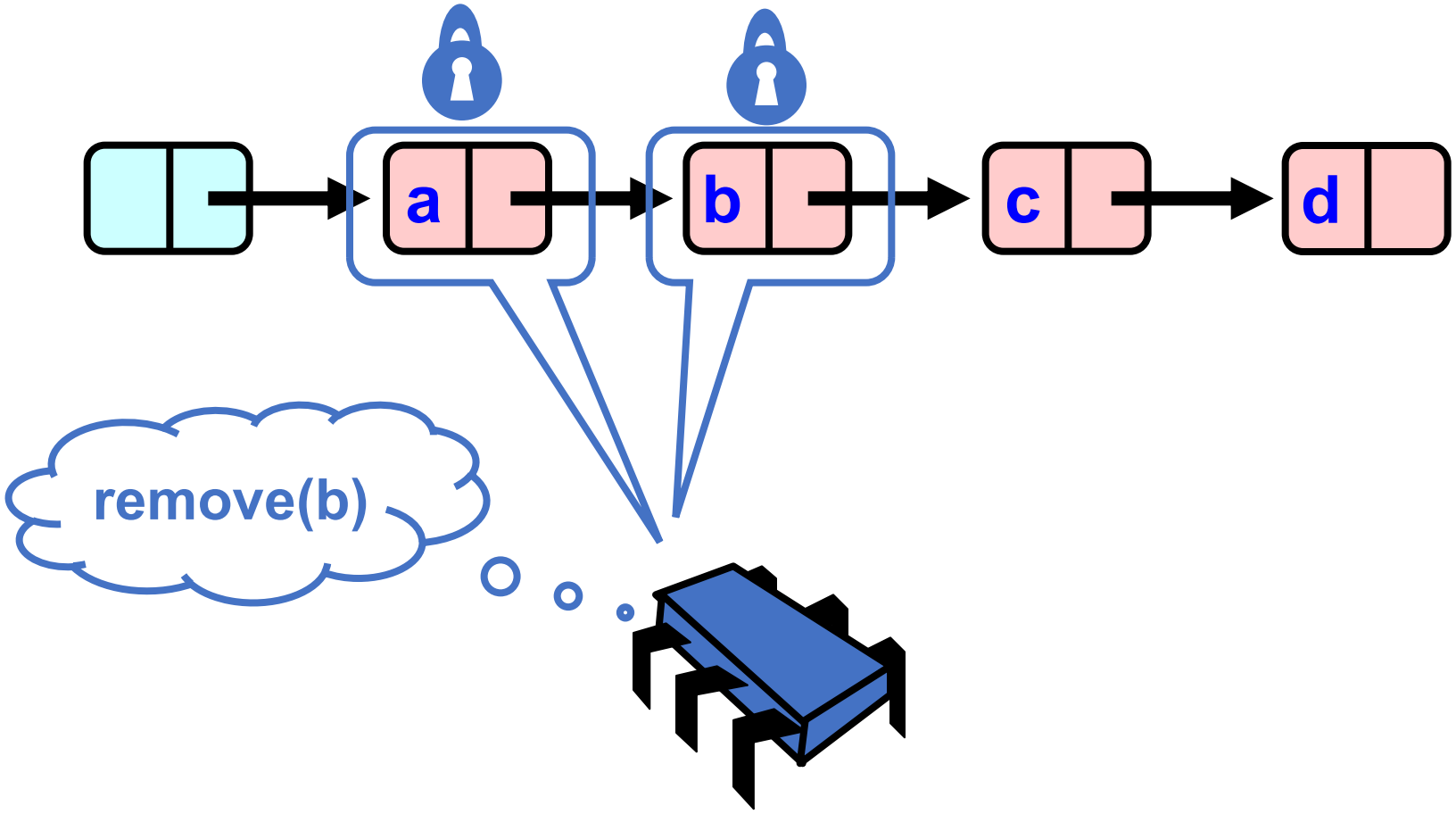

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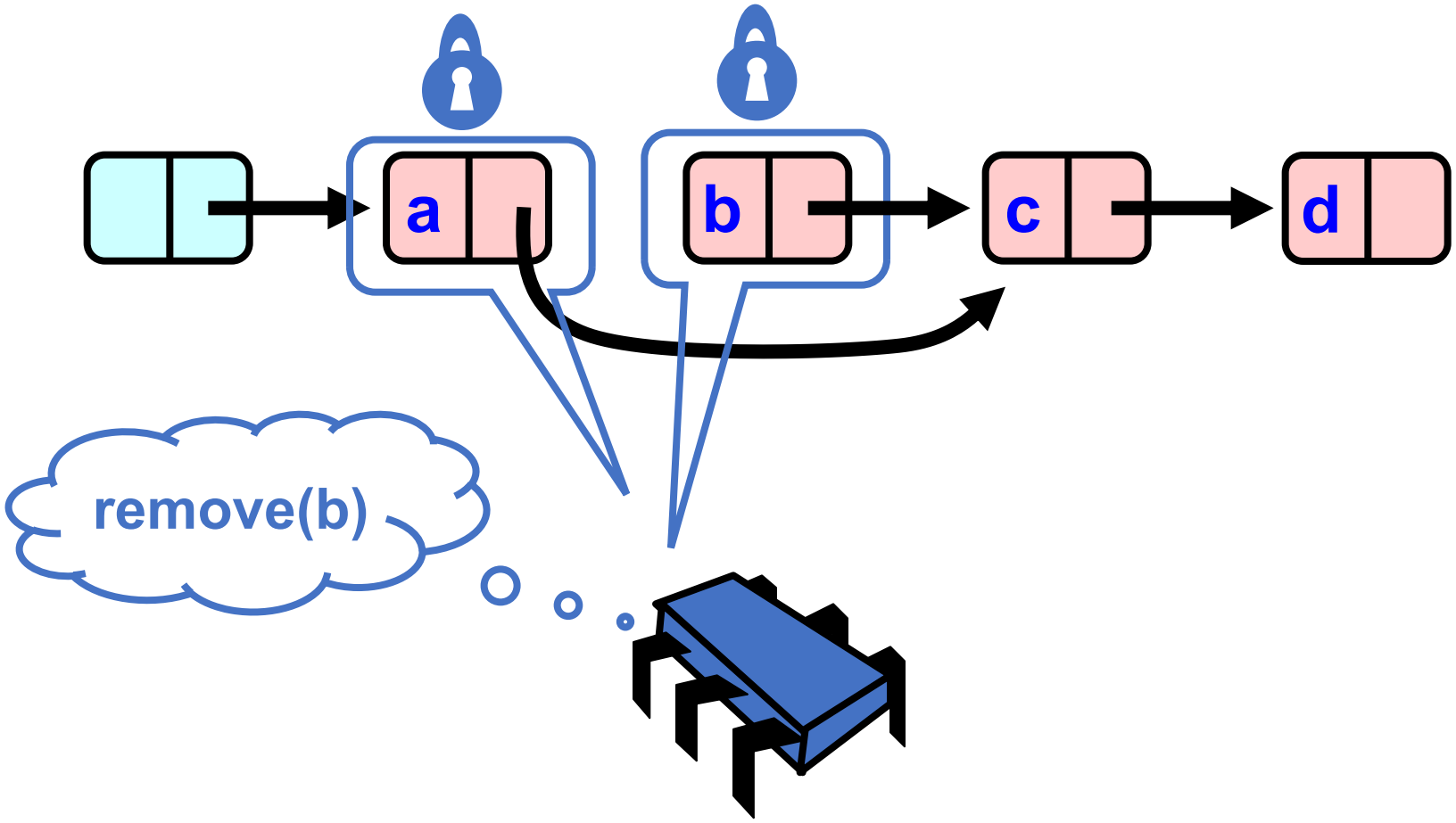

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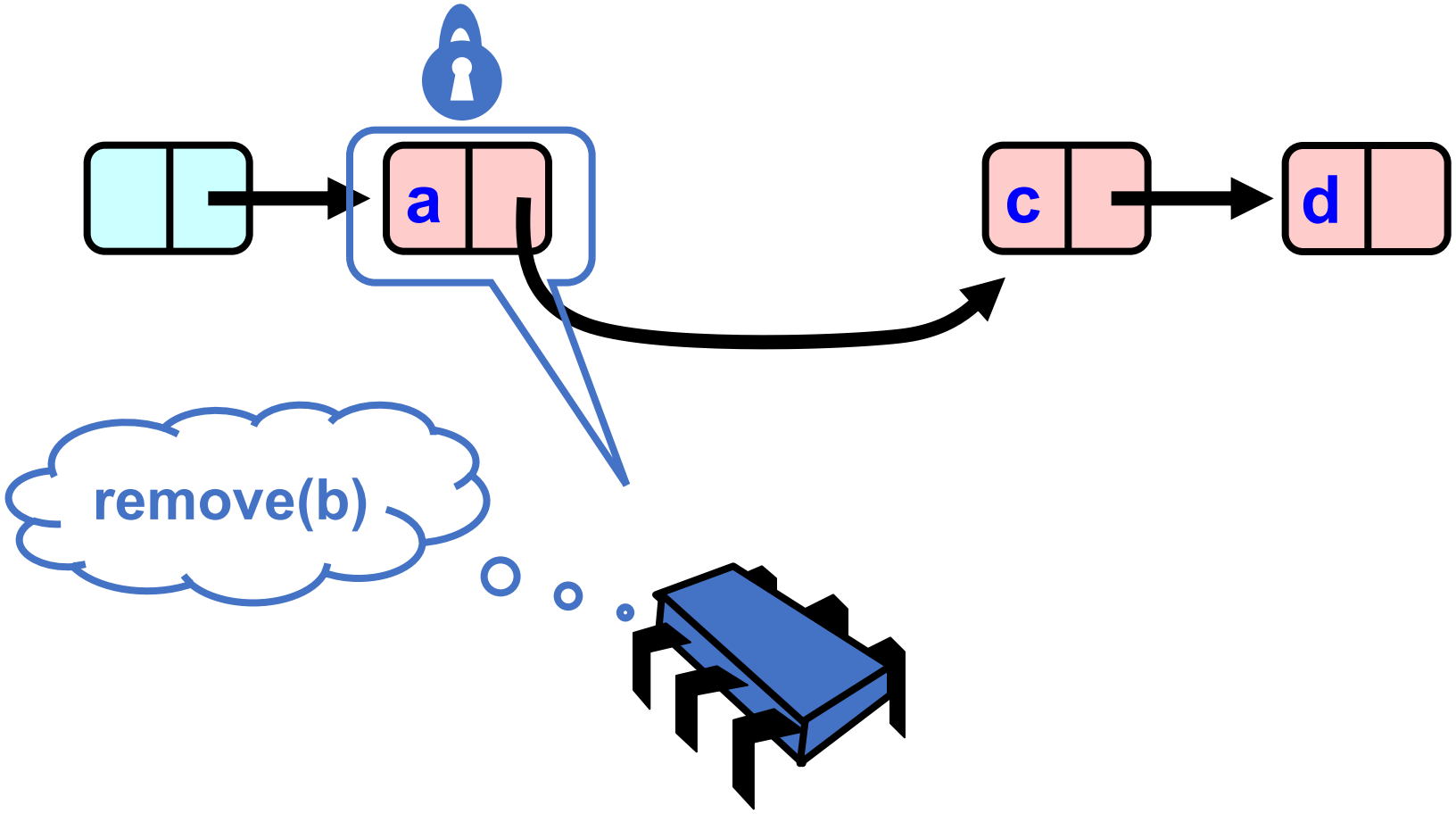

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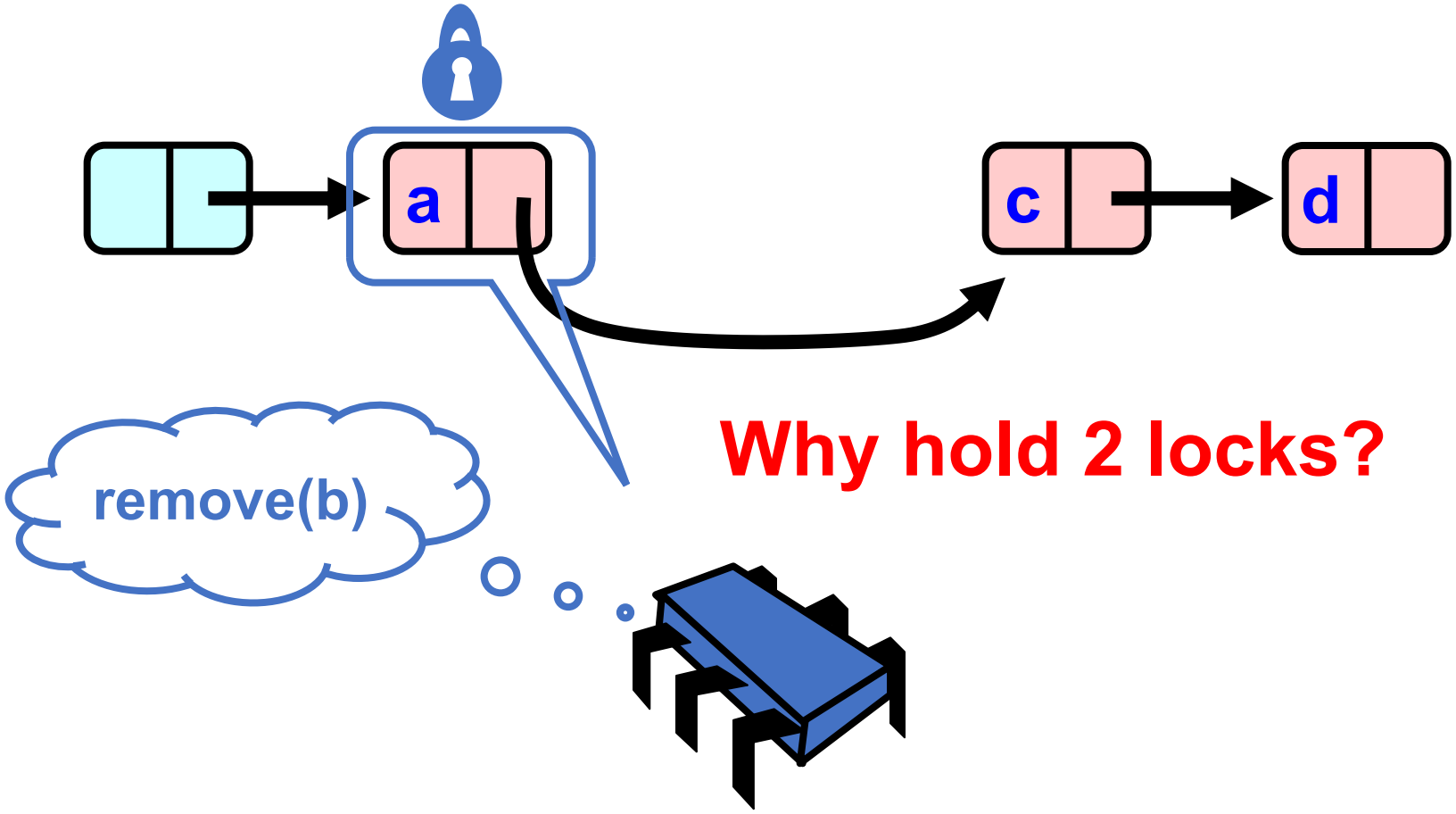
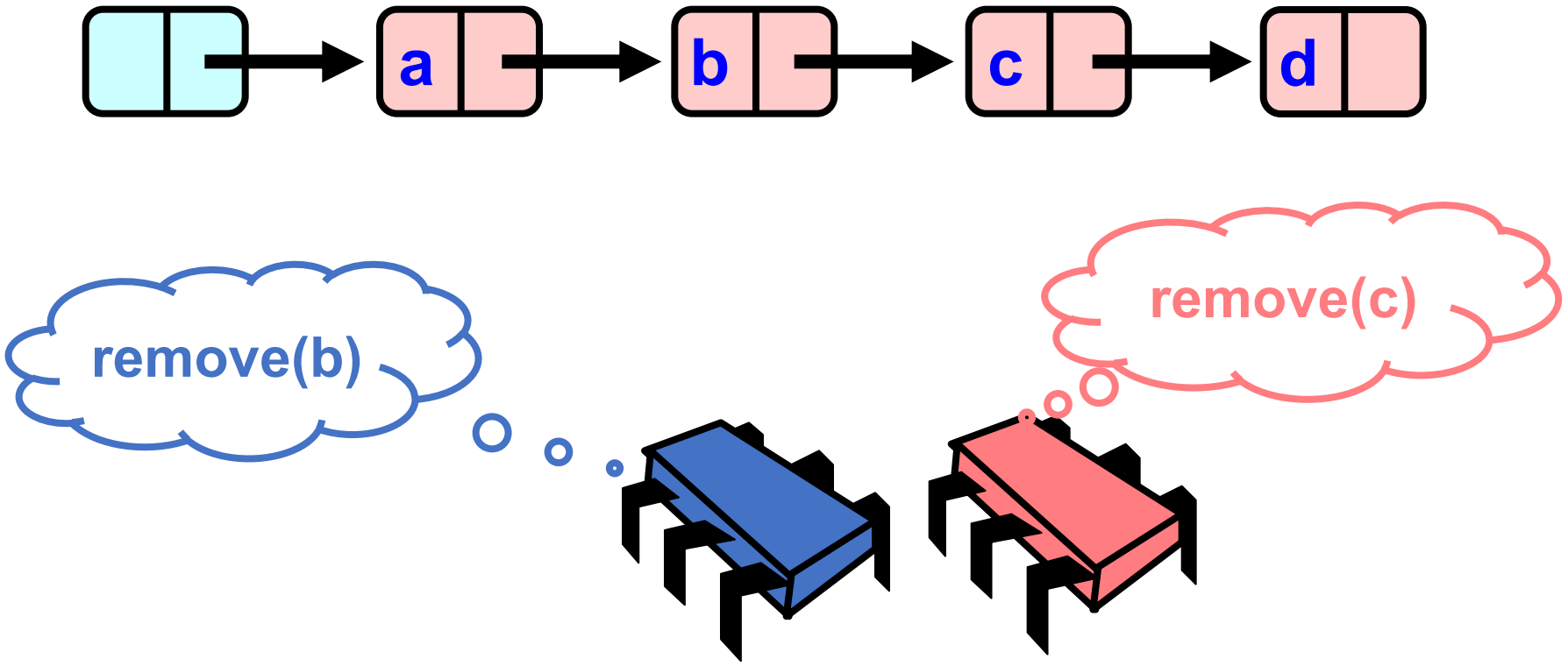


# Concurrent Removes



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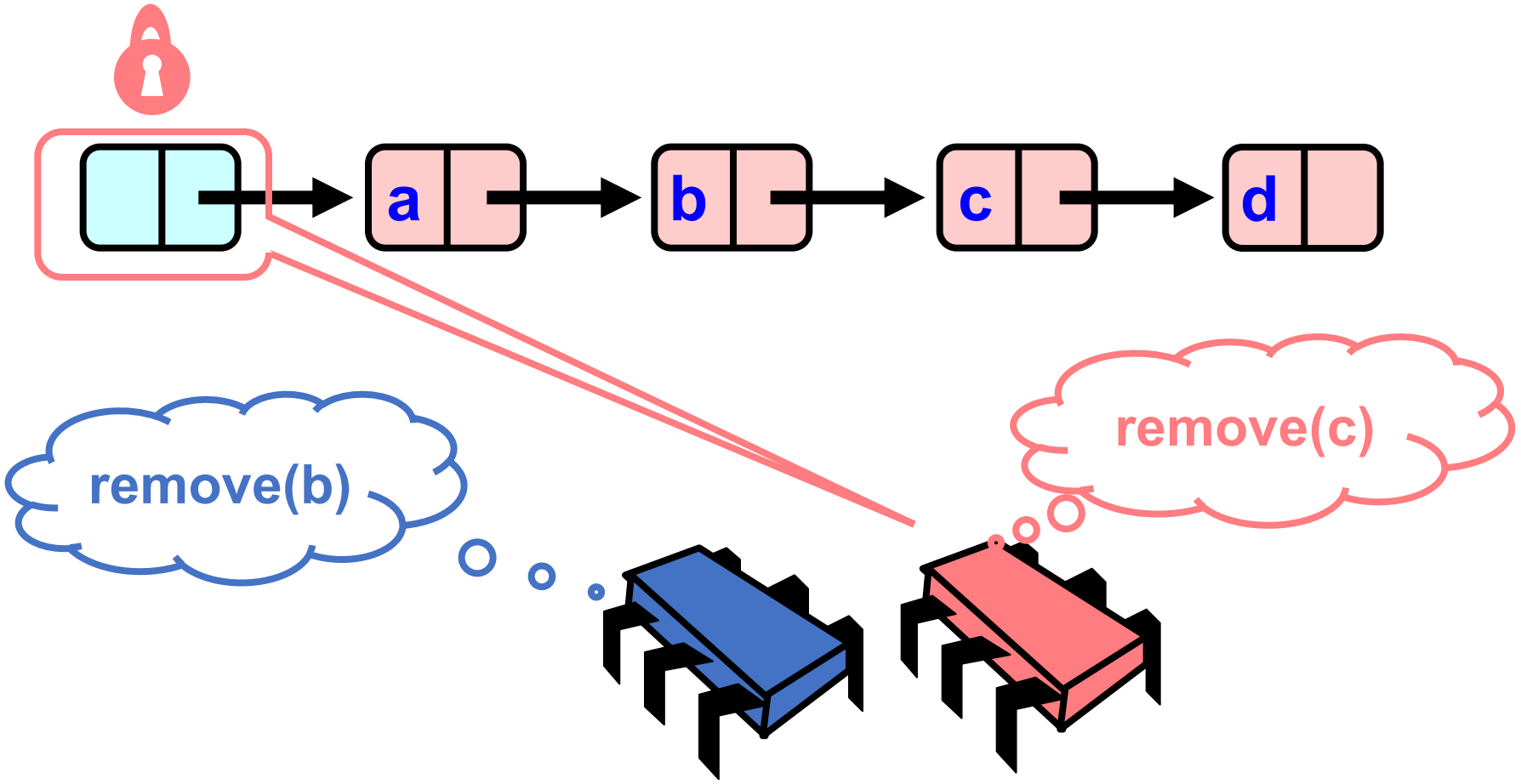

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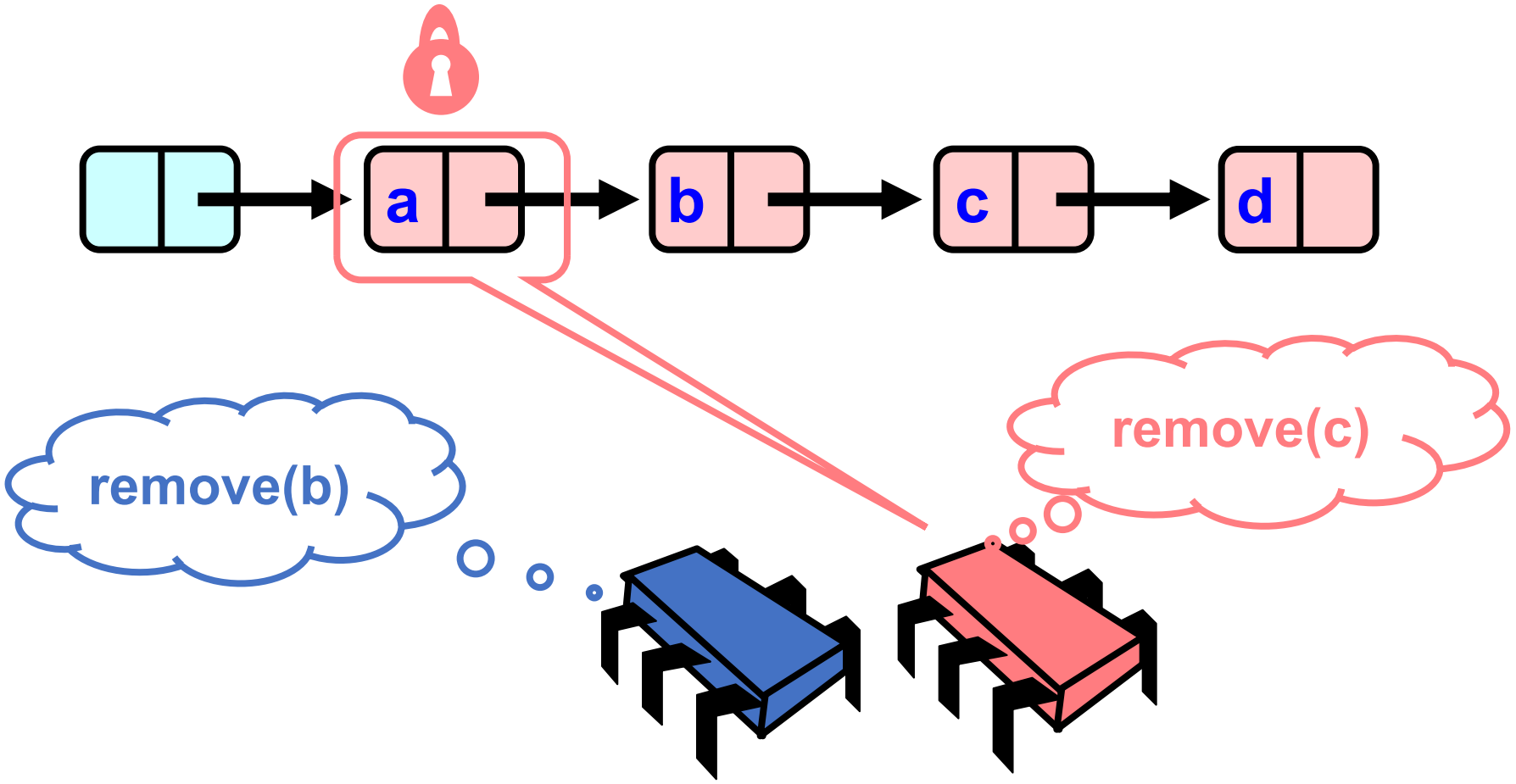

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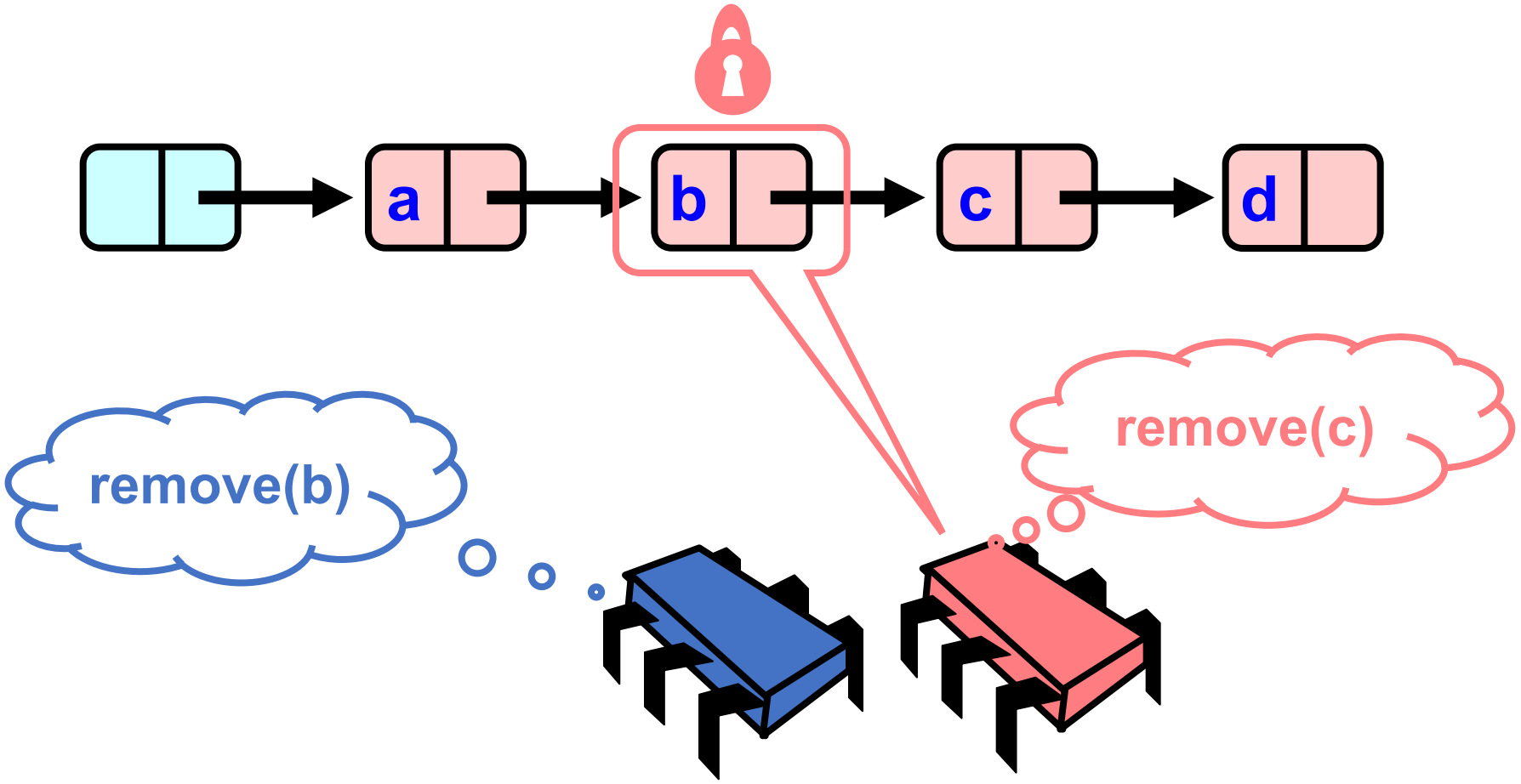

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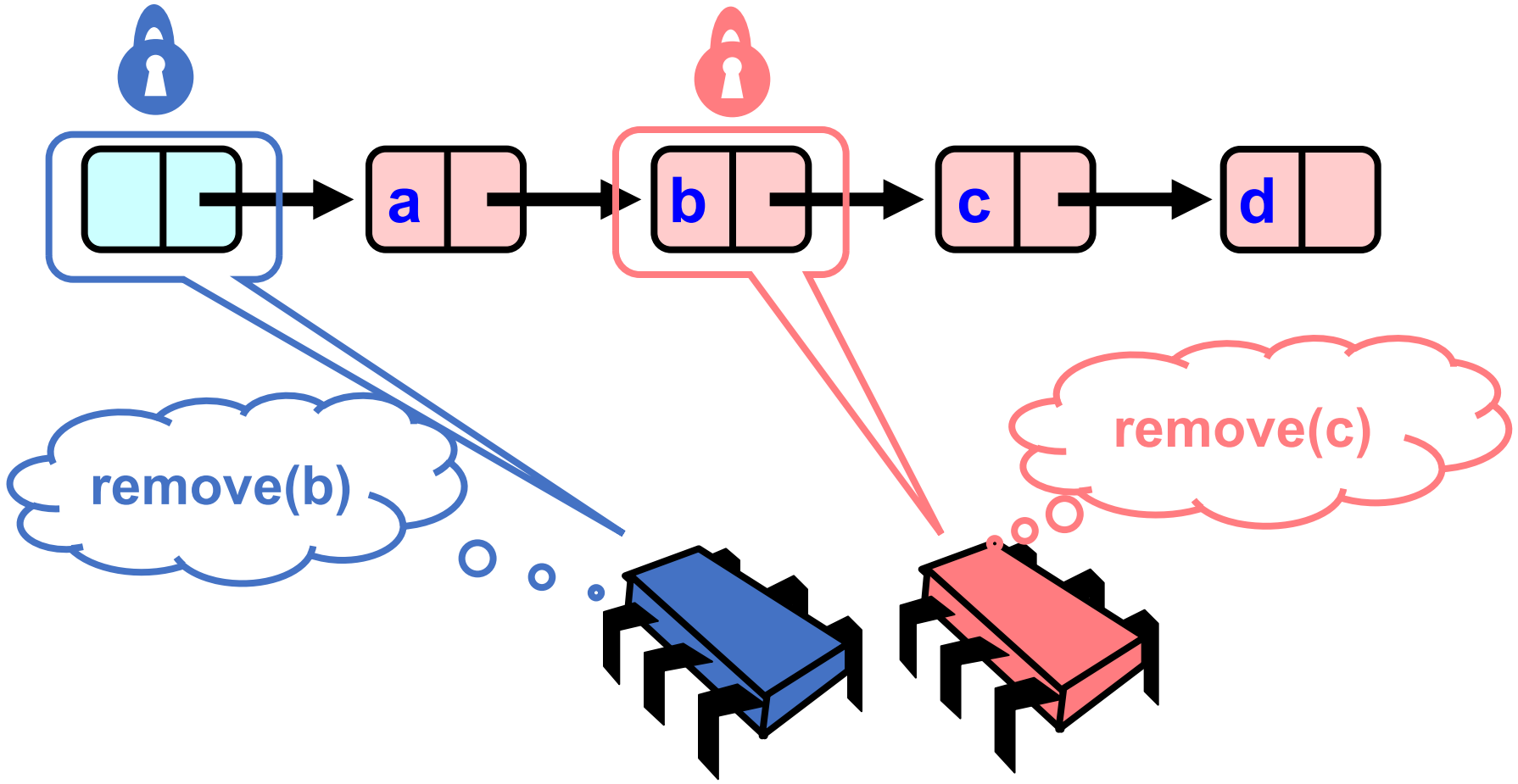

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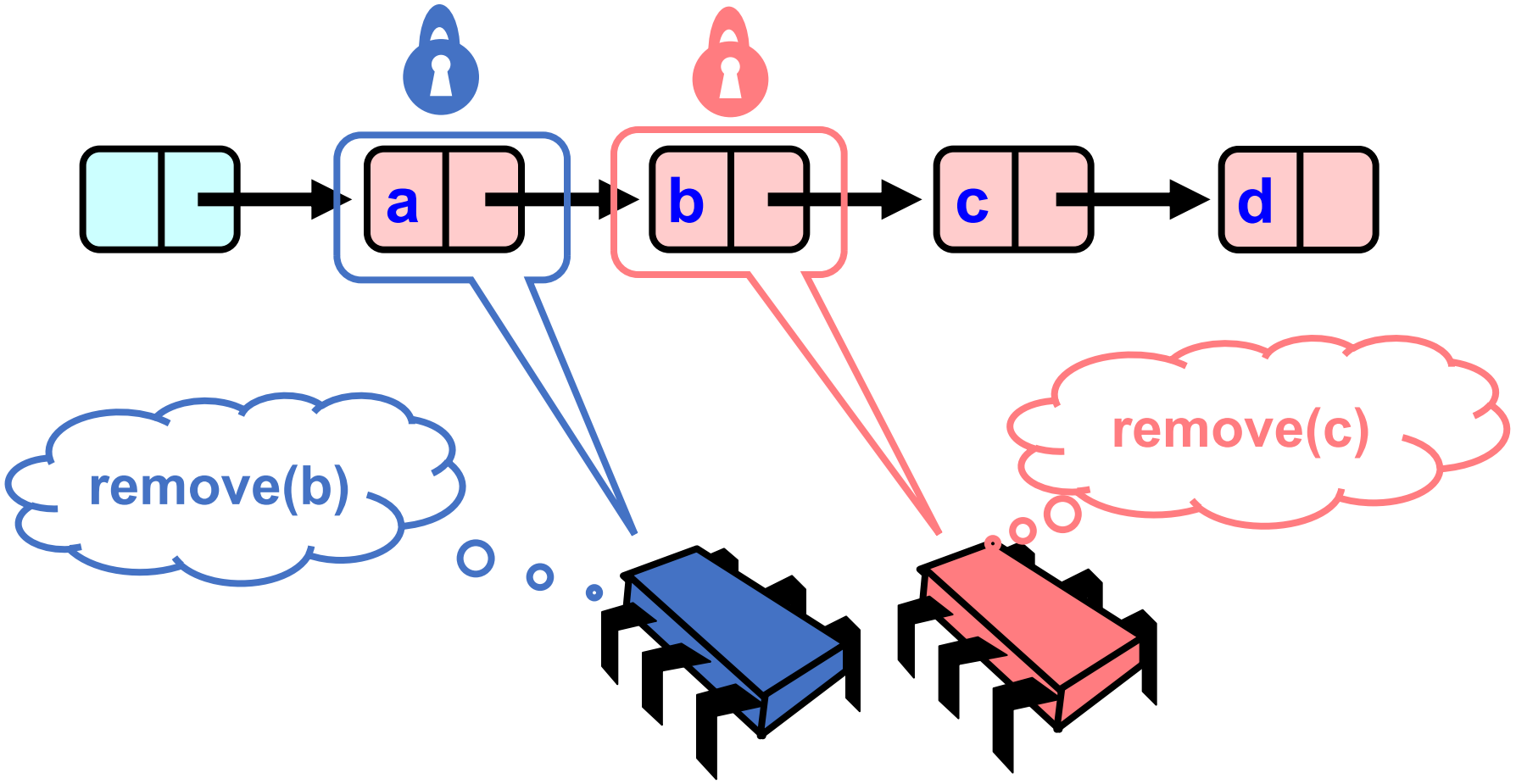

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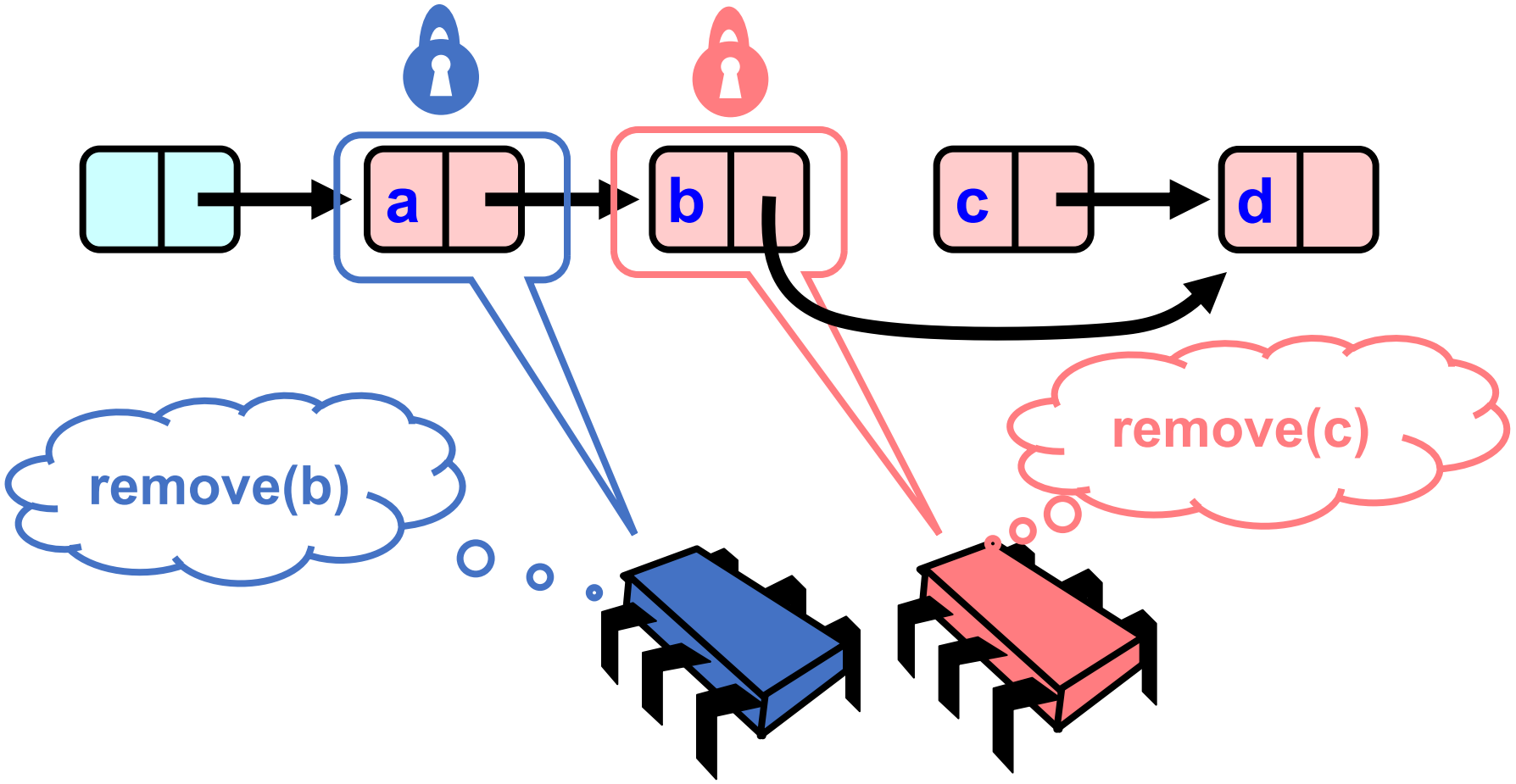

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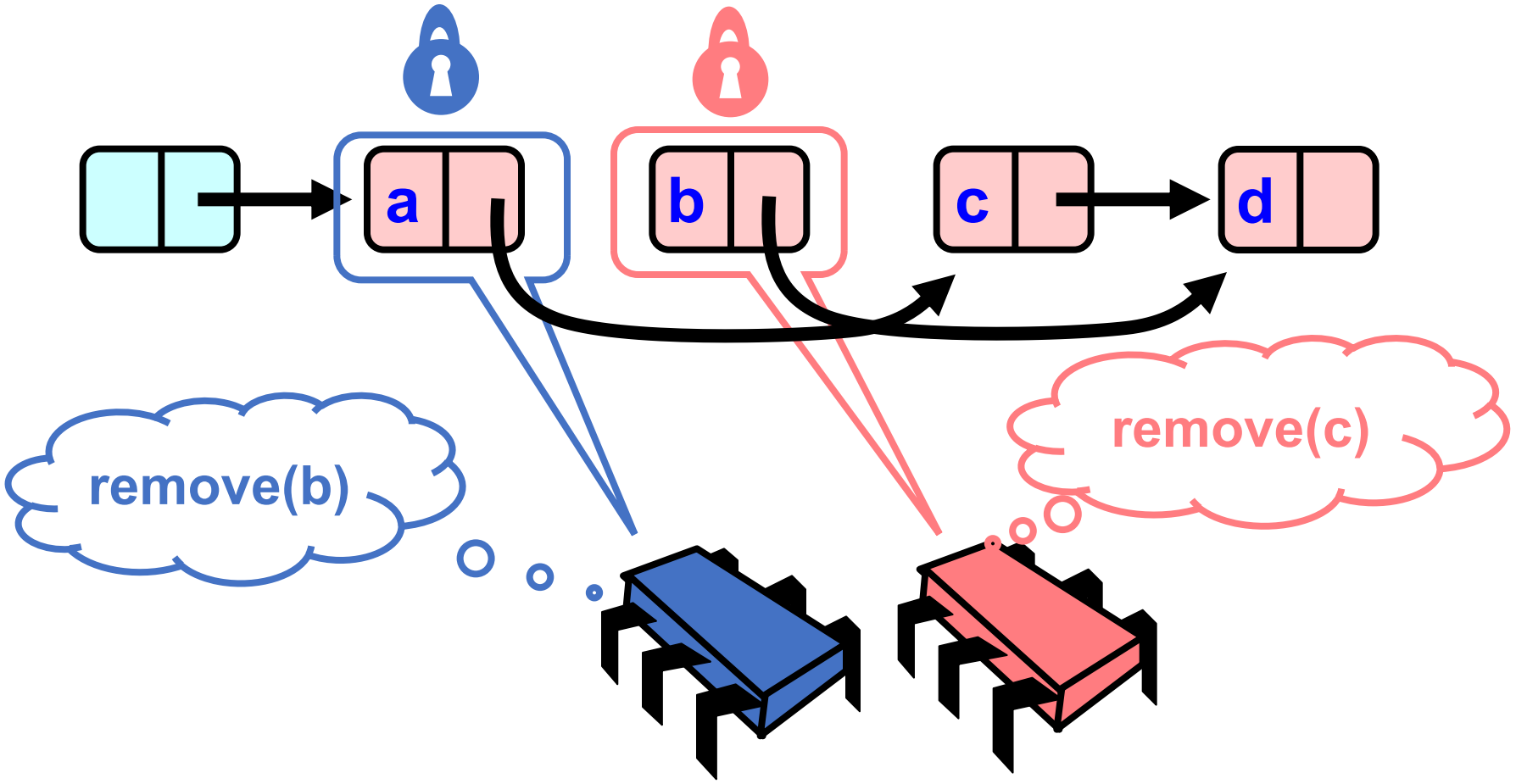
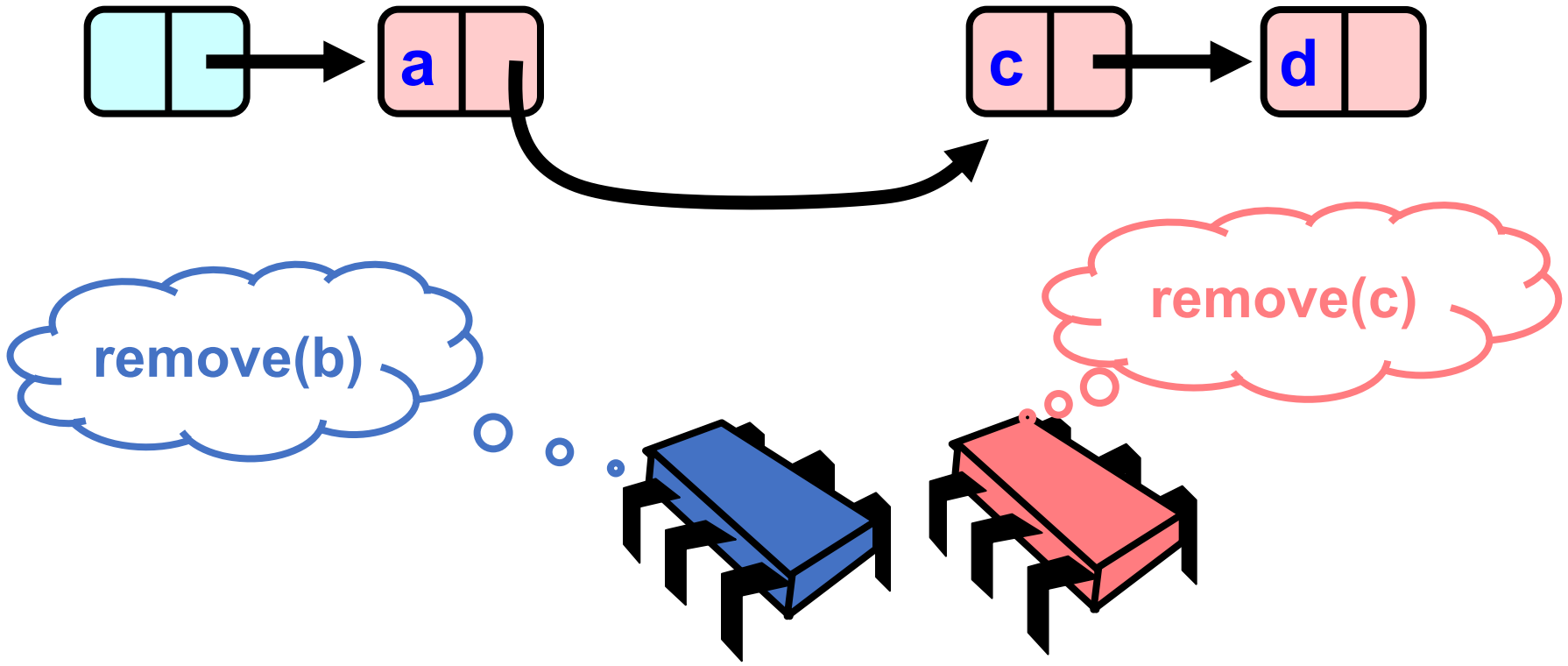


# Uh, Oh



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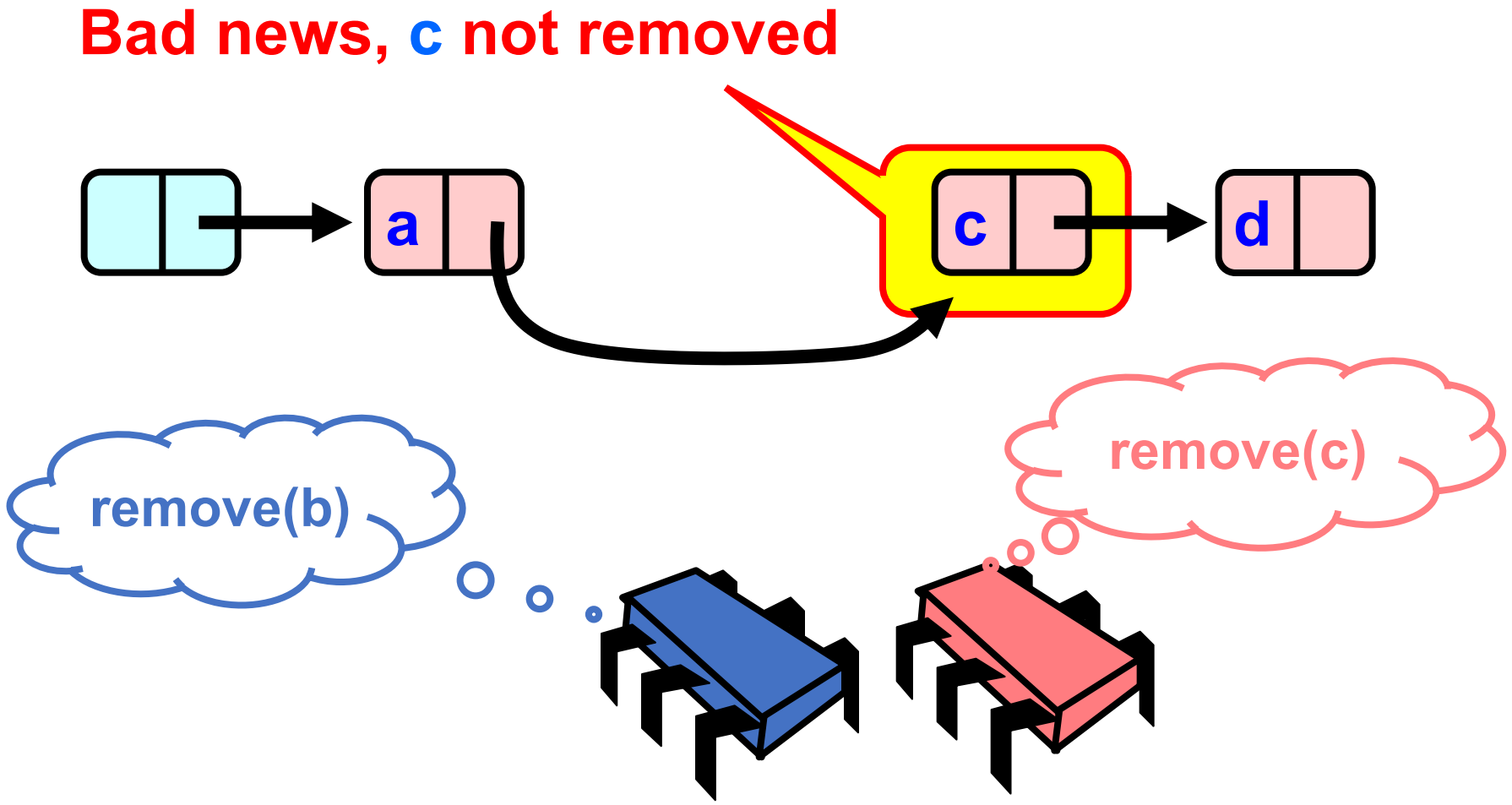
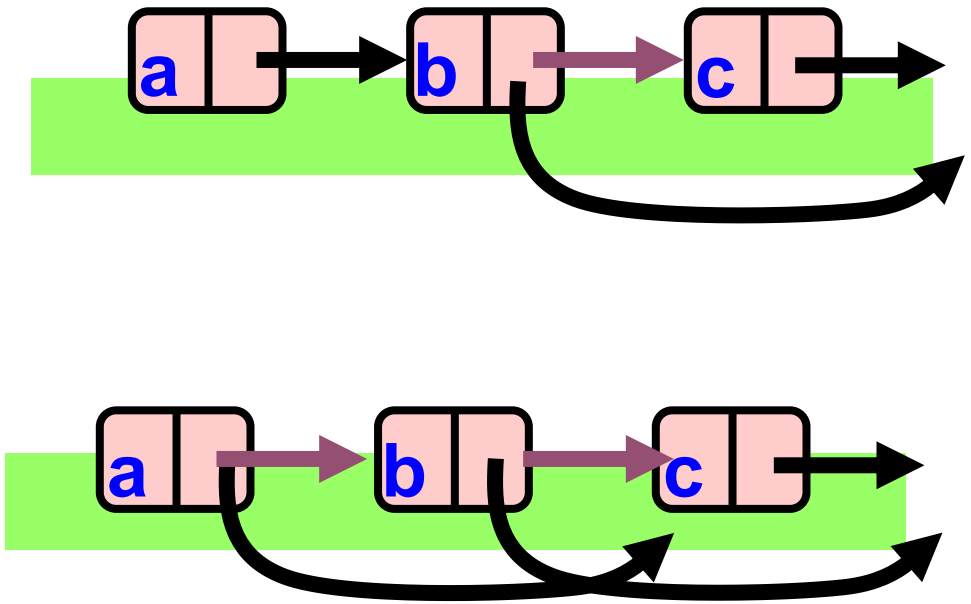


# Problem

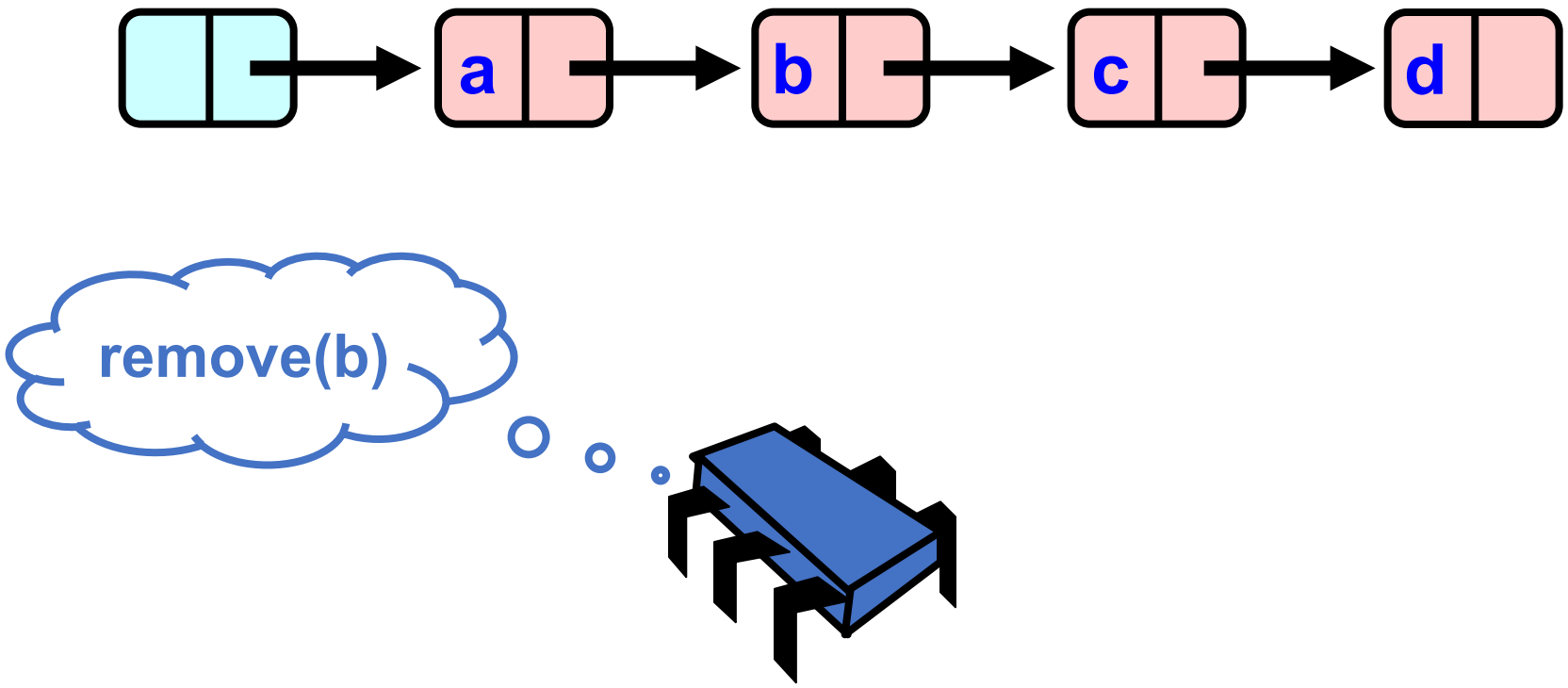
- To delete node c
  - Swing node b's next field to d
- Problem is,
  - ***Data conflict:***
  - Someone deleting b concurrently could direct a pointer to C



# Insight

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

# Hand-Over-Hand Again



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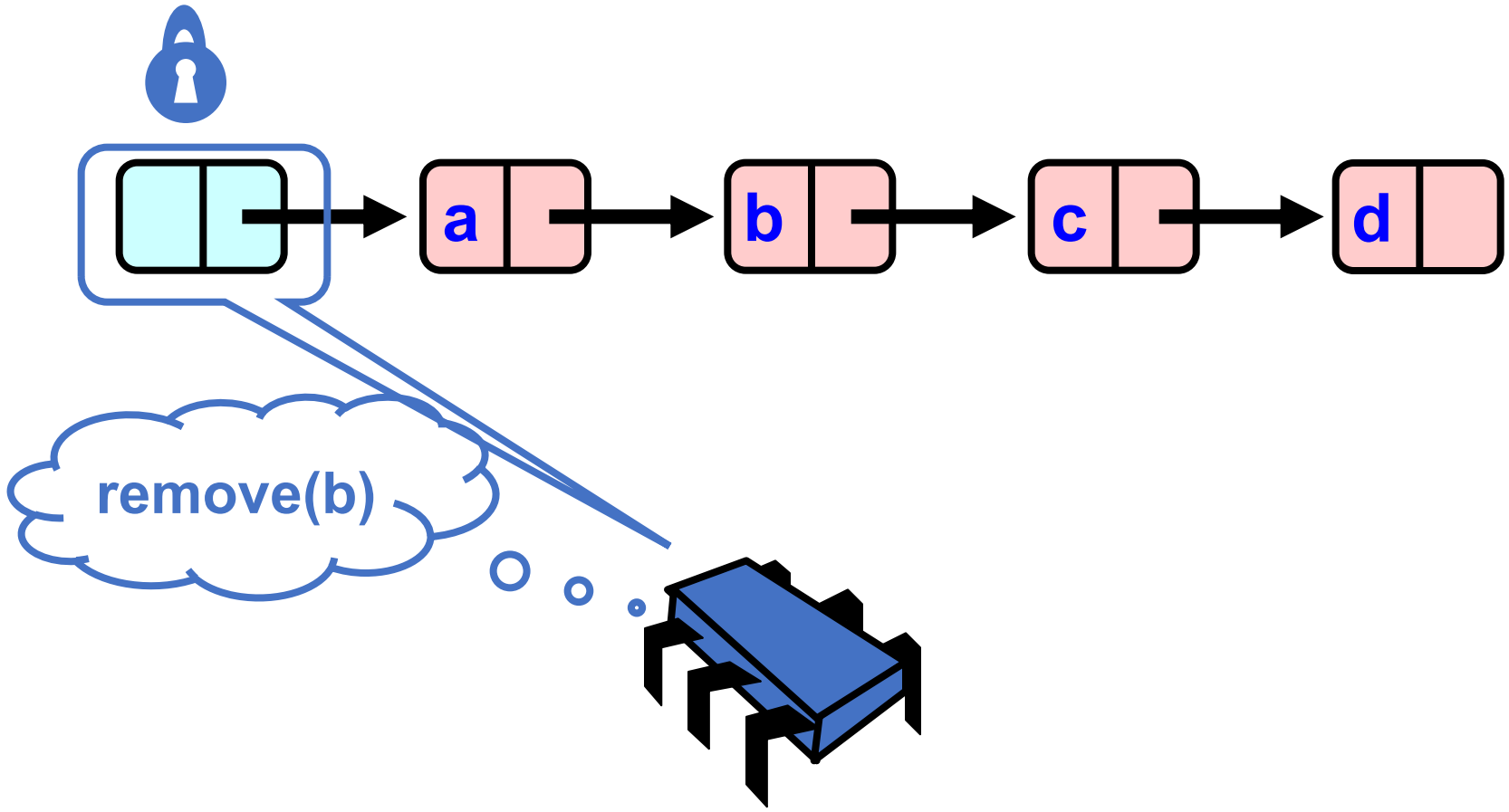

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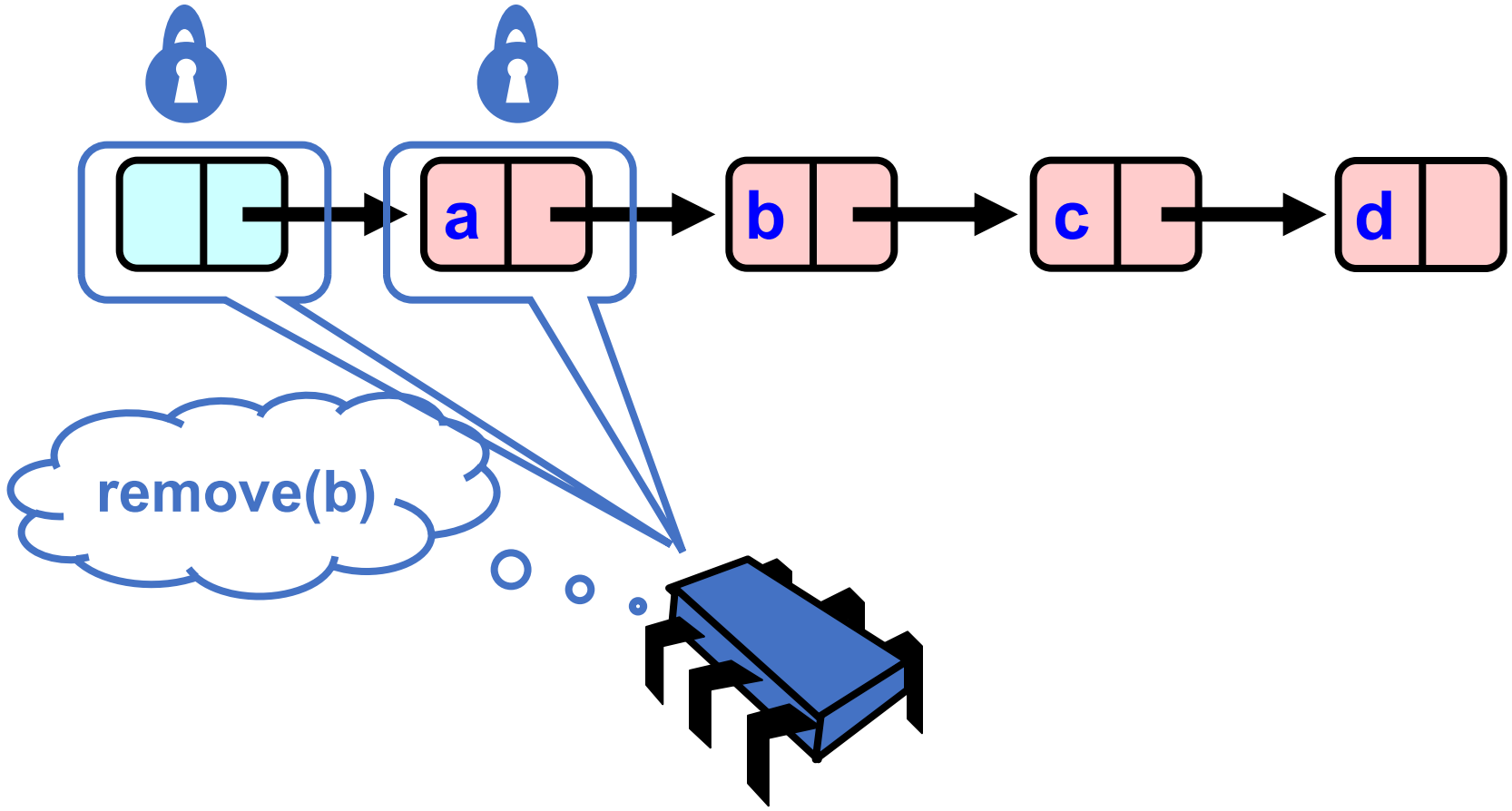

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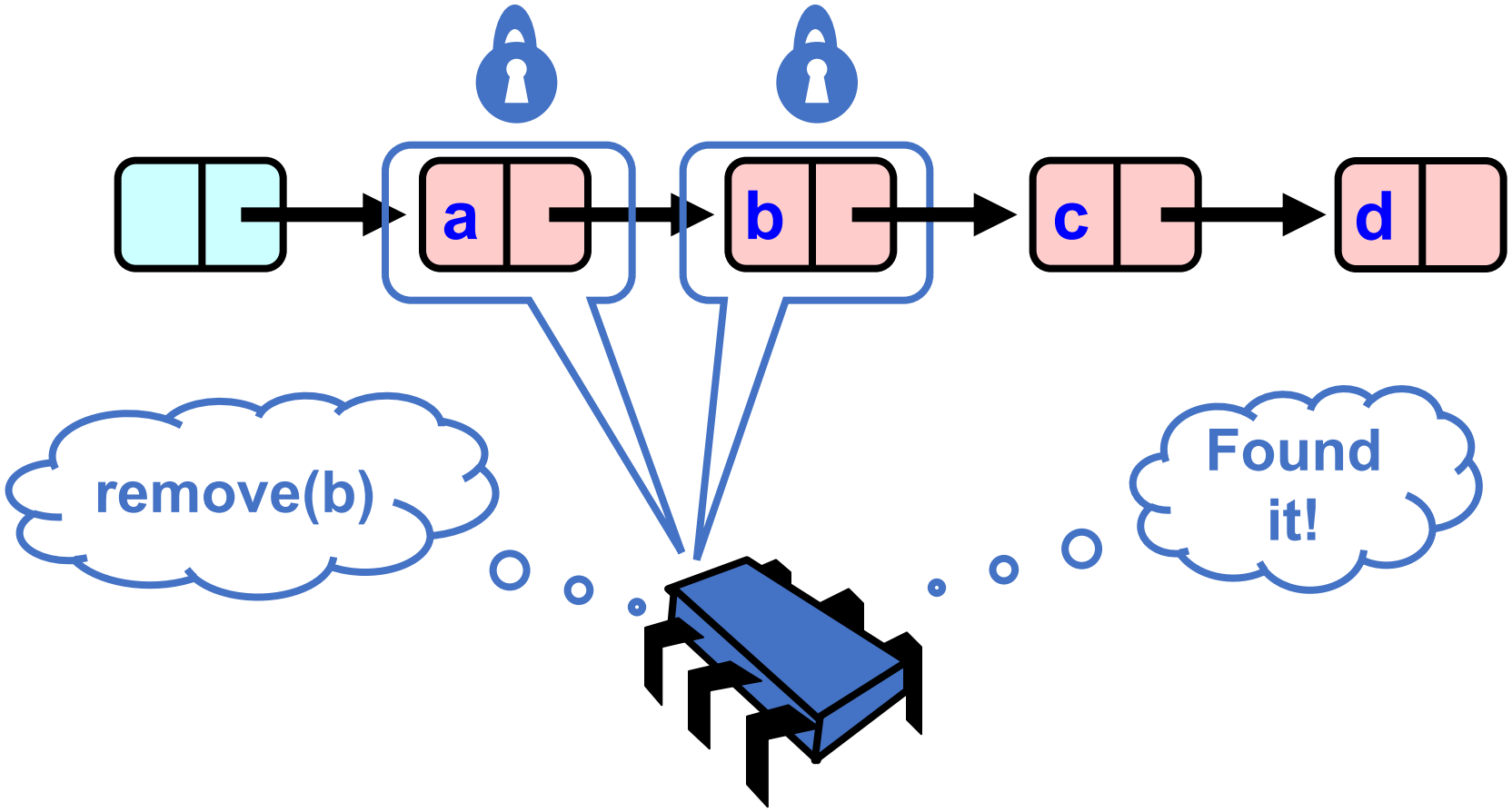

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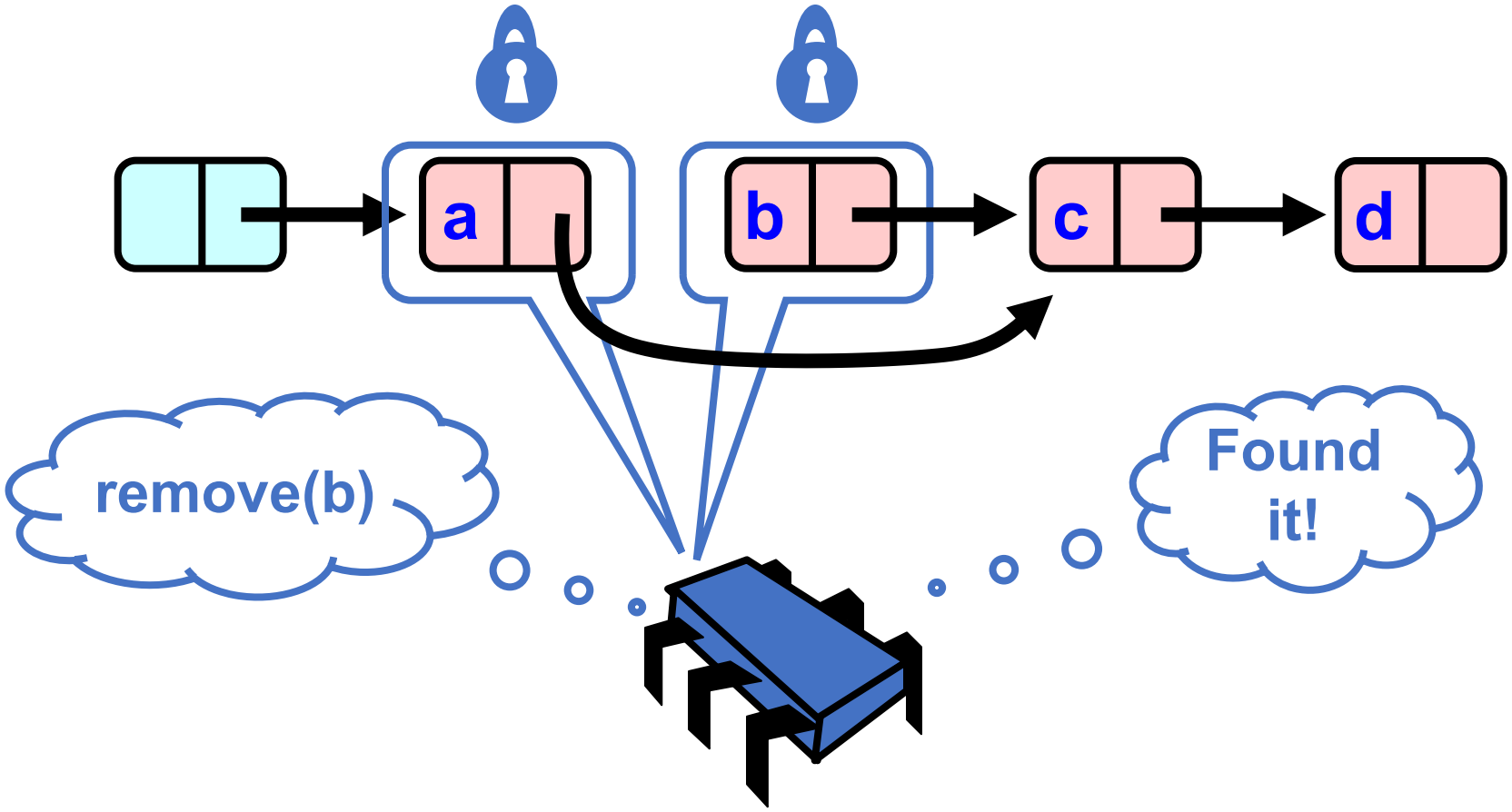
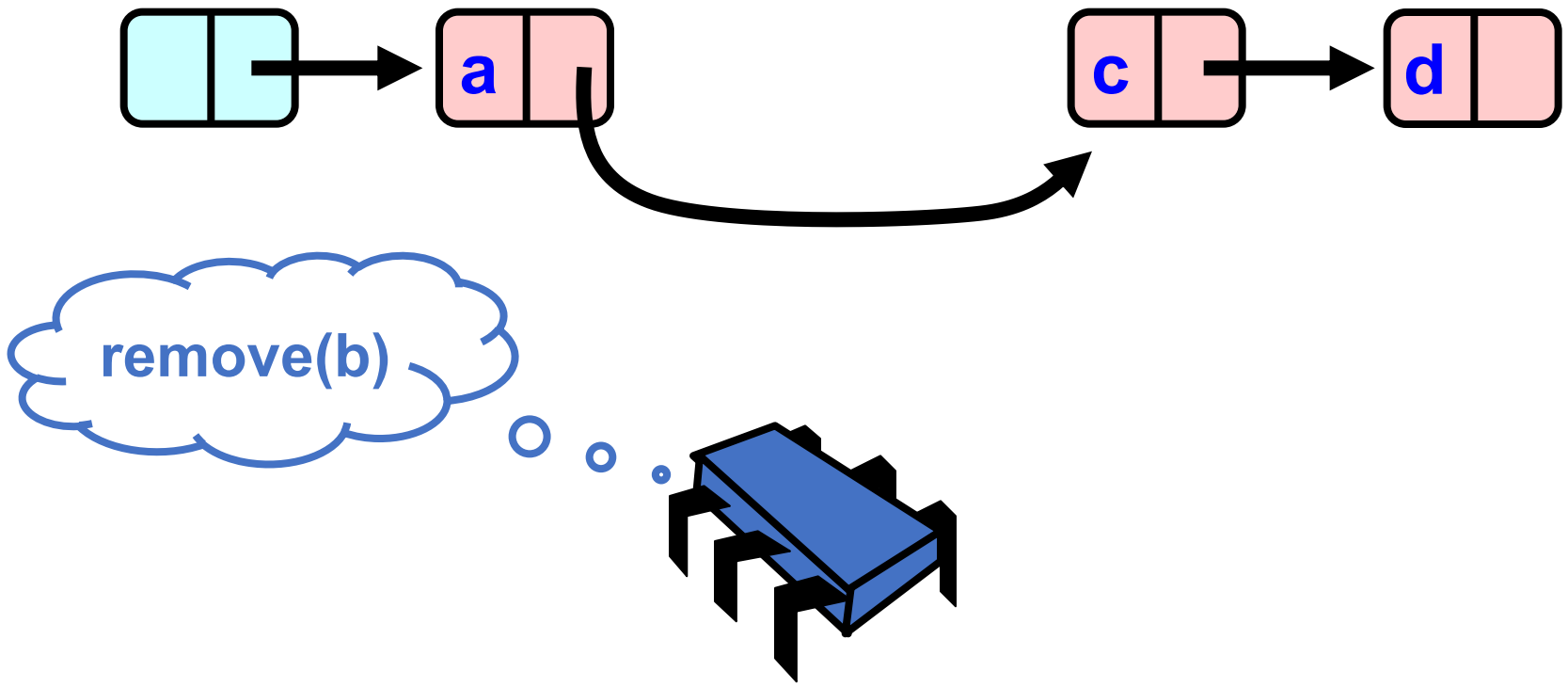
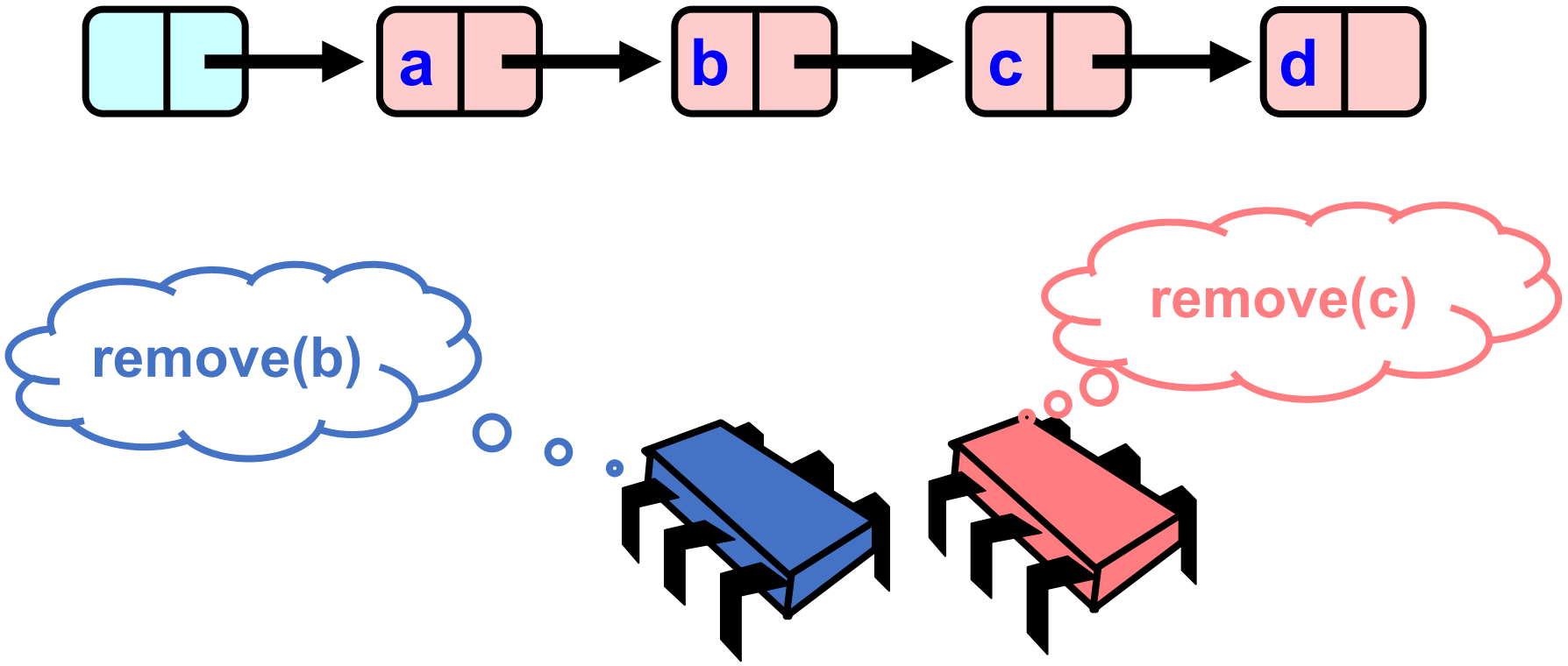


# Hand-Over-Hand Again



# Removing a Node



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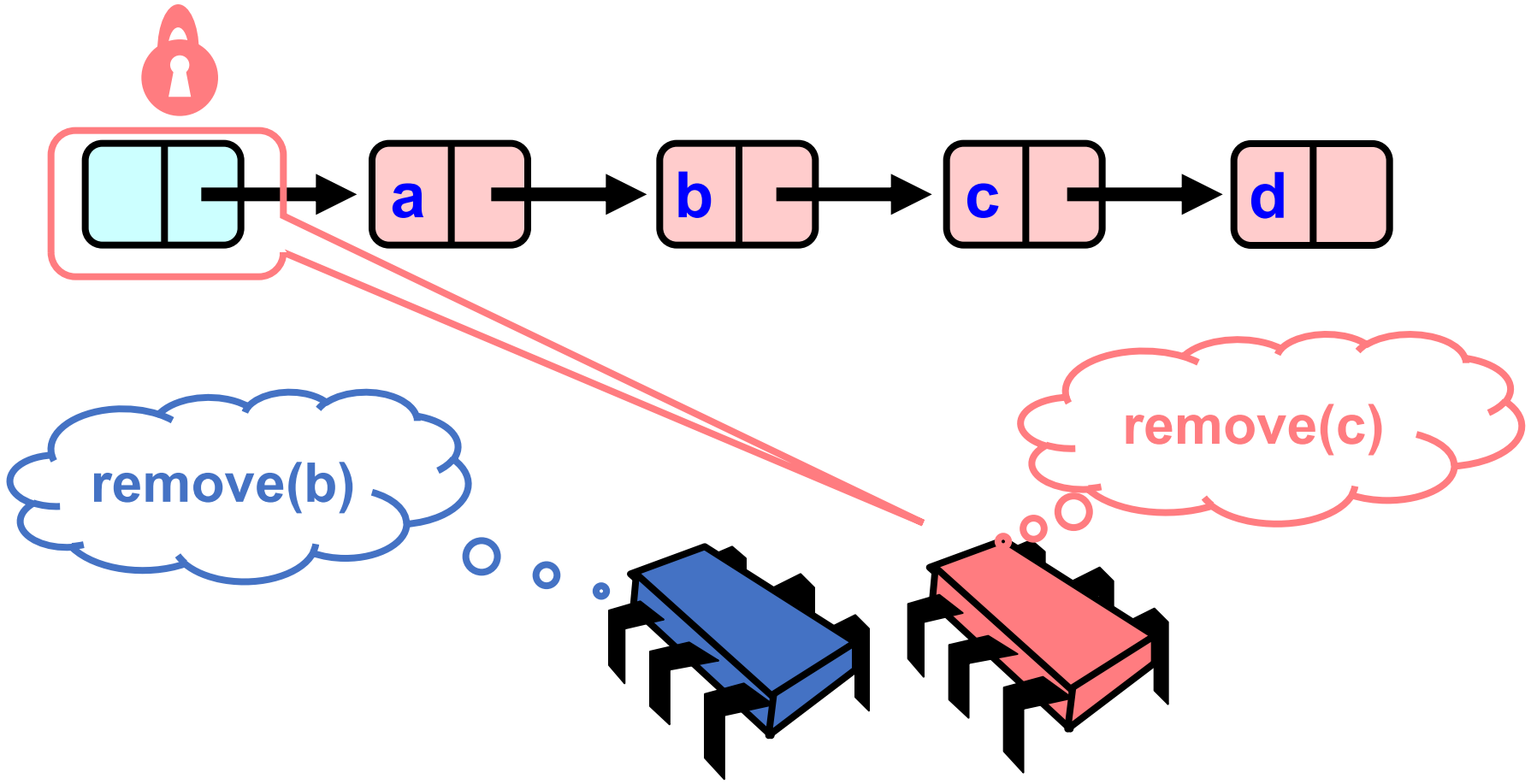

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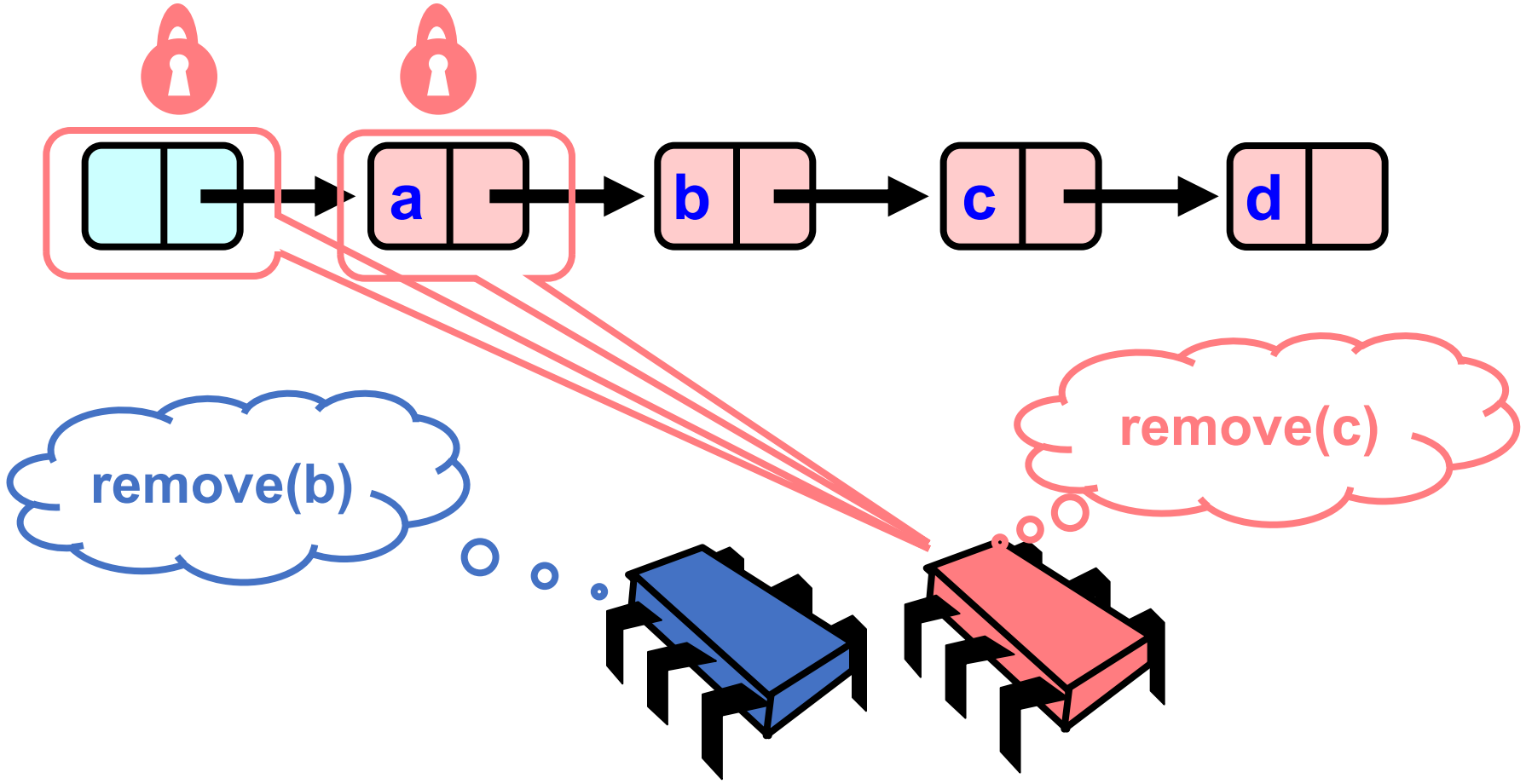

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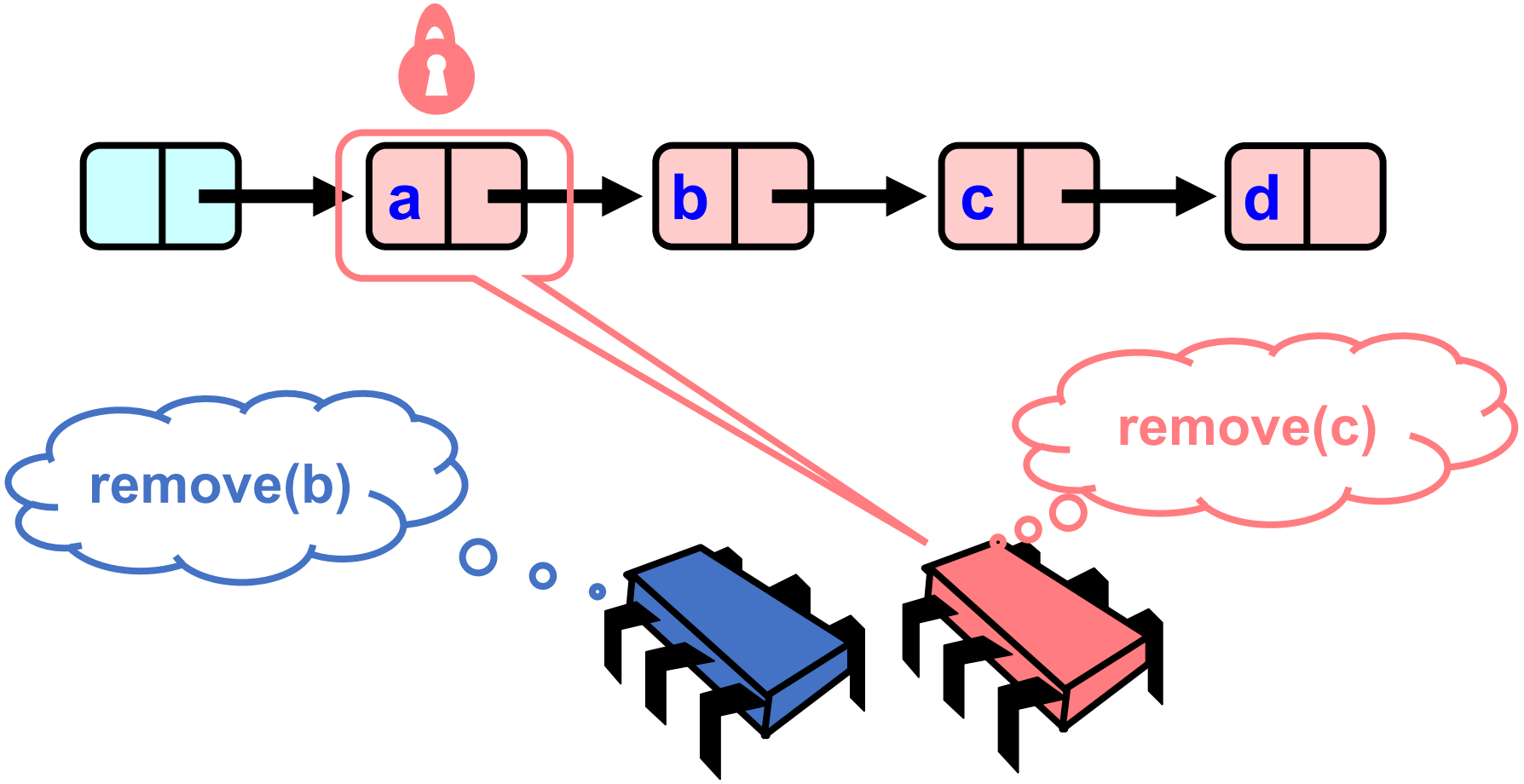

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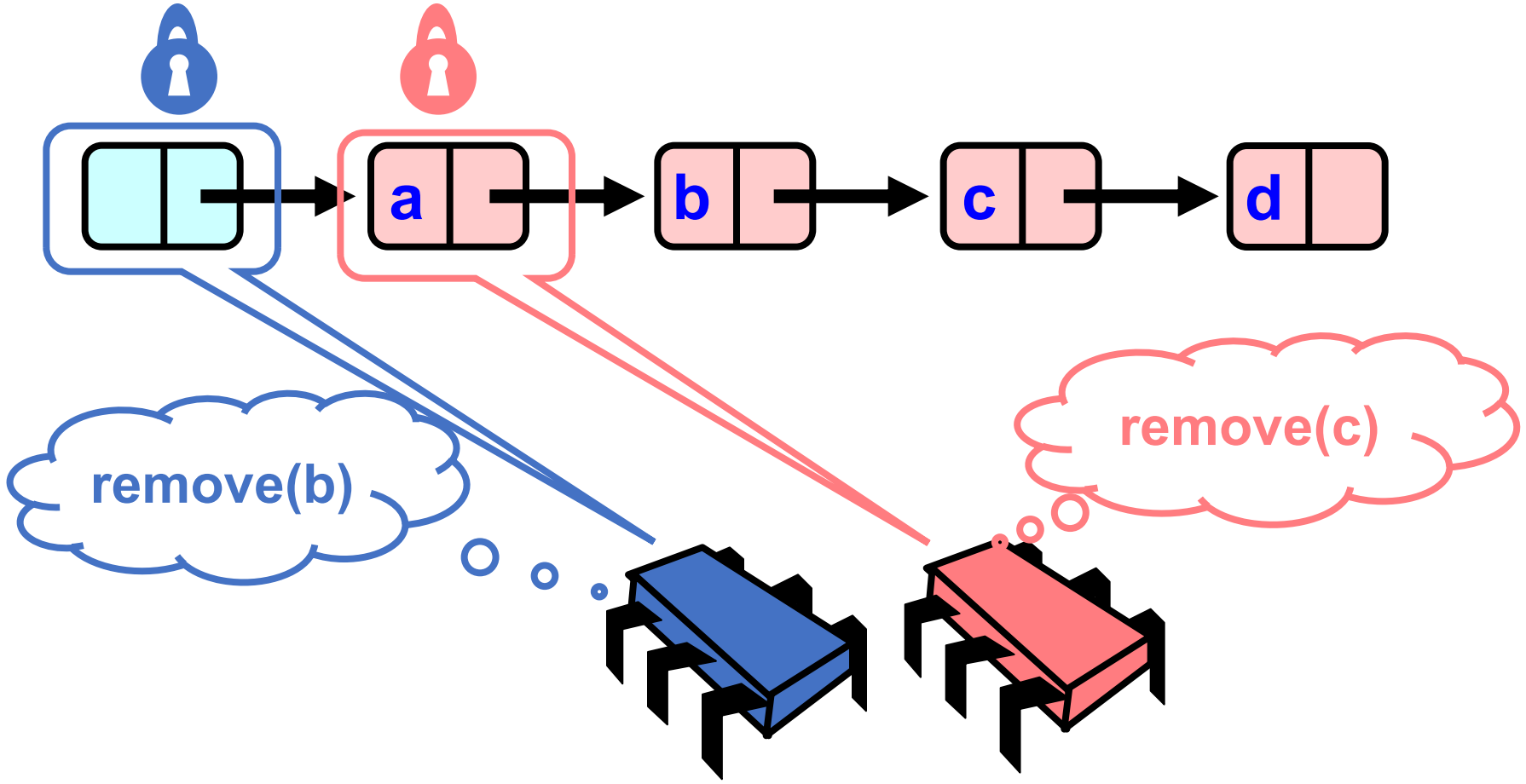

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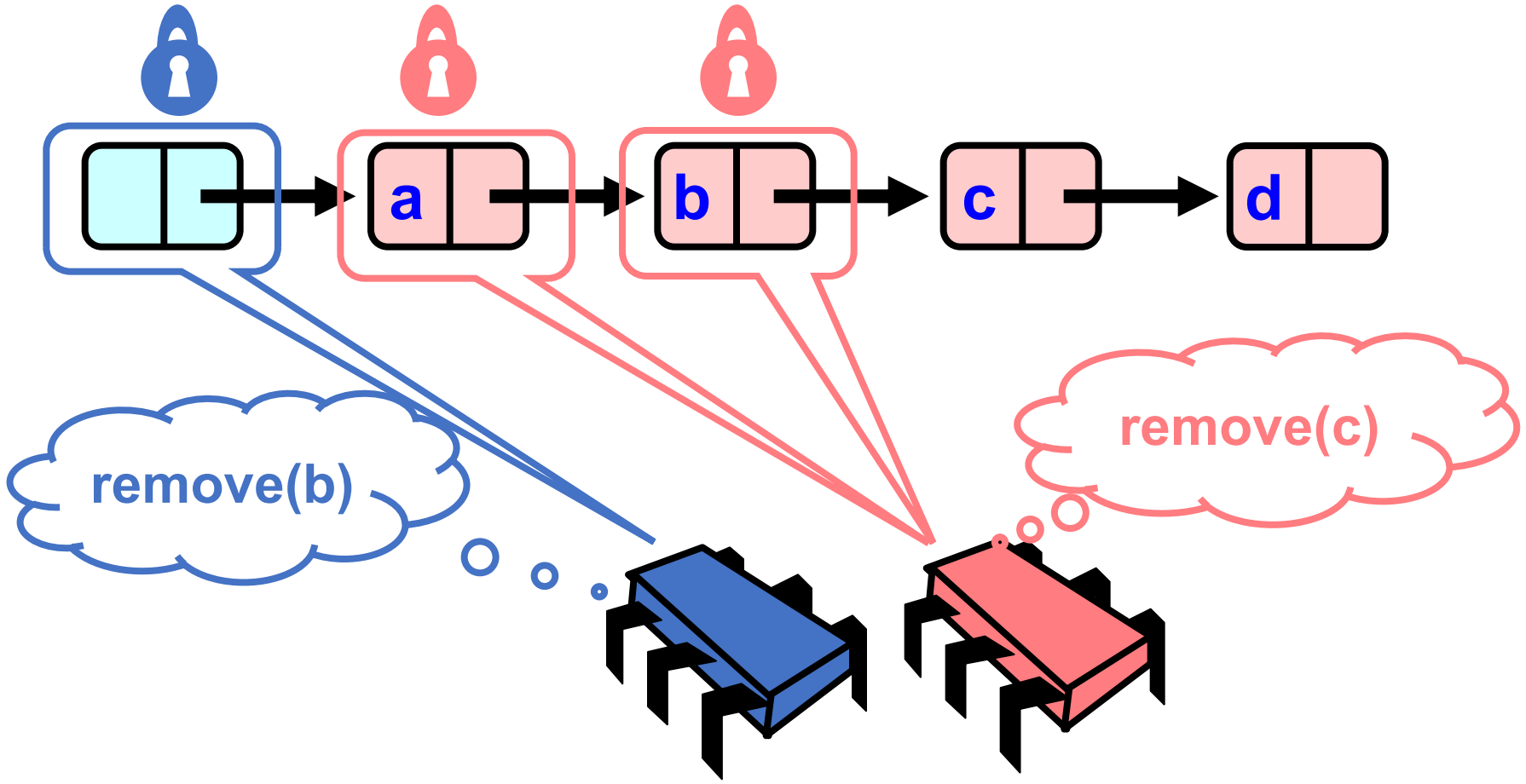

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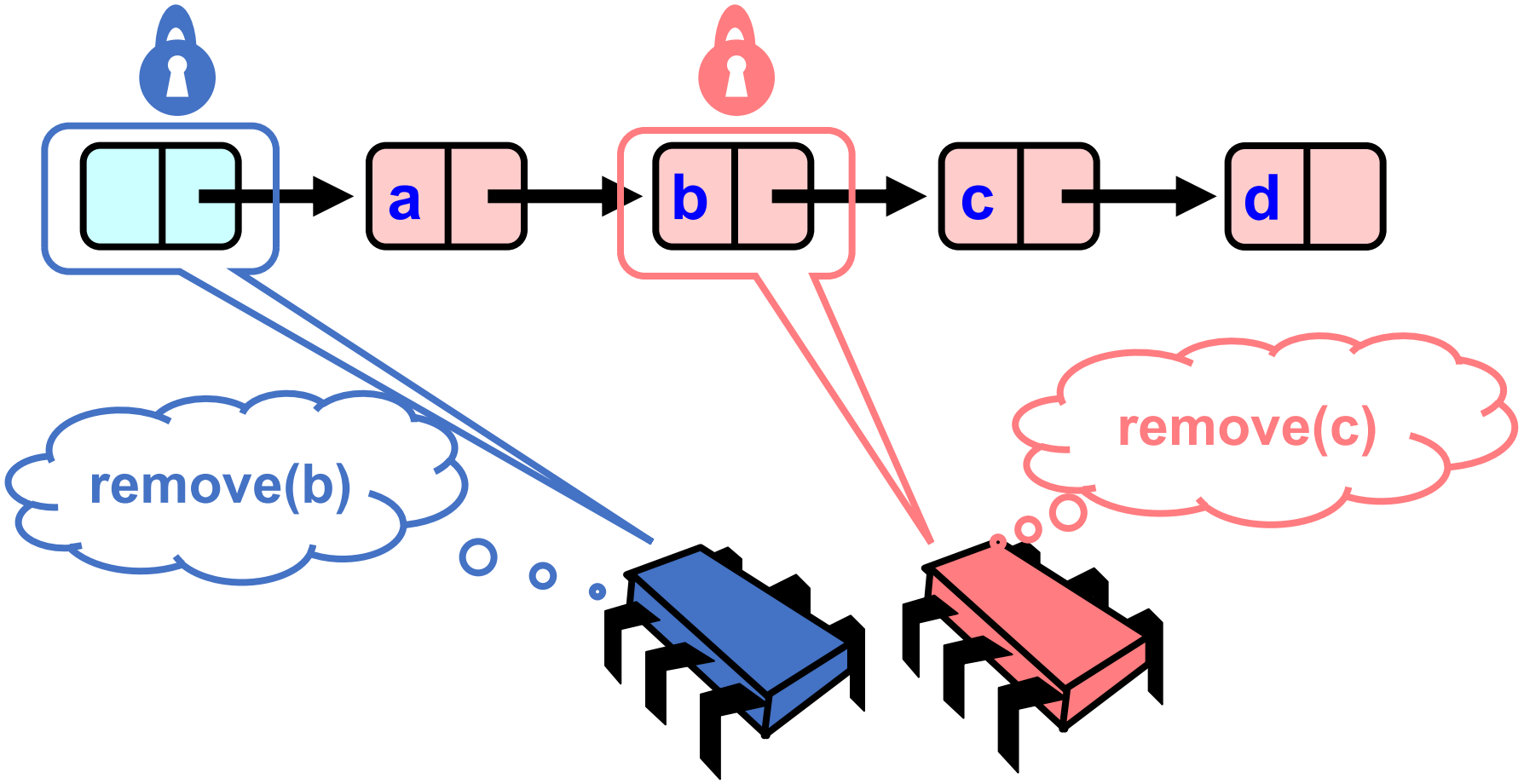
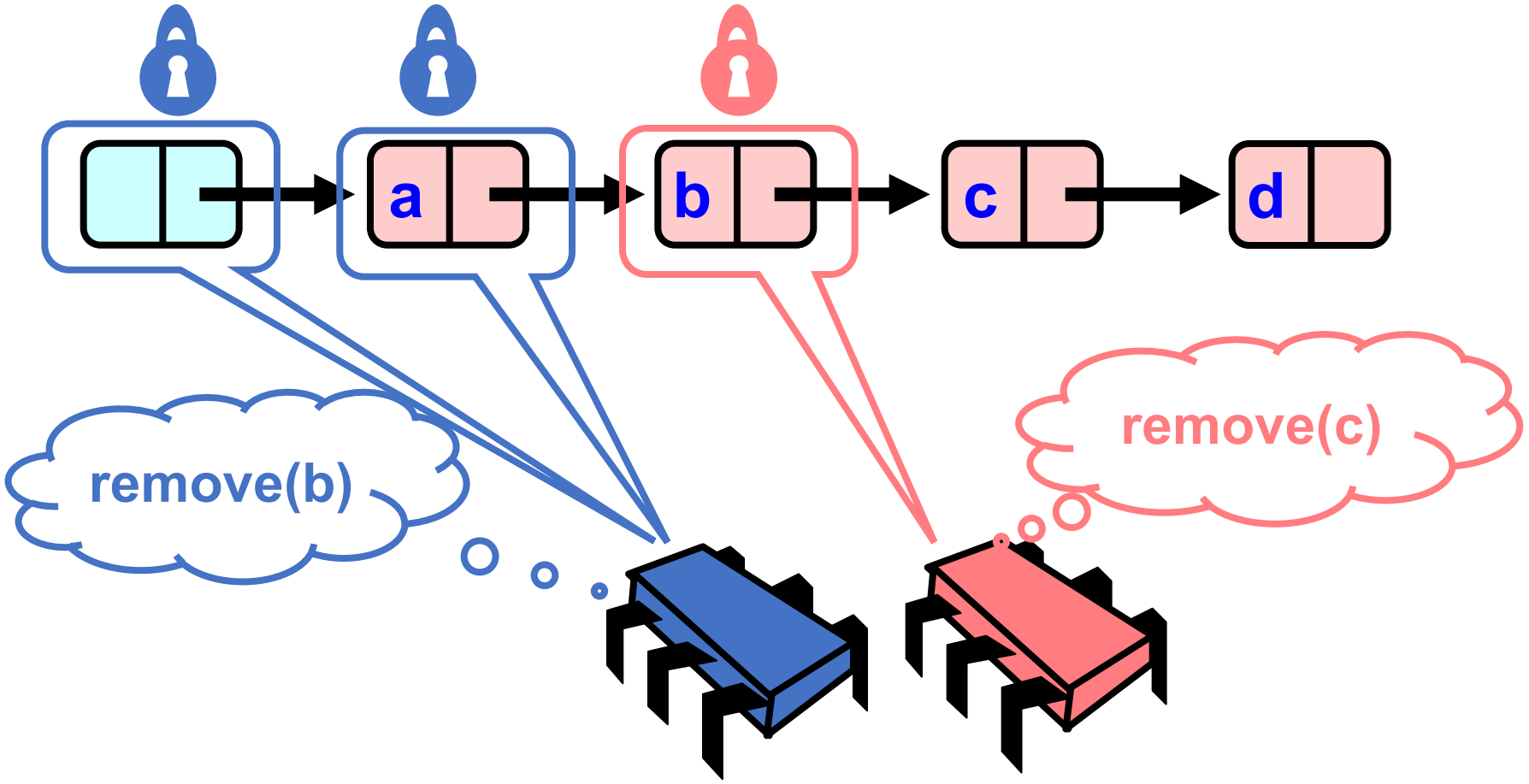
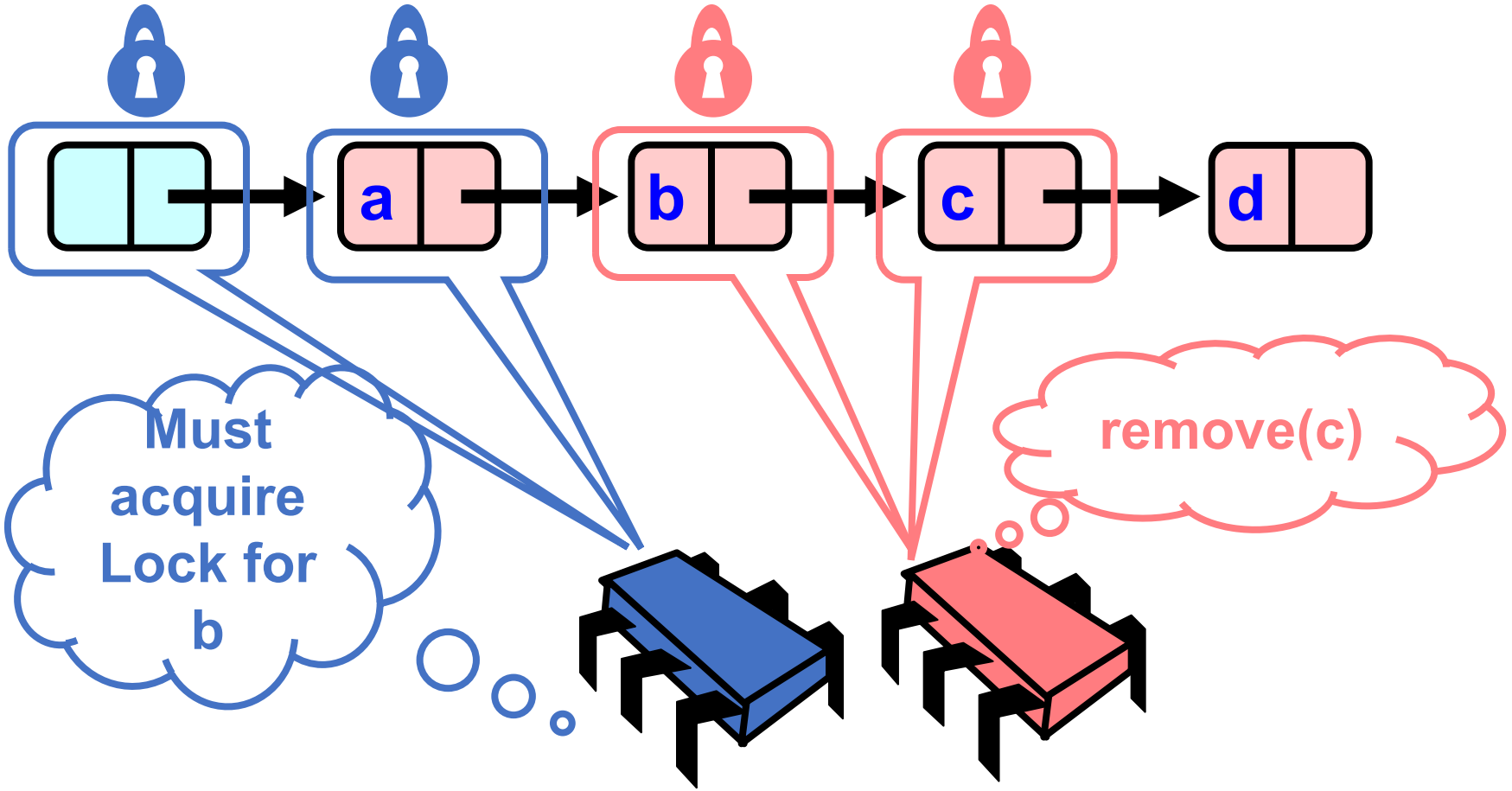


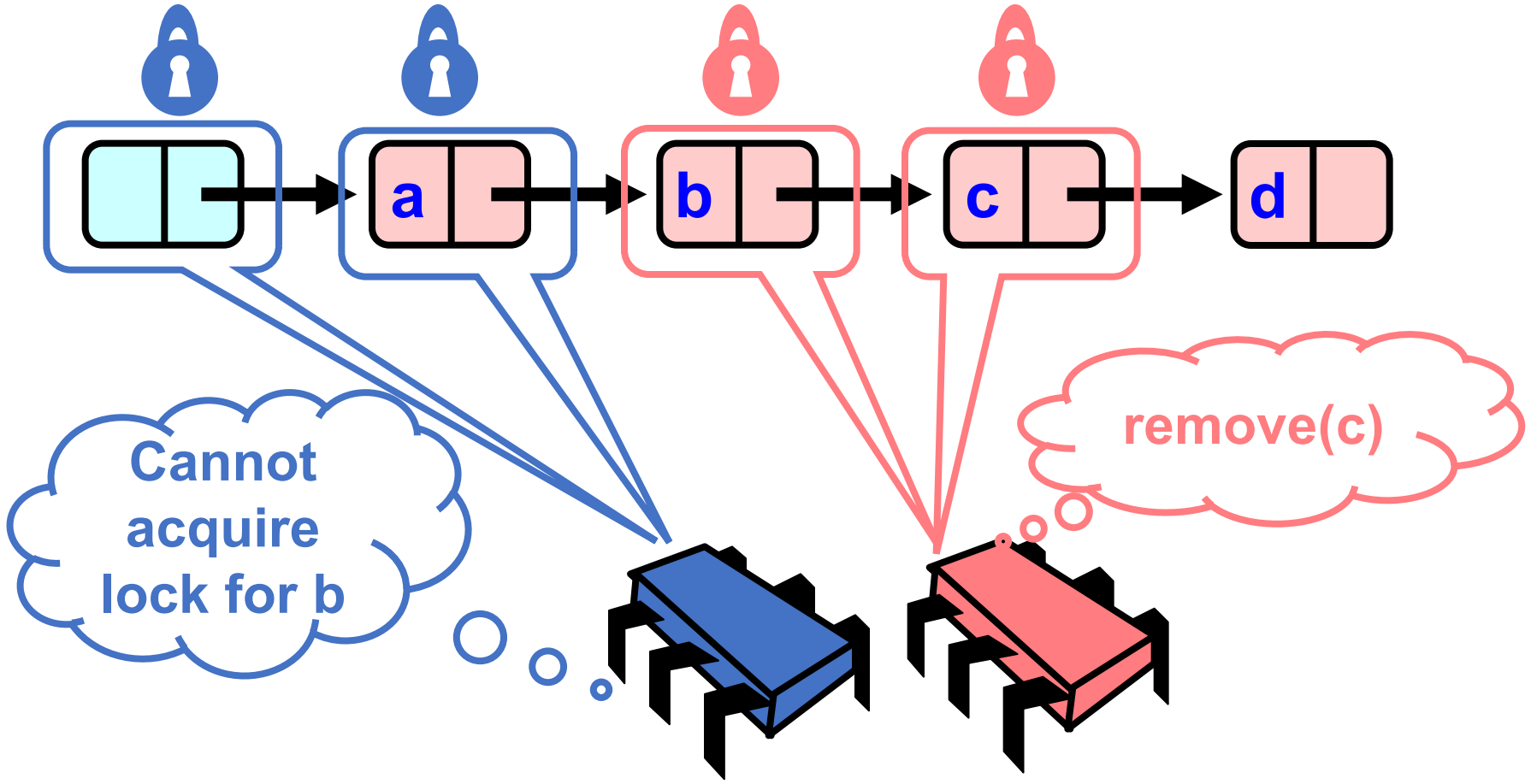
# Removing a Node



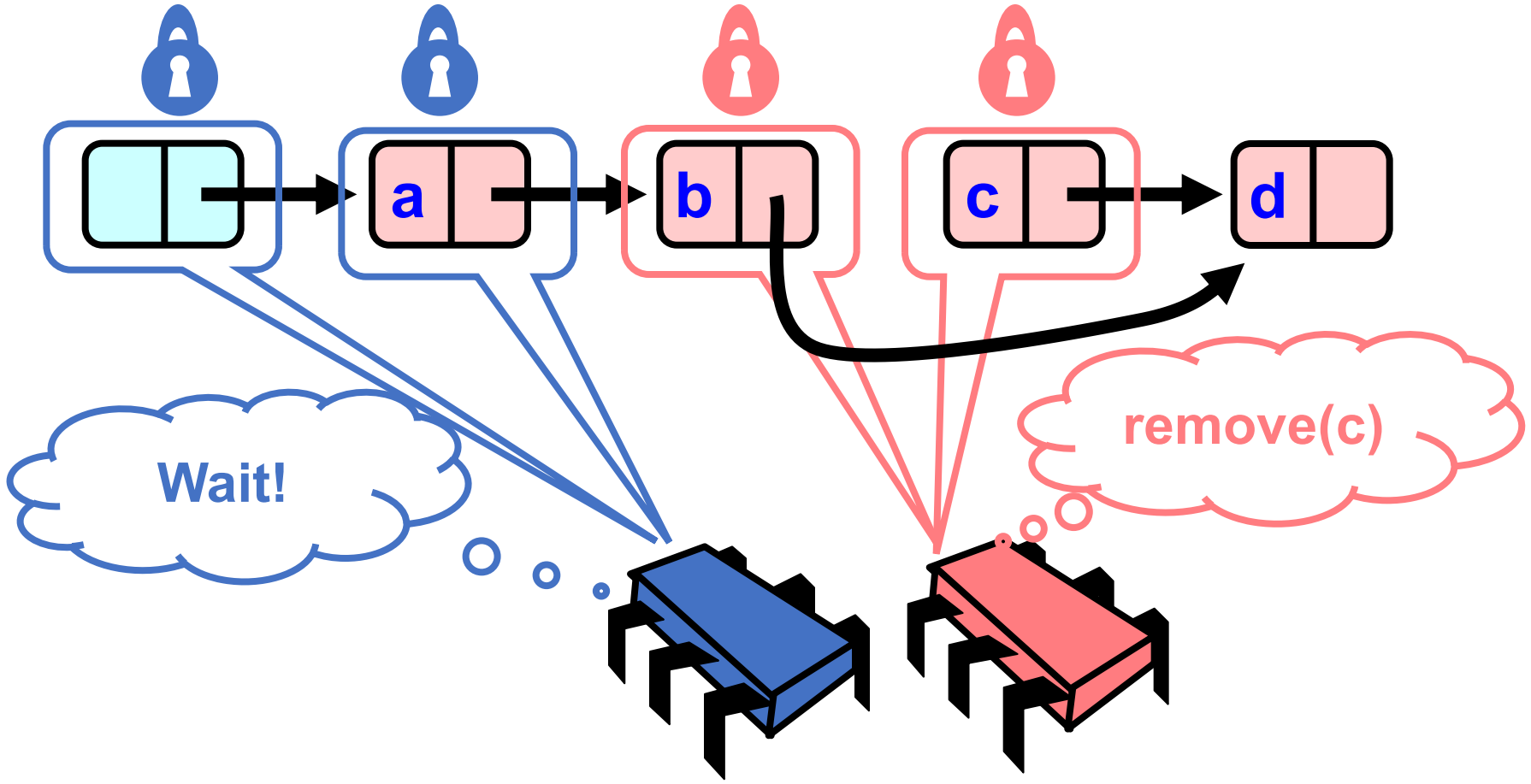
# Removing a Node



# Removing a Node



# Removing a Node



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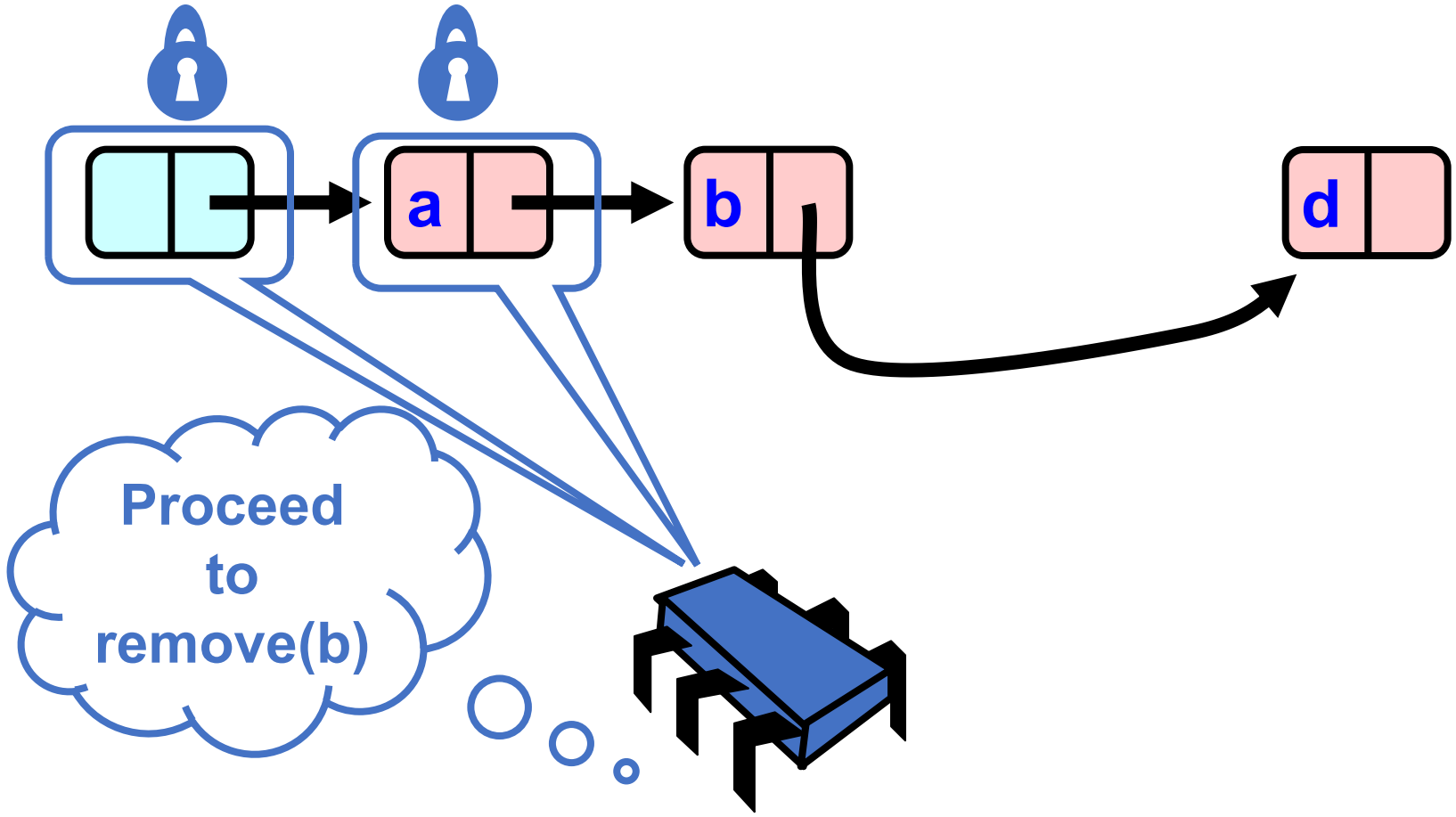

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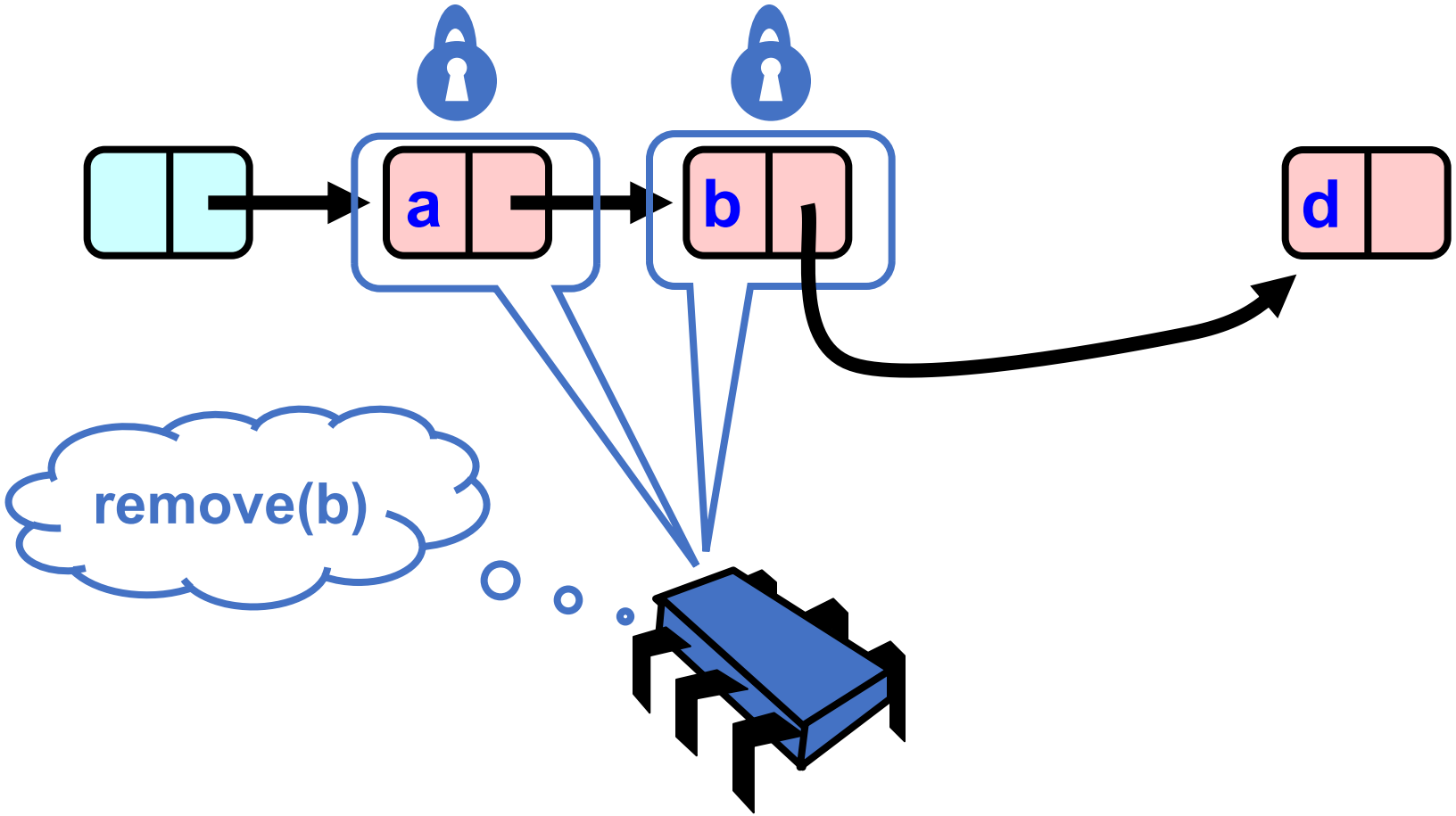

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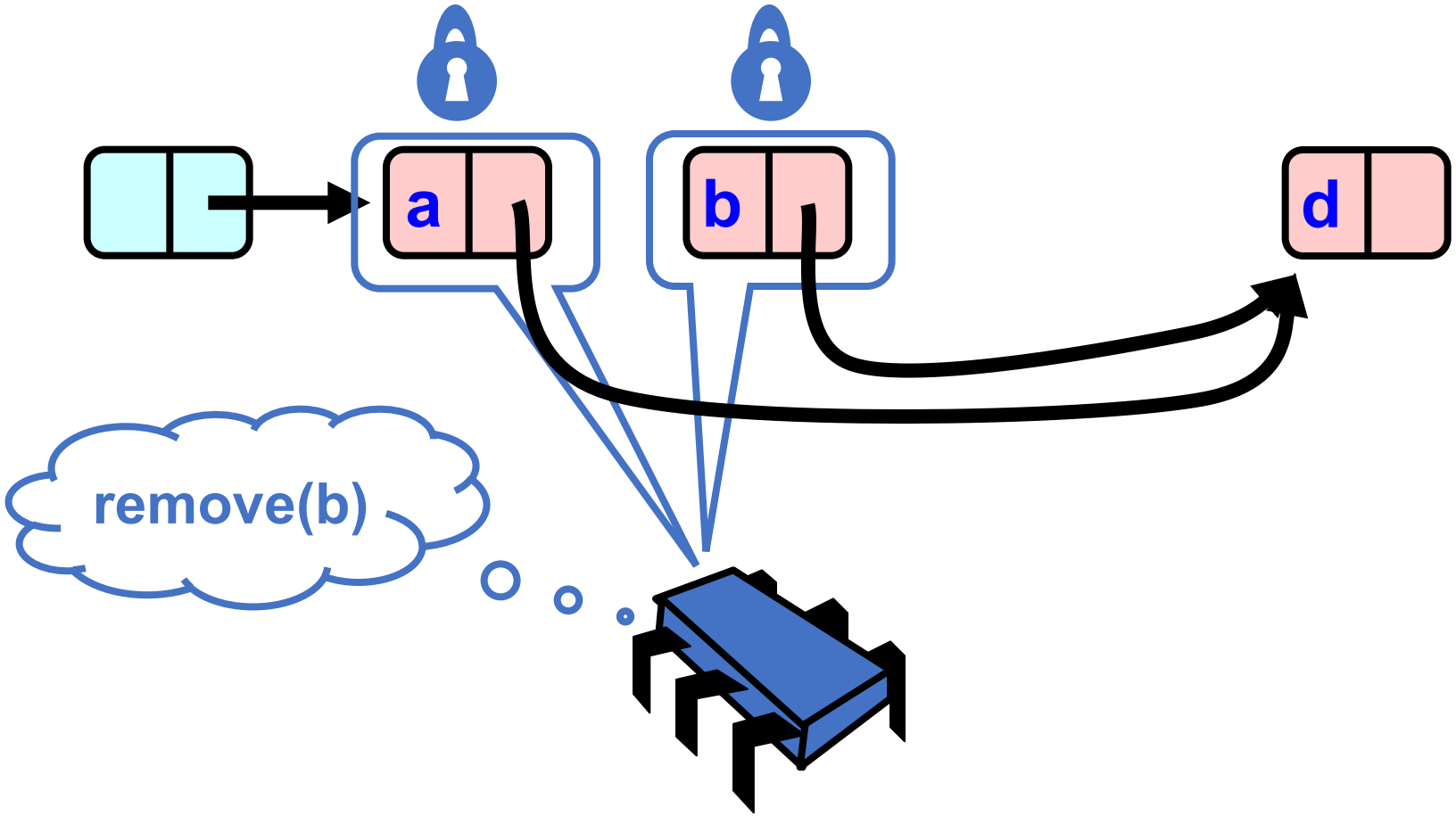

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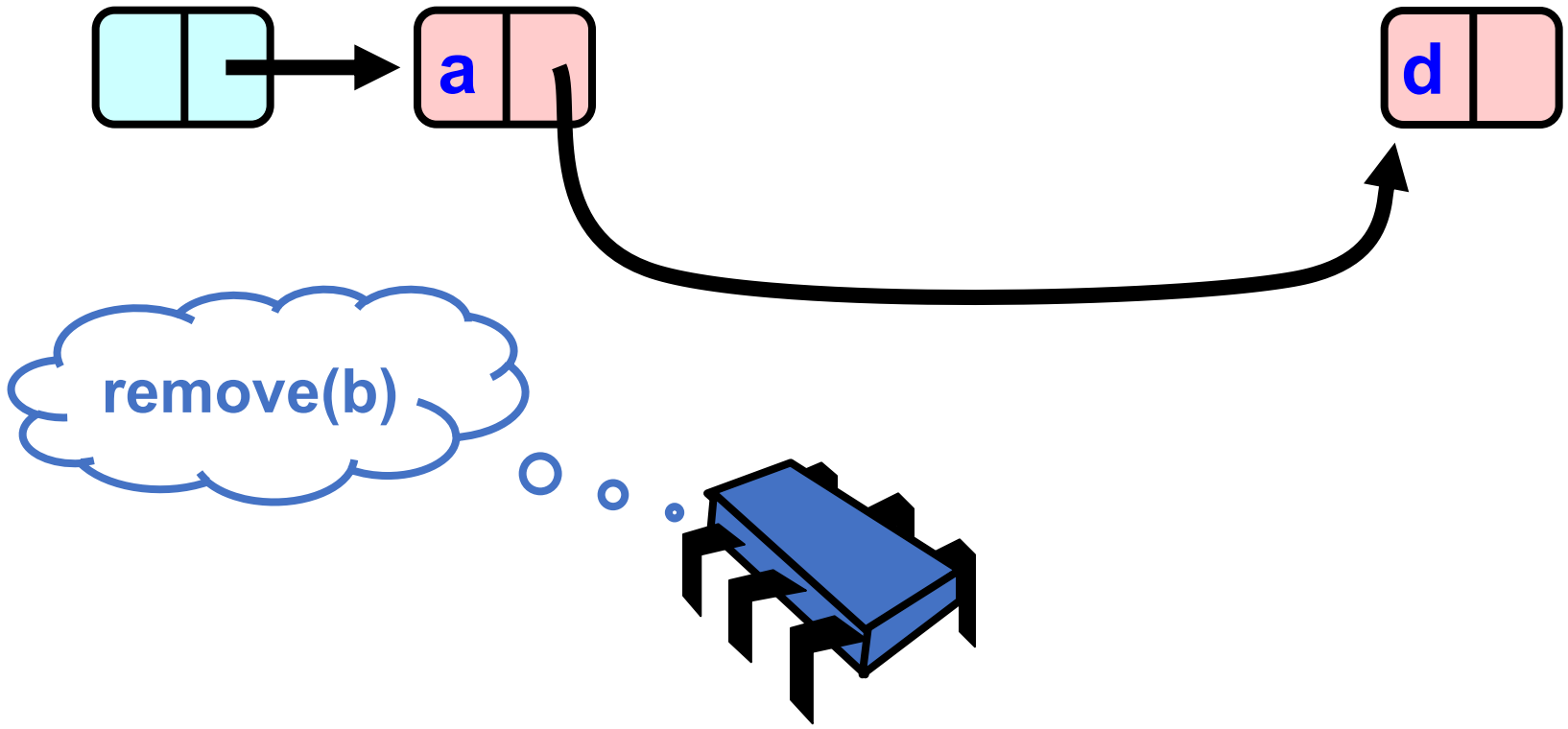

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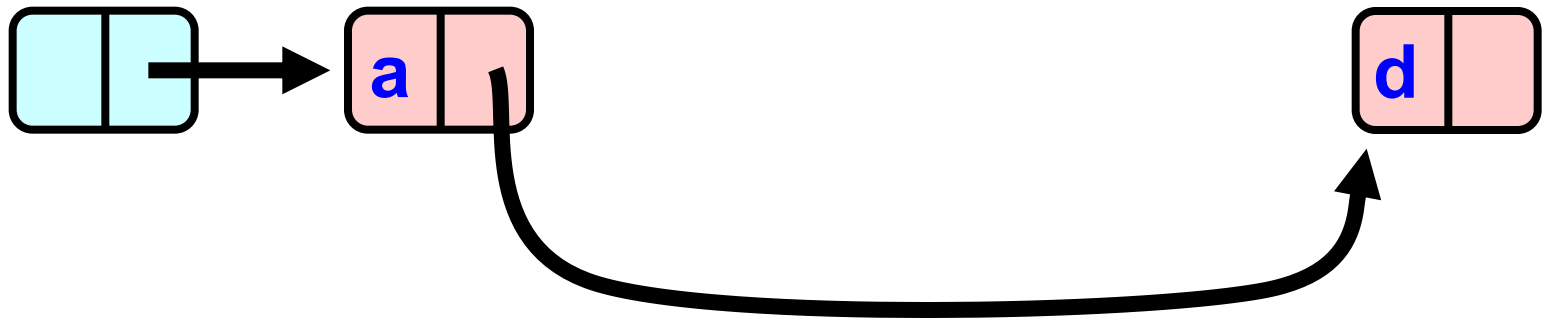

# Adding Nodes

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

# Drawbacks

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

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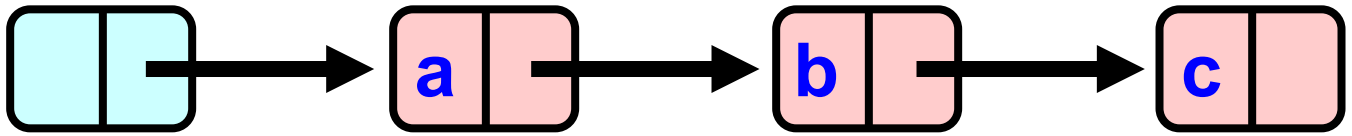


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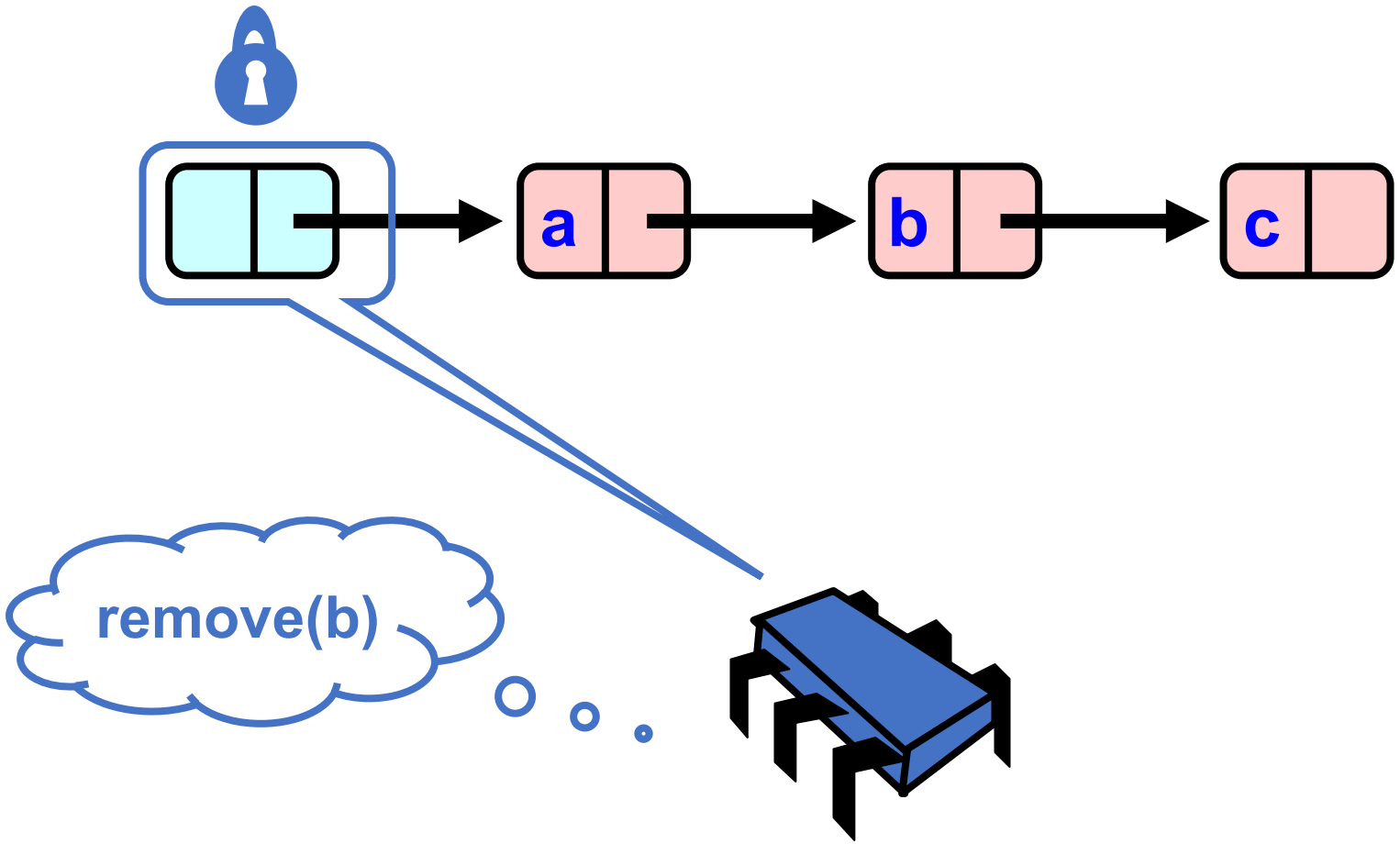

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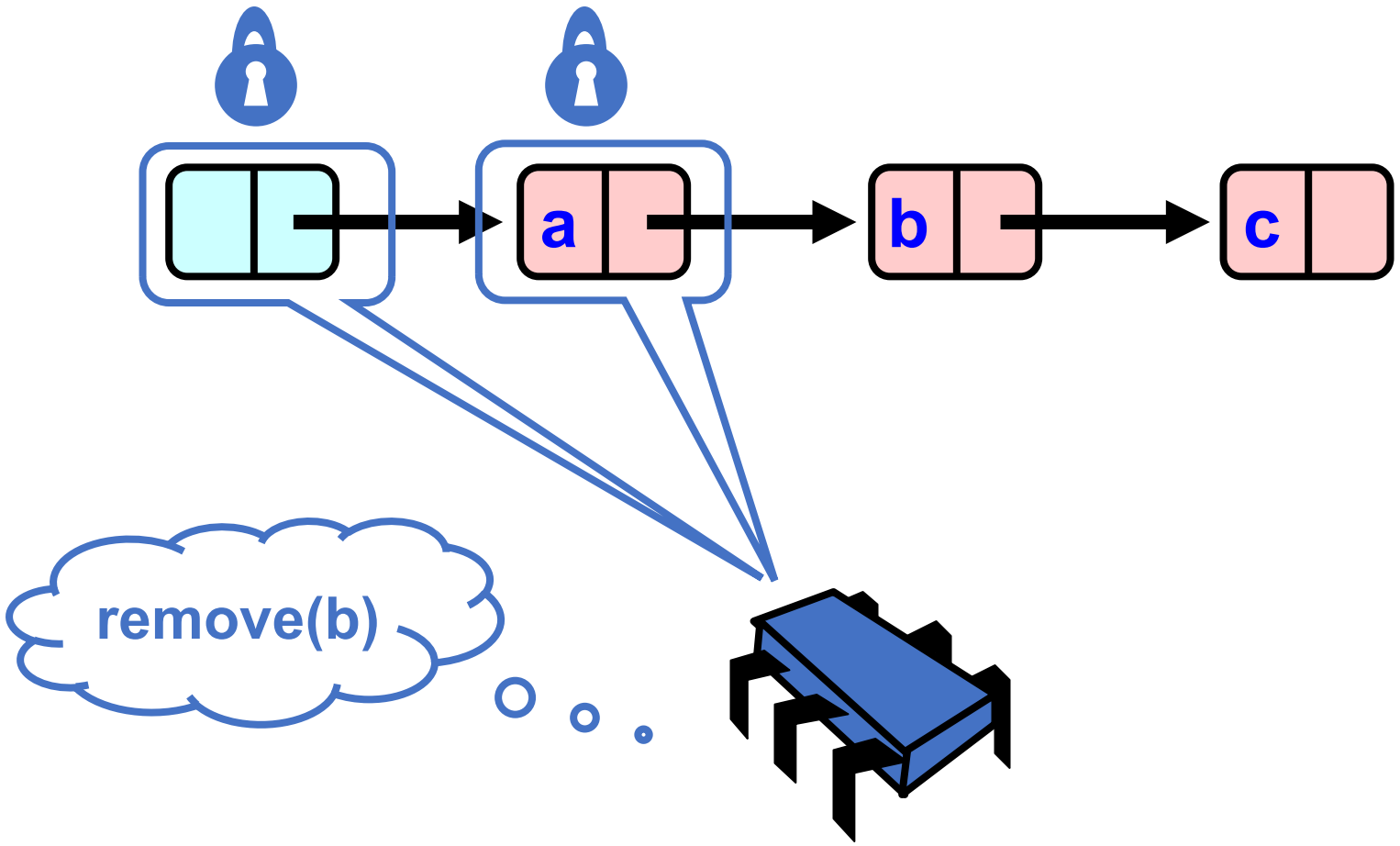

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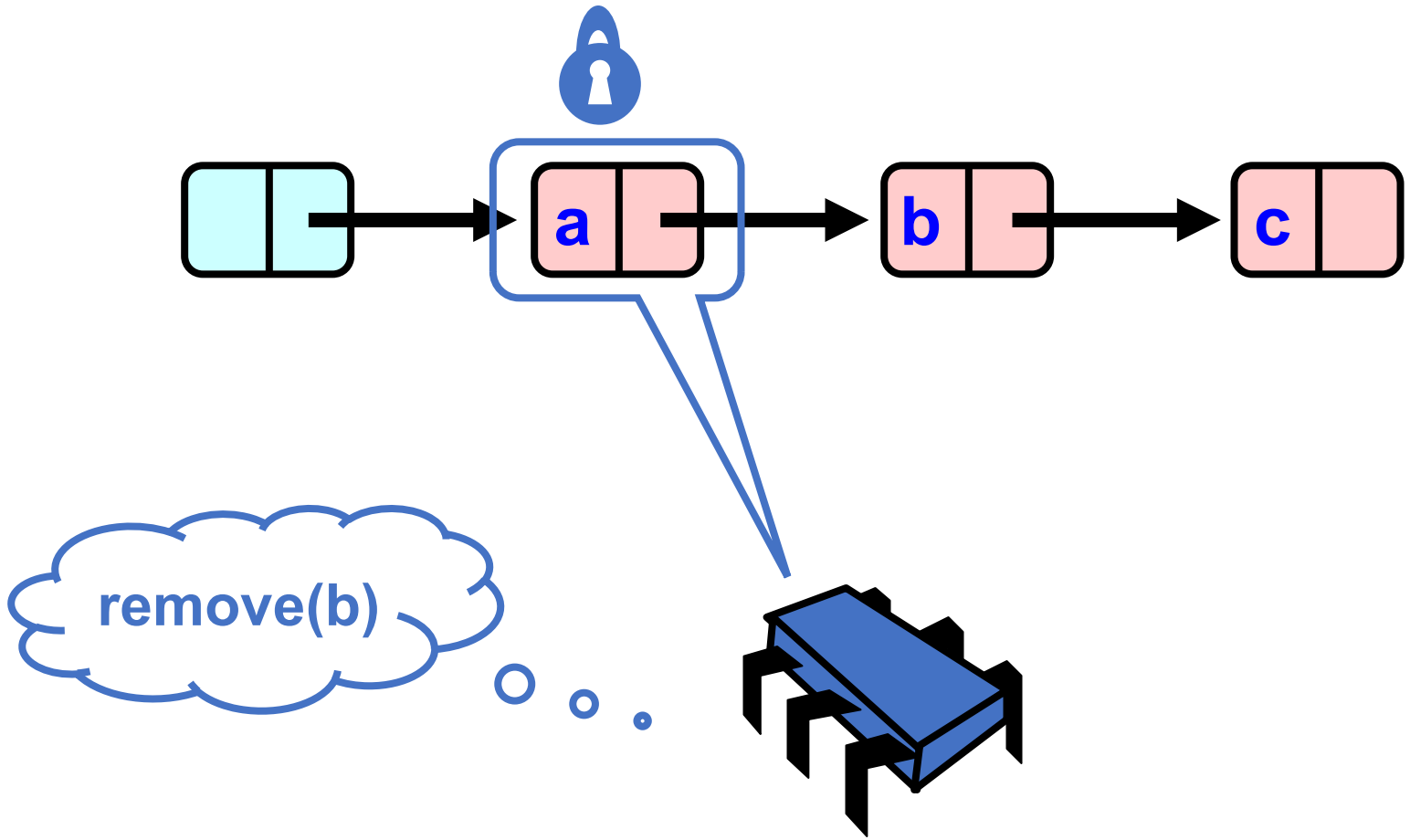

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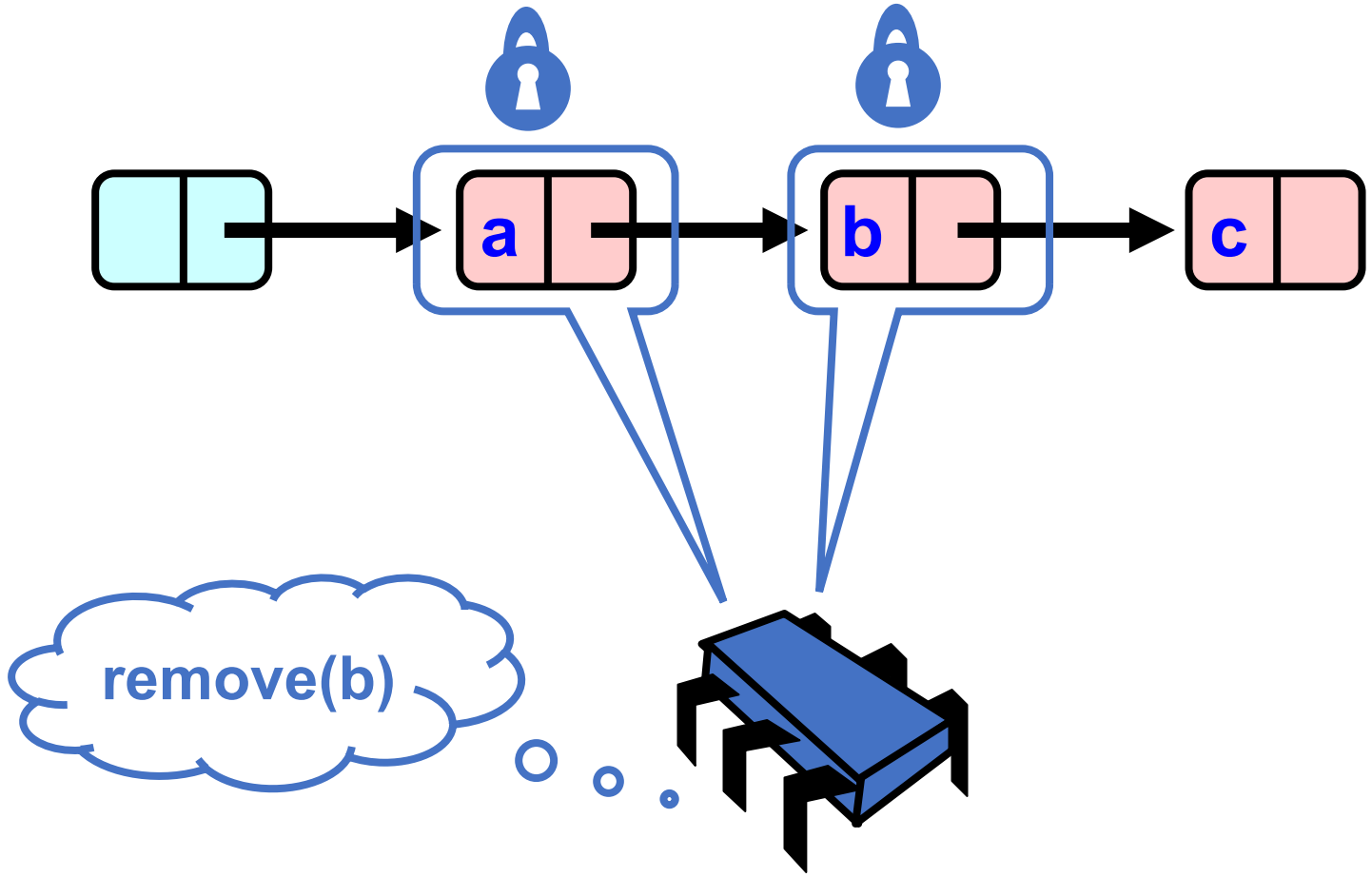

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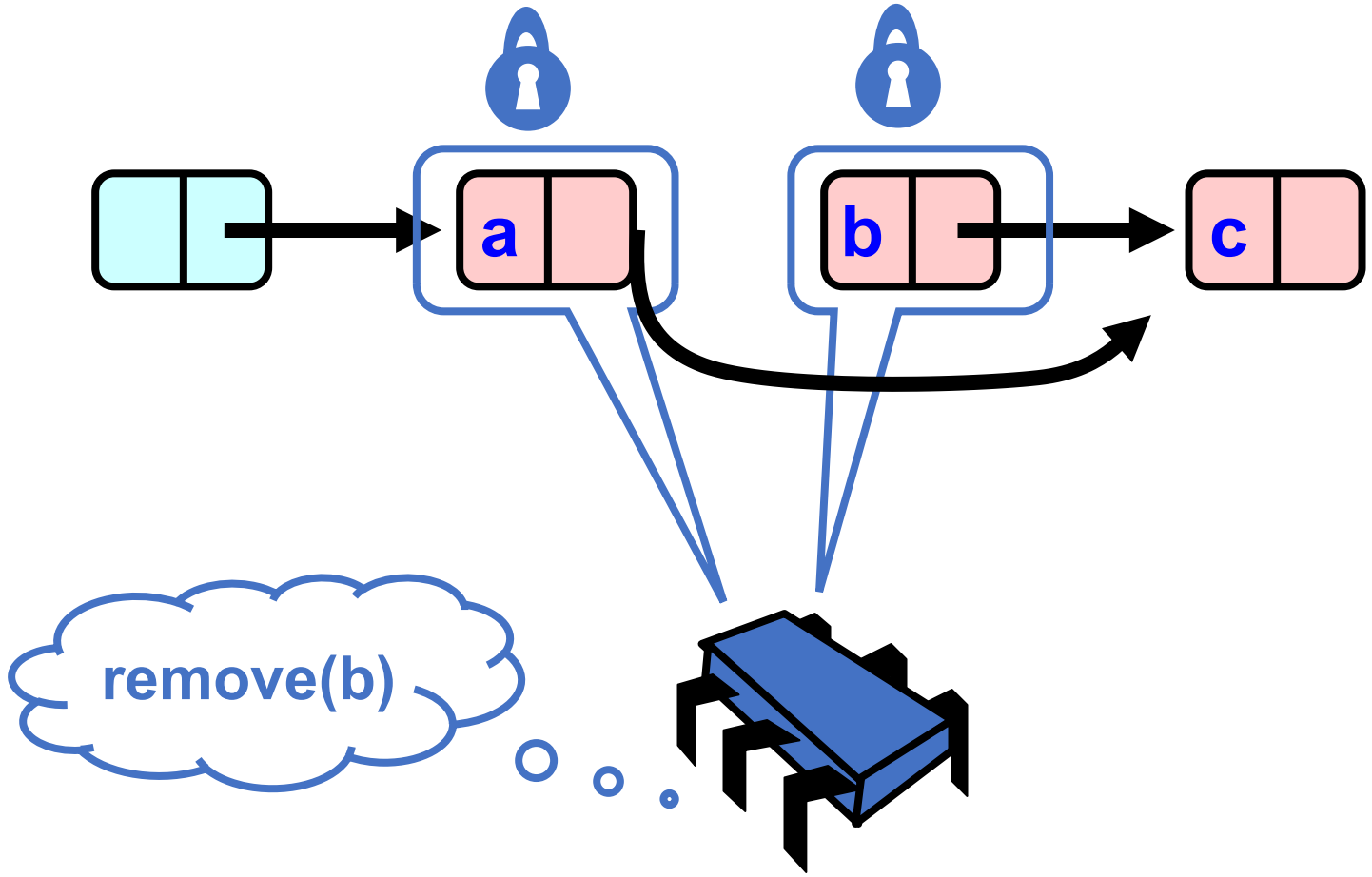

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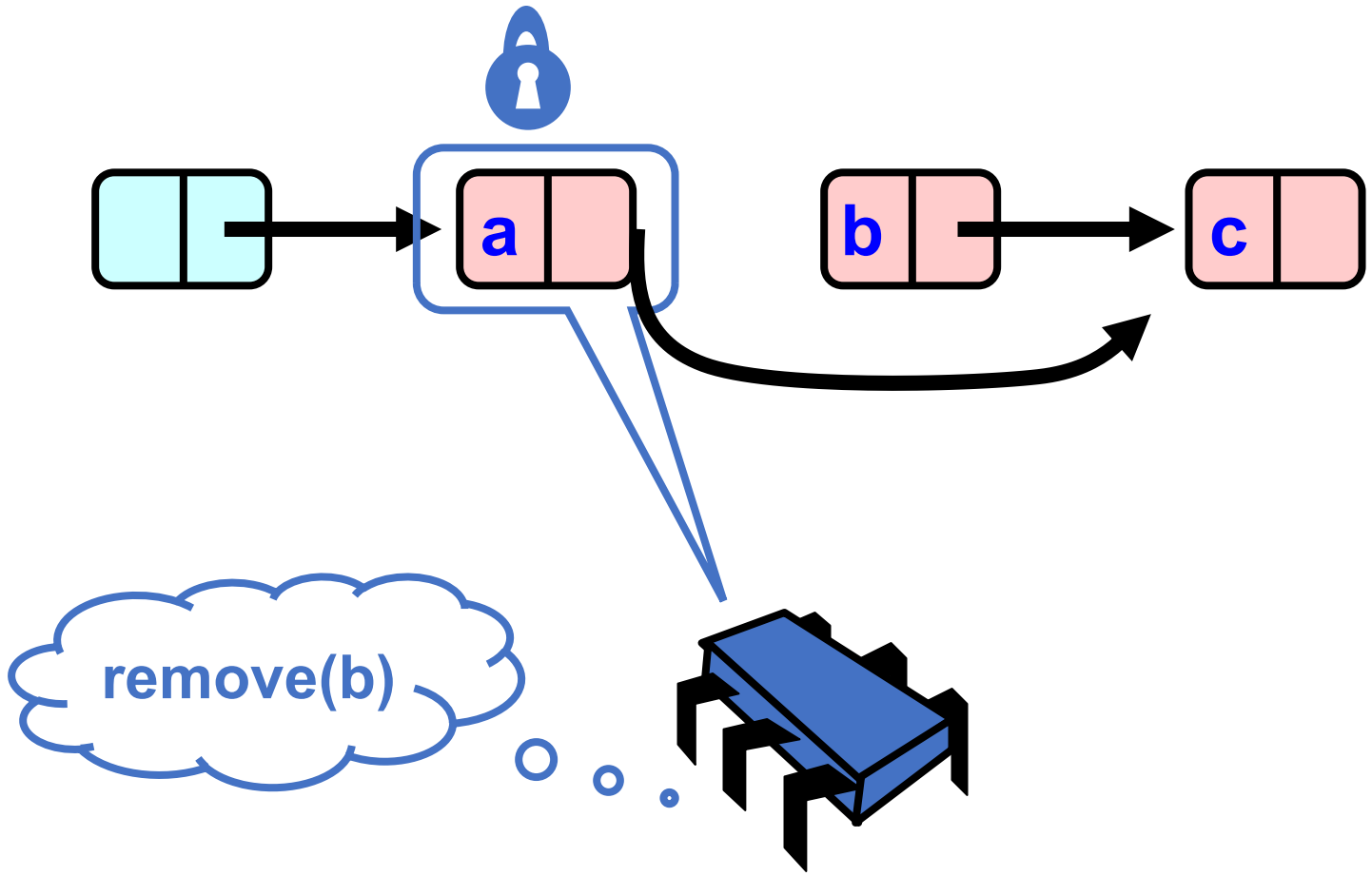

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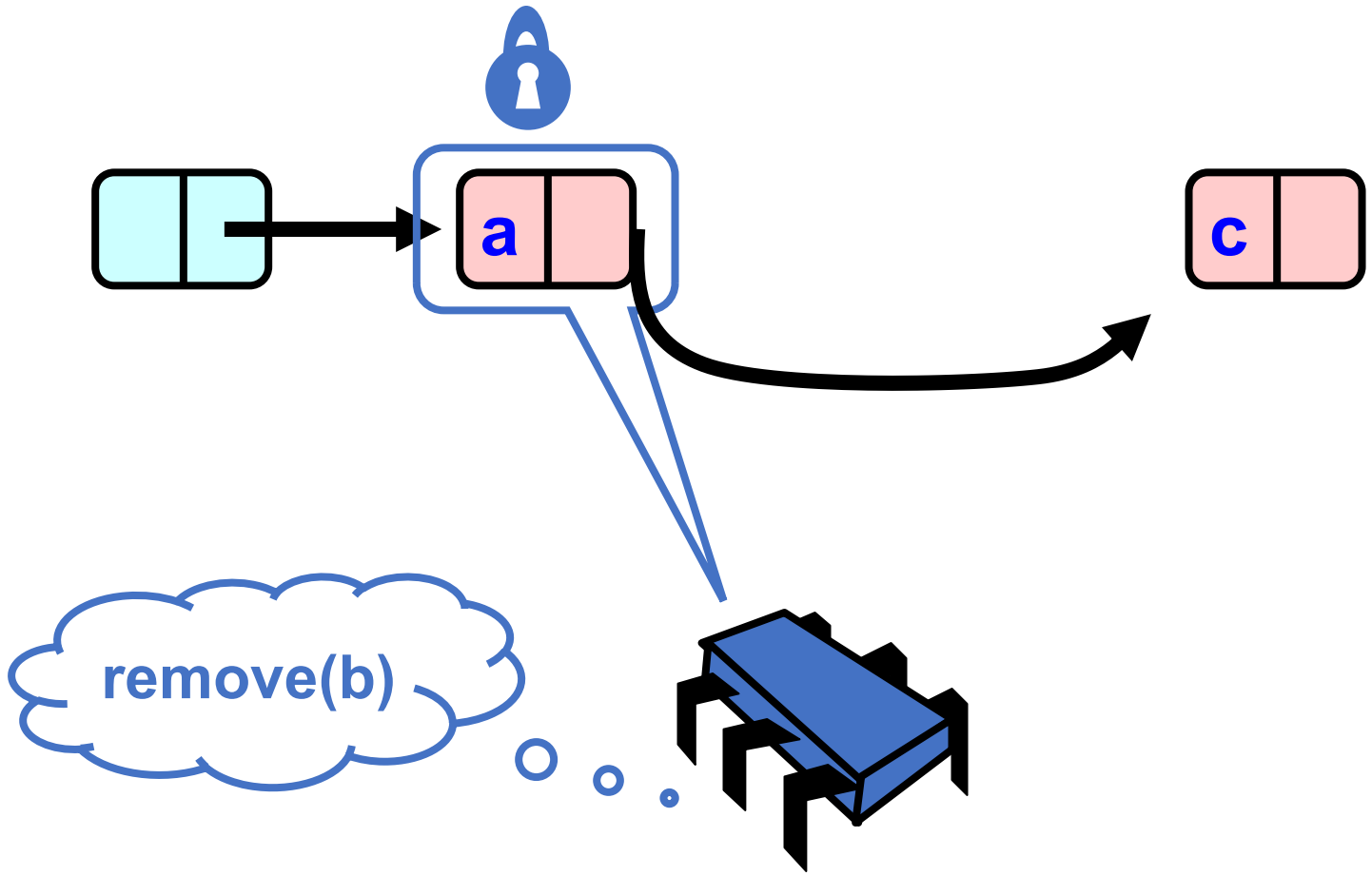

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}
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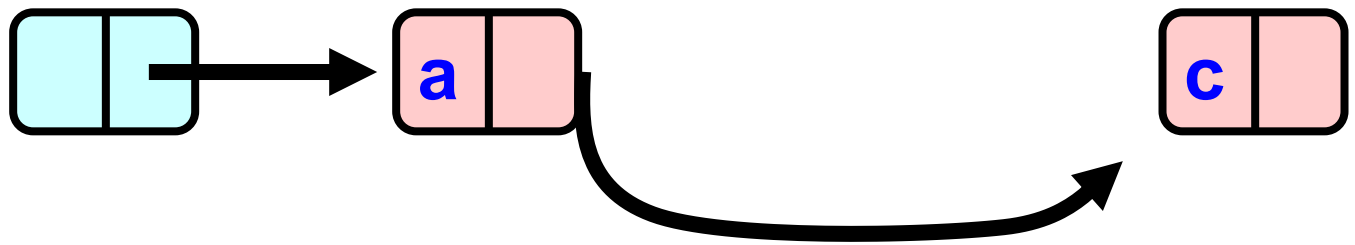
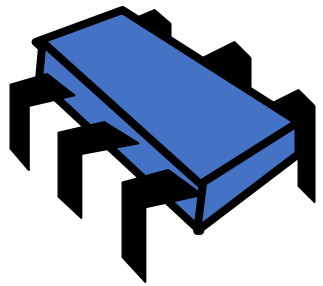


# Schedule

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

# How can we improve

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

# Optimistic Synchronization

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

# Optimistic Synchronization

- Find nodes without locking

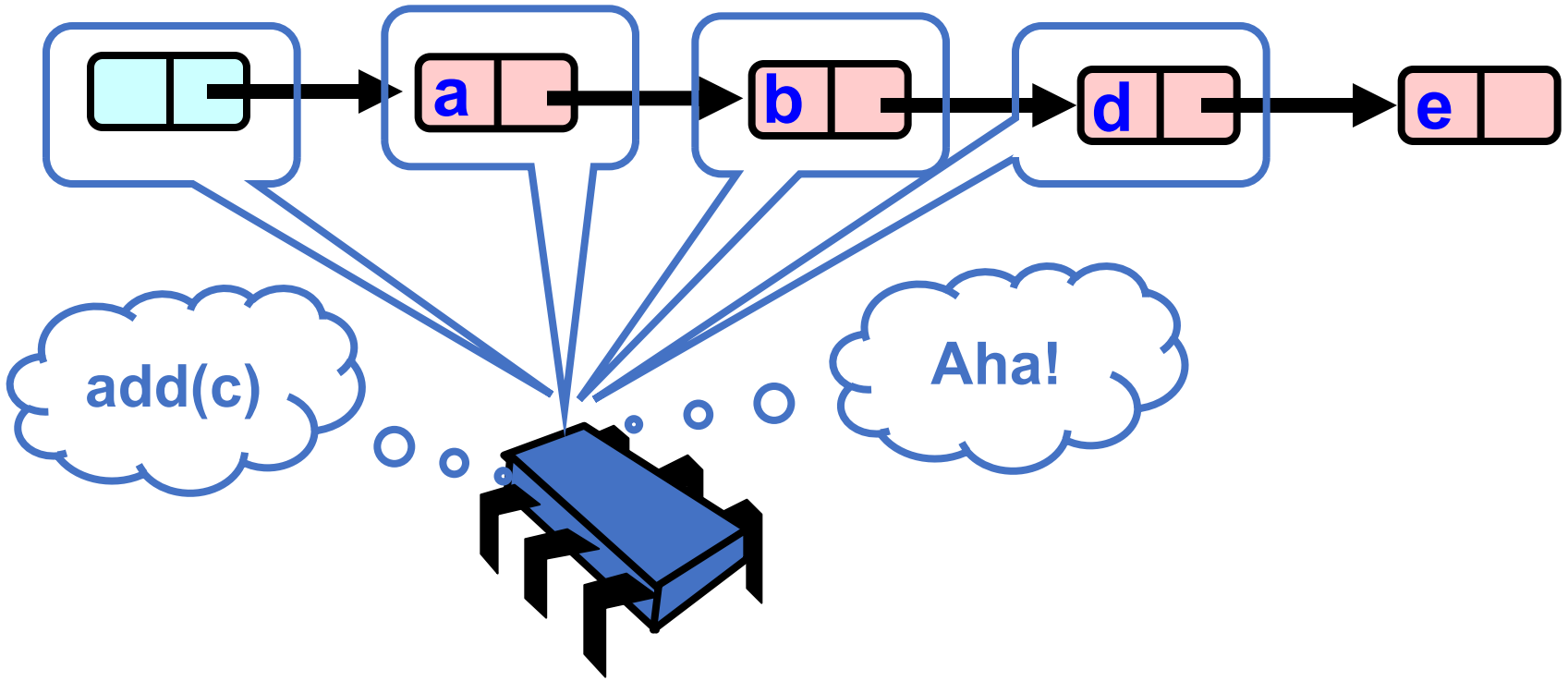
# Optimistic Synchronization

- Find nodes without locking
- Lock nodes

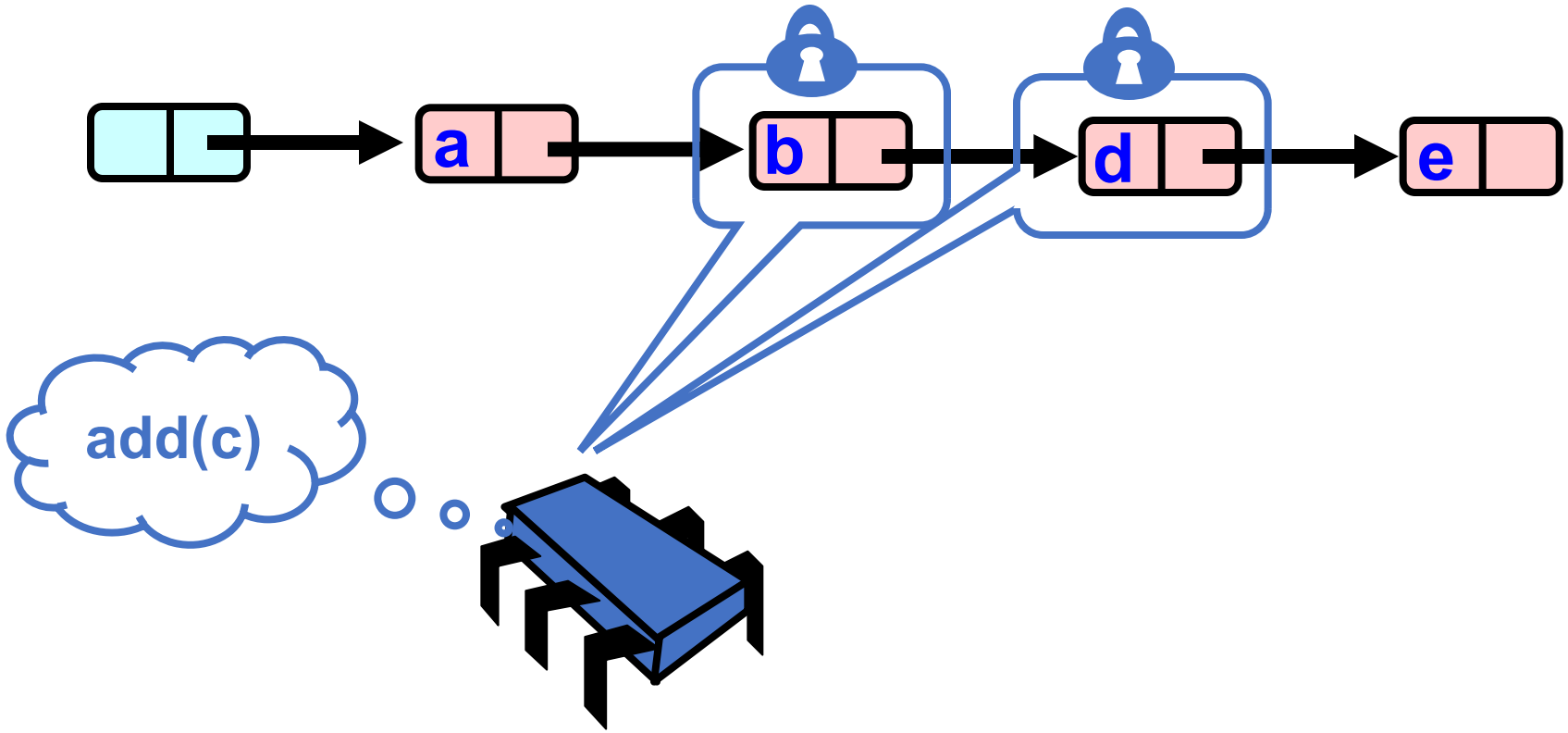
# Optimistic Synchronization

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

# Optimistic: Traverse without Locking



# Optimistic: Lock and Load



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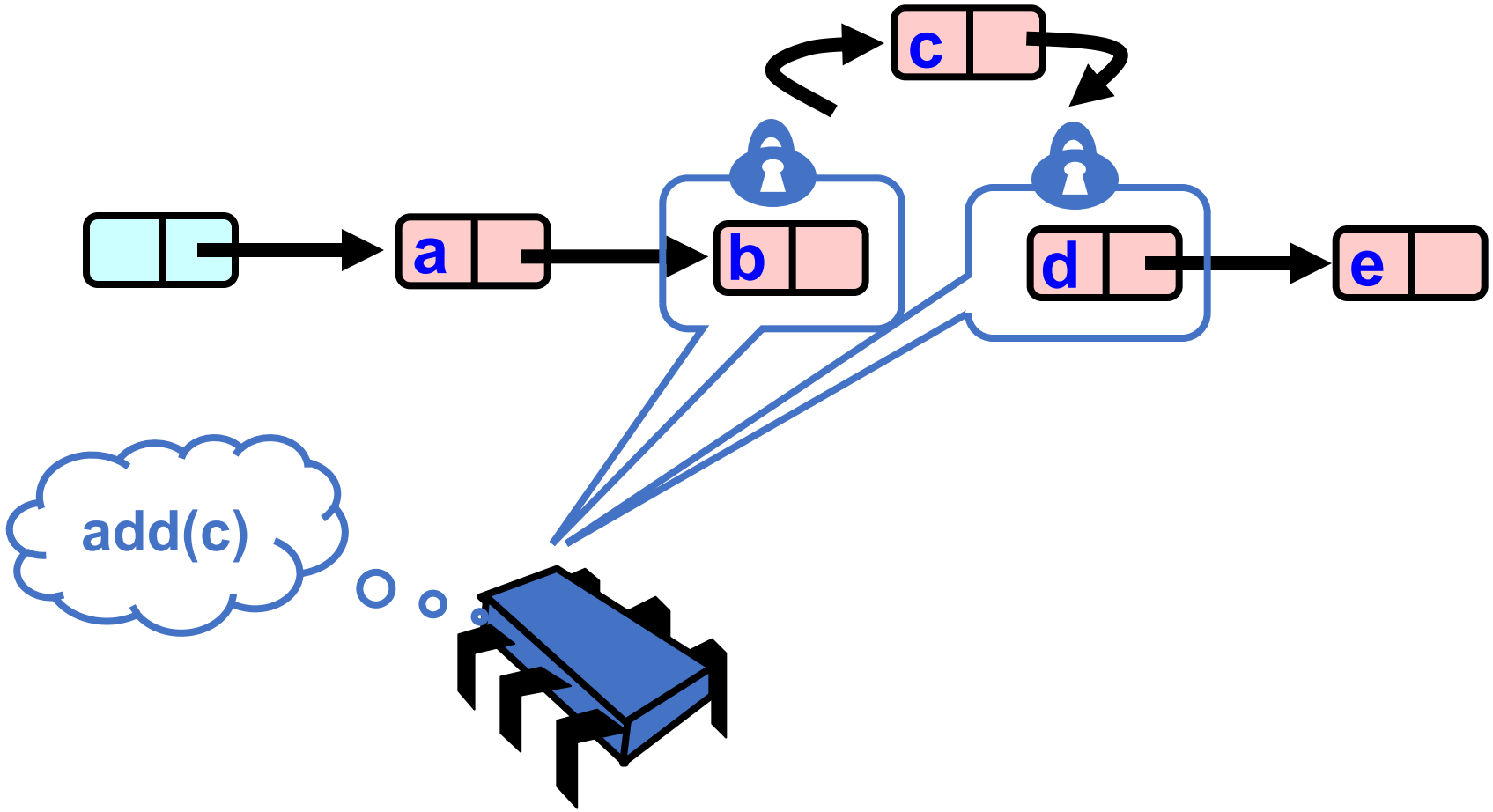
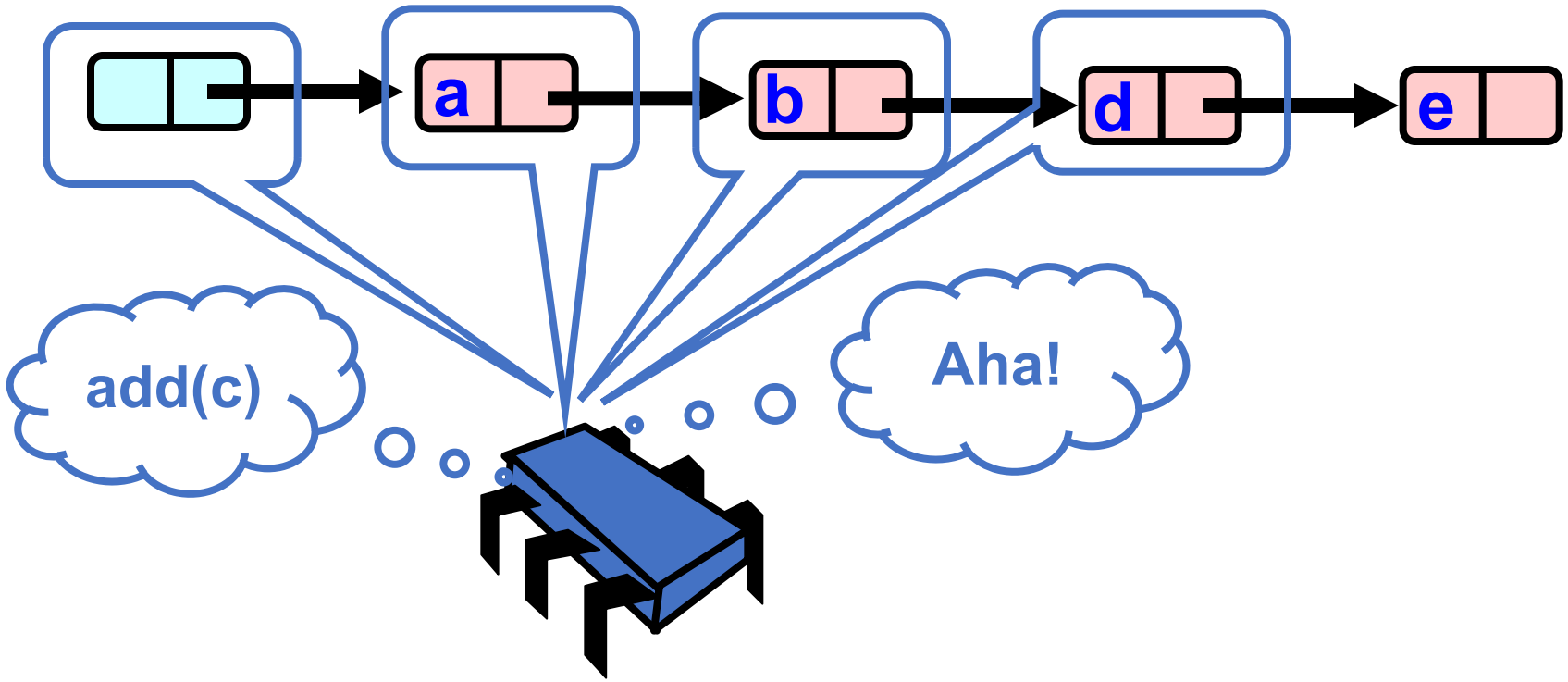


# What could go wrong?



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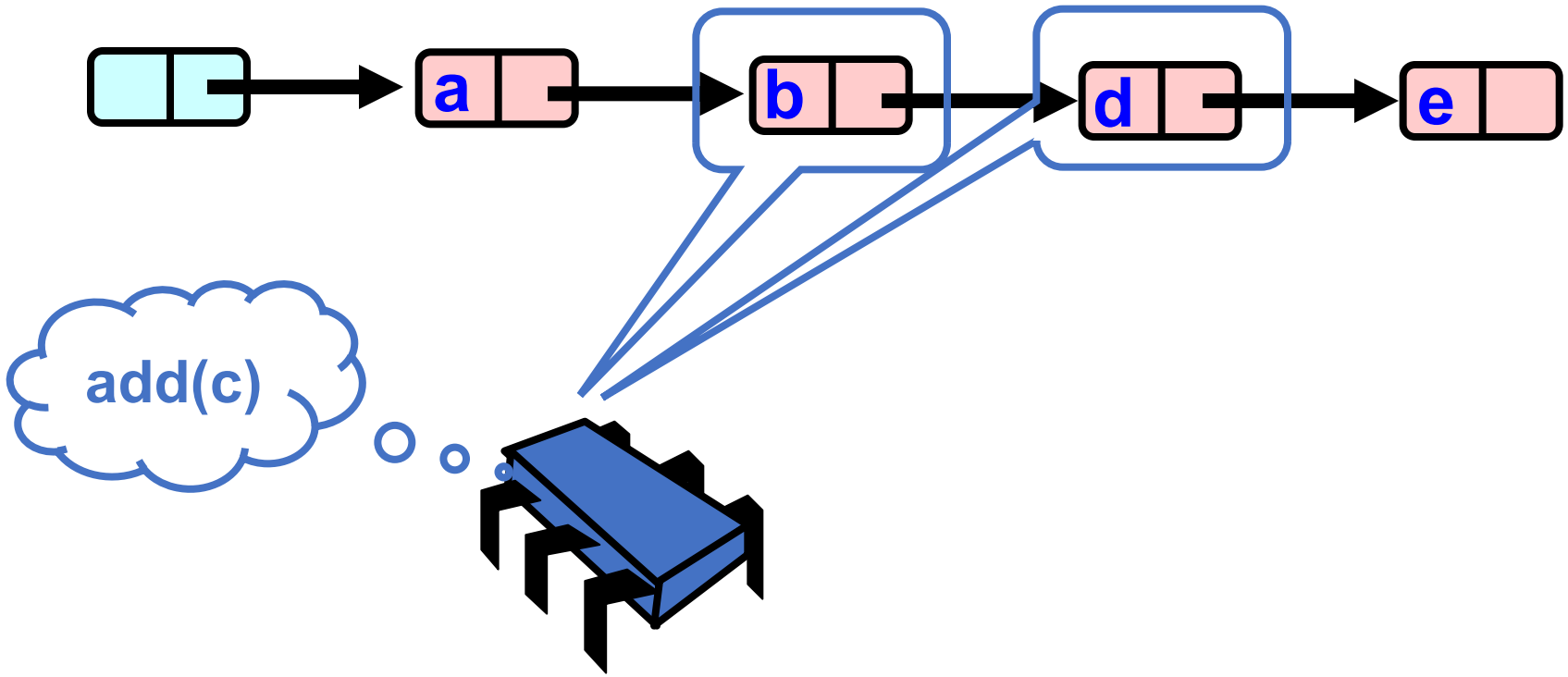

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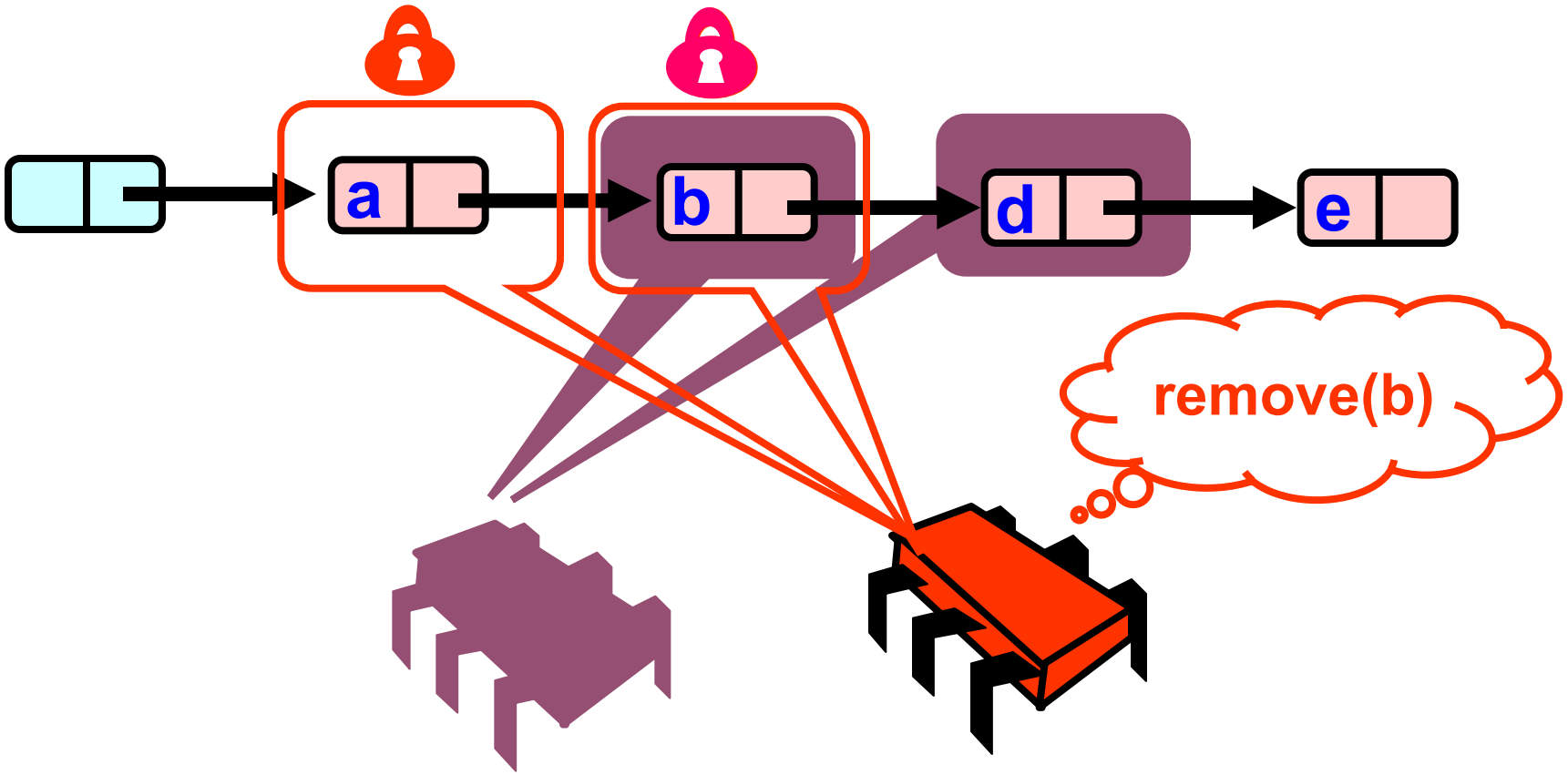


# Data conflict!

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

- What do we do?

# Data conflict!

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

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

# Lock-free reasoning

- We can use atomic variables

# Lock-free reasoning

- Default atomic accesses are documented to be sequentially consistent.

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

# Lock-free reasoning

- Default atomic accesses are documented to be sequentially consistent.

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

Create an atomic pointer type using C++ templates

# Lock-free reasoning

- Default atomic accesses are documented to be sequentially consistent.

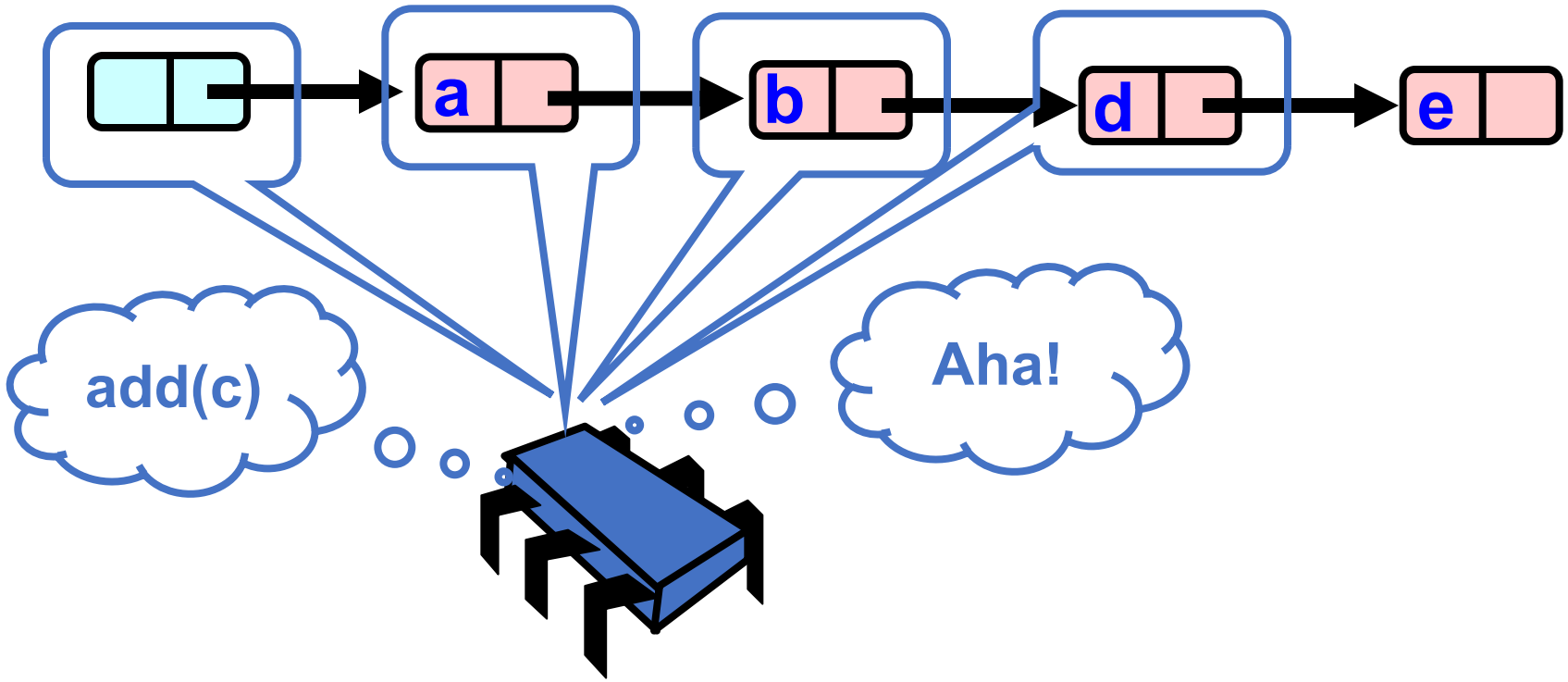
```
void traverse(node *n) {
  while (n->next != NULL) {
    n = n->next;
  }
}
```

# Lock-free reasoning

- Default atomic accesses are documented to be sequentially consistent.

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

# What could go wrong?



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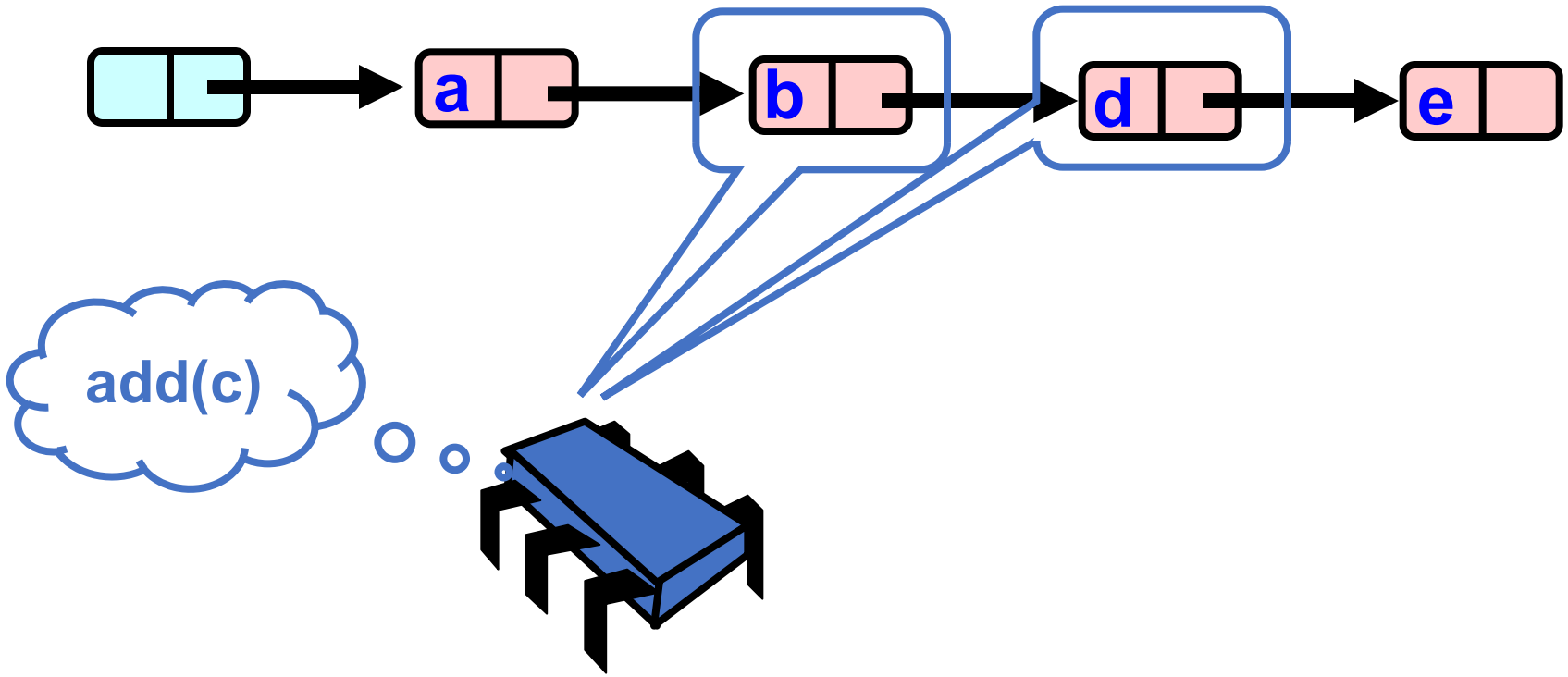

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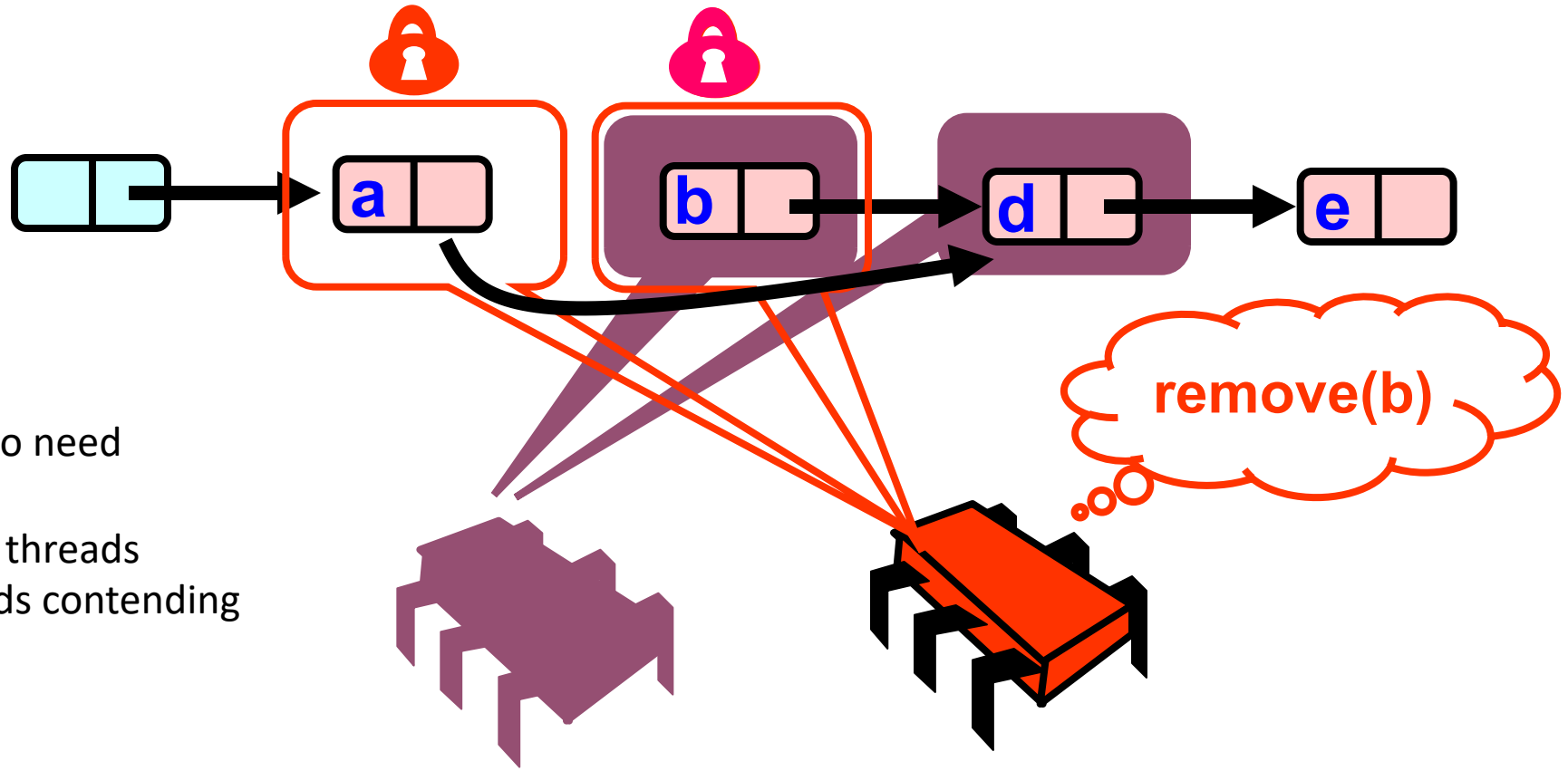
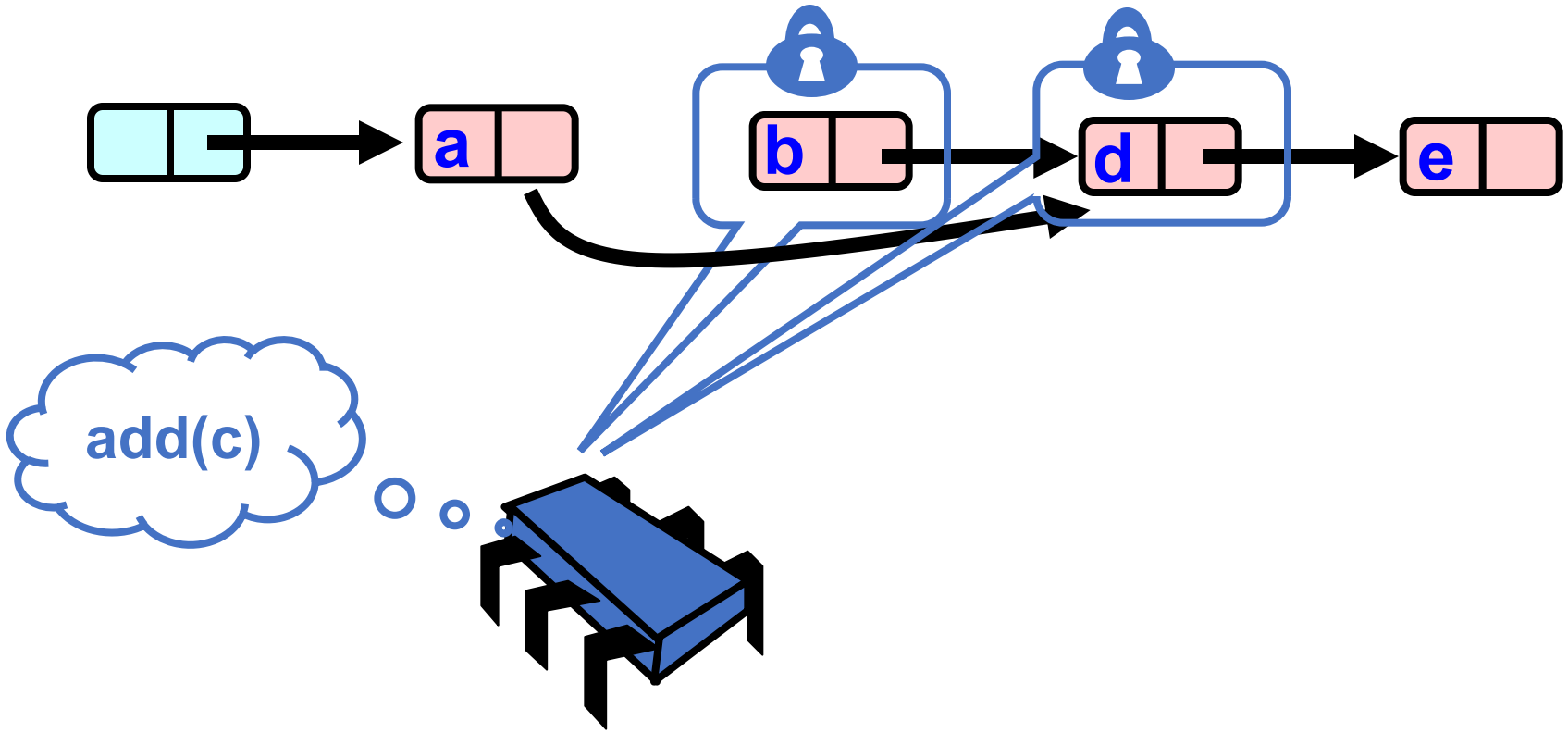



No more data conflict, but we do need to reason about interleavings and threads concurrent threads contending for values.

# What could go wrong?



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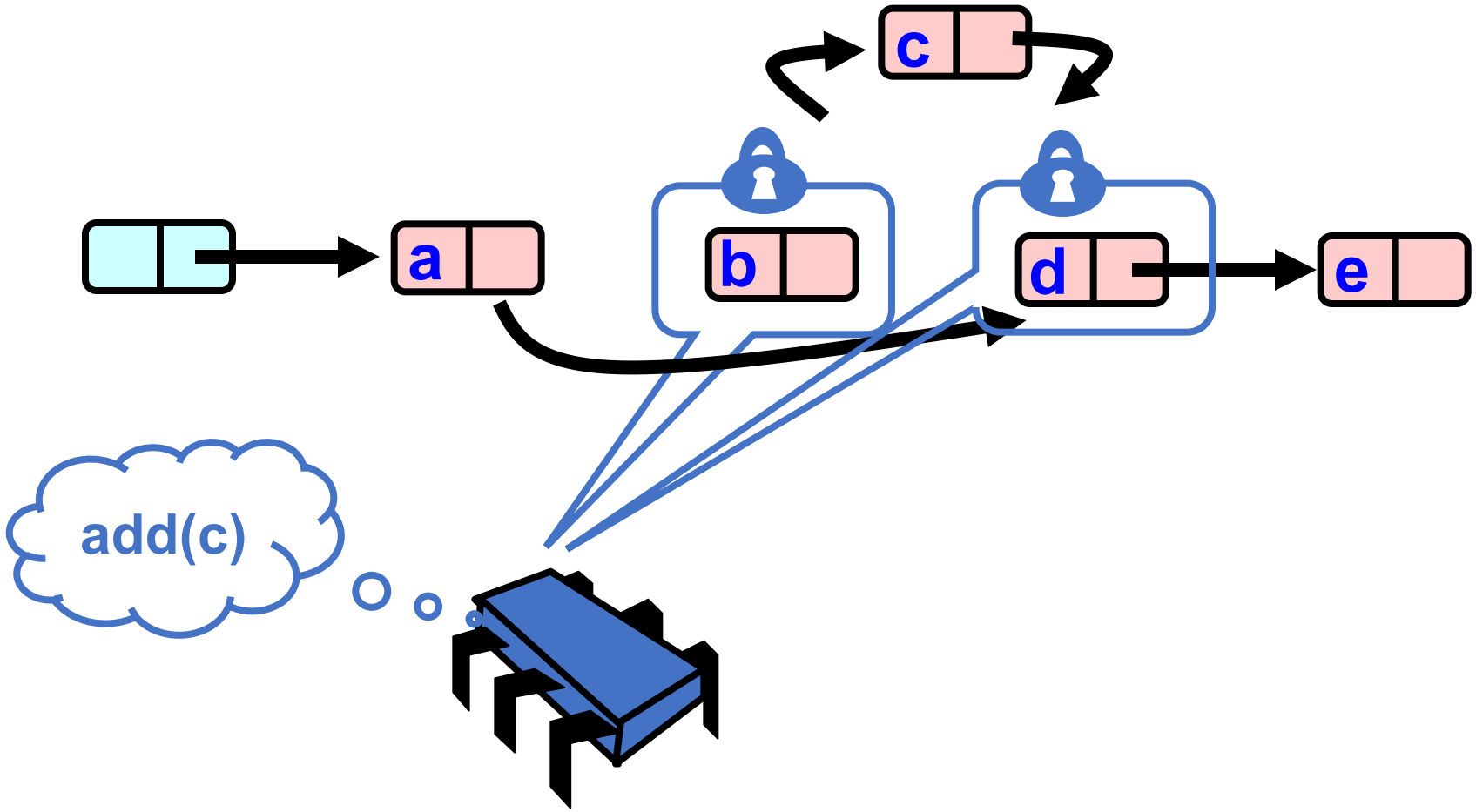

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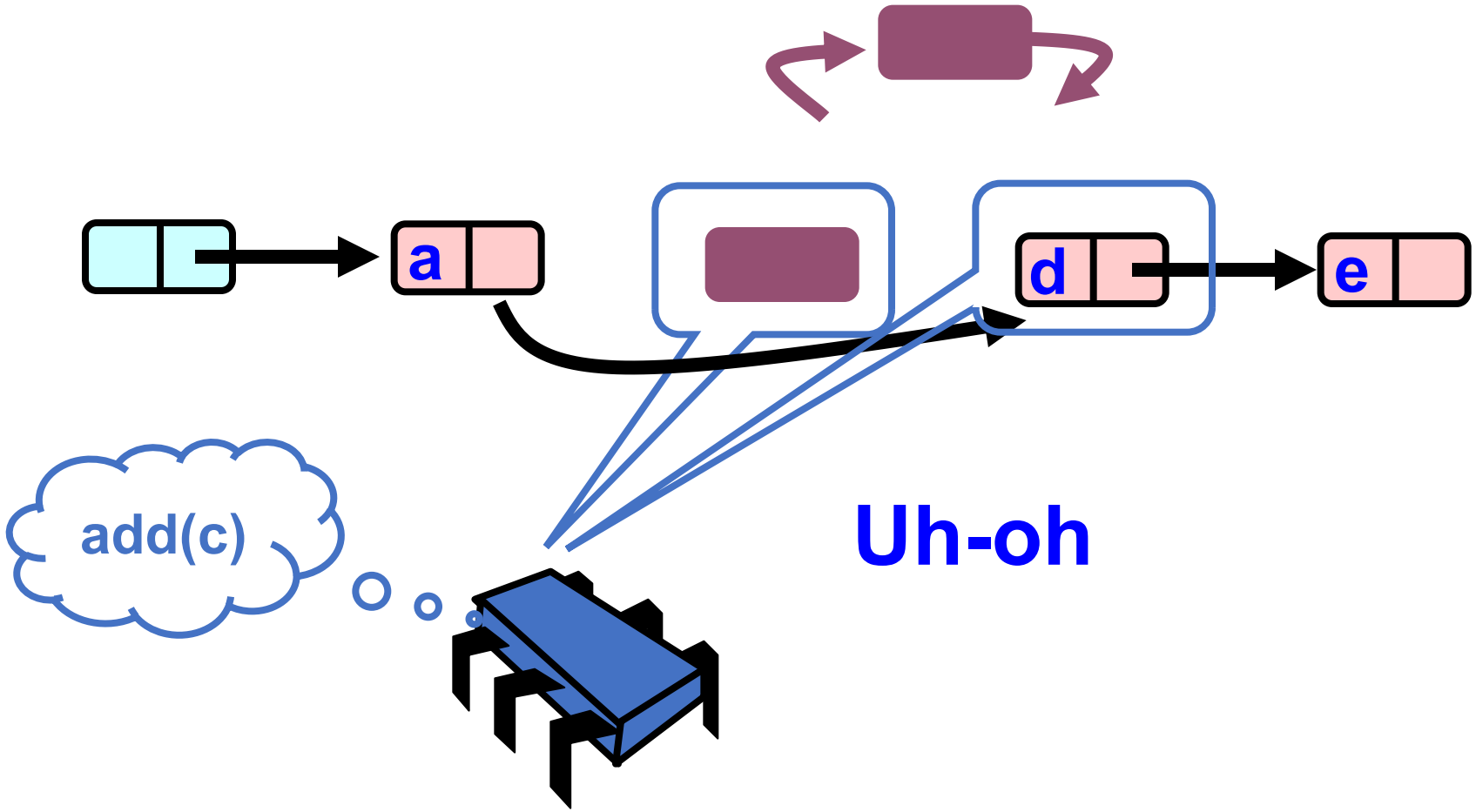
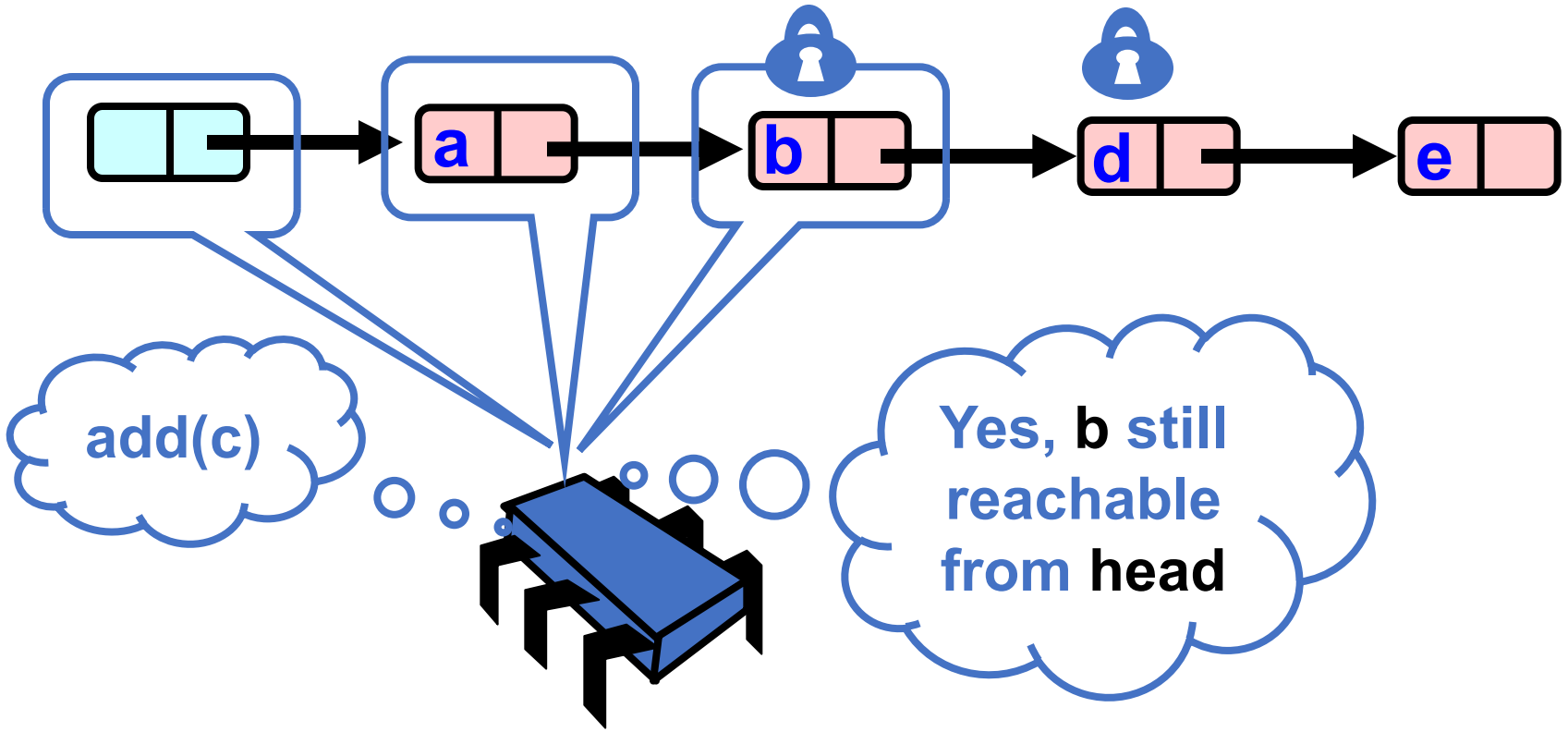


# Validate – Part 1



# What happens if failure?

- Ideas?

# What happens if failure?

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

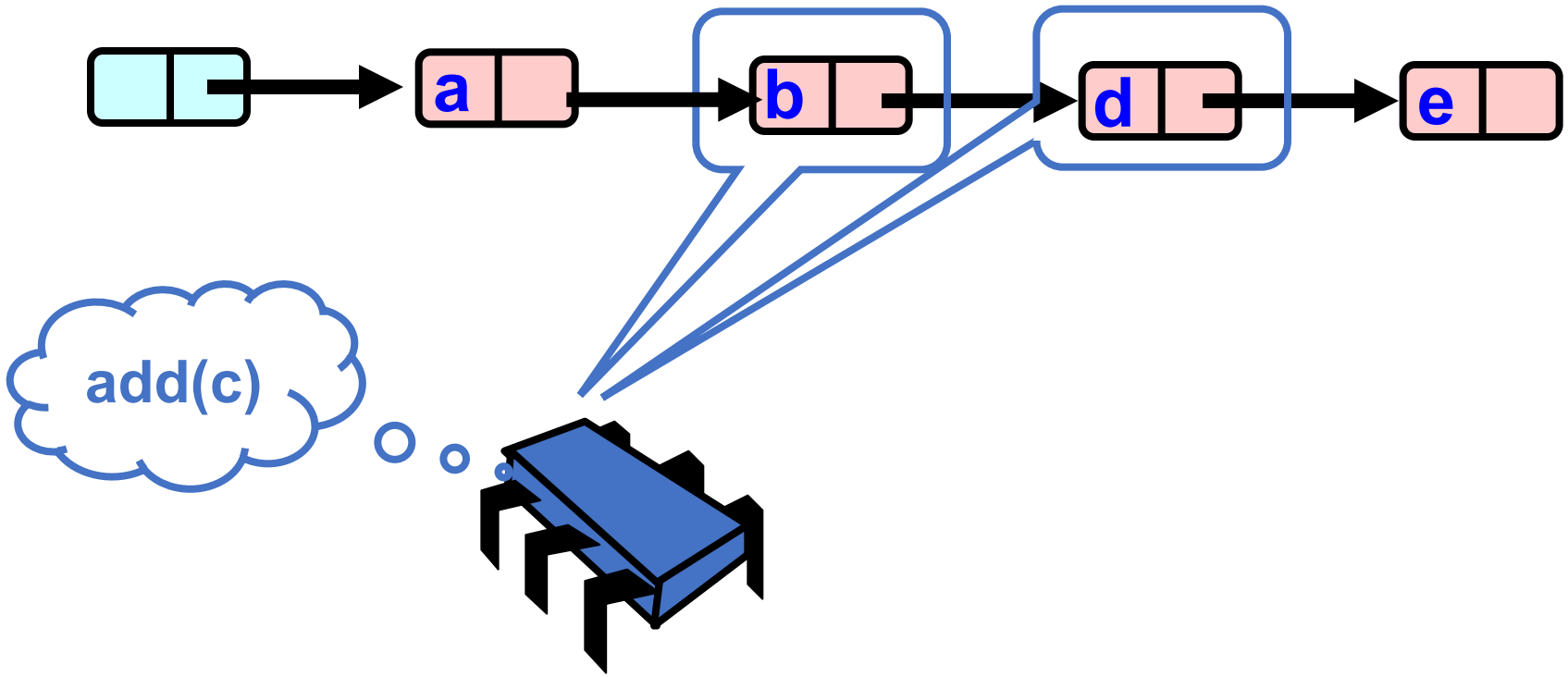
# What happens if failure?

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

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

# What about deletion?

# Can threads that remove a node delete it?



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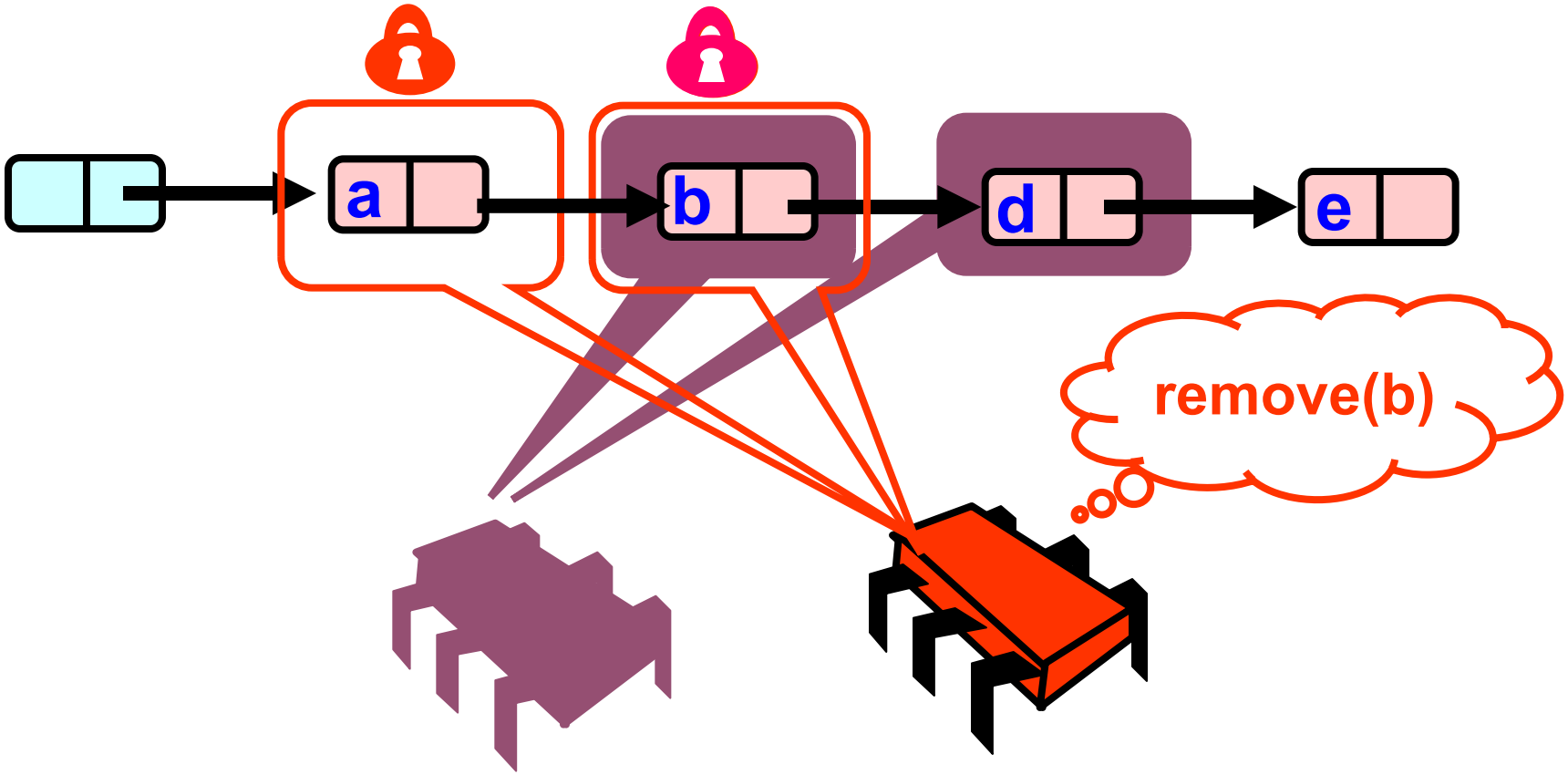

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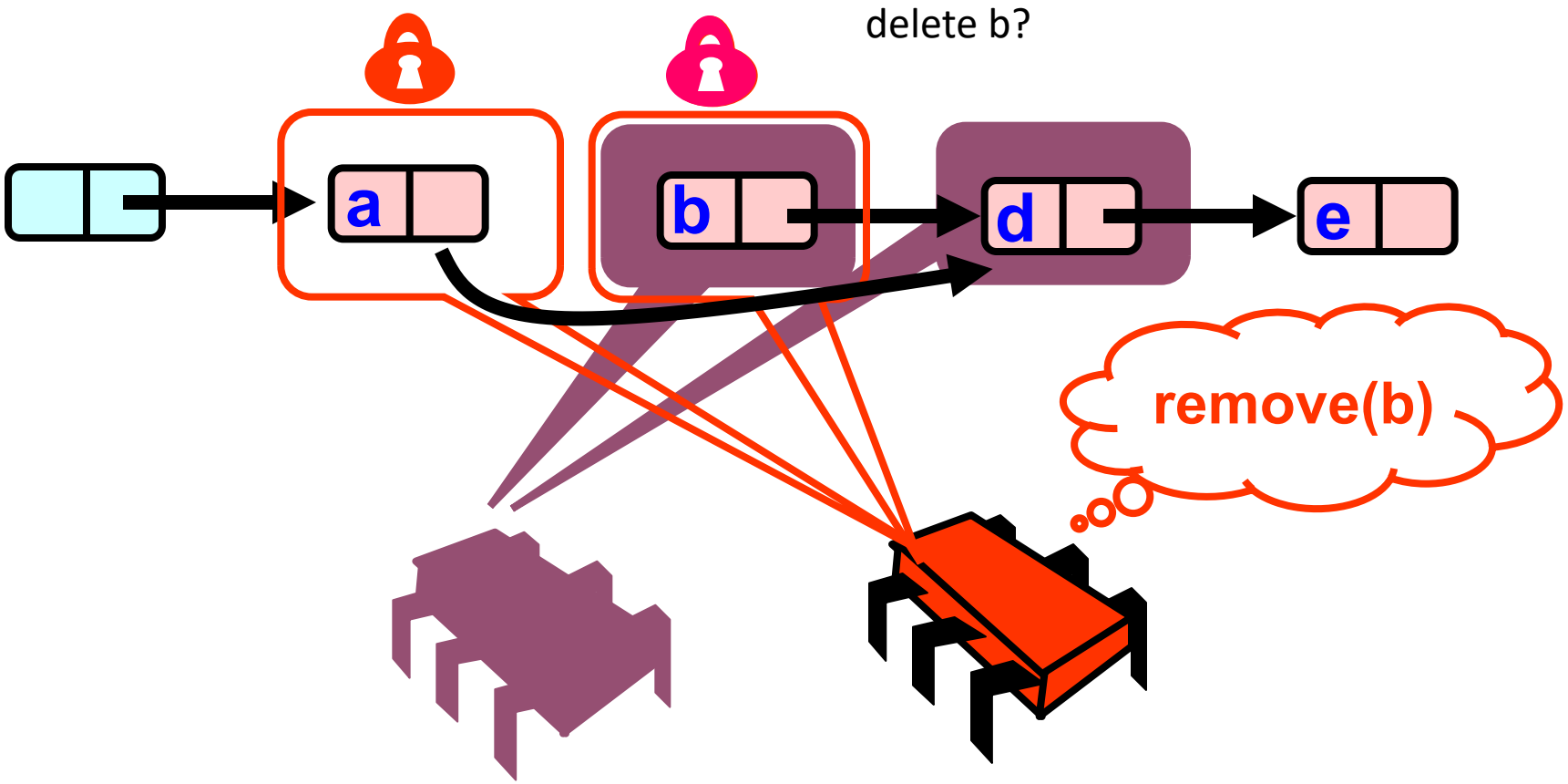

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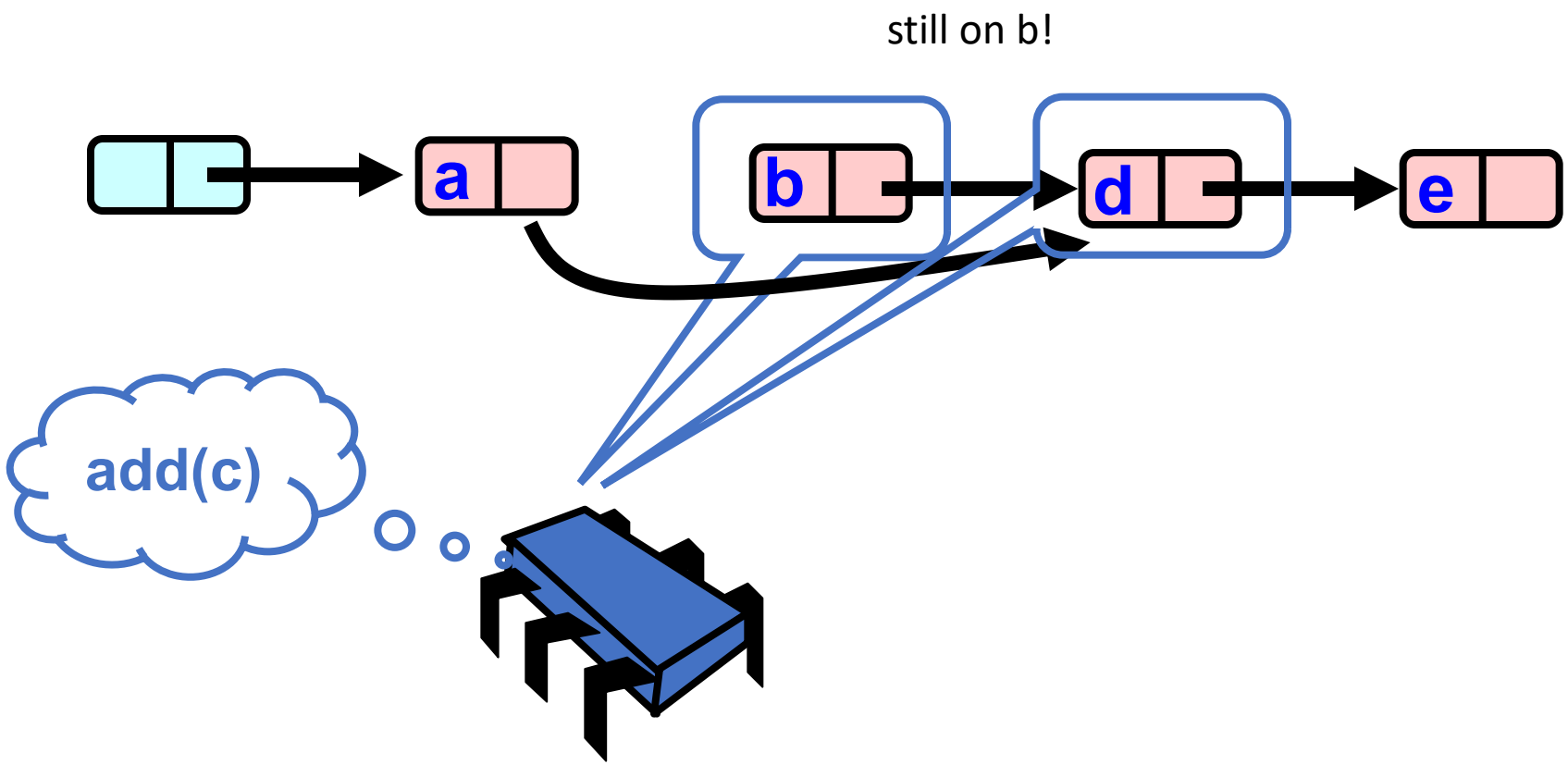
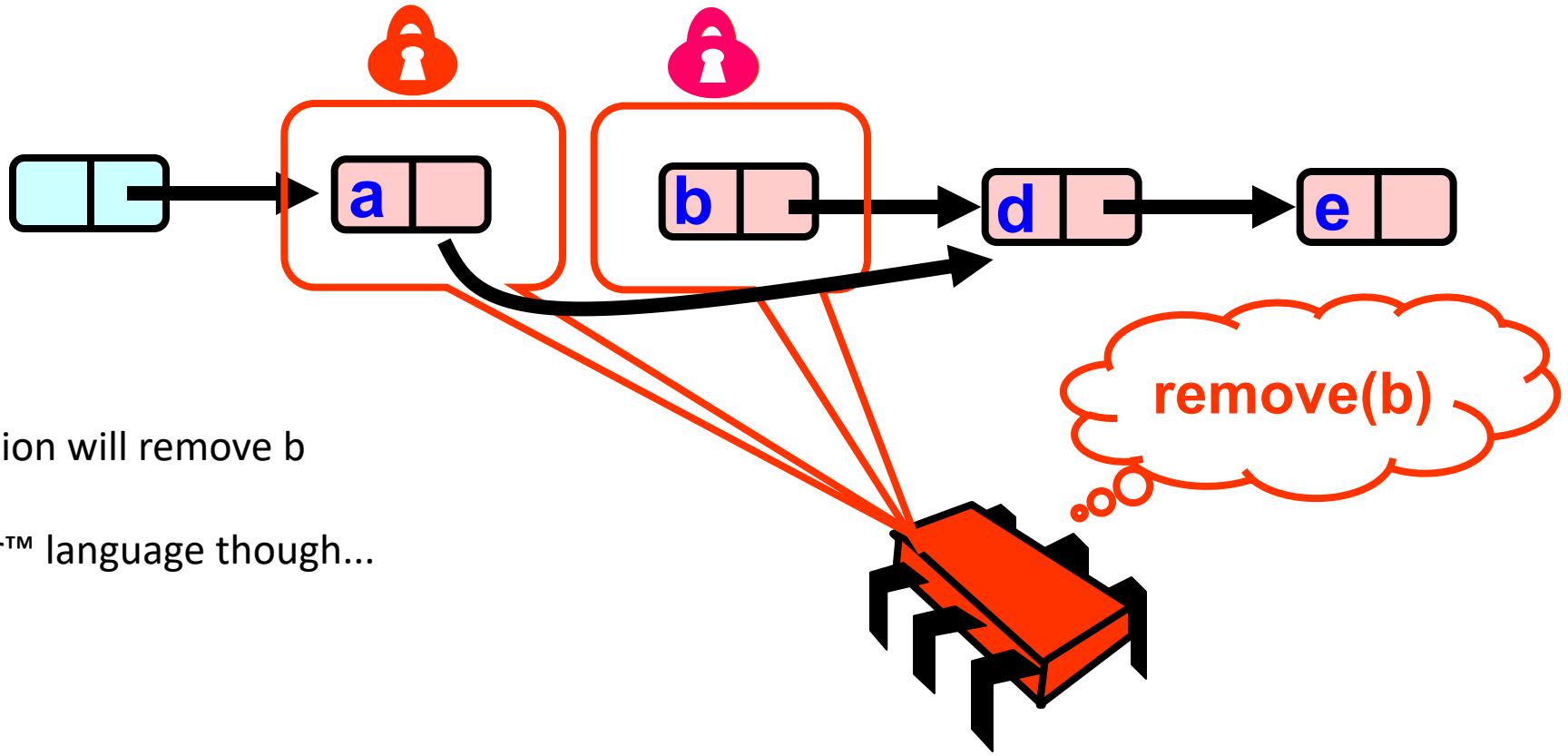


# Our own garbage collector




Java's garbage collection will remove b

We are using a better™ language though...

maintain a list to delete:

# Our own garbage collector


Java’s garbage collection will remove b

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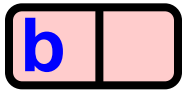

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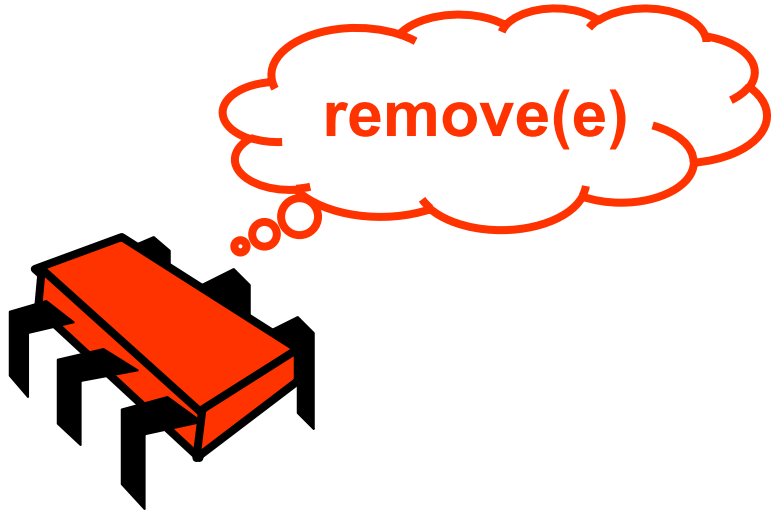


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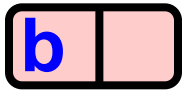

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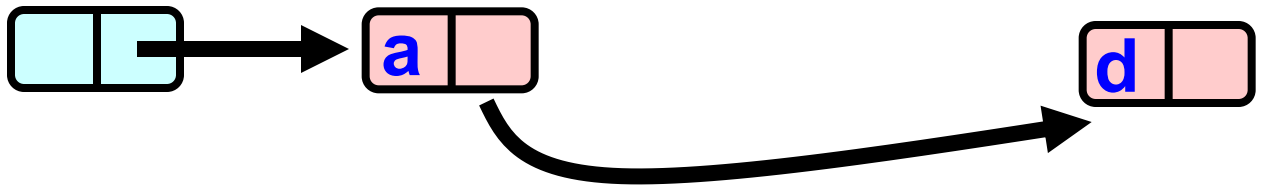


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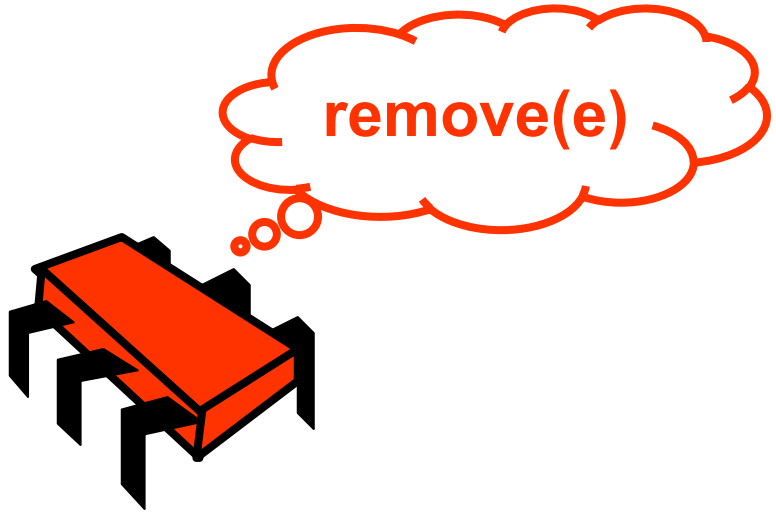


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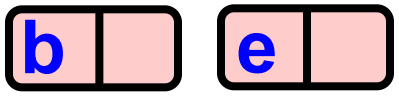
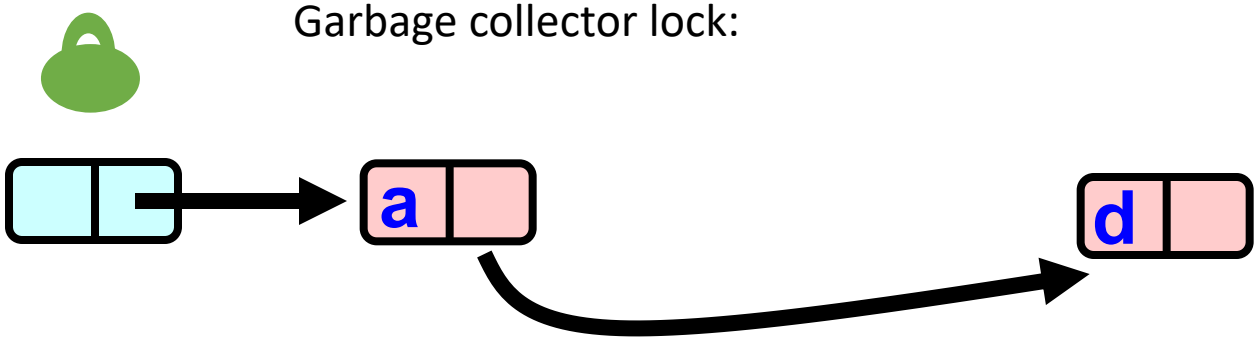
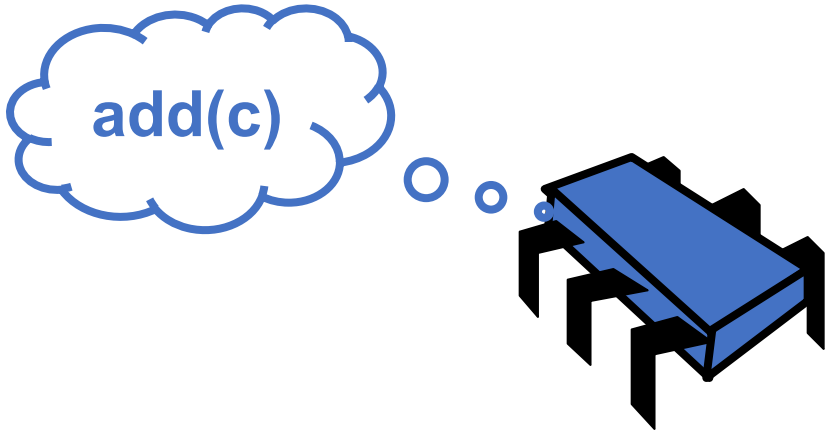


# Our own garbage collector

Garbage collector lock:

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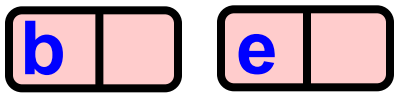
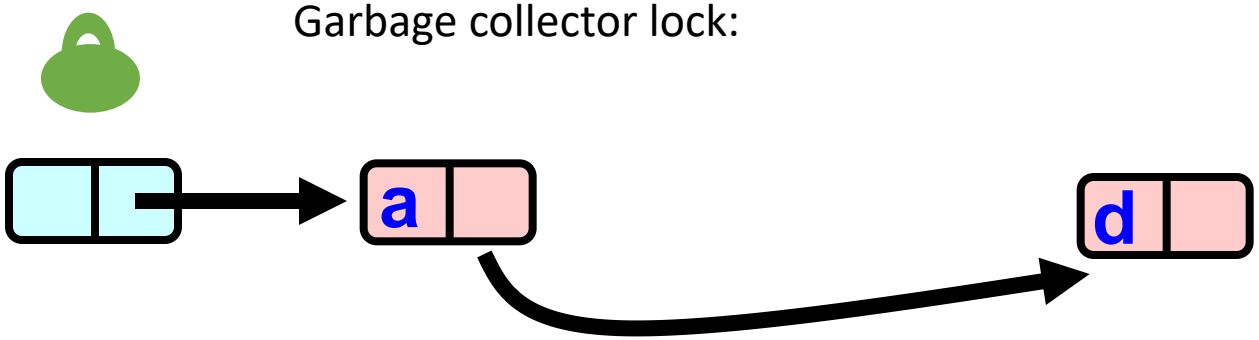
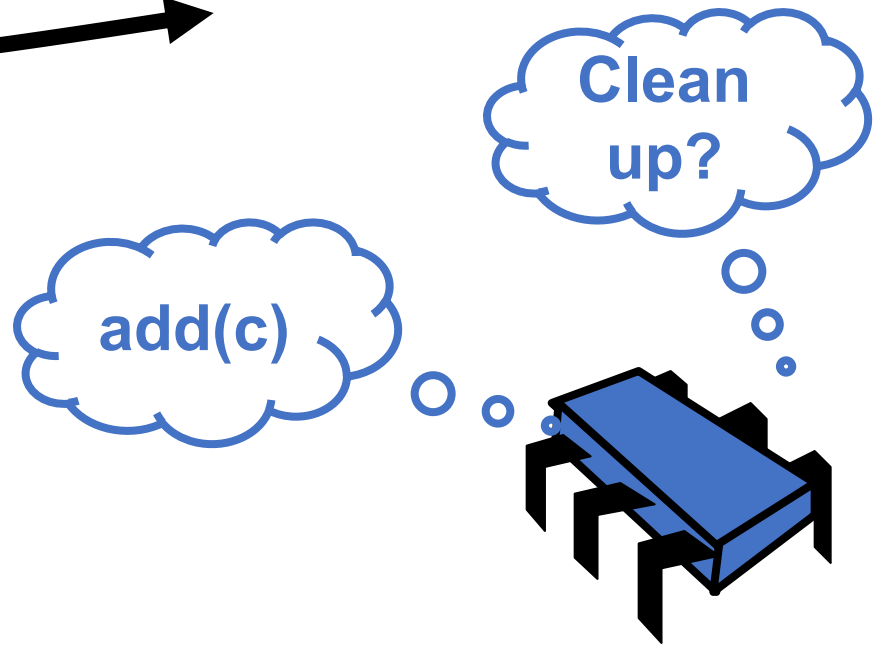


# Our own garbage collector

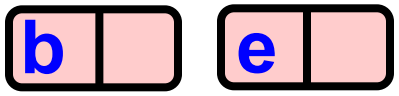
Garbage collector lock:




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

maintain a list to delete:



# Garbage collector lock

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

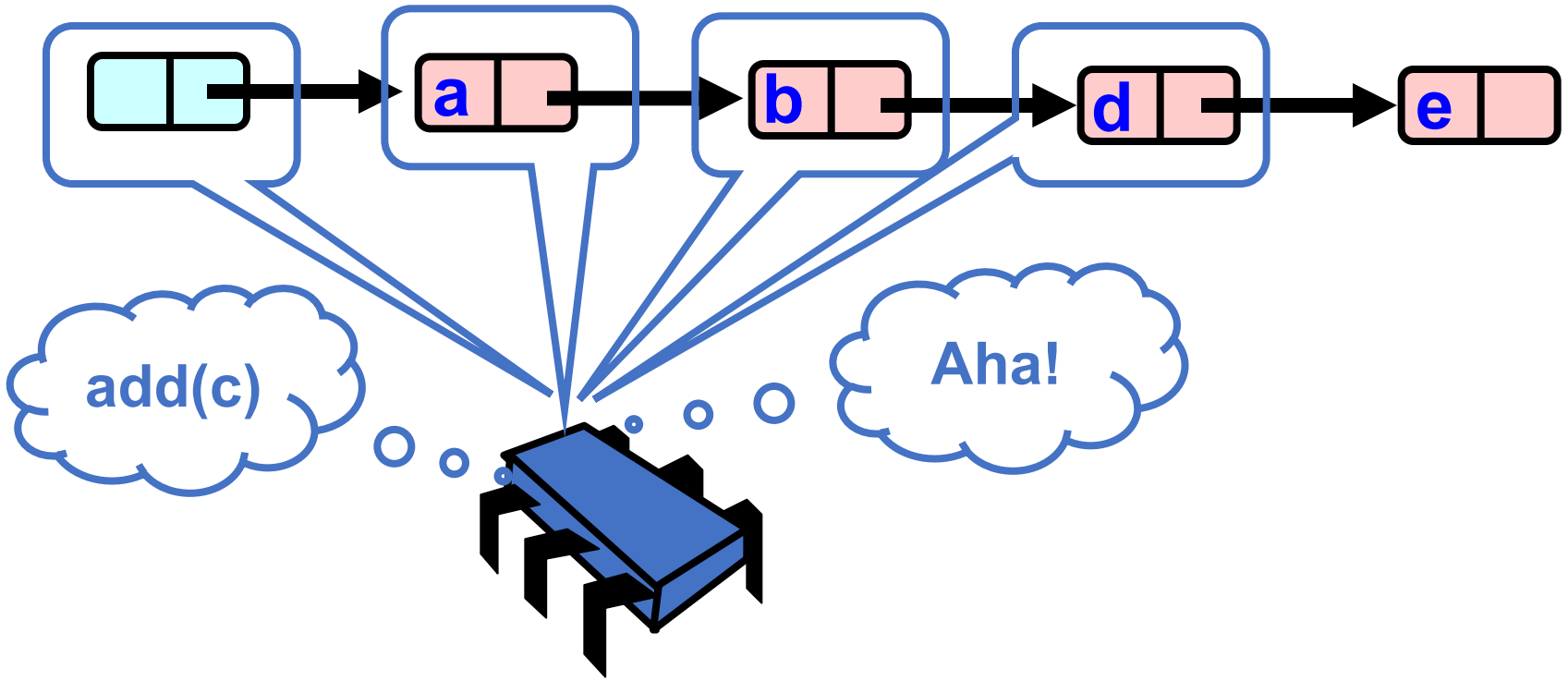
- **Strat 1:** Threads always try once to take the garbage collector lock:
  - if failed, no worries, the next operation will get a chance
  - if succeeded, then there was no contention
  - can starve garbage collection

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

# Back to the linked list

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

# What Else Could Go Wrong?



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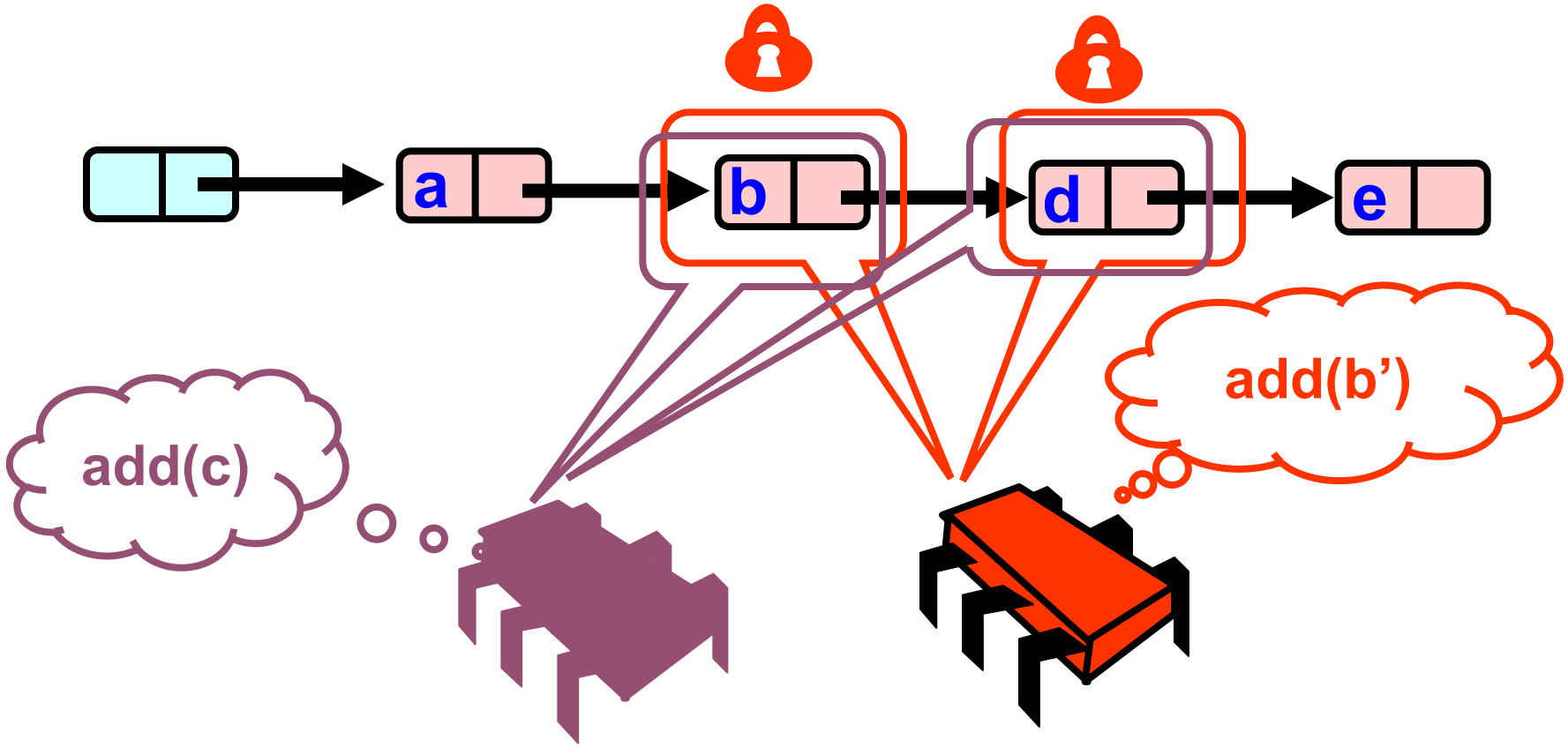

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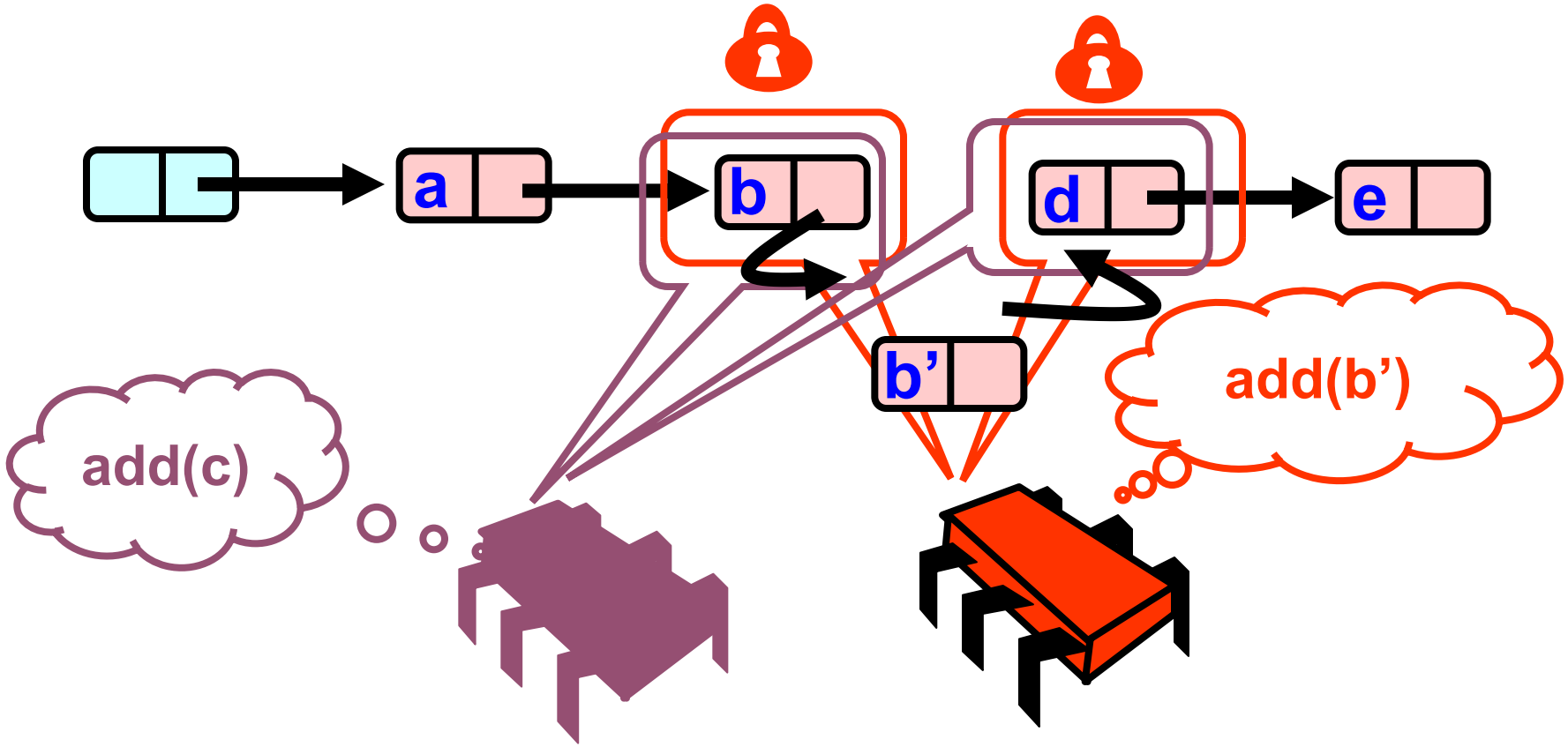

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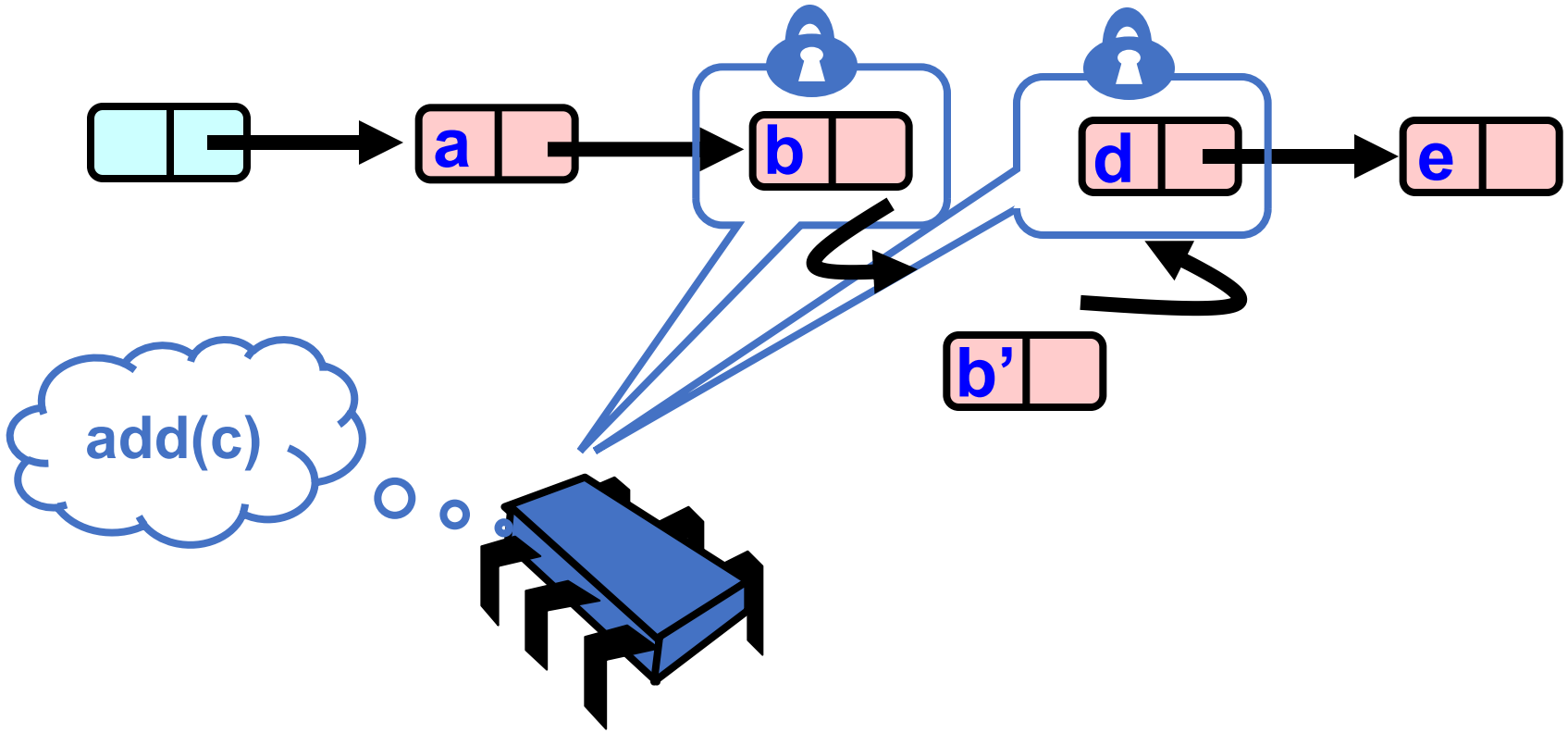
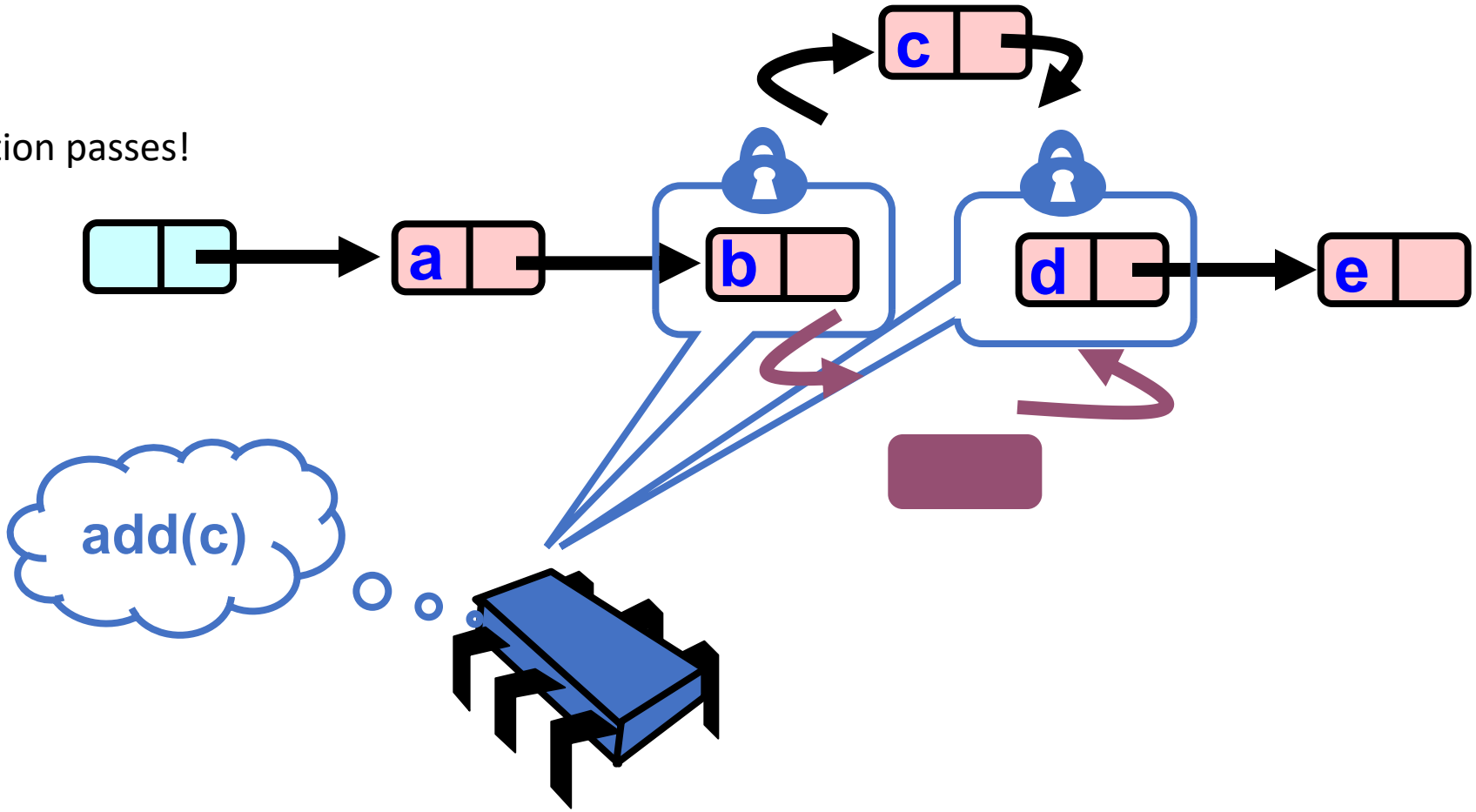
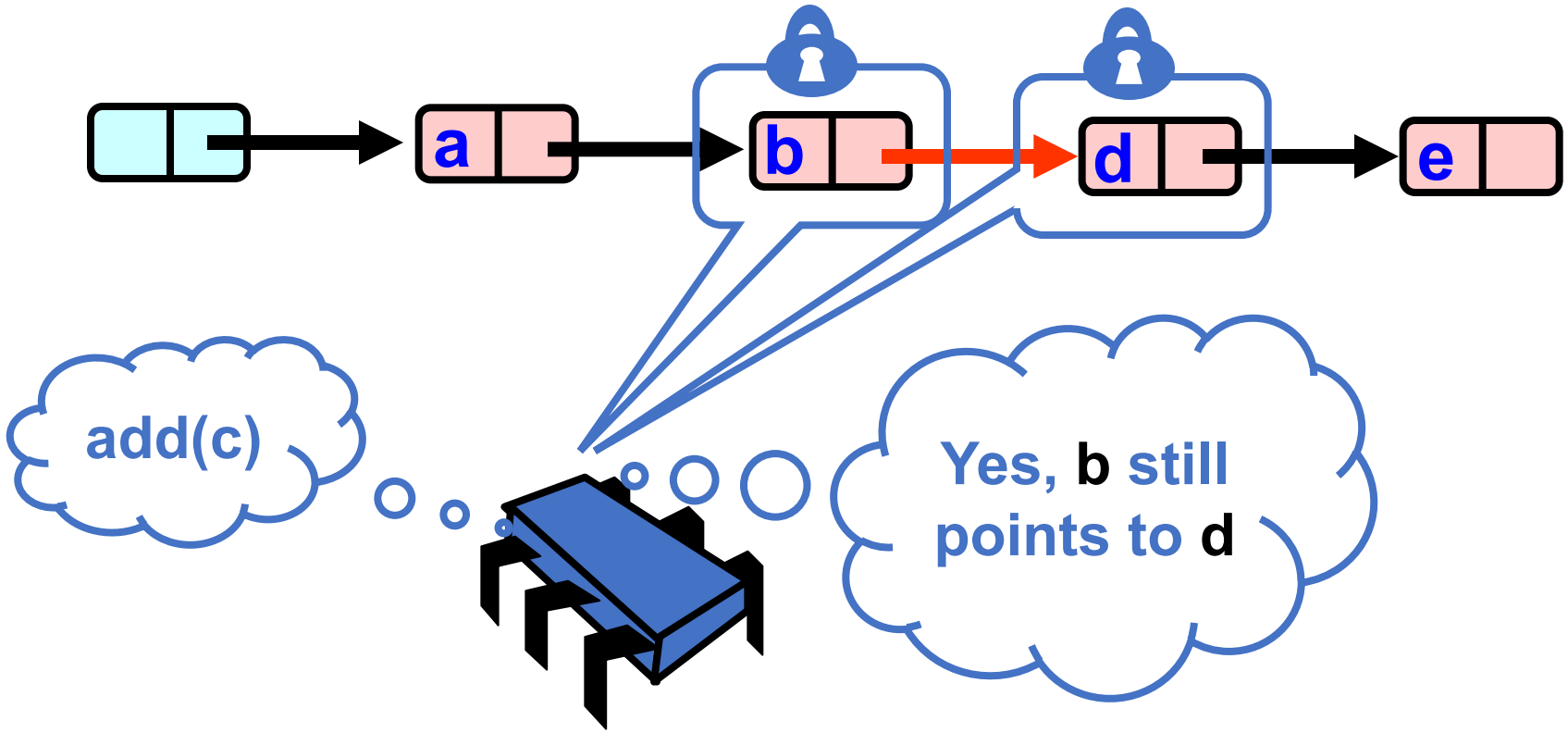


# What Else Could Go Wrong?

Validation passes!



# Validate Part 2
# (while holding locks)



# Summary

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

# Summary

- We will make the set lock free next time!