Programmazione concorrente

Laurea Magistrale in Ingegneria Informatica
Università Tor Vergata
Docente: Romolo Marotta

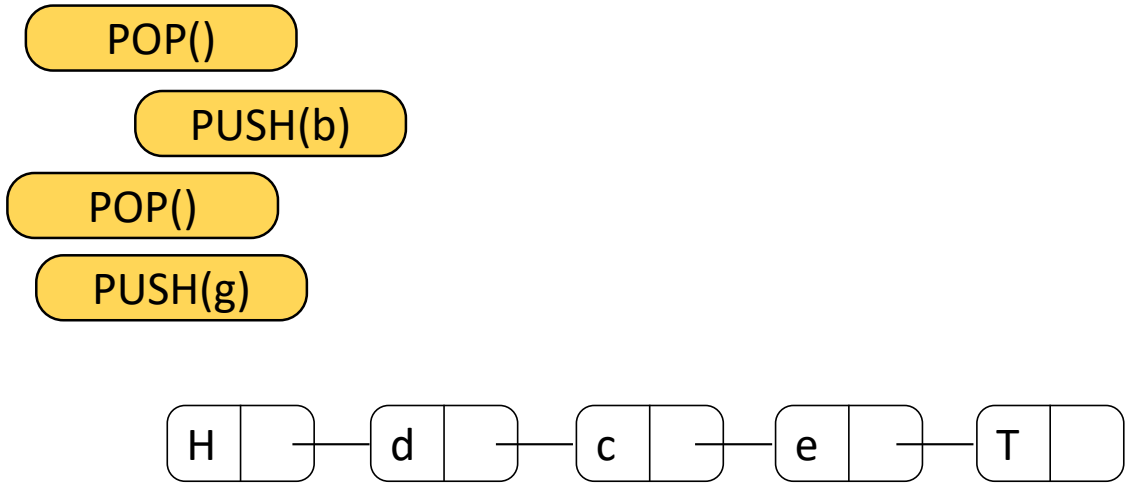
Concurrent data structures

1. Stack
2. Set

Concurrent Data Structures: Stacks

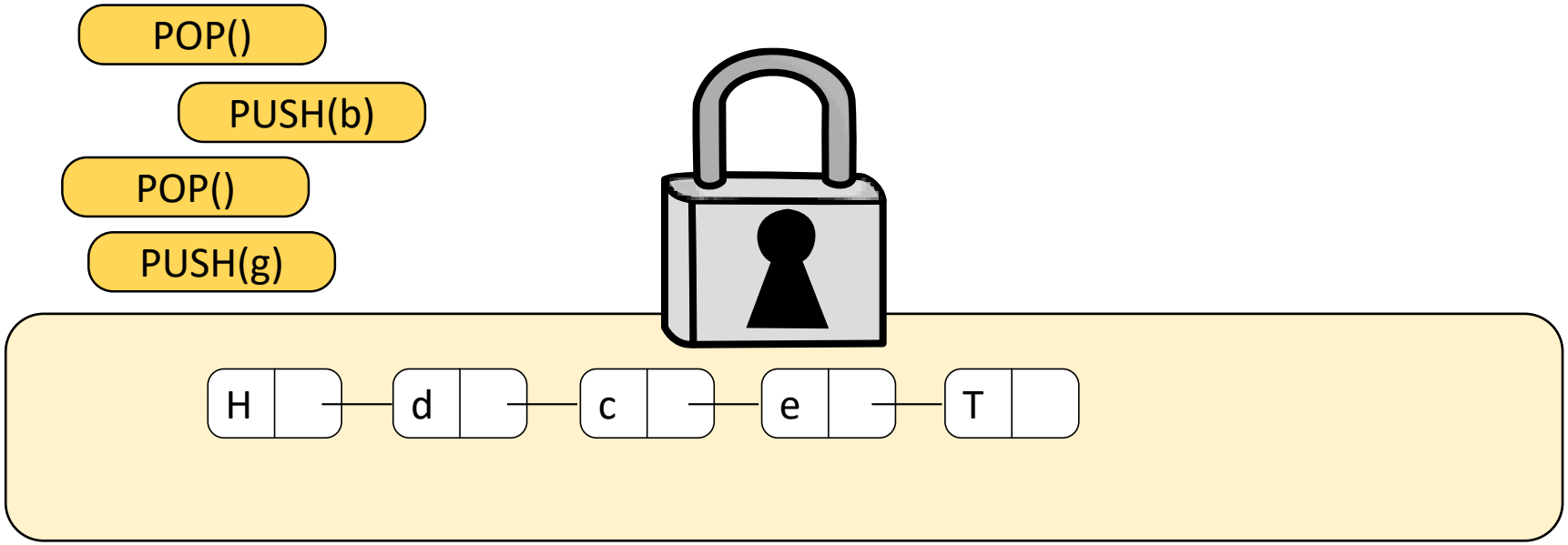
Stack implementation

- Stack methods:
  - `push(v)`
  - `pop()`
- Implemented as a linked list



Concurrent stack implementations

- Resort to a global lock



Read-Modify-Write

- RMW instructions allow to read memory and modify its content in an apparently instantaneous fashion.

```
1.RMW(MRegister *r, Function f){
2.   atomic{
3.     old = r;
4.     *r = f(r);
5.     return old;
6.   }
7.}
```

- Even conventional atomic Load and Store can be seen as RMW operations

Compare-And-Swap

- Compare-and-Swap (CAS) is an atomic instruction used in multithreading to achieve synchronization
  - It compares the contents of a memory area with a supplied value
  - If and only if they are the same
  - The contents of the memory area are updated with the new provided value
- Atomicity guarantees that the new value is computed based on up-to-date information
- If, in the meanwhile, the value has been updated by another thread, the update fails
- This instruction has been introduced in 1970 in the IBM 370 trying to limit as much as possible the use of spinlocks

Compare-And-Swap

- RMW instructions allow to read memory and modify its content in an apparently instantaneous fashion.

```
1. CAS(Mregister *r, Value old_value, Value new_value f){
2.   atomic{
3.      Value res = *r;
4.      if(*r == old_value) *r = new_value;
5.      return res;
6.   }
7. }
```

- CAS is implemented by x86 architectures (see CMPXCHG)
- gcc offers the `__sync_val_compare_and_swap` builtin

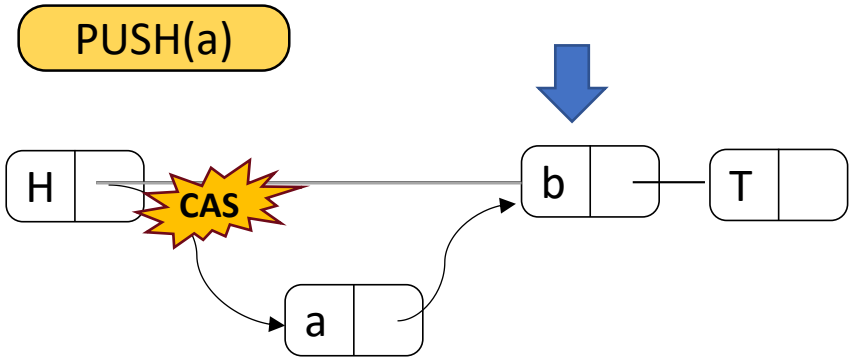
Attempt 1

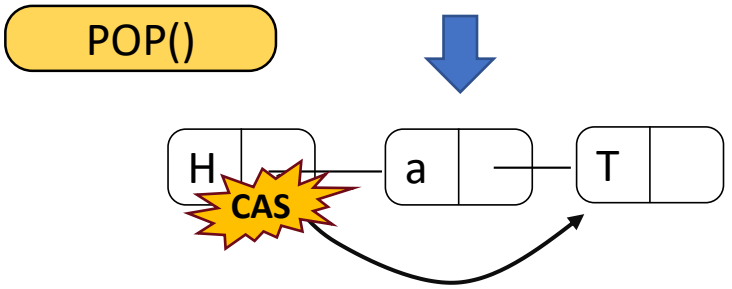
Push:

1. Get head next
2. Insert the new item with a CAS
3. If CAS fails, restart

Delete:

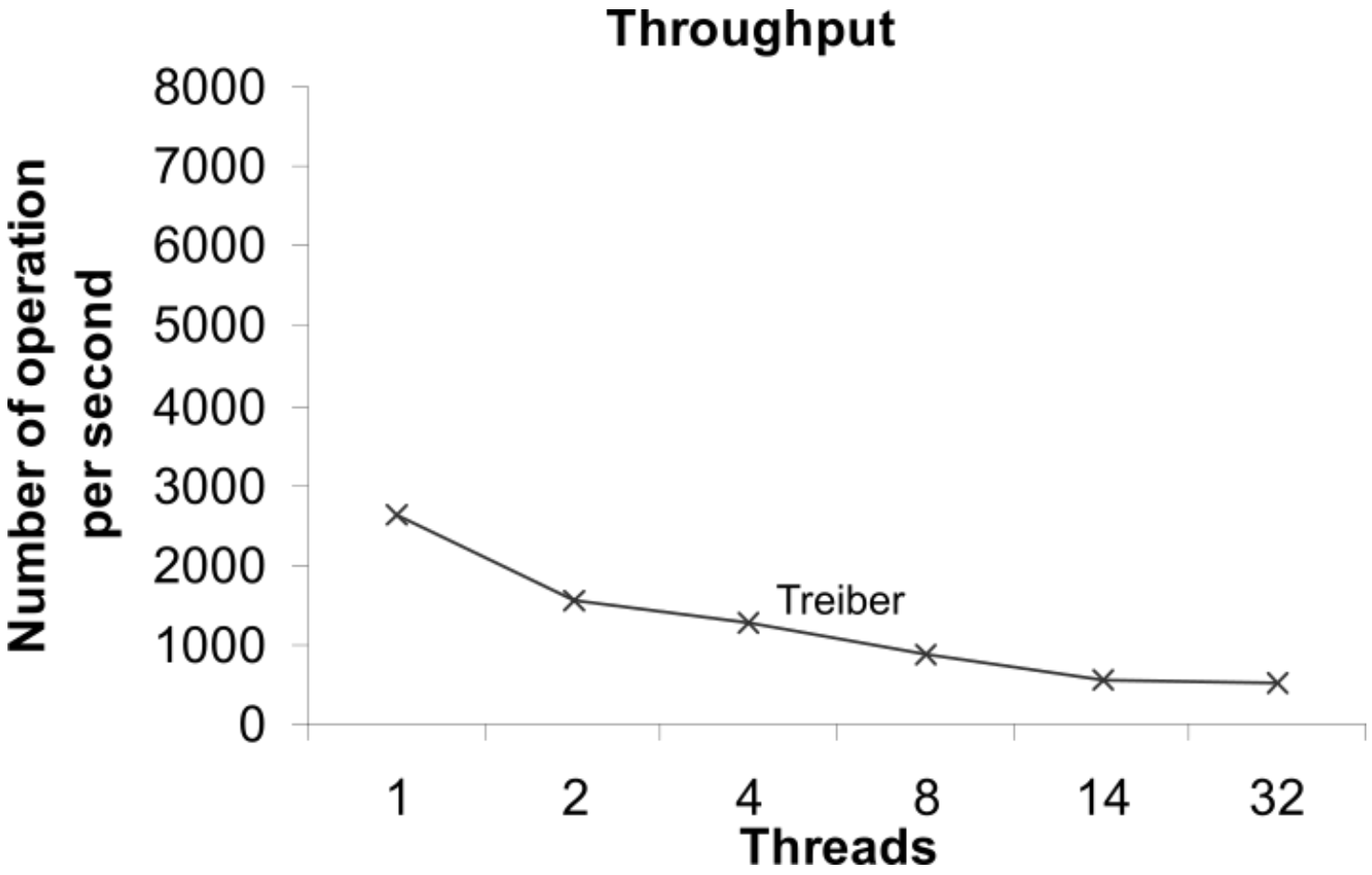
1. Get head next
2. Disconnect the item with a CAS
3. If CAS fails, restart





- Is it scalable?

Non-blocking stack – Attempt 2 [Treiber+BO]



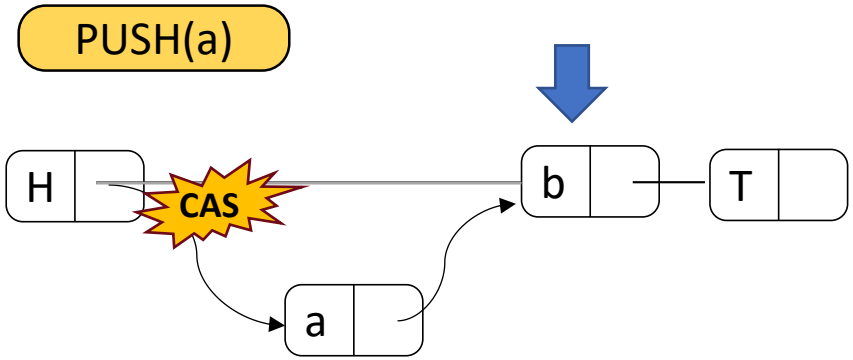
Non-blocking stack – Attempt 2 [Treiber+BO]

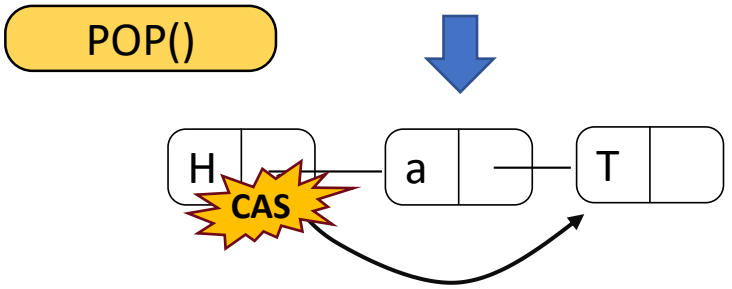
Push:

1. Get head next
2. Insert the new item with a CAS
3. If CAS fails, ~~restart~~ backoff and restart

Delete:

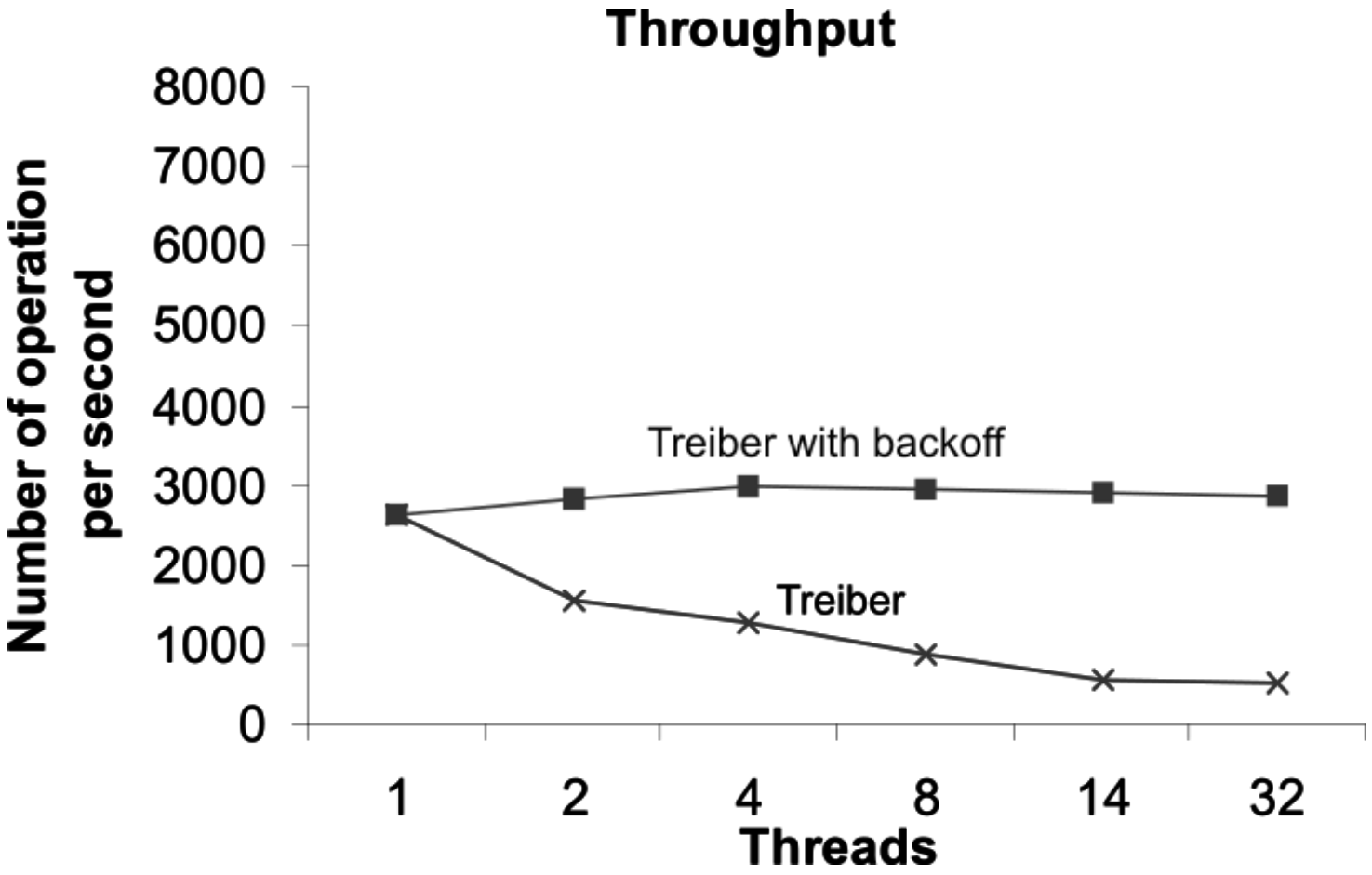
1. Get head next
2. Disconnect the item with a CAS
3. If CAS fails, ~~restart~~ backoff and restart





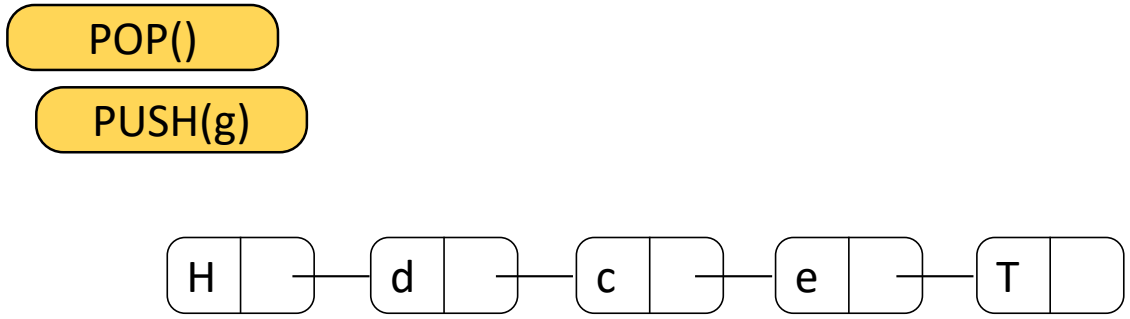
- Is it scalable?

Non-blocking stack – Attempt 2 [Treiber+BO]



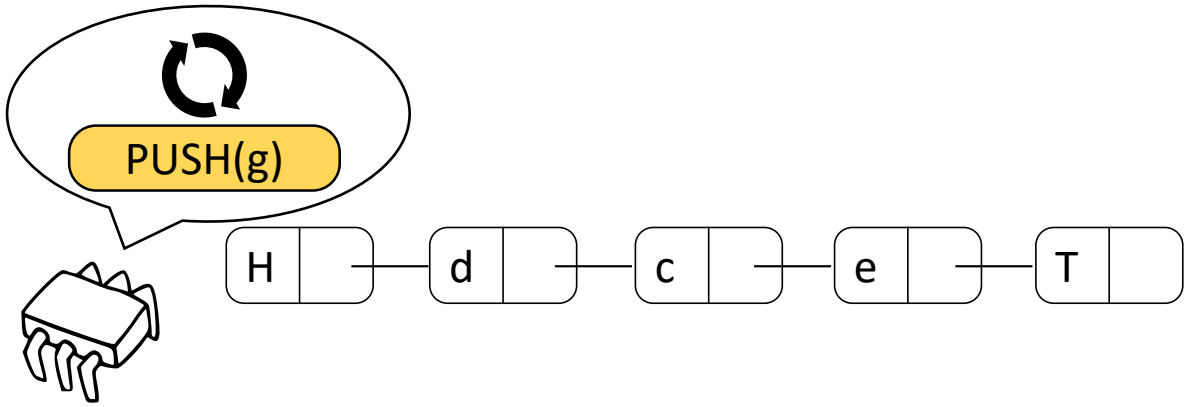
Concurrent stack implementations

- Resort to a global lock
  - Do not scale
- Resort to a naïve non-blocking approach
  - Do not scale
- Resort to a naïve non-blocking approach + Back off
  - Do not scale, but conflict resilient
- How achieve scalability? Make back-off times useful



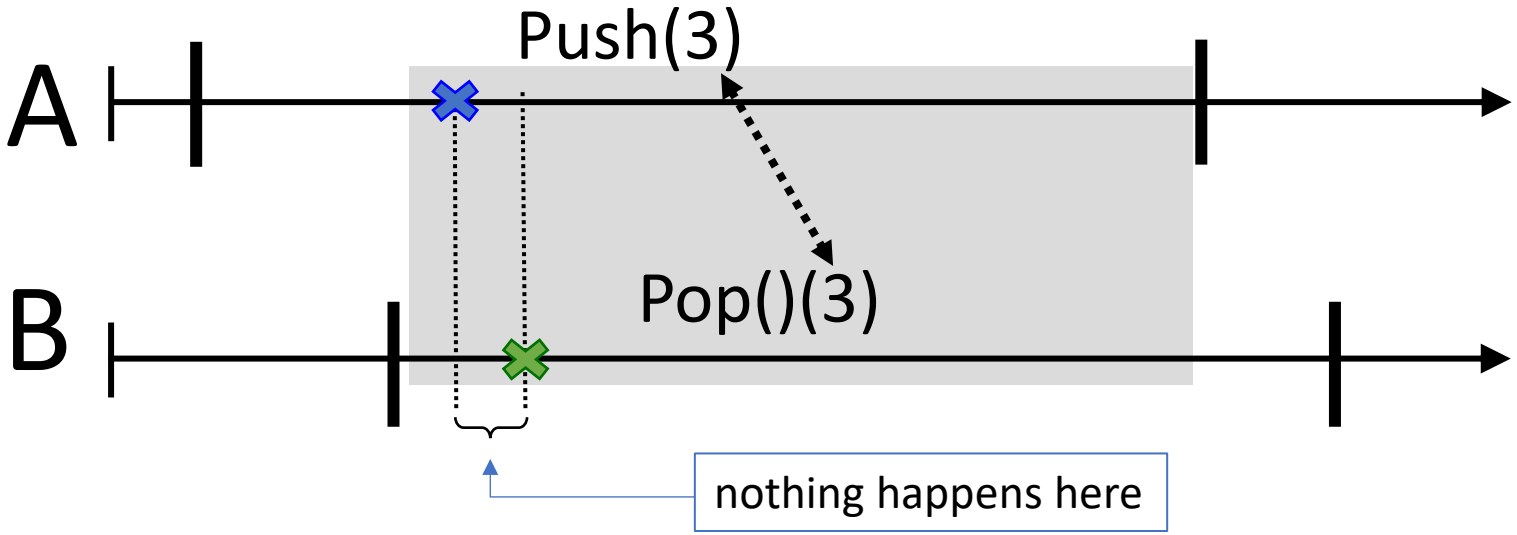
Non-blocking stack – Attempt 3

- How to take advantage of back-off times?



Observation

- Concurrent matching push/pop pairs are always linearizable



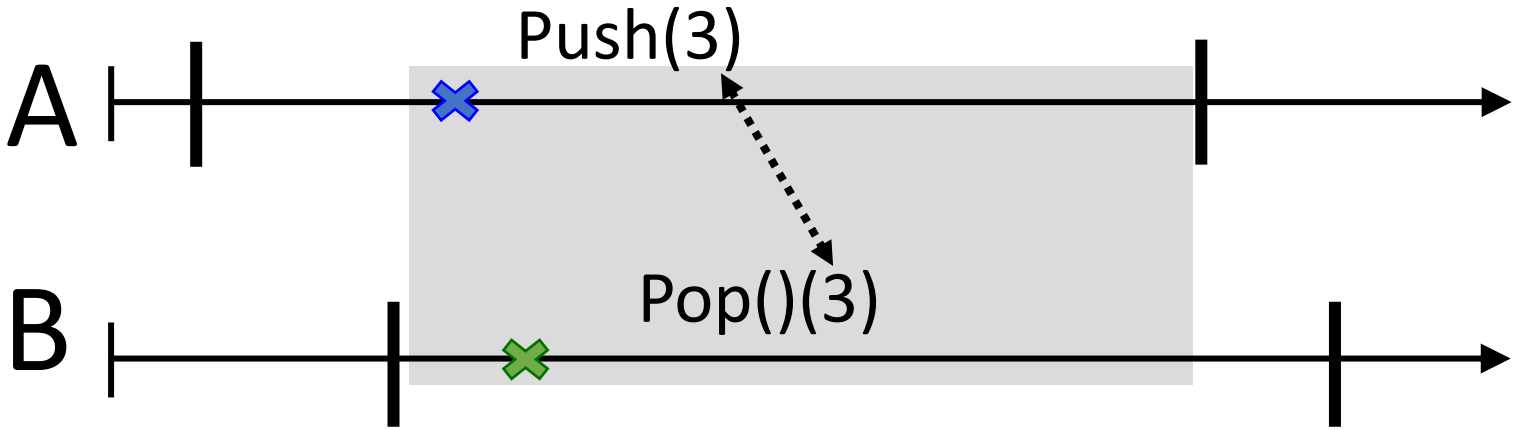
- A push A and a pop B are:
  - concurrent to each other
  - B returns the item inserted by A

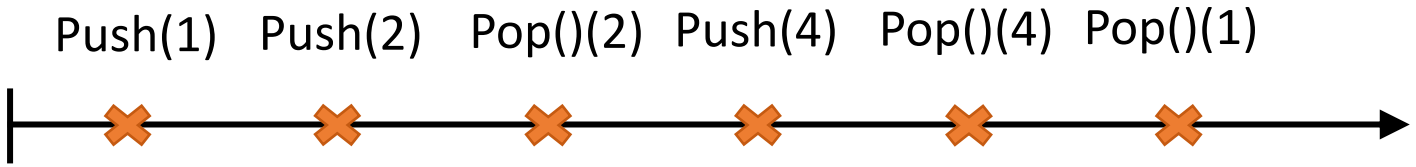
$\Rightarrow$ we can always take two points such that:

  - A is the last one to insert an item before A linearizes
  - B appears to extract the last item inserted (by A)

Observation

- Concurrent matching push/pop pairs are always linearizable





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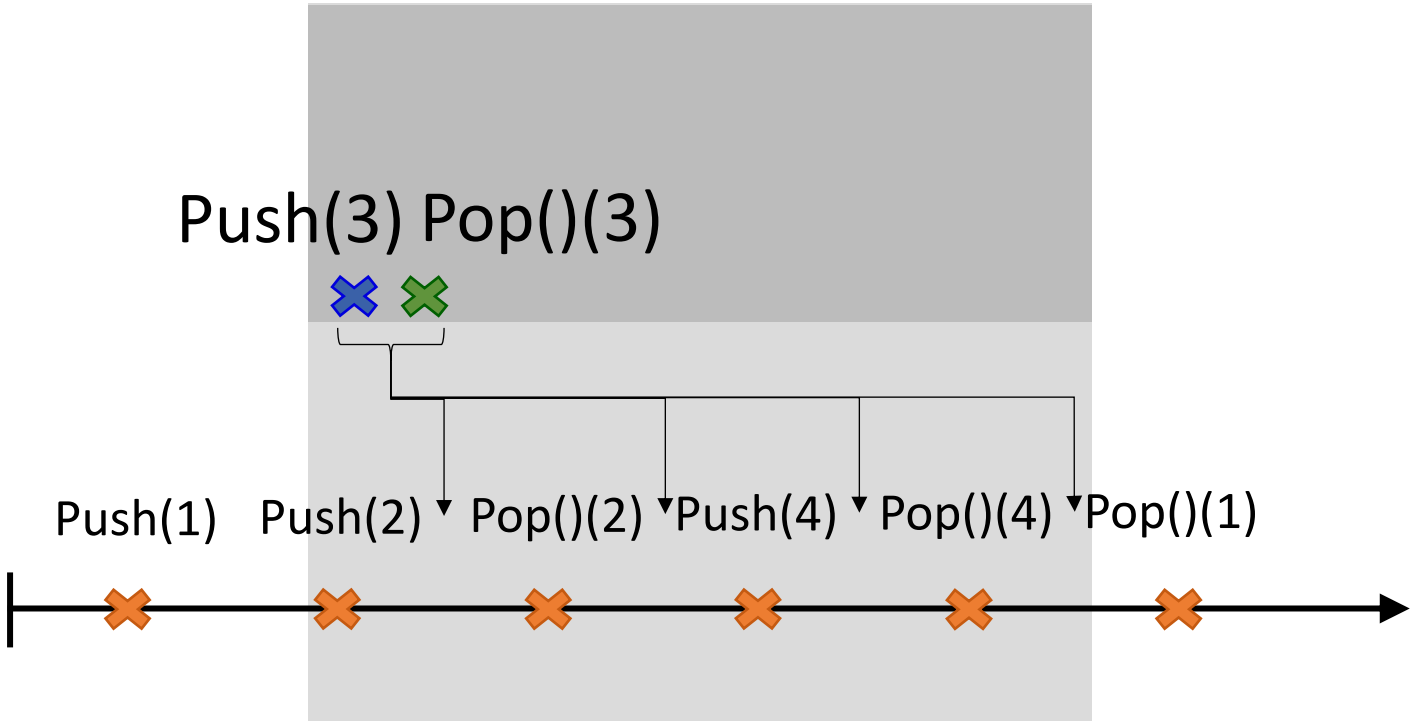
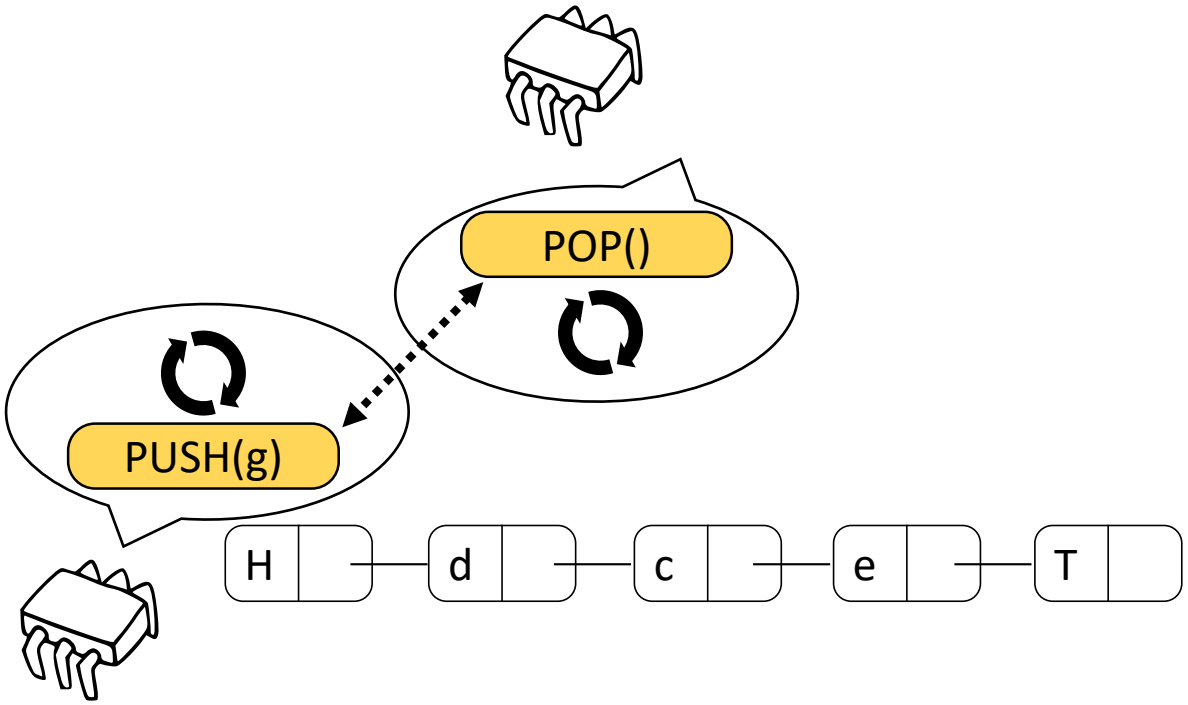


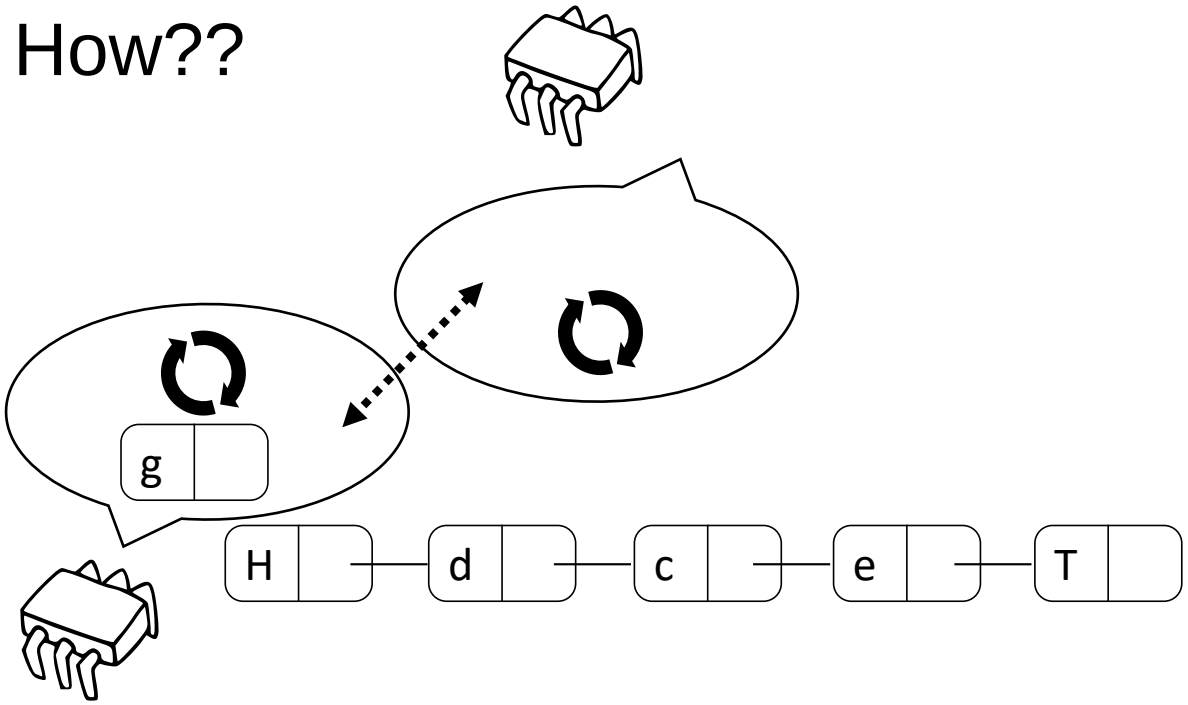
Non-blocking stack – Attempt 3

- How to take advantage of back-off times?
- Hope that an opposite operation arrives while waiting
- Match the two without interacting with the stack



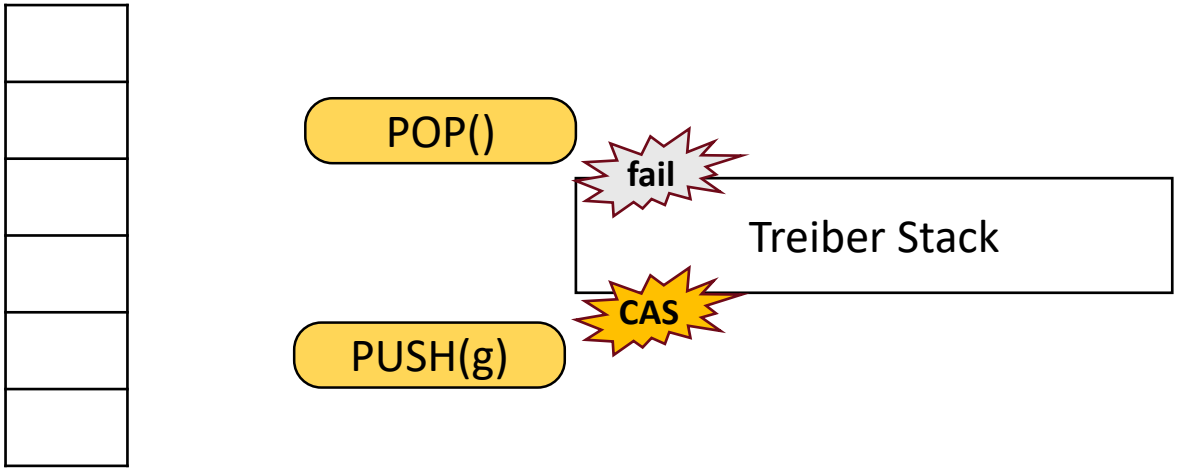
Non-blocking stack – Attempt 3

- How to take advantage of back-off times?
- Hope that an opposite operation arrives while waiting
- Match the two without interacting with the stack
- How??



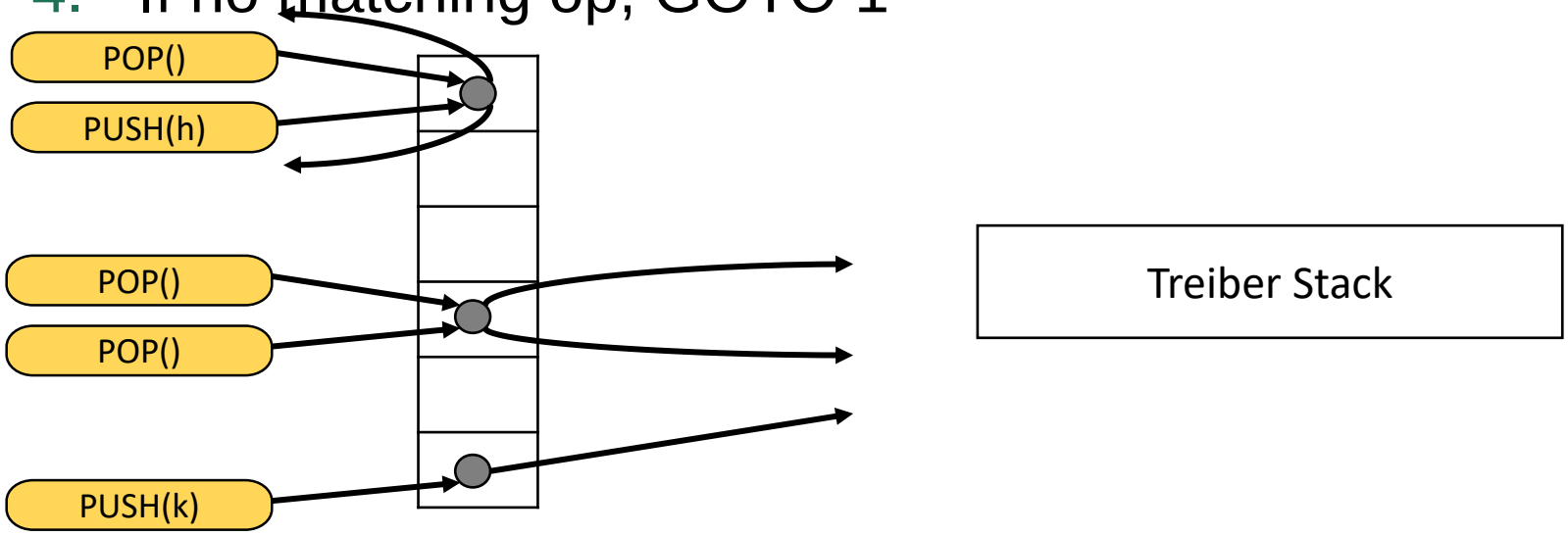
Non-blocking stack – Elimination stack

- Pair the Treiber stack with an array
- Algorithm:
  1. Update the original stack via CAS
  2. If CAS fails, publish the operation in a random cell of the array

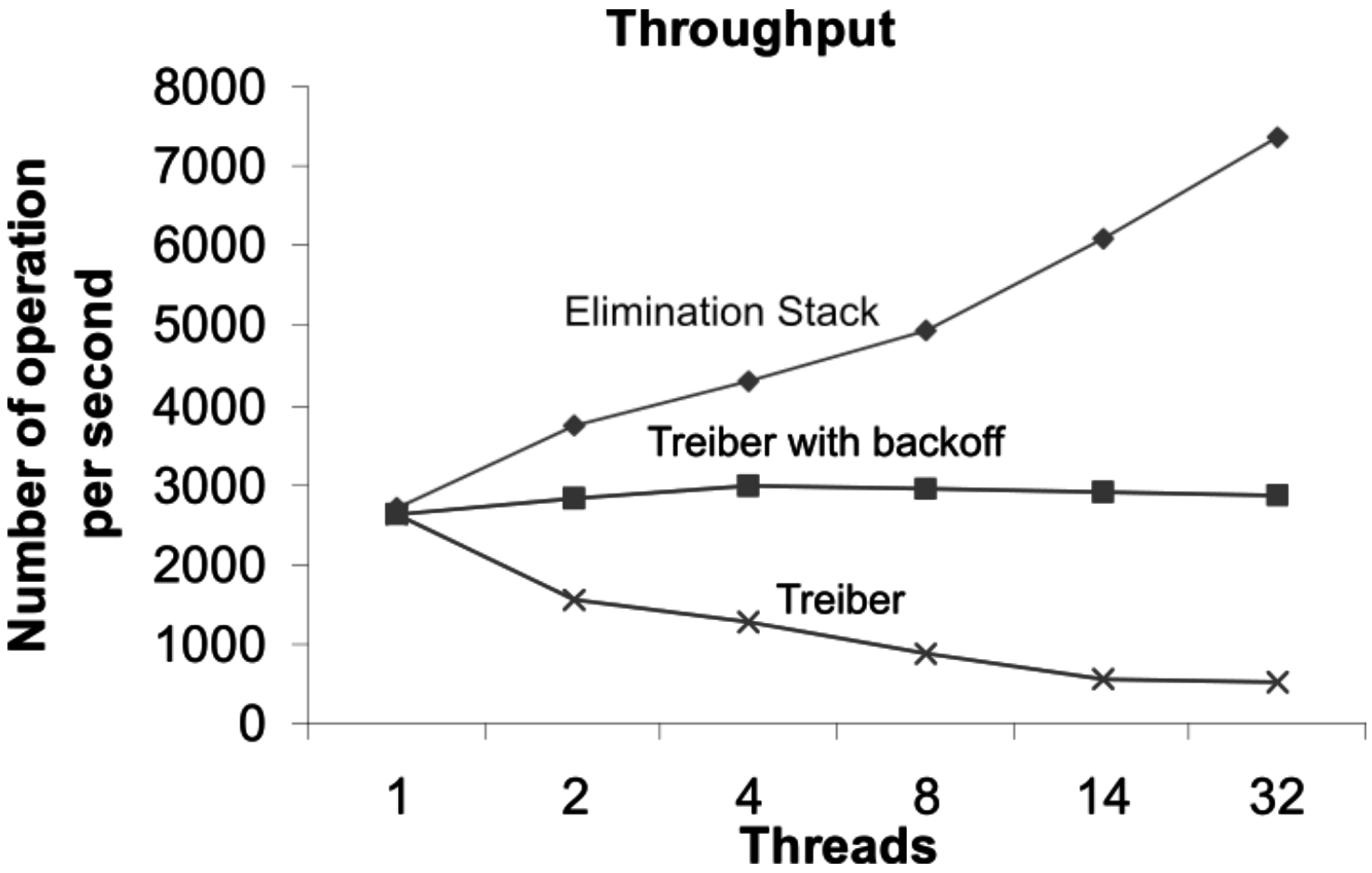


Non-blocking stack – Elimination stack

- Pair the Treiber stack with an array
- Algorithm:
  1. Update the original stack via CAS
  2. If CAS fails, publish the operation in a random cell of the array
  3. Wait for a matching operation
  4. If no matching op, GOTO 1



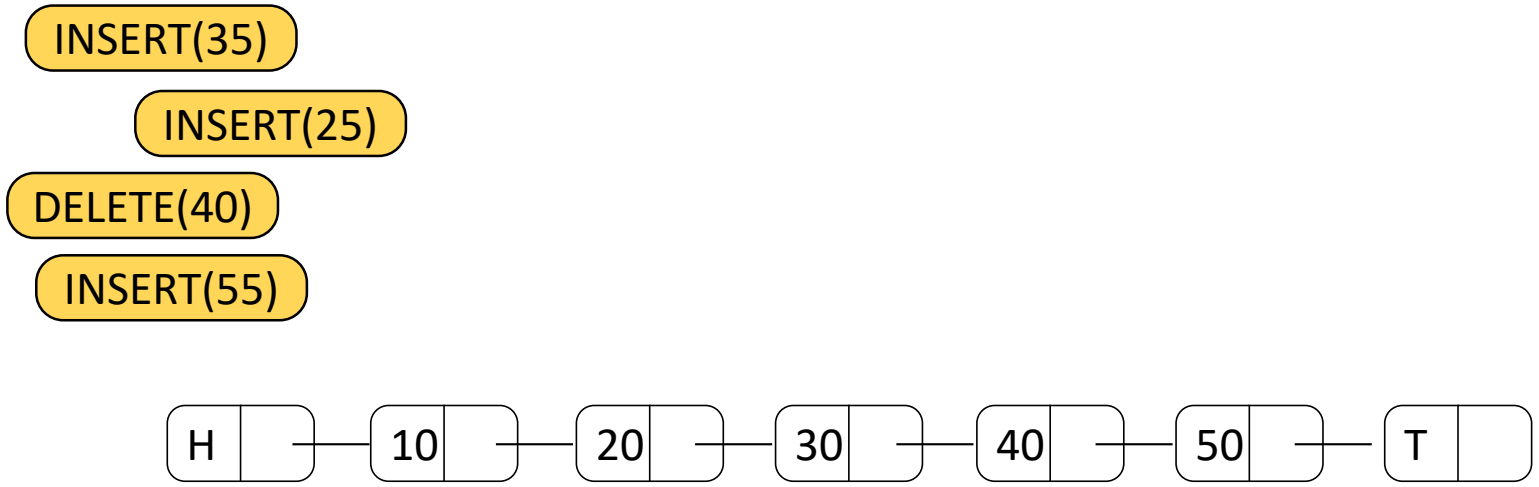
Non-blocking stack – Attempt 3



Concurrent Data Structures: Sets

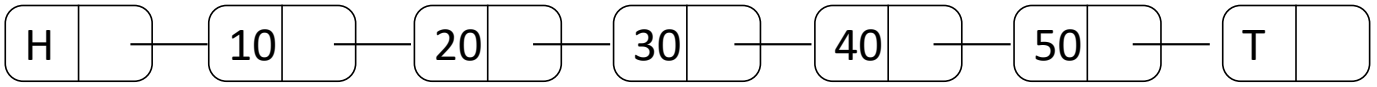
Set implementations

- Set methods:
  - `insert(k)`
  - `delete(k)`
  - ~~`find(k)`~~
- Implemented as an ordered linked list

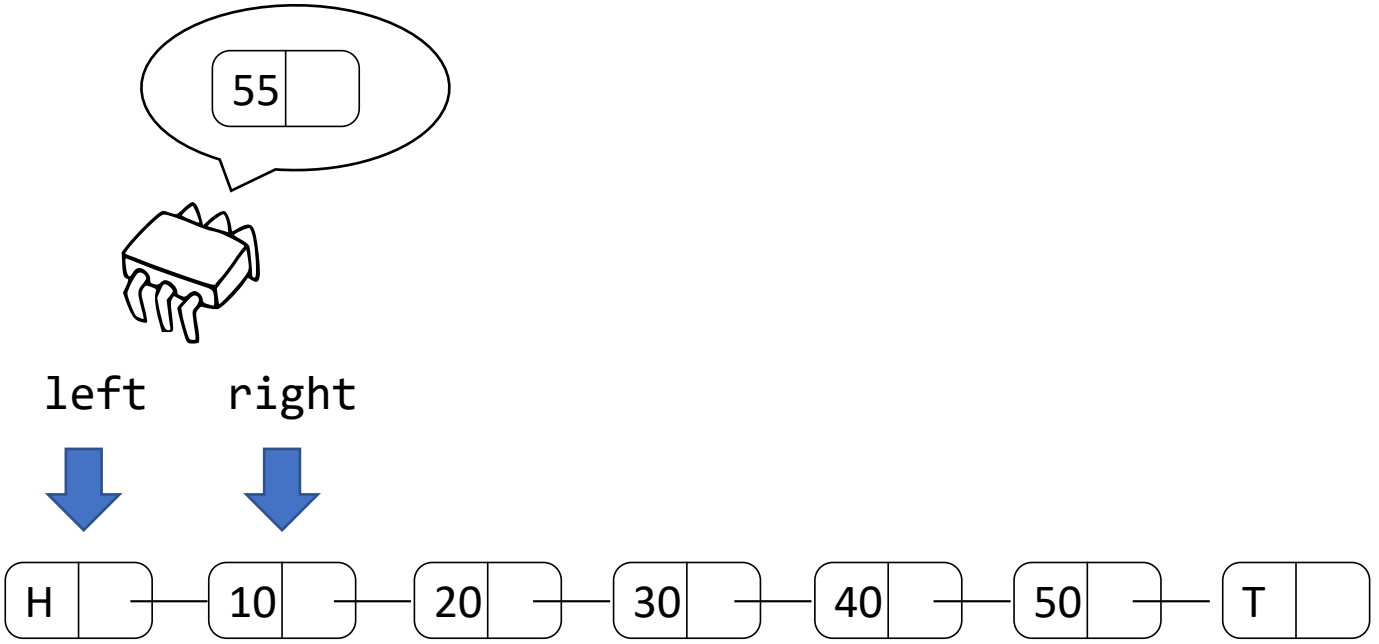


Insert algorithm

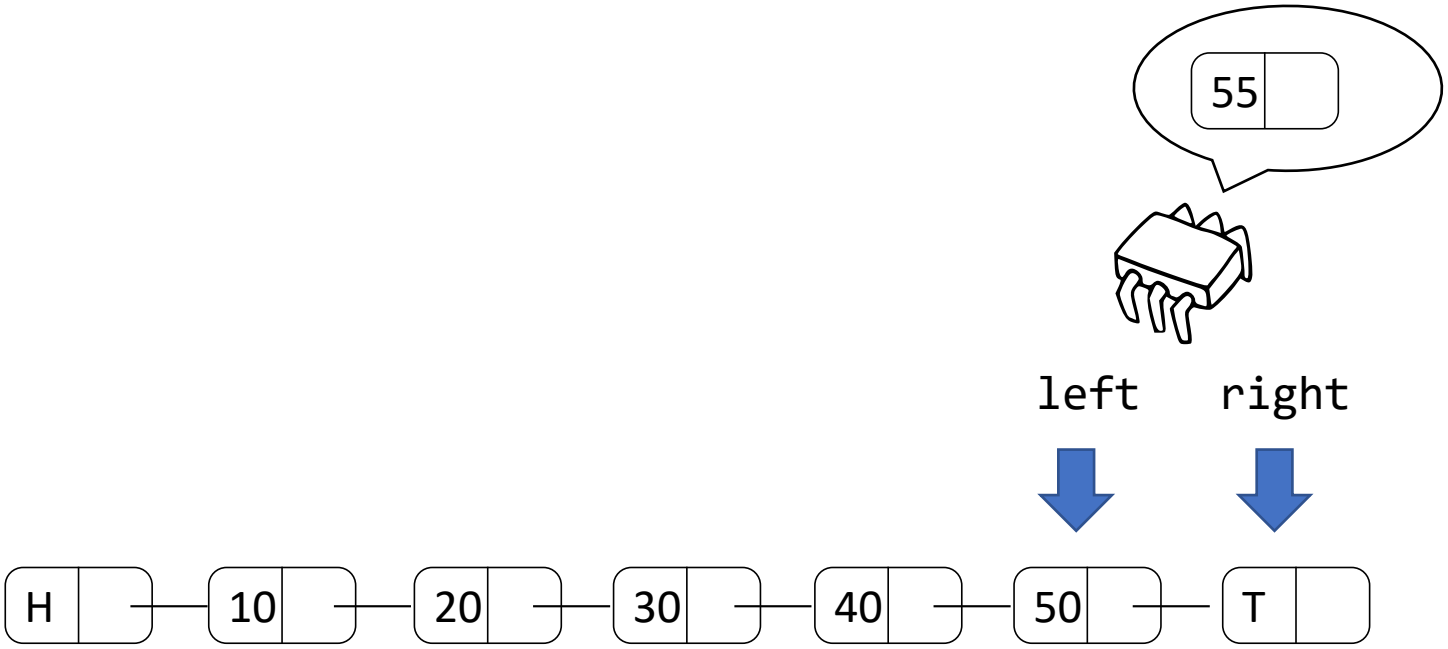
INSERT(55)



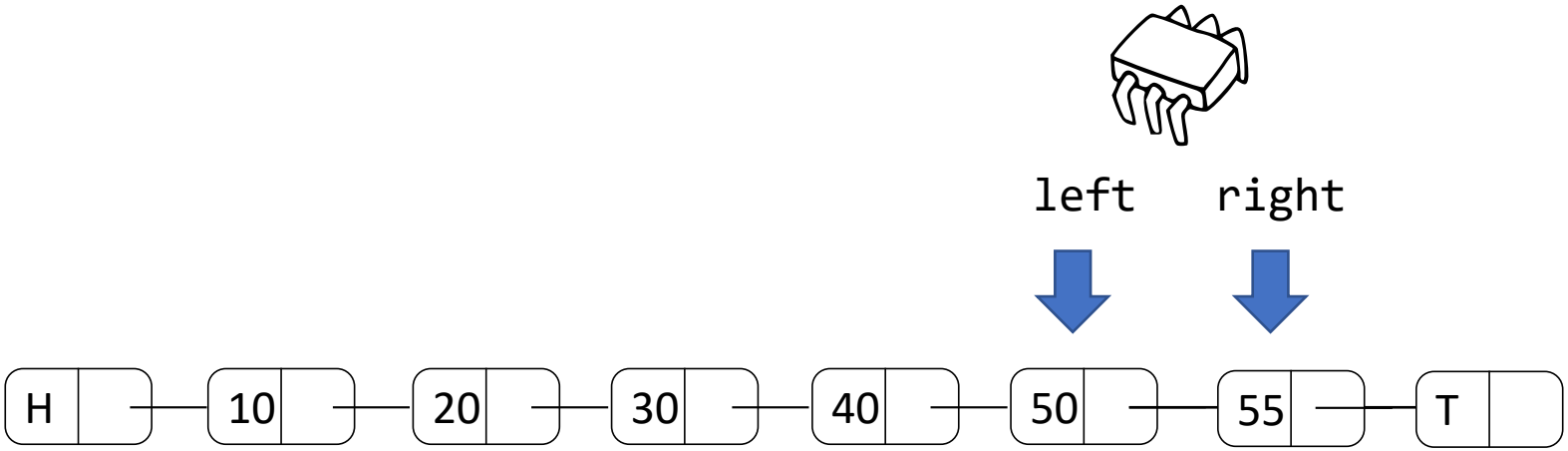
Insert algorithm



Insert algorithm

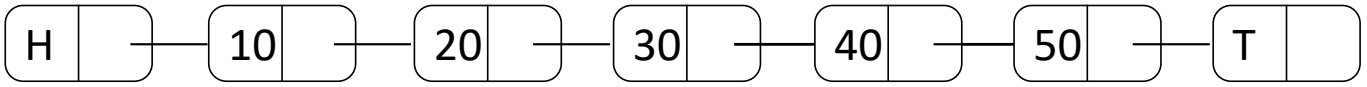


Insert algorithm

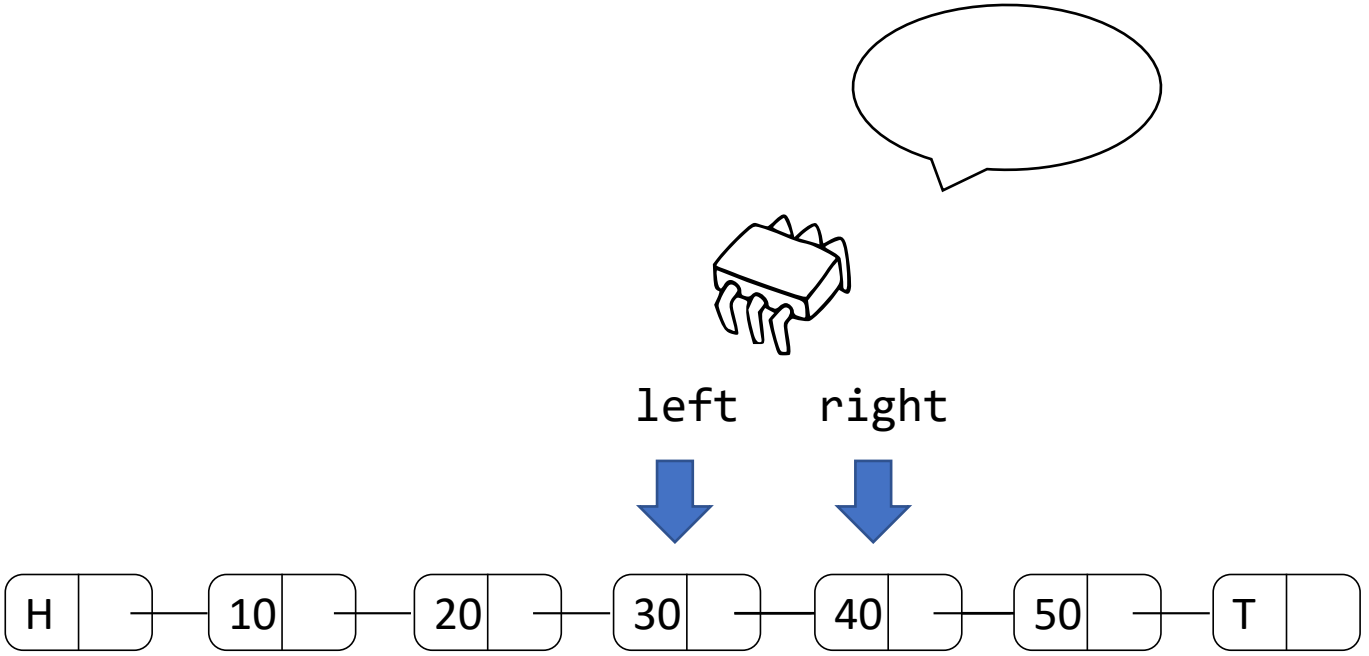


Delete algorithm

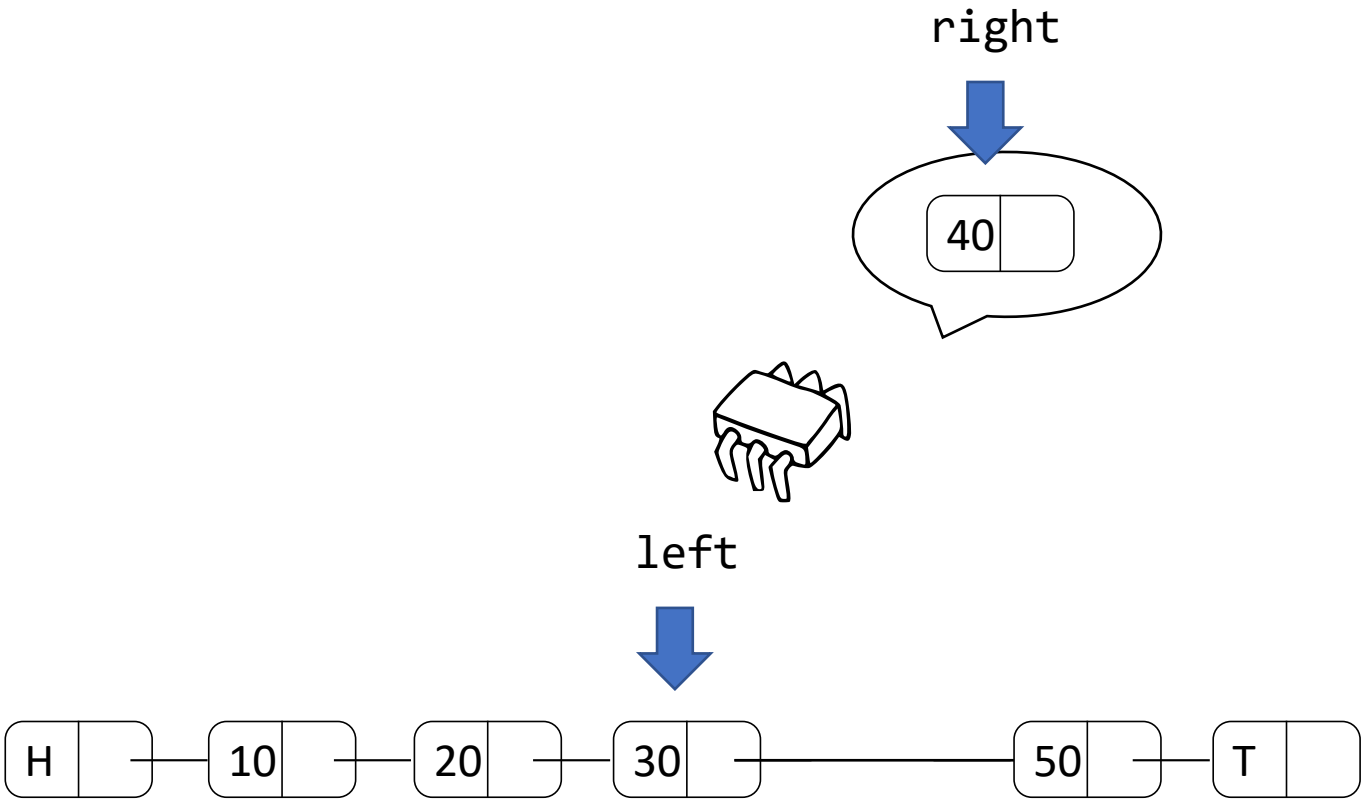
DELETE(40)



Delete algorithm



Delete algorithm



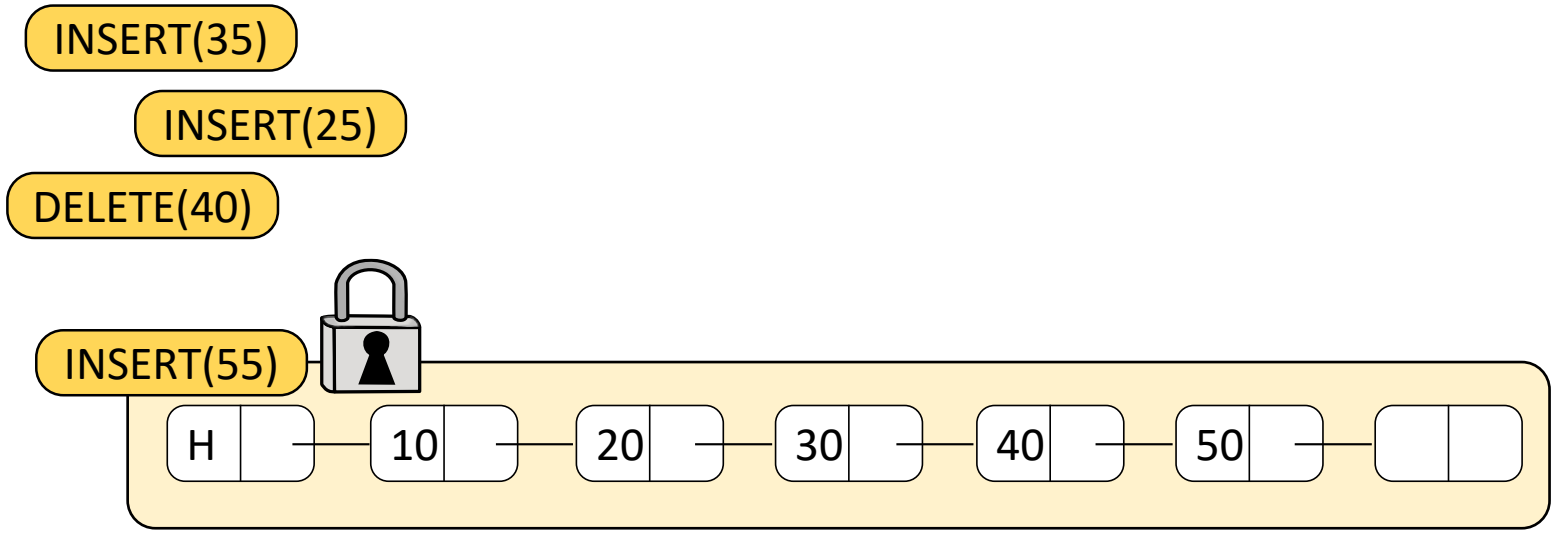
Sequential set implementation

```
1. bool do_operation(int k, int op_type){
2.   bool res = true;
3.   node *l,*r;
4.
5.   l = search(k, &r);
6.   switch(op_type){
7.     case(INSERT):
8.       if(r->key == k)
9.         res = false;
10.      else
11.        l->next = new node(k,r);
12.      break;
13.    case(DELETE):
14.      if(r->key == k)
15.        l->next = r->next;
16.      else
17.        res = false;
18.      break;
19.  }
20.
21.
22.  return res;
23.}
```

```
1. node* search(int k, node **r){
2.   node *l, *r_next;
3.   l = set->head;
4.
5.   *r = l->next;
6.
7.   r_next = (*r)->next;
8.   while((*r)->key < k){
9.
10.    l = *r;
11.    *r = r_next;
12.
13.    r_next = (*r)->next;
14.  }
15.}
```

Concurrent set – Attempt 1

- PESSIMISTIC approach
- Synchronize via global lock



Concurrent set – Attempt 1 (SRC)

```
1. bool do_operation(int k, int op_type){
2.   bool res = true;
3.   node *l,*r;
4.   LOCK(&glock);
5.   l = search(k, &r);
6.   switch(op_type){
7.     case(INSERT):
8.       if(r->key == k)
9.         res = false;
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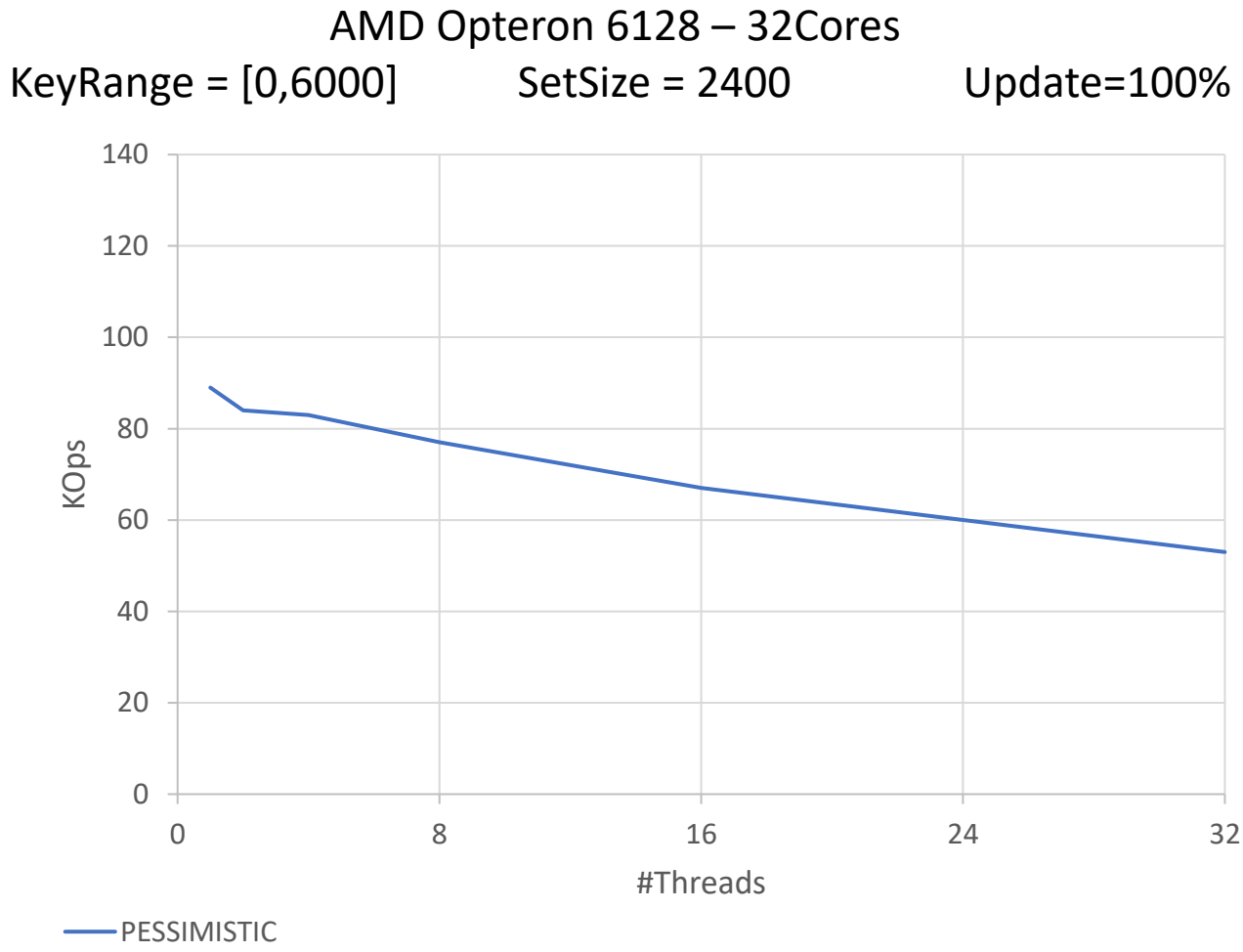
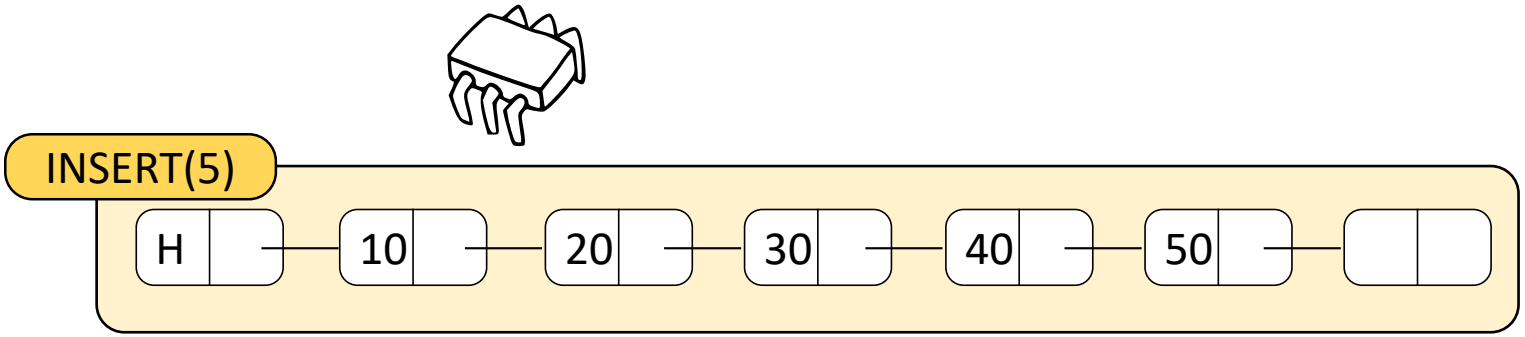
11.        l->next = new node(k,r);
12.      break;
13.    case(DELETE):
14.      if(r->key == k)
15.        l->next = r->next;
16.      else
17.        res = false;
18.      break;
19.  }
20.  UNLOCK(&glock);
21.
22.  return res;
23.}
```

```
1. node* search(int k, node **r){
2.   node *l, *r_next;
3.   l = set->head;
4.
5.   *r = l->next;
6.
7.   r_next = (*r)->next;
8.   while((*r)->key < k){
9.
10.    l = *r;
11.    *r = r_next;
12.
13.    r_next = (*r)->next;
14.  }
15.}
```

Concurrent set – Attempt 1



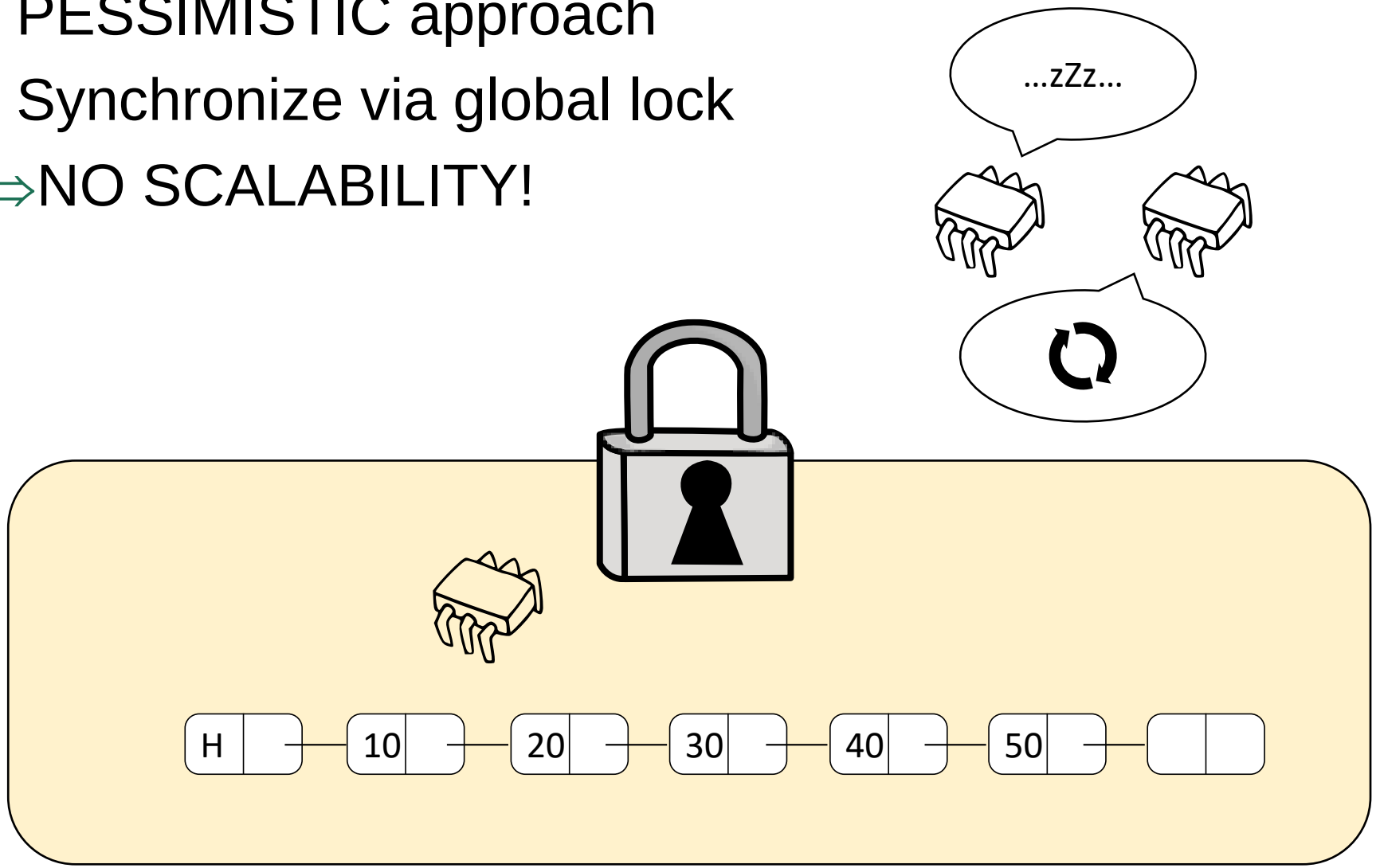
Concurrent set – Attempt 1



Concurrent set – Attempt 1

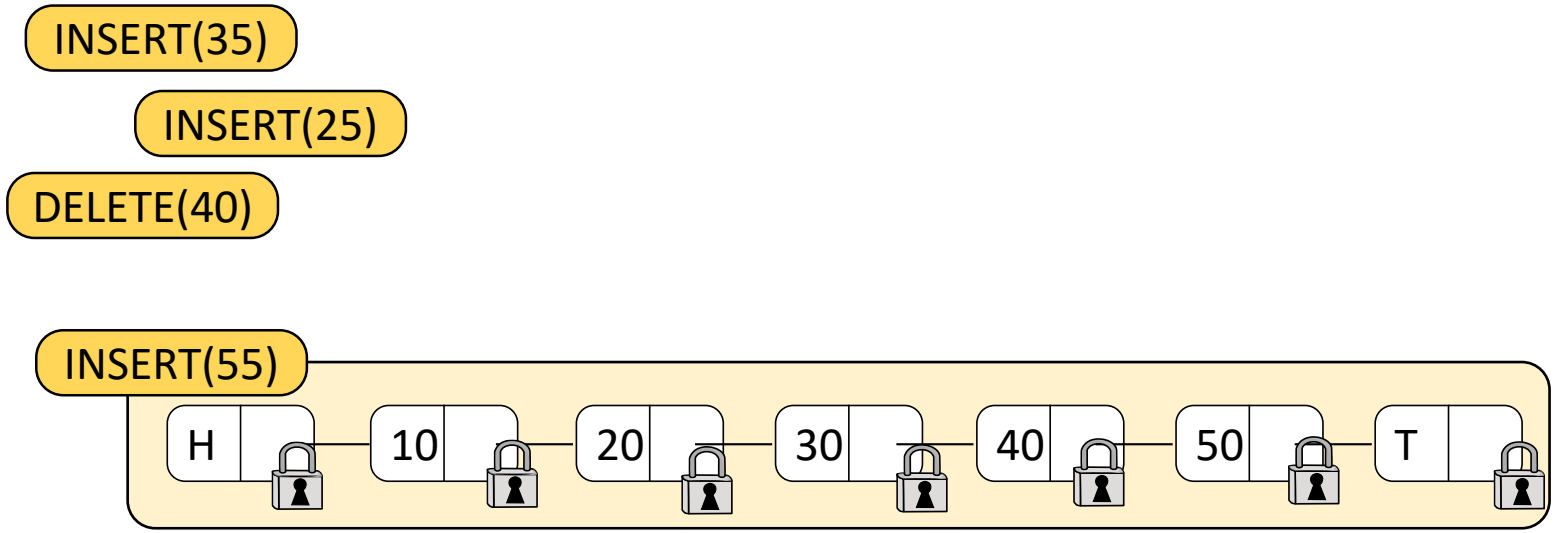
- PESSIMISTIC approach
- Synchronize via global lock

⇒NO SCALABILITY!



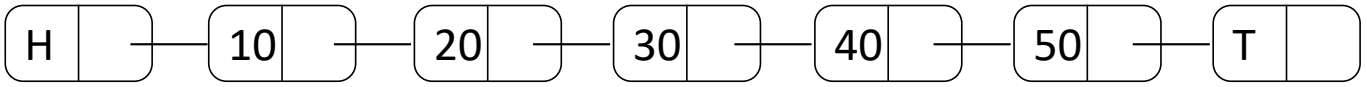
Concurrent set – Attempt 2

- Fine-grain approach
- Each node has its own lock
- Keep two locks at a time (lock coupling):
  - One on the current node
  - One on its predecessor



Search algorithm

INSERT(55)



Search algorithm

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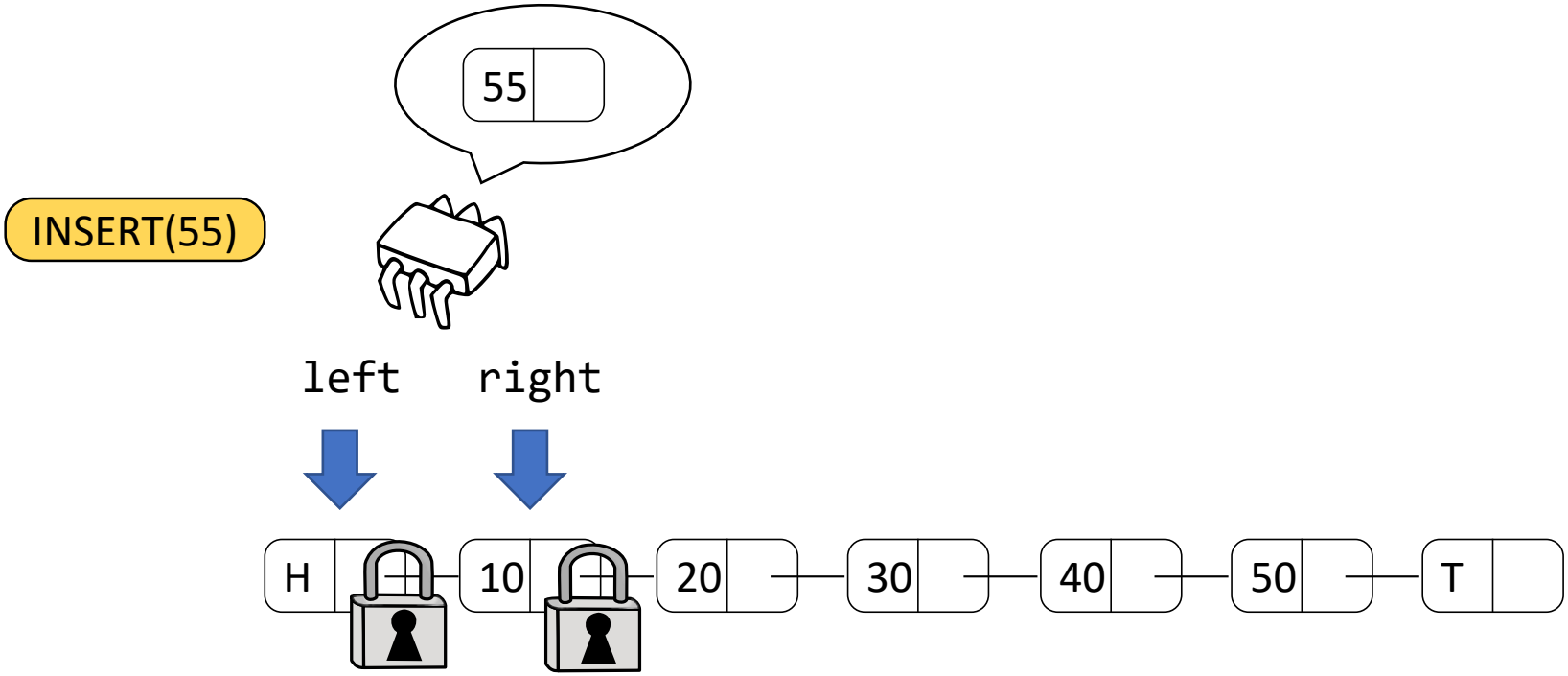

Search algorithm

- Keep two locks at a time (lock coupling):
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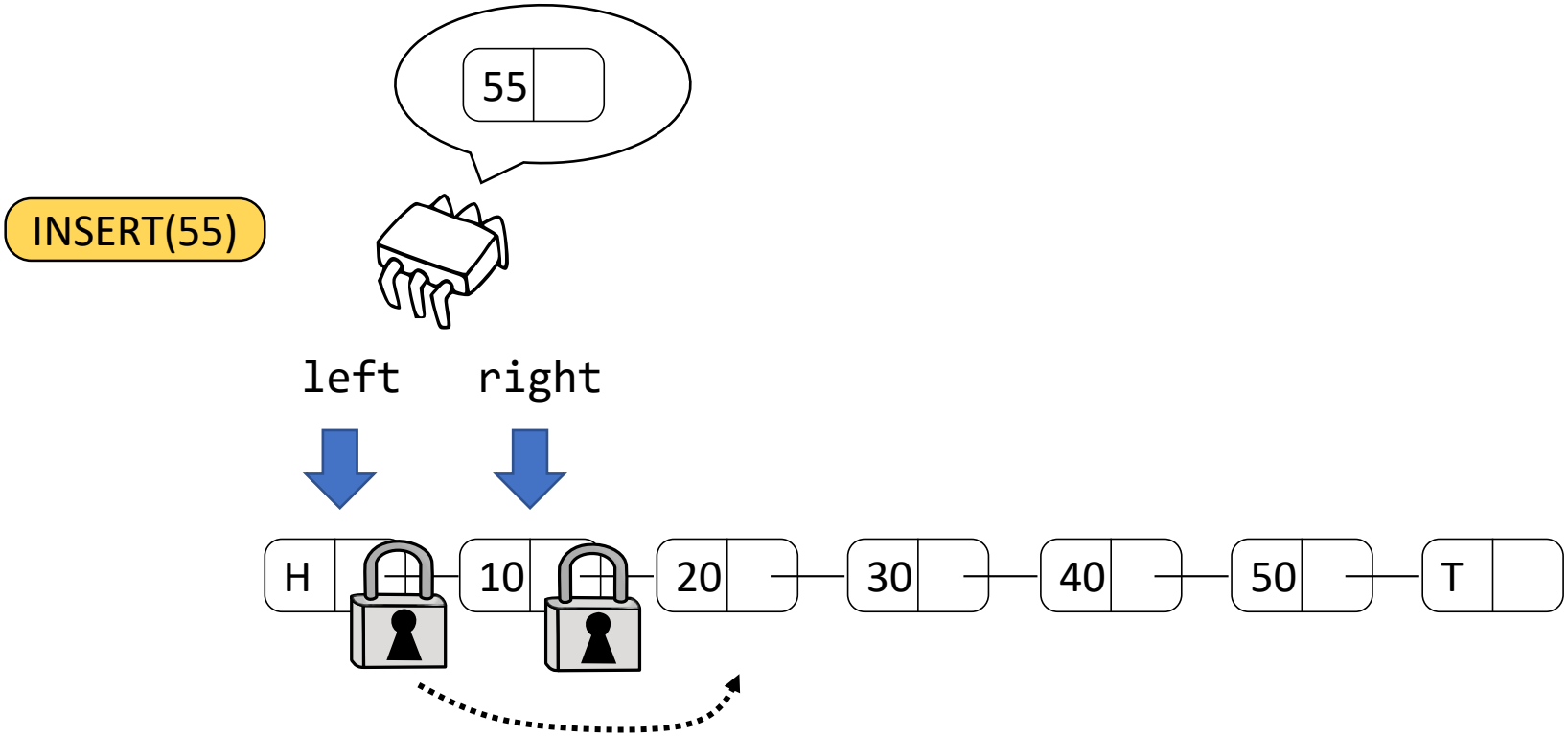

Search algorithm

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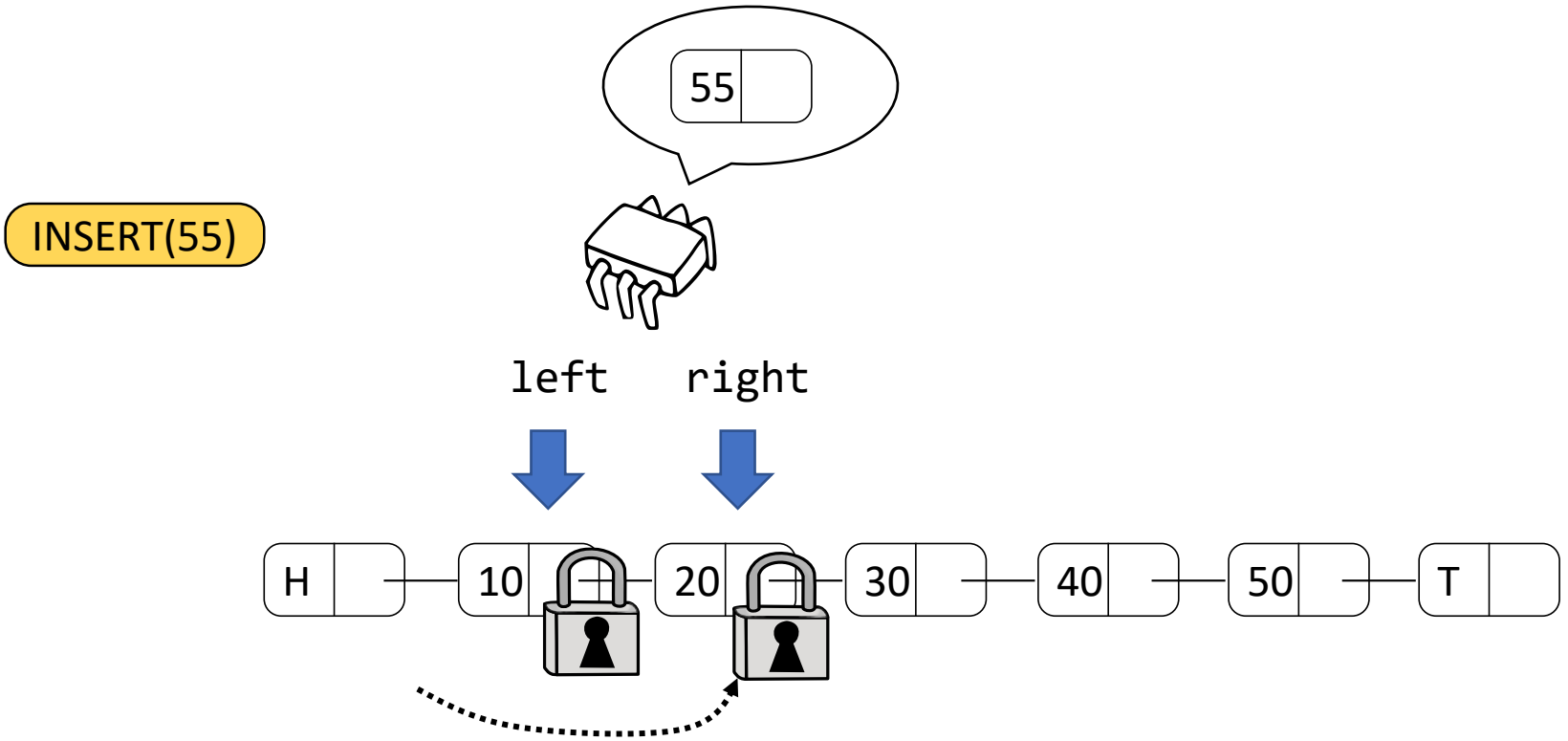

Search algorithm

- Keep two locks at a time (lock coupling):
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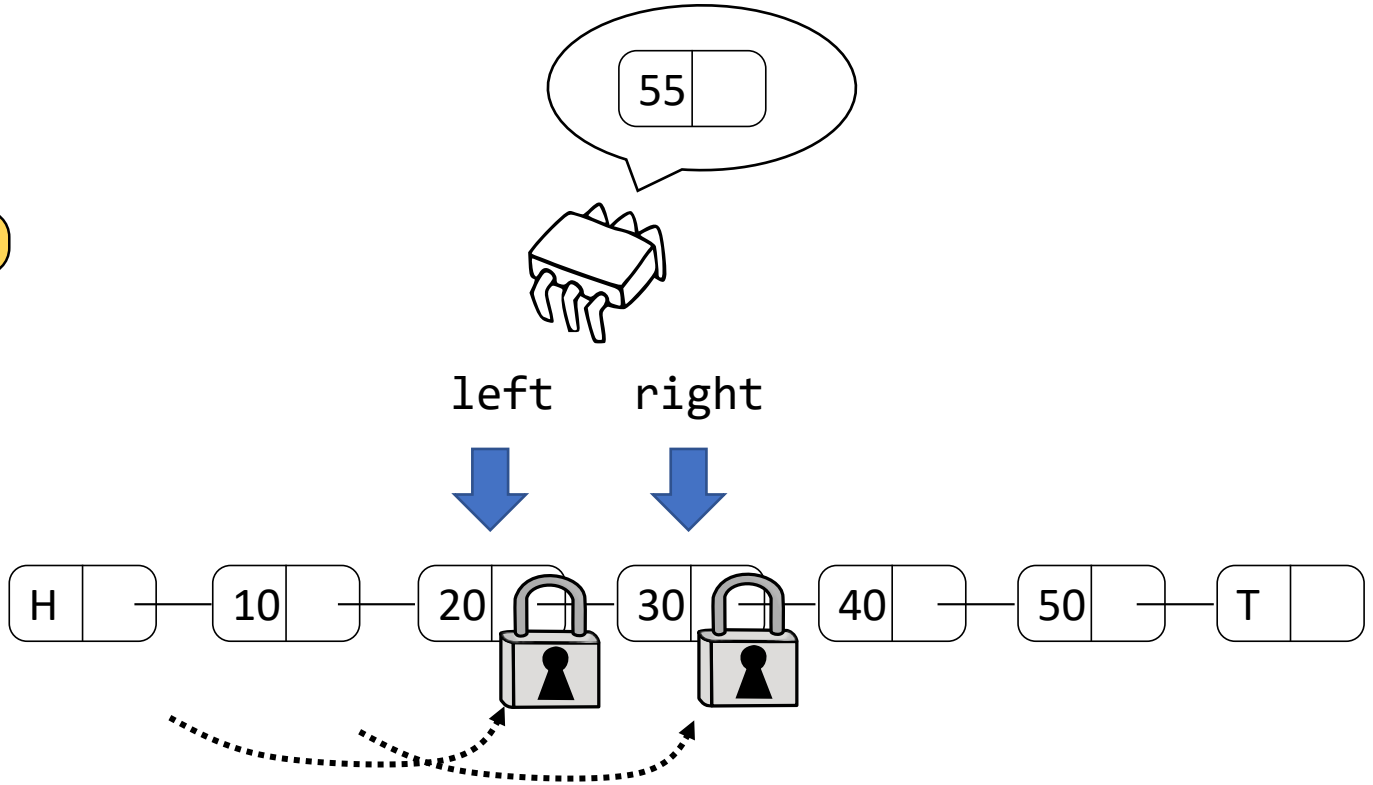
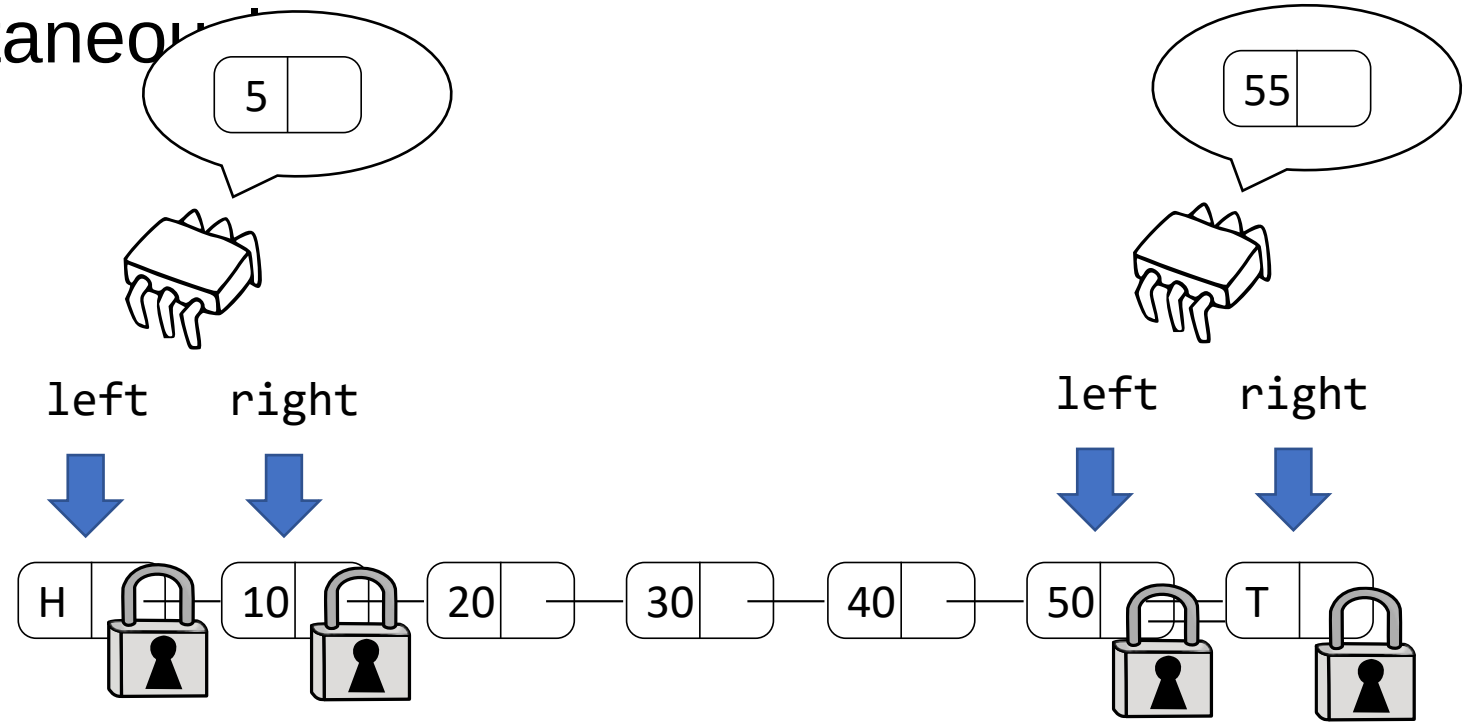
INSERT(55)



Search algorithm

- Keep two locks at a time (lock coupling):
  - One on the current node
  - One on its predecessor
- Multiple threads access the data structure simultaneou

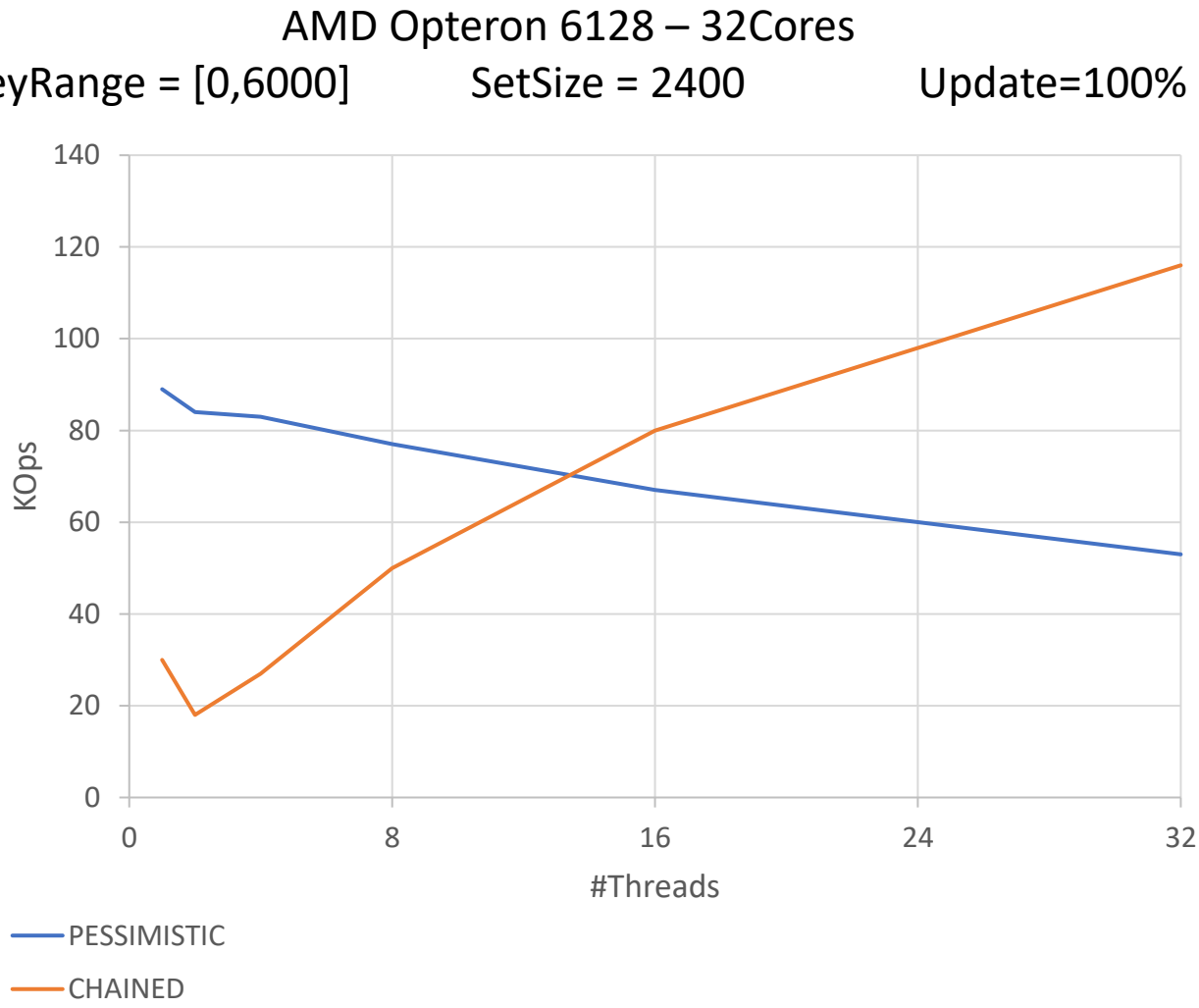


Concurrent set – Attempt 2 (SRC)

```
1. bool do_operation(int k, int op_type){
2.   bool res = true;
3.   node *l,*r;
4.   LOCK(&glock);
5.   l = search(k, &r);
6.   switch(op_type){
7.     case(INSERT):
8.       if(r->key == k)
9.         res = false;
10.      else
11.        l->next = new node(k,r);
12.      break;
13.    case(DELETE):
14.      if(r->key == k)
15.        l->next = r->next;
16.      else
17.        res = false;
18.      break;
19.  }
20.  UNLOCK(&glock);
21.  UNLOCK(&l->lock);
22.  UNLOCK(&r->lock);
23. return res;
24.}
```

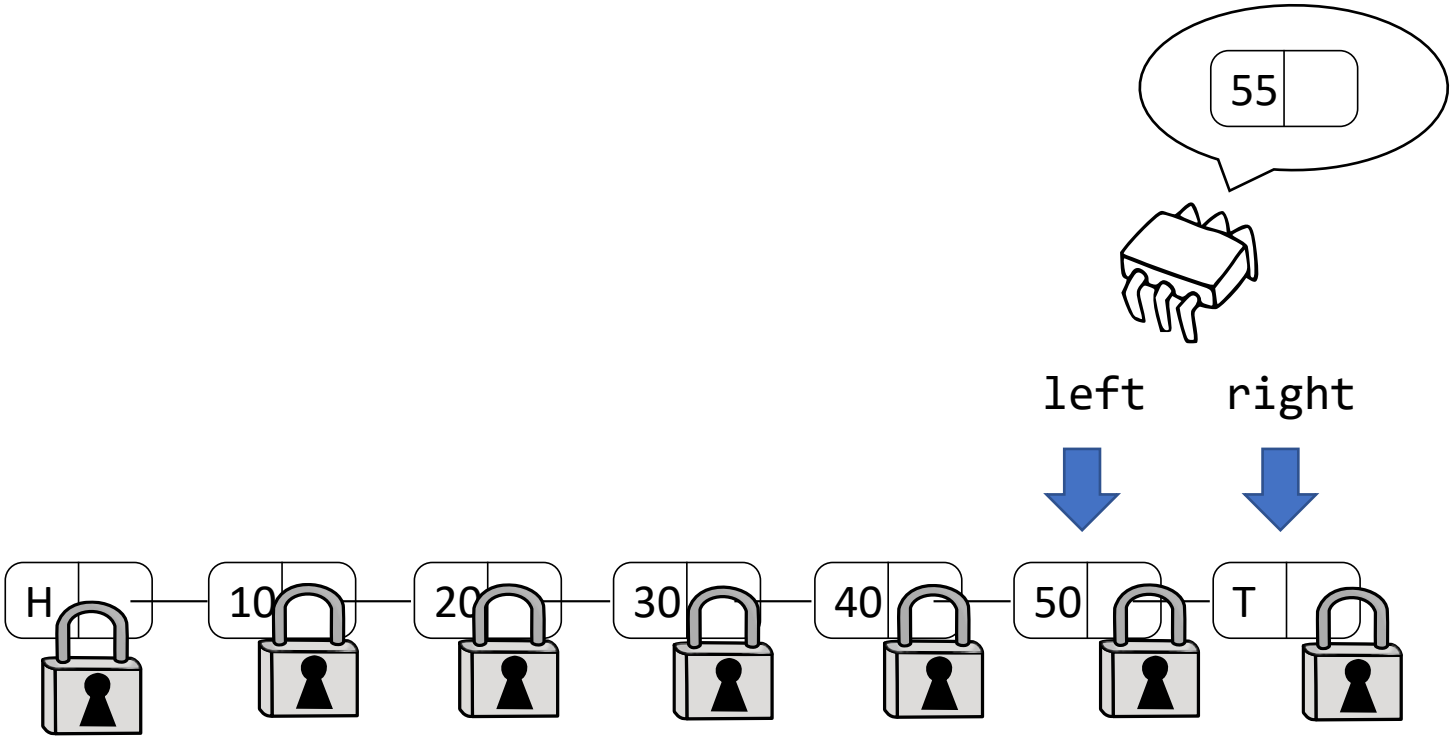
```
1. node* search(int k, node **r){
2.   node *l, *r_next;
3.   l = set->head;
4.   LOCK(&l->lock);
5.   *r = l->next;
6.   LOCK(&(*r)->lock);
7.   r_next = (*r)->next;
8.   while((*r)->key < k){
9.     UNLOCK(&l->lock);
10.    l = *r;
11.    *r = r_next;
12.    LOCK(&(*r)->lock);
13.    r_next = (*r)->next;
14.  }
15.}
```

Concurrent set – Attempt 2



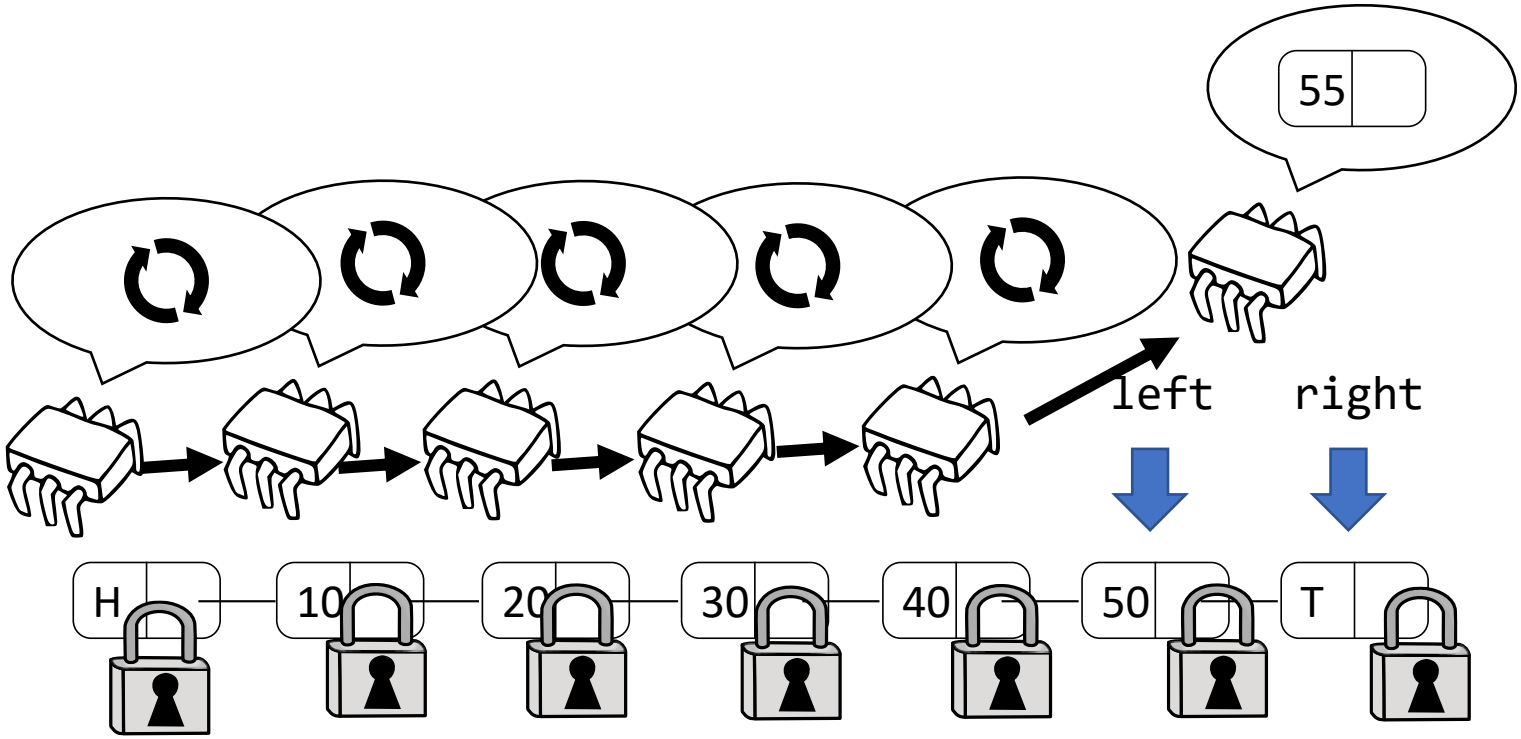
Search algorithm

- Allows an increased parallelism but…



Search algorithm

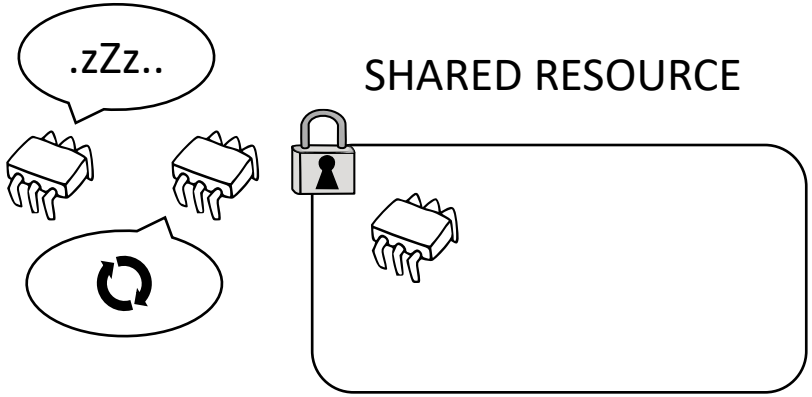
- Allows an increased parallelism but…
- High costs for lock handover



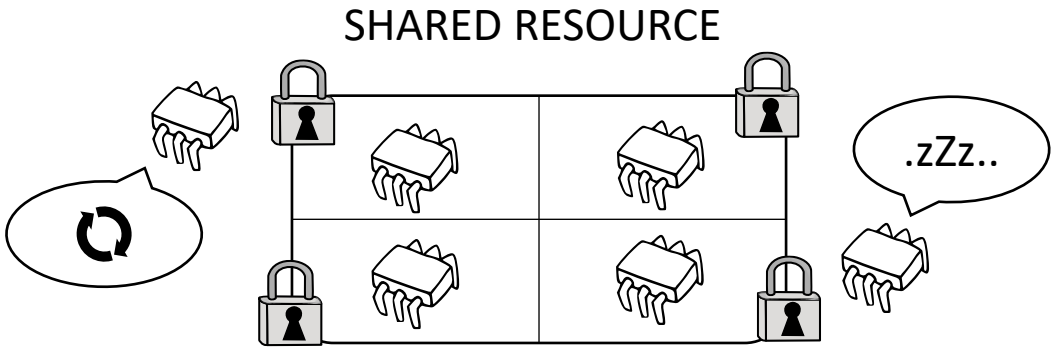
Recap

- Explored two blocking strategies:

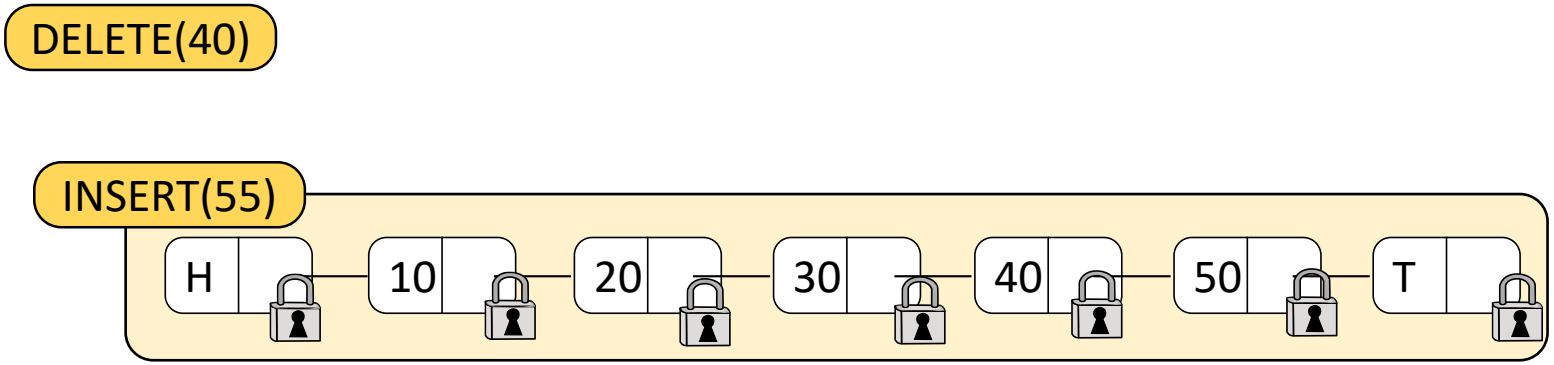
1. Global (coarse-grain) lock



2. (Fine-grain) Lock coupling

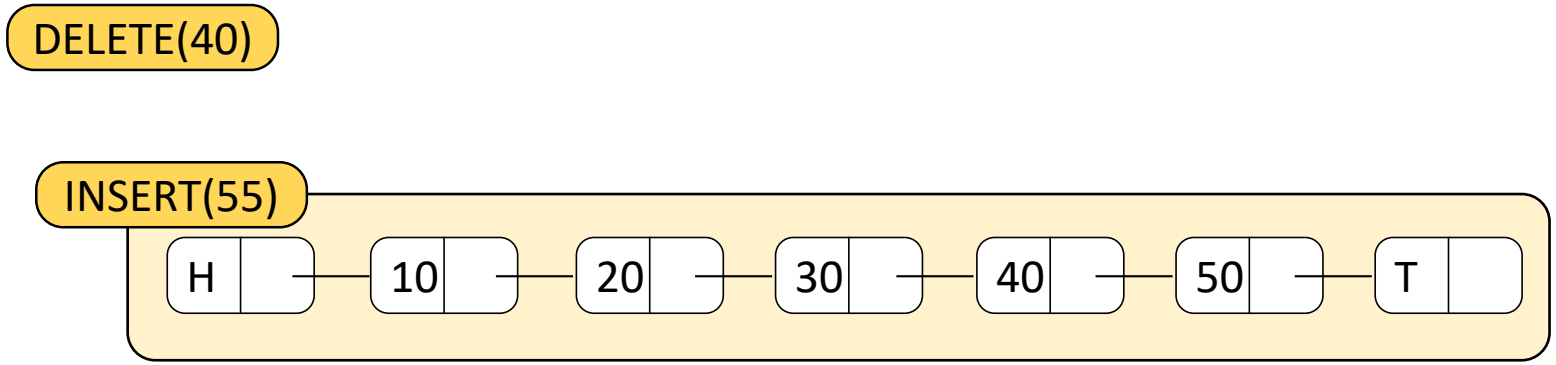


Concurrent set – Attempt 3



Concurrent set – Attempt 3

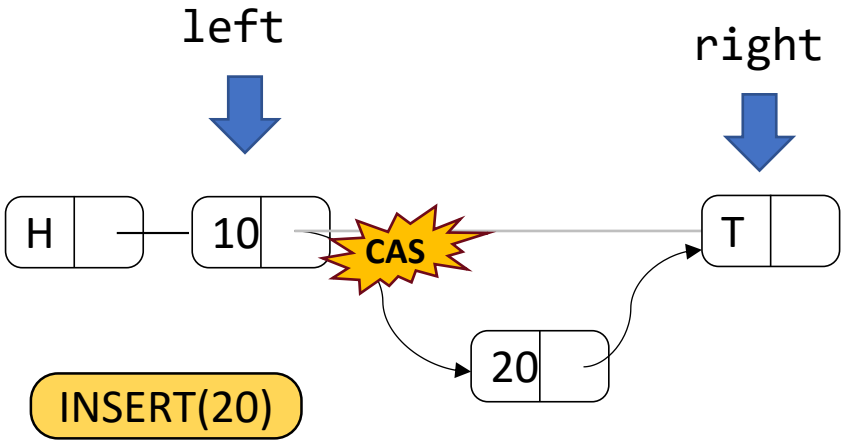
- NON-BLOCKING approach [Harris linked list]
- Search without acquiring any lock
- Apply updates with individual atomic instructions



Non-blocking insert & delete algorithms

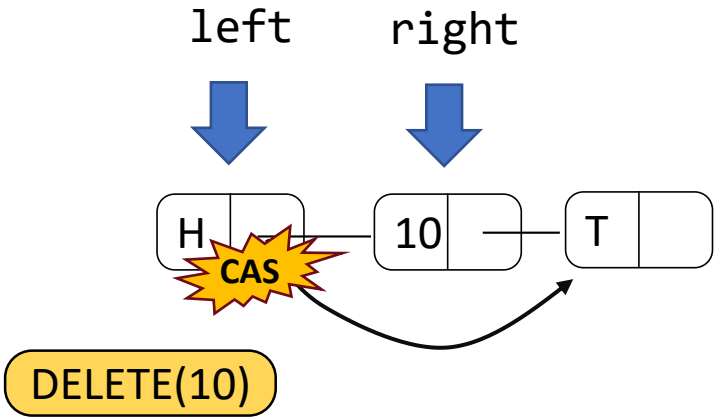
Insert:

1. Search left and right nodes
2. Insert the new item with a CAS
3. If CAS fails restart from 1



Delete:

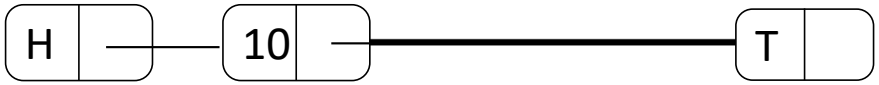
1. Search left and right nodes
2. Disconnect the item with a CAS
3. If CAS fails restart from 1



- Is it correct?

Incorrect delete algorithm

- Edge cases might lead to losing items!



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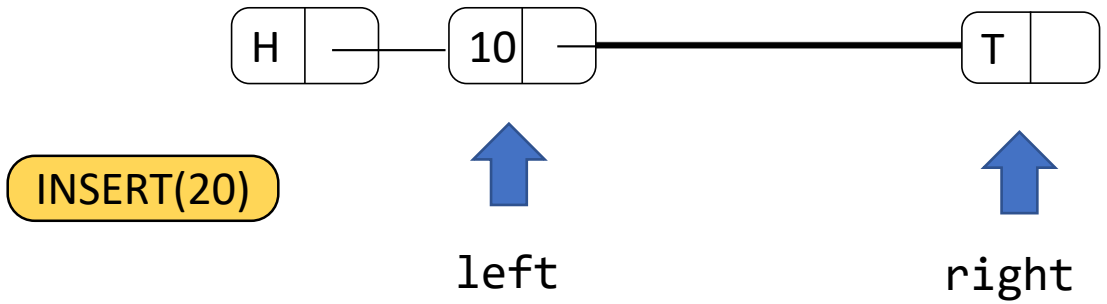
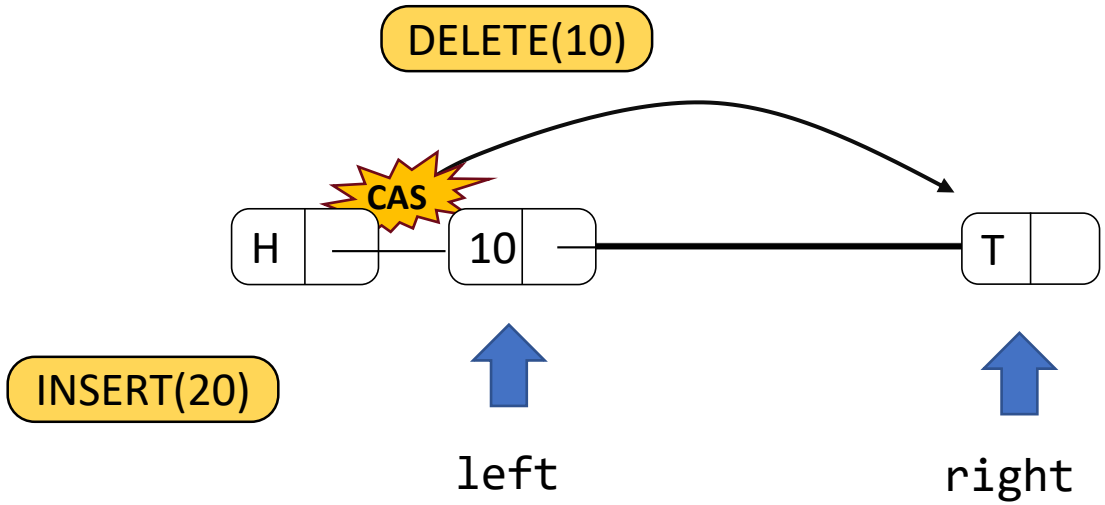


1. Thread A gets left and right node and go to sleep
2. Thread B disconnects the node containing 10
3. Thread A wakes up and add 20 after 10
4. The new item is lost

Incorrect delete algorithm

- Edge cases might lead to losing items!



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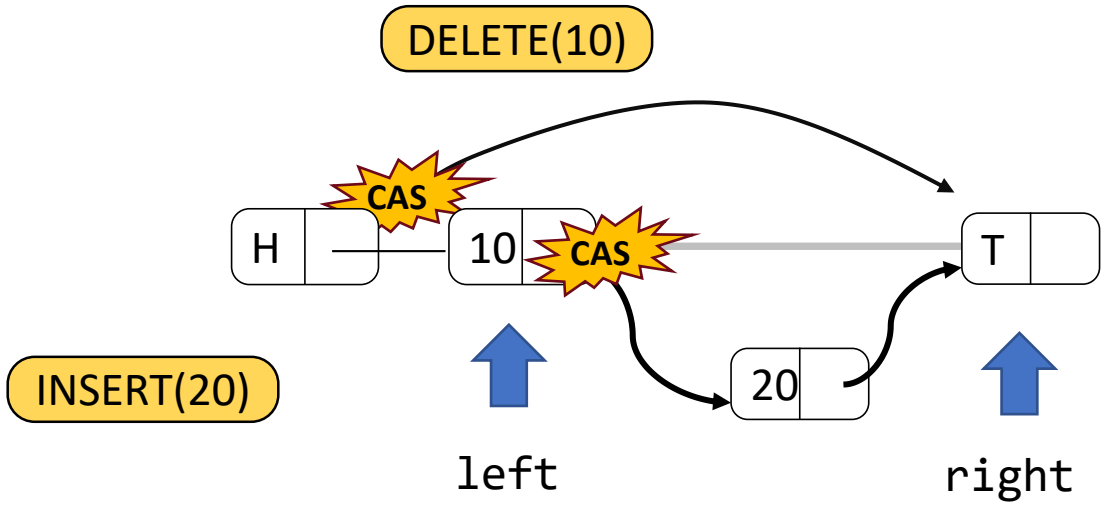

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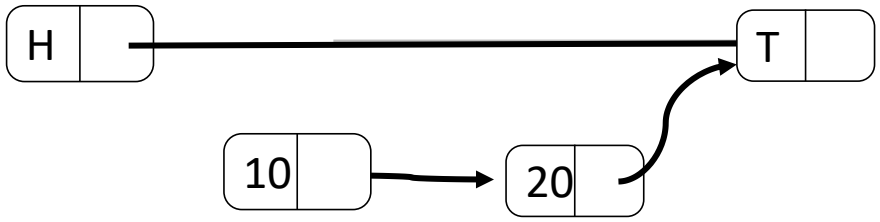

1. Thread A gets left and right node and go to sleep
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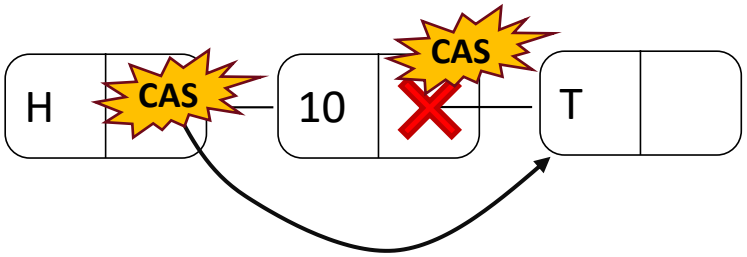
The correct delete algorithm

- Adopt logical deletion:

1. Get left and right node
2. Mark the item as deleted via CAS (*logical* deletion)
3. If CAS fails GOTO 1
4. Disconnect the item via CAS (*physical* deletion)
5. If CAS fails GOTO 4



The correct delete algorithm

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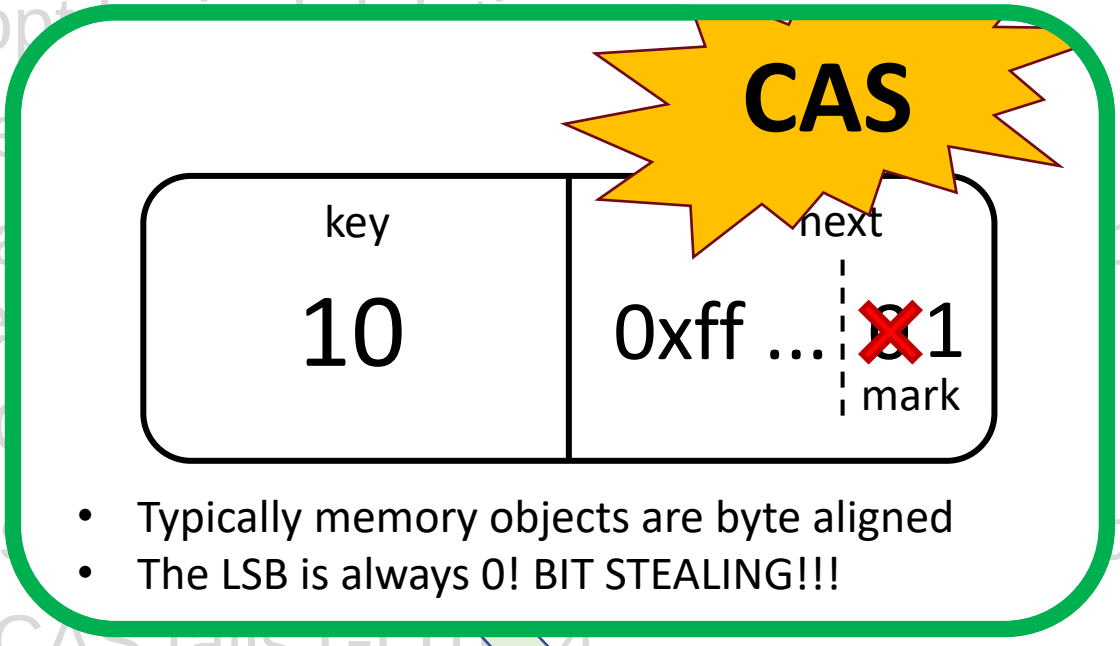

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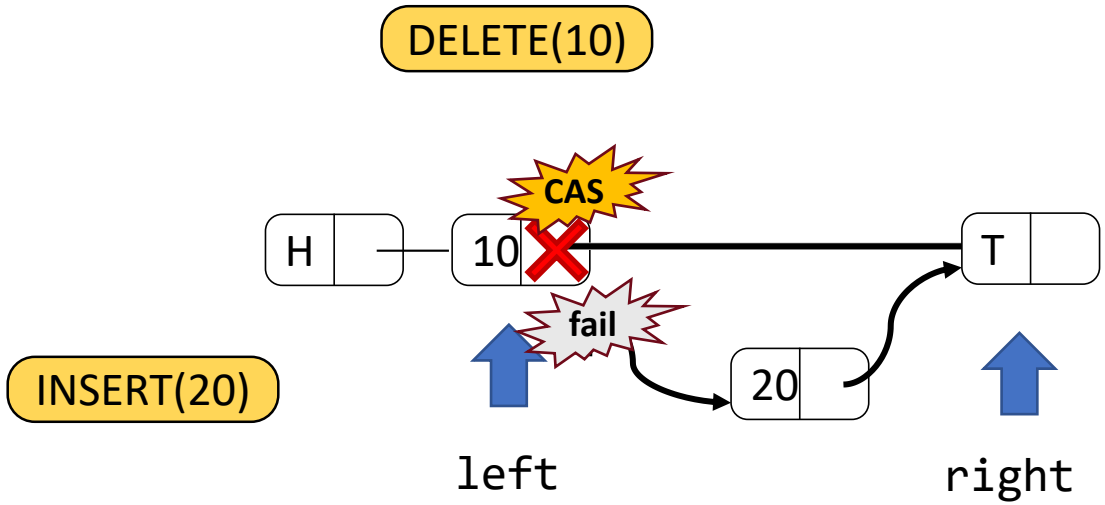
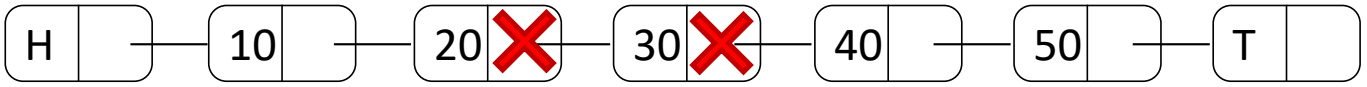


- Updates of the ”next” field by two opposite concurrent operations cannot both succeed
- What to do upon conflict (failed CAS)? RESTART FROM SCRATCH!!

Non-blocking search

- The search returns two adjacent non-marked (left and right) nodes
- Housekeeping: disconnect logically delete items during searches



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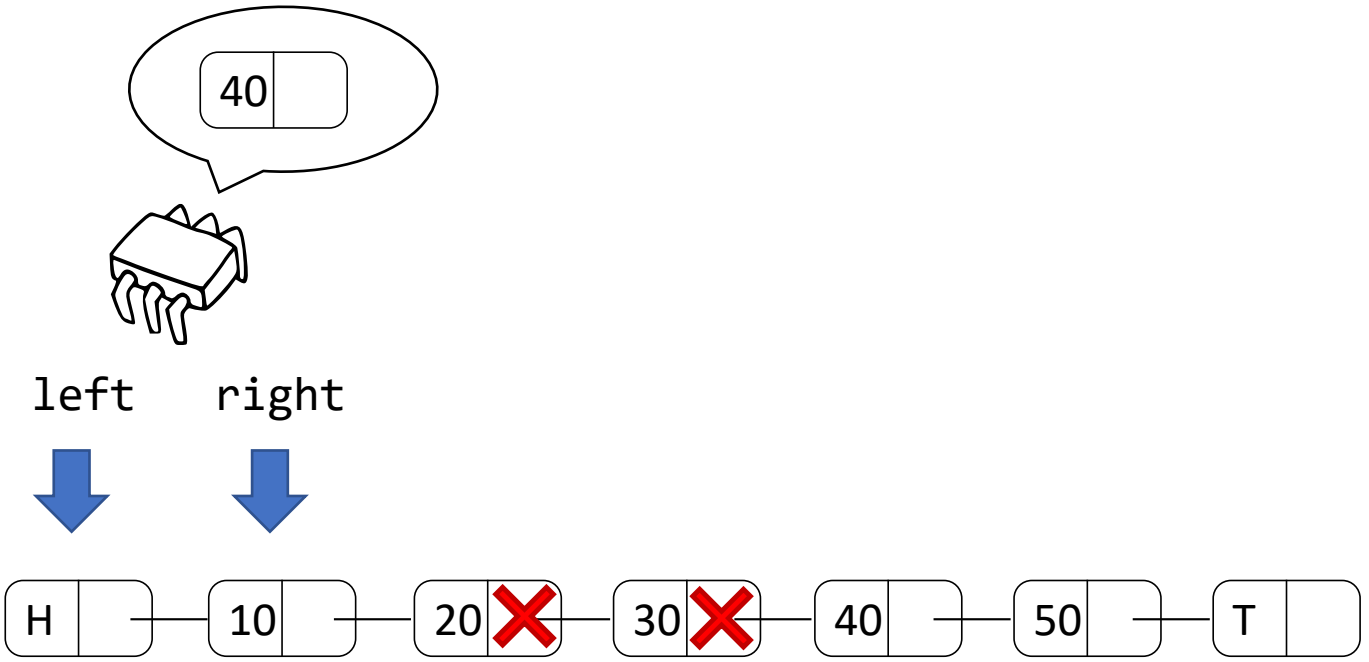

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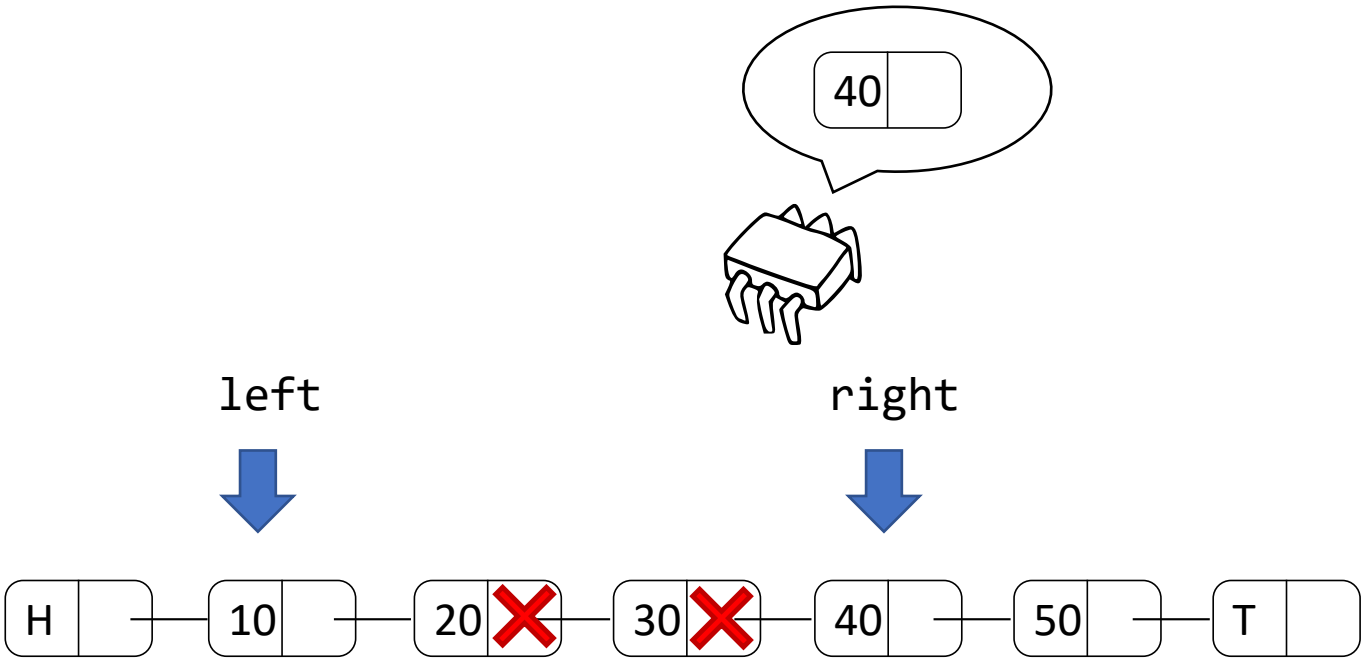

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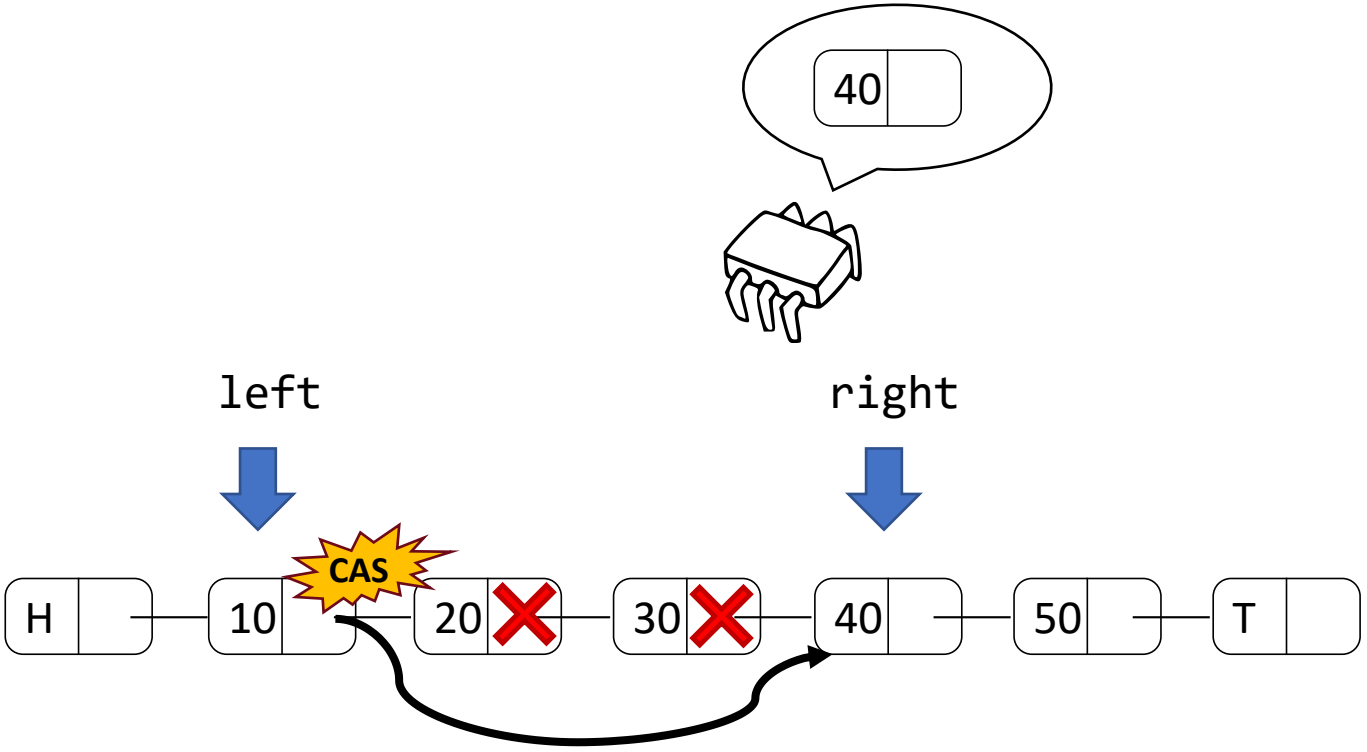

Concurrent set – Attempt 3 (SRC)

```
1. bool do_operation(int k, int op_type){
2.   node *l,*r, *n = new node(k);
3.   l = search(k, &r);                    /* get left and right node */
4.   switch(op_type){
5.     case(INSERT):
6.       if(r->key == k) return false;    /* key present in the set */
7.       n->next = r;
8.       l->next = n;                     /* insert the item        */
9.
10.
11.      break;
12.    case(DELETE):
13.      if(r->key != k) return false;    /* key not present        */
14.      l->next = r->next;               /* remove the key         */
15.
16.
17.
18.      break;
19.  }
20.  return true;
21.}
```

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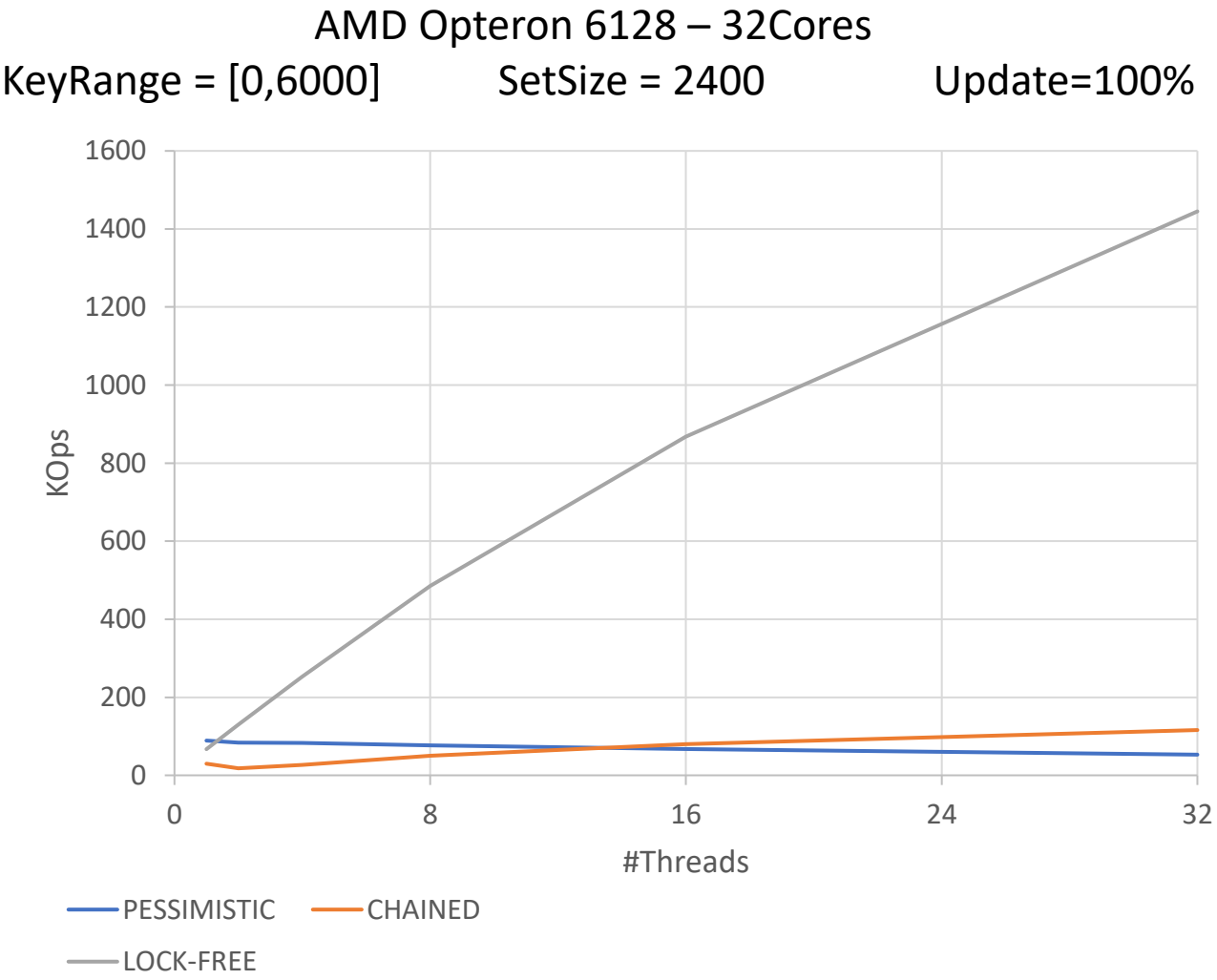
6.       if(r->key == k) return false;  /* key present in the set */
7.       n->next = r;
8.       l->next = n;                    /* insert the item        */
9.       if(!CAS(&l->next, r, n))
10.         goto 3;          /* insertion failed the item -> restart */
11.      break;
12.    case(DELETE):
13.      if(r->key != k) return false;  /* key not present        */
14.      l->next = r->next;              /* remove the key         */
15.      if(is_marked_ref((l=r->next)) || !CAS(&r->next, l, mark(l)))
16.         goto 3;          /* insertion failed the item -> restart */
17.      search(k,&r);                   /* repeat search          */
18.      break;
19.  }
20.  return true;
21.}
```

Concurrent set – Attempt 3 (SRC)

```
1.  node* search(int k, node **r){
2.    node *l, *t, *t_next, *l_next;
3.    *t = set->head;
4.     t_next = t->head->next;
5.     while(1){                          /* FIND LEFT AND RIGHT NODE */
6.        if(!is_marked(t_next)){
7.           l = t;
8.           l_next = t_next;
9.        }
10.      t = get_unmarked_ref((t_next);
11.      t_next = t->next;
12.      if(!is_marked_ref(t_next) && t->key >= k) break;
13.   }
14.   *r = t;
15.   /* DEL MARKED NODES */
16.   if(l_next != *r && !CAS(&l->next, l_next, *r) goto 3;
17.   return l;
18. }
```

Concurrent set – Attempt 3



Safety and liveness guarantees

- The algorithm is NON-BLOCKING (LOCK-FREE):
  - If a thread A is stuck in a retry loop => a CAS fails each time
  - If a CAS fail, it is because of another CAS that was successfully executed by a thread B
  - Thread B is making progress
- The algorithm is LINEARIZABLE:
  - Each method execution take effect in an atomic point (a successful CAS) contained between its invocation and reply
  - The order obtained by using these points has been proved to be compliant with the Set semantic

Progress (Lock freedom)

- Each method update method has two main steps
  - A search, which might end with a CAS
  - A CAS to insert delete a node

1. Suppose an update method is stuck in a search:
   - The key range is finite, so the number of node is finite
   - It continuously fails to disconnect marked nodes
   - It means that new nodes have been both inserted and marked!
     - Other threads have completed update methods
2. Suppose an updated method always fails its last step (insertion or marking)
   - Other threads have modified the target next pointer
   - If it is due to the disconnection of marked nodes, see point 1
   - If it is due to the updated step other methods have completed

Safety (Linearizability)

1. The search returns 2 adjacent nodes in an atomic point
    1. The read of next field of the left node
    2. The CAS that make left and right adjacent

- It is like that the search made a snapshot of interested key interval

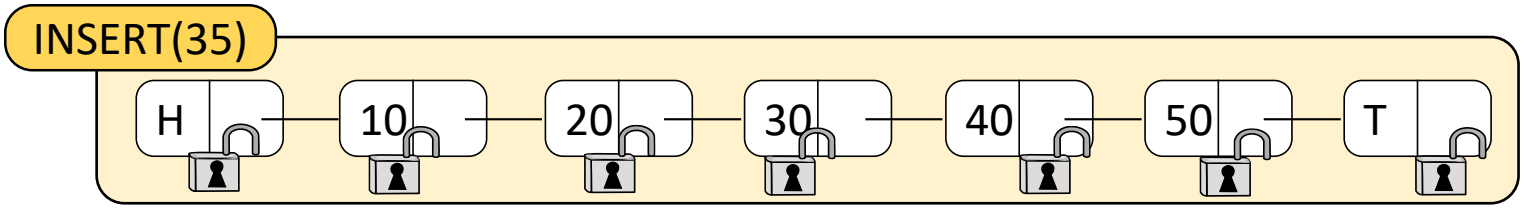
2. Find, unsuccessful delete and unsuccessful insert linearize with the search (1.1 or 1.2)
3. Insert linearizes with the successful CAS to connect a new node
4. Delete linearizes with the successful CAS to mark a node

Problems

- It is not possible to flip a bit of a reference on memory-managed languages (e.g. JAVA)
- How to solve?

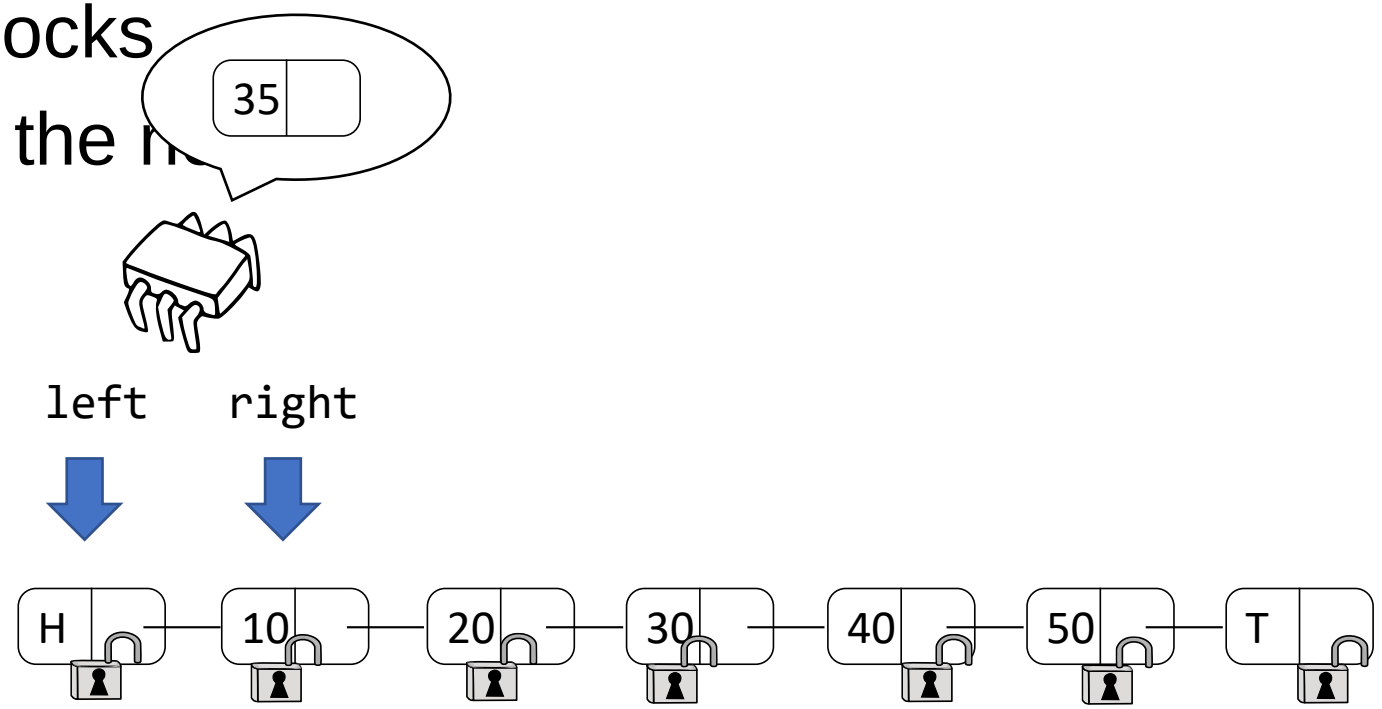
Locks + Optimism

- Use one lock per node
- Move “marked” to a dedicated field



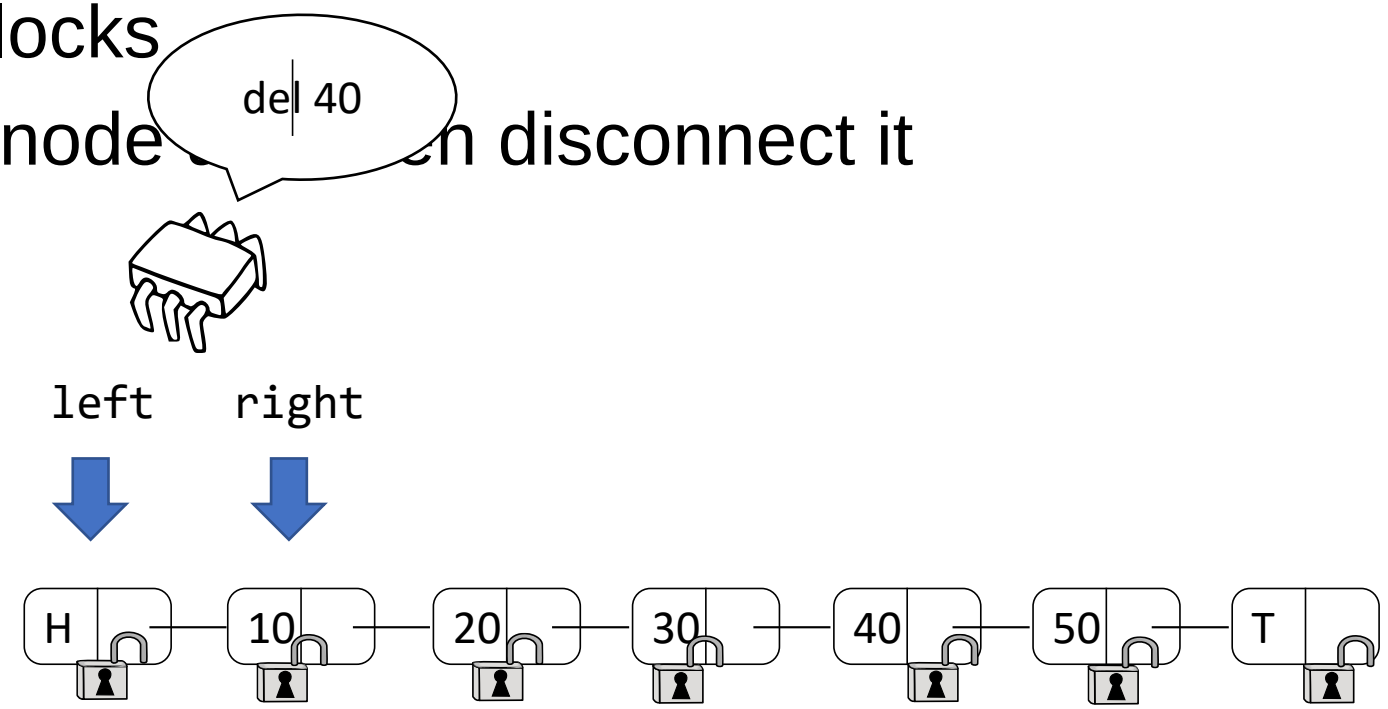
Locks + Optimism (insert)

- Use one lock per node
- Move “marked” to a dedicated field
- Find left and right without taking locks!
- Take locks
- Insert the n



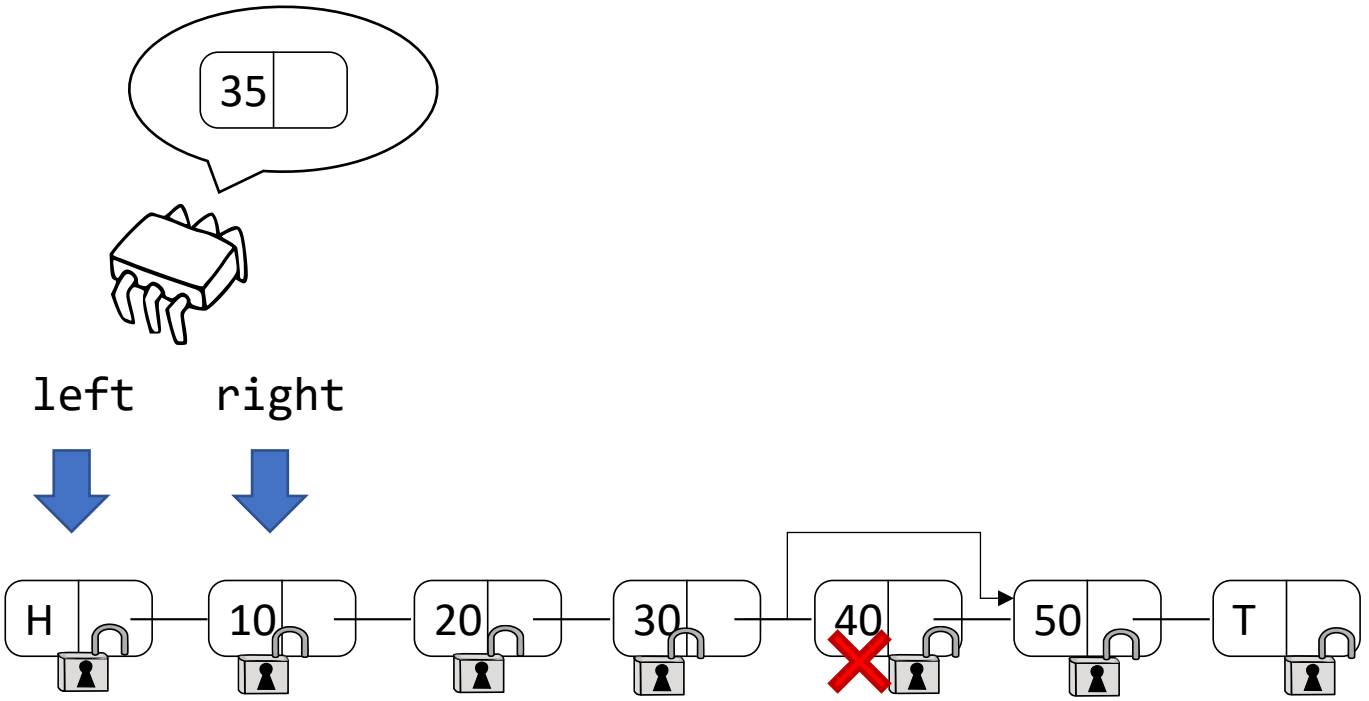
Locks + Optimism (delete)

- Use one lock per node
- Move “marked” to a dedicated field
- Find left and right without taking locks!
- Take locks
- Mark node [illegible]n disconnect it



Locks + Optimism (delete)

- Why “optimistic”? Do work (search) and hope nothing wrong happens!
- What could go wrong?



Locks + Optimism (delete)

- Why “optimistic”? Do work (search) and hope nothing wrong happens!
- What could go wrong?
  - Left and/or right being marked
  - Left and right not adjacent
- How to solve?
- Validation of search results:
  - Left unmarked
  - Right unmarked
  - Left.next = right

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Locks + Optimism = Lazy List

- What about correctness?
- What about progress?

Can we do better?

- Costs: O(n)
- Starting from scalable “simple” set implementation we can build faster set implementations
  - Hash table: O(1)
    - Array of buckets
    - Buckets are concurrent ordered-list based sets
- We know that a search in an ordered set could be more efficient O(log(n))
- How?