# Concurrent Algorithms & Memory

**Concurrent Algorithms**

**Fall 2018**

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[Some slides courtesy of Tudor David]

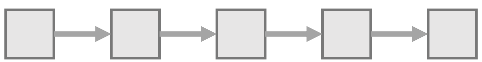
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

# Introduction

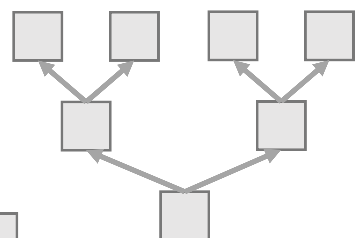
- This lecture is about memory in how it relates to concurrent computing
- So far, we have assumed that memory is:
  - Infinite
  - Volatile
- These assumptions need not be true:
  - ~~Infinite~~ -> Finite -> **Memory reclamation**
  - ~~Volatile~~ -> **Persistent**
- Both topics of ongoing research (my thesis)

# Concurrent Data Structures

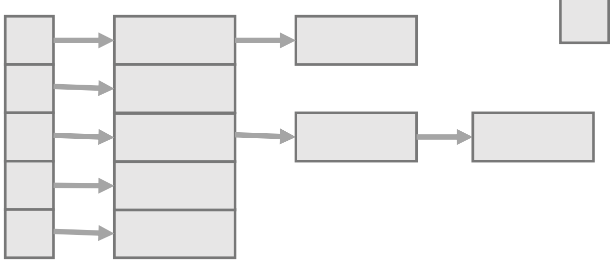
Lists



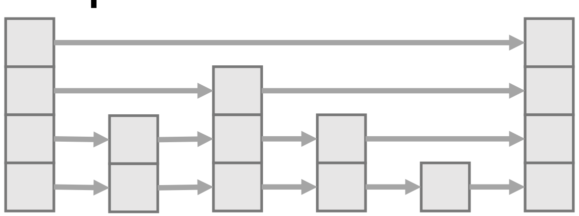
Trees



Hash tables



Skip lists



Linux

MySQL

RocksDB

monetdb

LEVELDB

MEMCACHED

mongoDB

Part 1

# Concurrent Memory Reclamation

# What is Memory Reclamation (MR)?

- Applications need memory
- Most realistic applications grow and shrink in memory
- Grow = allocate memory
- Shrink = free no-longer-useful memory

# What is Memory Reclamation (MR)?

```
ds = new_data_structure(…);
node n = new_node(…);
insert(ds, n);
// use n in some way
remove(ds,n);
```

Need to free n!

# Freeing Memory is Necessary

- Otherwise, applications might run out of memory or use too much memory

# Automatic Garbage Collection

- Some languages (e.g., Java) have automatic memory management
- Memory is allocated & freed without explicit programmer intervention
- Garbage collector decides automatically when a pointer should be freed

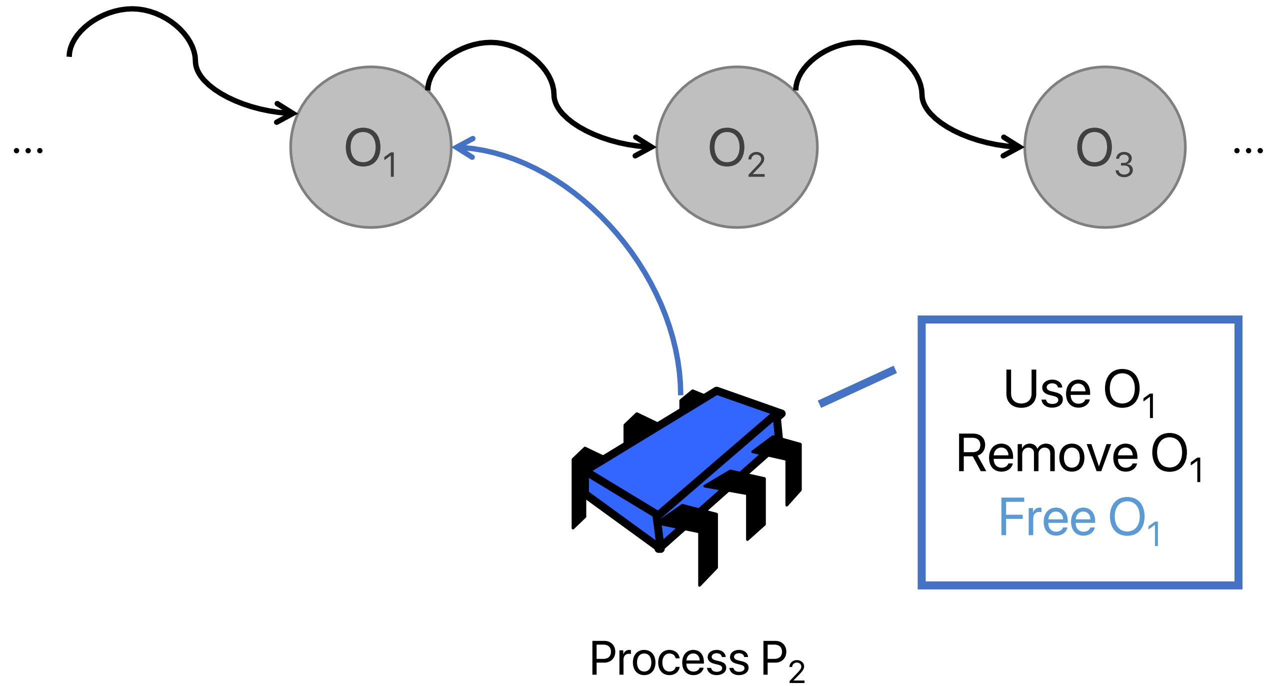
# Explicit Memory Management

- Other languages (e.g., C, C++) require the programmer to allocate & free memory explicitly
- Programmer needs to determine when to free some memory location
- This is our focus for this class

# 1-process MR is Easy

- Allocate some memory
- Use it
- Free after last use

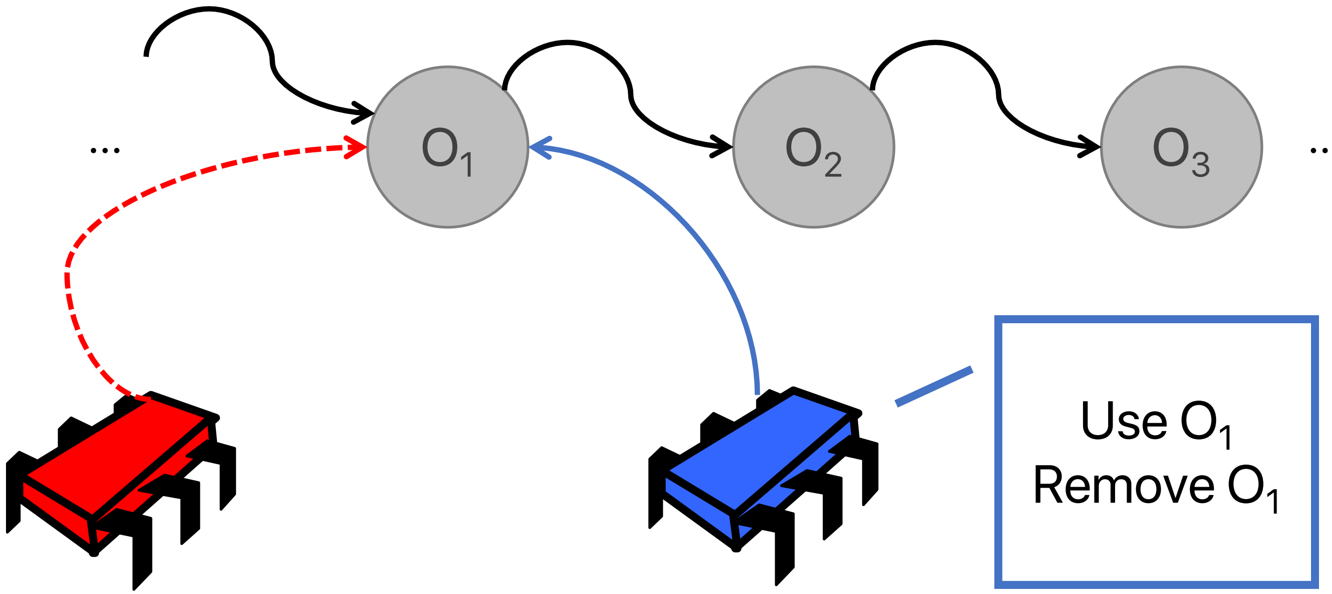
# 1-process MR is Easy



# Concurrent MR is Difficult

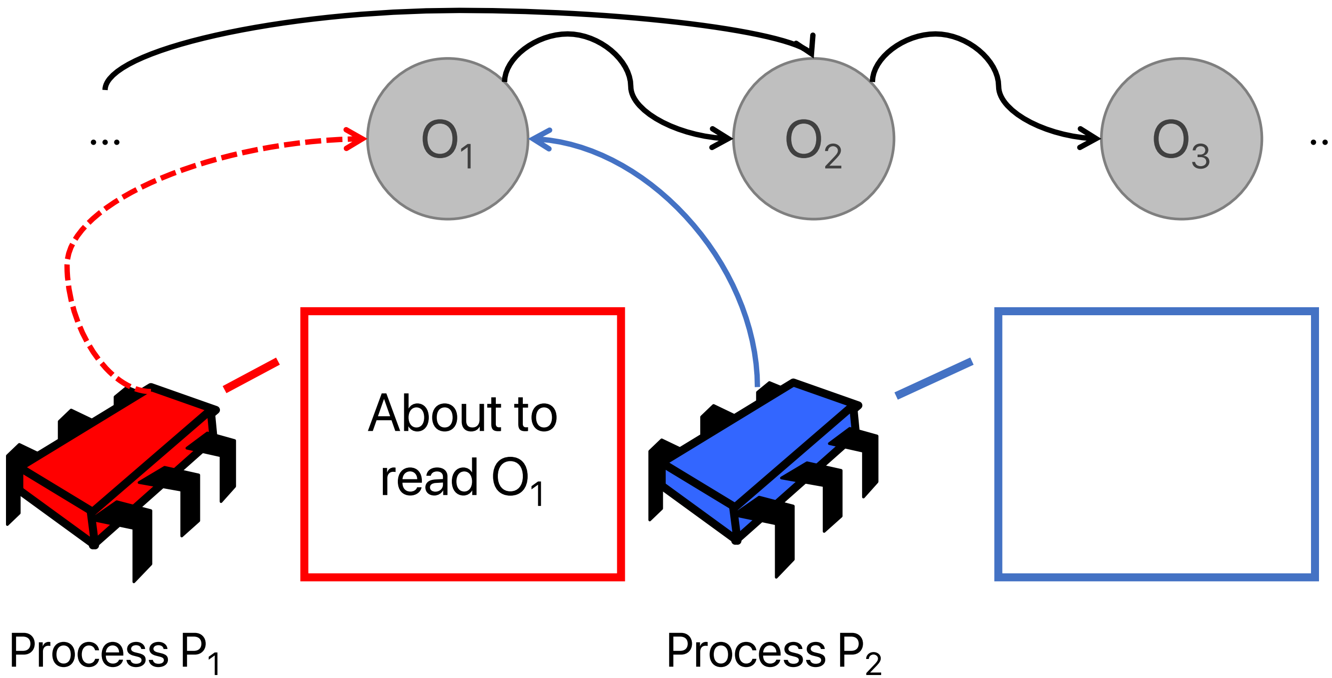
- No easy way for a process to determine if a memory location will be used later by a different process

# Concurrent MR is Difficult




Process $P_1$ Process $P_2$

# Concurrent MR is Difficult



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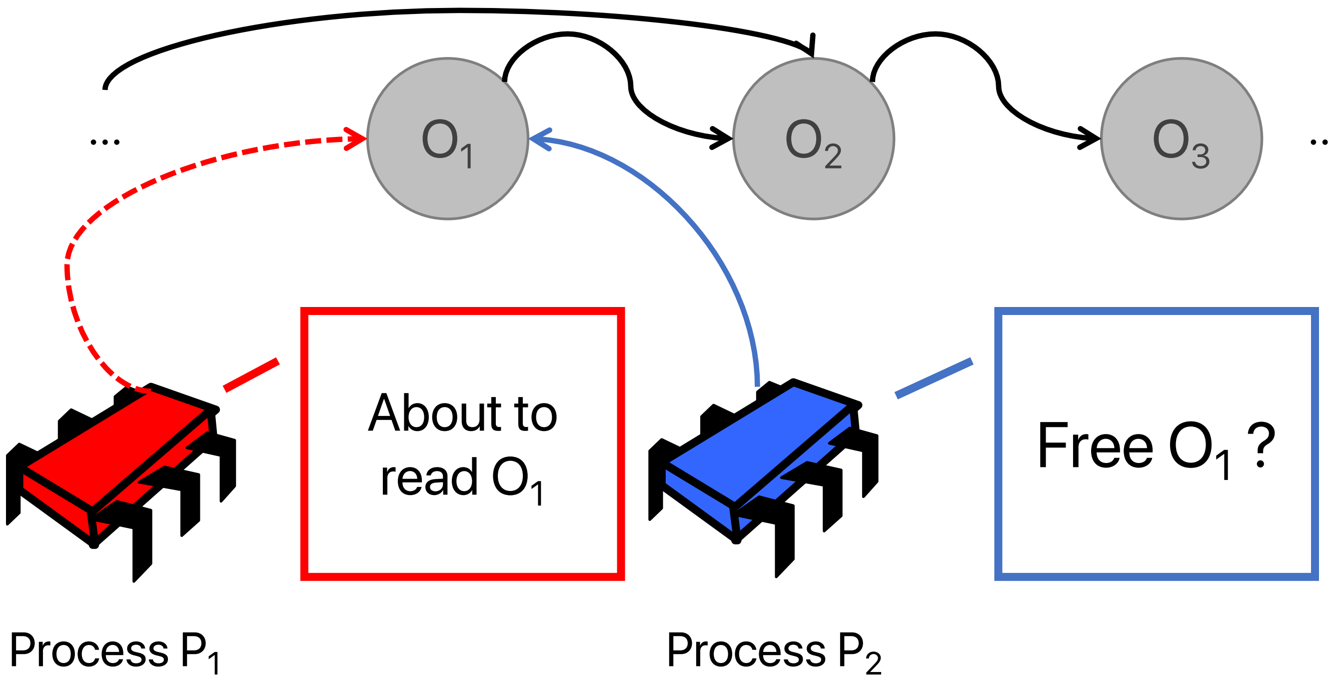

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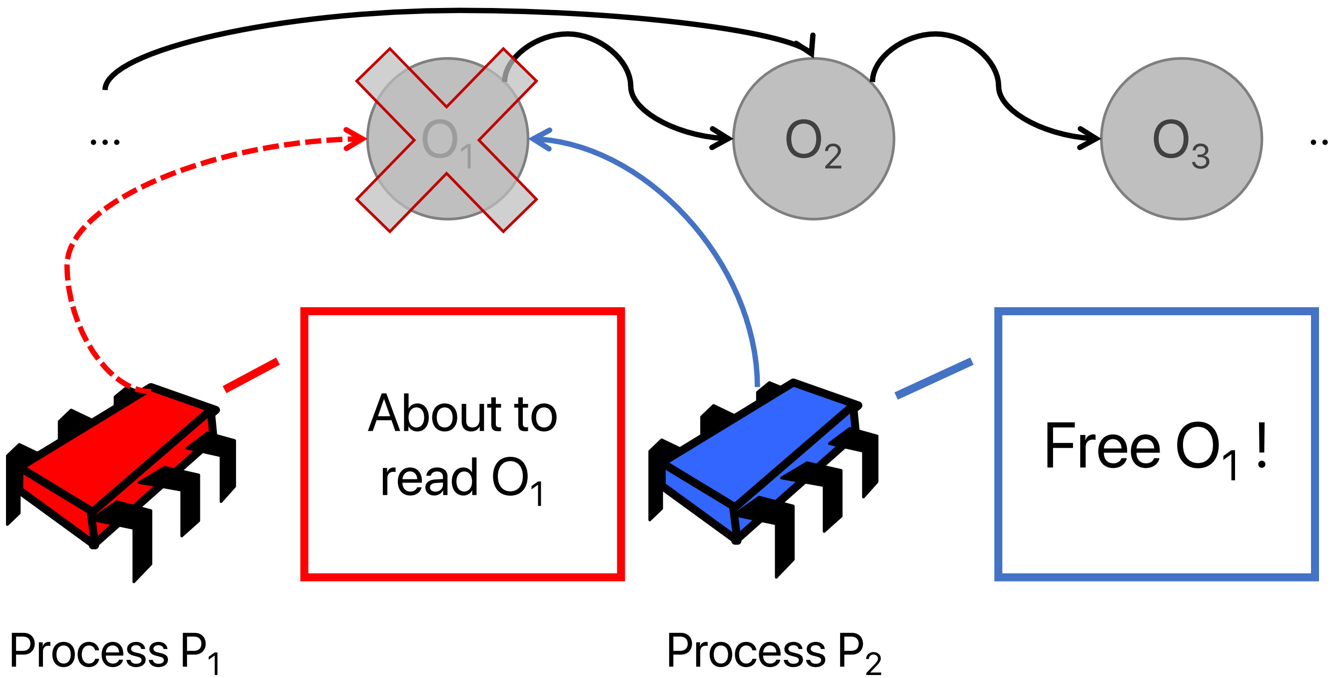

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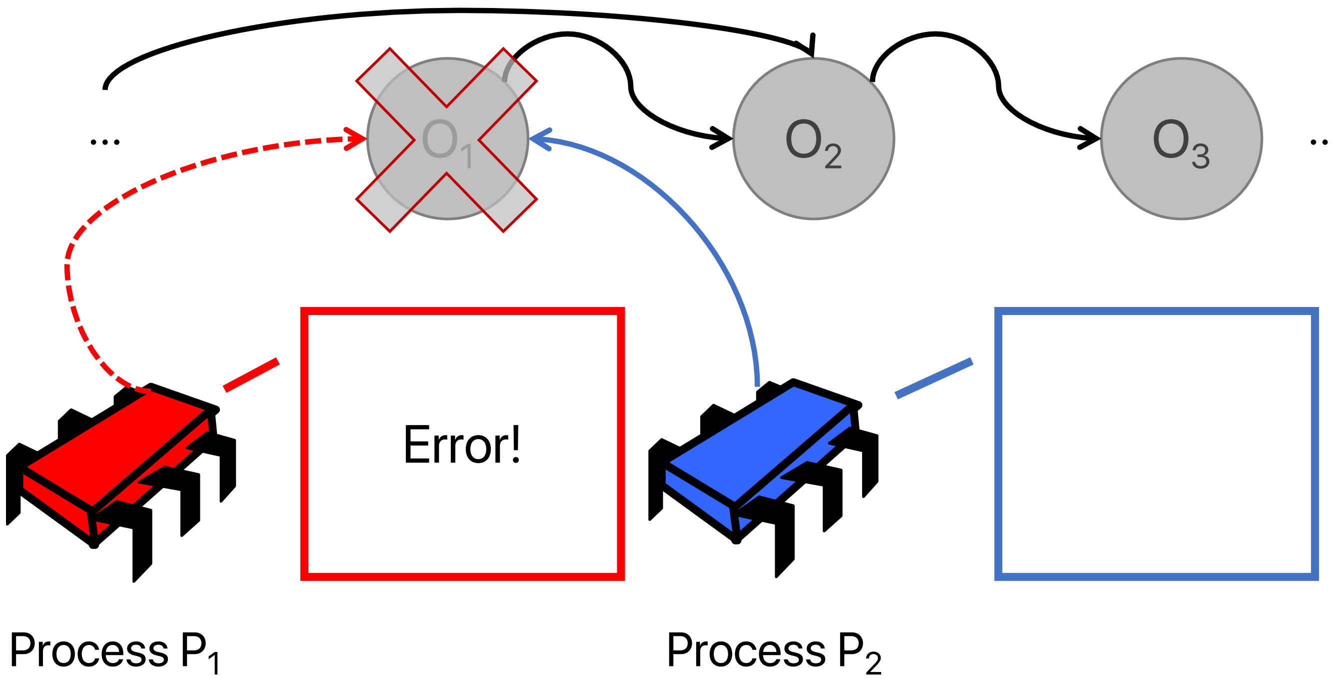


# Take-away So Far

- Memory reclamation = deciding when to free memory
- Necessary:
  - Most applications need to allocate + free
  - C, C++ are here to stay
  - No MR → excessive memory use
- Challenging (concurrent case):
  - Need a way to determine when all processes are done with some memory location

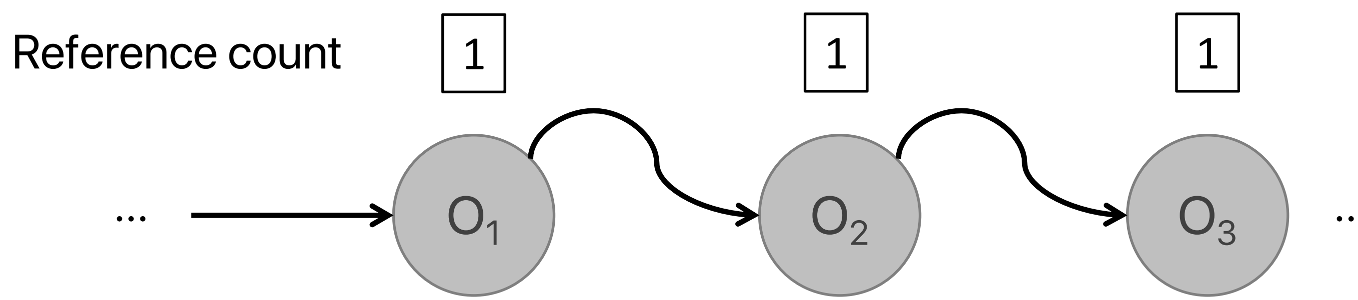
# A Few MR Techniques

- Lock-free Reference Counting
- Hazard Pointers
- Epoch-Based Reclamation

# Lock-free Reference Counting

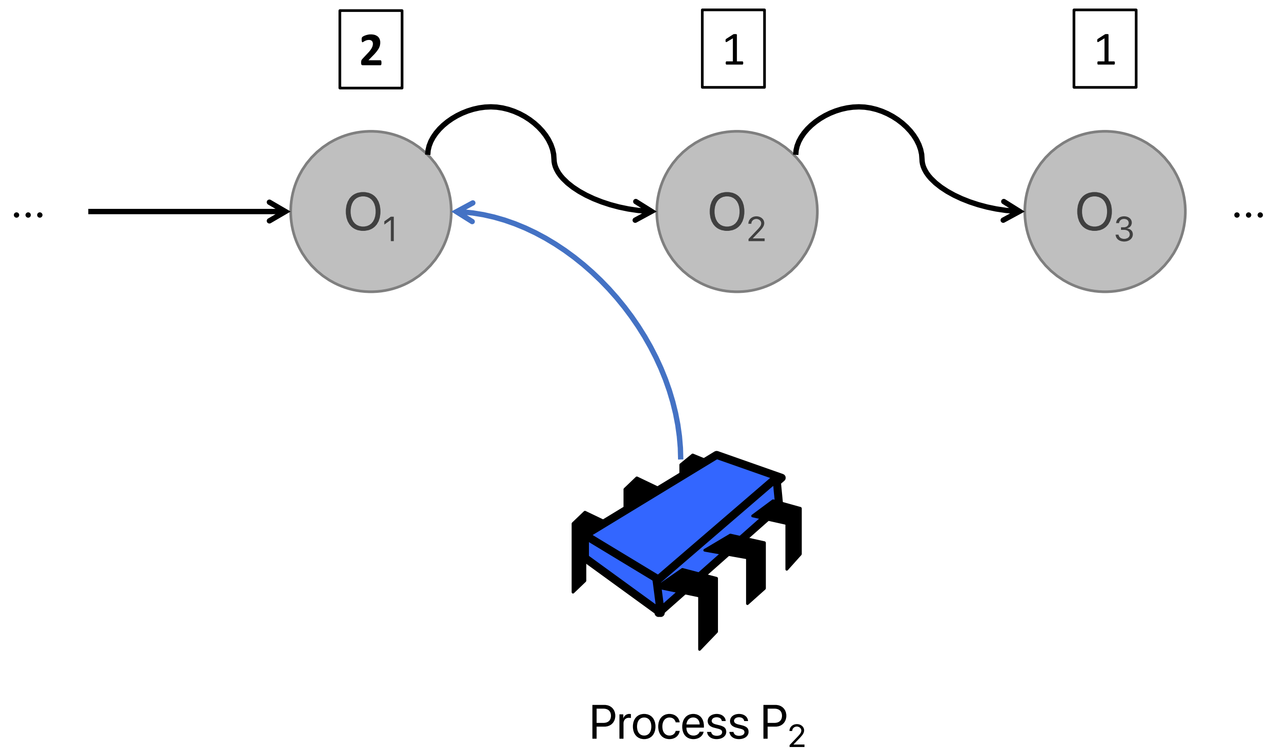
- Main idea:
  - For each memory location, keep track of how many references are held to it.
  - When there are 0 references, safe to reclaim.

# LFRC Example



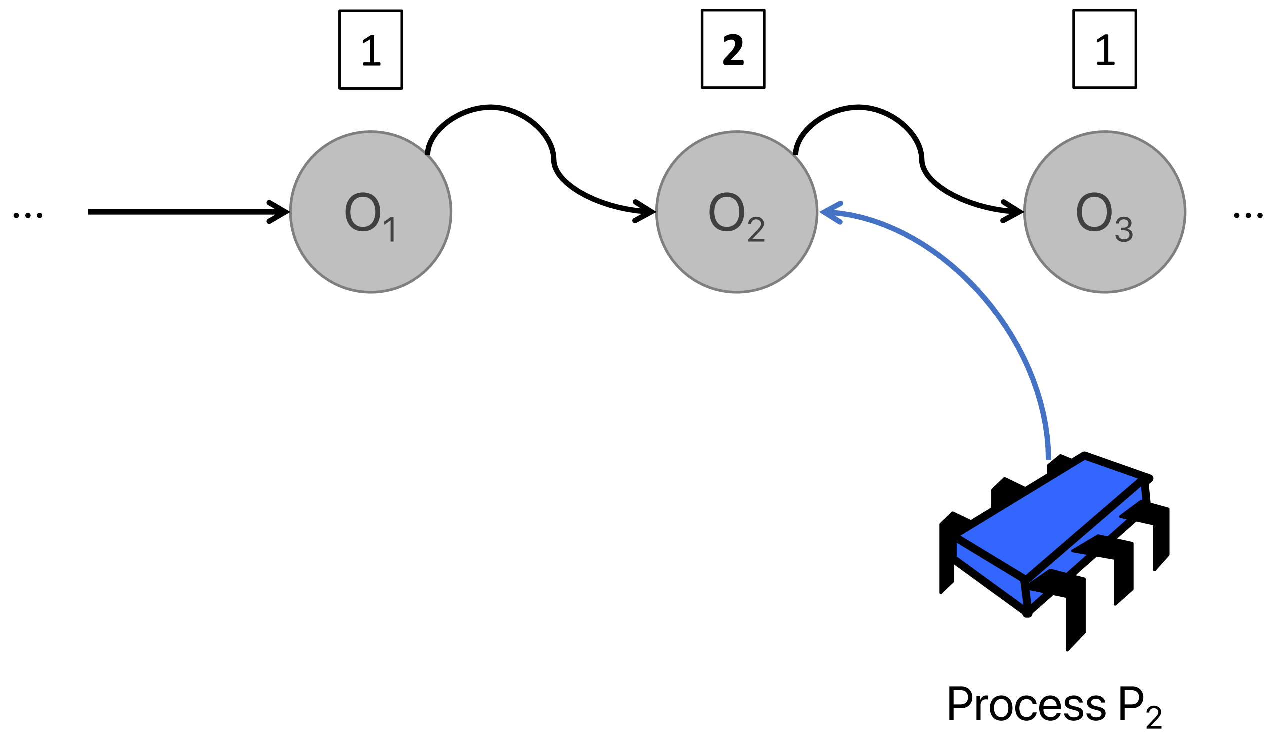

*A linked list. No process has references. Each node has reference count = 1 (the reference from the previous node in the list).*

# LFRC Example




*A thread is reading. The node that the thread is currently looking at has reference count = 2.*

# LFRC Example

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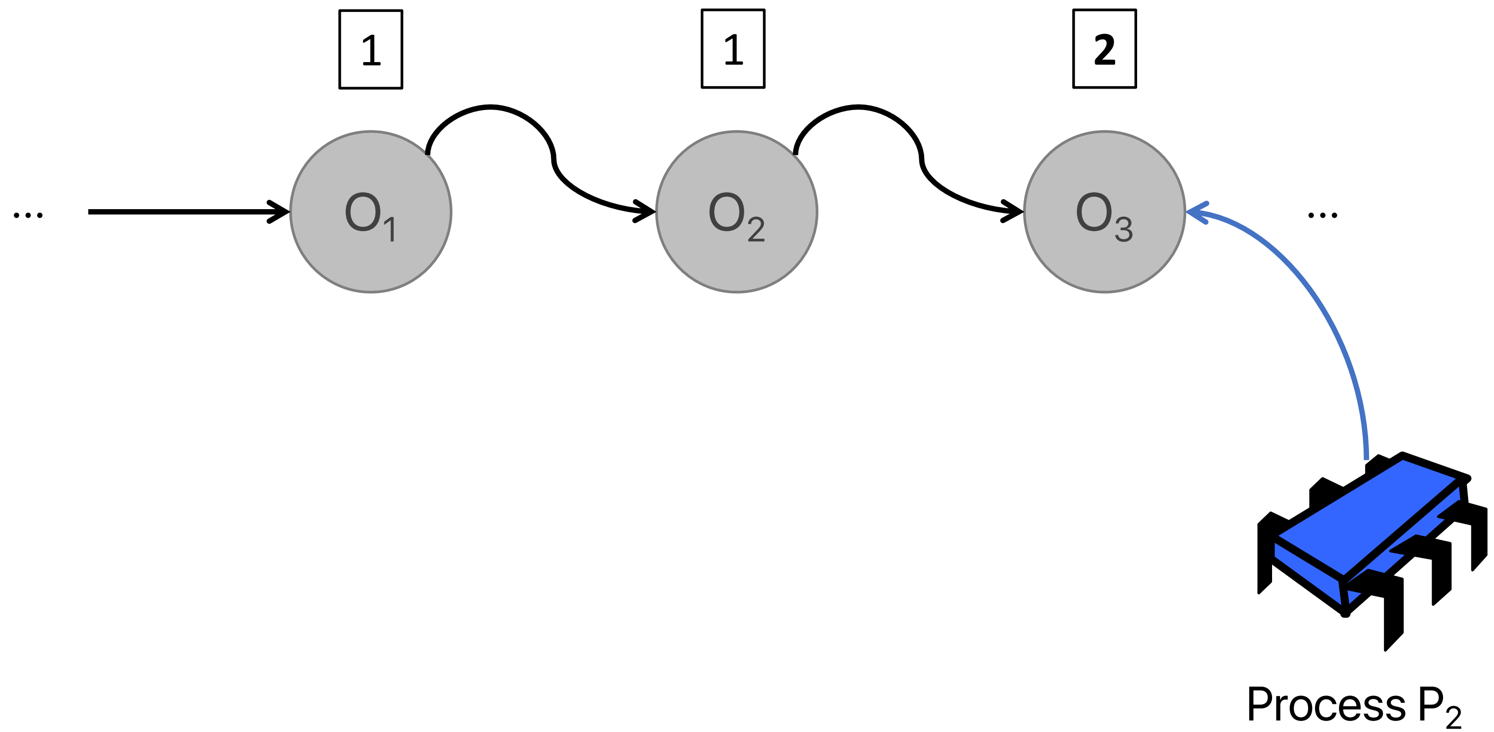


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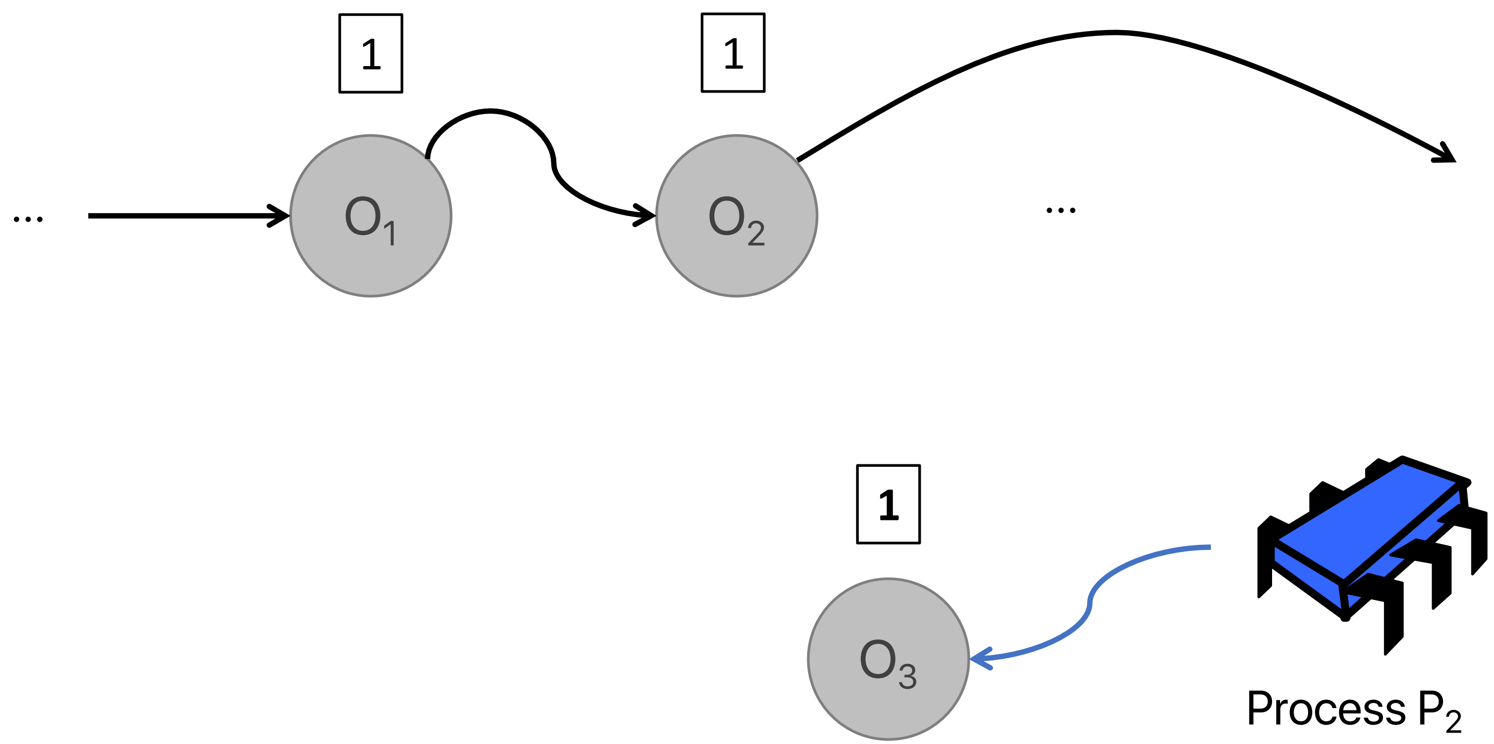
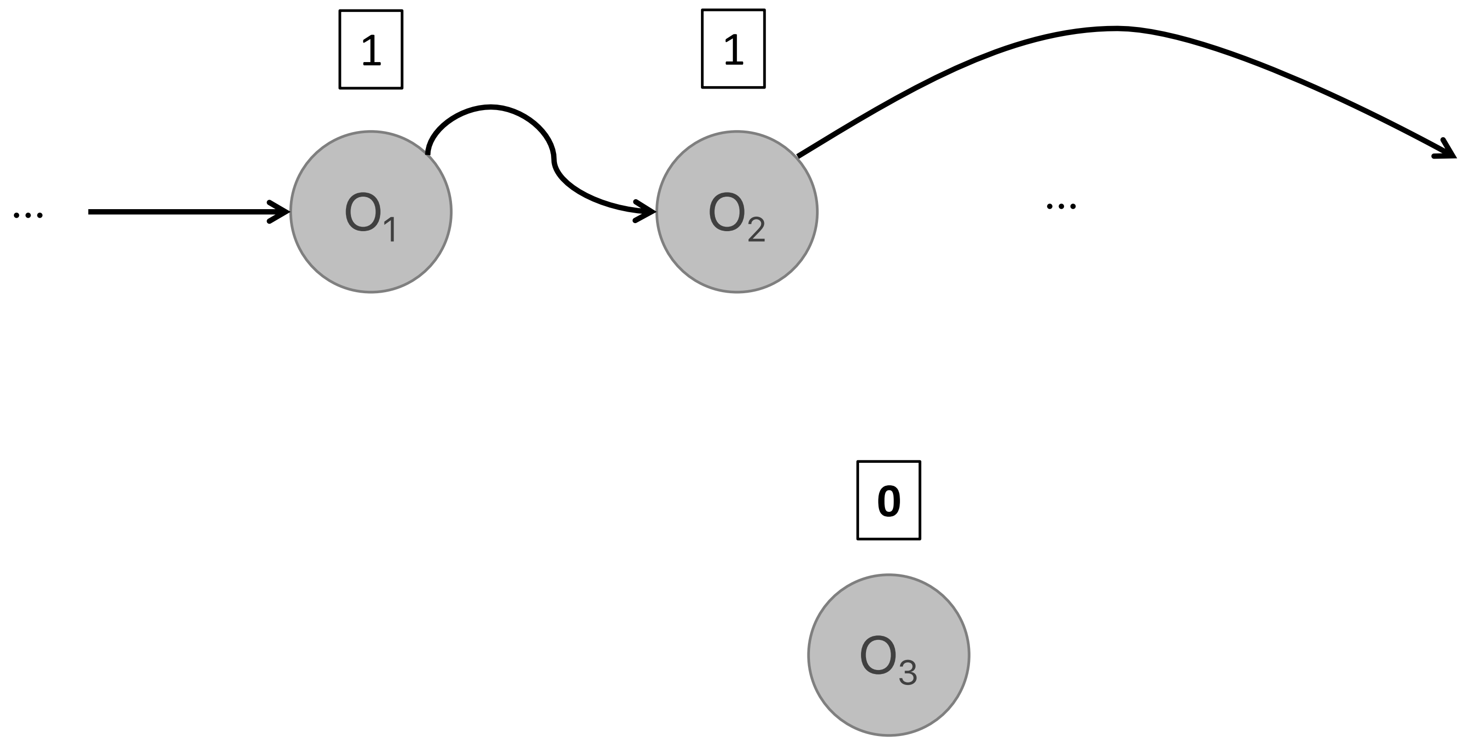



*A thread has removed node $O_3$ from the list. $O_3$ now has reference count = 1 (the reference from the thread).*

# LFRC Example




*The thread has released its reference to $O_3$. $O_3$ now has 0 references. Its memory can be freed.*

# Pros and cons of LFRC

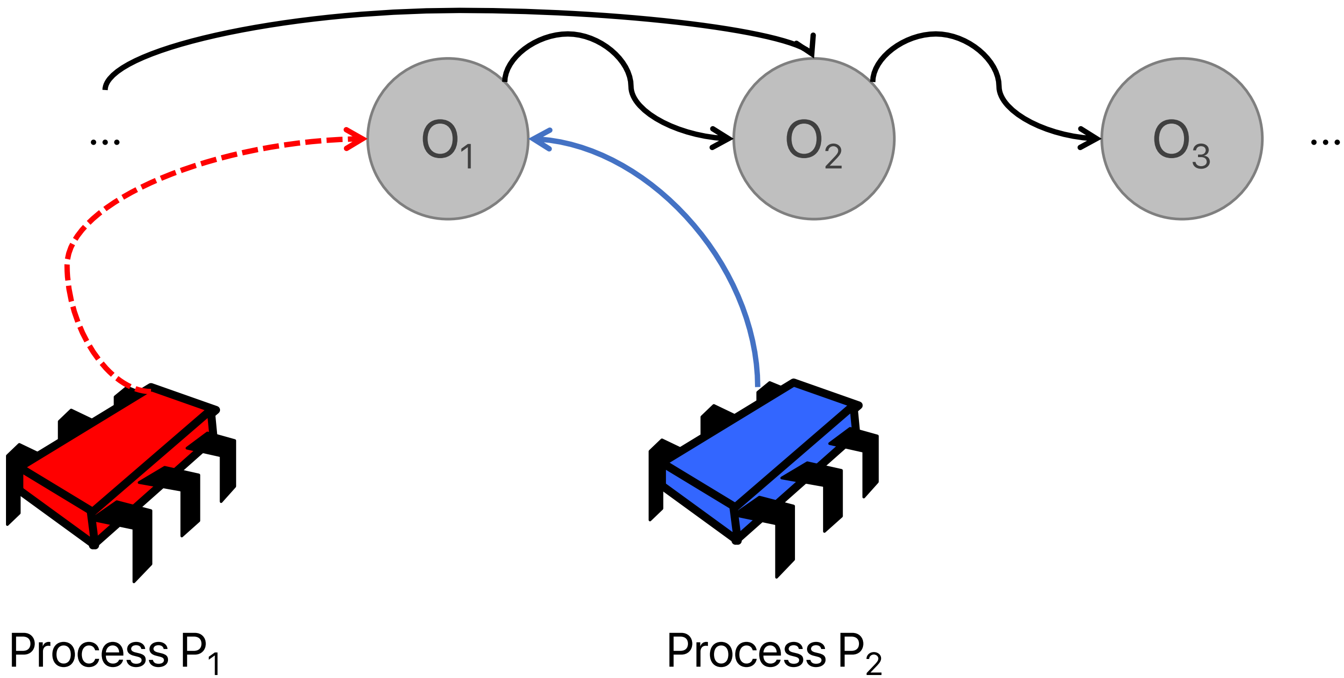
- ✓ Lock-free (wait-free version exists)
- ✓ Easy to understand & implement

- ✗ Need to update reference counter on every access, even if read-only → bad performance
- ✗ Update of reference counter requires expensive atomic instructions → extremely bad performance!

# Hazard Pointers (HP)

- Main idea:
  - Each process announces memory locations it plans to access: hazard pointers
  - Processes only free memory that is not protected by hazard pointers

# Hazard Pointers (HP)



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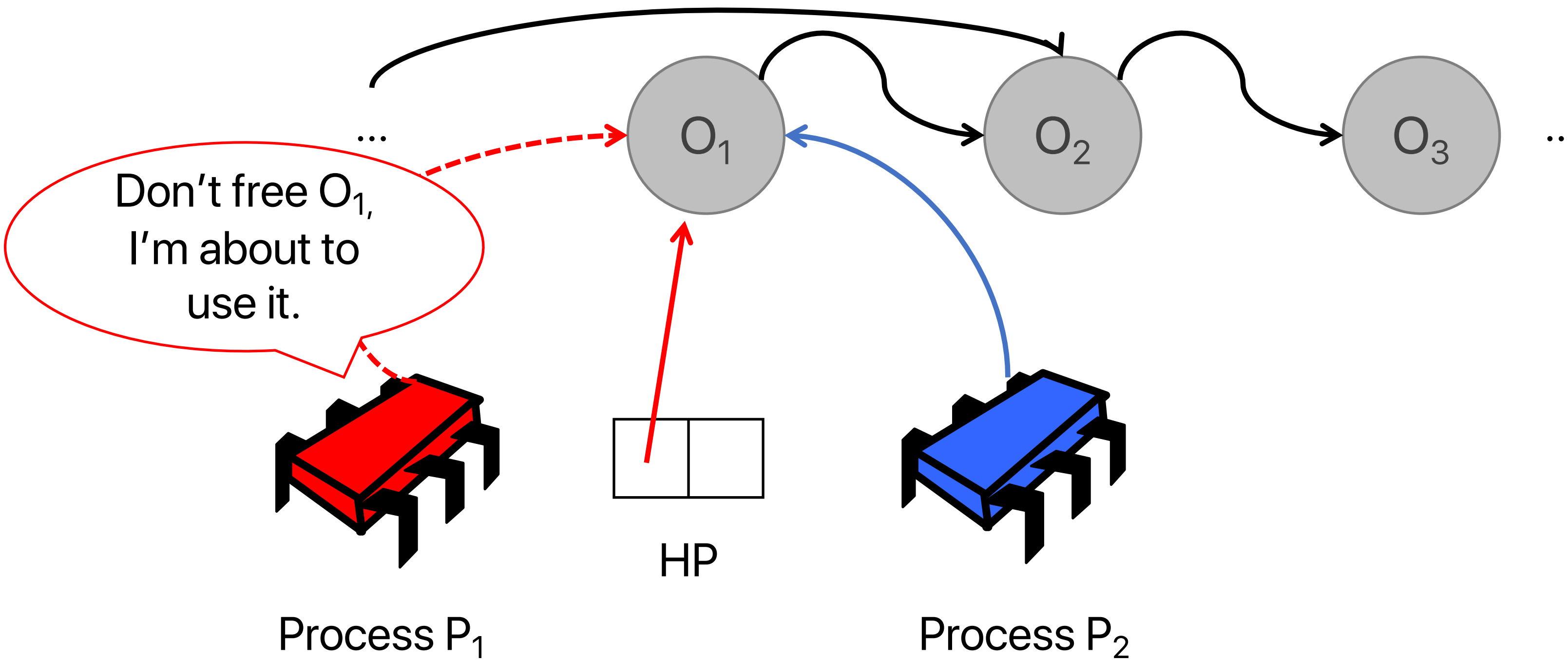

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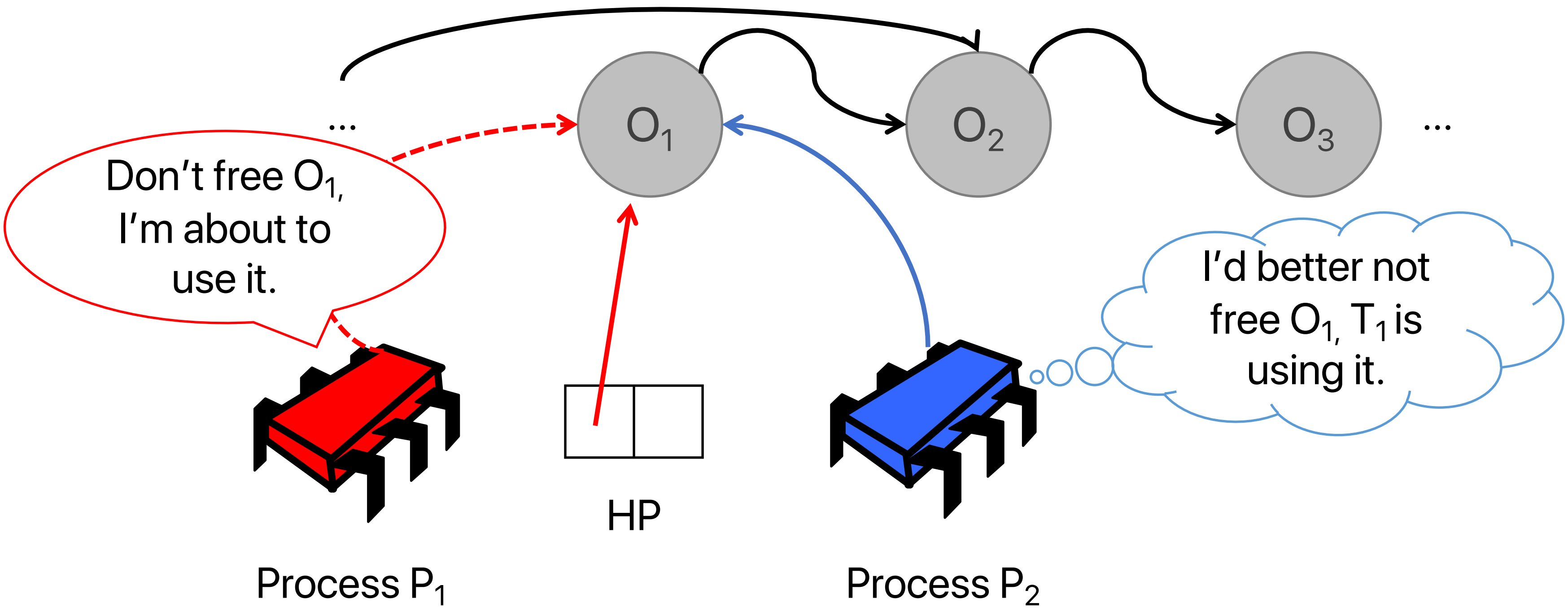
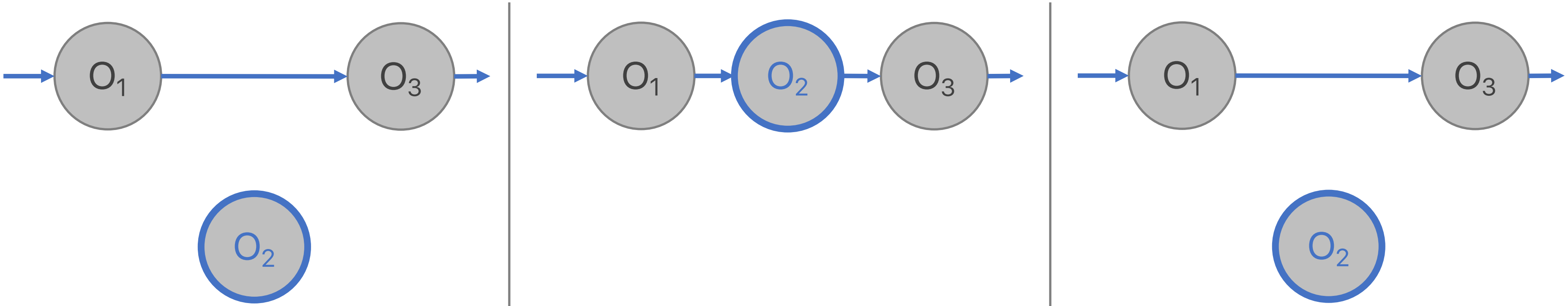


# HP – More Details

0. Reachability

- Reachable node = can be found by following pointers from data structure root(s)




Before inserting
→ $O_2$ not yet reachable

In the data structure
⇔ $O_2$ reachable

After deletion
→ $O_2$ no longer reachable

# HP – More Details

1. Announcing hazard pointers

Without hazard pointers

```
1. Read a reference p
2. Do something with p
3. (Release reference to p)
```

With hazard pointers

```
1. Read a reference p
2. HP = p // protect p
3. Check if p is still
   reachable. If yes,
   continue, otherwise
   restart operation.
4. Do something with p
5. (Release reference to p)
```

# HP – More Details

2. Deleting elements

- Each process has a “limbo list” containing nodes that have been deleted but not yet freed
- After process $p_i$ deletes a node *n* from the data structure, it adds *n* to $p_i$’s limbo list

# HP – More Details

3. Reclaiming memory

- When the limbo list grows to a certain size $R$, $p_i$ initiates a **scan**:
  - For each node $n$ in the limbo list:
    - Look at HPs of all processes. Is any of them pointing to $n$?
    - If not, free $n$'s memory
    - (If yes, do nothing)

# Pros and Cons of HP

- ✓ Limits memory use
- ✓ Lock-free

- ✗ Need to update HP on every access, even if read-only → bad performance
- ✗ Complex to implement & use → prone to errors

# Epoch-based Reclamation (EBR)

- Main idea:
  - Processes keep track of each other's progress
  - After deleting an object, when all processes have made enough progress, memory can be freed

# EBR, Step by Step

- Step 1: processes declare when they enter & exit **critical sections**

```
// code
enter_critical_section();
// more code
exit_critical_section();
// even more code
```

Here, we may access "dangerous" memory (memory that can be freed)

Here, only safe memory accesses are allowed (memory that is never freed)

# EBR, Step by Step

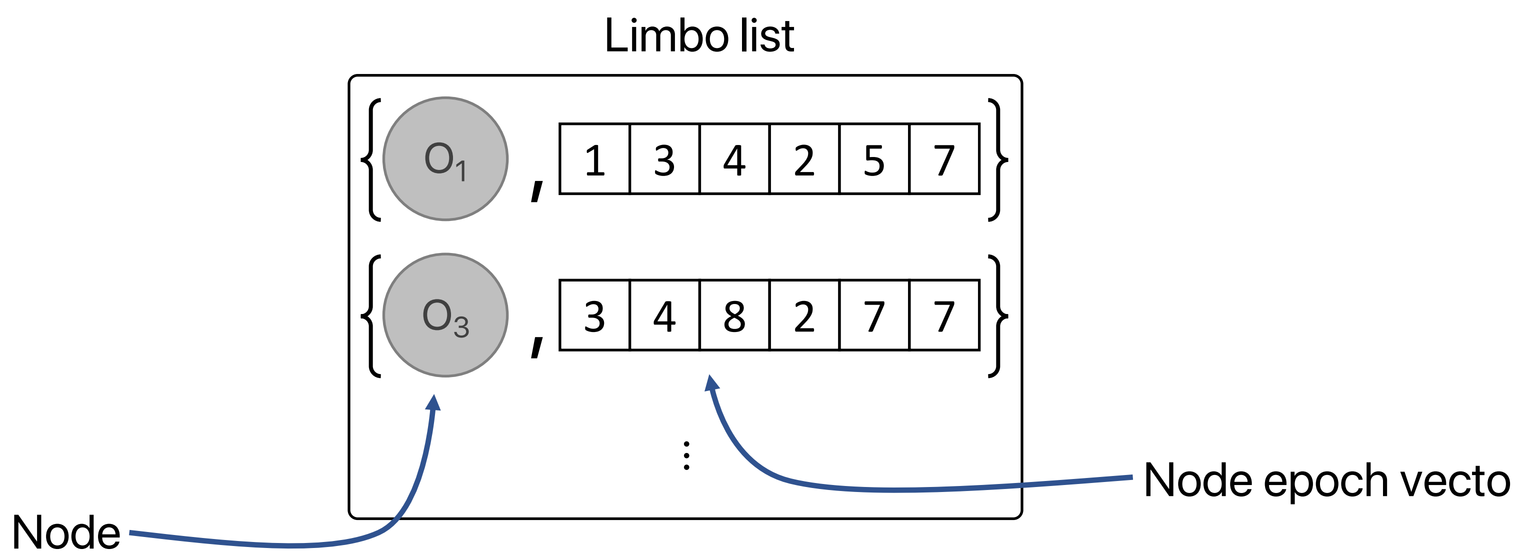
- Step 2: each process has an *epoch* (an integer, initially 0). The epoch is incremented by 1 when entering and exiting a critical section.

```
// code                         <- epoch = 0
enter_critical_section();
// more code                    <- epoch = 1
exit_critical_section();
// even more code               <- epoch = 2
```

→ epoch is **odd** if inside critical section and **even** otherwise

# EBR, Step by Step

- Step 3: After deleting an element, add it to a per-process limbo list, together with current epochs of all processes



# EBR, Step by Step

- Step 4: Periodically scan limbo list

Scan:
- cur_vec = current epoch vector
- For each node *n* in the limbo list:
    - node_vec = n's epoch vector
    - For each process i:
        - if node_vec[i] is odd
            - if node_vec[i] >= cur_vec[i]
                - Continue to next node
    - Free node

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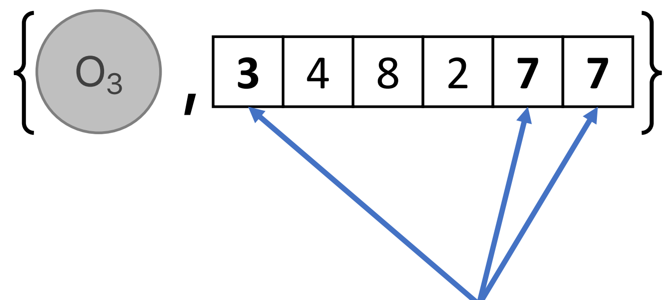


Only care about odd entries (processes inside crit. sec.)! Processes outside crit. sec. cannot access this node.

# EBR, Step by Step

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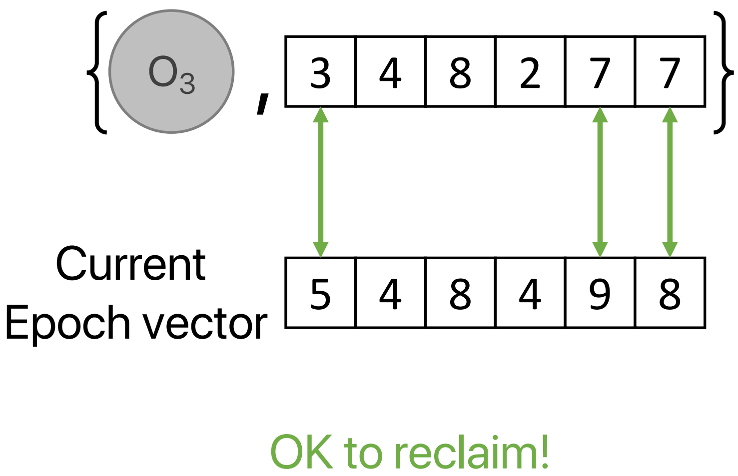

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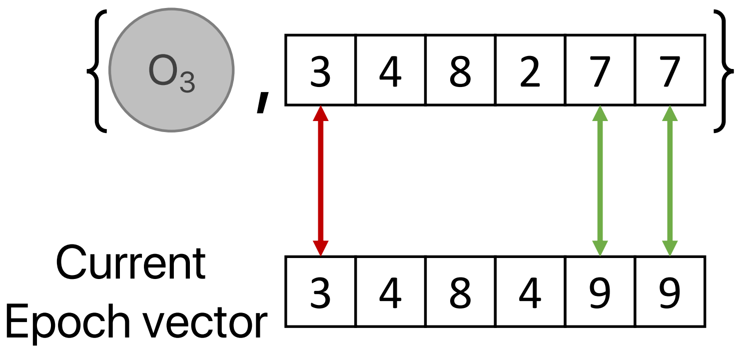



Not OK to reclaim!

# Pros and Cons of EBR

✓ Small overhead → very good performance

✓ Easy to use

✗ Blocking (not lock-free)

→ can invalidate lock- or wait-freedom of data structure

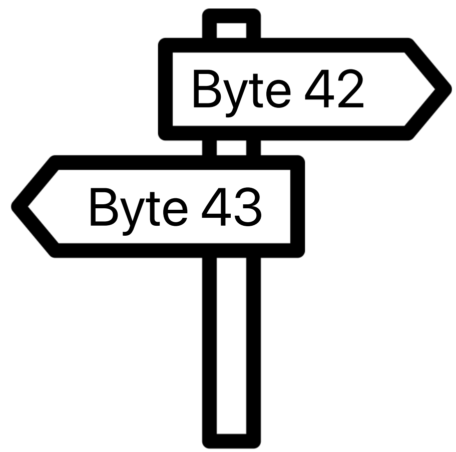
→ if some process is delayed inside a critical section, memory cannot be reclaimed any more

Part 2

# Persistent Memory

# What Is Persistent Memory?

Durability in the face of crashes & recoveries

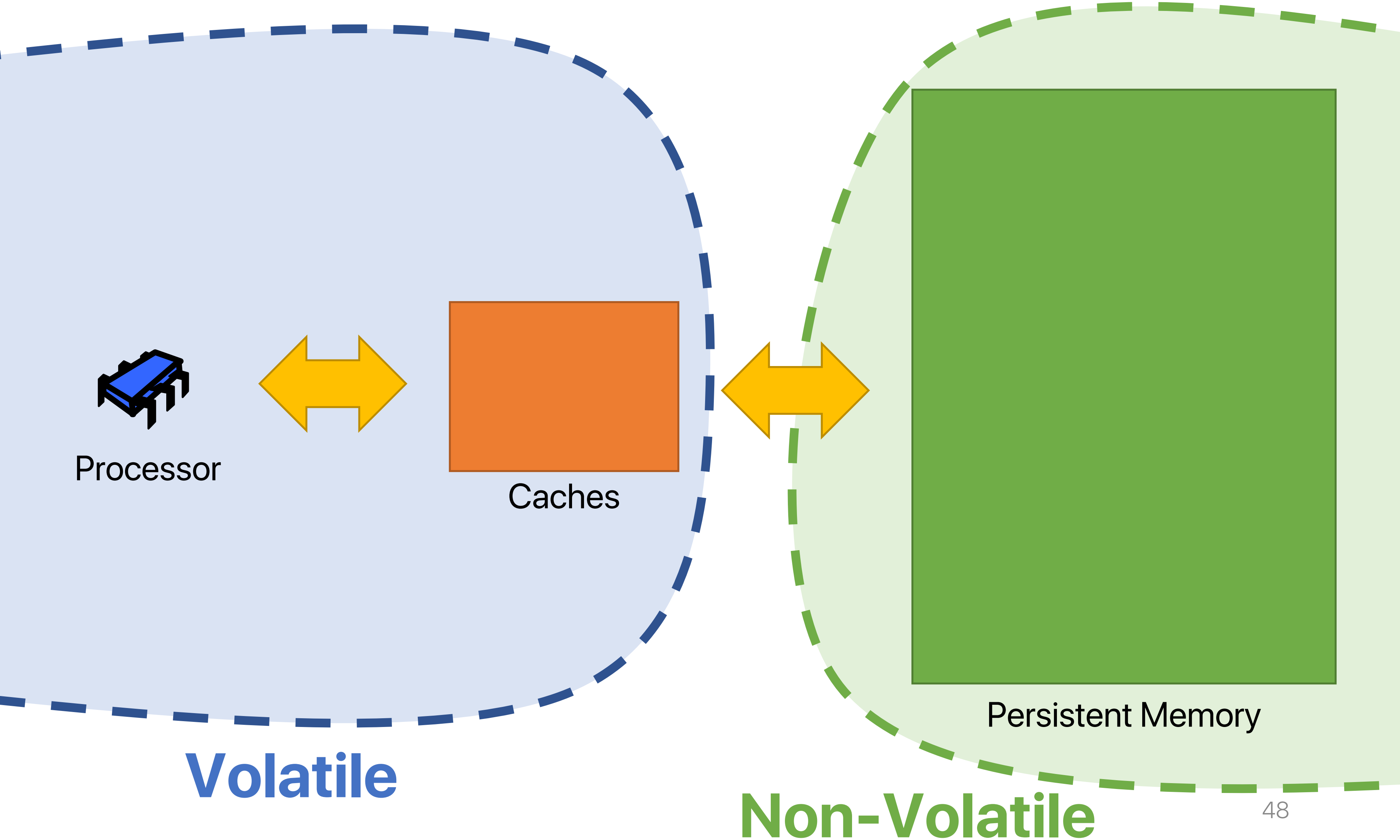



Byte-addressability

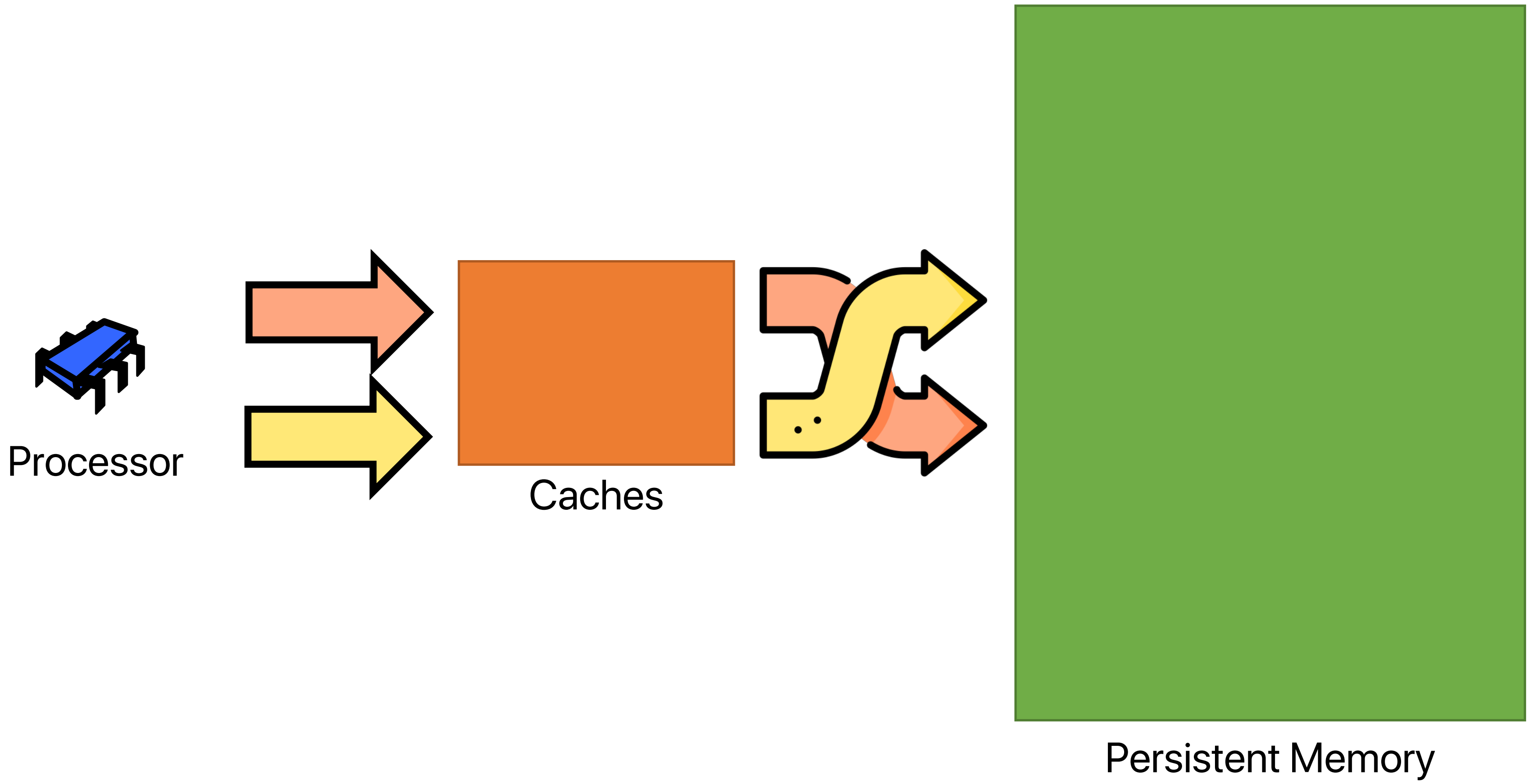
Access times ~ RAM

☞ Concurrent data structures for PM

# Obstacle #1: Caches are Volatile

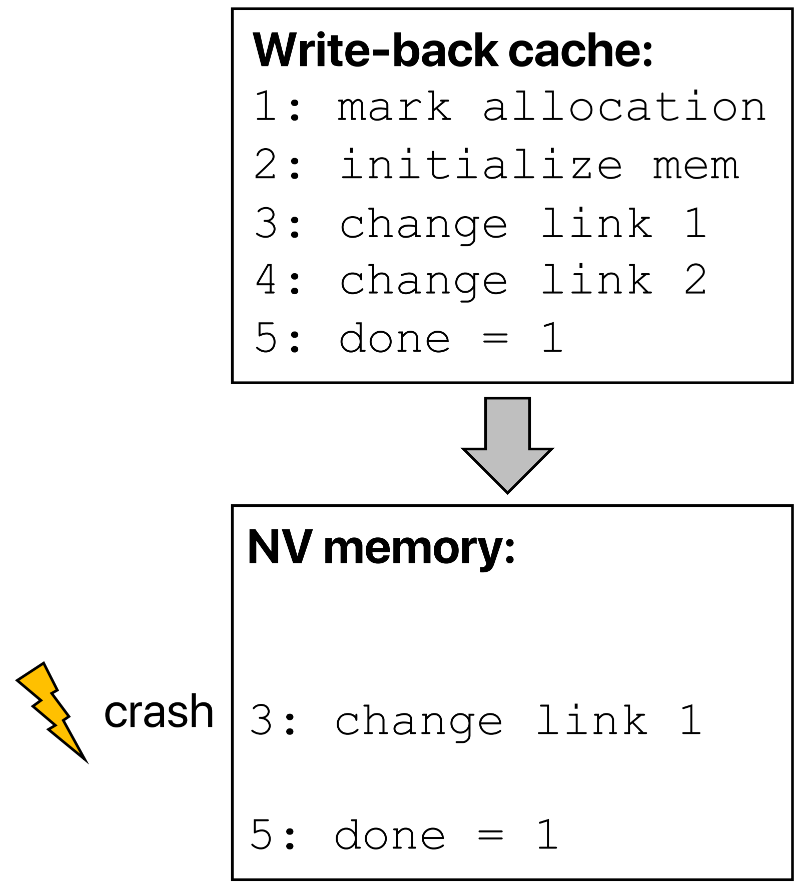


# Obstacle #2: (Re-)ordering



# Obstacles Illustrated

```
1: mark memory as allocated
2: initialize memory
3: change link of node 1
4: change link of node 2
5: done = 1
```




**Upon restart: incorrect state**

# Obstacles Illustrated

1: mark memory as allocated
2: **persist allocation**
3: initialize memory
4: **persist memory content**
5: change link of node 1
6: **persist new link**
7: change link of node 2
8: **persist modified link**
9: done = 1

**Write-back cache:**
1: mark allocation
2: initialize mem
3: change link 1
4: change link 2
5: done = 1

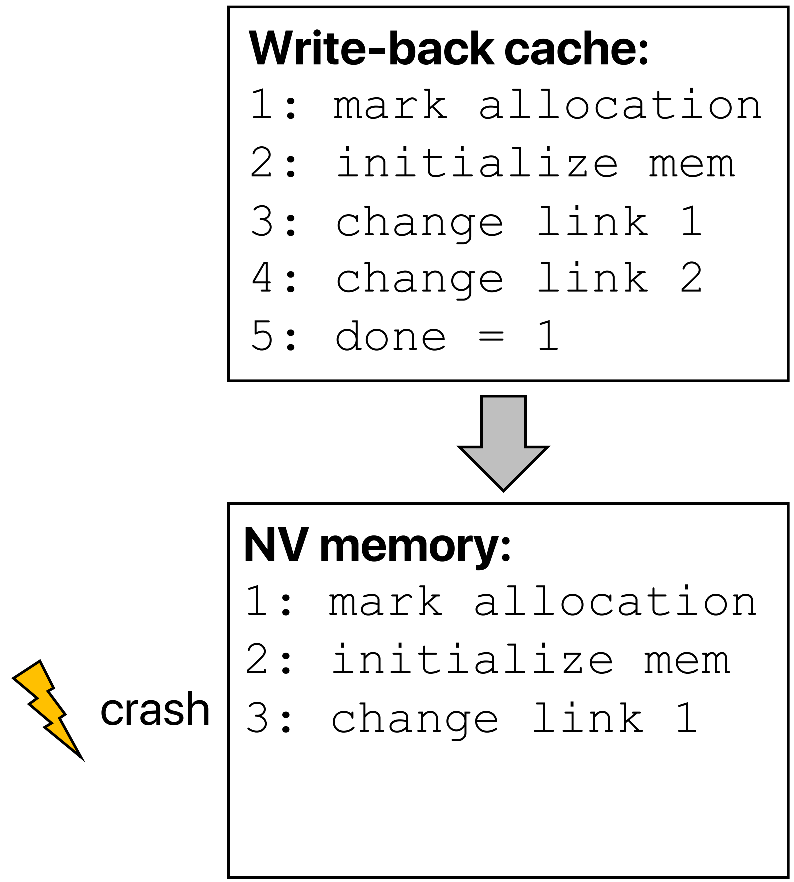
crash

**NV memory:**
3: change link 1
5: done = 1

**Upon restart: incorrect state**

# Obstacles Illustrated

```
1: mark memory as allocated
2: persist allocation
3: initialize memory
4: persist memory content
5: change link of node 1
6: persist new link
7: change link of node 2
8: persist modified link
9: done = 1
```




**Upon restart: incomplete operation**

# Common Solution: Logging

**log[0] = starting transaction X**<br>
**persist log[0]**<br>
**log[1] = allocating a node at address A**<br>
**persist log[1]**<br>
mark memory as allocated<br>
persist allocation<br>
initialize memory<br>
persist memory content<br>
**log[2] = previous value of link**<br>
**persist log[2]**<br>
change link 1<br>
persist modified link<br>
**log[3] = previous value of link**<br>
**persist log[3]**<br>
change link 2<br>
persist modified link<br>
done = 1<br>
**persist done**<br>
**mark transaction X as finished**

Frequent waiting for data to be persisted

# The Problem with Logging

- Logging -> frequent waiting
  - slows down data structure performance
- Data structure performance is essential to overall system performance

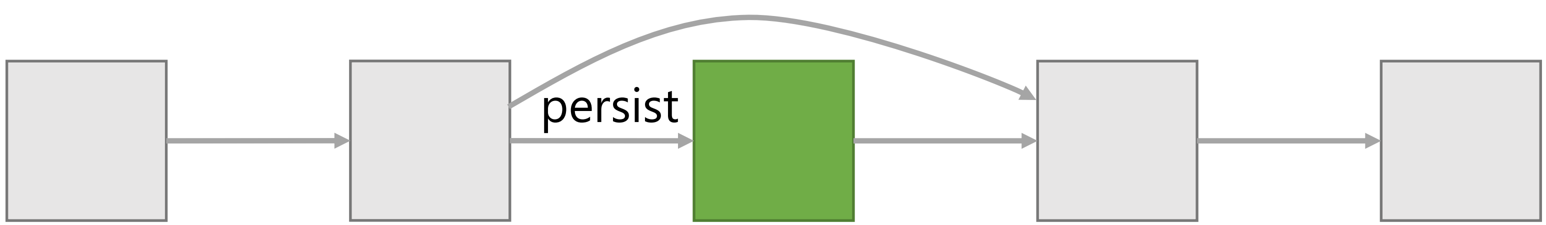
**The solution: reduce (or eliminate) logging**

# Log-free Data Structures

- The main idea: use lock-free algorithms
  - They never leave the structure in an inconsistent state
  - No need for logging in the data structure algorithm

# Detour: Durable Linearizability

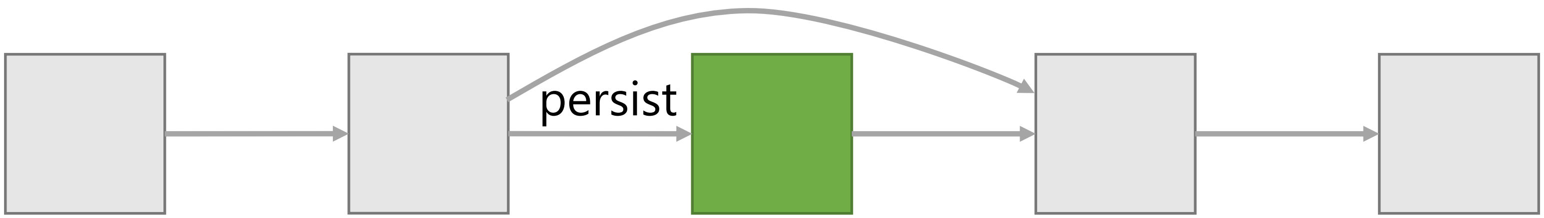
- After a restart, the structure reflects:
  - all operations completed (linearized) before the crash;
  - (potentially) some operations that were ongoing when the crash occurred;




If crash between steps 2 and 3, violation of durable linearizability

1. Persistently allocate and initialize node
2. Add link to new node
3. Persist link to new node

# Log-free Data Structures

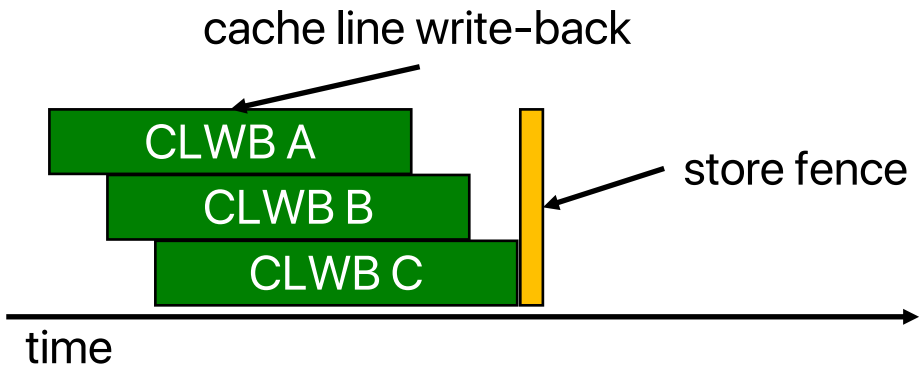



1. Persistently allocate and initialize node
2. Add **marked** link to new node
3. Persist link to new node
4. Remove mark

Other threads - persist marked link if needed

**Link-and-persist**: atomic “modify” and “persist” link

# Going Further: Batching



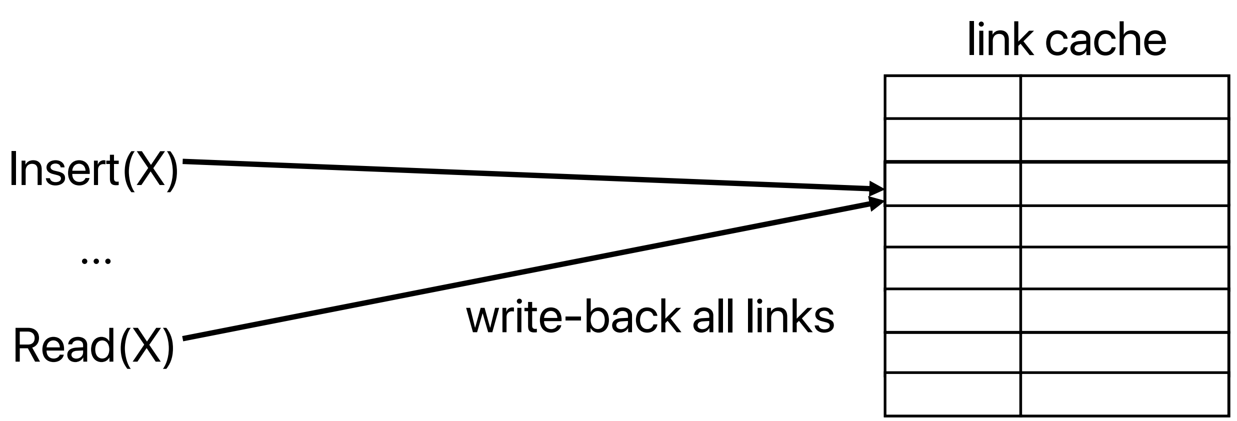

Batching write-backs:
beneficial for performance

# Going Further: Batching

- A link only needs to be persisted when an operation depends on it
- Store all un-persisted links in a fast concurrent cache
- When an operation directly depends on a link in the cache:

batch write-backs of all links in the cache

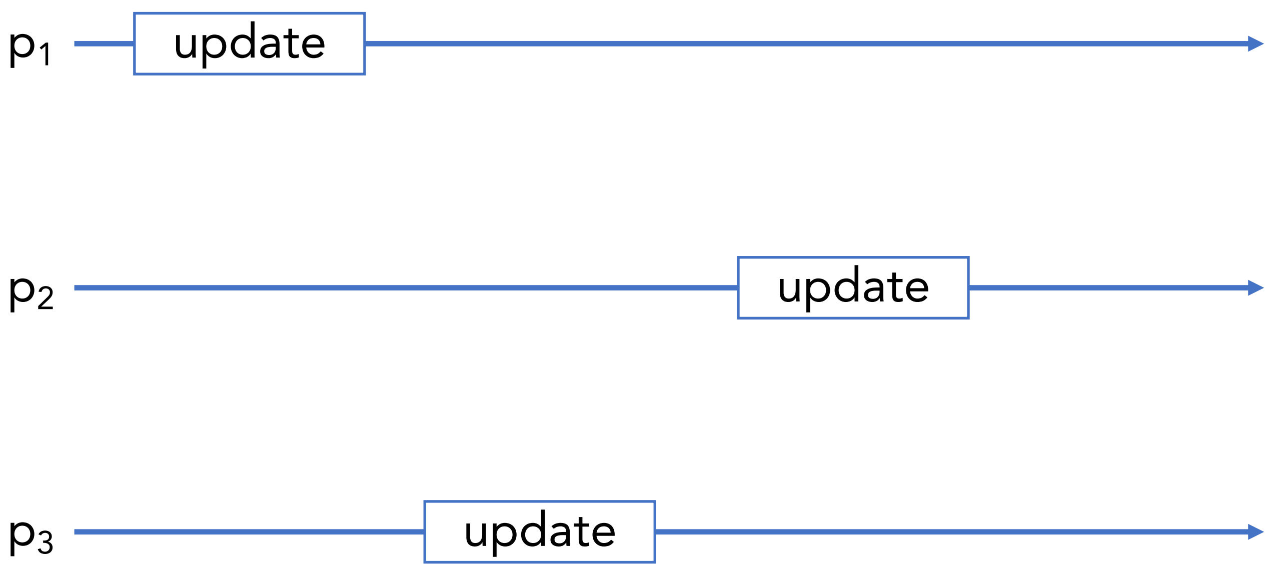
(and empty the cache)



# You Can’t Eliminate Fences

- For any lock-free concurrent implementation of a persistent object
- there exists an execution E such that
- in E, every update operation performs at least 1 persistent fence

# Lower Bound: Sequential Case



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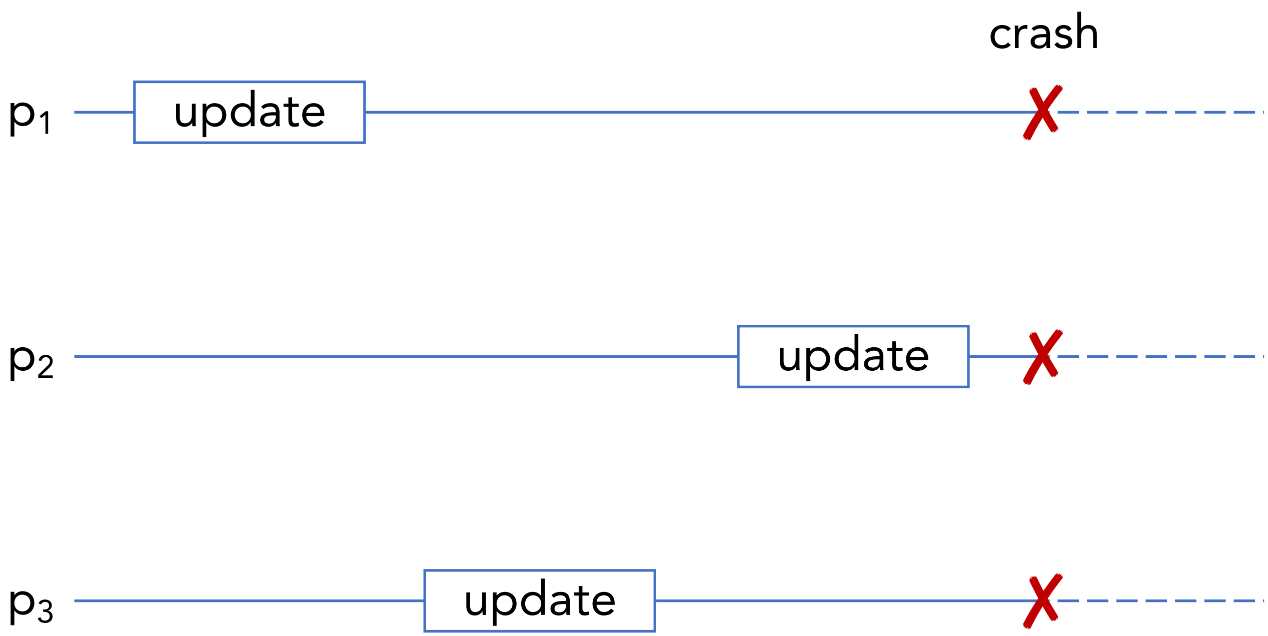

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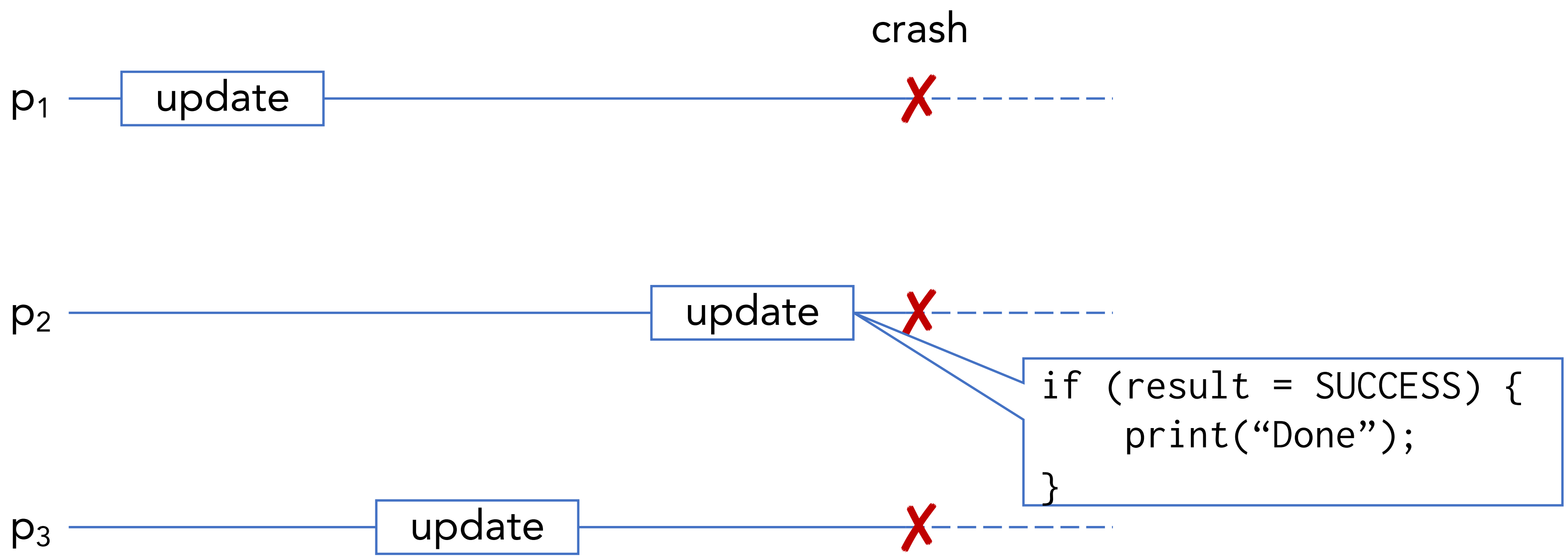

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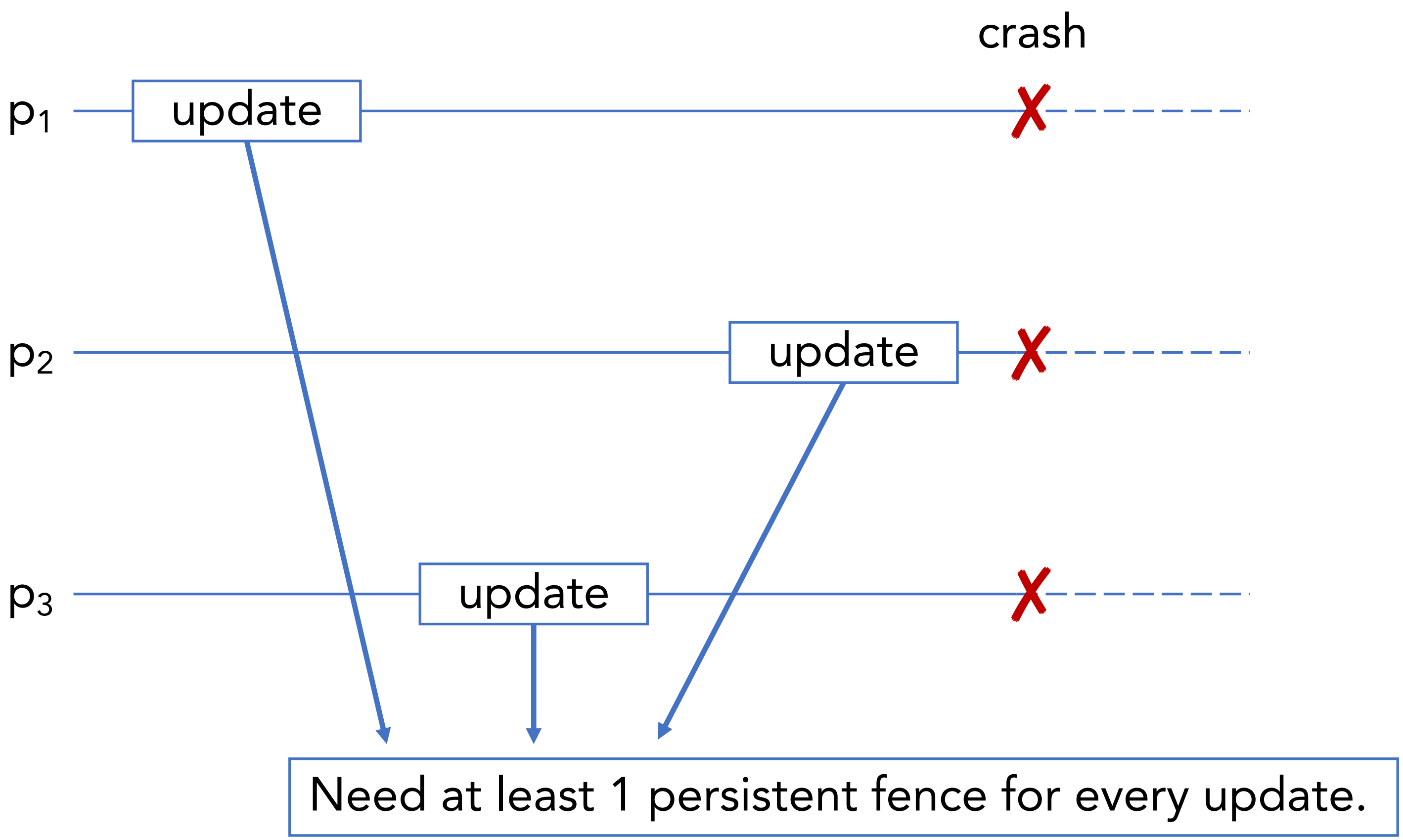

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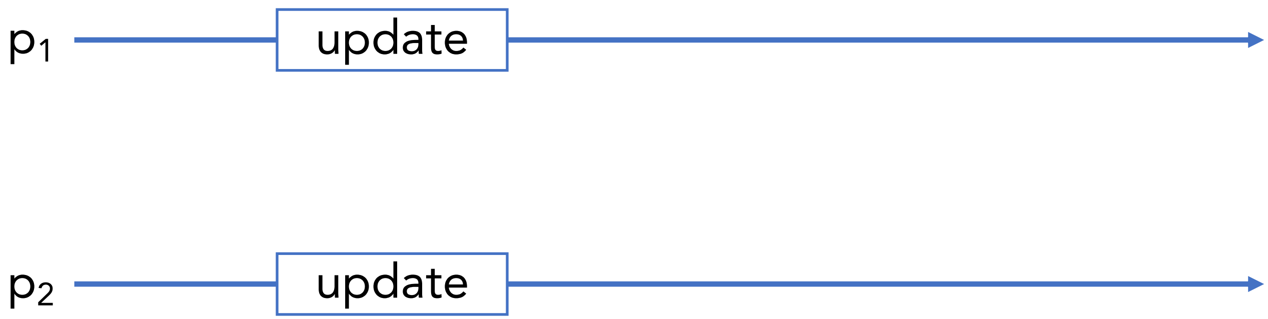

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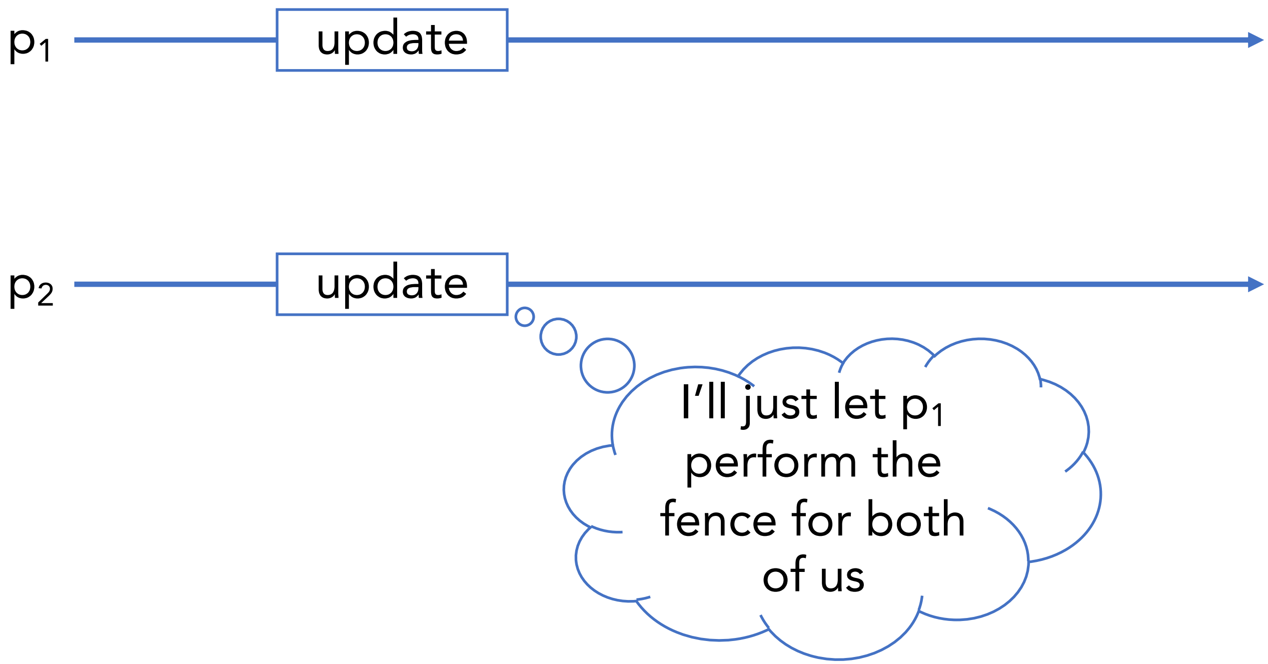

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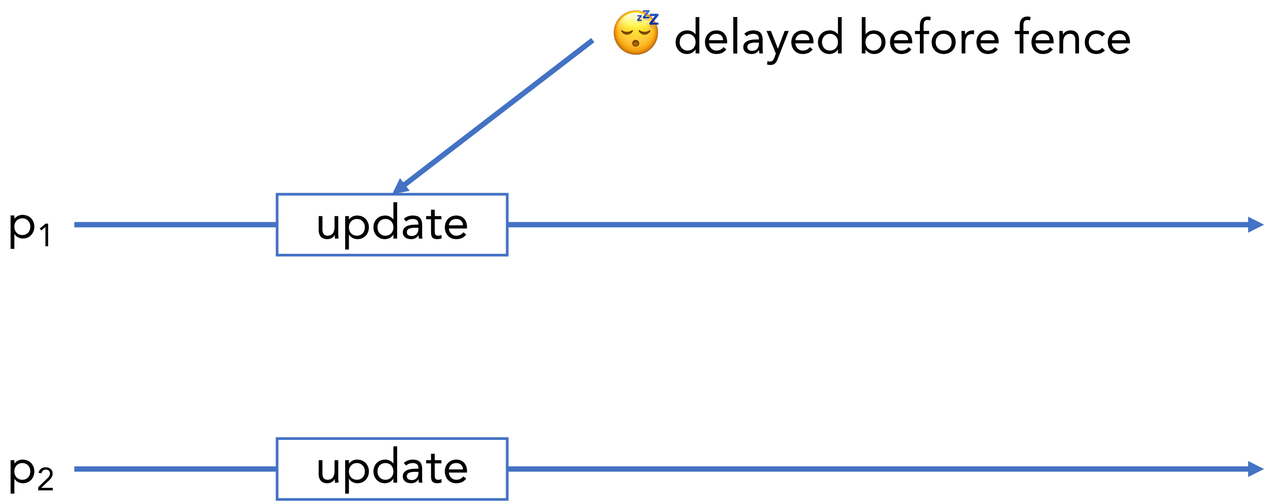

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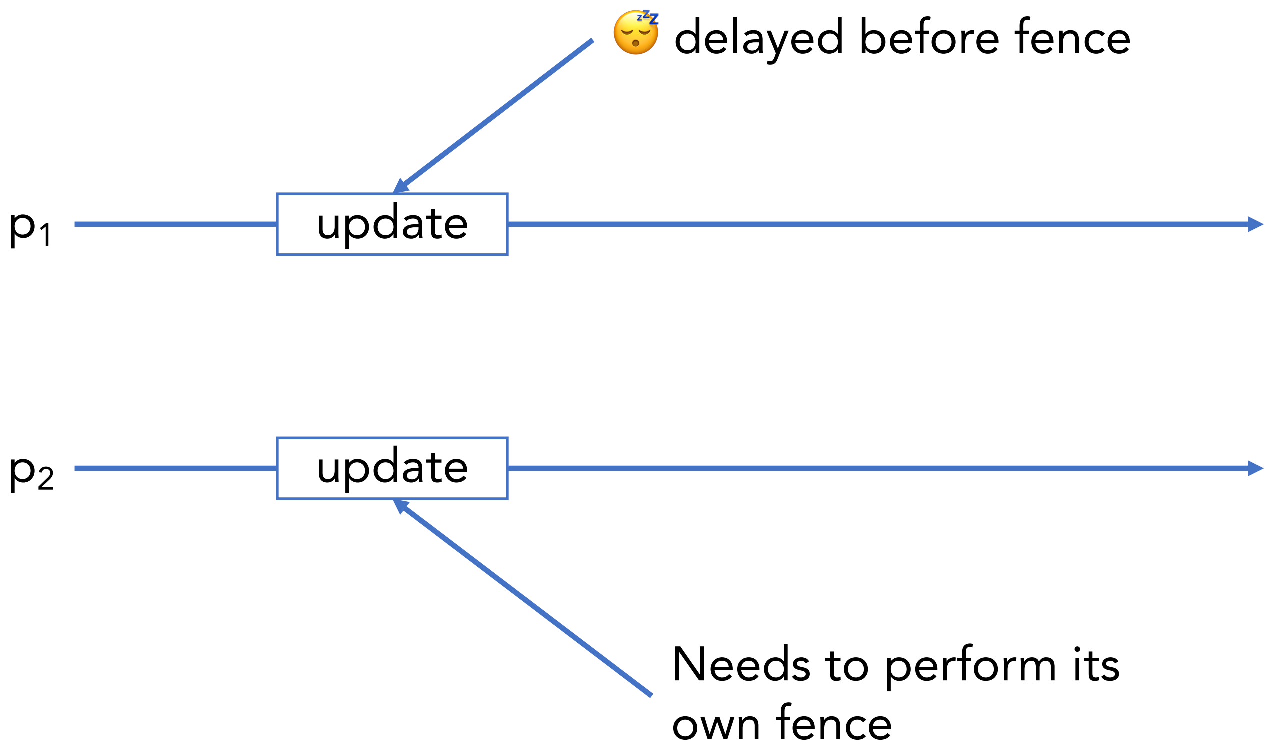

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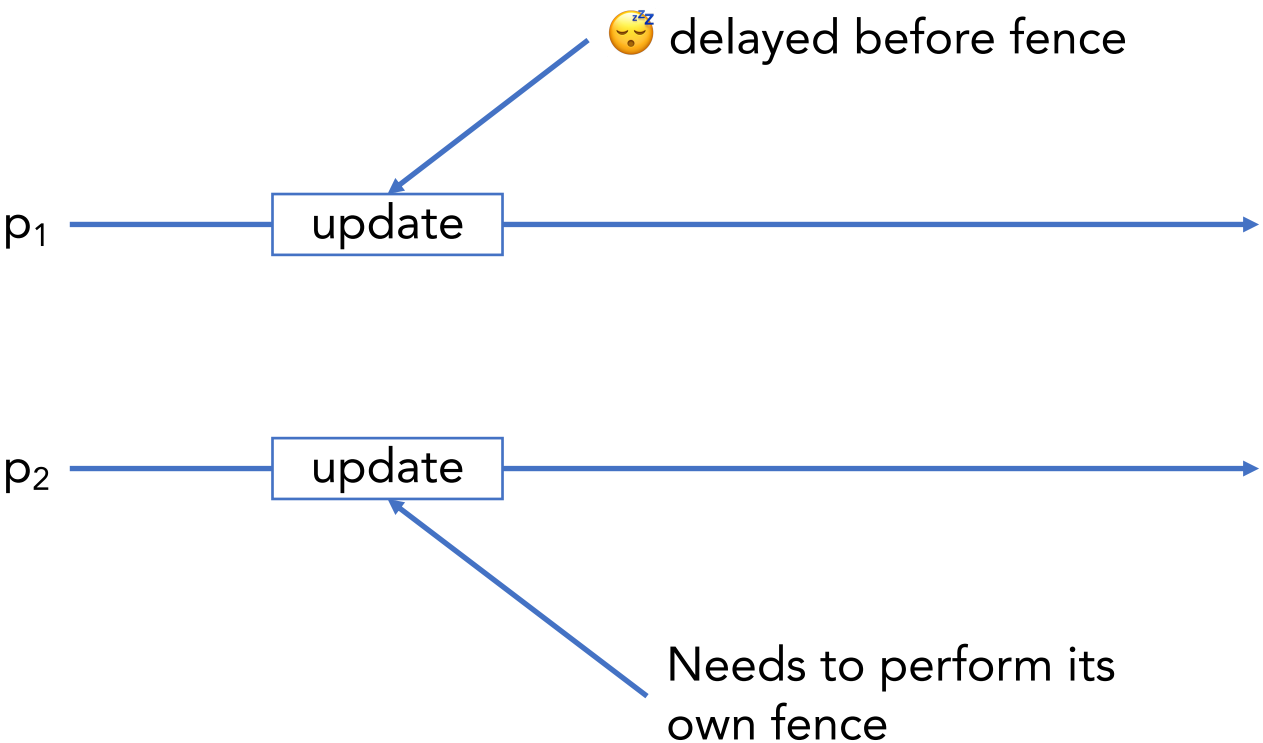


Both processes perform one fence per update operation.

# Further Reading


- T. E. Hart, P. E. McKenney, A. D. Brown, and J. Walpole. Performance of memory reclamation for lockless synchronization. Journal of Parallel and Distributed Computing, 67(12), 2007.
- J. D. Valois. Lock-free linked lists using compare-and-swap. PODC 1995.
- M.M. Michael, M.L. Scott. Correction of a memory management method for lock-free data structures. Technical Report TR599, Computer Science Department, University of Rochester. 1995.
- D. L. Detlefs, P. A. Martin, M. Moir, and G. L. Steele, Jr. Lock-free reference counting. PODC 2001.
- M. M. Michael. Hazard pointers: Safe memory reclamation for lock-free objects. IEEE Trans. Parallel Distrib. Syst., 15(6), 2004.
- O. Balmau, R. Guerraoui, M. Herlihy, and I. Zablotchi. Fast and Robust Memory Reclamation for Concurrent Data Structures. SPAA 2016.
- T. David, A. Dragojevic, R. Guerraoui, and I. Zablotchi. Log-Free Concurrent Data Structures. USENIX ATC 2018
- N. Cohen, R. Guerraoui, and I. Zablotchi. The Inherent Cost of Remembering Consistently. SPAA 2018