A Skiplist-based Concurrent Priority Queue with Minimal Memory Contention

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Contributions

Motivation: Improve performance of concurrent Discrete Event Simulator.
Outcome: New lock-free skiplist-based priority queue.

- New representation for logically deleted nodes.
- Minimizes the contention.
- Improved performance over existing algorithms by 30 – 80% on multiprocessors.
- Linearizable.

Outline

Priority Queues

- Priority Queue - A set of (key,value) pairs with two operations:
  - Insert(*key*, *value*)
  - DeleteMin()
- Applications: Discrete Event Simulation, Numerical algorithms.

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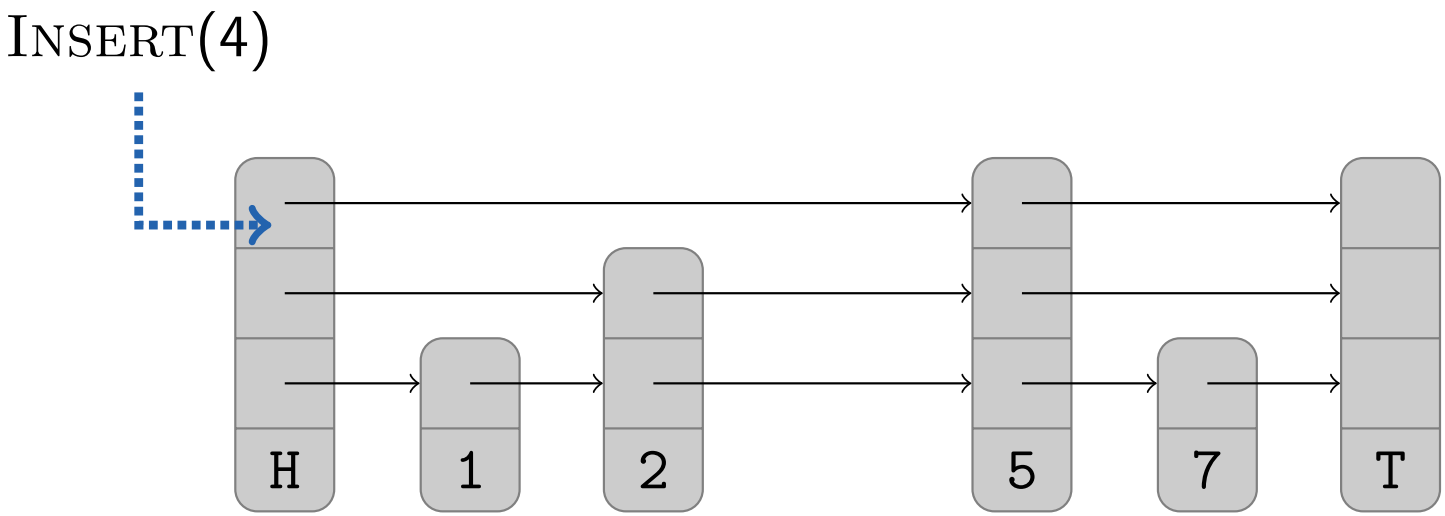
- Applications: Discrete Event Simulation, Numerical algorithms.
- Implementations:
  - Traditionally, implemented on top of heaps or tree data structures.
  - Skiplists [Pugh:1990] have been used for several parallel implementations.

Skiplist

- layered linked list
- lowest-level list defines logical state, ordered
- higher-level lists are shortcuts
- probabilistic guarantee of logarithmic search time



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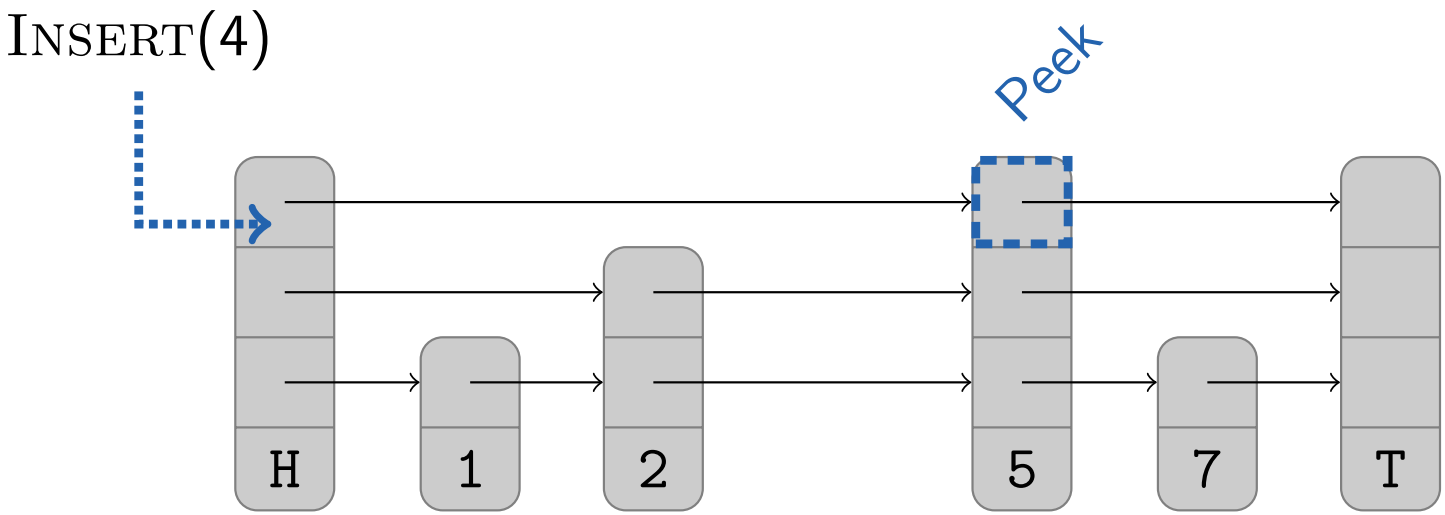

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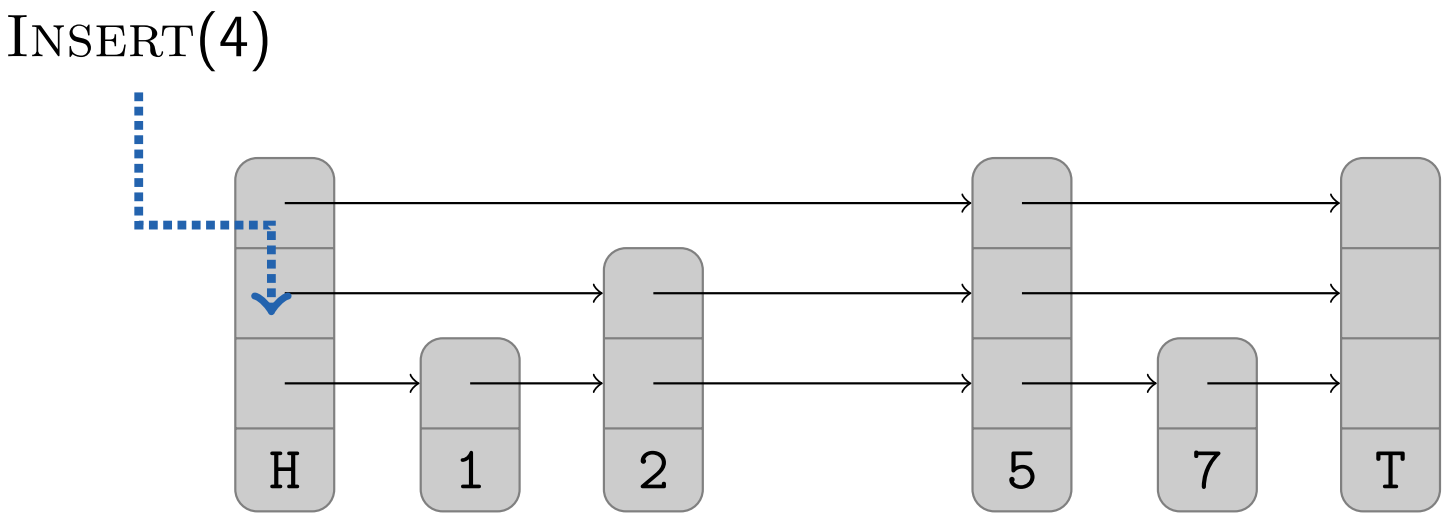

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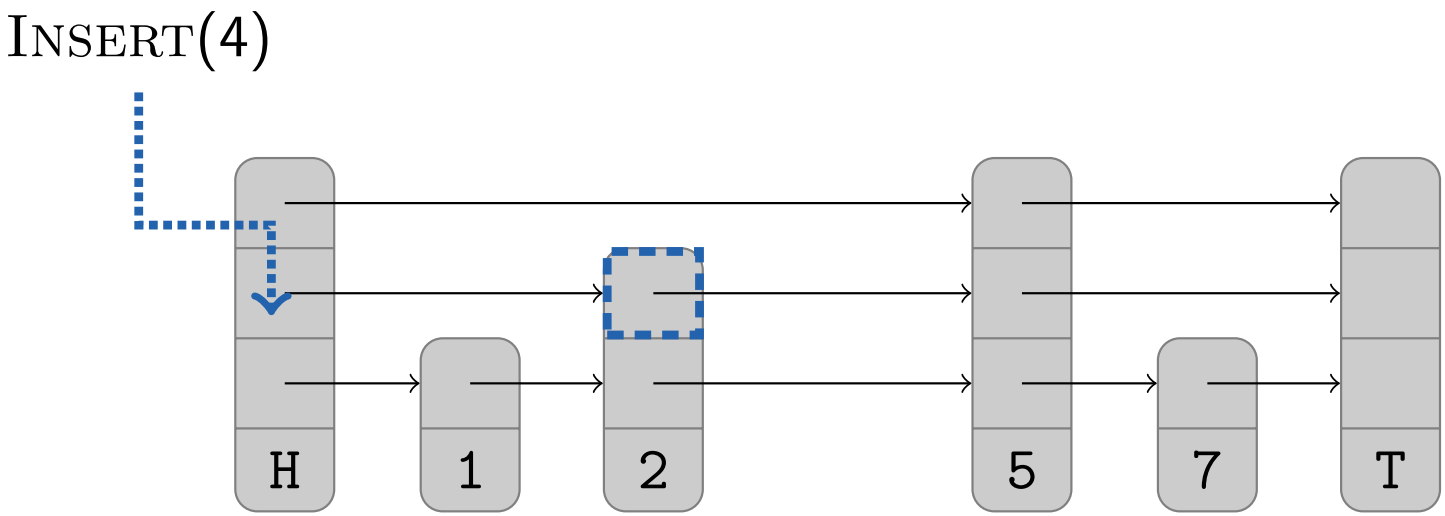

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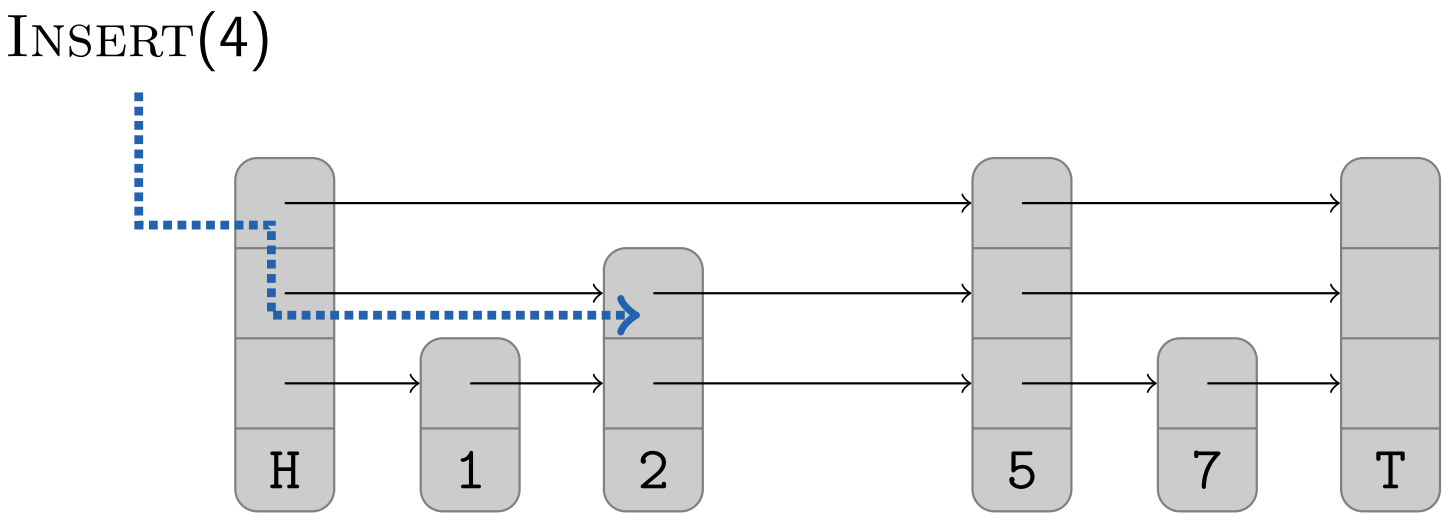

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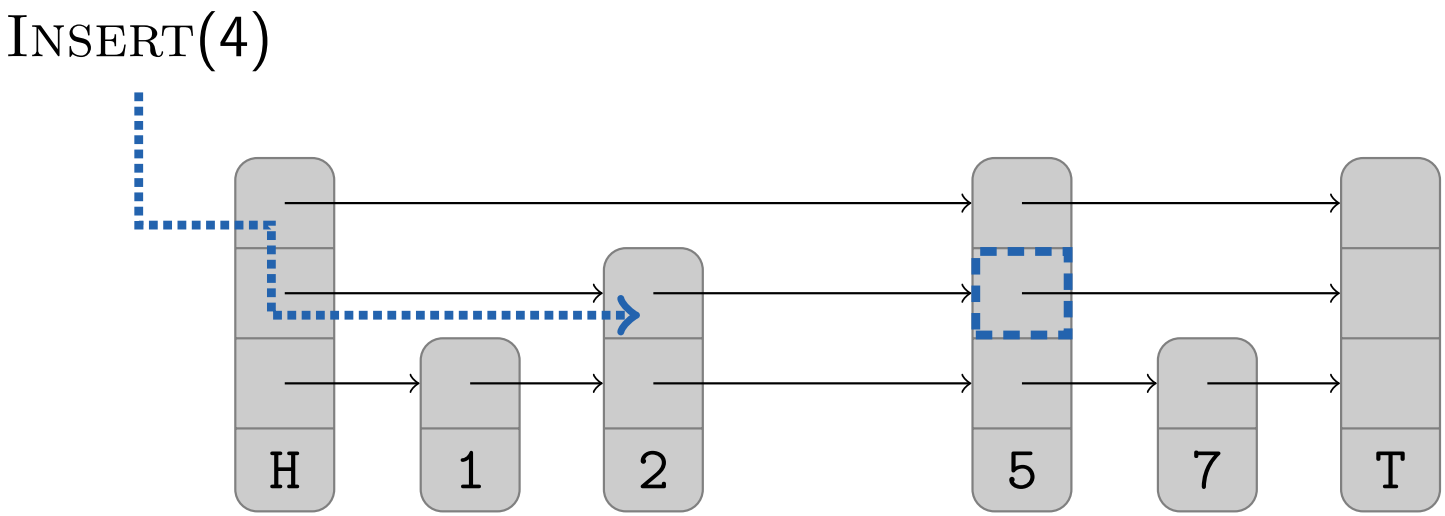

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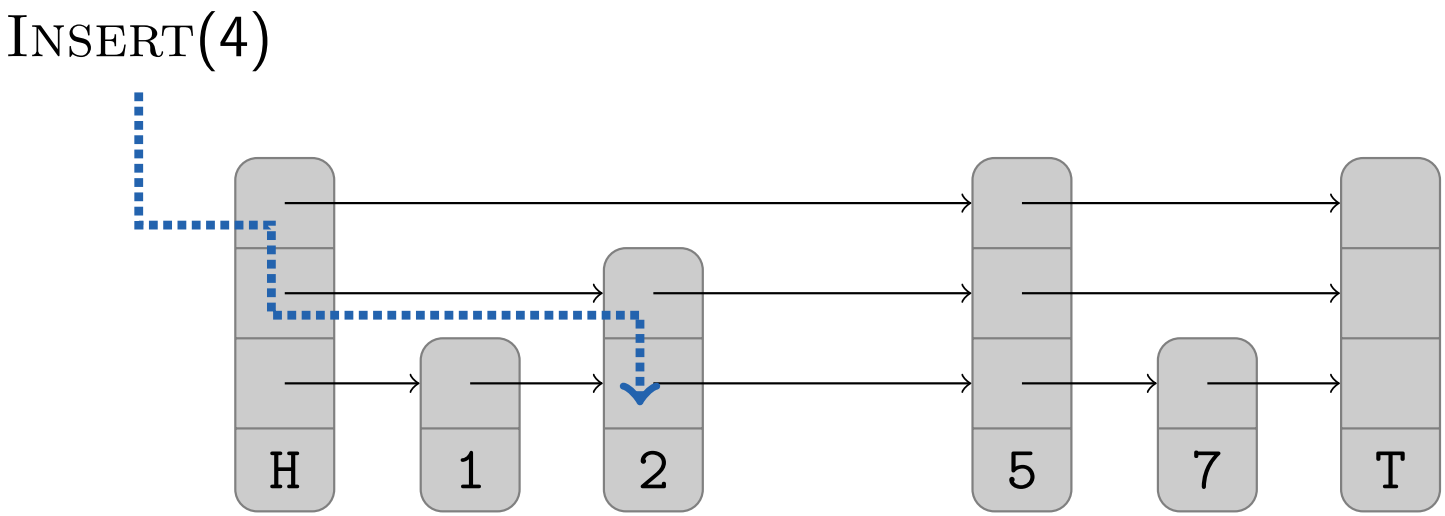

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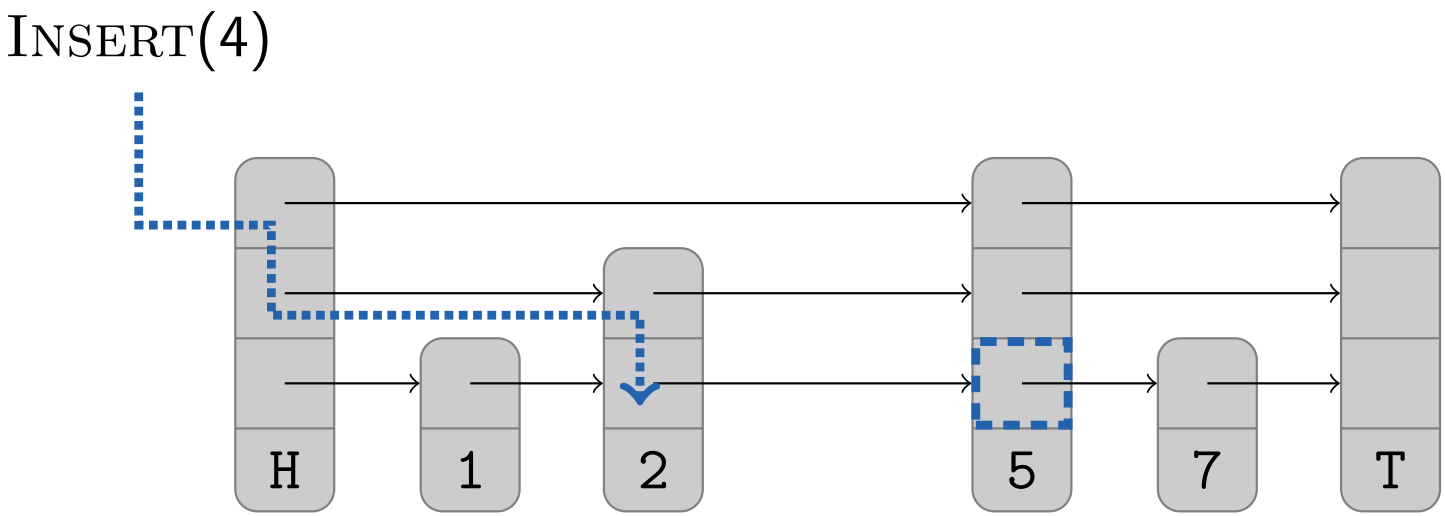

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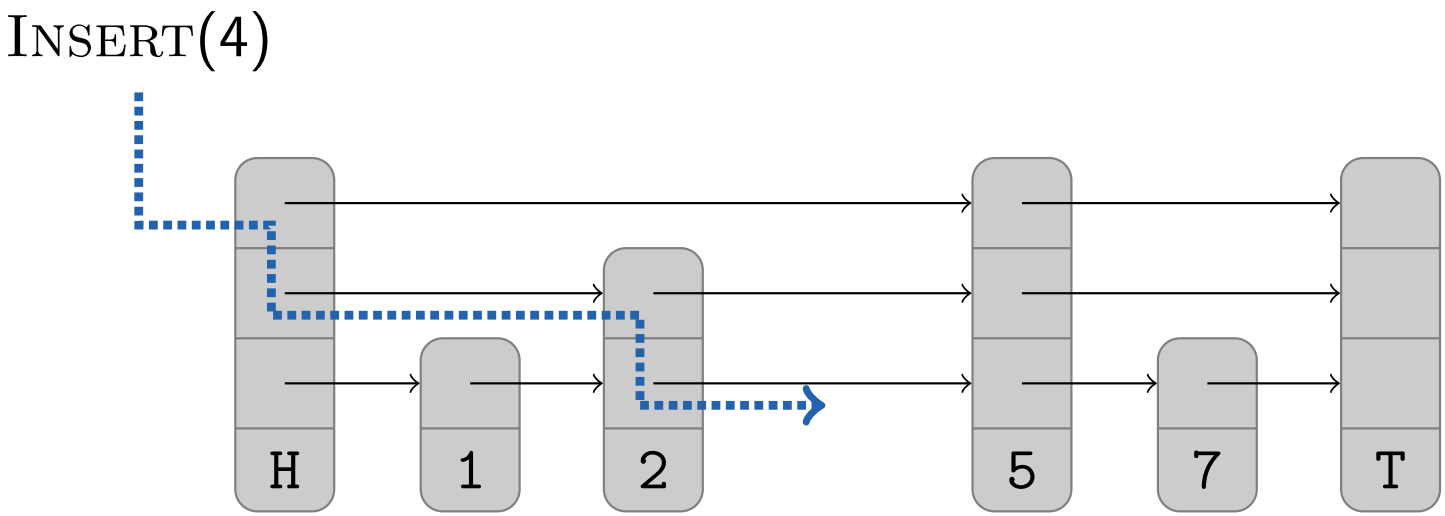

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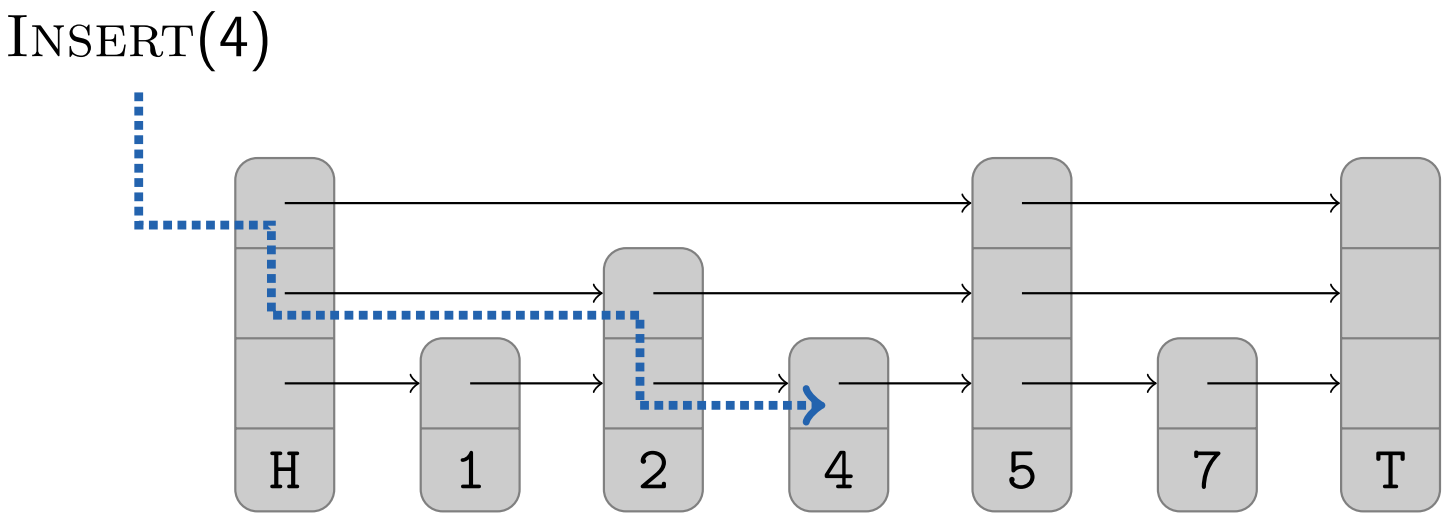

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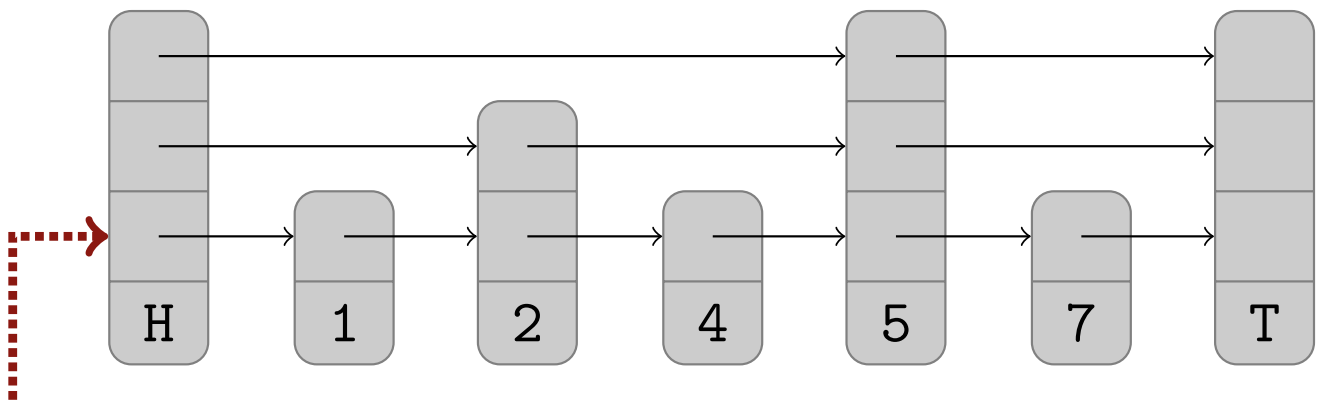
- Smallest element at the beginning of the lowest-level list.



DeleteMin entry point

Concurrent skiplist-based priority queues

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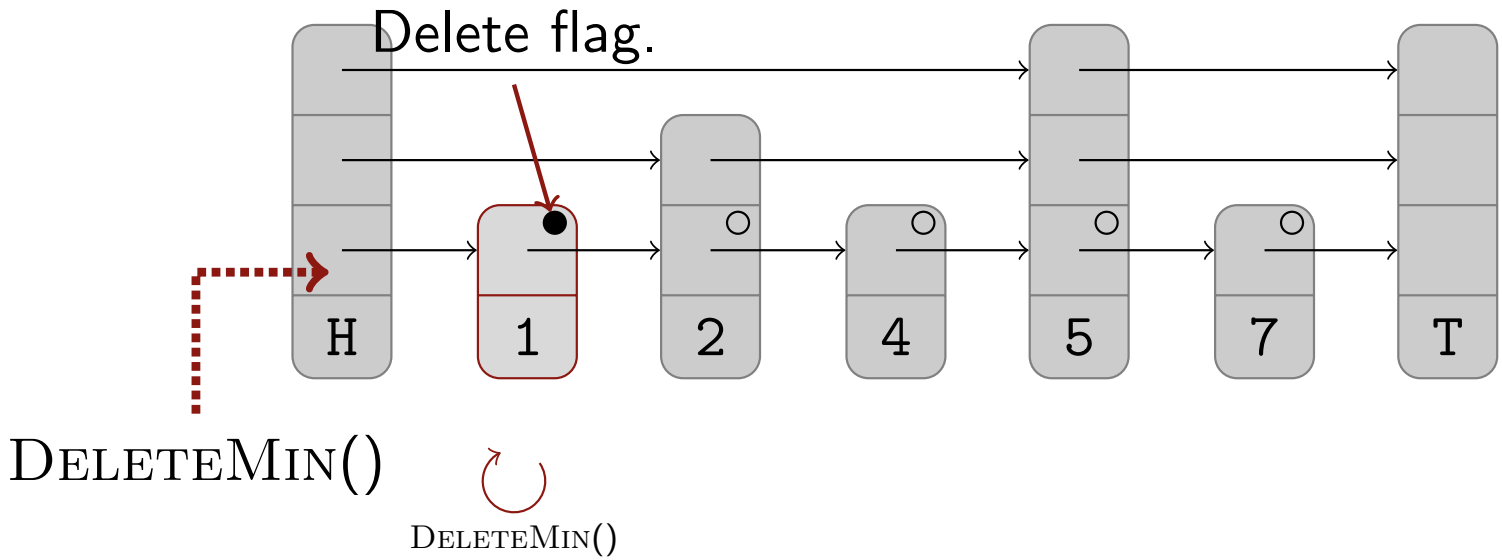
- Skiplists scale well when concurrent threads access different parts of the structure.
- Bottleneck: concurrent DeleteMin operations in priority queues try to remove the same element.

Standard solution

Standard solution to increase concurrency:

- *logical deletion* by setting a delete flag.
- *physical deletion* unlinks the node after the logical deletion has succeeded.



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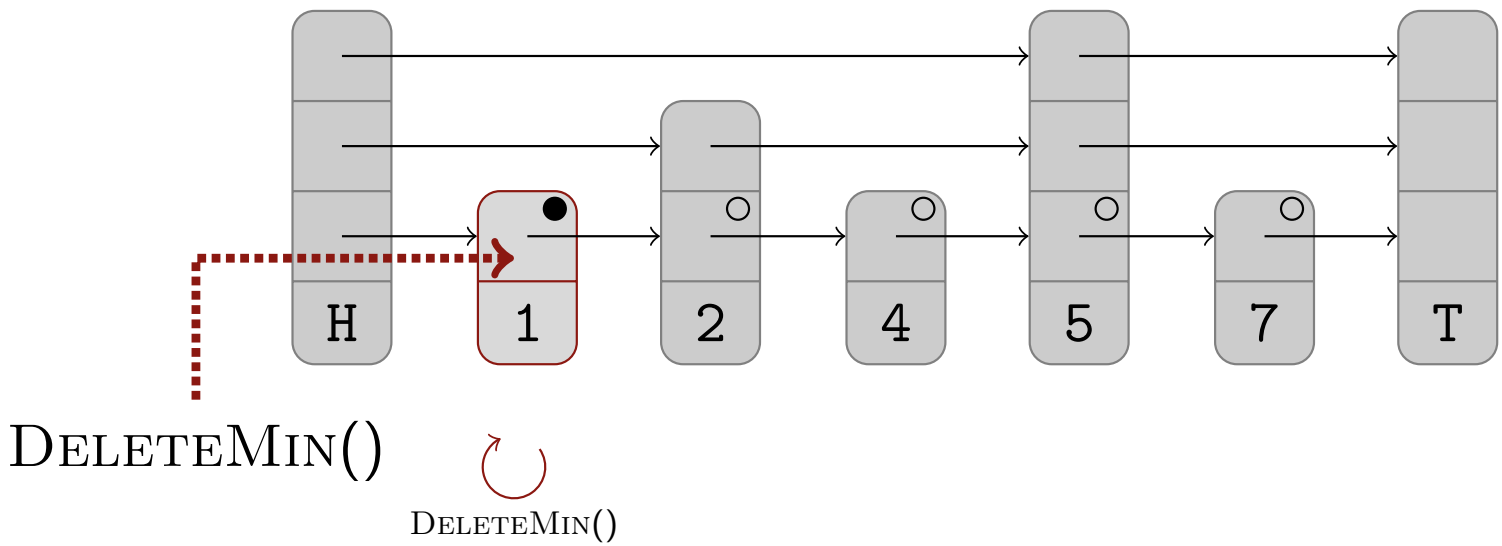

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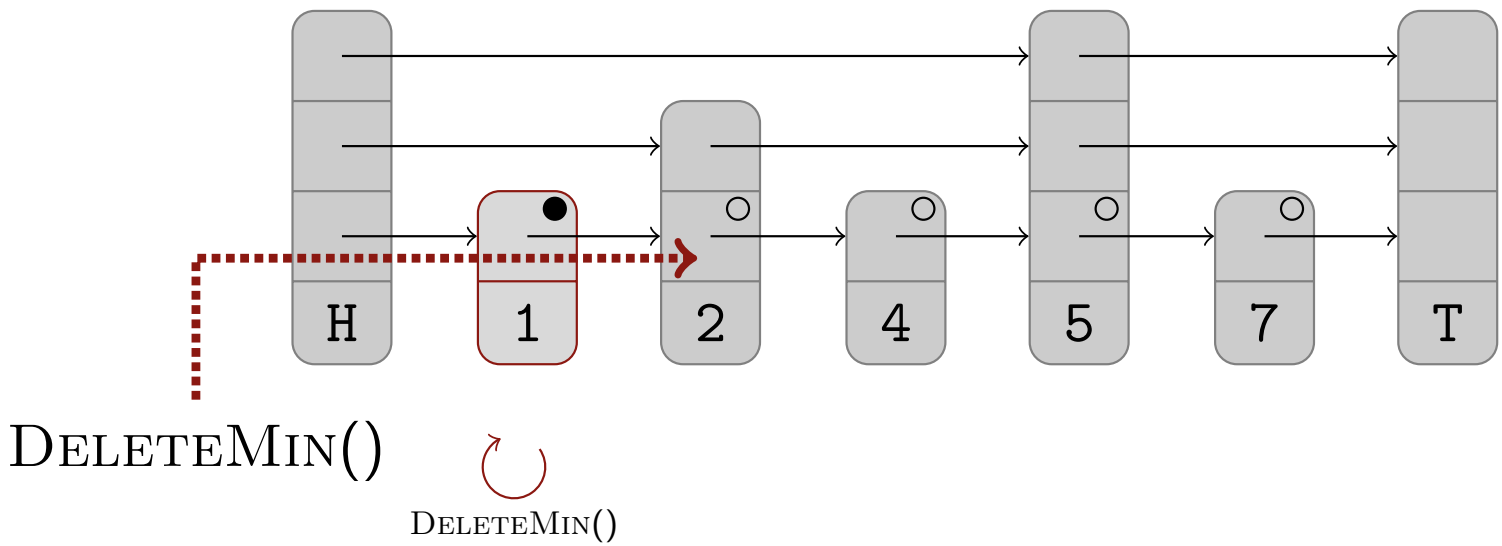

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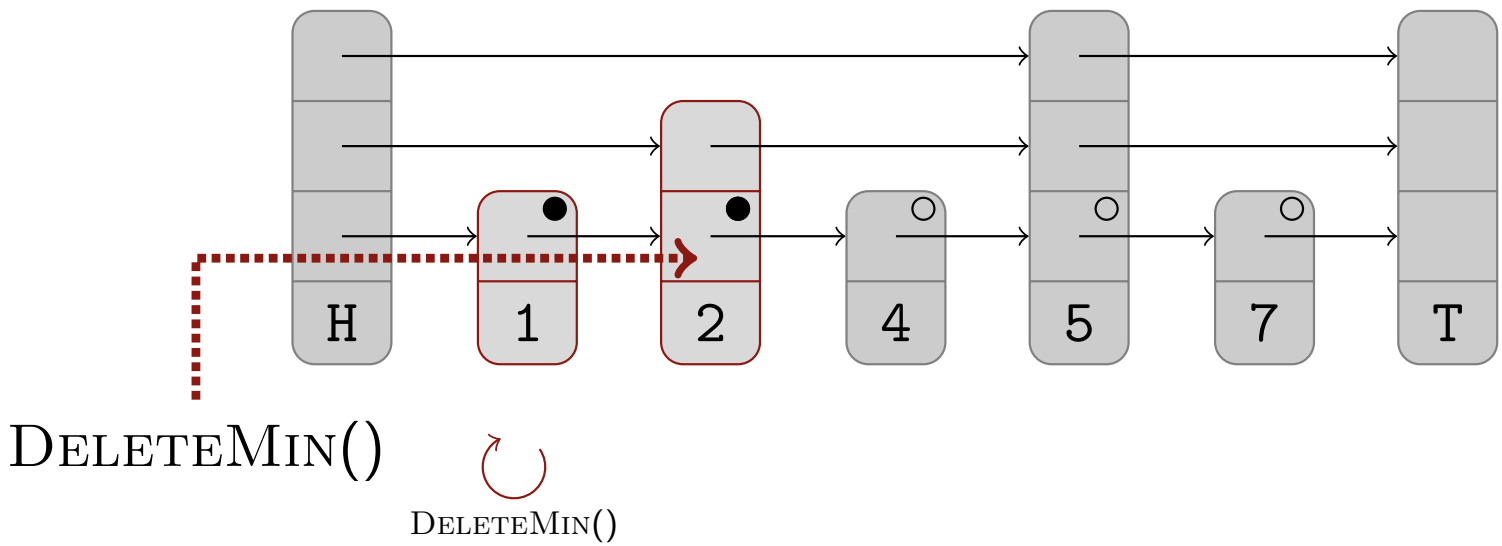

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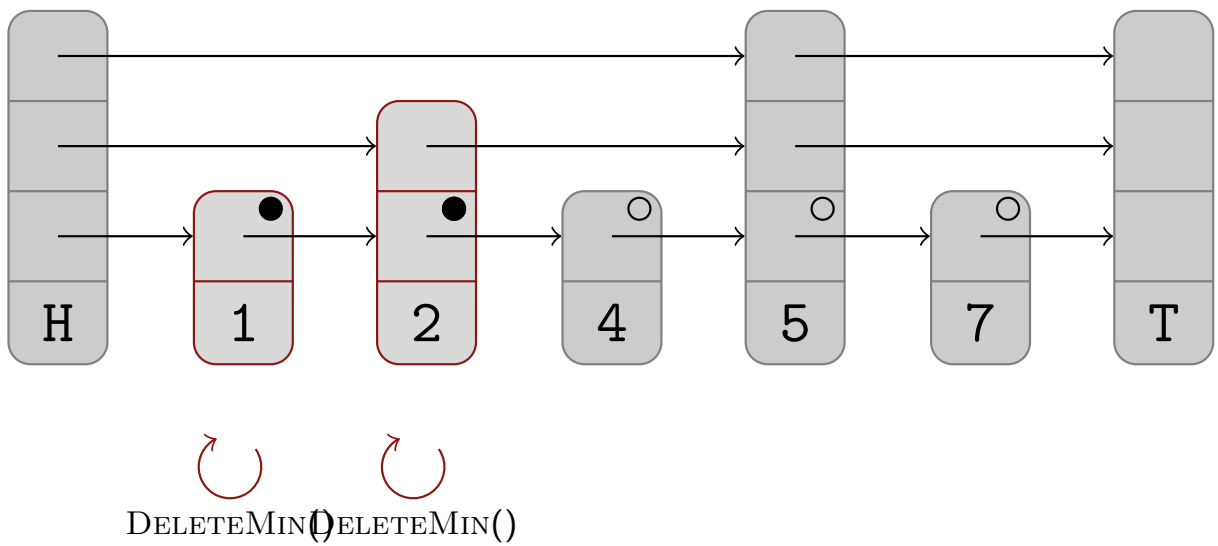

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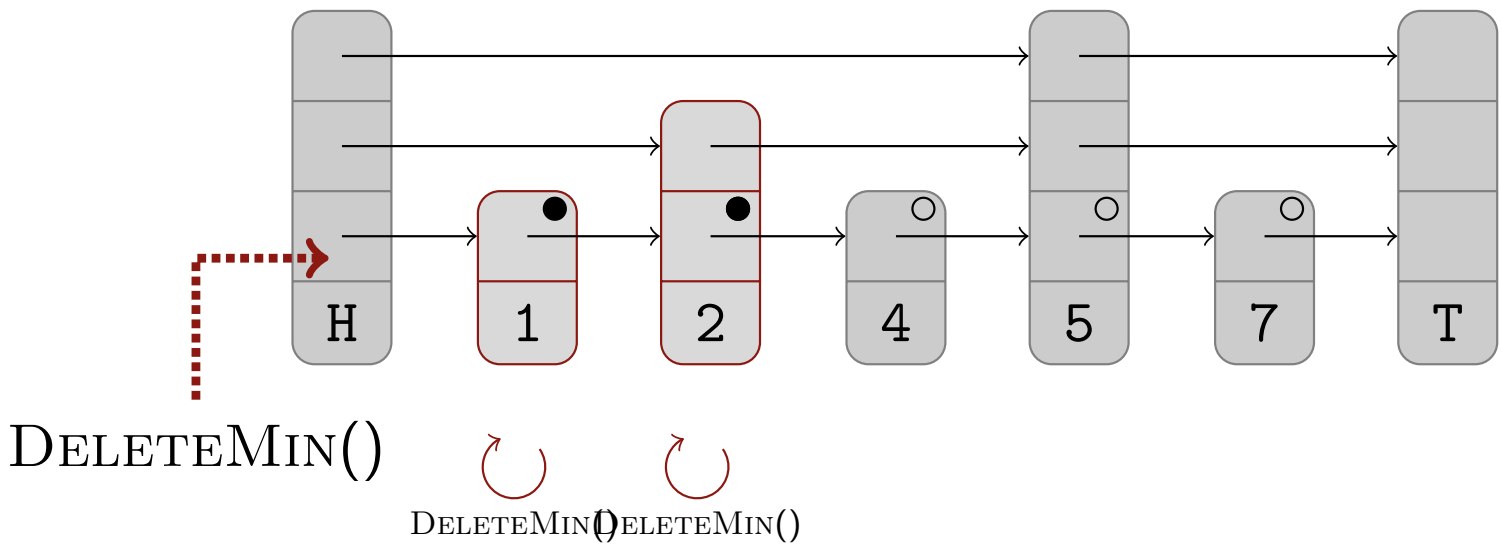

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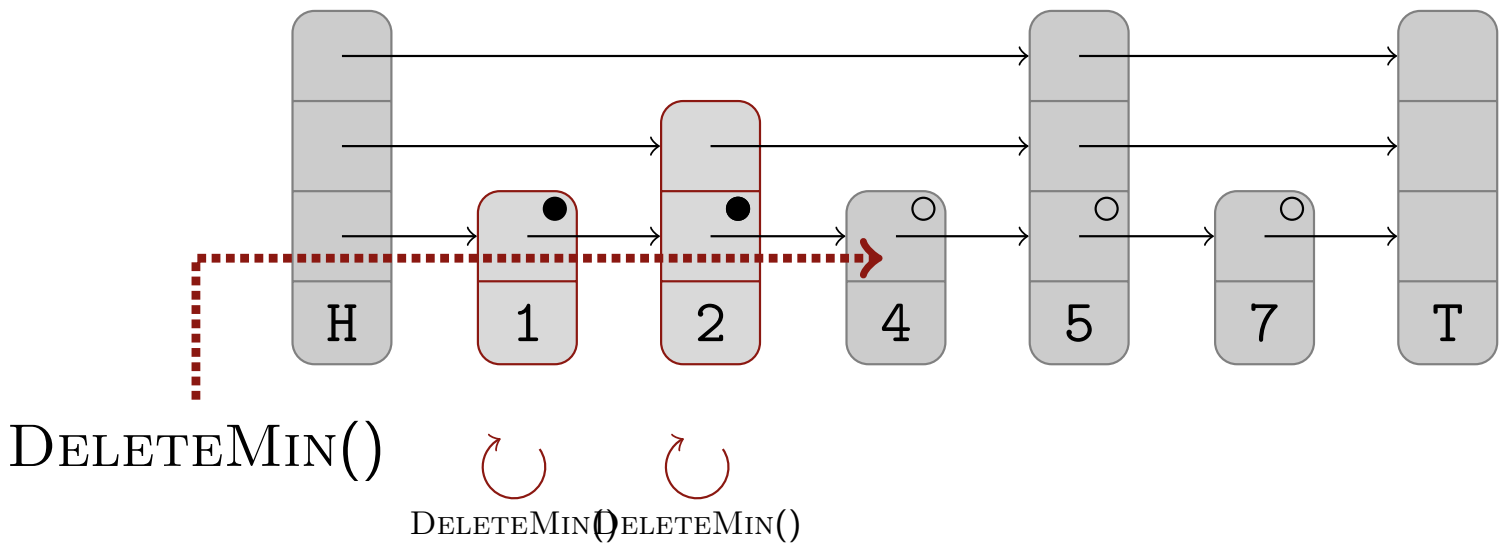

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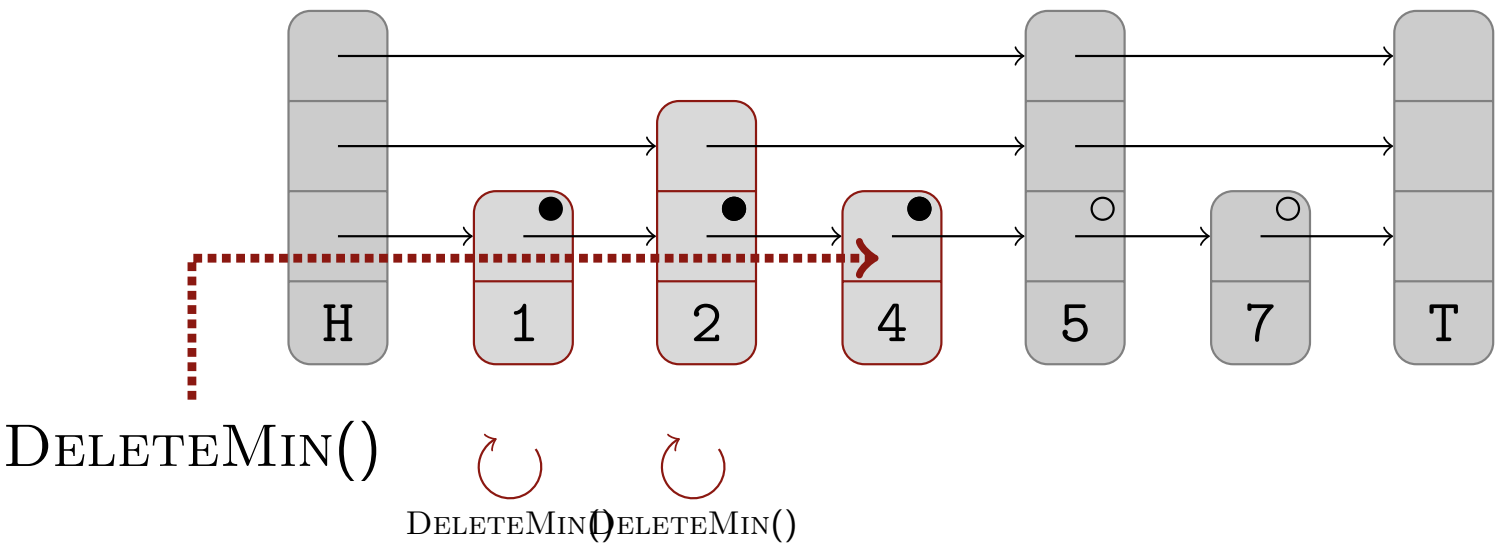
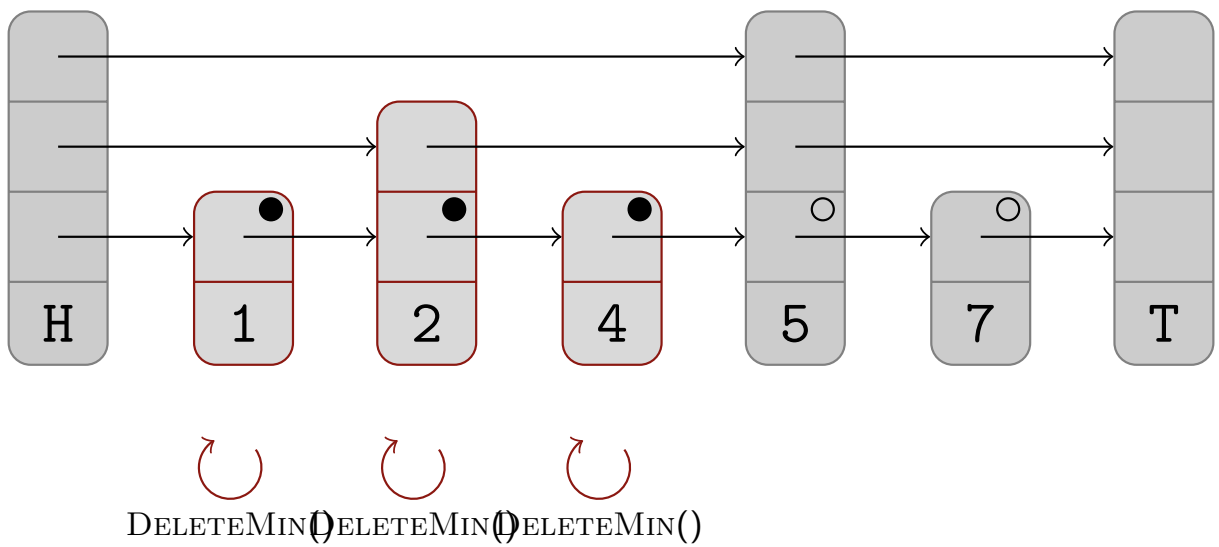
- Lock-free:
  - Perform all writes using Compare-and-Swap (CAS)
  - Colocate delete flag together with each next pointer, e.g., in the lowest order bit [Harris 2001], to make physical deletion safe.



Contention

Bottleneck: CAS in DeleteMin

- Several types of contention:
  - (i) Multiple CASes compete



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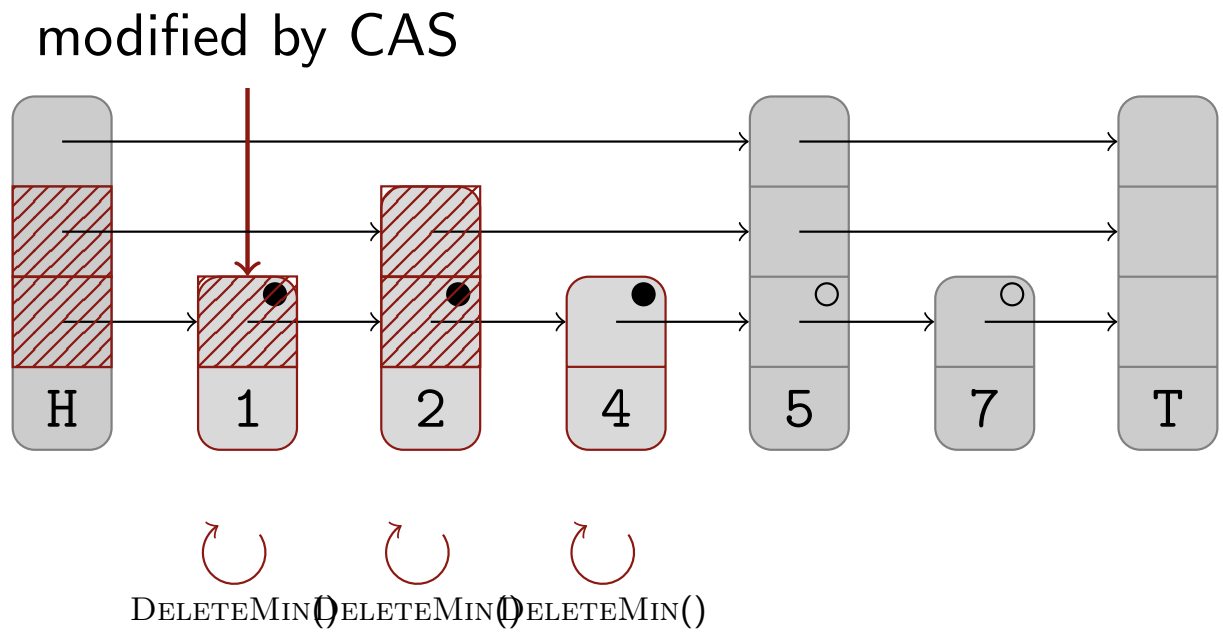

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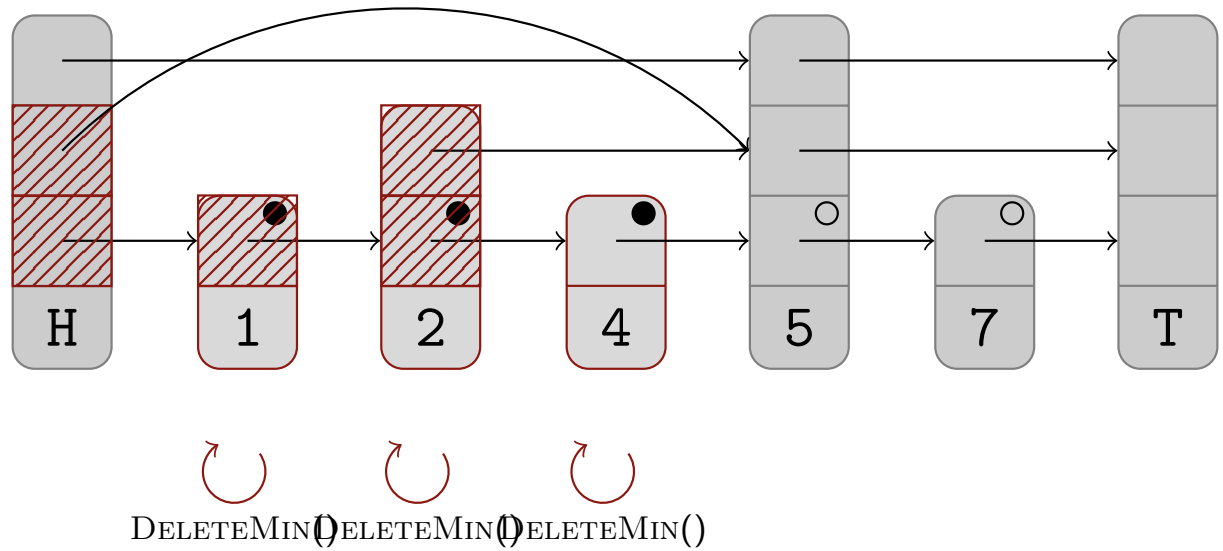

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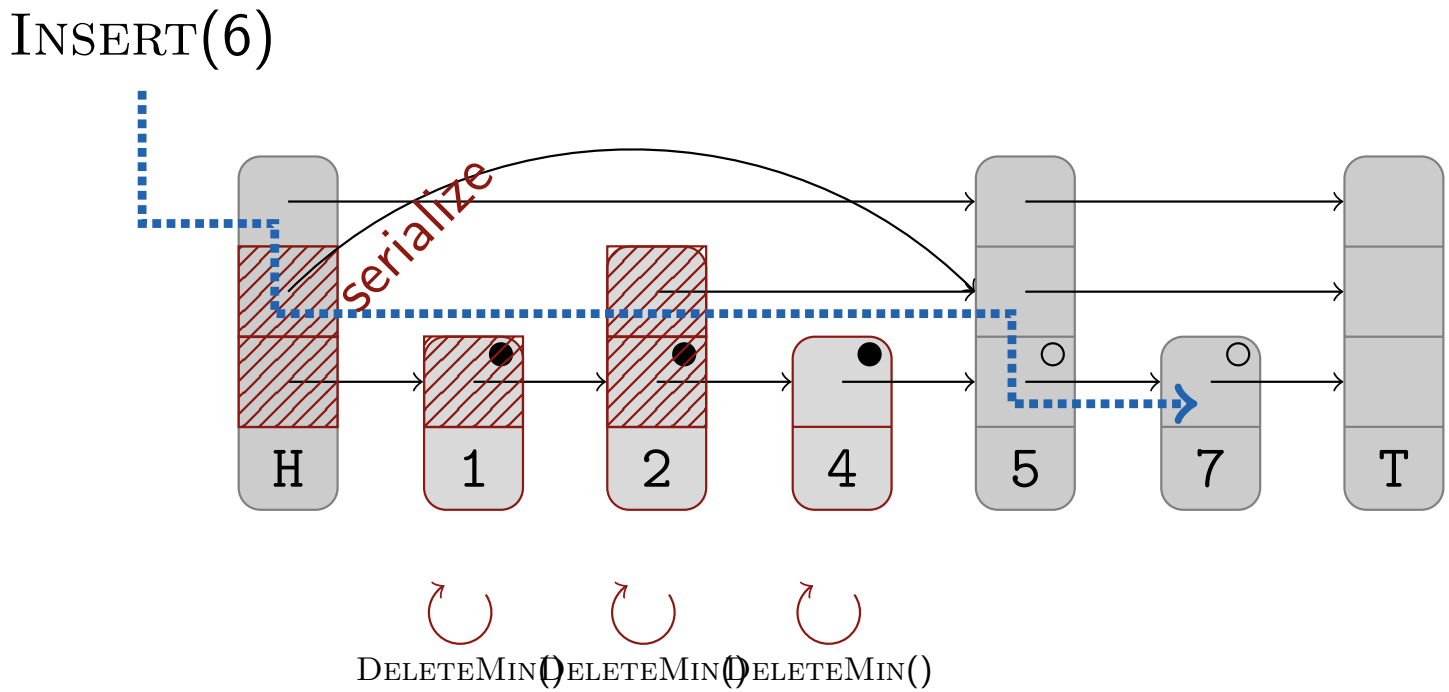
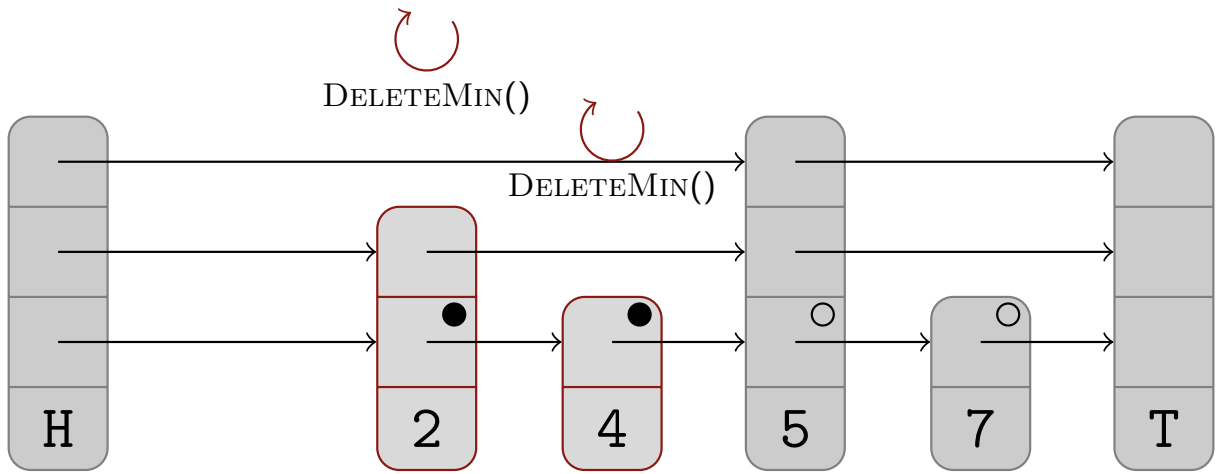


Our algorithm

Our solution

Key idea: No physical deletion after logical deletion!

- Instead, delete nodes in batches.



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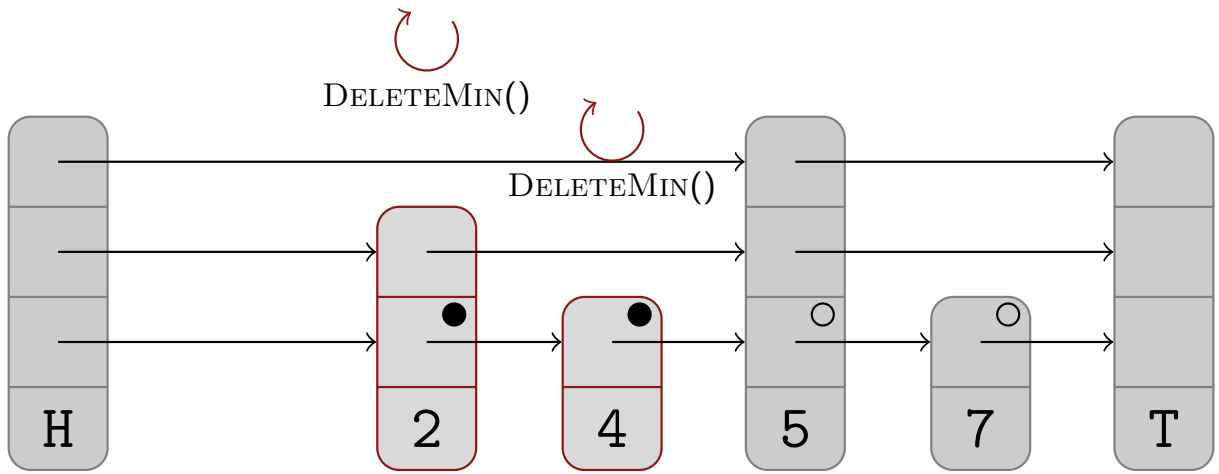

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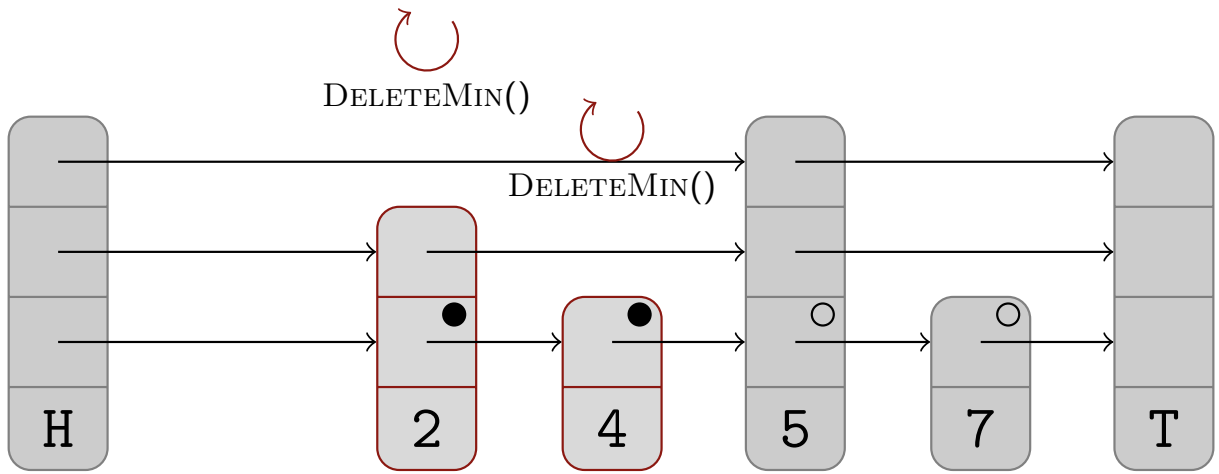

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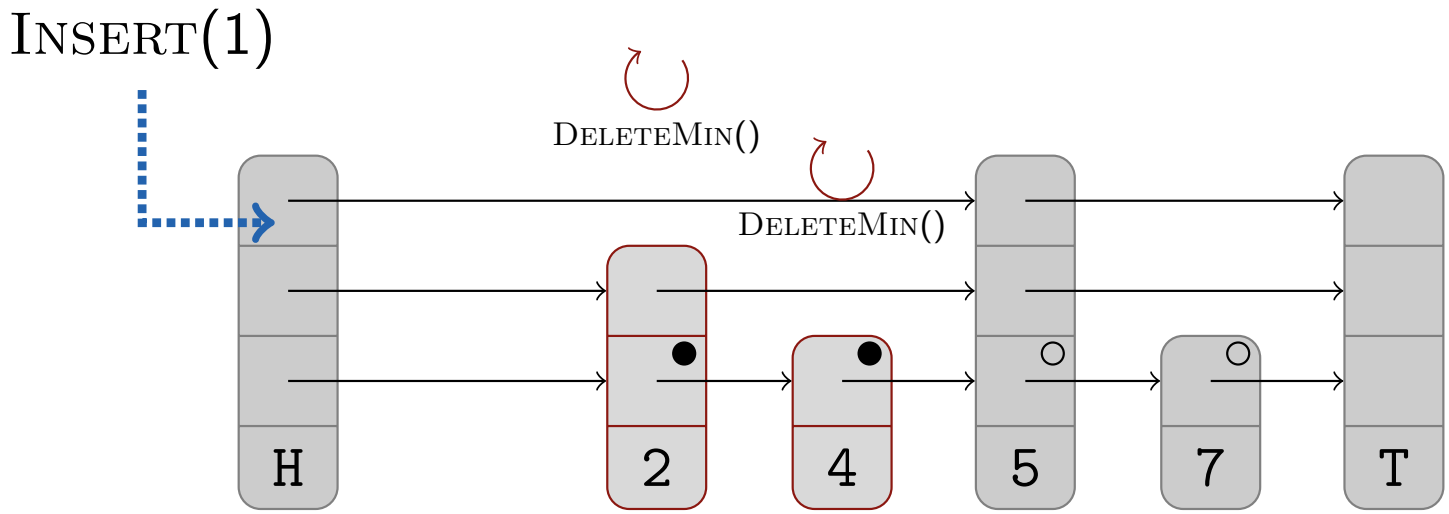

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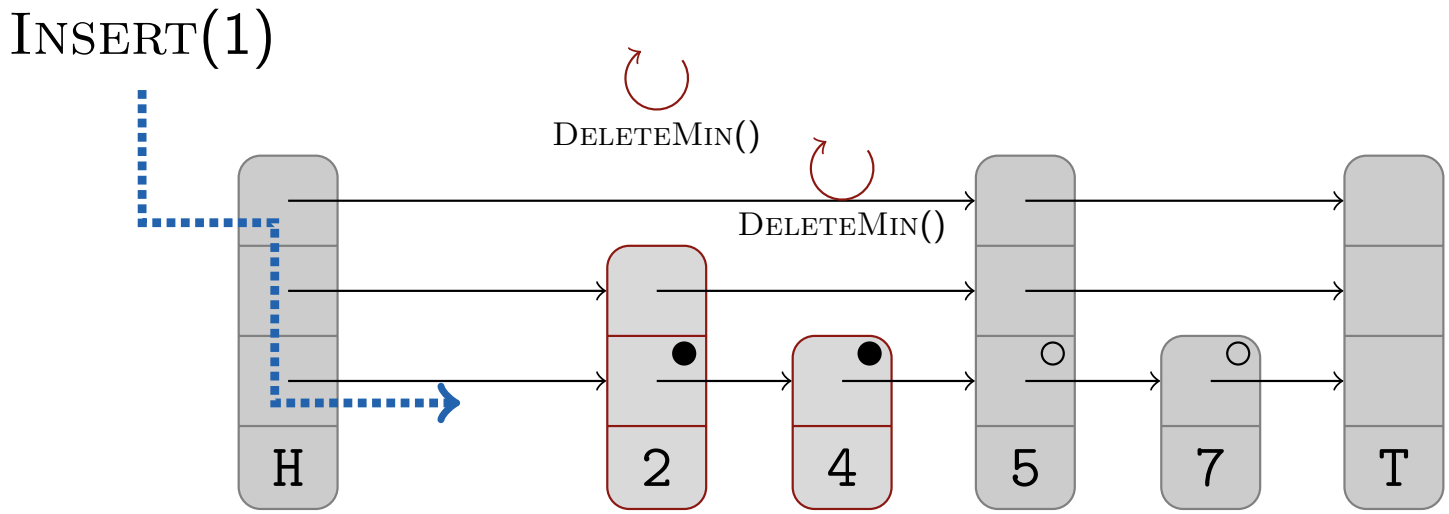

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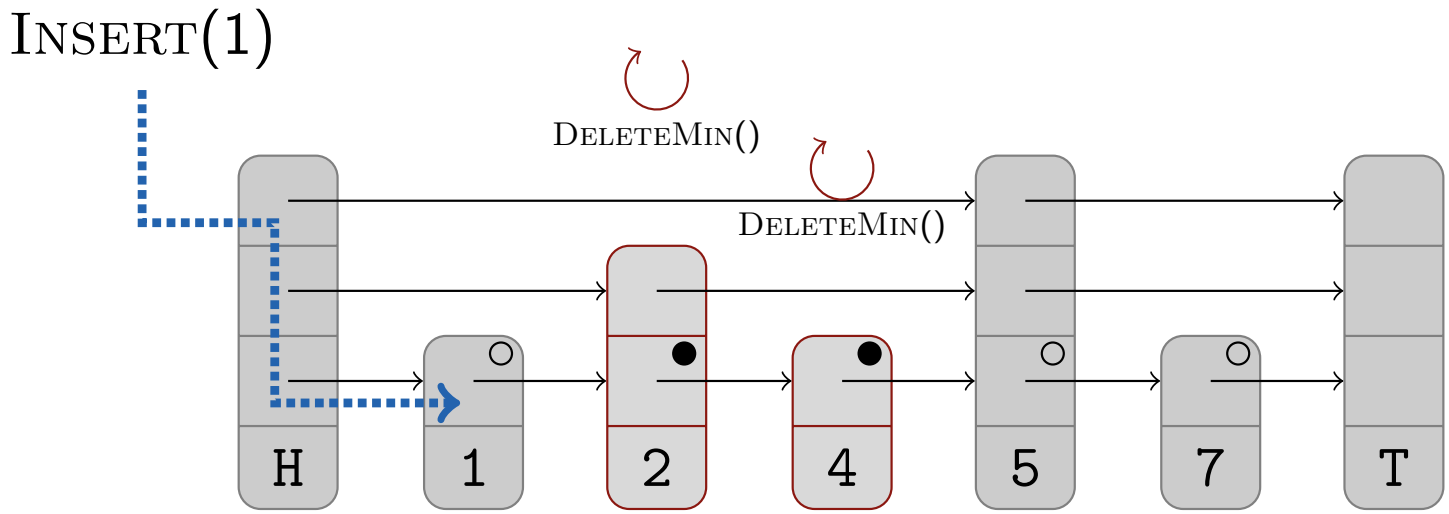

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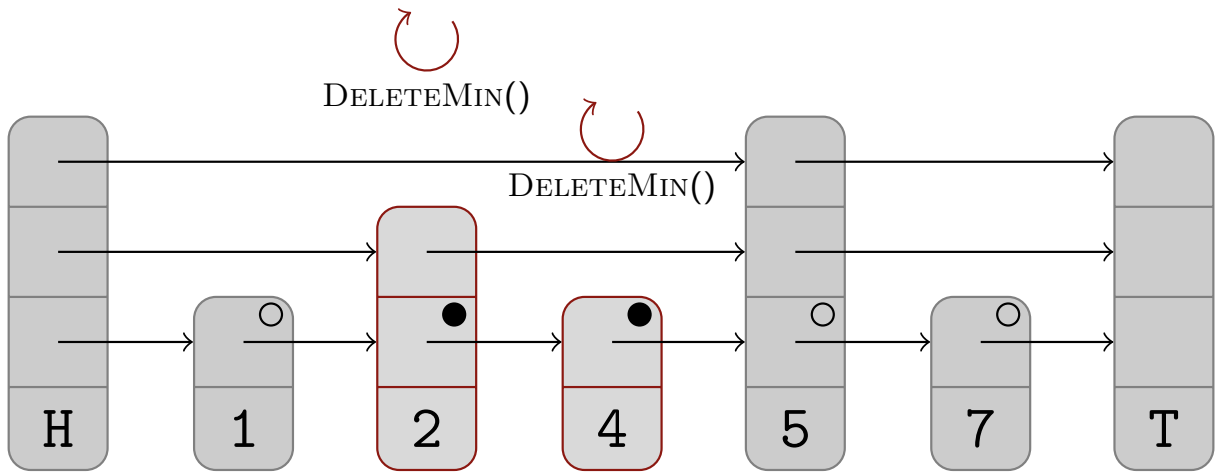

Does not work!

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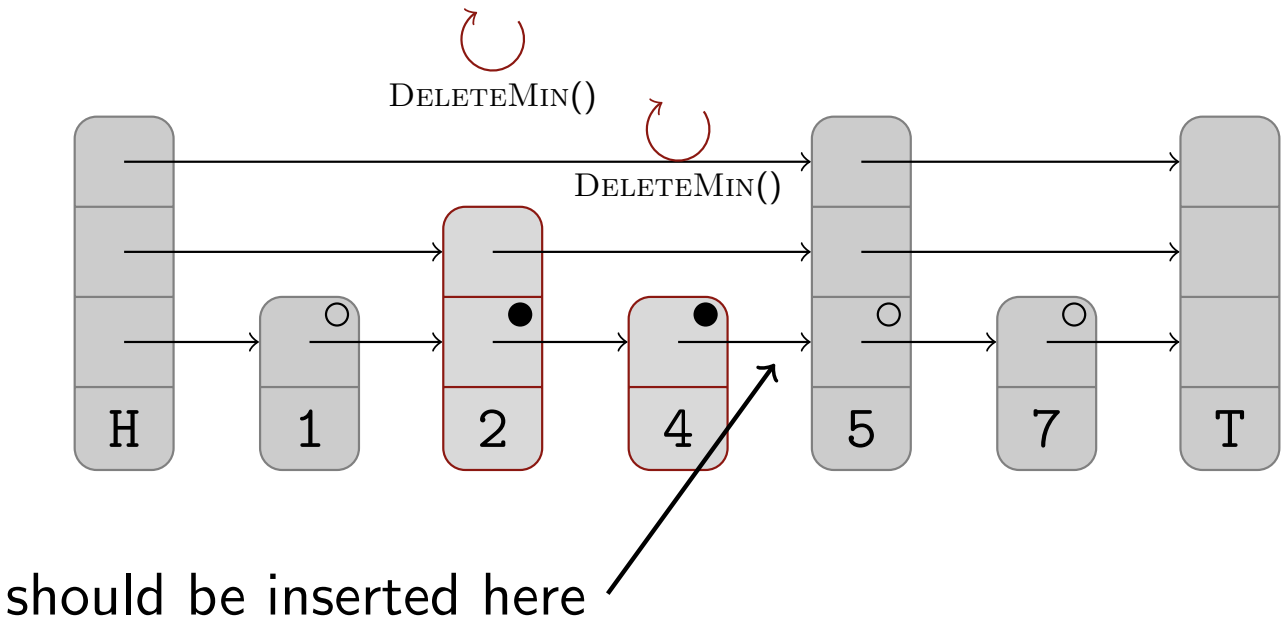

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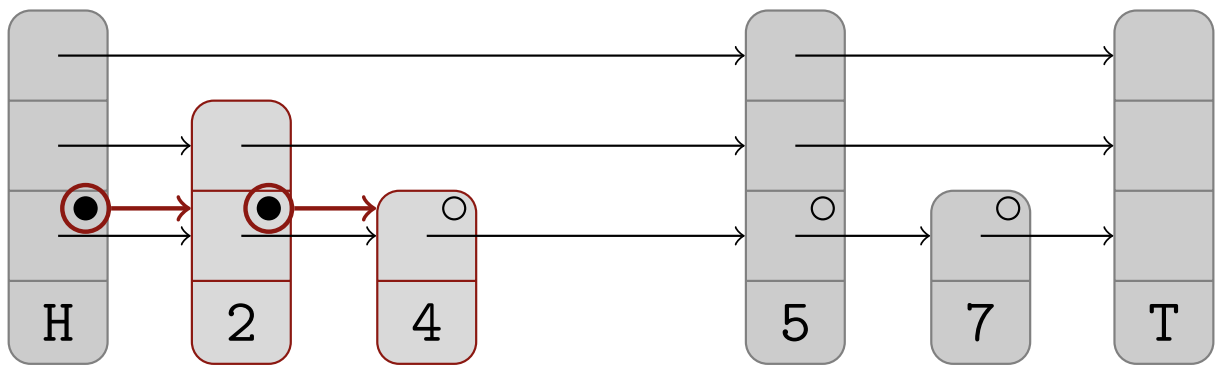
To guarantee prefix property,

- Store delete flag together with the *predecessor's* next pointer.



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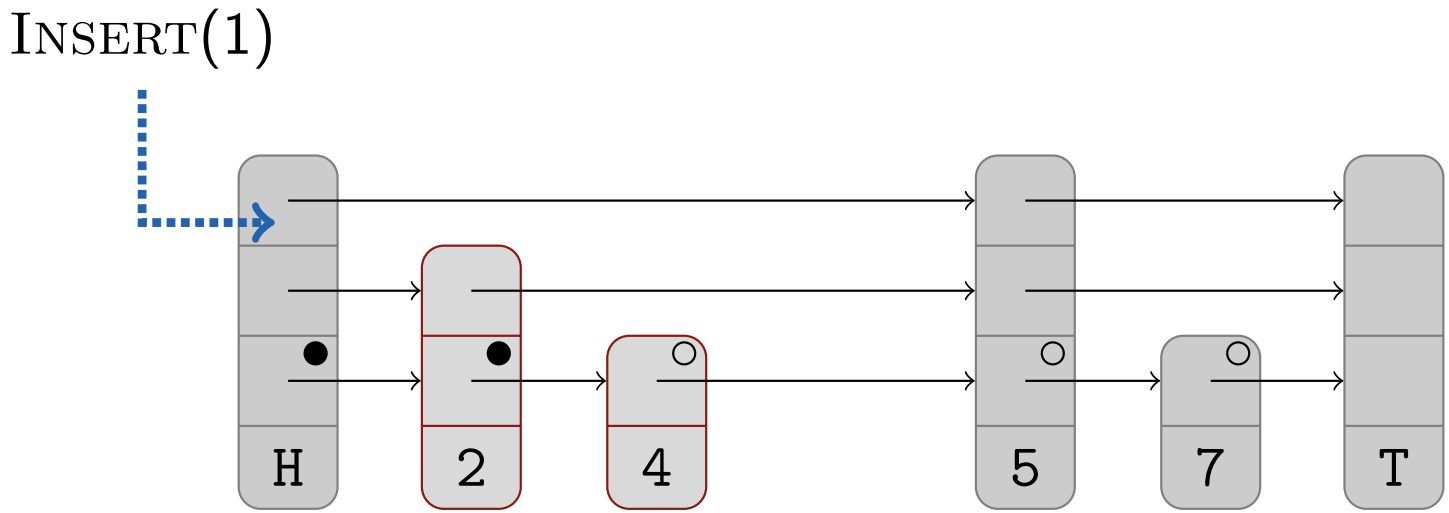

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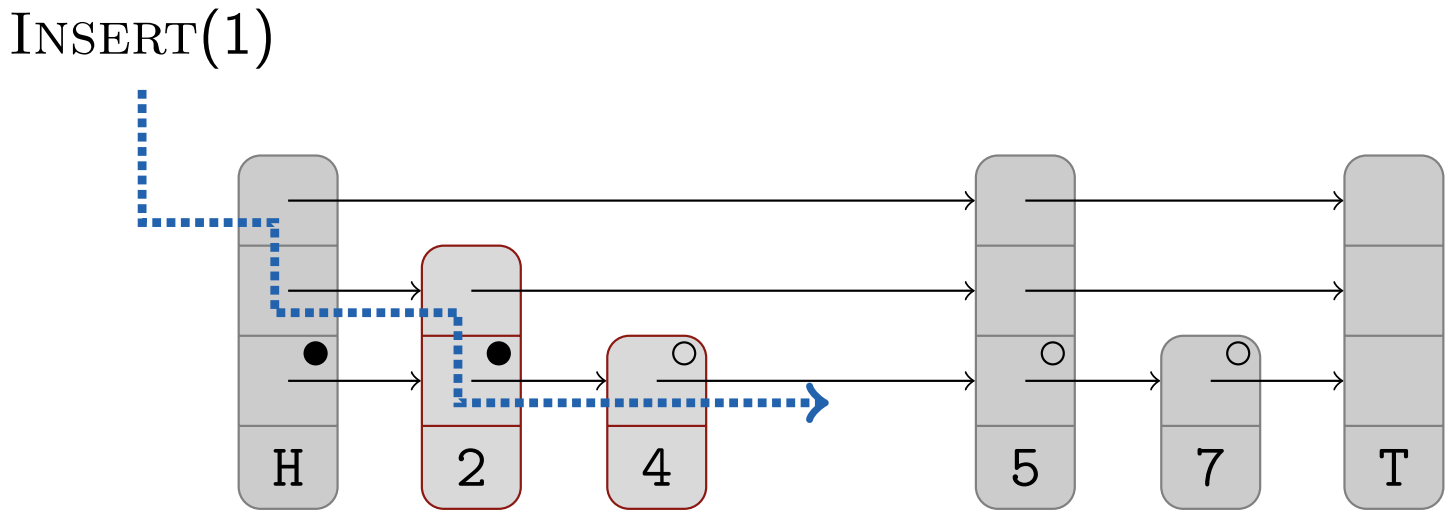

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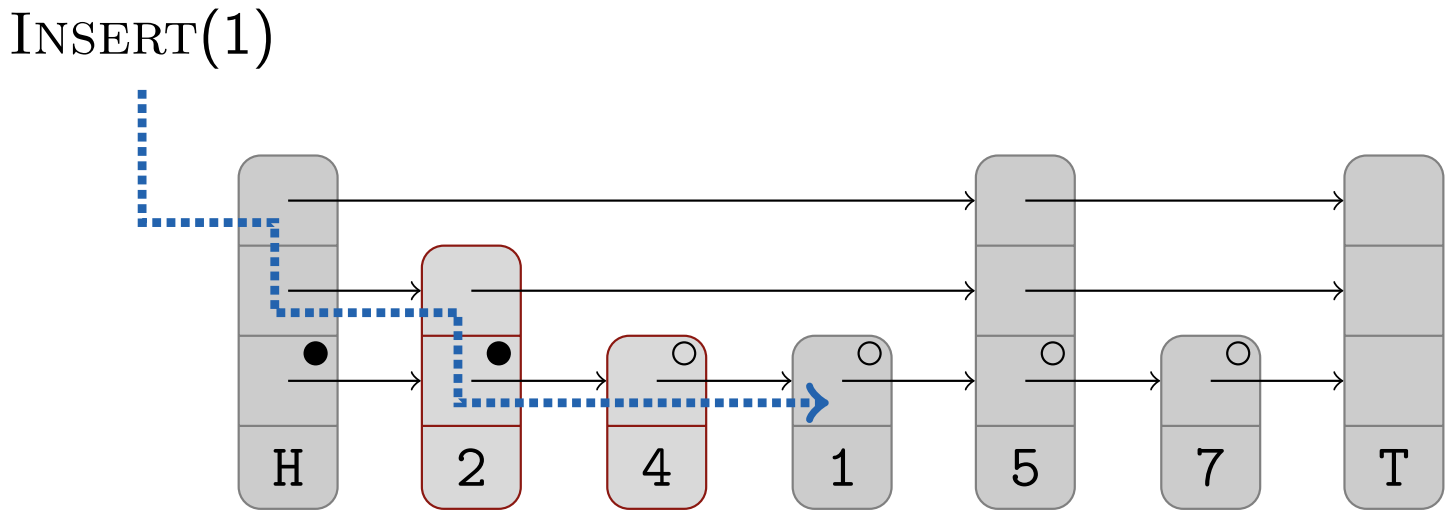

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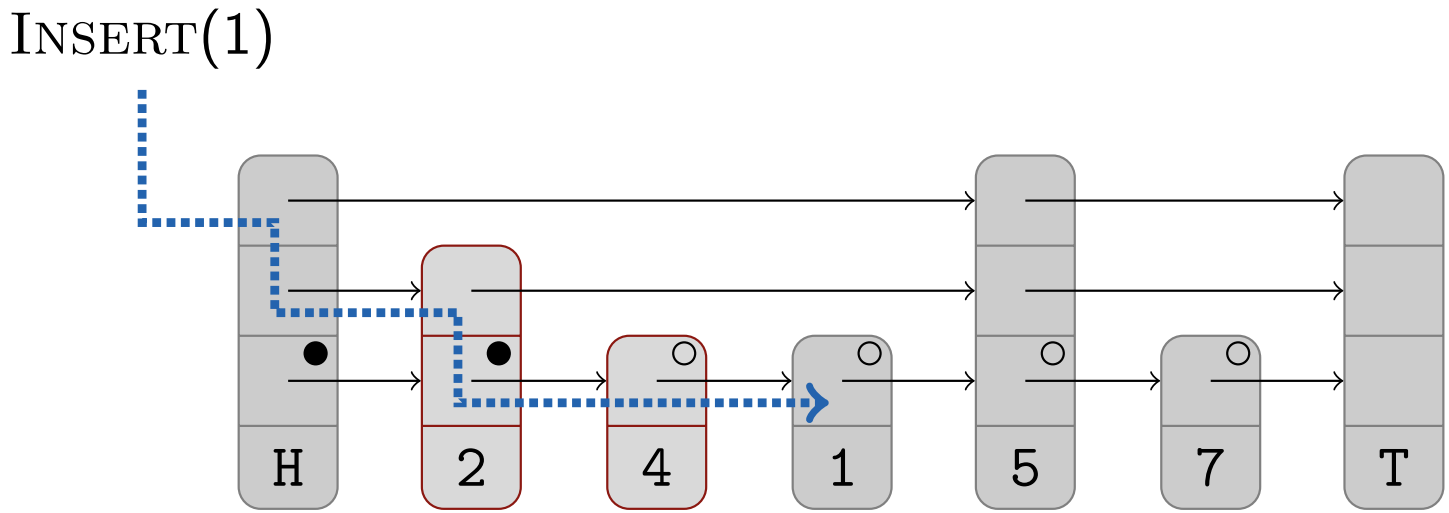

Still a prefix!

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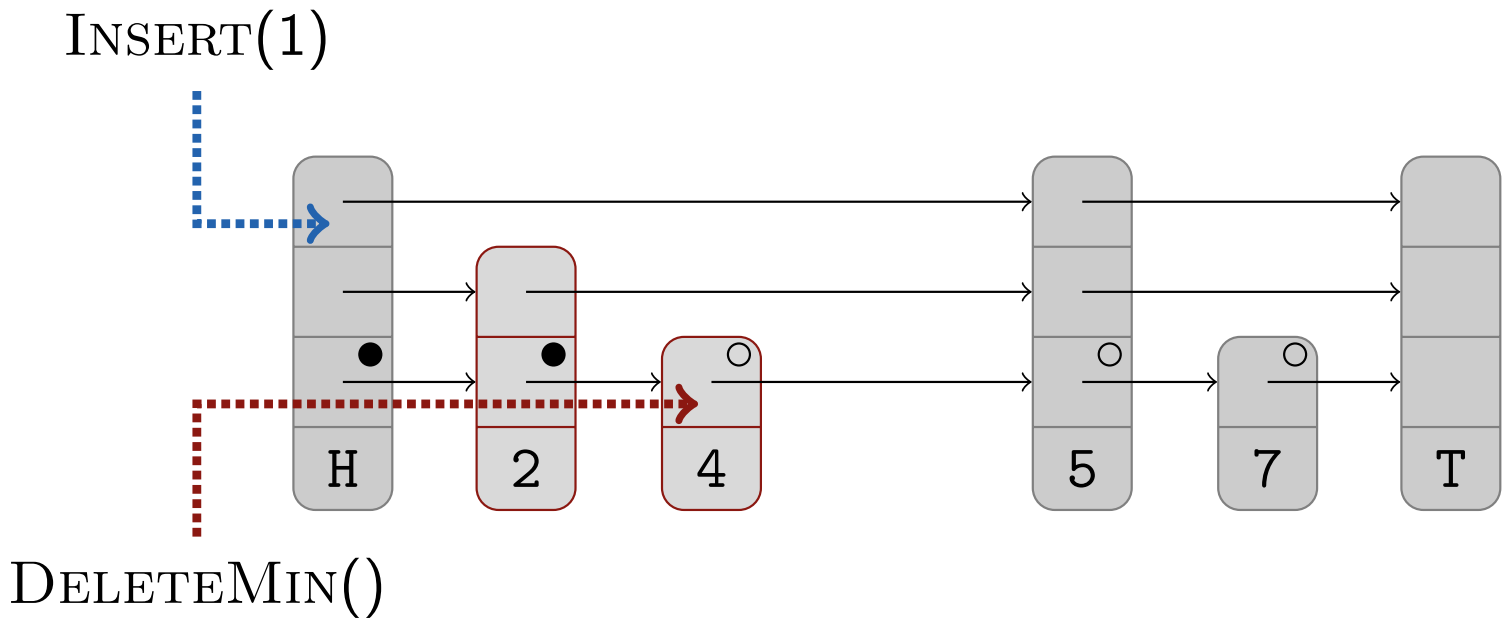
Resolving conflicts between INSERT and DELETEMIN.



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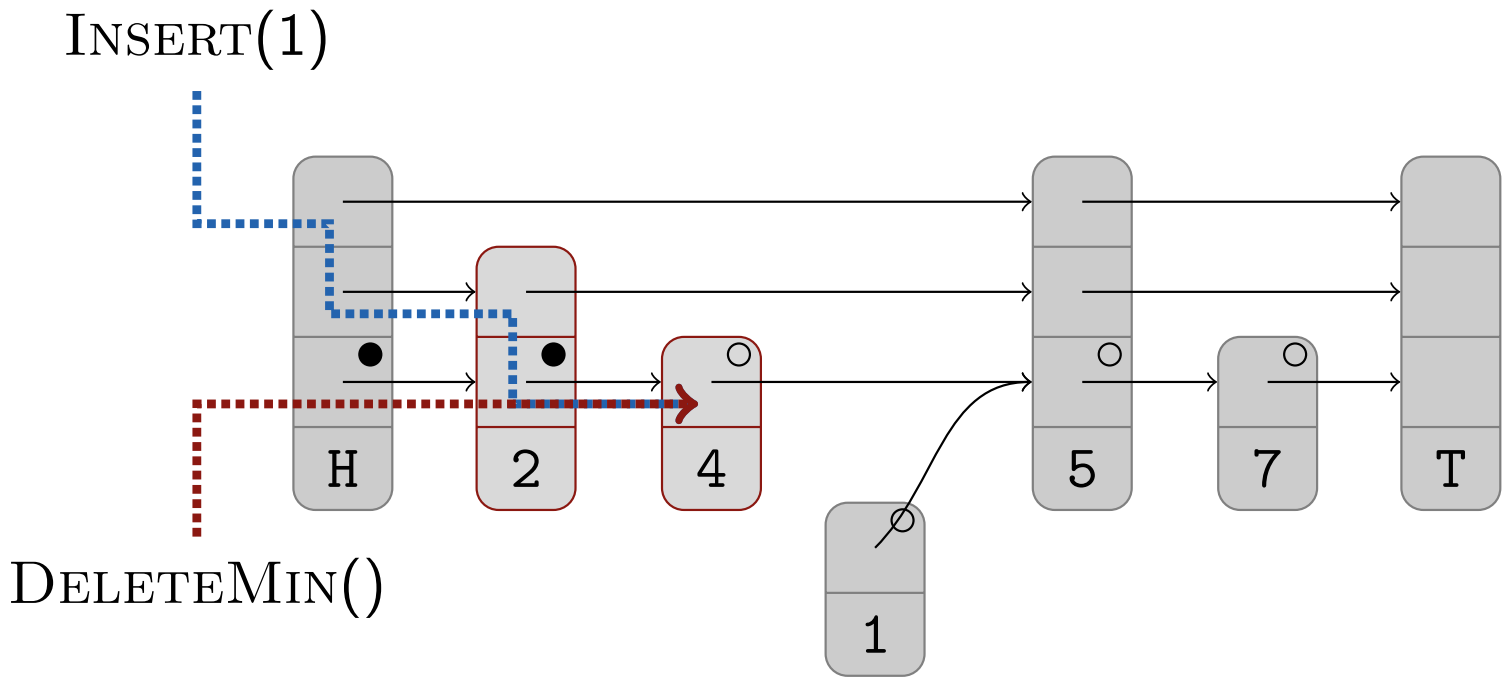

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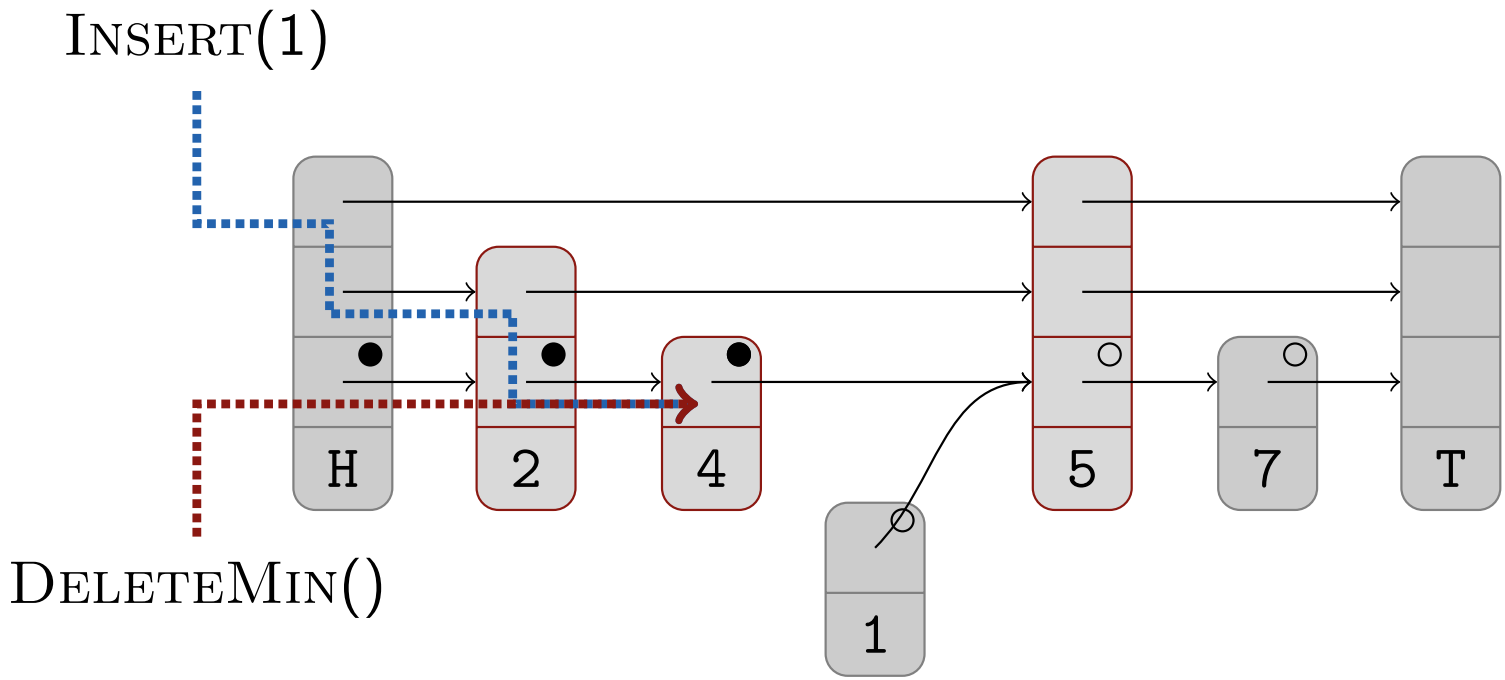

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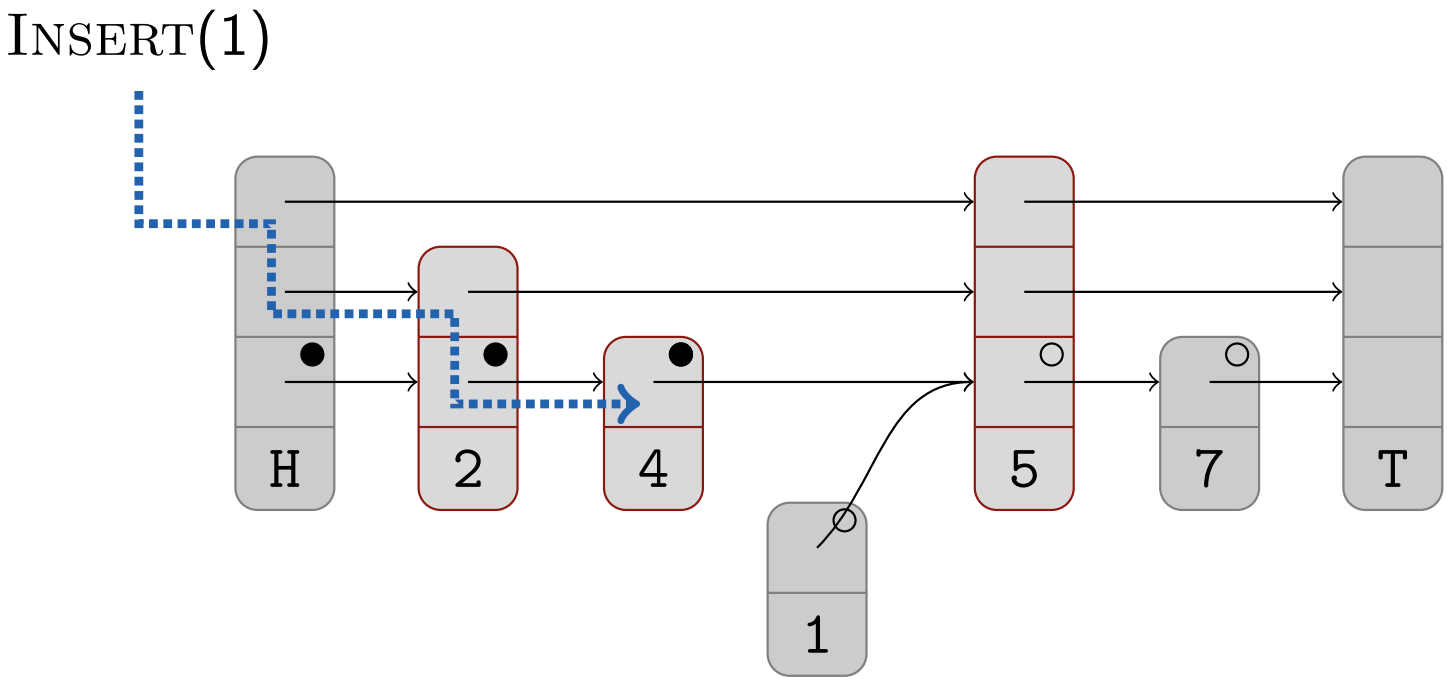

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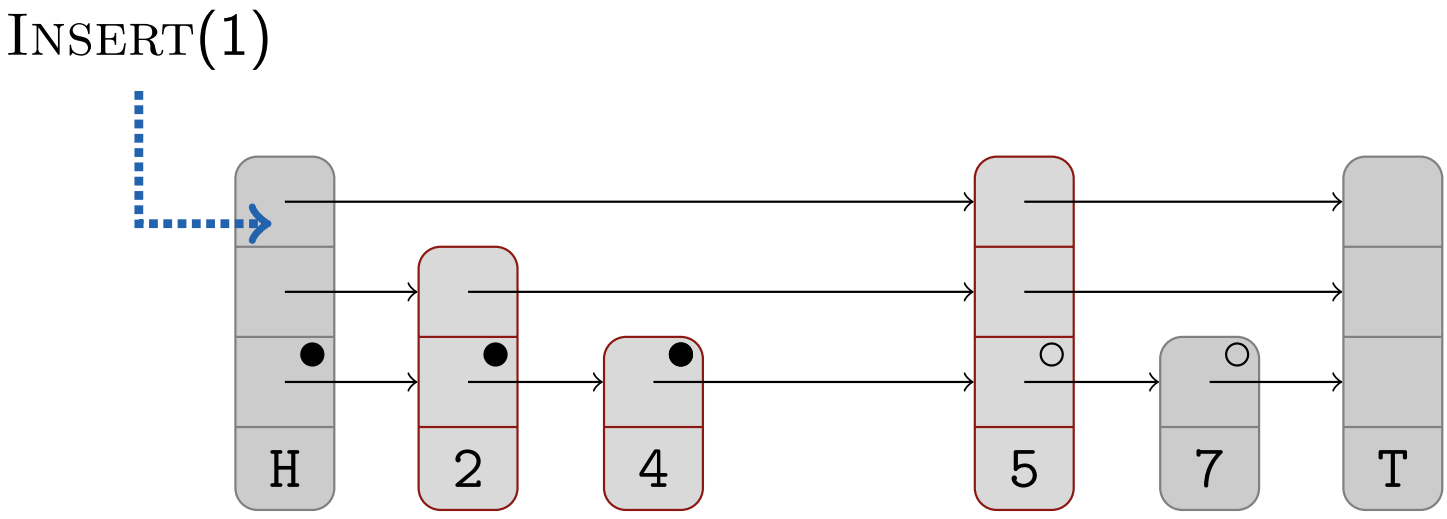

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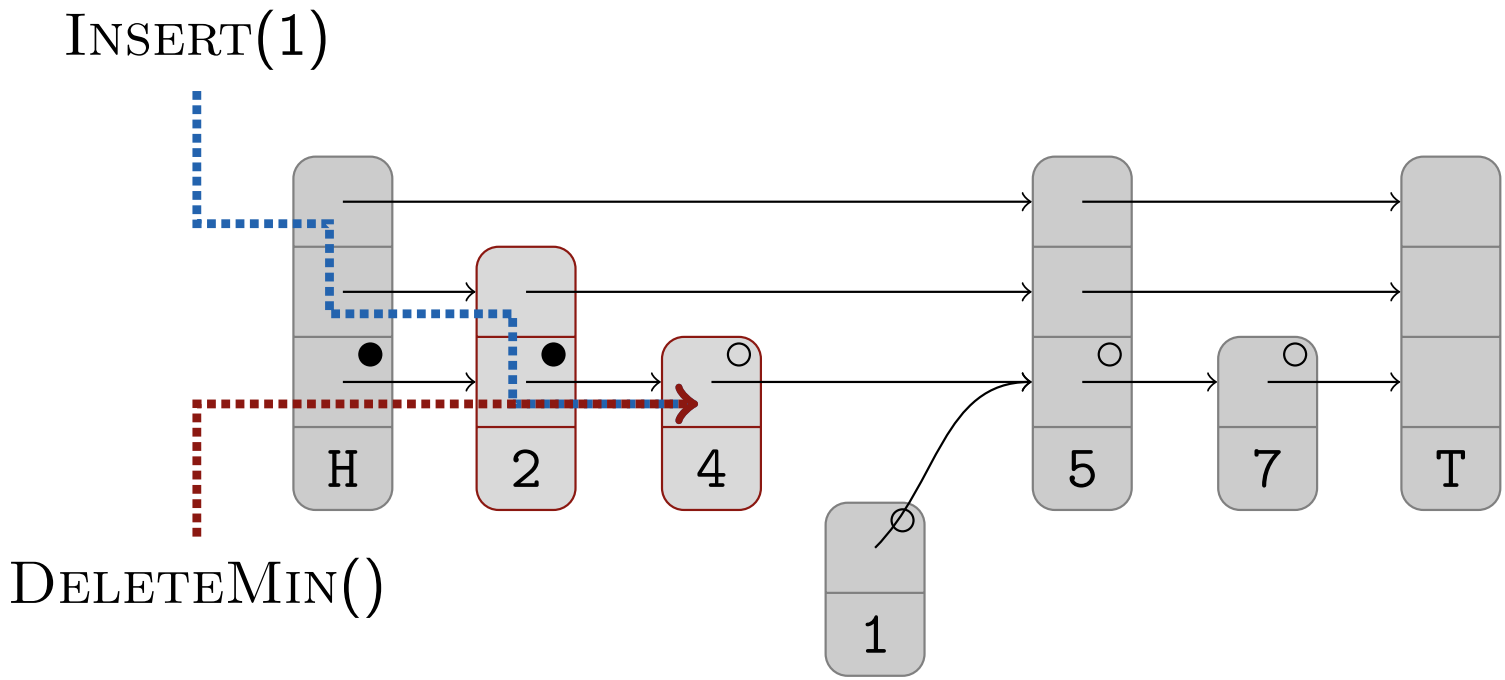

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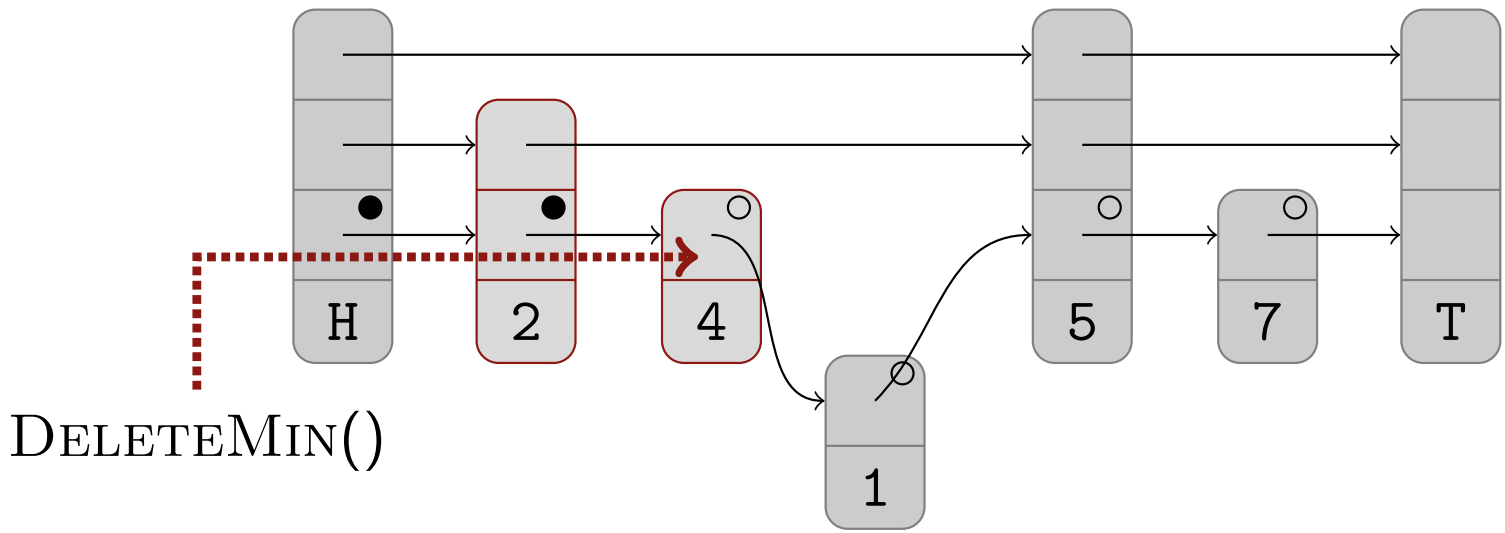

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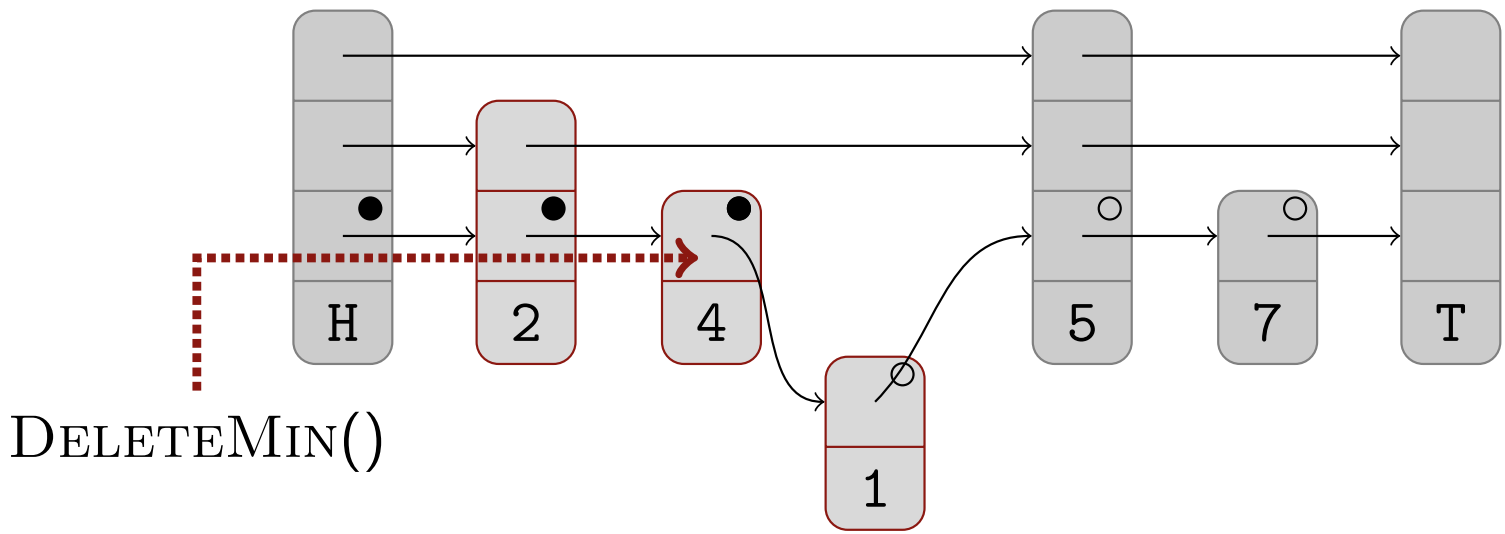
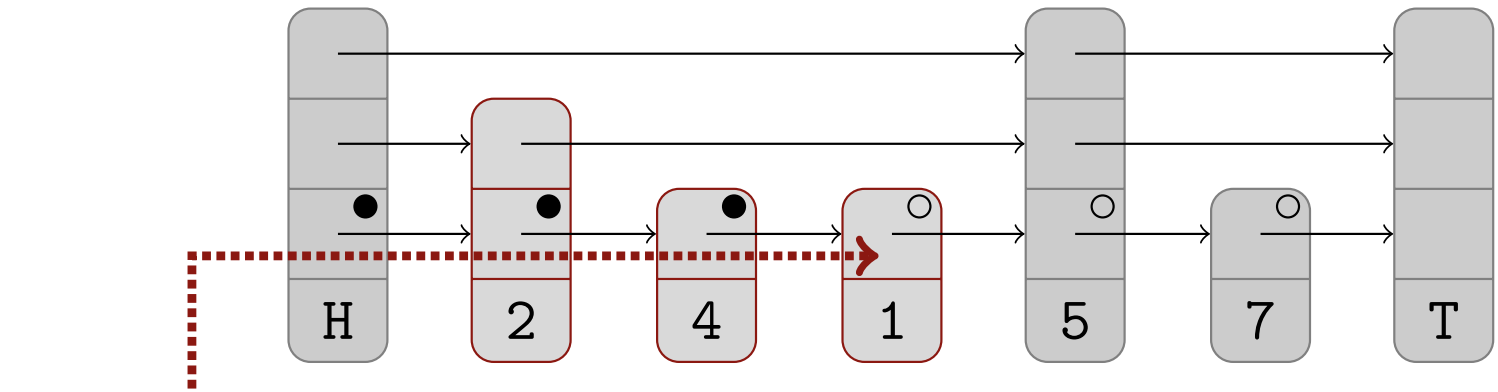


Physical batch deletion

- Physical batch deletion: update pointers in the head
- Done by DeleteMin, when the prefix of deleted nodes exceeds a threshold



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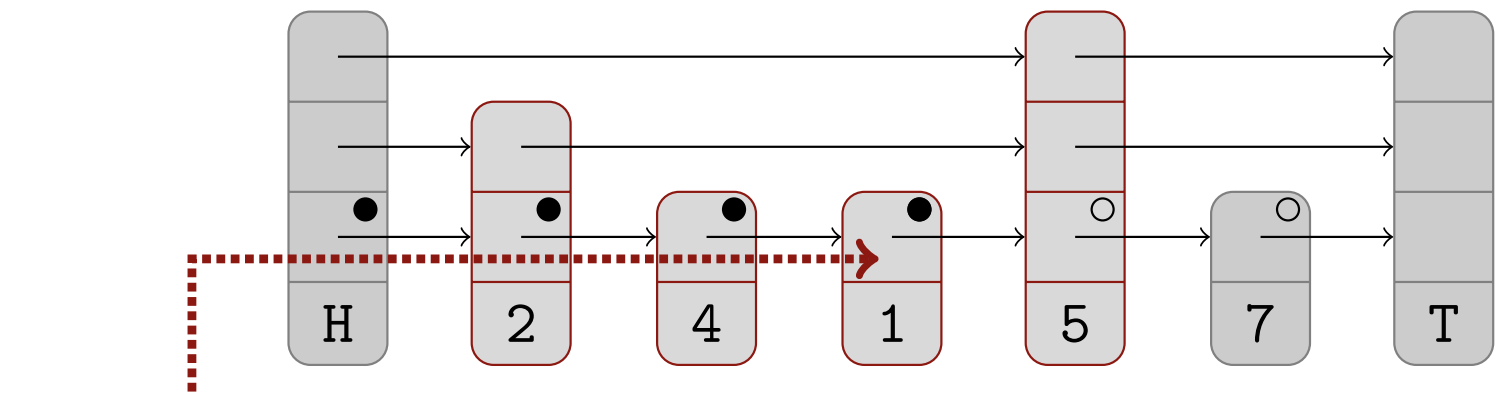

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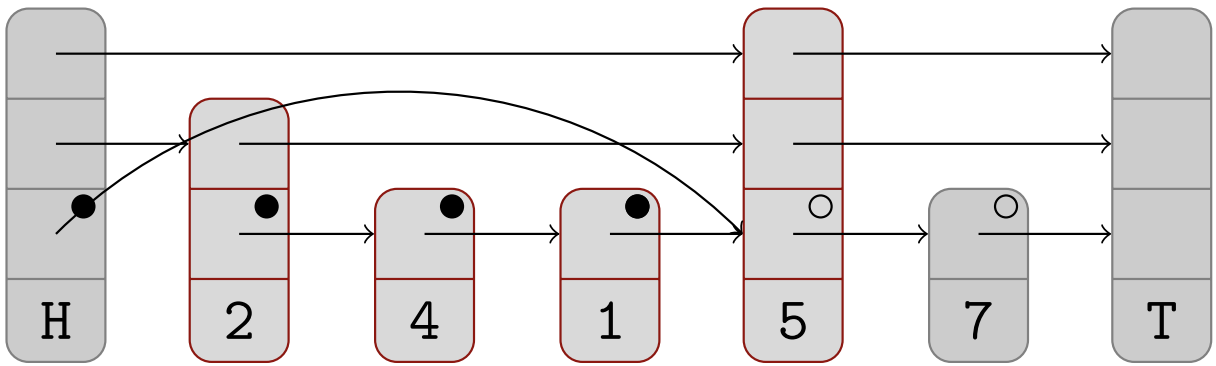


Correctness

- linearizable concurrent priority queue
- Correctness proof based on assertional reasoning in the paper
- Follows rather easily after establishing that the lowest level list consists of a deleted prefix followed by a sorted list which defines the logical state of the queue.
- We have also modeled the algorithm in SPIN and performed extensive state-space exploration

Evaluation

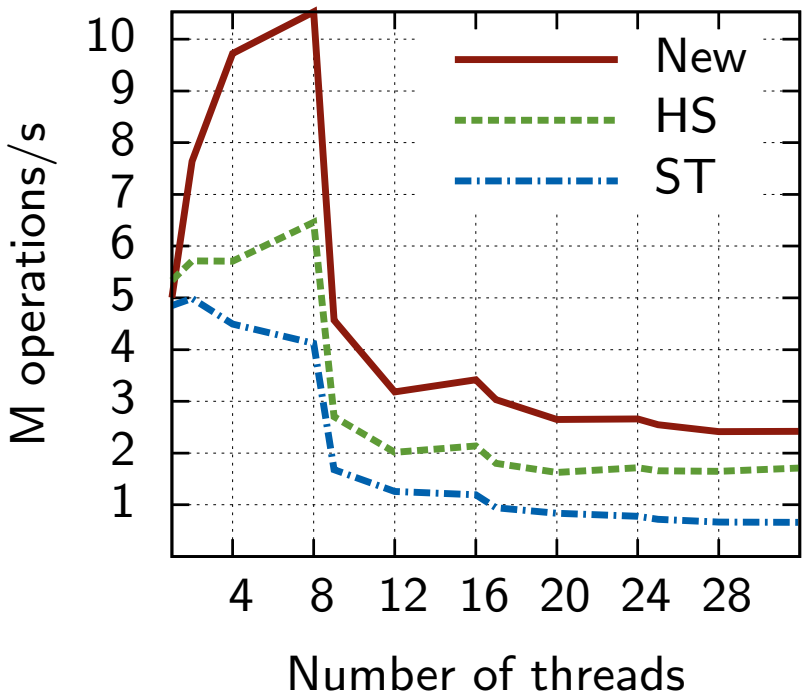
Comparison of maximal throughput

Compared against other lock-free skiplist-based priority queues:

- Sundell & Tsigas (*ST*): Only a single logically deleted node allowed in the lowest-level list.
- Herlihy & Shavit (*HS*): Lock-free adaptation of [Lotan & Shavit]. Logically deleted nodes need not form a prefix.

Comparison of maximal throughput

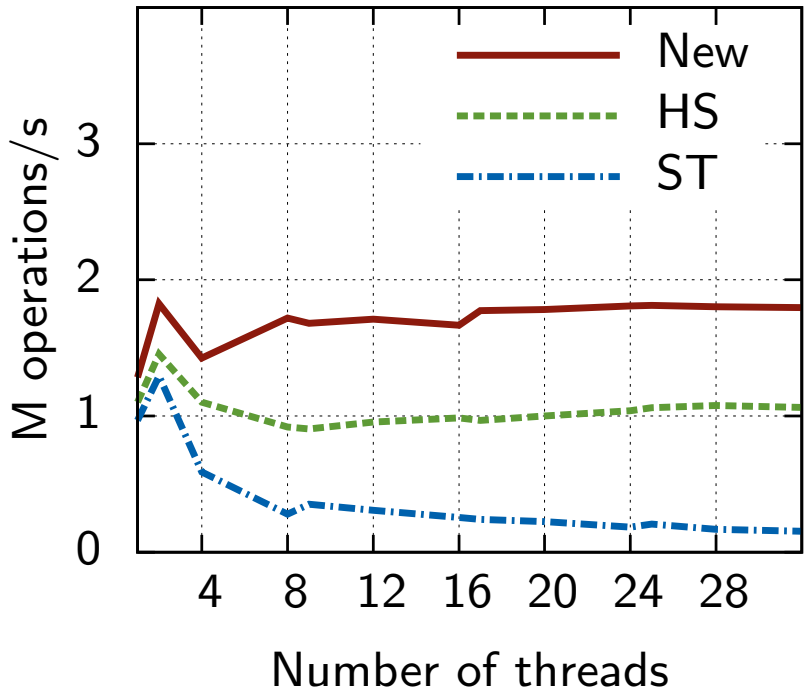
Benchmark: 50% Insert, 50% DeleteMin, 4 socket Intel sandybridge machine.



- 30 – 80% improvement in comparison to *HS*
- 1-8 cores: single socket (shared L3 cache)

Evaluation

Benchmark: DES workload, 4-socket AMD bulldozer machine.



- 30 – 80% improvement in comparison to *HS*
- 1 – 2 cores: shared L2 cache

More resources

- `http://user.it.uu.se/~jonli208/priorityqueue`
  - BSD licensed implementation
  - SPIN model
  - extended technical report
- Performance bug in the version in the proceedings: in the RESTRUCTURE algorithm which updates the head pointers – please see the extended technical report.

Conclusions

- a new linearizable, lock-free, skiplist-based priority queue algorithm.
- new representation of logical deletion.
- This reduces the number of CASes to critical shared memory locations
- 30 – 80 % performance improvement over existing such algorithms.

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Thank you.