Skiplist Timing Attack Vulnerability

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Talk Overview

- Introduction
- Probabilistic Skiplist
- Skiplist structure mapping
- Possible attacks on Skiplists
- Splay List as a proposed defense
- Summary

Introduction

- Database Characteristics:
  - Underlying data structure – graphs, trees, lists and so on.
  - Data types/formats – text, discrete or continuous numeric values, coordinates and others.
  - Query types and behavior.
- Targets
  - Identify potential weaknesses and attack vectors based on DB characteristics, and offer defenses.
  - Offer computational complexity for attack/defense.

Run-time Based Attack

- The underlying architecture of a database may be comprised of a single or multiple data structures: graphs, trees, stacks, etc…
- The organization of the data may hold information regarding the data itself (as in the case of a binary search tree).
- Run-time of queries is also dependent on the structure and may leak information
  - Futoransky et al. describe such an attack on SQL databases (insertion attack).
- We show an example of an attack based on the Skiplist structure.
  - Skiplists are a probabilistic alternative to balanced trees.
  - Maintain an ordered structure with multiple levels.
  - Contains *log n* levels with $\frac{n}{2^{l-1}}$ nodes per level l.

Probabilistic Skiplist - Example

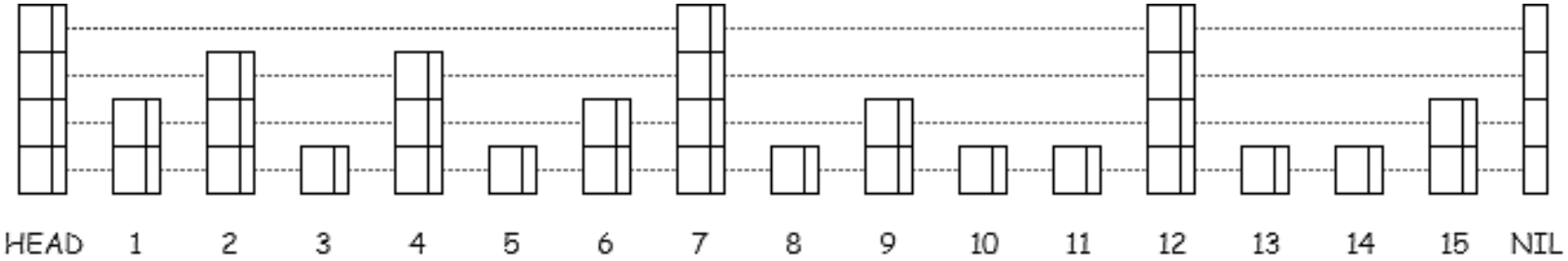


Figure 1 – 4 level Skiplist with 15 nodes

- Skiplist creation:
  - Search for ordered placement of node.
  - Insert node at level 1.
  - With 0.5 probability, add next level to node.
  - Continue to subsequent level with probability 0.5 until either next level was not added, or max level has been reached.
- Skiplist implementations:
  - MemSQL, Redis

Skiplist Mapping

- We give an algorithm, SkipListMap, that maps the structure of a given probabilistic Skiplist using the search function.
  - The size of the structure, *n*, is known.
  - The structure holds unique values.
  - The range of possible values in the structure is known and is of size *O(n)*.
  - The runtime of the search algorithm is consistent.
- Using SkipListMap to discover the structure of the Skiplist allows us to perform attacks.
- Goal:
  - Restructure the Skiplist to cause worst case performance.
  - Create hidden channel between two parties.

SkipListMap Algorithm

- Consists of two phases:
  - Search time mapping
  - Skiplist reconstruction
- Search operation example for Skiplist in figure 2
  - Search for “10” – requires 6 comparisons.

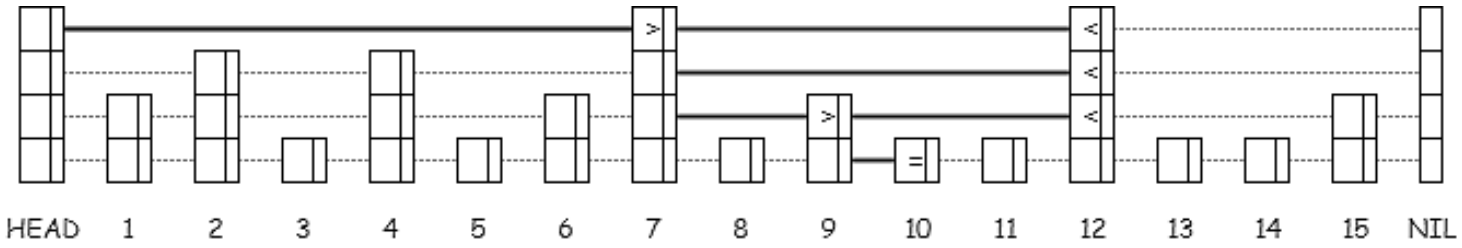


Figure 2 – Skiplist search example

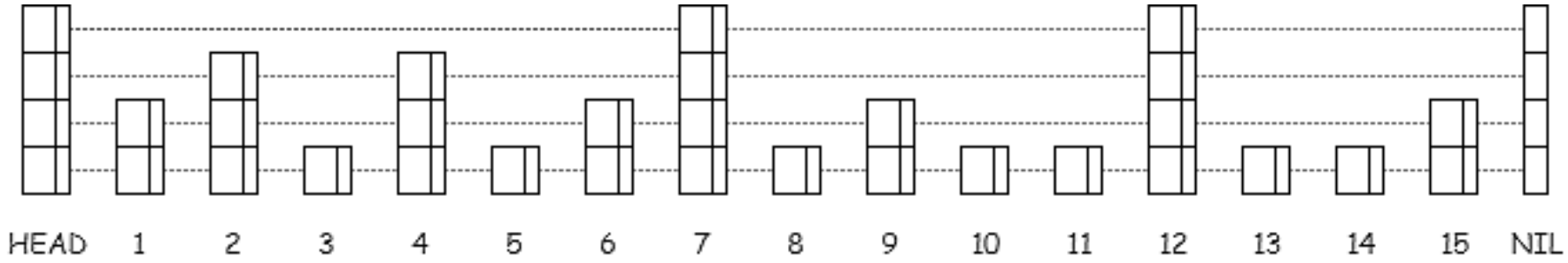
SkipListMap - Search Time Mapping

Algorithm 1 Map Skiplist search times

```
1: procedure MapRuntime(skiplist, values)
2:     runtimes = newArray
3:     for x_i in values do
4:         T_{x_i} ← runtime of skiplist.find(x_i)
5:         runtimes.append(T_{x_i})
6:     end for
7:     T_min ← min(runtimes)                ▷ Minimum over all runtimes
8:     for T_{x_i} in runtimes do
9:         T_{x_i} = T_{x_i} / T_min
10:    end for
11:    return runtimes
12: end procedure
```

- Search for all possible values, x_i, in the Skiplist.
- For each value found, denote its search time T_{x_i}.
- Denote the the lowest runtime to be T_{min}.
- Normalize runtimes based on T_{min} such that $T_{min} = 1$.
- Normalized T_{x_i} is the length of the search path to x_i.

Search Time Mapping - Example



- For our example:
  - $T_1 = 3, T_2 = 2, T_3 = 5, T_4 = 3,$
    $T_5 = 6, T_6 = 5, T_7 = 1, T_8 = 5,$
    $T_9 = 4, T_{10} = 6, T_{11} = 7, T_{12} = 2,$
    $T_{13} = 6, T_{14} = 7, T_{15} = 5.$

SkipListMap - Reconstruction

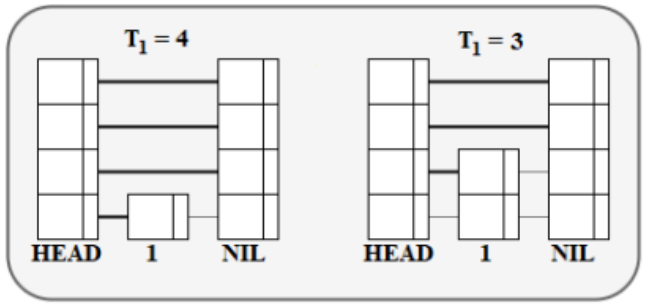
Algorithm 2 Reconstruct Skiplist by search times

```
1:  procedure ReconstructSkiplist(values, runtimes, T_min)
2:      reconstructedList ← newSkiplist()
3:      runtimes ← sortAscending(runtimes)        ▷ Sort runtimes from min to max
4:      for T_{x_i} in runtimes do
5:          t = 0                                  ▷ zero current search time
6:          L = 1                                  ▷ initialize insertion level
7:          do
8:              reconstructedList.insert(x_i, L)   ▷ Insert x_i at level L
9:              t ← runtime of reconstructedList.find(x_i)
10:             t = t / T_min                      ▷ Normalize runtime
11:             L = L + 1                          ▷ Increase level for next iteration
12:         while t ≠ T_{x_i}
13:     end for
14:     return reconstructedList
15: end procedure
```

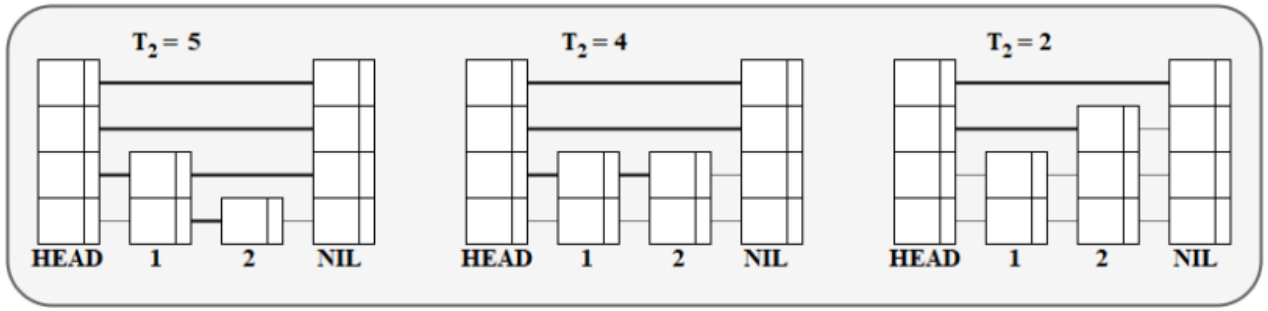
- Create empty Skiplist with *log n* levels (in our example, 4)
- Insert nodes in order of increasing values of x_i, beginning at level 1
  - After each level insertion attempt, search for x_i.
  - Repeat until correct search time is found.

Reconstruction - Example

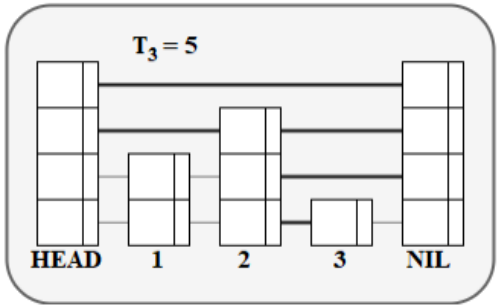
- Reconstruction of first 4 nodes.
- Note that once a node level is chosen, inserting nodes to the right does not change search time of previous nodes.



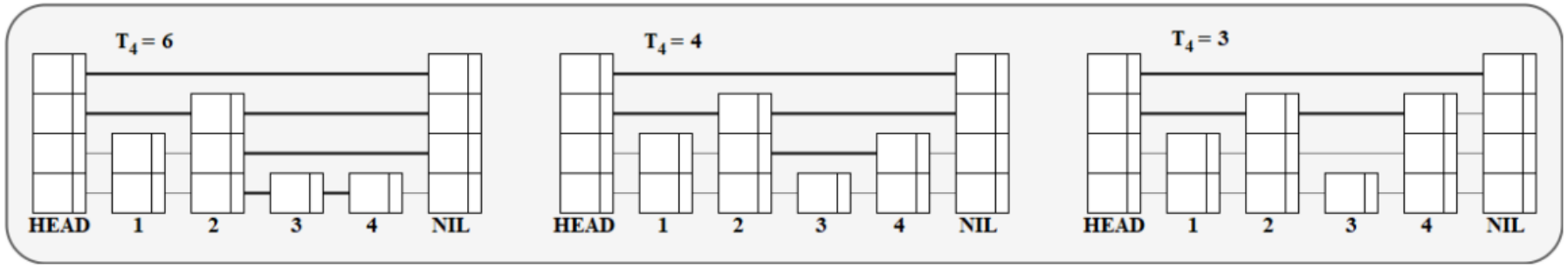
(a) Inserting x_1 into level 2.



(b) Inserting x_2 into level 3.



(c) Inserting x_3 into level 1.



(d) Inserting x_4 into level 3.

Skiplist Runtime Attack

- Runtime Attack requires “write” access
- Restructure the Skiplist to cause worst case performance.
- Remove all items which exists above level 1.
- Re-insert all items that were removed. Approximately 0.75 will be in level 1.
- Repeat removal/insertion until reducing Skiplist structure to a linked list with a search time of *O(n)*.

Skiplist Hidden Channel Attack

- Hidden Channel Attack requires 2 parties, one with “write” access.
  - Transmitter and Receiver
- Original Skiplist database is distributed publicly.
- Each attacker maps the Skiplist structure.
- Transmitter holds private knowledge regarding nodes.
- Transmitter selectively removes and re-inserts nodes, marking them.
  - Allows transfer of 1 extra bit of information regarding nodes.
    - For example – gender information, placebo/drug differentiation…
  - Alternatively, allows *n*-bit message encoding.
- Transmitter re-distributes Skiplist with structure change only.
- Receiver can decipher hidden channel using SkiplistMap.

Splay List: Skiplist Variation

- Suggested defense from SkipListMap attacks – conceal runtime.
- Propose Splay List structure, a variant of Skiplist.
- Based on Splay Tree concept of re-ordering nodes when search is performed.
- Splay algorithm (after the search has been completed)
  - Swap levels between 2 nodes: random and searched.
  - Remove connections when lowering level, connecting preceding and succeeding nodes.
  - Add connections when increasing levels, disconnecting preceding and succeeding nodes.
- Runtime is *O(log n)*

Splay List Behavior

- Addition and removal of nodes remains the same as Skiplist.
- Change in the search function:
  - Denote the corresponding searched node u_x.
  - Select a random node u_r .
  - Swap between the levels of u_x and u_r using the Splay Node algorithm.
- Slightly increasing the runtime of the search but remaining in *O(log n)*.
  - Search for additional node
  - Lowering level of node - similar to node removal
  - Raising level of node - similar to node addition

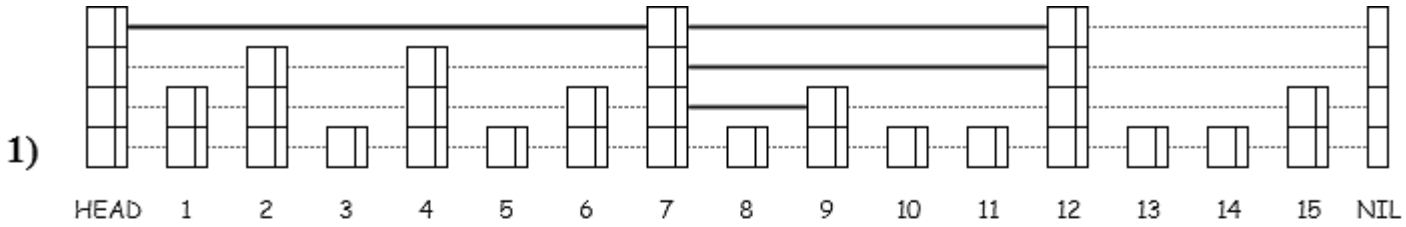
Splay Node Algorithm

Algorithm 3 Splay Skiplist node: change node level

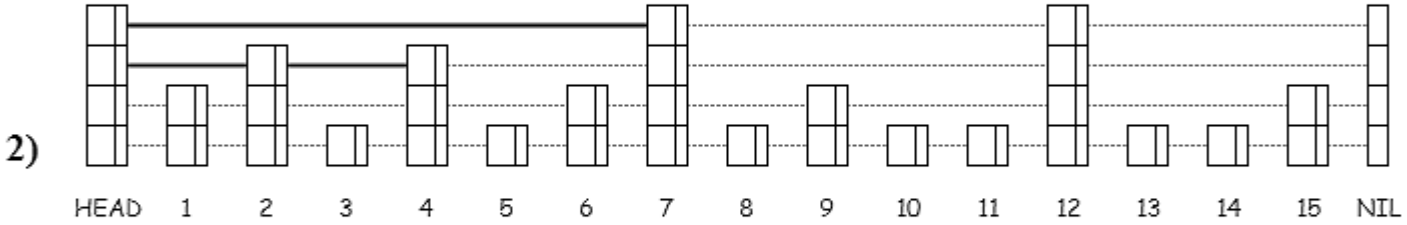
```
 1: procedure SplayNode(v, newLevel, prevNodesArray)
 2:     max ← maxLevel(v)                          ▷ Find current max level of v
 3:     if max > newLevel then
 4:         for l in max + 1 ... newLvel do
 5:             v_l ← newnodeLevel(v)              ▷ Create new level in node v
 6:             v_l.next ← nextNodesArray[l].next  ▷ Connect v to next node in level
 7:             prevNodesArray[l].next ← v_l       ▷ Connect v to previous node in level
 8:         end for
 9:     end if
10:     if max < newLevel then
11:         for l in newLevel + 1 ... max do
12:             prevNodesArray[l].next ← v_l.next
13:             v.deleteLevel(l)                   ▷ Remove level l from v
14:         end for
15:     end if
16: end procedure
```

Figure 3 (Splay List Search)

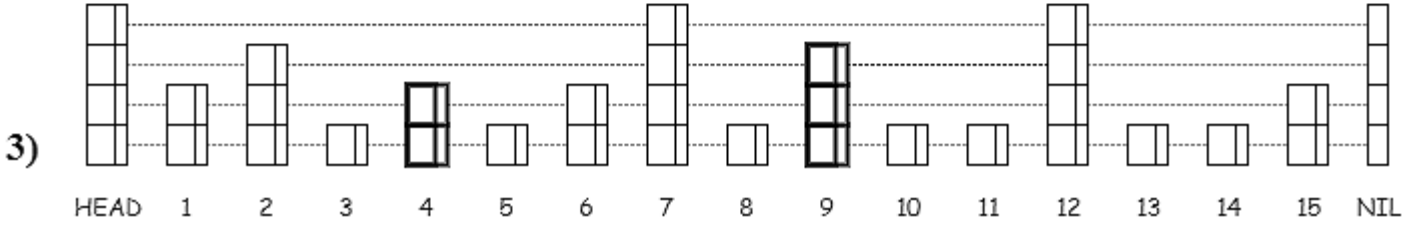
Search for node in Splay List.



Node 9 found.



Node 4 chosen for swap and found in Splay List.



Top levels swapped between nodes 9 and 4.

Summary

- Probabilistic Skiplist structure to be vulnerable to a timing attack.
  - Allows mapping of the structure.
- Possible attacks:
  - Runtime attack – performance degradation.
  - Hidden Channel attack – undetected transfer of data using structure.
- Proposed defense – Splay list.
  - Randomize structure after search.
  - Retain O(log *n*) performance.
- Future directions:
  - Consider the behavior of multiple releases over time.
  - Consider attacks based on other data structures (trees, graphs, etc…)

Thank You!