

CS 240 – Data Structures and Data Management

Module 5: Other Dictionary Implementations

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Based on lecture notes by many previous cs240 instructors

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Outline

- 1 Dictionaries with Lists revisited
 - Dictionary ADT: Implementations thus far
 - Skip Lists
 - Re-ordering Items

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Dictionary ADT: Implementations thus far

A *dictionary* is a collection of key-value pairs (KVPs), supporting operations *search*, *insert*, and *delete*.

Realizations we have seen so far:

- **Unordered array or linked list:** $\Theta(1)$ insert, $\Theta(n)$ search and delete
- **Ordered array:** $\Theta(\log n)$ search, $\Theta(n)$ insert and delete
- **Binary search trees:** $\Theta(\text{height})$ search, insert and delete
- **Balanced BST** (AVL trees):
 $\Theta(\log n)$ search, insert, and delete

Dictionary ADT: Implementations thus far

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Improvements/Simplifications?

- **Can show:** If the KVPs were inserted in random order, then the expected height of the binary search tree would be $O(\log n)$.
- How can we use randomization within the data structure to mirror what would happen on random input?

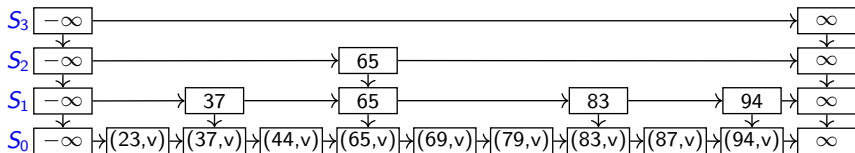
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- Dictionary ADT: Implementations thus far
- **Skip Lists**
- Re-ordering Items

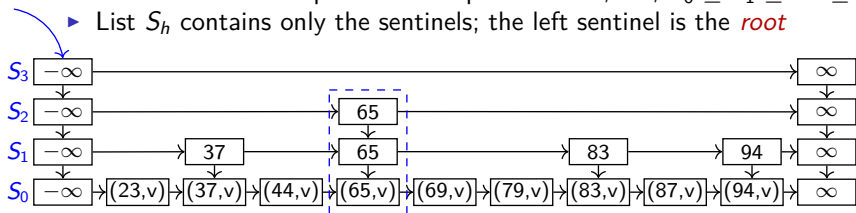
Skip Lists

- A hierarchy S of ordered linked lists (*levels*) S_0, S_1, \dots, S_h :
 - ▶ Each list S_i contains the special keys $-\infty$ and $+\infty$ (sentinels)
 - ▶ List S_0 contains the KVPs of S in non-decreasing order.
(The other lists store only keys, or links to nodes in S_0 .)
 - ▶ Each list is a subsequence of the previous one, i.e., $S_0 \supseteq S_1 \supseteq \dots \supseteq S_h$
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- Each KVP belongs to a **tower** of nodes
- There are (usually) more *nodes* than *keys*
- The skip list consists of a reference to the topmost left node.
- Each node p has references $p.after$ and $p.below$

Search in Skip Lists

For each level, find **predecessor** (node before where k would be).
This will also be useful for *insert/delete*.

getPredecessors (k)

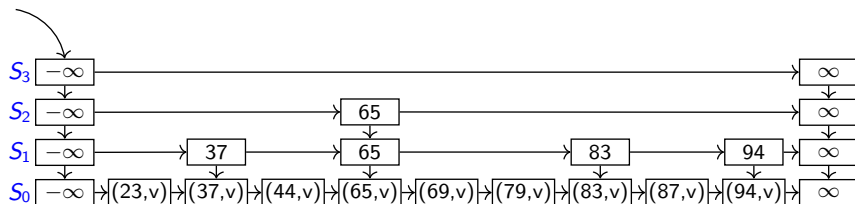
1. $p \leftarrow \text{root}$
2. $P \leftarrow$ stack of nodes, initially containing p
3. **while** $p.\text{below} \neq \text{NIL}$ **do**
4. $p \leftarrow p.\text{below}$
5. **while** $p.\text{after.key} < k$ **do** $p \leftarrow p.\text{after}$
6. $P.\text{push}(p)$
7. **return** P

skipList::search (k)

1. $P \leftarrow \text{getPredecessors}(k)$
2. $p_0 \leftarrow P.\text{top}()$ // predecessor of k in S_0
3. **if** $p_0.\text{after.key} = k$ **return** $p_0.\text{after}$
4. **else return** "not found, but would be after p_0 "

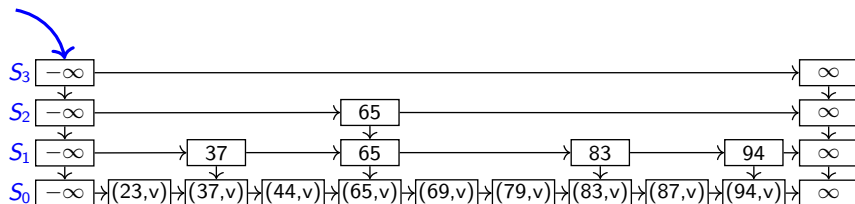
Example: Search in Skip Lists

Example: *search*(87)



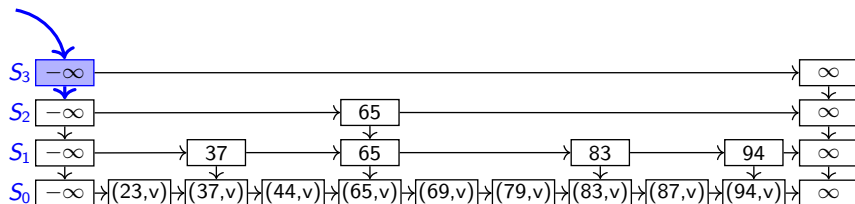
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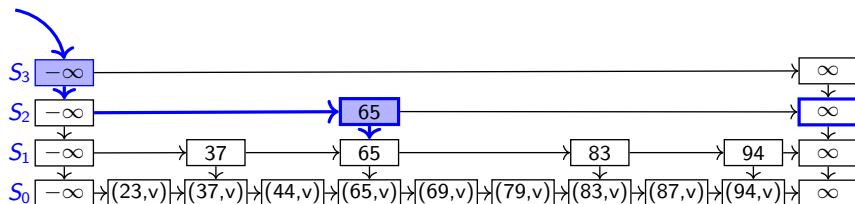
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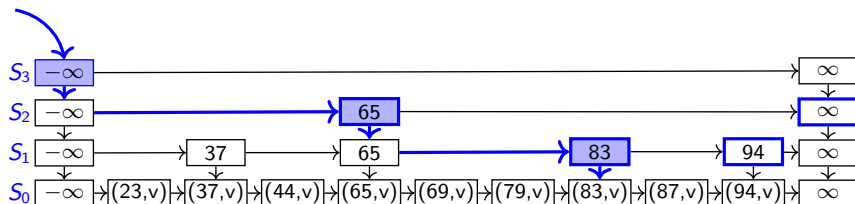
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- key compared with k
- added to P

Example: Search in Skip Lists

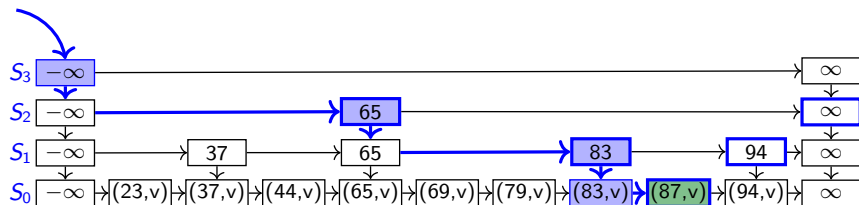
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Example: Search in Skip Lists

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Insert in Skip Lists

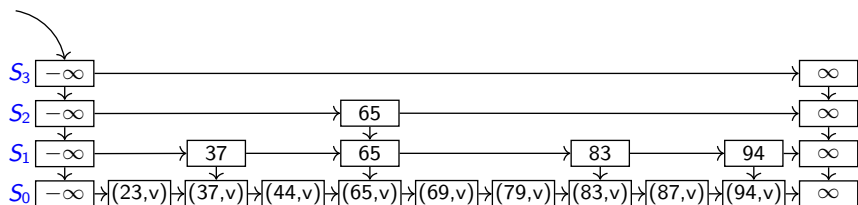
skipList::insert(k, v)

- Randomly repeatedly toss a coin until you get tails
- Let i the number of times the coin came up heads
 - ▶ we want k to be in lists S_0, \dots, S_i .
 - ▶ $i \rightarrow$ *height* of tower of k
 - ▶ $P(\text{tower of key } k \text{ has height } \geq i) = \left(\frac{1}{2}\right)^i$
- Increase height h of skip list, if needed, to have $h > i$ levels.
- Use *getPredecessors*(k) to get stack P .
The top i items of P are the predecessors p_0, p_1, \dots, p_i of where k should be in each list S_0, S_1, \dots, S_i
- Insert (k, v) after p_0 in S_0 , and k after p_j in S_j for $1 \leq j \leq i$

Example: Insert in Skip Lists

Example: *skipList::insert*(52, *v*)

Coin tosses: H,T $\Rightarrow i = 1$

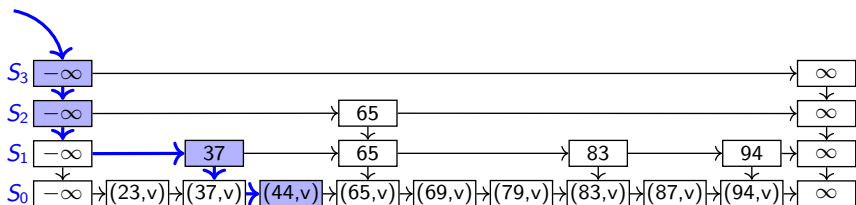


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getPredecessors(52)

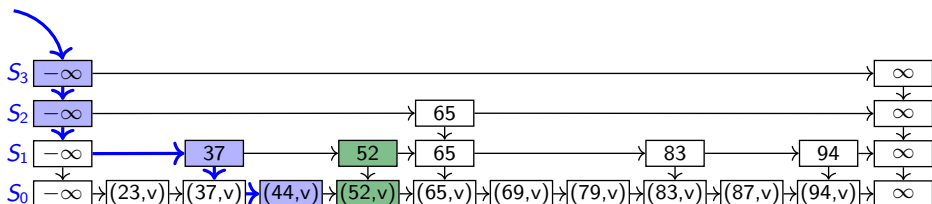


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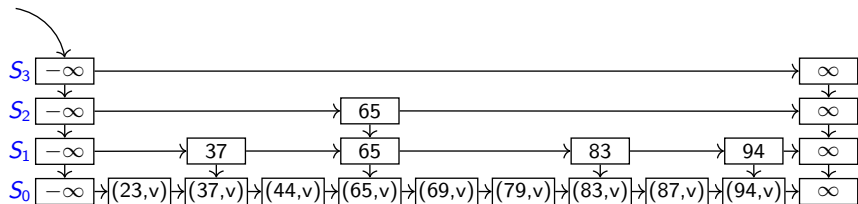
getPredecessors(52)



Example 2: Insert in Skip Lists

Example: `skipList::insert(100, v)`

Coin tosses: H,H,H,T $\Rightarrow i = 3$

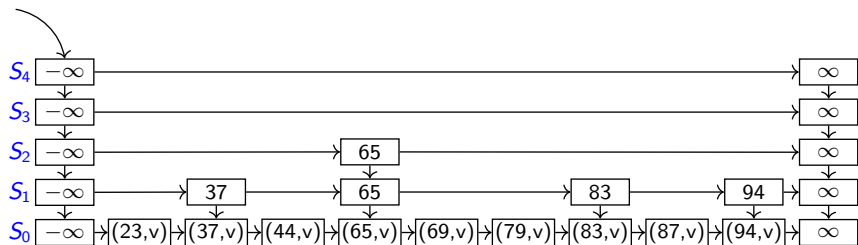


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Height increase



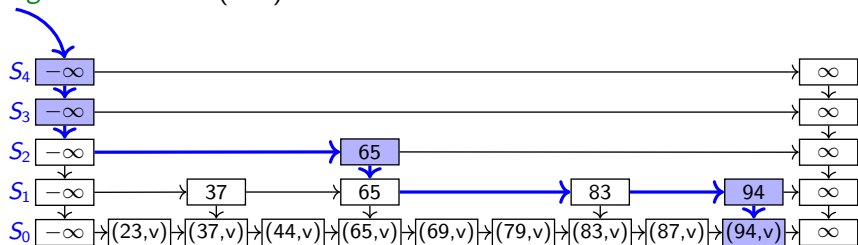
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Height increase

`getPredecessors(100)`



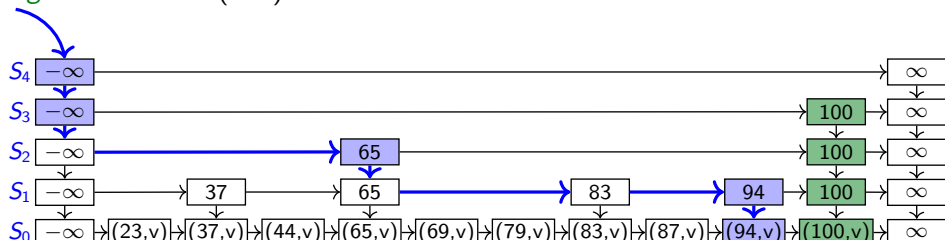
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Coin tosses: H,H,H,T $\Rightarrow i = 3$

Height increase

`getPredecessors(100)`



Insert in Skip Lists

skipList::insert(k, v)

1. $P \leftarrow \text{getPredecessors}(k)$
2. **for** ($i \leftarrow 0$; $\text{random}(2) = 1$; $i \leftarrow i+1$) {} // random tower height
3. **while** $i \geq P.\text{size}()$ // increase skip-list height?
4. $\text{root} \leftarrow$ new sentinel-only list, linked in appropriately
5. add left sentinel of root at bottom of stack P
6. $p \leftarrow P.\text{pop}()$ // insert (k, v) in S_0
7. $z_{\text{below}} \leftarrow$ new node with (k, v), inserted after p
8. **while** $i > 0$ // insert k in S_1, \dots, S_i
9. $p \leftarrow P.\text{pop}()$
10. $z \leftarrow$ new node with k added after p
11. $z.\text{below} \leftarrow z_{\text{below}}$; $z_{\text{below}} \leftarrow z$
12. $i \leftarrow i - 1$

Delete in Skip Lists

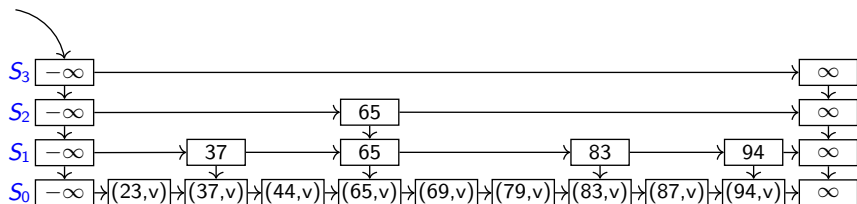
It is easy to remove a key since we can find all predecessors.
Then eliminate layers if there are multiple ones with only sentinels.

```
skipList::delete(k)
1.    $P \leftarrow \text{getPredecessors}(k)$ 
2.   while  $P$  is non-empty
3.        $p \leftarrow P.\text{pop}()$  // predecessor of  $k$  in some layer
4.       if  $p.\text{after.key} = k$ 
5.            $p.\text{after} \leftarrow p.\text{after}.\text{after}$ 
6.       else break // no more copies of  $k$ 

7.    $p \leftarrow$  left sentinel of the root-list
8.   while  $p.\text{below.after}$  is the  $\infty$ -sentinel
       // the two top lists are both only sentinels, remove one
9.        $p.\text{below} \leftarrow p.\text{below}.\text{below}$ 
10.       $p.\text{after}.\text{below} \leftarrow p.\text{after}.\text{below}.\text{below}$ 
```

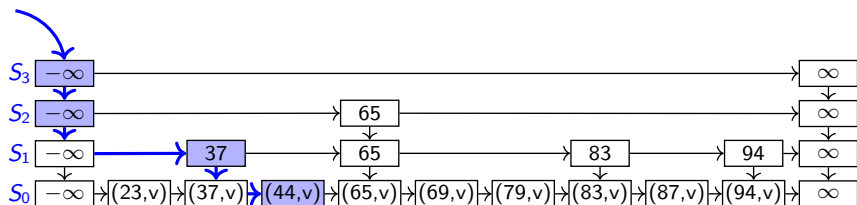
Example: Delete in Skip Lists

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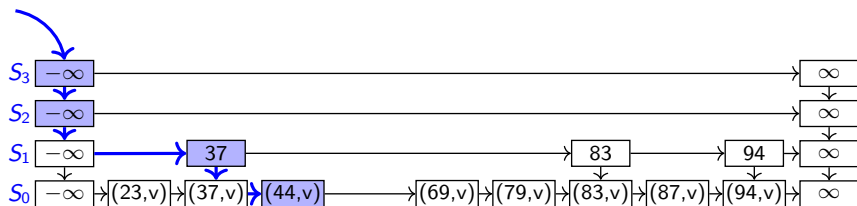
Example: Delete in Skip Lists

Example: *skipList::delete*(65)
getPredecessors(65)



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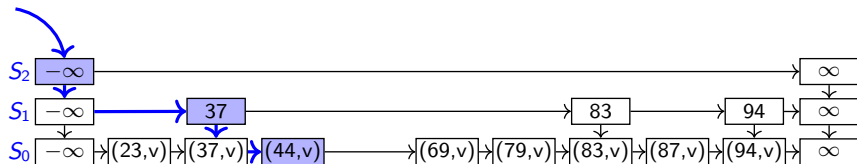


Example: Delete in Skip Lists

Example: *skipList::delete*(65)

getPredecessors(65)

Height decrease

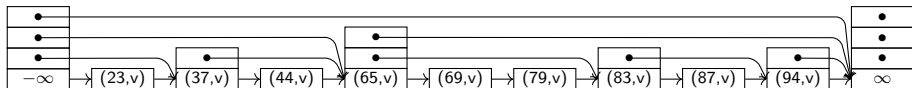


Analysis of Skip Lists

- Expected **space** usage: $O(n)$
- Expected **height**: $O(\log n)$
- Crucial for all operations:
 - ▶ How often do we **drop down** (execute $p \leftarrow p.\text{below}$)?
 - ▶ How often do we **step forward** (execute $p \leftarrow p.\text{after}$)?
- **skipList::search**: $O(\log n)$ expected time
 - ▶ # drop-downs = height
 - ▶ expected # forward-steps is ≤ 1 in each level
 - ▶ expected total # forward-steps is in $O(\log n)$
- **skipList::insert**: $O(\log n)$ expected time
- **skipList::delete**: $O(\log n)$ expected time

Summary of Skip Lists

- $O(n)$ expected space, all operations take $O(\log n)$ expected time.
- As described they are no faster than randomized binary search trees.
- Can show: A biased coin-flip to determine tower-height gives smaller expected run-times.
- Can save links (hence space) by implementing towers as array.



- Then skip lists are fast in practice and simple to implement.

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Re-ordering Items

- Recall: Unordered list/array implementation of ADT Dictionary
search: $\Theta(n)$, *insert*: $\Theta(1)$, *delete*: $\Theta(1)$ (after a search)
- Lists/arrays are a very simple and popular implementation. Can we do something to make search more effective in practice?

Re-ordering Items

- Recall: Unordered list/array implementation of ADT Dictionary
search: $\Theta(n)$, *insert*: $\Theta(1)$, *delete*: $\Theta(1)$ (after a search)
- Lists/arrays are a very simple and popular implementation. Can we do something to make search more effective in practice?
- No: if items are accessed equally likely
- Yes: otherwise (we have a probability distribution of the items)
 - ▶ Intuition: Frequently accessed items should be in the front.
 - ▶ Two cases: Do we know the access distribution beforehand or not?
 - ▶ For short lists or extremely unbalanced distributions this may be faster than AVL trees or Skip Lists, and much easier to implement.

Optimal Static Ordering

Example:

key	A	B	C	D	E
frequency of access	2	8	1	10	5
access-probability	$\frac{2}{26}$	$\frac{8}{26}$	$\frac{1}{26}$	$\frac{10}{26}$	$\frac{5}{26}$

- We count cost i for accessing the key in the i th position.
- Order A, B, C, D, E has expected access cost
$$\frac{2}{26} \cdot 1 + \frac{8}{26} \cdot 2 + \frac{1}{26} \cdot 3 + \frac{10}{26} \cdot 4 + \frac{5}{26} \cdot 5 = \frac{86}{26} \approx 3.31$$
- Order D, B, E, A, C has expected access cost
$$\frac{10}{26} \cdot 1 + \frac{8}{26} \cdot 2 + \frac{5}{26} \cdot 3 + \frac{2}{26} \cdot 4 + \frac{1}{26} \cdot 5 = \frac{66}{26} \approx 2.54$$

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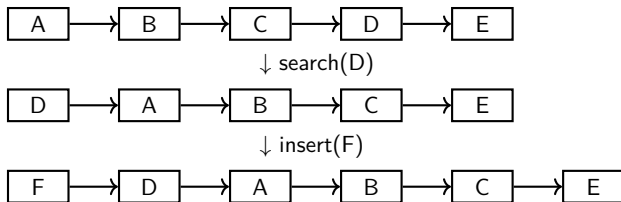
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- **Claim:** Over all possible static orderings, the one that sorts items by non-increasing access-probability minimizes the expected access cost.
- **Proof Idea:** For any other ordering, exchanging two items that are out-of-order according to their access probabilities makes the total cost decrease.

Dynamic Ordering: MTF

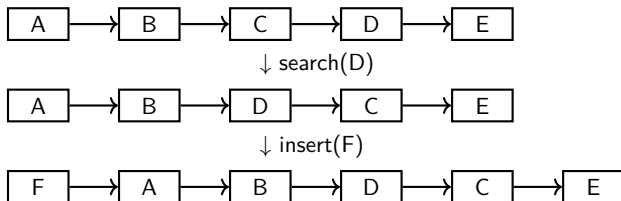
- What if we do *not know the access probabilities* ahead of time?
- Rule of thumb (**temporal locality**): A recently accessed item is likely to be used soon again.
- In list: Always insert at the front
- **Move-To-Front heuristic** (MTF): Upon a successful search, move the accessed item to the front of the list



- We can also do MTF on an array, but should then insert and search from the *back* so that we have room to grow.

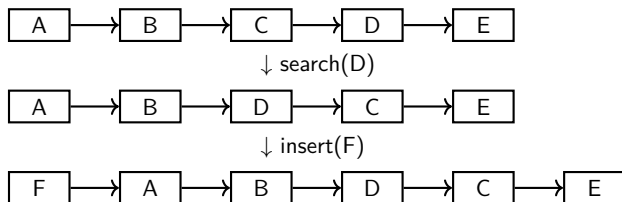
Dynamic Ordering: Transpose

Transpose heuristic: Upon a successful search, swap the accessed item with the item immediately preceding it



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Performance of dynamic ordering:

- Transpose does not adapt quickly to changing access patterns.
- MTF works well in practice.
- **Can show:** MTF is “2-competitive”:
No more than twice as bad as the optimal static ordering.