

# 11. Fundamental Data Structures

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Abstract data types stack, queue, implementation variants for linked lists  
[Ottman/Widmayer, Kap. 1.5.1-1.5.2, Cormen et al, Kap. 10.1.-10.2]

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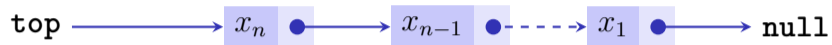
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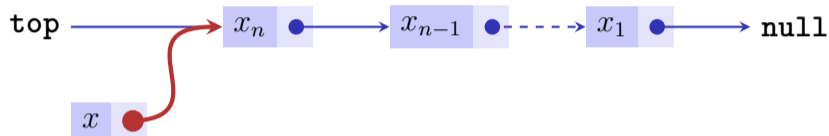
# Implementation Push



**push**( $x, S$ ):



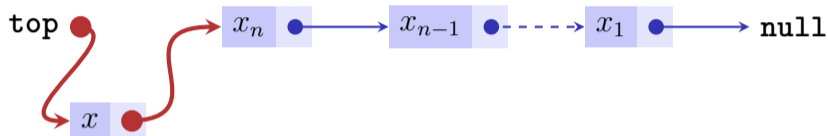
# Implementation Push



**push**( $x, S$ ):

1. Create new list element with  $x$  and pointer to the value of **top**.

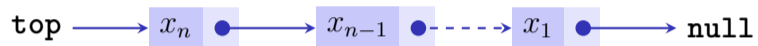
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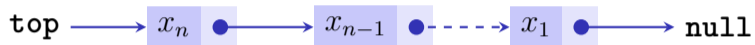
1. Create new list element with  $x$  and pointer to the value of **top**.
2. Assign the node with  $x$  to **top**.

# Implementation Pop



`pop(S)`:

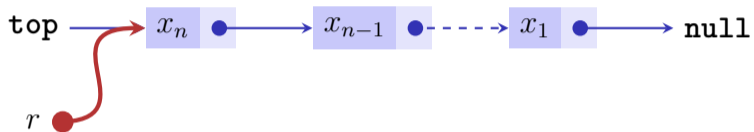
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**pop**( $S$ ):

1. If **top**=**null**, then return **null**

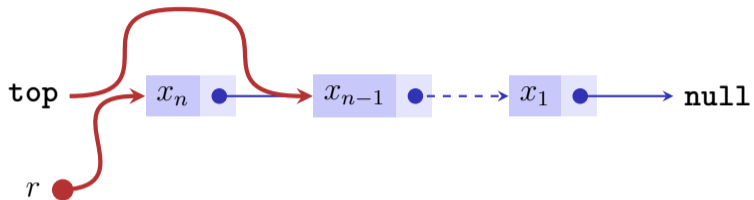
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1. If **top**=**null**, then return **null**
2. otherwise memorize pointer  $p$  of **top** in  $r$ .
3. Set **top** to  $p.next$  and return  $r$

# Analysis

Each of the operations **push**, **pop**, **top** and **isEmpty** on a stack can be executed in  $\mathcal{O}(1)$  steps.

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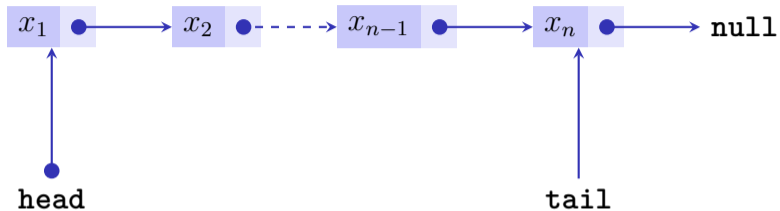
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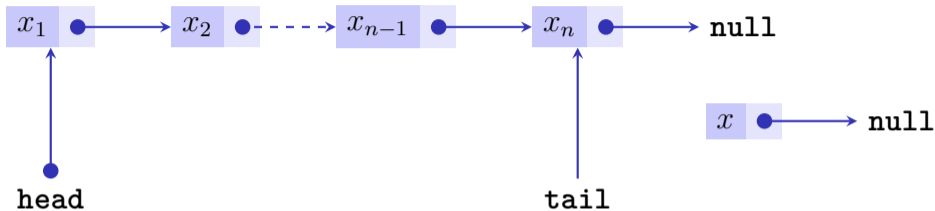
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- **emptyQueue**(): returns empty queue.

# Implementation Queue



`enqueue( $x, S$ ):`

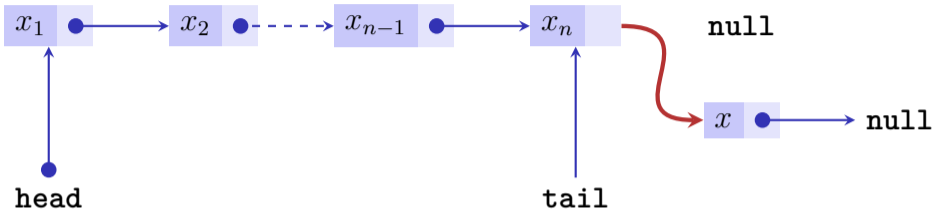
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**enqueue**( $x, S$ ):

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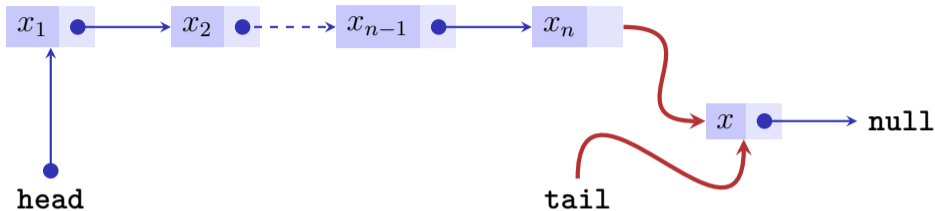


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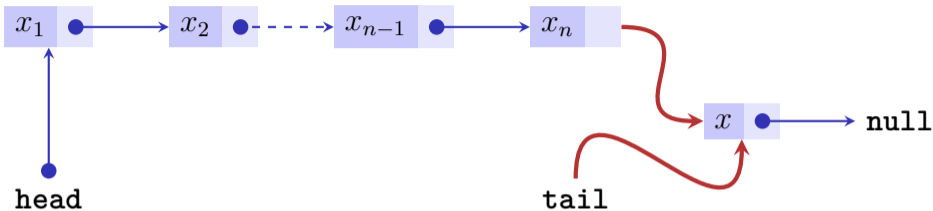
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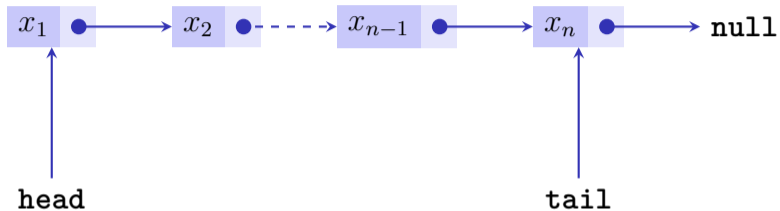
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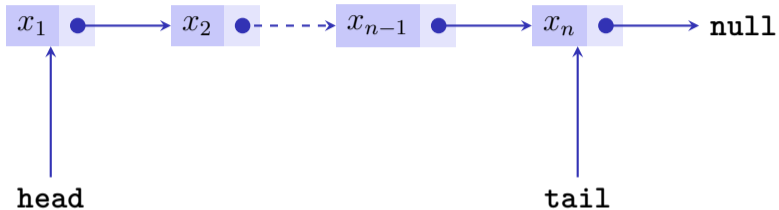
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4. If **head** = **null**, then set **head** to **tail**.

# Invariants



With this implementation it holds that

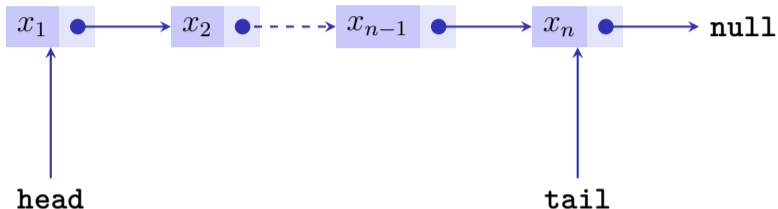
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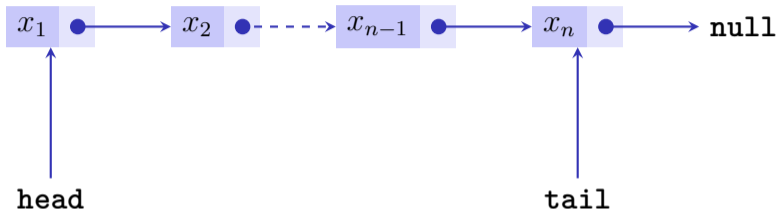
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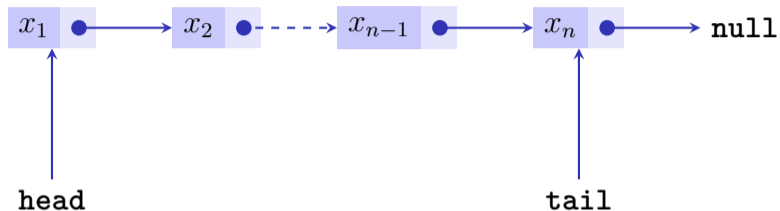
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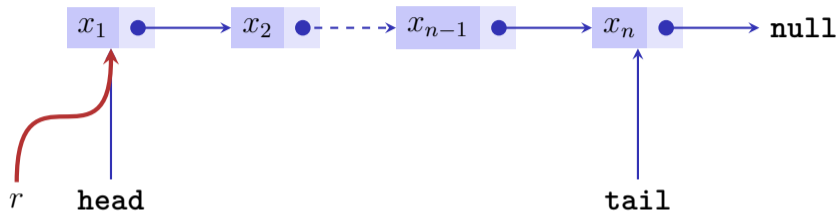
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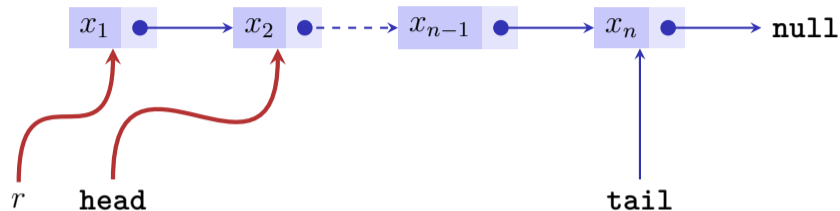


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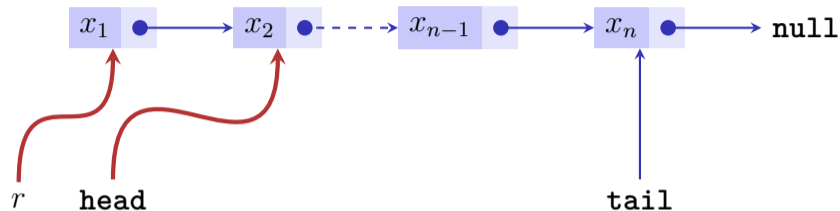
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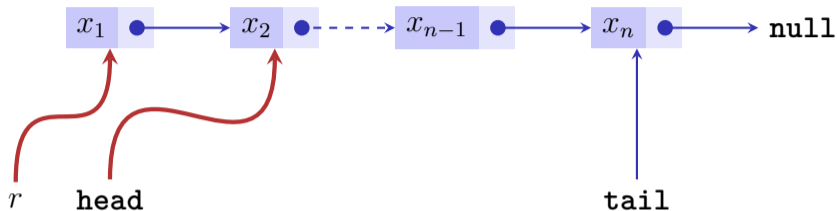
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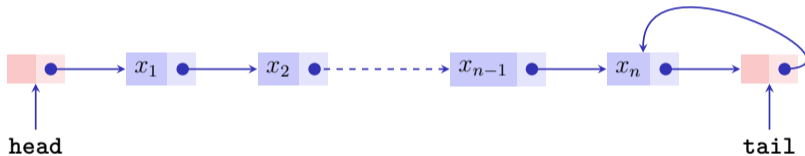
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4. Return the value of  $r$ .

# Analysis

Each of the operations **enqueue**, **dequeue**, **head** and **isEmpty** on the queue can be executed in  $\mathcal{O}(1)$  steps.

# Implementation Variants of Linked Lists

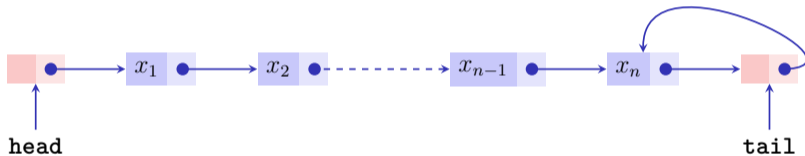
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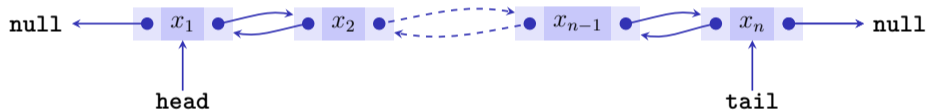


Advantage: less special cases

Variant: like this with pointer of an element stored singly indirect.  
(Example: pointer to  $x_3$  points to  $x_2$ .)

# Implementation Variants of Linked Lists

Doubly linked list



# Overview

	enqueue	delete	search	concat
(A)	$\Theta(1)$	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$
(B)	$\Theta(1)$	$\Theta(n)$	$\Theta(n)$	$\Theta(1)$
(C)	$\Theta(1)$	$\Theta(1)$	$\Theta(n)$	$\Theta(1)$
(D)	$\Theta(1)$	$\Theta(1)$	$\Theta(n)$	$\Theta(1)$

(A) = singly linked

(B) = Singly linked with dummy element at the beginning and the end

(C) = Singly linked with indirect element addressing

(D) = doubly linked



## 12. Amortized Analysis

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Amortized Analysis: Aggregate Analysis, Account-Method, Potential-Method  
[Ottman/Widmayer, Kap. 3.3, Cormen et al, Kap. 17]

# Multistack

Multistack adds to the stack operations **push** and **pop**

**multipop**( $k, S$ ): remove the  $\min(\text{size}(S), k)$  most recently inserted objects and return them.

Implementation as with the stack. Runtime of **multipop** is  $\mathcal{O}(k)$ .

# Academic Question

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How to make a better estimation?

# Amortized Analysis

- Upper bound: **average** performance of each considered operation in the **worst case**.

$$\frac{1}{n} \sum_{i=1}^n \text{cost}(\text{op}_i)$$

- Makes use of the fact that a few expensive operations are opposed to many cheap operations.
- In amortized analysis we search for a credit or a potential function that captures how the cheap operations can “compensate” for the expensive ones.

# Aggregate Analysis

Direct argument: compute a bound for the total number of elementary operations and divide by the total number of operations.

# Aggregate Analysis: (Stack)

- With  $n$  operations at most  $n$  elements can be pushed onto the stack. Therefore a maximum of  $n$  elements can be removed from the stack
- For the total costs we get

$$\sum_{i=1}^n \text{cost}(\text{op}_i) \leq 2n$$

and thus

$$\mathbf{\text{amortized cost}}(\text{op}_i) \leq 2 \in \mathcal{O}(1)$$



# Accounting Method

## Model

- The computer is driven with coins: each elementary operation of the machine costs a coin.
  - For each operation  $op_k$  of a data structure, a number of coins  $a_k$  has to be put on an account  $A$ :  $A_k = A_{k-1} + a_k$
  - Use the coins from the account  $A$  to pay the true costs  $t_k$  of each operation.
  - The account  $A$  needs to provide enough coins in order to pay each of the ongoing operations  $op_k$ :  $A_k - t_k \geq 0 \forall k$ .
- $\Rightarrow a_k$  are the amortized costs of  $op_k$ .

# Accounting Method (Stack)

- Each call of **push** costs 1 CHF and additionally 1 CHF will be deposited on the account. ( $a_k = 2$ )
- Each call to **pop** costs 1 CHF and will be paid from the account. ( $a_k = 0$ )

Account will never have a negative balance.

$a_k \leq 2 \forall k$ , thus: constant amortized costs.

# Potential Method

Slightly different model

- Define a **potential**  $\Phi_i$  that is **associated to the state of a data structure** at time  $i$ .
- The potential shall be used to level out expensive operations and therefore needs to be chosen such that it is increased during the (frequent) cheap operations while it decreases for the (rare) expensive operations.

# Potential Method (Formal)

Let  $t_i$  denote the real costs of the operation  $op_i$ .

Potential function  $\Phi_i \geq 0$  to the data structure after  $i$  operations.

Requirement:  $\Phi_i \geq \Phi_0 \forall i$ .

Amortized costs of the  $i$ th operation:

$$a_i := t_i + \Phi_i - \Phi_{i-1}.$$

It holds

$$\sum_{i=1}^n a_i = \sum_{i=1}^n (t_i + \Phi_i - \Phi_{i-1}) = \left( \sum_{i=1}^n t_i \right) + \Phi_n - \Phi_0 \geq \sum_{i=1}^n t_i.$$

# Example stack

Potential function  $\Phi_i =$  number element on the stack.

- **push**( $x, S$ ): real costs  $t_i = 1$ .  $\Phi_i - \Phi_{i-1} = 1$ . Amortized costs  $a_i = 2$ .
- **pop**( $S$ ): real costs  $t_i = 1$ .  $\Phi_i - \Phi_{i-1} = -1$ . Amortized costs  $a_i = 0$ .
- **multipop**( $k, S$ ): real costs  $t_i = k$ .  $\Phi_i - \Phi_{i-1} = -k$ . amortized costs  $a_i = 0$ .

All operations have **constant amortized cost!** Therefore, on average Multipop requires a constant amount of time.<sup>12</sup>

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<sup>12</sup>Note that we are not talking about the probabilistic mean but the (worst-case) average of the costs.

# Example Binary Counter

**Given:** counter with  $k$  bits. We count from 0 to  $n - 1$  where  $n = 2^k$ .

**Wanted:** average counting costs as number bit-flips per operation

**Naive:** per operation maximally  $k$  bit-flips. Thus, in total  $\mathcal{O}(n \cdot k)$  operations or  $\mathcal{O}(\log n)$  bitflips per count operation on average.

# Example Binary Counter

**Real costs**  $t_i$  = number bit flips from 0 to 1 plus number of bit-flips from 1 to 0.

$$\dots 0 \underbrace{1111111}_{l \text{ Ones}} + 1 = \dots 1 \underbrace{0000000}_{l \text{ Zeroes}}.$$

$$\Rightarrow t_i = l + 1$$

# Binary Counter: Aggregate Analysis

Count the number of bit flips when counting from 0 to  $n - 1$ .

Observation

- Bit 0 flips each time
- Bit 1 flips each 2. time
- Bit 2 flips each 4. time
- ...

Thus, total number bit flips

$$\sum_{i=0}^{n-1} \frac{n}{2^i} \leq n \cdot \sum_{i=0}^{\infty} \frac{1}{2^i} = 2n$$

Amortized cost for operation:  $\mathcal{O}(1)$  bit flips.

0000  
0001  
0010  
0011  
0100  
0101  
0110  
0111  
1000  
1001  
1010  
1011  
1100  
1101  
1110  
1111



# Binary Counter: Account Method

**Observation:** for each increment exactly one bit is incremented to 1, while many bits may be reset to 0. Only a bit that had previously been set to 1 can be reset to 0.

**Amortised costs**  $a_i = 2$ :

- 1 CHF real cost for setting  $0 \mapsto 1$
- plus 1 CHF to deposit on the account.
- Every reset  $1 \rightarrow 0$  can be paid from the account.

# Binary Counter: Potential Method

$$\dots 0 \underbrace{11111111}_{l \text{ ones}} + 1 = \dots 1 \underbrace{00000000}_{l \text{ zeros}}$$

**potential** function  $\Phi_i$ : number of 1-bits of  $x_i$ .

$$\begin{aligned} 0 &= \Phi_0 \leq \Phi_i \quad \forall i, \\ \Phi_i - \Phi_{i-1} &= 1 - l_i, \\ \Rightarrow a_i &= t_i + \Phi_i - \Phi_{i-1} \\ &= l_i + 1 + (1 - l_i) \\ &= 2. \end{aligned}$$

Amortized constant cost per count operation. 😊

## 13. Dictionaries

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Dictionary, Self-ordering List, Implementation of Dictionaries with Array / List /Skip lists. [Ottman/Widmayer, Kap. 3.3,1.7, Cormen et al, Kap. Problem 17-5]

# Dictionary

ADT to manage keys from a set  $\mathcal{K}$  with operations

- **insert**( $k, D$ ): Insert  $k \in \mathcal{K}$  to the dictionary  $D$ . Already exists  $\Rightarrow$  error message.
- **delete**( $k, D$ ): Delete  $k$  from the dictionary  $D$ . Not existing  $\Rightarrow$  error message.
- **search**( $k, D$ ): Returns **true** if  $k \in D$ , otherwise **false**

# Idea

Implement dictionary as sorted array

Worst case number of fundamental operations

Search

Insert

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Search  $\mathcal{O}(\log n)$  😊

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# Other idea

Implement dictionary as a linked list

Worst case number of fundamental operations

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Insert

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<sup>13</sup>Provided that we do not have to check existence.

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Search	$\mathcal{O}(n)$	
Insert	$\mathcal{O}(1)$ <sup>13</sup>	
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## 13.1 Self Ordering

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# Self Ordered Lists

Problematic with the adoption of a linked list: linear search time

**Idea:** Try to order the list elements such that accesses over time are possible in a faster way

For example

- Transpose: For each access to a key, the key is moved one position closer to the front.
- Move-to-Front (MTF): For each access to a key, the key is moved to the front of the list.

# Transpose

Transpose:



Worst case: Alternating sequence of  $n$  accesses to  $k_{n-1}$  and  $k_n$ .

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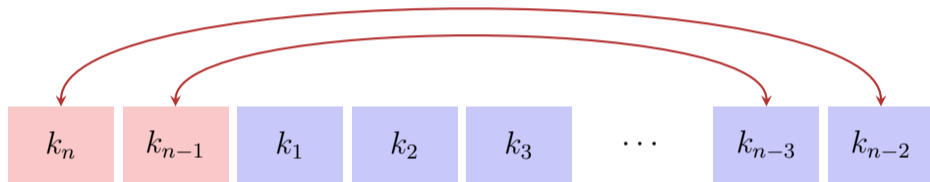
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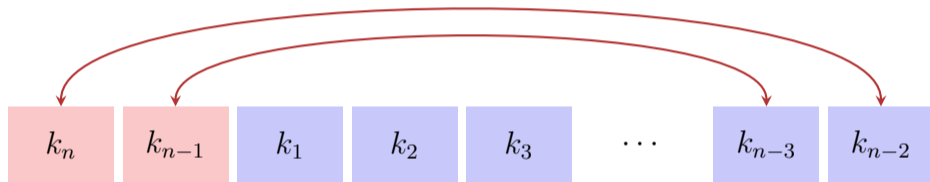
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Alternating sequence of  $n$  accesses to  $k_{n-1}$  and  $k_n$ .

# Move-to-Front

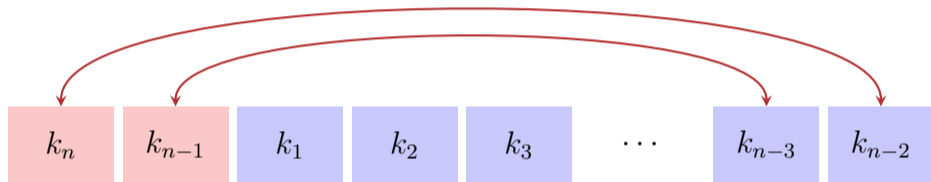
Move-to-Front:



Alternating sequence of  $n$  accesses to  $k_{n-1}$  and  $k_n$ . Runtime:  $\Theta(n)$

# Move-to-Front

Move-to-Front:



Alternating sequence of  $n$  accesses to  $k_{n-1}$  and  $k_n$ . Runtime:  $\Theta(n)$

Also here we can provide a sequence of accesses with quadratic runtime, e.g. access to the last element. But there is no obvious strategy to counteract much better than MTF.

# Analysis

Compare MTF with the best-possible competitor (algorithm) A. How much better can A be?

Assumptions:

- MTF and A may only move the accessed element.
- MTF and A start with the same list.

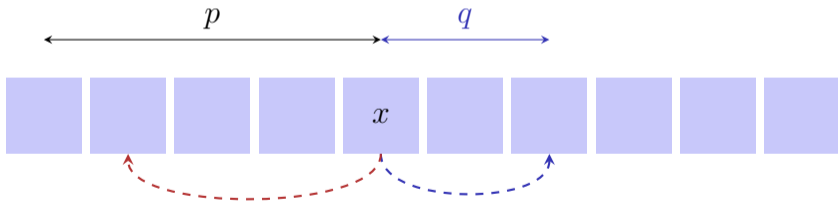
Let  $M_k$  and  $A_k$  designate the lists after the  $k$ th step.  $M_0 = A_0$ .



# Analysis

Costs:

- Access to  $x$ : position  $p$  of  $x$  in the list.
- No further costs, if  $x$  is moved **before**  $p$
- Further costs  $q$  for each element that  $x$  is moved **back** starting from  $p$ .



# Amortized Analysis

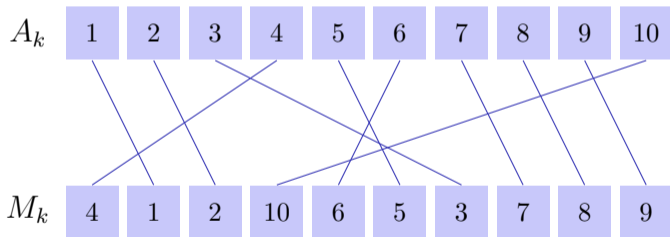
Let an arbitrary sequence of search requests be given and let  $G_k^{(M)}$  and  $G_k^{(A)}$  the costs in step  $k$  for Move-to-Front and A, respectively. Want estimation of  $\sum_k G_k^{(M)}$  compared with  $\sum_k G_k^{(A)}$ .

⇒ Amortized analysis with potential function  $\Phi$ .

# Potential Function

Potential function  $\Phi =$  Number of inversions of  $A$  vs. MTF.

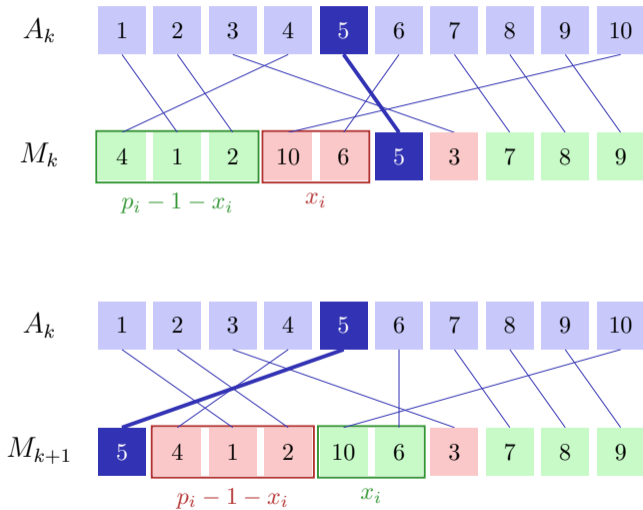
Inversion = Pair  $x, y$  such that for the positions of  $a$  and  $y$   
 $(p^{(A)}(x) < p^{(A)}(y)) \neq (p^{(M)}(x) < p^{(M)}(y))$



#inversion = #crossings

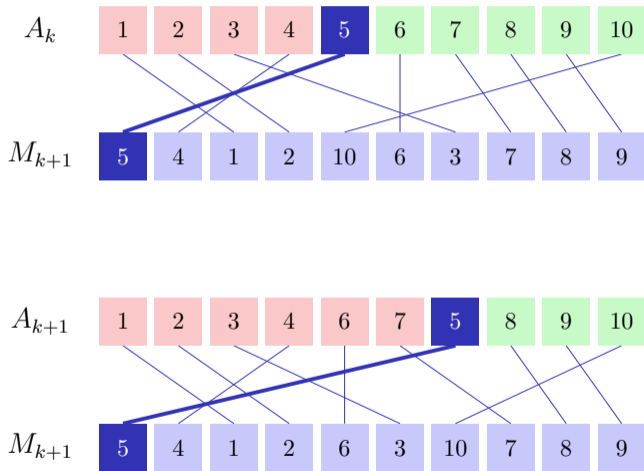
# Estimating the Potential Function: MTF

- Element  $i$  at position  $p_i := p^{(M)}(i)$ .
- access costs  $C_k^{(M)} = p_i$ .
- $x_i$ : Number elements that are in M before  $p_i$  and in A after  $i$ .
- MTF removes  $x_i$  inversions.
- $p_i - x_i - 1$ : Number elements that in M are before  $p_i$  and in A are before  $i$ .
- MTF generates  $p_i - 1 - x_i$  inversions.



# Estimating the Potential Function: A

- Wlog element  $i$  at position  $p^{(A)}(i)$ .
- $X_k^{(A)}$ : number movements to the back (otherwise 0).
- access costs for  $i$ :  
 $C_k^{(A)} = p^{(A)}(i) \geq p^{(M)}(i) - x_i$ .
- A increases the number of inversions maximally by  $X_k^{(A)}$ .



# Estimation

$$\Phi_{k+1} - \Phi_k \leq -x_i + (p_i - 1 - x_i) + X_k^{(A)}$$

Amortized costs of MTF in step  $k$ :

$$\begin{aligned} a_k^{(M)} &= C_k^{(M)} + \Phi_{k+1} - \Phi_k \\ &\leq p_i - x_i + (p_i - 1 - x_i) + X_k^{(A)} \\ &= (p_i - x_i) + (p_i - x_i) - 1 + X_k^{(A)} \\ &\leq C_k^{(A)} + C_k^{(A)} - 1 + X_k^{(A)} \leq 2 \cdot C_k^{(A)} + X_k^{(A)}. \end{aligned}$$

# Estimation

Summing up costs

$$\begin{aligned}\sum_k G_k^{(M)} &= \sum_k C_k^{(M)} \leq \sum_k a_k^{(M)} \leq \sum_k 2 \cdot C_k^{(A)} + X_k^{(A)} \\ &\leq 2 \cdot \sum_k C_k^{(A)} + X_k^{(A)} \\ &= 2 \cdot \sum_k G_k^{(A)}\end{aligned}$$

In the worst case MTF requires at most twice as many operations as the optimal strategy.

## 13.2 Skip Lists

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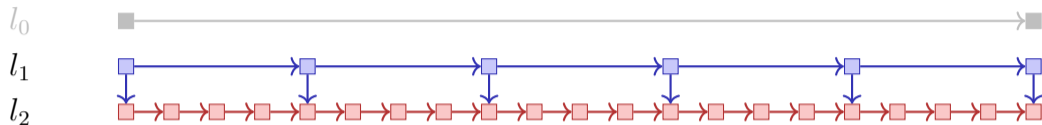


# Sorted Linked List



Search for element / insertion position: **worst-case**  $n$  Steps.

# Sorted Linked List with two Levels



■ Number elements:  $n_0 := n$

■ Stepsize on level 1:  $n_1$

■ Stepsize on level 2:  $n_2 = 1$

⇒ Search for element / insertion position: worst-case  $\frac{n_0}{n_1} + \frac{n_1}{n_2}$ .

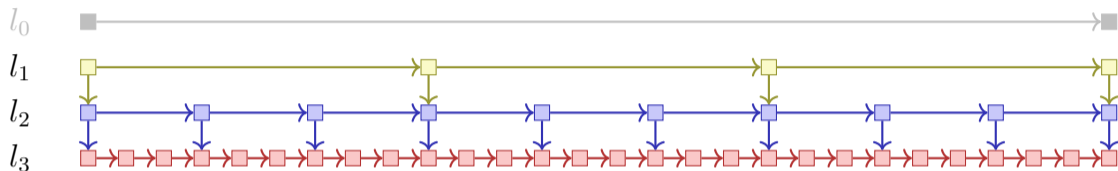
⇒ Best Choice for<sup>14</sup>  $n_1$ :  $n_1 = \frac{n_0}{n_1} = \sqrt{n_0}$ .

Search for element / insertion position: **worst-case**  $2\sqrt{n}$  steps.

---

<sup>14</sup>Differentiate and set to zero, cf. appendix

# Sorted Linked List with two Levels



- Number elements:  $n_0 := n$
- Stepsizes on levels  $0 < i < 3$ :  $n_i$
- Stepsize on level 3:  $n_3 = 1$

⇒ Best Choice for  $(n_1, n_2)$ :  $n_2 = \frac{n_0}{n_1} = \frac{n_1}{n_2} = \sqrt[3]{n_0}$ .

Search for element / insertion position: **worst-case**  $3 \cdot \sqrt[3]{n}$  steps.

# Sorted Linked List with $k$ Levels (Skiplist)

- Number elements:  $n_0 := n$
- Stepsizes on levels  $0 < i < k$ :  $n_i$
- Stepsize on level  $k$ :  $n_k = 1$

⇒ Best Choice for  $(n_1, \dots, n_k)$ :  $n_{k-1} = \frac{n_0}{n_1} = \frac{n_1}{n_2} = \dots = \sqrt[k]{n_0}$ .

Search for element / insertion position: **worst-case**  $k \cdot \sqrt[k]{n}$  steps<sup>15</sup>.

Assumption  $n = 2^k$

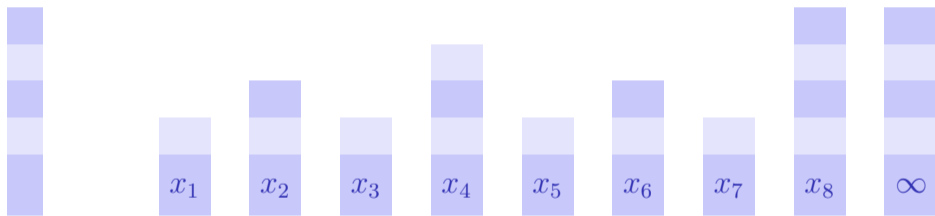
⇒ worst case  $\log_2 n \cdot 2$  steps and  $\frac{n_i}{n_{i+1}} = 2 \forall 0 \leq i < \log_2 n$ .

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<sup>15</sup>(Derivation: Appendix)

# Search in a Skiplist

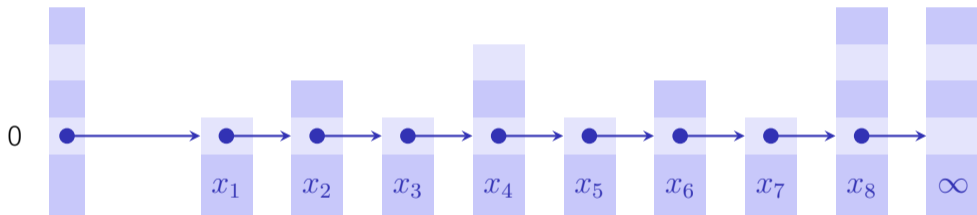
skip list



$$x_1 \leq x_2 \leq x_3 \leq \cdots \leq x_9.$$

# Search in a Skiplist

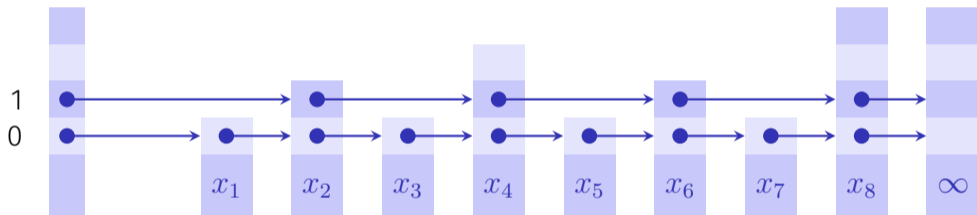
skiplist



$$x_1 \leq x_2 \leq x_3 \leq \cdots \leq x_9.$$

# Search in a Skiplist

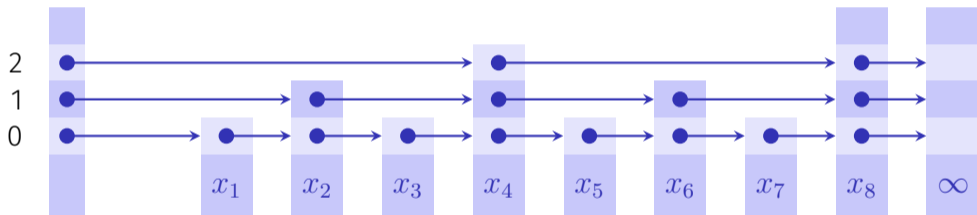
skiplist



$$x_1 \leq x_2 \leq x_3 \leq \cdots \leq x_9.$$

# Search in a Skiplist

skiplist

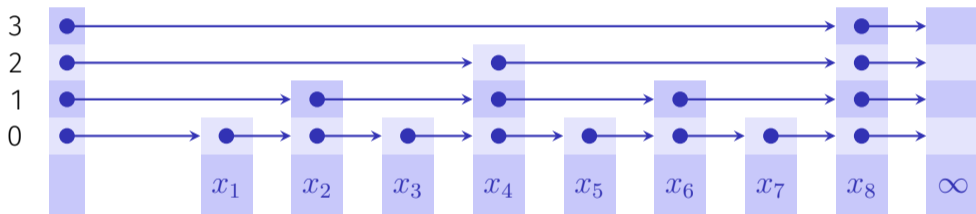


$$x_1 \leq x_2 \leq x_3 \leq \dots \leq x_9.$$



# Search in a Skiplist

Perfect skip list

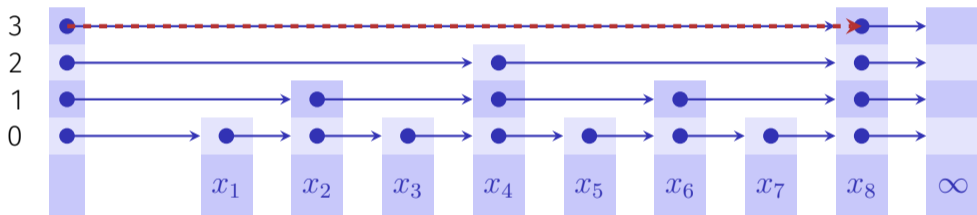


$x_1 \leq x_2 \leq x_3 \leq \dots \leq x_9$ .

Example: search for a key  $x$  with  $x_5 < x < x_6$ .

# Search in a Skiplist

Perfect skip list

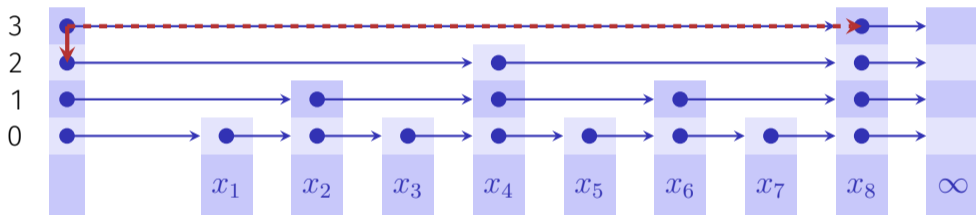


$x_1 \leq x_2 \leq x_3 \leq \dots \leq x_9$ .

Example: search for a key  $x$  with  $x_5 < x < x_6$ .

# Search in a Skiplist

Perfect skip list

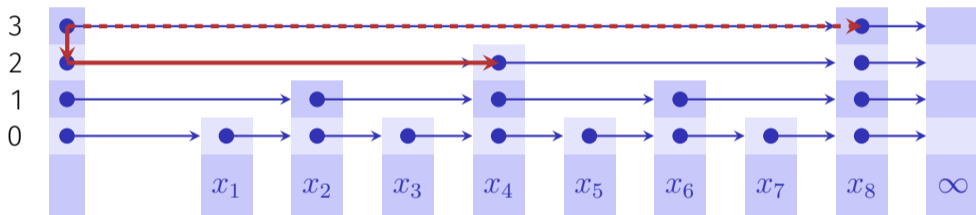


$x_1 \leq x_2 \leq x_3 \leq \dots \leq x_9$ .

Example: search for a key  $x$  with  $x_5 < x < x_6$ .

# Search in a Skiplist

Perfect skip list

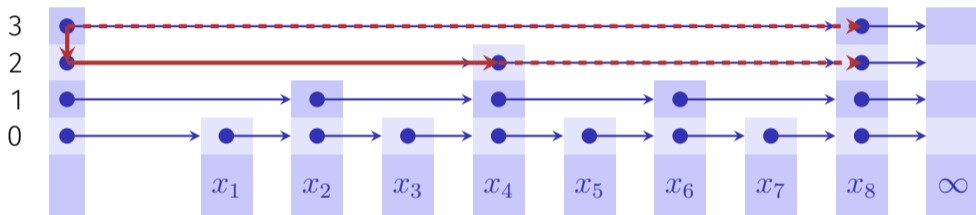


$x_1 \leq x_2 \leq x_3 \leq \dots \leq x_9$ .

Example: search for a key  $x$  with  $x_5 < x < x_6$ .

# Search in a Skiplist

Perfect skip list

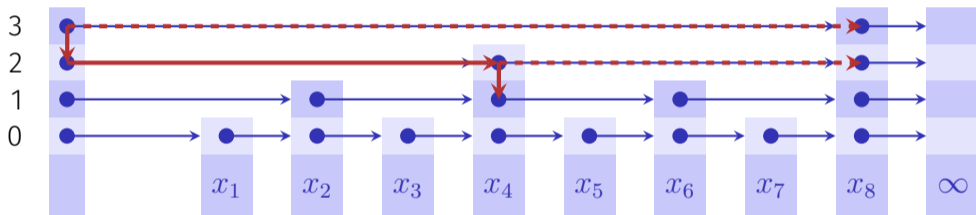


$x_1 \leq x_2 \leq x_3 \leq \dots \leq x_9$ .

Example: search for a key  $x$  with  $x_5 < x < x_6$ .

# Search in a Skiplist

Perfect skip list

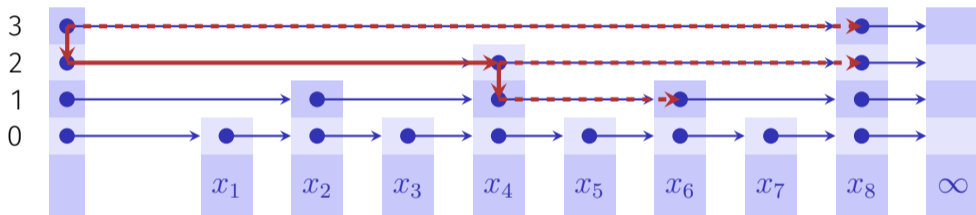


$x_1 \leq x_2 \leq x_3 \leq \dots \leq x_9$ .

Example: search for a key  $x$  with  $x_5 < x < x_6$ .

# Search in a Skiplist

Perfect skip list

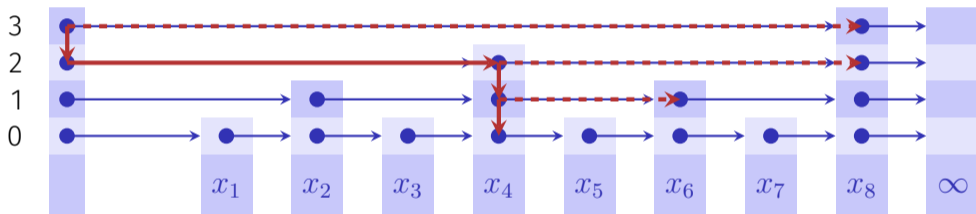


$x_1 \leq x_2 \leq x_3 \leq \dots \leq x_9$ .

Example: search for a key  $x$  with  $x_5 < x < x_6$ .

# Search in a Skiplist

Perfect skip list



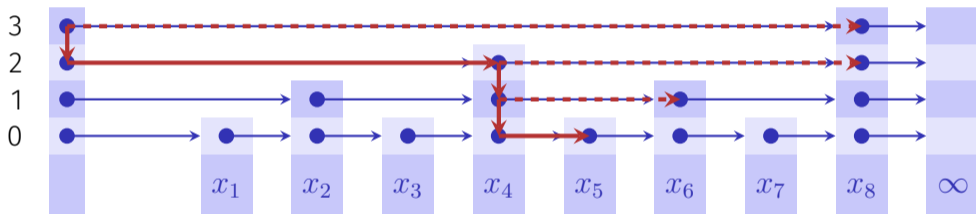
$x_1 \leq x_2 \leq x_3 \leq \dots \leq x_9$ .

Example: search for a key  $x$  with  $x_5 < x < x_6$ .



# Search in a Skiplist

Perfect skip list

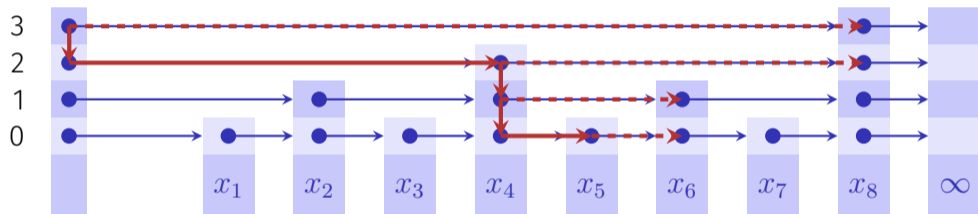


$x_1 \leq x_2 \leq x_3 \leq \dots \leq x_9$ .

Example: search for a key  $x$  with  $x_5 < x < x_6$ .

# Search in a Skiplist

Perfect skip list



$x_1 \leq x_2 \leq x_3 \leq \dots \leq x_9$ .

Example: search for a key  $x$  with  $x_5 < x < x_6$ .

# Analysis perfect skip list (worst cases)

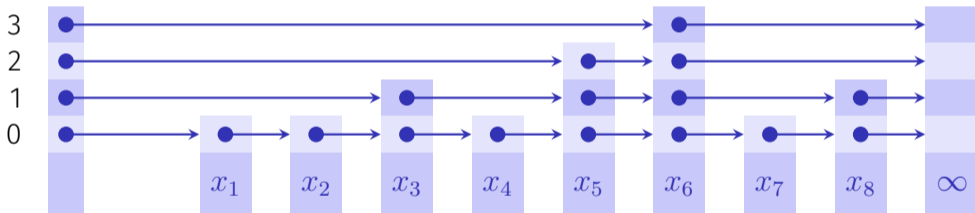
Search in  $\mathcal{O}(\log n)$ . Insert in  $\mathcal{O}(n)$ .

# Randomized Skip List

Idea: insert a key with random height  $H$  with  $\mathbb{P}(H = i) = \frac{1}{2^{i+1}}$ .

# Randomized Skip List

Idea: insert a key with random height  $H$  with  $\mathbb{P}(H = i) = \frac{1}{2^{i+1}}$ .



# Analysis Randomized Skip List

## *Theorem 16*

*The expected number of fundamental operations for Search, Insert and Delete of an element in a randomized skip list is  $\mathcal{O}(\log n)$ .*

The lengthy proof that will not be presented in this course observes the length of a path from a searched node back to the starting point in the highest level.

## 13.3 Appendix

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Mathematik zur Skipliste

# [ $k$ -Level Skiplist Math]

Let the number of data points  $n_0$  and number levels  $k > 0$  be given and let  $n_l$  be the numbers of elements skipped per level  $l$ ,  $n_k = 1$ . Maximum number of total steps in the skip list:

$$f(\vec{n}) = \frac{n_0}{n_1} + \frac{n_1}{n_2} + \dots + \frac{n_{k-1}}{n_k}$$

Minimize  $f$  for  $(n_1, \dots, n_{k-1})$ :  $\frac{\partial f(\vec{n})}{\partial n_t} = 0$  for all  $0 < t < k$ ,

$$\frac{\partial f(\vec{n})}{\partial n_t} = -\frac{n_{t-1}}{n_t^2} + \frac{1}{n_{t+1}} = 0 \Rightarrow n_{t+1} = \frac{n_t^2}{n_{t-1}} \text{ and } \frac{n_{t+1}}{n_t} = \frac{n_t}{n_{t-1}}.$$



# [ $k$ -Level Skiplist Math]

Previous slide  $\Rightarrow \frac{n_t}{n_0} = \frac{n_t}{n_{t-1}} \frac{n_{t-1}}{n_{t-2}} \cdots \frac{n_1}{n_0} = \left(\frac{n_1}{n_0}\right)^t$

Particularly  $1 = n_k = \frac{n_1^k}{n_0^{k-1}} \Rightarrow n_1 = \sqrt[k]{n_0^{k-1}}$

Thus  $n_{k-1} = \frac{n_0}{n_1} = \sqrt[k]{\frac{n_0^k}{n_0^{k-1}}} = \sqrt[k]{n_0}$ .

Maximum number of total steps in the skip list:  $f(\vec{n}) = k \cdot (\sqrt[k]{n_0})$

Assume  $n_0 = 2^k$ , then  $\frac{n_l}{n_{l+1}} = 2$  for all  $0 \leq l < k$  (skiplist halves data in each step) and  $f(n) = k \cdot 2 = 2 \log_2 n \in \Theta(\log n)$ .