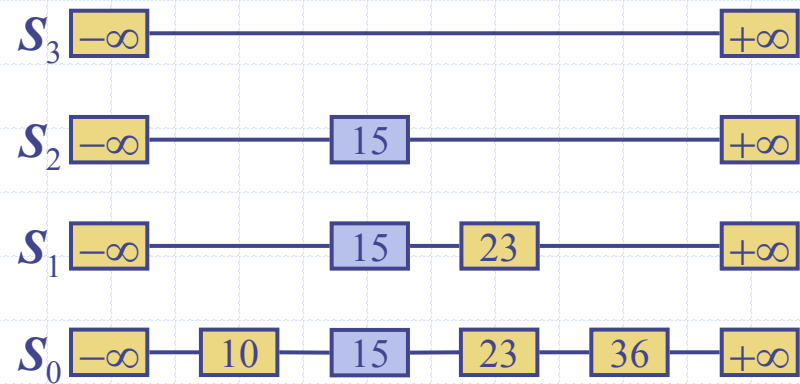
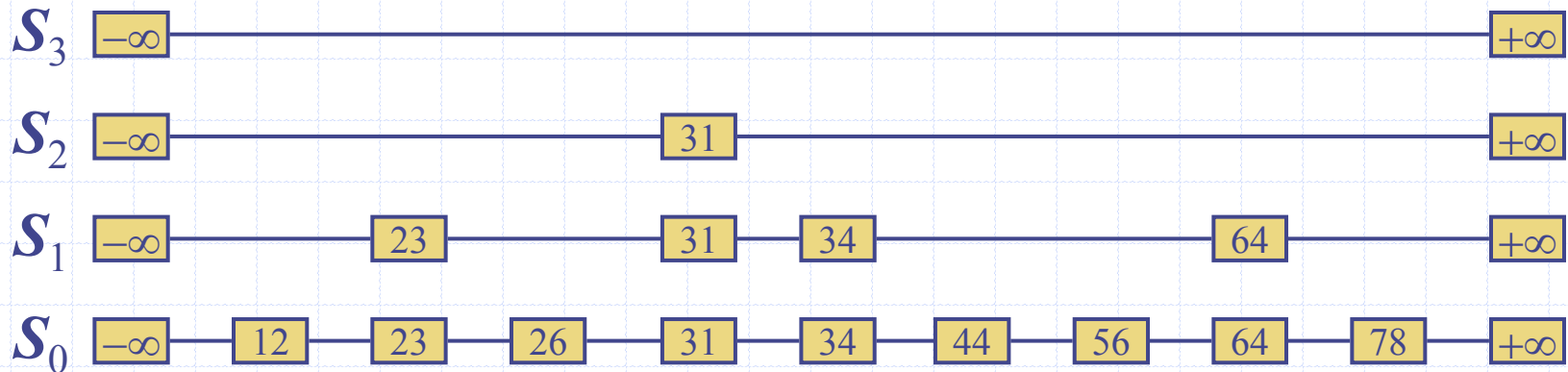


# Skip Lists



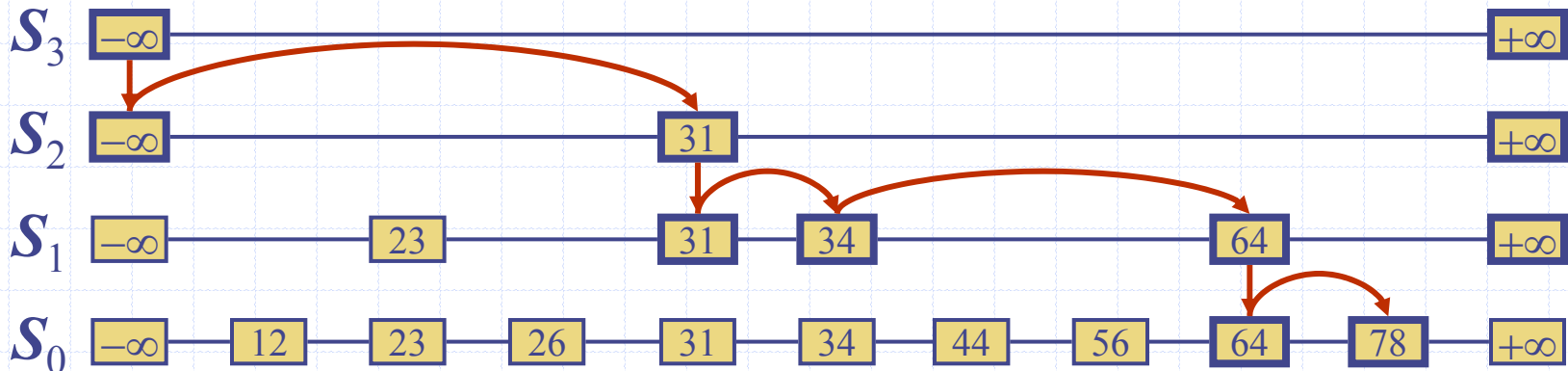
# What is a Skip List

- ◆ A **skip list** for a set  $S$  of distinct (key, element) items is a series of lists  $S_0, S_1, \dots, S_h$  such that
  - Each list  $S_i$  contains the special keys  $+\infty$  and  $-\infty$
  - List  $S_0$  contains the keys of  $S$  in nondecreasing order
  - Each list is a subsequence of the previous one, i.e.,
$$S_0 \supseteq S_1 \supseteq \dots \supseteq S_h$$
  - List  $S_h$  contains only the two special keys
- ◆ We show how to use a skip list to implement the dictionary ADT



# Search

- ◆ We search for a key  $x$  in a skip list as follows:
  - We start at the first position of the top list
  - At the current position  $p$ , we compare  $x$  with  $y \leftarrow \text{key}(\text{next}(p))$ 
    - $x = y$ : we return  $\text{element}(\text{next}(p))$
    - $x > y$ : we "scan forward"
    - $x < y$ : we "drop down"
  - If we try to drop down past the bottom list, we return *null*
- ◆ Example: search for 78



# Randomized Algorithms

- ◆ A randomized algorithm performs coin tosses (i.e., uses random bits) to control its execution

- ◆ It contains statements of the type

```
b ← random()
```

```
if b = 0
```

```
  do A ...
```

```
else { b = 1 }
```

```
  do B ...
```

- ◆ Its running time depends on the outcomes of the coin tosses

- ◆ We analyze the expected running time of a randomized algorithm under the following assumptions

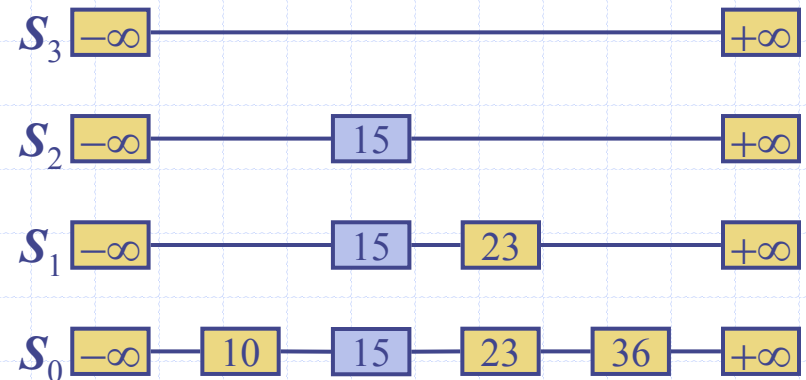
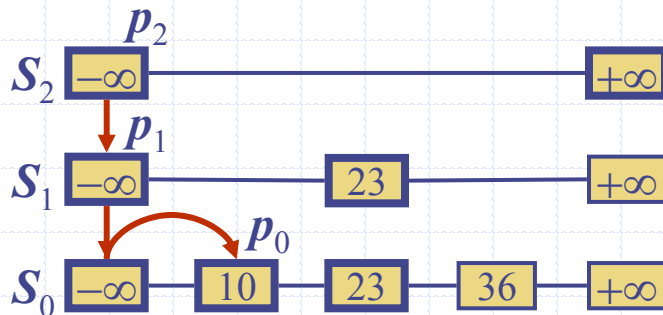
- the coins are unbiased, and
- the coin tosses are independent

- ◆ The worst-case running time of a randomized algorithm is often large but has very low probability (e.g., it occurs when all the coin tosses give “heads”)

- ◆ We use a randomized algorithm to insert items into a skip list

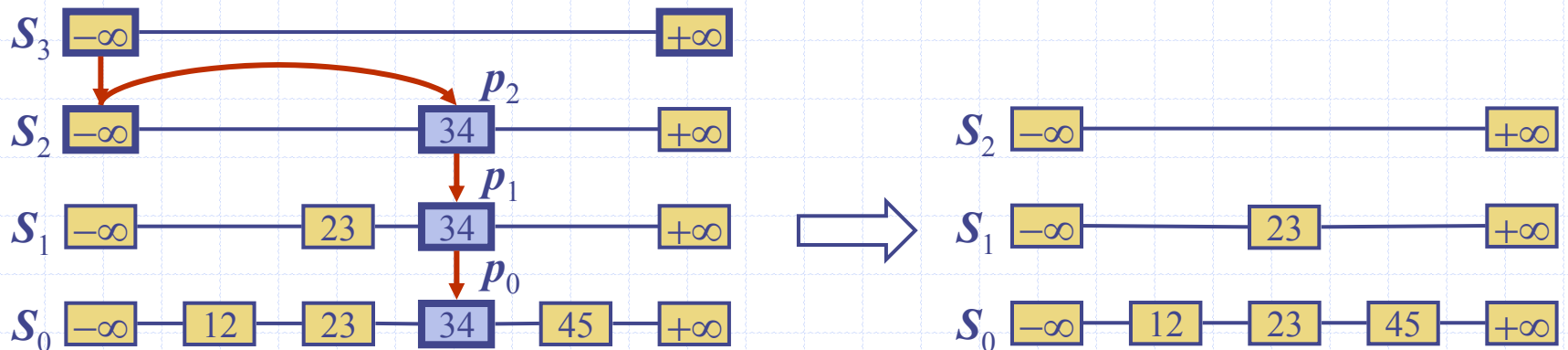
# Insertion

- ◆ To insert an entry  $(x, o)$  into a skip list, we use a randomized algorithm:
  - We repeatedly toss a coin until we get tails, and we denote with  $i$  the number of times the coin came up heads
  - If  $i \geq h$ , we add to the skip list new lists  $S_{h+1}, \dots, S_{i+1}$ , each containing only the two special keys
  - We search for  $x$  in the skip list and find the positions  $p_0, p_1, \dots, p_i$  of the items with largest key less than  $x$  in each list  $S_0, S_1, \dots, S_i$
  - For  $j \leftarrow 0, \dots, i$ , we insert item  $(x, o)$  into list  $S_j$  after position  $p_j$
- ◆ Example: insert key 15, with  $i = 2$



# Deletion

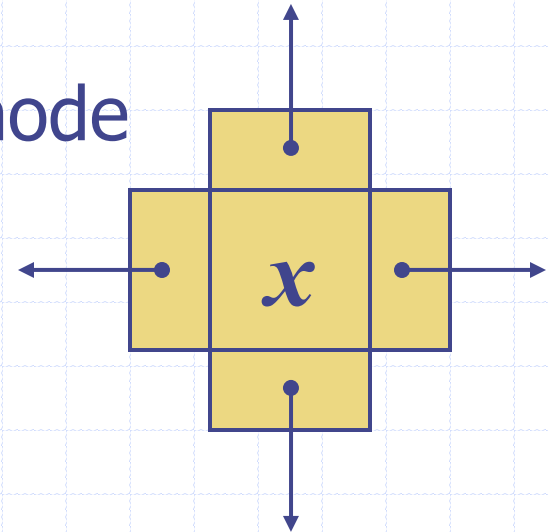
- ◆ To remove an entry with key  $x$  from a skip list, we proceed as follows:
  - We search for  $x$  in the skip list and find the positions  $p_0, p_1, \dots, p_i$  of the items with key  $x$ , where position  $p_j$  is in list  $S_j$
  - We remove positions  $p_0, p_1, \dots, p_i$  from the lists  $S_0, S_1, \dots, S_i$
  - We remove all but one list containing only the two special keys
- ◆ Example: remove key 34



# Implementation

- ◆ We can implement a skip list with quad-nodes
- ◆ A quad-node stores:
  - entry
  - link to the node prev
  - link to the node next
  - link to the node below
  - link to the node above
- ◆ Also, we define special keys `PLUS_INF` and `MINUS_INF`, and we modify the key comparator to handle them

quad-node



# Space Usage

- ◆ The space used by a skip list depends on the random bits used by each invocation of the insertion algorithm
- ◆ We use the following two basic probabilistic facts:
  - Fact 1:** The probability of getting  $i$  consecutive heads when flipping a coin is  $1/2^i$
  - Fact 2:** If each of  $n$  entries is present in a set with probability  $p$ , the expected size of the set is  $np$

- ◆ Consider a skip list with  $n$  entries
  - By Fact 1, we insert an entry in list  $S_i$  with probability  $1/2^i$
  - By Fact 2, the expected size of list  $S_i$  is  $n/2^i$
- ◆ The expected number of nodes used by the skip list is

$$\sum_{i=0}^h \frac{n}{2^i} = n \sum_{i=0}^h \frac{1}{2^i} < 2n$$

- ◆ Thus, the expected space usage of a skip list with  $n$  items is  $O(n)$



# Height

- ◆ The running time of the search and insertion algorithms is affected by the height  $h$  of the skip list
- ◆ We show that with high probability, a skip list with  $n$  items has height  $O(\log n)$
- ◆ We use the following additional probabilistic fact:  
**Fact 3:** If each of  $n$  events has probability  $p$ , the probability that at least one event occurs is at most  $np$
- ◆ Consider a skip list with  $n$  entries
  - By Fact 1, we insert an entry in list  $S_i$  with probability  $1/2^i$
  - By Fact 3, the probability that list  $S_i$  has at least one item is at most  $n/2^i$
- ◆ By picking  $i = 3 \log n$ , we have that the probability that  $S_{3 \log n}$  has at least one entry is at most
$$n/2^{3 \log n} = n/n^3 = 1/n^2$$
- ◆ Thus a skip list with  $n$  entries has height at most  $3 \log n$  with probability at least  $1 - 1/n^2$

# Search and Update Times

- ◆ The search time in a skip list is proportional to
  - the number of drop-down steps, plus
  - the number of scan-forward steps
- ◆ The drop-down steps are bounded by the height of the skip list and thus are  $O(\log n)$  with high probability
- ◆ To analyze the scan-forward steps, we use yet another probabilistic fact:
  - Fact 4:** The expected number of coin tosses required in order to get tails is 2
- ◆ When we scan forward in a list, the destination key does not belong to a higher list
  - A scan-forward step is associated with a former coin toss that gave tails
- ◆ By Fact 4, in each list the expected number of scan-forward steps is 2
- ◆ Thus, the expected number of scan-forward steps is  $O(\log n)$
- ◆ We conclude that a search in a skip list takes  $O(\log n)$  expected time
- ◆ The analysis of insertion and deletion gives similar results

# Summary

- ◆ A skip list is a data structure for dictionaries that uses a randomized insertion algorithm
- ◆ In a skip list with  $n$  entries
  - The expected space used is  $O(n)$
  - The expected search, insertion and deletion time is  $O(\log n)$
- ◆ Using a more complex probabilistic analysis, one can show that these performance bounds also hold with high probability
- ◆ Skip lists are fast and simple to implement in practice