

Chapter 8: Sorting in Linear Time

Lower Bound for Sorting

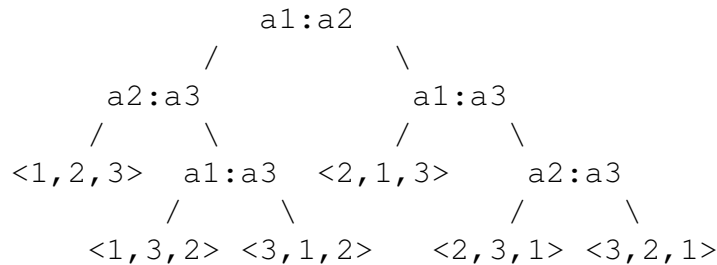
Comparison sort: A sorting algorithm is based only on comparisons between the input elements.

Comparison sorts can be viewed abstractly in terms of decision trees.

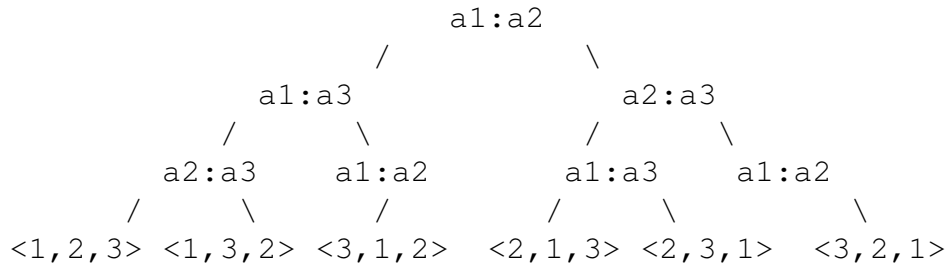
Decision trees: Given an input sequence $\langle a_1, a_2, \dots, a_n \rangle$,

- Each internal node is denoted by $a_i : a_j$, for $1 \leq i, j \leq n$.
- Each leaf node is denoted by a permutation $\langle \pi(1), \pi(2), \dots, \pi(n) \rangle$.
- Each path from the root to a leaf corresponds to an execution of the sorting algorithm for a specific input.
- The left branch of an internal node means $a_i \leq a_j$.
The right branch for an internal node means $a_i > a_j$.
- There are $n!$ permutations for n elements \implies there are at least $n!$ leaf nodes.

Ex: The decision tree for insertion sort with 3 elements.



Ex: The decision tree for selection sort with 3 elements.



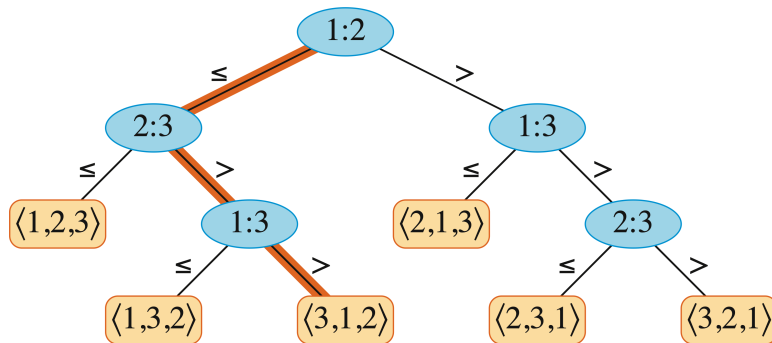
There are $n!$ permutations for n elements \implies the tree has at least $n!$ leaves.

Let h be the height of the tree \implies the tree has no more than 2^h leaves.

Thus,

$$n! \leq 2^h \implies h \geq \log(n!) \implies h = \Omega(n \log n)$$

The height of a decision tree means the number of comparisons for sorting in the worst-case.



\implies All comparison sorts have a lower bound running time $\Omega(n \log n)$ for the worst-case.

\implies It is impossible to find a new comparison based sorting algorithm that is asymptotically better than merge sort.

However, some non-comparison based sorting algorithms may run in linear time.

Counting Sort

Counting sort assumes that each of the n input elements is an integer within a range $[0..k]$, for some integer k .

An input array $A[1 : n]$, an output array $B[1 : n]$, and a temporary working storage $C[0 : k]$ are necessary for this algorithm. Thus, counting sort does not sort in place.

During the execution of counting sort, $C[i]$ maintains the # of elements less than or equal to i . For each element j in A , put it into B at position $C[j]$.

Counting-Sort(A, n, k)

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1. let  $B[1:n]$  and  $C[0:k]$  be new arrays
2. for  $i = 0$  to  $k$ 
3.      $C[i] = 0$ 
4. for  $j = 1$  to  $n$ 
5.      $C[A[j]] = C[A[j]] + 1$ 
6. //  $C[i]$  contains the # of elements that is equal to  $i$ 
7. for  $i = 1$  to  $k$ 
8.      $C[i] = C[i] + C[i-1]$ 
9. //  $C[i]$  now contains the # of elements less than or equal to  $i$ 
10. // Copy  $A$  to  $B$ , starting from the end of  $A$ 
11. for  $j = n$  downto  $1$ 
12.      $B[C[A[j]]] = A[j]$ 
13.      $C[A[j]] = C[A[j]] - 1$  // to handle duplicate values

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Ex:

	1	2	3	4	5	6	7	8
A	2	5	3	0	2	3	0	3

	0	1	2	3	4	5
C	2	0	2	3	0	1

(a)

	0	1	2	3	4	5
C	2	2	4	7	7	8

(b)

	1	2	3	4	5	6	7	8
B						3		

	0	1	2	3	4	5
C	2	2	4	6	7	8

(c)

	1	2	3	4	5	6	7	8
B		0					3	

	0	1	2	3	4	5
C	1	2	4	6	7	8

(d)

	1	2	3	4	5	6	7	8
B		0				3	3	

	0	1	2	3	4	5
C	1	2	4	5	7	8

(e)

	1	2	3	4	5	6	7	8
B	0	0	2	2	3	3	3	5

(f)

- Running time analysis:

Counting-Sort's running time is $\Theta(n + k)$.

If $k = O(n)$, then $\Theta(n + k) = \Theta(n)$. It's a linear time!

- Counting sort is a **stable** sorting algorithm: elements with the same value in the output array should be in the same order as they do in the input array.
 - Insertion Sort: stable (if no “=” sign in comparison)
 - Selection Sort: stable (if no “=” sign in comparison)
 - Merge Sort: stable (if the “=” sign is in the comparison)
 - Heap Sort: not stable (exchange $A[1] \rightarrow A[n]$)
 - Quick Sort: not stable.
- Ex: input: $\langle 5, 5', 5'', 3, 4 \rangle$ and the output is $\langle 3, 4, 5'', 5, 5' \rangle$.

Radix Sort

The Radix-Sort sorts by the least significant digit first, then by the 2nd least significant digit,

The sorting algorithm used to sort each digit should be stable; otherwise Radix-Sort will not work.

Ex:

213		321		312		123
312		312		212		132
123		212		213		212
212	stable	132	stable	321	stable	213
321	----->	213	----->	123	----->	312
132		123		132		321
^		^		^		

Ex:

213		321		312		123
312		312		213 <-		132
123		212		212 <-		213 <-
212	stable	132	not stable	321	stable	212 <-
321	----->	213	----->	123	----->	312
132		123		132		321
^		^		^		

Another example:

329	720	720	329
457	355	329	355
657	436	436	436
839	457	839	457
436	657	355	657
720	329	457	720
355	839	657	839

→ → →

Radix-Sort (A, d)

1. for i = 1 to d
2. use a stable sort to sort array A[1:n] on digit i

Two questions:

- Why does the algorithm need to use a stable sort to sort each digit?
- Why does the sorting start from sorting the least significant digit first?

Running time analysis: Suppose all n numbers have d or less digits.

If we use Counting-Sort as the sorting algorithm to sort each digit, then the running time for Radix-Sort is $d \cdot \Theta(n+k) = \Theta(dn+dk)$

If $k = O(n)$ and d is a constant, then the running time becomes $\Theta(n)$.

It's a linear time!

Recommended Exercise: Show how to sort n integers in the range 0 to $n^2 - 1$ in $O(n)$ time.

Solution:

We will assume that each digit has value in the range $0..n-1$, that is $k = n$. That is, as if the numbers are written in radix- n or base- n (instead of the usual base 2 or base 10).

Counting sort now requires $O(n+k) = O(n)$ time.

Then each number will have two digits, so $d = 2$ as the range of the numbers is $[0..n^2 - 1]$.

Since $d = 2$, radix-sort requires two passes of Counting sort that each take $O(n)$ time. This the total run-time for radix-sort for this type of input is $O(n)$.

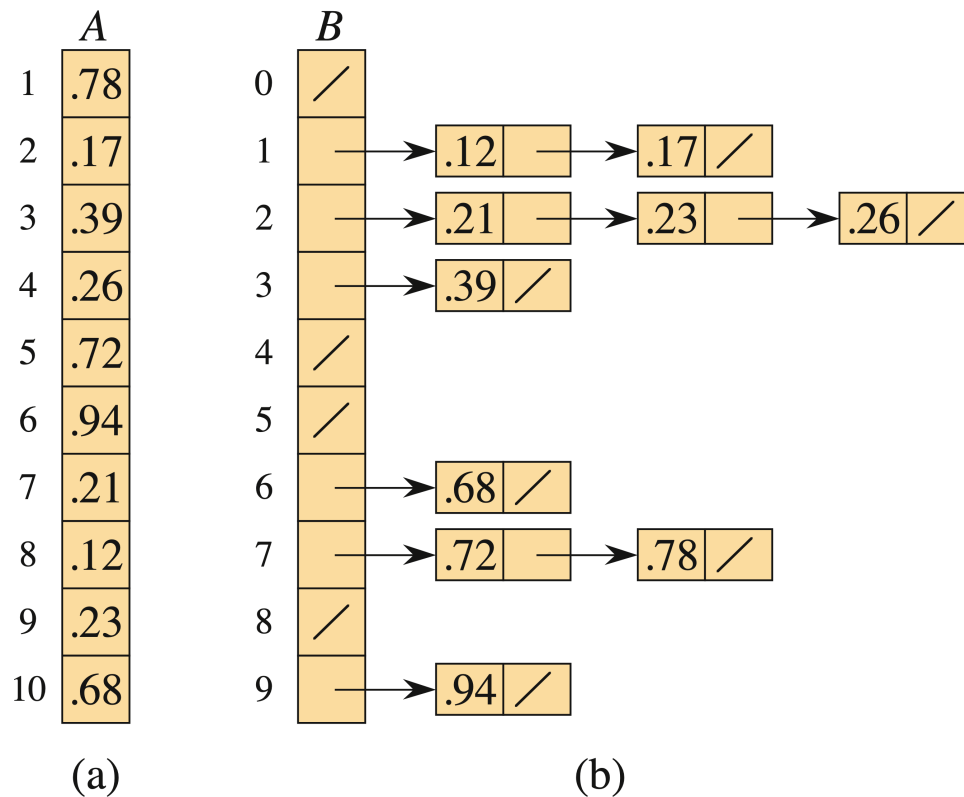
Bucket sort

Assumption: input is drawn from the range $[0..1)$ with a uniform probability distribution.

Average case is $O(n)$.

Bucket-Sort (A, n)

1. let $B[0..n-1]$ be a new array
2. for $i = 0$ to $n - 1$
3. make $B[i]$ an empty list
4. for $i = 1$ to n
5. insert $A[i]$ into list $B[\text{floor}(n A[i])]$
6. for $i = 0$ to $n - 1$
7. sort $B[i]$ using insertion sort
8. concatenate the lists $B[0], B[1], \dots, B[n-1]$ together in order
9. return the concatenated lists



If each list is of size $O(1)$, then the run-time is $O(n)$. The average case analysis requires advanced math so we will skip it here.

Notes: If the key values are uniformly distributed, we can still get $O(n)$ average case run time if we know the probability distribution. How can we take advantage of knowing the probability distribution to get all buckets to be of size $O(1)$ on the average?