

Algorithms and Data Structures

A12. Sorting: Quicksort (& Heapsort)

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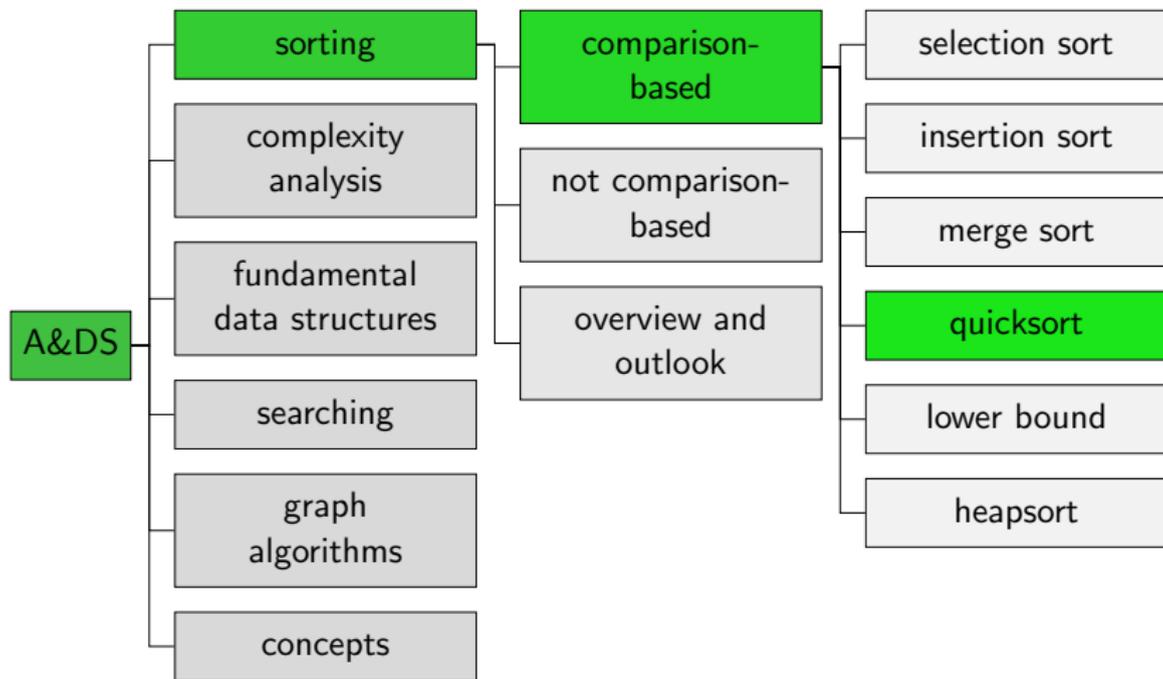
A12.1 Quicksort

A12.2 Heapsort

A12.3 Summary

A12.1 Quicksort

Content of the Course



Quicksort: Idea

- ▶ Like merge sort a **divide-and-conquer algorithm**.
- ▶ In contrast to merge sort, the sequence is not divided by position but by values.
- ▶ For this purpose, select one element P (the so-called **pivot**).
- ▶ Divide (rearrange) the array, such that P is at its final position, left of P there are only elements $\leq P$, and right of P only elements $\geq P$.



- ▶ Conquer by calling quicksort recursively for the ranges left of P and right of P .
- ▶ Combine by doing nothing (recursive calls already lead to fully sorted array).

Quicksort: Algorithm

```
1 def sort(array):
2     sort_aux(array, 0, len(array)-1)
3
4 def sort_aux(array, lo, hi):
5     if hi <= lo:
6         return
7     choose_pivot_and_swap_it_to_lo(array, lo, hi)
8     pivot_pos = partition(array, lo, hi)
9     sort_aux(array, lo, pivot_pos - 1)
10    sort_aux(array, pivot_pos + 1, hi)
```

How do we Choose the Pivot?

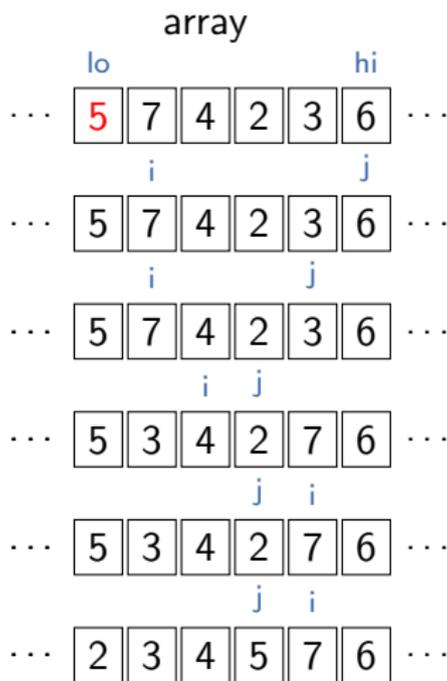
For the correctness of the algorithm, any choice is fine. (Why?)

Example strategies:

- ▶ **Naïve:** Always use the first element.
- ▶ **Median of Three:** Use median of first, middle and last element.
- ▶ **Randomized:** Use a random element.

Good pivots separate the range into roughly equally-sized ranges.

How do we Partition the Range?



Pivot is at position lo.

Initialize $i = lo + 1, j = hi$

i to the right until element \geq pivot

j to the left until element \leq pivot

If $i < j$: swap elements, $i++$, $j--$

i to the right until element \geq pivot

j to the left until element \leq pivot

$i \geq j$: swap pivot to position j

Done!

Quicksort: Partitioning

```
1 def partition(array, lo, hi):
2     pivot = array[lo]
3     i = lo + 1
4     j = hi
5     while (True):
6         while i < hi and array[i] < pivot:
7             i += 1
8         while array[j] > pivot:
9             j -= 1
10        if i >= j:
11            break
12
13        array[i], array[j] = array[j], array[i]
14        i, j = i + 1, j - 1
15    array[lo], array[j] = array[j], array[lo]
16    return j
```

Exercise

What is the content of array `[6, 5, 7, 8, 3]` after a call of `partition` for the entire range (from position 0 to 4)?



Partitioning: Variants

- ▶ partitioning performs **Hoare's partitioning** method.
 - ▶ Tony Hoare: British computer scientist, inventor of quicksort
- ▶ There is also Lomuto's partitioning:
 - ▶ Inferior to Hoare's method.
 - ▶ Three times more swaps on average.
 - ▶ Leads to bad running time if all elements are equal.
 - ▶ Since it is easier to explain and analyze, used in some teaching resources (e.g. Cormen et al. textbook).
- ▶ We only consider Hoare's method.

Quicksort: Running Time I

Best case: Pivot separates into equally-sized ranges.

- ▶ $O(\log_2 n)$ recursive calls
- ▶ Each has hi-lo key comparisons during partitioning.
- ▶ On a single recursion depth overall $O(n)$ comparisons in partitioning.

→ $O(n \log n)$

Worst case: Pivot always smallest or largest element.

- ▶ overall $n-1$ (nontrivial) recursive calls for length $n, n-1, \dots, 2$.
- ▶ Each has hi-lo key comparisons during partitioning.

→ $\Theta(n^2)$

Quicksort: Running Time II

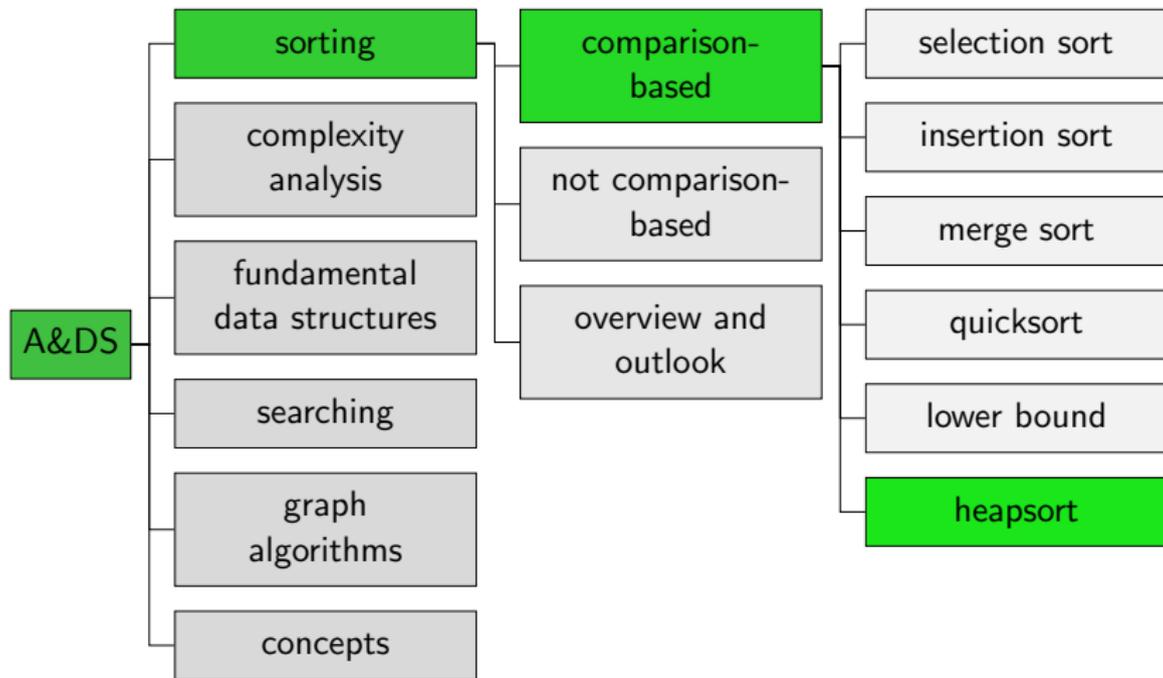
Average case:

- ▶ Assumption: n different elements, each of the $n!$ permutations has equal probability, random choice of pivot
- ▶ $O(\log n)$ recursive calls
- ▶ overall $O(n \log n)$
- ▶ $\approx 39\%$ slower than best case

With a random choice of the pivot, the worst case is extremely unlikely. Therefore, quicksort is often considered an $O(n \log n)$ algorithm.

A12.2 Heapsort

Content of the Course



Heapsort

- ▶ **Heap:** data structure that allows to find and remove the largest element quickly:
find: $\Theta(1)$, remove: $\Theta(\log n)$
- ▶ **Basic idea as in selection sort but from right to left:**
Successively swap the largest element to the end of the non-sorted range.
- ▶ We can **represent the heap directly in the input sequence**, so that heap sort only needs constant additional storage.
- ▶ The running time is linearithmic.
- ▶ We cover the details once we have introduced heaps.

A12.3 Summary

Summary

- ▶ **Quicksort** is a **divide-and-conquer** approach that divides the range relative to a **pivot** element.
- ▶ In the **worst case**, quicksort has **quadratic running time**.
- ▶ In the **average case**, the running time is **linearithmic**.
- ▶ With a random choice of the pivot, the worst case is extremely unlikely.