

Wiley-Blackwell 2023/24 6 / 28

Introduction Bubble sort Insertion sort Merge sort Quicksort Bucket/radix sort

Insertion sort

demonstration 7

```

for i in range(1, len(seq)):
    cur = seq[i]
    j = i
    while seq[j - 1] > cur and j > 0:
        seq[j] = seq[j - 1]
        j -= 1
    seq[j] = cur

```

C. Gökhan, BB / University of Tilburg Winter Semester 2021/22 6 / 26

Introduction Bubble sort Insertion sort Merge sort Quicksort Bucket/radix sort

Insertion sort

performance

- Worst case: $O(n^2)$ comparisons, $O(n^2)$ swaps
- Average case: $O(n^2)$ comparisons, $O(n^2)$ swaps
- Best case: $O(n)$ comparisons, $O(1)$ swaps
- Space complexity: $O(1)$
- In practice, insertion sort is faster than the bubble sort (and also selection sort)

```

for i in range(1, len(seq)):
    cur = seq[i]
    j = i
    while seq[j - 1] > cur and j > 0:
        seq[j] = seq[j - 1]
        j -= 1
    seq[j] = cur

```

C. Gökhan, BB / University of Tilburg Winter Semester 2021/22 7 / 26

Introduction Bubble sort Insertion sort Merge sort Quicksort Bucket/radix sort

Insertion sort

summary

- Insertion sort is simple
- It is efficient for short sequences
- For long sequences it is much worse than more advanced algorithms like merge sort or quicksort (coming next)
- It is in-place
- It is *online*: it can sort items as they arrive
- It is *stable*: it does not swap elements with equal keys
- It is *adaptive*: faster if order of elements is closer to the sorted sequence

C. Gökhan, BB / University of Tilburg Winter Semester 2021/22 8 / 26

Introduction Bubble sort Insertion sort Merge sort Quicksort Bucket/radix sort

Merge sort

Introduction

- Merge sort is a divide-and-conquer algorithm for sorting
- It is relatively easy to understand (once you get your head around recursion)
- It has good asymptotic performance
- There are many practical cases where merge sort is used
- Basic idea is divide-and-conquer:
 - split the sequence
 - sort the subsequences
 - merge the sorted lists

C. Gökhan, BB / University of Tilburg Winter Semester 2021/22 9 / 26

Introduction Bubble sort Insertion sort Merge sort Quicksort Bucket/radix sort

Merge sort

demonstration - divide

C. Gökhan, BB / University of Tilburg Winter Semester 2021/22 10 / 26

Introduction Bubble sort Insertion sort Merge sort Quicksort Bucket/radix sort

Merge sort

demonstration - combine

C. Gökhan, BB / University of Tilburg Winter Semester 2021/22 11 / 26

Introduction Bubble sort Insertion sort Merge sort Quicksort Bucket/radix sort

Merging sequences

```

# s1, s2: sequences to be merged
# s: target sequence
i, j = 0, 0
n = len(s1) + len(s2)
while i + j < n:
    if j == len(s2) or \
        i < len(s1) and s1[i] < s2[j]:
        s[i+j] = s1[i]
        i += 1
    else:
        s[i+j] = s2[j]
        j += 1

```

- Keep two indices on both sequences, starting from the beginning
- Pick the smallest, place it in the target sequence
- The algorithm requires $O(n)$ steps to complete

C. Gökhan, BB / University of Tilburg Winter Semester 2021/22 12 / 26

Introduction Bubble sort Insertion sort Merge sort Quicksort Bucket/radix sort

Complexity of the merge sort

$O(n) = n \log n$

C. Gökhan, BB / University of Tilburg Winter Semester 2021/22 13 / 26

Introduction Bubble sort Insertion sort Merge sort Quicksort Bucket/radix sort

Merge sort

the implementation

```

def merge_sort(a):
    n = len(a)
    if n <= 1: return a
    s1, s2 = a[:n//2], a[n//2:]
    merge_sort(s1)
    merge_sort(s2)
    merge(s1, s2, a)

```

- Once we have `merge()`, the rest is trivial:
 - Split the array into two
 - Recursively sort both sides
 - Stop when the input is length 1

C. Gökhan, BB / University of Tilburg Winter Semester 2021/22 14 / 26

Introduction Bubble sort Insertion sort Merge sort Quicksort Bucket/radix sort

Merge sort: summary

- Straightforward application of divide-and-conquer
- Worst case $O(n \log n)$ complexity (best/average cases are the same)
- Merge sort is not in-place: requires $O(n)$ additional space
- It is particularly useful for settings with low random-access memory, or sequential access
- Merge sort is stable
- It is a well studied algorithm, there are many variants (in-place, non-recursive)

C. Gökhan, BB / University of Tilburg Winter Semester 2021/22 15 / 26

Introduction Bubble sort Insertion sort Merge sort Quicksort Bucket/radix sort

A short divergence to complexity

the difference between $O(n^2)$ and $n \log n$

n	$n \log n$	n^2
2	2	4
8	24	64
64	384	4096
1K	10240	1 048 576
1M	20 971 520	1 099 511 627 776
1G	32 212 254 720	1 152 921 504 606 846 976

C. Gökhan, BB / University of Tilburg Winter Semester 2021/22 16 / 26

Introduction Bubble sort Insertion sort Merge sort Quicksort Bucket/radix sort

A short divergence to complexity

the difference between $O(n^2)$ and $n \log n$

C. Gökhan, BB / University of Tilburg Winter Semester 2021/22 17 / 26

Introduction Bubble sort Insertion sort Merge sort **Quicksort** Bucket sort

Quicksort

introduction

- Quicksort is another popular divide-and-conquer sorting algorithm
- The main difference from the merge sort is that big part of the work is done before splitting
- Its worst time complexity is $O(n^2)$, but in practice it performs better than merge sort on average
- General idea: pick a pivot p , and divide the sequence into three parts as
 - L: smaller than a particular element p
 - G: larger than a particular element p
 - E: equal to a particular element p
- sort L and G recursively
- combination is simple concatenation

C. G. Kölsch, SR | University of Tübingen Winter Semester 2023/24 17 / 38

Introduction Bubble sort Insertion sort Merge sort **Quicksort** Bucket sort

Quicksort

demonstration – divide

At each divide step

- Pick a **pivot**
- Recursively call quicksort twice
 - L: for items less than the pivot
 - G: for items greater than the pivot
- $O(n)$ operations

C. G. Kölsch, SR | University of Tübingen Winter Semester 2023/24 18 / 38

Introduction Bubble sort Insertion sort Merge sort **Quicksort** Bucket sort

Quicksort

demonstration – combine

At each combine step:

- Simply concatenate
 - L: the sorted items less than p
 - E: items equal to p
 - G: the sorted items greater than p
- No need for $O(n)$ merging

C. G. Kölsch, SR | University of Tübingen Winter Semester 2023/24 19 / 38

Introduction Bubble sort Insertion sort Merge sort **Quicksort** Bucket sort

Quicksort

Python three-line implementation

```
def qsort(seq):
    if len(seq) <= 1: return seq
    return qsort([x for x in seq if x < seq[-1]]) +
           [x for x in seq if x == seq[-1]] +
           qsort([x for x in seq if x > seq[-1]])
```

- Practical implementations are not very different
- Common improvements include
 - in-place sorting
 - selecting the pivot more carefully

C. G. Kölsch, SR | University of Tübingen Winter Semester 2023/24 20 / 38

Introduction Bubble sort Insertion sort Merge sort **Quicksort** Bucket sort

Quicksort

analysis

- Similar to the merge sort, quicksort performs $O(n)$ operations at each level in recursion
- The overall complexity is proportional to $n \times \ell$, where ℓ is depth of the tree
- The recursion tree of merge sort is balanced, so depth is $\log n$.
- For quicksort, we do not have a balanced-tree guarantee
- In the worst case, the depth of the tree can be n , resulting in $O(n^2)$ complexity

C. G. Kölsch, SR | University of Tübingen Winter Semester 2023/24 21 / 38

Introduction Bubble sort Insertion sort Merge sort **Quicksort** Bucket sort

Quicksort

average-case complexity and preventing the worst case

- Worst case of the quicksort is when the input sequence is sorted
- If the input sequence is (approximately) random, the *expected* number of elements in each divide is $n/2$
- To reduce the probability of worst case, *randomized* quicksort picks the pivot randomly
- Best case happens if we pick the *median* of the sequence as the pivot, but finding median already requires $O(n \log n)$ (or $O(n)$, but not very practical)
- A common approach is picking three values (typically first, middle and last) from the sequence, and selecting the 'median of three' as the pivot

C. G. Kölsch, SR | University of Tübingen Winter Semester 2023/24 22 / 38

Introduction Bubble sort Insertion sort Merge sort **Quicksort** Bucket sort

Quicksort

summary

- Complexity: $O(n \log n)$ average, $O(n^2)$ worst
- Despite its worst-case $O(n^2)$ complexity, quicksort is faster than merge sort on average (in practice)
- The algorithm can easily be implemented in-place (in-place version is more common)
- Quicksort is not stable
- Quicksort is one of the most-studied algorithms: there are many variants, its properties are well known

C. G. Kölsch, SR | University of Tübingen Winter Semester 2023/24 23 / 38

Introduction Bubble sort Insertion sort Merge sort **Quicksort** Bucket sort

Sorting algorithms so far, and the lower bound

Algorithm	worst	average	best	memory	in-place	stable
Bubble sort	n^2	n^2	n	1	yes	yes
Insertion sort	n^2	n^2	n	1	yes	yes
Merge sort	$n \log n$	$n \log n$	$n \log n$	n	no	yes
Quicksort	n^2	$n \log n$	$n \log n$	$\log n$	yes	no

- Can we do better than $O(n \log n)$?
- If our sorting algorithms requires comparing individual elements, the answer turns out to be 'no'
- Lower bound of worst-case sorting is $\Omega(n \log n)$
- In some special cases, linear-time complexity is possible

C. G. Kölsch, SR | University of Tübingen Winter Semester 2023/24 24 / 38

Introduction Bubble sort Insertion sort Merge sort **Quicksort** Bucket sort

Bucket sort

introduction

- Bucket sort puts elements of the input into a pre-defined number of ordered 'buckets'
- Elements in each bucket are sorted (typically using insertion sort)
- We can then retrieve the sorted elements by visiting each bucket
- The bucket sort *does not compare elements* to each other when deciding which bucket to place them
- In special cases, this results in $O(n)$ worst-case complexity

C. G. Kölsch, SR | University of Tübingen Winter Semester 2023/24 25 / 38

Introduction Bubble sort Insertion sort Merge sort **Quicksort** Bucket sort

Bucket sort

demonstration

- While placing the elements into the buckets, no comparisons between the keys
- Inside the buckets worst-case $O(n^2)$ (insertion sort)
- What if we had as many buckets as the keys?
 - n insertion operations
 - n retrieval operations
 - $O(n)$ sorting time

C. G. Kölsch, SR | University of Tübingen Winter Semester 2023/24 26 / 38

Introduction Bubble sort Insertion sort Merge sort **Quicksort** Bucket sort

Radix sort

- In a large number of cases, we want to sort objects with multiple keys
- In such cases, we define the order of key pairs as $(k_1, l_1) < (k_2, l_2)$ if $k_1 < k_2$, or $k_1 = k_2$ and $l_1 < l_2$
- This definition can be generalized to key tuples of any length
- This ordering is known as *lexicographic* or dictionary order
- Radix sort is the name for the technique that uses multiple stable bucket sorts for this purpose

C. G. Kölsch, SR | University of Tübingen Winter Semester 2023/24 27 / 38

Introduction Bubble sort Insertion sort Merge sort **Quicksort** Bucket sort

Summary

- Sorting is an important and well-studied computational problem
- Most sorting algorithms/applications used in practice are highly optimized, often based on multiple basic algorithms
- Naive sorting algorithms run in $O(n^2)$ time
- Lower bound on worst-case sorting time is $\Omega(n \log n)$, divide-and-conquer algorithms achieve this
- Reading: Goodrich, Tamassia, and Goldwasser (2013, chapter 12)
- And a fun way to see sorting in action: <https://www.youtube.com/user/AlgoRythmics>

Next:

- Trees
- Reading: Goodrich, Tamassia, and Goldwasser (2013, chapter 8)

C. G. Kölsch, SR | University of Tübingen Winter Semester 2023/24 28 / 38

Acknowledgments, credits, references

 Goodrich, Michael T., Roberto Tamassia, and Michael H. Goldwasser (2013). *Data Structures and Algorithms in Python*. John Wiley & Sons, Incorporated. [isrc: 9781118476734](#).